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Yemen Fisheries and Climate Change

State Fragility initiative

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الجهاز التنفيذي
The Executive Bureau

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About

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Contents

Acronym

Ω	Aragonite
°C	Degree Celsius
Chl-a	Chlorophyll-a
CNN	Convolutional Neural Network
CO_2	Carbon Dioxide
CPUE	Catch-per-unit-effort
DIC	Dissolved Inorganic Carbon
DJF	December-January-Fenruary
ENSO	El Niño–Southern Oscillation
FAO	Food and Agriculture Organisation of the United Nations
GDP	Gross Domestic Product
HAB	Harmful Algal Bloom
IUU	Illegal, Unreported, and Unregulated
IRG	Internationally Recognized Government
JJA	June-July-August
KSA	Kingdom of Saudi Arabia
m	metre
MAM	March-April-May
MoAIF	Ministry of Agriculture, Irrigation and Fisheries
MSBRA	Marine Science and Biological Research Authority
OMZ	Oxygen Minimum Zone
PERSGA	Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden
PSU	Practical Salinity Units
SON	September-October-November
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TA	Total Alkalinity
USD	United States Dollar

Glossary

Aragonite Saturation: A measure indicating ocean water's capacity to support the formation and preservation of calcium carbonate shells in marine organisms.

Argo Float: Autonomous instruments drifting in oceans, measuring temperature, salinity, and other oceanographic variables to depths of 2,000 meters.

Atmospherics: Environmental factors related to the atmosphere, including weather conditions and gaseous composition.

Boron Isotope: A chemical tracer in marine science used to reconstruct past ocean pH and carbonate chemistry conditions.

Calcification: Biological process by which marine organisms, such as corals and shellfish, form calcium carbonate structures.

Carbonate Chemistry: Study of chemical equilibrium involving dissolved carbon dioxide and carbonate ions in seawater, crucial for marine life.

Catch-per-unit-effort (CPUE): A measure of fish abundance, calculated by dividing the catch by fishing effort.

Chlorophyll-a: The primary pigment in phytoplankton used as an indicator of marine productivity.

Convolutional Neural Network (CNN): A deep learning algorithm specialized in image processing and pattern recognition tasks.

Demersal: Marine organisms that live near or on the ocean floor.

Dissolved Inorganic Carbon (DIC): Total amount of carbon dioxide, bicarbonate, and carbonate ions dissolved in seawater.

El Niño–Southern Oscillation (ENSO): A periodic climate pattern characterized by variations in ocean surface temperatures and atmospheric conditions across the tropical Pacific Ocean.

Fishing Effort: The amount of resources (time, equipment, labor) used to catch fish.

Freshening: A decrease in ocean salinity, typically due to increased freshwater input.

In situ: Measurements or observations taken directly in the natural environment where phenomena occur.

Indian Ocean Dipole (IOD): A climate phenomenon involving sea surface temperature differences between eastern and western Indian Ocean waters, affecting global weather patterns.

Marine Heatwaves: Prolonged periods of abnormally high ocean temperatures impacting marine ecosystems.

mg/m³: Milligrams per cubic meter, a unit commonly used to measure concentrations of substances in water or air.

Moored Buoy: Anchored oceanographic instruments that continuously collect environmental data at fixed locations.

NASA MODIS-aqua Pod: An ocean-monitoring instrument onboard NASA's Aqua satellite providing high-resolution data on ocean color, chlorophyll, and productivity.

Ocean Acidification: A decrease in ocean pH caused by the absorption of atmospheric carbon dioxide.

Ocean pH: A scale measuring seawater acidity or alkalinity.

Oligotrophic: Waters characterized by low nutrient levels and biological productivity.

Oxygen Minimum Zone (OMZ): A mid-water ocean layer where dissolved oxygen concentrations are exceptionally low.

Pelagic Fish: Fish species living in the upper layers of the water (tuna, mackerel, and the Bayad fish family).

Phenology: The study of timing of biological events in organisms in relation to climate and environmental conditions.

Phytoplankton: Microscopic marine algae performing photosynthesis, forming the base of oceanic food webs.

Phytoplankton Blooms: Rapid increases in phytoplankton abundance and biomass, typically linked to nutrient availability.

Planktonic Pteropods: Free-swimming marine snails sensitive to ocean acidification, important indicators of ecosystem health.

PSU: Practical Salinity Units, a dimensionless unit for measuring seawater salinity.

Salinization: Increase in water salinity typically due to evaporation, saltwater intrusion, or reduced freshwater input.

Sea Surface Salinity: Concentration of dissolved salts on the ocean surface.

Sea Surface Temperature (SST): Temperature of the ocean's surface waters, crucial for climate and ecosystem dynamics.

SEABASS: SNASA's repository for marine bio-optical data.

Sediment Suspension: Resuspension of sediment particles within the water column due to turbulence or currents.

Stability/Stable Layer: A stratified layer of water resistant to mixing due to density gradients.

Temporal: Relating to changes occurring over time.

Thermal Stratification: Vertical layering in the ocean due to temperature differences.

Total Alkalinity: A measure of seawater's capacity to neutralize acids, influencing carbonate chemistry.

Turbidity: Degree to which water loses transparency due to suspended particles.

Upwelling: Process where deeper, nutrient-rich ocean water rises toward the surface, stimulating productivity.

Winter Stratification: Formation of layered ocean waters during colder months due to differences in temperature and salinity.

You Only Look Once (YOLO): A real-time object detection algorithm widely used in computer vision.

Zooplankton: Heterotrophic microscopic organisms drifting in the ocean, feeding primarily on phytoplankton.

Executive Summary

Yemen's extensive coastline, encompassing the southern Red Sea, Gulf of Aden, and northwest Arabian Sea, is home to rich marine biodiversity and historically productive fisheries, crucial for the nation's economy, food security, and livelihoods (Figure 1). However, the intersection of global climate change and a prolonged internal conflict has significantly disrupted marine ecosystems and fisheries management, exacerbating already critical challenges.

This report addresses these pressing issues through two interconnected analyses. The first examines recent climate-driven changes in marine ecosystem health indicators, providing insights into seasonal variability, long-term trends, and impacts from extreme climate events such as Cyclone Tej in 2023. The second analysis investigates the status of Yemen's fisheries, highlighting historical trends, the impacts of conflict, and gaps in current monitoring and management practices.

Leveraging innovative methodologies, satellite remote sensing, computer vision, and collaborative in situ data collection, the report aims to present a cohesive framework for revitalizing Yemen's marine research and fisheries management. Ultimately, the findings underscore the urgency of implementing targeted, adaptive, and evidence-based policies to sustain Yemen's coastal ecosystems and the livelihoods dependent upon them.

The report is structured as follows: Section 1 presents analysis of seasonal variability, climate shocks and extreme events along with longer-term temporal trends on temperature, oceanic biomass and productivity, salinity and ocean acidification in Yemen's coastal waters; Section 2 presents analysis of the fisheries sector, notably identifying the existing data gaps and the absence of reliable monitoring as a result of the ongoing unrest; based on these analyses, Section 3 proposes a framework for the creation of a dynamic fisheries monitoring and management model; and Section 4 concludes with policy recommendations.

While this study does not include formal projections, observed decadal trends across Yemen's marine regions allow for indicative interpretation of the likely direction of change in key ecosystem indicators. The table below summarizes historical trajectories (2004 – 2024) of these variables, which may inform expectations of future biological productivity if current drivers persist.

Geographic Area	**Sea Surface Temperature (SST)**	**Chlorophyll-a (Productivity)**	**Sea Surface Salinity (SSS)**	**Proxy for Ocean Acidification**	**Overall Outlook for Biological Productivity**
Northern Red Sea	↑ Strong warming (~+0.4 °C per decade)	↓ Moderate decline from stratification	↑ Salinization	↓ Increased acidification risk (alkalinity limited)	**Unfavourable:** Thermal stress + lower nutrients
Southern Red Sea	↑ Warming (~+0.2 °C per decade)	↔ Stable to slightly ↑ (localized upwelling)	↑ Slightly	↔ Moderate buffering capacity	**Mixed:** Some resilient zones, but warming continues
Gulf of Aden	↑ Warming (~+0.3 °C per decade)	↓ in western Gulf / ↑ east (variability linked to monsoon)	↓ Freshening (~0.3 PSU / decade)	↔ Likely stable due to mixing and alkalinity input	**Mixed-Declining:** High variability, upwelling under stress
Eastern Arabian Sea Coast	↑ Warming (~+0.5 °C per decade)	↑ Localized Chl-a (> 3 mg/m³ in monsoon months)	↓ Mild freshening	Unclear trend	**Relatively Favourable:** Upwelling still strong but warming may erode benefits
Socotra Archipelago	↑ Warming trend	↓ Productivity near shore (post-cyclone turbidity) but ↑ offshore blooms	↔ Variable	↔ Likely stable	**Seasonally Favourable: Cyclone-sensitive**

Table 1. Historical summary of key maritime indicators along Yemen coastline (2004 – 2024)

1. Climate Analysis

1.1 Introduction

Yemen's coastal waters span a unique confluence of marine regions, the southern Red Sea, the Gulf of Aden, and the northwest Arabian Sea, all of which are experiencing the impacts of global climate change (Figure 1). Rising ocean temperatures, shifting productivity, and changes in ocean salinity can disrupt marine food webs and fisheries, posing new challenges for coastal communities. Over the past decade, research in the region and similar neighboring waters has intensified as countries have sought to monitor these indicators and assess the consequences for marine ecosystems and fisheries. However, since the start of the conflict in 2014, direct studies focusing on Yemen's waters remain limited, creating knowledge gaps that this work aims to highlight and fill. Below, we review recent peer-reviewed studies on temperature, oceanic biomass and productivity, salinity and ocean acidification in Yemen's coastal context. Our area of focus includes findings from the Red Sea, Gulf of Aden, and Arabian Sea, and we further assess implications for marine health and fisheries. We then conduct analysis to highlight seasonal variability, climate shocks and extreme events along with longer-term temporal trends.

Figure 1: Map of Yemen coastline

1.2. Indicators of Marine Ecosystem Health

Climate change is reshaping marine environments worldwide and four diverse, widely monitored factors, Surface Sea Temperature (SST), Chlorophyll-a (Chl-a), Surface Sea Salinity

(SSS) and Ocean Acidification, have emerged as critical indicators of ecosystem health under these shifting conditions. When examined together, SST, Chl-a, SSS and Ocean Acidification paint a comprehensive picture of the thermal, biological, and chemical stresses facing coastal regions, helping researchers and policymakers track changes, anticipate cascading impacts on fisheries, and prioritize conservation efforts.

SST directly influences metabolic rates of oceanic organisms, species distributions, and the prevalence of thermal stress events (like coral bleaching and marine heatwaves). Ocean warming is a major consequence of climate change, and even modest warming can push warm-water organisms toward their thermal tolerance limits (Chaidez, V., et al. 2017). Marine species respond by shifting their migration ranges and altering seasonal behaviors (phenology) to cope with warming. In tropical seas, higher SSTs have been linked to habitat degradation (for e.g., coral reef bleaching) and changes in fish spawning and migration patterns (Chaidez, V., et al. 2017). Thus, SST anomalies serve as a key indicator of marine ecosystem stress and are closely monitored for impacts on biodiversity and fisheries.

Chl-a is a proxy for phytoplankton biomass and primary production, forming the base of the marine food web. It is a key bioindicator of phytoplankton and marine productivity, making it crucial for monitoring the health of marine ecosystems (Yang, M., et al. 2024). High Chl-a generally signifies productive waters that can support abundant zooplankton, fish, and other marine life, whereas declining Chl-a may signal reduced nutrient supply or ecosystem infertility. Many studies use Chl-a to gauge the capacity of waters to support fisheries, since fluctuations in phytoplankton can cascade to affect fish stock productivity (Yang, M., et al. 2024). Chl-a variability is tightly linked to marine ecosystem health and fishery yields, especially in upwelling regions like the Gulf of Aden and Arabian Sea where seasonal plankton blooms fuel food webs.

Ocean Acidification refers to the long-term decrease in ocean pH due to absorption of atmospheric carbon dioxide (CO_2). It affects the ability of many organisms to calcify (build shells or skeletons) and can alter ecosystem structure. Meta-analyses of biological responses to Ocean Acidification reveal reductions in survival, calcification, growth, development, and abundance across a broad range of marine organisms as pH drops (Kroeker, K.J., et al. 2013). Heavily calcified organisms such as corals, mollusks, and some plankton are among the most negatively impacted. Coral reefs, which serve as fish nursery habitats, are particularly vulnerable; acidification weakens coral skeletons and can slow reef growth, threatening reef-associated fisheries. Oceanic organisms are further affected as reef degradation and food web changes alter their habitats. Monitoring pH and carbonate chemistry (Ω aragonite saturation) is important for assessing long-term ecosystem health. Ocean Acidification has emerged as a key indicator of marine stress under climate change, on par with temperature changes, especially for regions with coral reefs or shellfish fisheries.

Sea Surface Salinity is the concentration of dissolved salts in the surface ocean, typically measured in practical salinity units (PSU). SSS is a key indicator of the water cycle (balance of evaporation and precipitation) and influences ocean circulation and stratification. In Yemen's region, salinity varies widely: the northern Red Sea is one of the saltiest open-ocean regions on Earth (SSS ~40 PSU or higher) due to intense evaporation and minimal freshwater input, whereas the Gulf of Aden and Arabian Sea have lower salinities (~35–37 PSU) influenced by exchange with the Indian Ocean and monsoon rains. Salinity, together with temperature, determines seawater density and thus drives thermohaline circulation patterns. For instance, the outflow of dense, salty water from the Red Sea into the Gulf of Aden changes in SSS can alter these circulation patterns and vertical mixing. Additionally, salinity affects carbonate chemistry: higher salinity leads to higher total alkalinity, enhancing the water's buffering capacity against pH changes, whereas lower salinity (from excess rainfall or runoff) can reduce alkalinity and potentially exacerbate acidification effects. SSS can also directly impact marine life; many species have narrow salinity tolerances especially during early life stages. In coastal areas, heavy rainfall or drought can swing salinity and stress mangroves, corals, and fish. Thus, tracking SSS provides insight into regional climate shifts (like changes in rainfall/evaporation) and their potential to influence ocean structure and ecosystems.

1.3. Regional Studies on Climate Change Impacts

1.3.1. Warming Trends in Sea Surface Temperature

Recent observations and research show that Yemen coastal waters are warming at rates exceeding the global average. In the Red Sea, satellite records show rapid warming over recent decades. The Red Sea's average SST has been rising about 0.17 ± 0.07 degree Celsius (°C) per decade (1982–2015), with the northern Red Sea warming even faster at 0.40–0.45 °C per decade, far above the global ocean warming rate of 0.11 °C (Chaidez, V., et al. 2017). This accelerated warming makes the Red Sea one of the fastest-warming marine regions, raising concerns about thermal stress on Red Sea corals and fisheries. Similar warming trends have been observed in the Arabian Sea. Although literature specific to Yemen's Arabian Sea coast is sparse, broader Indian Ocean analyses indicate significant SST increases. For example, a recent analysis of marine heatwaves (MHWs) found a significant warming trend over the last 40 years, with an intensification after 2016 (Hamdeno, M., et al. 2024). This accelerated warming led to more frequent and prolonged MHW events in the past decade, which can devastate marine life. Such findings suggest that Yemeni coastal waters, being part of these larger basins, are very likely experiencing similar rapid warming and more frequent extreme heat events. Warmer waters in the Gulf of Aden and Arabian Sea can drive tropical species to deeper or higher-latitude waters and may alter upwelling dynamics that local fisheries depend on.

1.3.2. Chlorophyll-a and Productivity Patterns

Yemen's adjacent seas are strongly influenced by monsoon-driven upwelling and have distinct seasonal phytoplankton cycles. A notable study by Gittings et al. (2017) focused on the Gulf of Aden using 15 years of satellite Chl-a data. The Gulf of Aden was described as a "relatively unexplored ecosystem" with historical data limitations, but the study revealed a detailed seasonal succession of phytoplankton blooms. Two primary blooms occur in separate seasons: a major bloom in summer and a secondary bloom in autumn (shown in figure 7). During the Southwest (SW) monsoon in mid-summer (July–August), strong SW winds induce coastal upwelling along the northern coastline of the gulf (Yemen), leading to an increase in nutrient availability and enhancing phytoplankton growth along the coastline and in the western part of the gulf. This summer bloom peaks in August, with Chl-a levels along Yemen's coast reaching roughly three times higher than those of the autumn bloom. In contrast, during the Northeast (NE) monsoon (around November), winds reverse and drive upwelling along the southern coast of the gulf (Somalia), fueling a smaller autumn phytoplankton bloom in the southern and central Gulf of Aden. These findings highlight how monsoonal wind oscillations regulate nutrient supply and productivity in the region, a dynamic also noted in the broader Arabian Sea.

In the open Arabian Sea, seasonal Chl-a patterns are likewise dominated by the monsoons, with high productivity in summer due to SW monsoon upwelling and a second, lower peak in winter during the NE monsoon (Yang, M., et al. 2024). The Arabian Sea is recognized as one of the world's most productive marine regions owing to these monsoonal cycles. Recent research by Yang et al. (2024) confirmed pronounced seasonal variability, with Chl-a concentrations often exceeding 3 mg/m^3 during the SW monsoon in the western Arabian Sea (near the Yemeni-Omani coasts). The same study, however, also assessed long-term trends and found signs of declining productivity in some areas. Significant Chl-a declines were detected along the coasts of the Arabian Sea and Persian Gulf (on the order of –0.002 mg/m^3 per year) over the two-decade period, while slight increases were seen in the southeastern Arabian Sea. Notably, rising SST anomalies were correlated with reduced Chl-a in the western Arabian Sea, suggesting that warming and stratification may be suppressing nutrient upwelling or otherwise inhibiting phytoplankton in coastal waters. In other words, the data hints that climate warming is making some traditionally productive coastal zones less fertile over time, even as open-ocean or southern areas see minor gains. These trends raise concerns for Yemen's fisheries, which depend on coastal upwelling productivity.

It is important to note that interannual variability (due to climate oscillations like the Indian Ocean Dipole or El Niño–Southern Oscillation (ENSO)) can modulate these trends, and robust conclusions on climate-driven Chl-a changes require a long time series and contextual understanding. The Red Sea for instance has its own internal trends: some studies suggest a slight increase in Chl-a in the southern Red Sea over recent decades, potentially due to increased water exchange or wind variability. The central Red Sea Chl-a may be declining as the region warms and stratifies (Alawad, K. A. et al., 2020). Nonetheless, regional studies consistently support using Chl-a as a health metric: healthy upwelling years show high Chl-a and likely better fisheries yields, whereas warming or anomalous conditions can diminish Chl-a and signal potential declines in fish productivity (Yang, M., et al. 2024). Given Yemen's reliance on fisheries, monitoring Chl-a in its waters is crucial.

1.3.3. Ocean Acidification and Carbonate Chemistry

Compared to SST and Chl-a, research on ocean acidification in the Red Sea and Gulf of Aden region is relatively sparse, but global and Indian Ocean studies provide context. The Red Sea's unique properties (high temperature and salinity, limited water circulation) mean its carbonate system differs from the open ocean. A comparative study of the Arabian Sea and Red Sea found a stark contrast in baseline saturation states: the Arabian Sea becomes undersaturated with respect to aragonite ($\Omega<1$) below about 600 m depth, whereas the Red Sea remains supersaturated throughout its water column (Omer W. M. M., 2016). This implies that deep waters in the Arabian Sea are already corrosive to aragonitic shells (partly due to respiration and CO_2 accumulation in its oxygen minimum zone), while the Red Sea's enclosed basin retains higher alkalinity. Surface pH in both seas still hovers slightly above 8.0 today, but the long-term trend is downward (Omer W. M. M., 2016). Reconstructions of Arabian Sea surface pH (from proxies like boron isotopes) indicate a clear decline since the industrial revolution, mirroring global ocean acidification (Osman, M. et al. 2020).

The biological implications of acidification are of great concern, as numerous studies worldwide have shown lowering pH and carbonate saturation hampers calcification in corals, coralline algae, mollusks, and many plankton, often reducing their growth and survival (Kroeker, K.J., et al. 2013). Coral reefs in the southern Red Sea and Gulf of Aden, including Yemen's Socotra archipelago, could face increasing difficulty in calcifying if local waters acidify significantly. While some Red Sea coral communities (especially in the north) have shown resilience to warming and acidification in short-term laboratory studies (Menoud M., 2017), this resilience may not hold indefinitely as carbonate chemistry continues to change. The loss of coral reef structure due to bleaching or acidification would negatively affect fisheries, since reefs serve as critical spawning and nursery areas and support fish biodiversity. Likewise, shellfish populations (oysters, clams) could suffer thinner shells, and planktonic pteropods ("sea butterflies"), important in the food chain, may decline, with ripple effects to the larger food chain and ecosystem. For these reasons, Ocean Acidification is tracked as an essential climate change indicator. In Yemen's context, direct observations of pH or aragonite saturation are lacking in recent literature, representing a gap. However, based on global projections, we expect that Yemen's coastal waters are following the global trend of acidification, albeit perhaps moderated by local factors (for e.g., Red Sea's high alkalinity).

1.3.4 Salinity Patterns and Changes

Salinity in the Red Sea and Gulf of Aden mainly reflects intense evaporation balanced by inflow. The Red Sea loses more water to evaporation than it gains through rainfall or rivers, so salts concentrate and raise salinity (PERSGA 2020). Fresher water from the Gulf of Aden flows in at the surface, while very salty Red Sea water exits at depth, creating a gradient from "moderately high" in the south to "very high" in the northern Red Sea. In contrast, the Gulf of Aden and Arabian Sea are connected to the broader Indian Ocean and see seasonal monsoon rains, keeping them moderately salty. Climate change is intensifying these patterns. Dry, evaporation-heavy regions get saltier while wet areas get fresher (Kim, Y., Brodnitz, S. 2023). Studies confirm that the Red Sea, already quite saline, and has become even saltier due to rising evaporation and reduced exchange with fresher sources (Mohamed and Skliris 2025). Salinity in the Arabian Sea is also increasing, partly from greater outflow of very salty water from the Persian Gulf and Red Sea (Cheng et al, 2020).

Regional rainfall can briefly lower coastal salinity, but overall aridity drives a steady rise. Globally, SSS extremes have become more pronounced, matching observations in the Red Sea and Arabian Sea. In the Red Sea, very salty surface water can sink, potentially strengthening its vertical circulation. In the Gulf of Aden, denser inflows from the Red Sea may alter nutrient transport and oxygen levels. While most marine life here tolerates high salinity, sudden spikes can still cause stress, especially if climate change intensifies swings in rainfall or evaporation. Monitoring already shows salinity-linked shifts in coral communities (Roik A. et al., 2018). Overall, these trends underscore the importance of tracking salinity alongside temperature and acidification to gauge climate impacts on regional marine ecosystems.

1.4. Expansion and Filling the Gaps

To understand both the long-term changes and seasonal variability within Yemen's coastal waters, we compiled satellite-derived monthly data on SST, and Chl-a covering the 2004–2024 period and SSS cover 2014-2024. For SST and Chlorophyll, we used NASA MODIS-aqua pod and for SSS we retrieved data from NASA's Soil Moisture Active Passive (SMAP) mission. We narrowed our geographic focus to Yemen's Exclusive Economic Zone (EEZ) in the Red Sea, Gulf of Aden, and Arabian Sea, reflecting the nation's broad marine frontier (Figure 2). We first clipped our data for Yemen's EEZ obtained from verified government sources, ensuring all data related to Yemen's waters only.

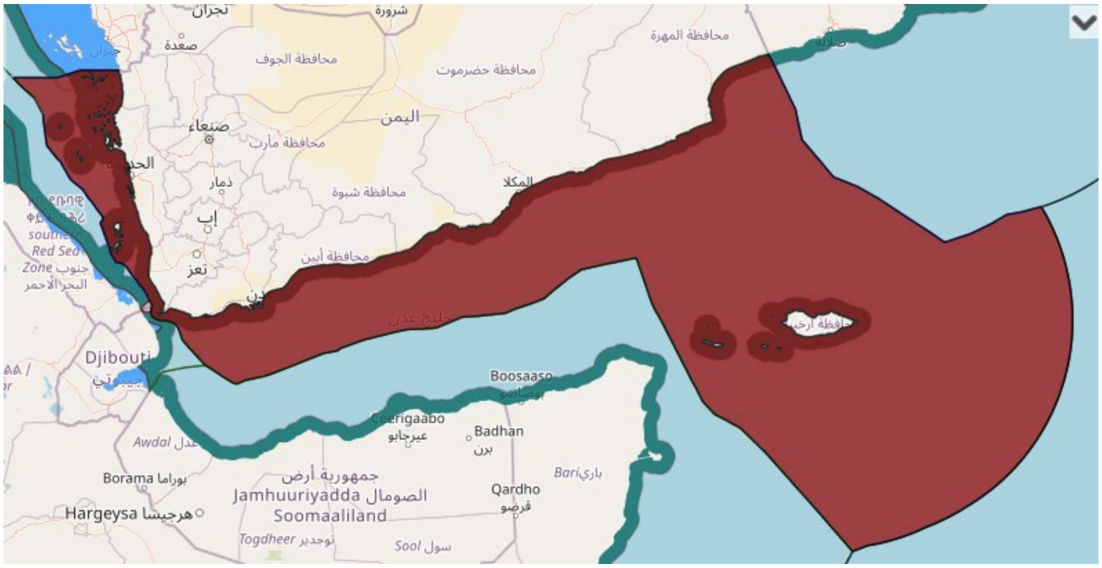

Figure 2: Map of Yemen Exclusive Economic Zone (EEZ)

Direct measurements of Ocean Acidification requires pH, total alkalinity (TA), dissolved inorganic carbon (DIC), or aragonite saturation (Ω Aragonite). Yet, data availability for these are largely absent in Yemen's marine domain due to the logistical challenges of in situ monitoring. These variables are not able to be reasonably observed from atmospherics. As an alternative, we use SSS as a rough proxy for acidification, recognizing that changes in freshwater input, evaporation, and oceanic mixing can influence carbonate system dynamics. A decline in SSS often suggests increased freshwater input (for e.g., from rainfall, river discharge, or glacial melt), which can lower alkalinity and reduce the ocean's buffering capacity against acidification. Conversely, increasing salinity may indicate greater evaporation dominance, often correlating with higher alkalinity levels that could slow pH decline. In the Red Sea and Gulf of Aden, where evaporation and water exchange strongly regulate salinity, a shift in long-term SSS patterns could provide early signals of changes in ocean carbonate chemistry. In this way SSS functions on its own as an important measure and further serves our interest in acidification. This methodology has been used in similar contexts (Land et al., 2019) (Shutler et al., 2024). By examining decadal SSS trends, we aim to infer potential acidification risks in Yemen's EEZ and identify areas where targeted monitoring should be prioritized.

We first compiled a dataset that had observations for each variable at matching points with 4 km resolution for each month. We used this for the first portion of our analysis to determine changes at a more granular scale. Next, we aggregated the monthly data by computing domain-wide averages for each month. This step provided an integrated time series of each variable, which is particularly relevant for examining large-scale climate signals, fisheries implications, and multi-year trends. We note, however, that domain-averaging can obscure local extremes (for e.g., hotspots of especially warm or cold upwelling zones). Nonetheless, it offers a practical "big picture" for national-scale assessments.

After generating a monthly EEZ-averaged series, we performed several analyses. We used linear regression on annual-mean values to detect decadal trends in SST, SSS, and Chl-a from 2004 through 2024. This allowed us to estimate whether each variable was increasing or decreasing over the decade and to evaluate the statistical significance of those trends. We then observed seasonal variance by observing monthly changes across years. This approach highlights recurring seasonal patterns, such as summertime upwelling or winter stratification. To understand how SST, SSS, and Chl-a co-vary, we examined Pearson correlations at two timescales: (1) annual, using the 10 (or 11) yearly data points, and (2) monthly anomalies, where we also tested lagged correlations to see if changes in temperature preceded changes in salinity or productivity. We then dive deeper into extreme events, using cyclone Tej as a case study for disruption of biomass and investigating Harmful Algal Blooms and MHWs. Finally, we summarize the analysis by focusing on interactivity between the elements of our analysis and offering practical suggestions for future development on this topic.

1.5. Decadal Trends (2004–2024)

1.5.1. Annual Means

After deriving an annual mean for each variable (SST, SSS, Chl-a) by averaging monthly data within a given year, we fit a simple linear regression to the resulting time series. This step was designed to capture any persistent multi-year drift in these indicators: warming or cooling for SST, freshening or salinization for SSS, and rising or declining productivity for Chl-a. While two decade's worth of data is relatively short from a climatological standpoint, it does offer insight into the recent trajectory of these variables in Yemen's EEZ.

SSS exhibited a slope of -0.0339, corresponding to roughly 0.34 PSU of freshening across the 2014–2024 interval ($p = 0.027$). This negative slope, while modest, suggests that Yemen's coastal waters are becoming slightly fresher. Possible explanations include increased freshwater input via precipitation or external inflows (for e.g., from the Gulf of Aden) and altered evaporation and precipitation balances in the region, consistent with some signs of heightened rainfall events in the southwestern Arabian Peninsula. Such freshening could have consequences for water column stratification and, ultimately, nutrient mixing.

SST showed a positive trend of +0.0488, implying an approximate 0.5 °C increase over the decade. Despite the short timeframe, this result is consistent with findings that the Red Sea and Arabian Sea are warming faster than many other global ocean regions. Warming in these tropical-subtropical waters can exacerbate thermal stress on corals, fish, and other marine life, and it may also affect the timing and magnitude of phytoplankton blooms by influencing stratification.

Chl-a displayed a weakly positive trend of around +0.0110 which amounts to about 0.11 mg/m^3 over a decade. Although this upward slope might suggest slightly enhanced phytoplankton productivity, recent studies in the western Indian Ocean have documented more complex patterns, with some coastal areas (like parts of the Arabian Sea) experiencing declining Chl-a while the Red Sea has seen increases in some areas. Hence, the small overall increase observed here could result from localized upwelling improvements in portions of Yemen's Gulf of Aden or variability in monsoon effects year to year. Chlorophyll is better studied at higher resolutions instead of across an entire coastline as noted in our literature review. We study this further in later sections.

1.5.2. In Zone Variance

To account for more localized changes and variance in oceanic conditions, we used our 4 km resolution monthly composite. We computed linear trends for SST, SSS, and Chl-a at each grid cell within Yemen's EEZ over the period 2004–2024. Using a polyfit function, we performed a linear regression at each latitude-longitude point along the time axis, allowing us to quantify whether each variable is increasing or decreasing over time at a local scale. The resulting slope maps show the rate of change in °C per year for SST, PSU per year for SSS, and mg/m³ per year for Chl-a, indicating long-term shifts in ocean conditions. The color scheme used a diverging colormap, where red represents increasing trends (for e.g., warming SST, rising salinity, or increasing phytoplankton biomass) and blue represents declining trends (for e.g., cooling SST, freshening waters, or decreasing productivity). This spatially explicit trend analysis provides a detailed picture of how different parts of Yemen's coastal environment have evolved over the past decade, highlighting regional variations in warming, salinity changes, and productivity shifts.

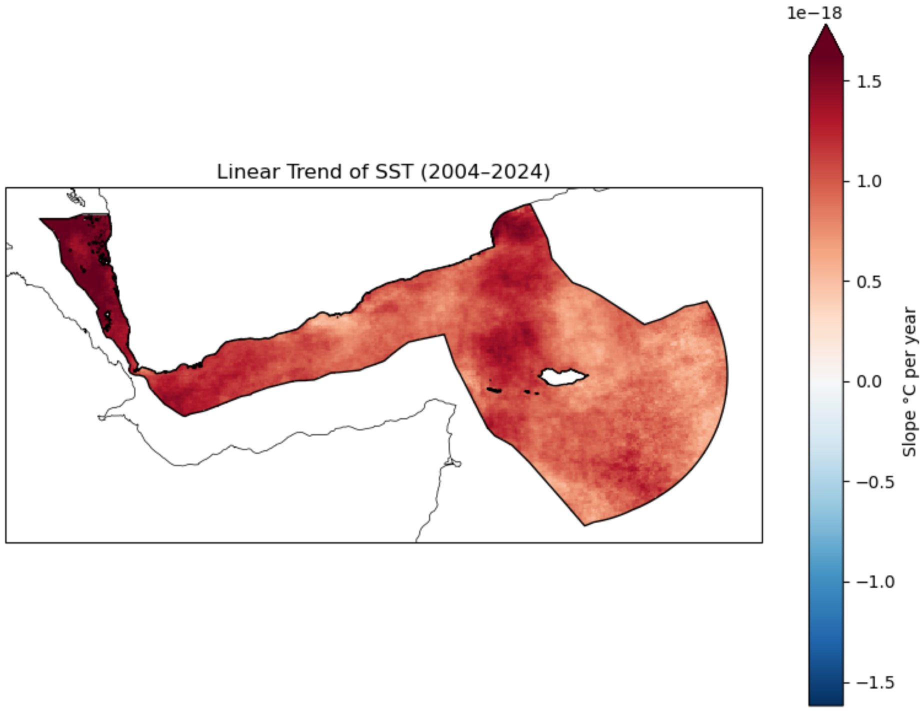

Figure 3: Linear trend of SST over time

Corroborating our generalized analysis of the zone, heating is persistent throughout. However, it is important to note that the highest levels of heating are along the coast, both in the Red Sea and the Gulf of Aden as well as farther down the coast towards the Oman border. Previous literature has suggested severe Red Sea warming trends and our analysis backs this. This is relevant in its own right but has downstream consequences for the Gulf of Aden and the entire Yemen coastline.

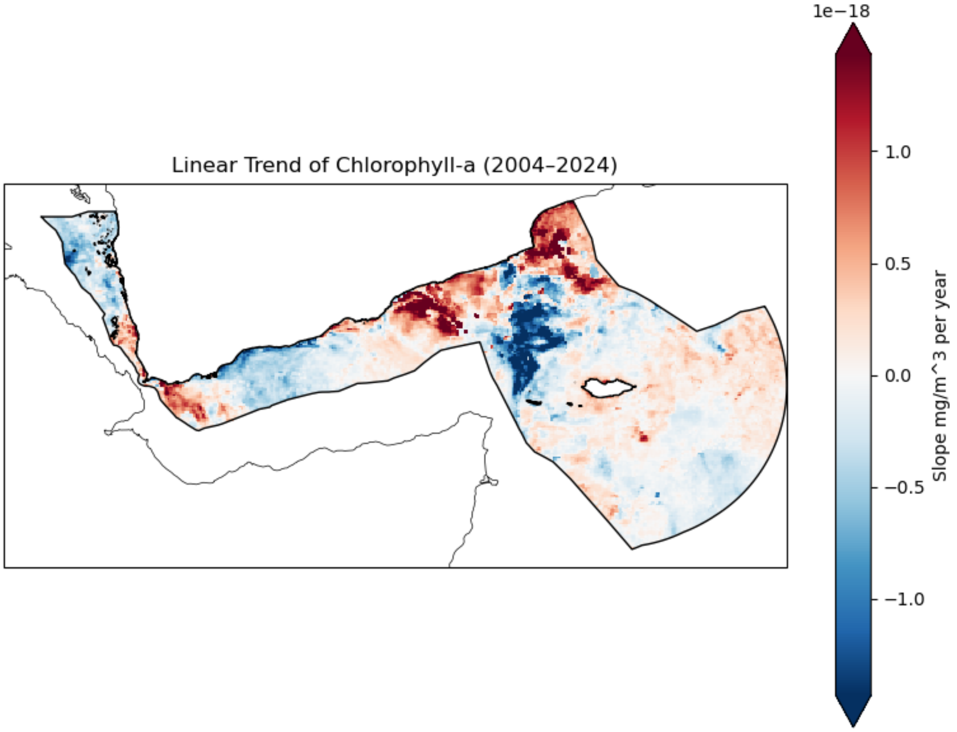

Figure 4: Linear trend of Chlorophyll-a over time

The distribution of Chl-a trends is much more spatially variant and extreme. There are large clumps of increased biomass towards the eastern portion of the coast in the Arabian Sea. This area has experienced increased levels of heating yet high levels of upwelling due to monsoonal patterns and seasonally affected hydro-environmental events seem to be offsetting the anticipated biomass decline. There is also a notable decrease in the northern Red Sea, the Gulf of Aden and between the coast and Socotra. This matches the temperature increases observed above. As SST rises, the upper ocean layer becomes more stratified, meaning that warmer, less dense surface waters form a stable layer that resists mixing with deeper, nutrient-rich waters. There is also evidence that monsoonal effects have been decreasing in that area resulting in less nutrient mixing and upwelling.

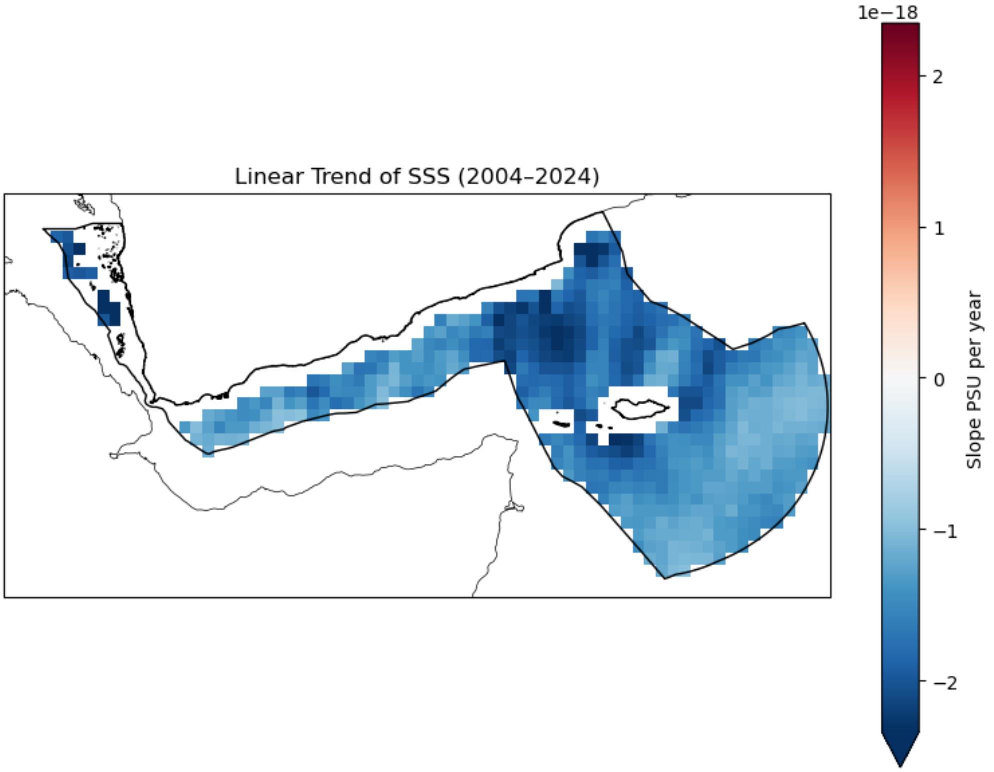

Figure 5: Linear trend of Chlorophyll-a over time

Several physical processes can contribute to the observed decrease in surface salinity in Yemen's EEZ. One possibility is a shift in the region's evaporation-precipitation balance as even relatively small increases in rainfall or decreases in evaporation lead to freshening over time. There is evidence that along with varying precipitation expectations, evaporative demand has clearly and significantly increased due to heating (World Bank 2014). Another factor is changing circulation patterns, alterations in ocean currents linked to phenomena like the Indian Ocean Dipole or shifts in monsoonal winds can bring fresher water masses into the Gulf of Aden and along Yemen's Red Sea coast. Finally, broader climatic trends, like a warming ocean that changes stratification and mixing, can interact with local processes, further influencing how salinity evolves in this region.

1.6. Seasonal Variance

1.6.1. Yearly Changes in Seasonality

To further highlight seasonal changes, we created monthly bar charts of our variables of observation. Each uses daily mean indicators for Yemen's coastal waters as its base. Each month is calculated for each year to highlight seasonality generality and changes year-over-year for each month.

Surface Sea Salinity Seasonal and Interannual Variability

SSS has mild seasonal variance and non-uniform yearly distributions. Month to month variations follow precipitation as rainfall becomes more prominent. The monsoon which is active from around April to September matches with the increased freshness at those months. Over the first five years of our period salinity trended down but has sense recovered. Our SMAP data only covered the past decade and SSS is notably variant and affected by microclimates and water patterns. A longer time period and more compartmentalized geographical focus would help to better understand salinity.

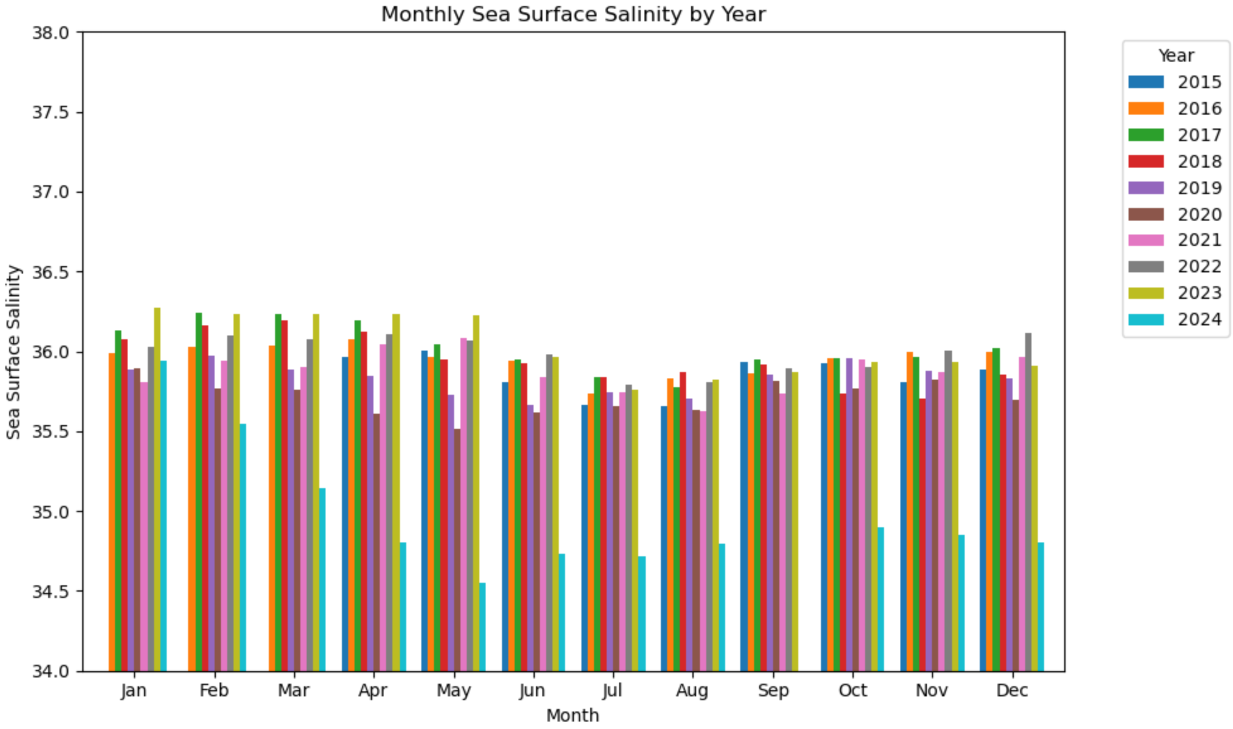

Figure 6: Monthly SSS by Year

Chlorophyll-a Seasonal and Interannual Variability

Unlike salinity, Chl-a concentrations show distinct seasonal variability, peaking during August across multiple years. This aligns with the SW monsoon upwelling season, when strong winds drive nutrient-rich deep water to the surface, stimulating phytoplankton blooms. The magnitude of these blooms varies significantly between years, with some years (for e.g., 2021) exhibiting extreme peaks (>3 mg/m³), while others (for e.g., 2017) show moderate increases. This variability may be linked to monsoon intensity, cyclone activity, or interannual climate phenomena such as El Niño–Southern Oscillation (ENSO), which influences wind patterns and nutrient transport.

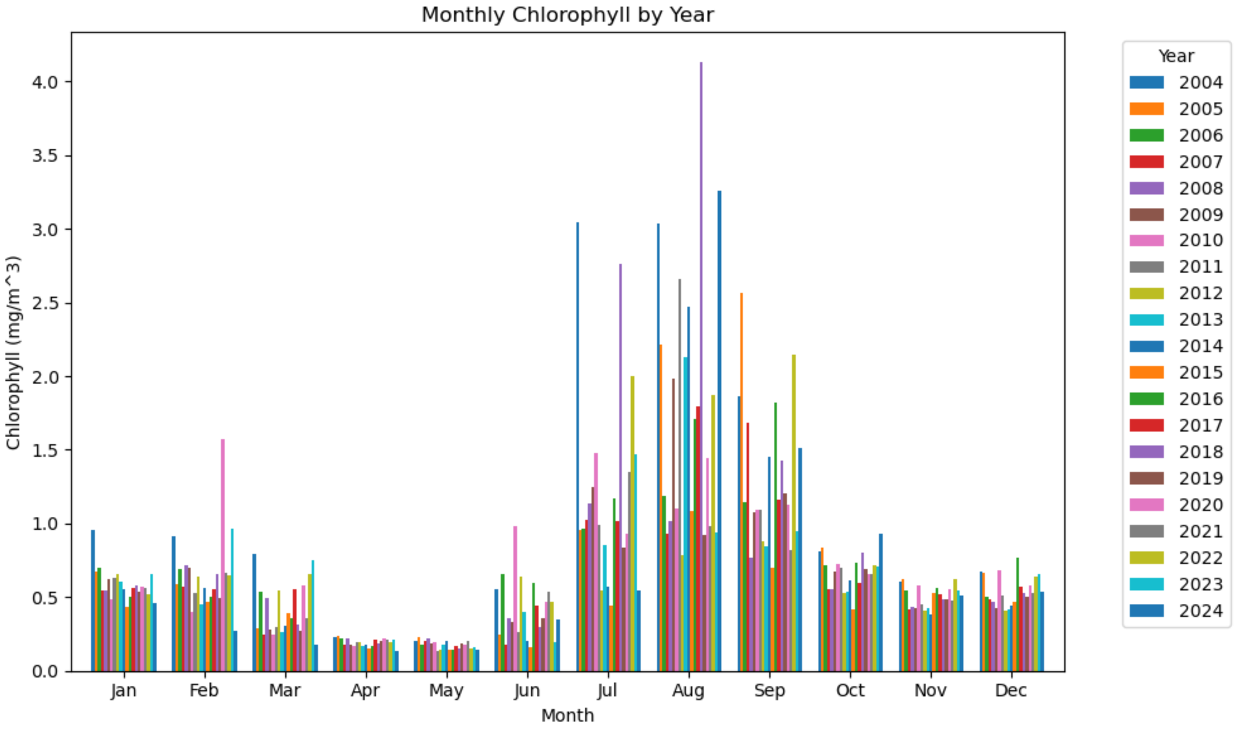

Figure 7: Monthly Chl-a by Year

Sea Surface Temperature Seasonal and Interannual Variability

SST exhibits a clear seasonal cycle, with temperatures rising from January to a peak around May, followed by a decline and a resulting second peak in October. This monthly pattern is consistent across all years, with slight interannual differences. SST values within each month have shown patterns of increase year-over-year. This is especially the case in the warmer months like April and May where strong linear increases in temperature is apparent.

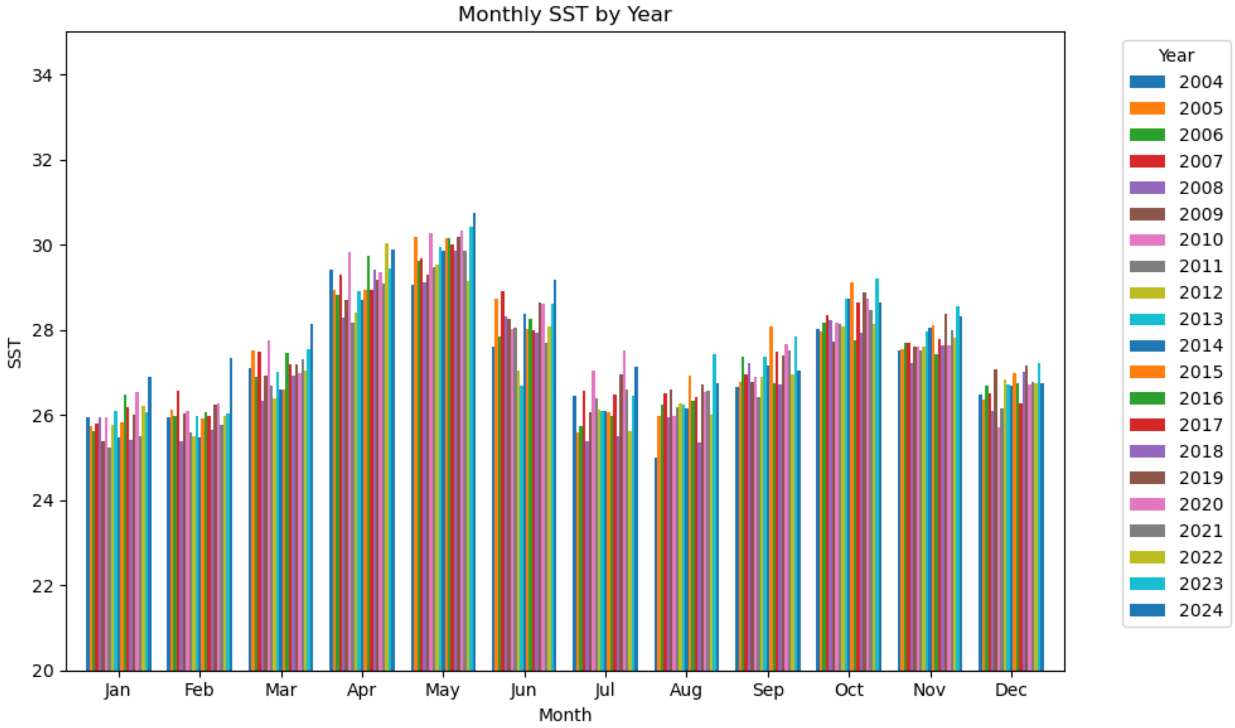

Figure 8: Monthly SST by Year

1.7. Correlation Matrix: Annual Means and Monthly Anomalies

Using the annual means for SST, SSS, and Chl-a, we formed a 3×3 correlation matrix. Notably, SSS–SST stood out with a correlation of –0.74, implying a robust inverse relationship: in years with higher temperature, surface salinity is relatively lower. Such an inverse link might reflect periods of enhanced rainfall, oceanic inflows accompanying warmer conditions, or possibly reflect large-scale changes in wind-driven circulation during warm years. The SSS–Chl-a correlation was virtually zero (–0.03), suggesting no consistent year-to-year link, whereas SST–Chl-a was a weak +0.06, implying minimal alignment at the annual scale. It is crucial to interpret these correlations carefully, given that regional interannual variability can arise from many confounding factors. Nevertheless, the negative SSS–SST correlation might hint that monsoon anomalies influencing temperature also affect salinity distribution in opposite directions.

Large area averages may lose the necessary variability that is more representative of these variables. As a result, we observed monthly anomalies for each variable and reassessed correlation. It is also worth noting that relationships are often not synchronous. Rainfall may have trailing effects on other variables. We investigated this by using different levels of time effects which revealed lagged relationships among the variables. For instance, SST and SSS showed a strongly negative correlation at lag=0 (about –0.63), consistent with the annual findings.

Our most important finding was related to SST and Chl-a. We found both real time and lag correlations which underscore a dynamic, two-step process between SST and Chl-a. In the immediate term (lag 0) correlation was approximately –0.63 suggesting warmer than normal SST coincides with lower Chl-a, providing support that thermal stratification inhibits the upward transport of nutrients and thus suppresses phytoplankton blooms. However, at around a 3- to 4-month lag, the correlation flips strongly positive (up to +0.64), indicating that an elevated SST anomaly today can spur later oceanographic or atmospheric shifts, such as monsoon-driven winds or current changes, that ultimately enhance nutrient availability and stimulate phytoplankton growth. This delayed positive association suggests that, while acute warming may dampen productivity initially, it can also trigger conditions conducive to later upwelling or mixing events that boost Chl-a. The result is a complex seasonal rhythm in which short-term warming suppresses plankton growth, but warmer phases can also, through lagged processes, pave the way for stronger phytoplankton blooms a few months down the line. Ultimately, this lagged effect may be simply that warm summer months, without upwelling and other positively enhancing bio-productivity events, predate highly productive months. A decent amount of this lagged relationship is likely within this reasoning, yet it is still worth investigating the lagged relationship further.

1.8. Extreme Events

1.8.1 Case Study: Cyclone Tej

Beyond long-term trends, short-term climate extremes can drastically impact marine conditions. Tropical cyclones are one such shock event, capable of rapidly cooling surface waters and boosting Chl-a via turbulent mixing and upwelling. In the northwestern Indian Ocean, cyclones are relatively rare but potentially increasing in intensity. When cyclones do occur, they can cause dramatic, if transient, changes in SST and productivity. Studies have documented cases where strong cyclones led to phytoplankton blooms. For example, an analysis of 31 cyclones in the Arabian Sea (2003–2018) found that only the most intense storms (for e.g., 2009 Cyclone Phyan and 2017 Cyclone Ockhi) “invoked a suitable condition for phytoplankton bloom,” injecting nutrients that briefly elevated Chl-a by several-fold (Shunmugapandi, R., et al. 2020). In those instances, satellite data showed marked increases in surface chlorophyll (5–8 mg/m³ in bloom patches) along the cyclone’s track, coupled with local SST drops as deeper, cooler water was brought up (Subrahmanyam, B, et al., 2002). On the other hand, weaker cyclones or those passing over nutrient-poor areas induced little biological response (Shunmugapandi, R., et al. 2020). These findings underscore that cyclones can have significant but case-specific effects on marine ecosystems. For Yemen, Cyclone Tej in October 2023 provides a salient recent example. Tej was an extremely severe cyclonic storm that made landfall on Yemen’s Al Mahrah coast, delivering torrential rains and coastal storm surges. While detailed scientific data on Tej’s oceanographic impact are still emerging, we can make the conjecture that it caused intense mixing in the Gulf of Aden and Arabian Sea waters around Socotra. Based on analogous events, one would expect short-term cooling of SST (as subsurface water mixed upward) and a pulse of nutrients enhancing Chl-a in the days to weeks after the cyclone's passage.

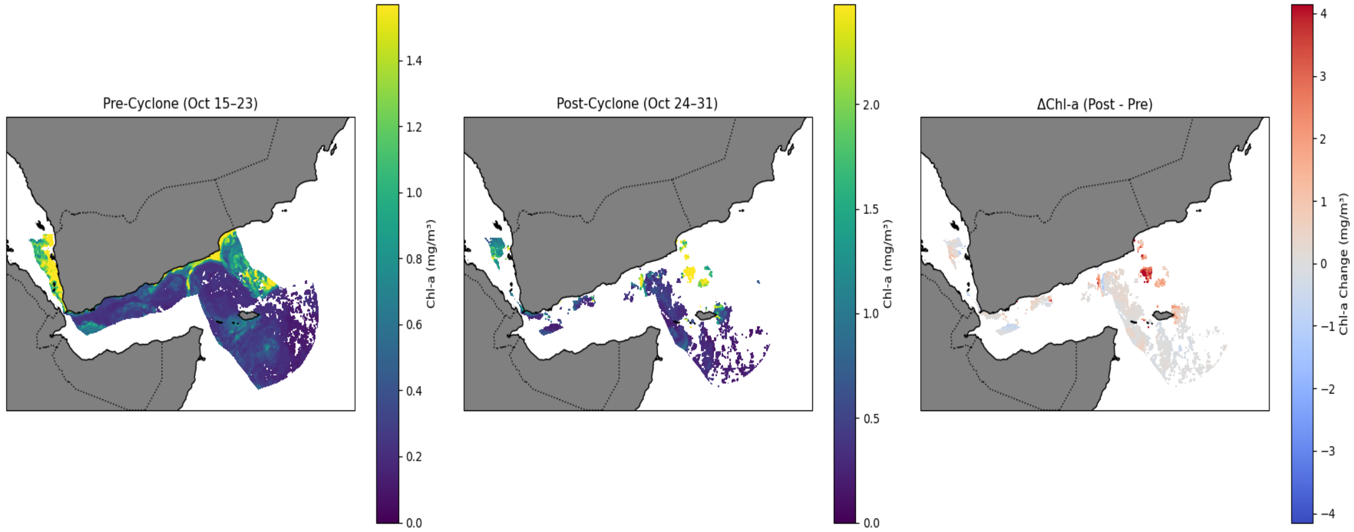

Figure 9: Cyclone Tej Chlorophyll Changes

Cyclone Tej had a notable impact on Chl-a concentrations in Yemen's EEZ, primarily by stimulating offshore phytoplankton blooms while simultaneously reducing productivity in nearshore waters. Before the cyclone (Oct 15–23), Chl-a levels were relatively low across much of the open ocean, indicative of oligotrophic conditions typical of the Arabian Sea. Higher concentrations were observed along the Yemeni coast and around the Socotra archipelago, where localized nutrient input from coastal upwelling and riverine discharge supported increased biological activity.

Following the cyclone (Oct 24–31), a distinct shift in Chl-a distribution occurred. Offshore regions, particularly south of Socotra and in parts of the Gulf of Aden, exhibited significant increases in Chl-a, signaling a post-cyclone phytoplankton bloom. This increase was likely driven by cyclone-induced upwelling, which brought nutrient-rich deep waters to the surface, fueling primary production. Such an effect is well-documented in the Arabian Sea, where previous cyclones, including Chapala (2015) and Ockhi (2017), triggered substantial phytoplankton blooms lasting several weeks. The observed maximum increase of +10.3 mg/m^3 in Chl-a following Tej aligns with these past events, underscoring the role of cyclones in enhancing marine productivity in this region.

Conversely, nearshore waters along the Yemeni coast experienced declines in Chl-a, with reductions reaching as much as -3.65 mg/m^3 in some areas. This decrease can likely be attributed to turbidity and sediment resuspension caused by the cyclone's strong winds and heavy rainfall. The influx of sediment and freshwater runoff may have reduced light penetration, inhibiting phytoplankton growth despite potential nutrient input. Such light limitation effects have been observed following other high-energy storms, where strong wave action and precipitation create plumes of suspended matter that suppress productivity.

1.8.2. Harmful Algal Blooms (HABs)

An additional climate-related phenomenon of concern is the occurrence of Harmful Algal Blooms (HABs). HABs are excessive growths of certain microalgae that can produce toxins or otherwise disrupt marine ecosystems (for example by depleting oxygen when they decay). These events can lead to fish kills, contaminate shellfish with toxins (affecting food safety), and harm tourism and aquaculture. The Red Sea and Arabian Sea have historically experienced HAB outbreaks. For instance, an overview by Al Shehhi et al. (2014) documented recurring HAB incidents in the Gulf of Aden and Red Sea, some of which caused significant fish mortality and economic losses. Similarly, Al-Yamani et al. (2025) note frequent blooms in the Arabian Gulf and Sea of Oman, including toxic *Chattonella* blooms that led to fish kills in Kuwaiti waters. Warmer stratified waters favor the proliferation of certain harmful dinoflagellates and cyanobacteria. Reports indicate that the Red Sea has seen unusual blooms of *Trichodesmium* (a cyanobacteria) during marine heatwave conditions (Al-Shehhi, M. R., & Abdul Samad, Y. 2022). Such blooms can discolor the water and lead to oxygen drops at night. HAB events pose a direct threat to Yemen’s fisheries: a toxic bloom could cause mass die-offs in coastal fish or make shellfish unsafe, directly impacting fisherfolk incomes and food supply. The observation and understanding of HAB’s provides a more complete picture of environmental challenges facing Yemen’s oceans.

1.8.3. Marine Heatwaves

MHWs refer to episodes of abnormally high SST that persist for five or more consecutive days, exceeding the typical seasonal threshold for a given region. These events have become more frequent and intense worldwide in the past few decades, mainly driven by anthropogenic warming. In the Red Sea and Arabian Sea, studies have documented an increasing number of heatwave days since about 2015, often linked to strong El Niño phases or anomalies in wind-driven mixing (Chaidez et al. 2017). MHWs can cause acute impacts on fisheries and marine ecosystems by resulting negative effects on upwelling and nutrient availability heat stress that leads to coral bleaching or fish kills. For example, in the Red Sea, coral bleaching episodes in 2015 and 2021 were linked to short but severe temperature spikes, while in the Gulf of Aden, brief MHWs in 2019 and 2020 corresponded to reduced phytoplankton abundance (Chatterjee 2022). Extreme heat events can also interact with other stressors, such as HABs or cyclonic activity, amplifying negative outcomes for both marine life and coastal communities. Below, Figures 10 and 11 show the increased propensity for MHWs over the past decade. Future projects universally predict this trend to continue.

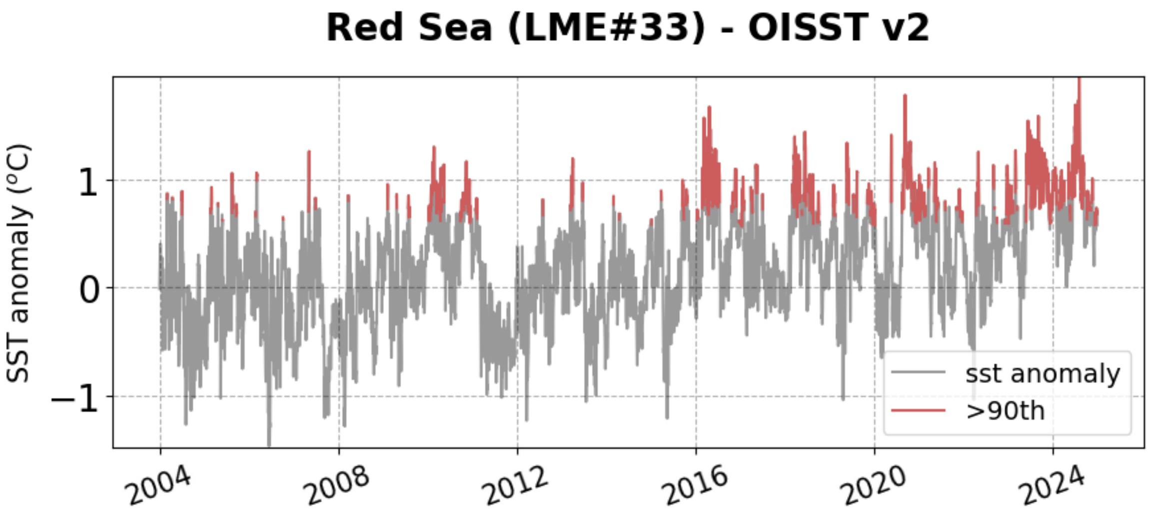

Figure 10: Marine Heatwaves in the Red Sea

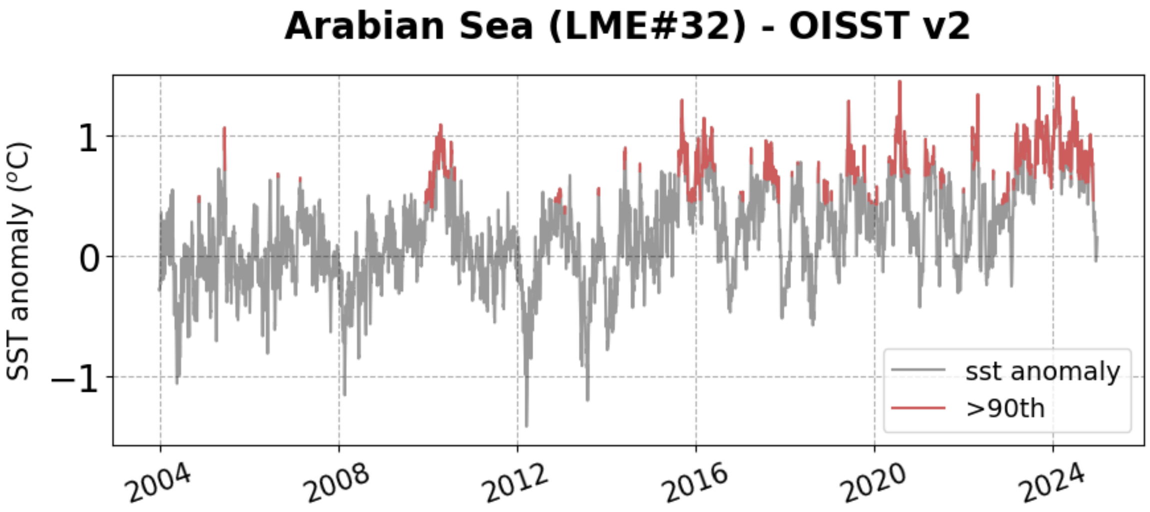

Figure 11: Marine Heatwaves in the Arabian Sea

1.9. Interactions Among SST, Chl-a, Salinity, and Acidification

Individually, the four environmental indicators, SST, chlorophyll, salinity, and Ocean Acidification, each influence marine ecosystems individually. However, these factors also interact with one another, often in complex ways to shape ecological outcomes. In Yemen’s marine waters, the combined effects of warming, nutrient changes, salinization, and acidification are already evident in shifting ecosystem structure.

Rising SST leads to stronger stratification of the upper ocean, especially when not offset by wind mixing. This stratification often results in a lagged decline in nutrient supply to the surface. For example, after several years of gradual warming, the Arabian Sea's nutrient upwelling efficiency has dropped, causing lower overall Chl-a and a reduction in primary productivity (Roxy, M. K. et al., 2016). The full ecological effect can be lagged by a season or more as a warmer year might lead to poorer phytoplankton blooms in the following upwelling season. Conversely, if wind mixing intensifies in a particular monsoon (as has happened in some recent years), it may temporarily overcome stratification to boost Chl-a. Thus, there is a delicate interconnected relationship: SST and wind drive Chl-a variability, with warming generally suppressing productivity but wind-driven upwelling enhancing it (Yang et al., 2024). The net effect observed off Yemen's coast has been negative for productivity in recent decades, suggesting warming's influence is dominating.

Changes in SSS feed back into circulation patterns. As noted, an increase in Red Sea salinity can strengthen the outflow of Red Sea water into the Gulf of Aden. This water is not only saline but also warm and oxygen-poor (having formed in the Red Sea where it picked up heat and lost oxygen). When it enters the Gulf of Aden at intermediate depths, it can alter nutrient and oxygen profiles in the region. A possible scenario is that higher salinity Red Sea outflow water could slightly deepen the thermocline in the Gulf of Aden, delaying the onset of the nutrient-rich upwelling season or reducing its intensity. There is also an interaction with oxygen minimum zones (OMZs): The Arabian Sea has one of the most pronounced OMZs in the world. Enhanced stratification from warming and changes in circulation from salinity can both expand the OMZ by reducing ventilation. This can create a lagged impact where declines in oxygen (driven by the physical changes of temperature and salinity) further suppress nutrient cycling and plankton community health over time. For instance, fish and zooplankton might avoid increasingly hypoxic bottom waters, effectively squeezing their habitat vertically. Such shifts might not be immediately noticeable year-to-year, but over a decade they result in fewer demersal fish in deep areas and more clustering in oxygen-rich surface layers.

SST and Ocean Acidification together impose compound stress on calcifying organisms. Warm-water coral reefs near Yemen (for e.g., in the Gulf of Aden and Red Sea) are dealing with thermal stress (bleaching risk in hot summers) while acidification slowly reduces their calcification rates. There may be synergistic effects: corals weakened by suboptimal pH may be less resilient to temperature extremes, and vice versa (Dilworth et al., 2024). These combined pressures can lead to phase shifts in ecosystems. For example, a bleached and slowly dissolving coral reef may transition to an algae-dominated state, reducing habitat complexity (McManus and Polsenberg, 2004). That, in turn, means fewer reef fish and crustaceans. Such changes have been observed globally and are a risk for Yemen's coral communities. Lagged relationships are also notable here as a reef might survive a bleaching event, but the growth slowdown from acidification could mean it doesn't recover fully before the next heat event, leading to cumulative degradation over years.

The environmental indicators in this study do not operate in isolation in Yemeni waters. Instead, they form an intertwined mosaic: warming and salinity affect stratification; stratification and warming reduce nutrients and oxygen thereby lowering Chl-a and altering plankton; acidification works in the background, steadily weakening calcifiers; those lower trophic changes and habitat degradations then ripple up to fish and fisheries. Importantly, some of these interactions manifest with time lags. As an example, a poor plankton year can result in lower fish catches a year or two later when that year's juveniles would have recruited to the fishery. This underscores the need for an ecosystem-based approach in monitoring and management: single-factor analyses may miss the compounding effects that are critical for fisheries and conservation. Yemen's marine ecosystems are resilient but are increasingly being pushed by multiple simultaneous climate-related pressures.

1.10. Limitations and Next Steps

There are several caveats and future directions that naturally arise from this analysis. The time span (2004–2024) covers 20 years, limiting our ability to detect multi-decadal trends or cyclical patterns (for e.g., from the Indian Ocean Dipole or El Niño). Longer series (30 years or more) are typically required to confirm these signals. Domain-averaged results can hide important spatial heterogeneity, such as distinct upwelling cells along the Gulf of Aden coastline or unique winter bloom regions in the southern Red Sea. Spatially resolved analyses, which we showed with our polyfit model, could further uncover "hotspots" of rapid warming or strong freshening and identify areas with different productivity trends.

While SSS provided a useful first-order approximation of Ocean Acidification potential, it remains an indirect measure and cannot replace direct carbonate chemistry observations. Several confounding factors, such as circulation changes, upwelling variability, and monsoonal forcing, can influence SSS trends independently of acidification processes, making it difficult to isolate climate-driven acidification signals from other hydrological shifts. Direct acidification metrics (pH, total alkalinity, pCO_2) are currently lacking in Yemen's waters; thus, the potential for ocean acidification to compound warming stress remains speculative. Generally, satellite data, especially for salinity and near-coast chlorophyll, can carry significant uncertainties. Ground-based validation in Yemeni waters is extremely limited, partly due to regional conflicts and logistical constraints on scientific surveys. Expanding in situ measurements (through research cruises, Argo floats, and moored buoys) would greatly improve confidence in these trends. Addressing these data gaps is vital to understanding and managing Yemen's marine resources under climate change.

2. Fisheries Analysis

2.1. Introduction

Yemen’s marine fisheries have historically played a pivotal role in the country’s food security and economic development, boasting a diverse range of species and productive waters along the Red Sea, Gulf of Aden, and Arabian Sea coasts. However, decades of inadequate data collection and overfishing, exacerbated by the outbreak of conflict in 2014, have severely undermined fish stock assessments and fisheries management. The disruption of key institutions, including the Ministry of Agriculture, Irrigation and Fisheries (MoAIF) and the Marine Science and Biological Research Authority (MSBRA), has resulted in minimal reporting on catch volumes and fishing efforts, leaving knowledge gaps about current stock health and fishing activities. In response, this analysis proposes a holistic approach to fisheries monitoring that integrates remote-sensing of oceanic conditions with in situ observations and computer vision techniques for vessel detection. By partnering closely with the MoAIF and MSBRA, this framework aims to fill critical data voids. The result is a robust, near-real-time system for tracking fishing conditions, estimating potential catch capacity, and informing adaptive policies that support both ecological sustainability and local livelihoods.

2.2. Background and Context

Yemen's marine fisheries are a significant food source and economic contributor. Yemen has a 2,520 km coastline spanning the Red Sea, Gulf of Aden, and Arabian Sea, with productive fishing grounds. Marine catches grew dramatically in the late 20th century as the total annual catch in Yemeni waters was around 40,000 tonnes in the 1950s, rising to ~175,000 tonnes by the mid-1980s (Tesfamichael et al. 2012). After the unification of North and South Yemen in 1990, catches surged again with industrialization of the fishery sector, peaking at 350,000 tonnes/ year in the early 2000s (Tesfamichael et al. 2012). Official statistics recorded 256,000 tonnes in 2004 (Impact Consulting/ UNDP 2019). Before the conflict began in 2014, the Food and Agriculture Organization of the United Nations (FAO) estimated that over 15% of Yemen's gross domestic product (GDP) came from the fishing industry. It was considered the third most important agricultural sub-sector and a major export earner, with fish exports reaching 50 countries (58% to Arab markets, notably Kingdom of Saudi Arabia (KSA), Egypt, and Oman) (Elayah, Ma. 2019). In 2013, Yemen’s fish export value boomed to USD 289 million, though it fell to USD 170 million in 2014 amid rising instability. The sector was dominated by artisanal fishers using about 19,500 small boats and contributing over 90% of production (Impact Consulting/ UNDP 2019). Recent UNDP value chain assessments in Yemen and Somalia further highlight the sector’s contribution to household incomes and the constraints across landing, processing, and marketing, underscoring the importance of fisheries for pro-poor growth (UNDP 2020; UNDP 2024).

Over 350 species of fish and marine life have been reported in Yemen's waters, making it one of the richest fisheries in the Middle East (Elayah, Ma. 2019) Nearly 1,000 marine fish species (857 bony fish, 68 sharks, 44 rays) have been recorded across Yemen's Red Sea and Gulf of Aden waters (Abubakr, M. M. 2004). Seasonal monsoons and oceanographic conditions drive fish migration and distribution; for example, many pelagic fish (tuna, mackerel) move between the Gulf of Aden and Red Sea through the Bab-el-Mandeb strait. A recent observation of skipjack tuna in the northern Red Sea illustrates this connectivity. Skipjack tuna were recorded entering the Red Sea from the Indian Ocean via Bab-el-Mandeb for the first time in 2021, indicating changing migration patterns likely influenced by ocean warming or ecosystem shifts (Adel, M. et al. 2022). Prior to 2014, several tagging and biodiversity studies noted that the Red Sea's narrow connection to the Indian Ocean limited interchange of some species, leading to unique localized stocks (Abubakr, M. M. 2004).

By the 2010s, concerns about the health of fish stocks in Yemen were mounting. Fisheries surveys revealed actual catches were roughly double the officially reported figures (Derrick, B et al., 2023), suggesting substantial unreported artisanal and subsistence fishing. This under-reporting masked the true fishing pressure. Catch-per-unit-effort (CPUE) had been declining, reflecting dwindling stocks. In the Socotra Archipelago, small-scale fishers' catch peaked around 2000 and then dropped sharply as total annual landings fell from around 12,000 tonnes in 2000 to just 3,300 tonnes by 2014 (Derrick, B., et al., 2023). A 2023 analysis found Socotra's CPUE declined 78% since 1950, highlighting severe overfishing (Derrick, B., et al., 2023). On the Red Sea coast, reef-associated fish catches were reported to be in decline before 2014, and valuable species like rock lobster showed signs of over-harvest. Shark populations were also under intense pressure from targeting for fins and meat, as Yemen was a regional hub in the shark trade (Abubakr, M. M. 2004). All of this was made even more complicated with the lack of comprehensive stock assessments. The fisheries sector was characterized by data gaps even pre-war as reliable statistics on landings and fishing effort were difficult due to the migratory and artisanal nature of the fishing industry (Elayah, M 2019). By the early 2010s, regulations existed (for e.g., a 2009 ban on industrial trawling in the Red Sea), but enforcement was logistically difficult (Al-Fareh, A. M. 2018). Yemen's fisheries were and remain a critical livelihood and food source, but stocks have been over-exploited and reliable data has been difficult to collect.

2.2. Yemen's Fisheries and Catch Types

Yemen's fisheries are a vital source of food security and livelihoods, particularly for coastal communities along the Red Sea and Gulf of Aden. The country's marine catch comprises a mix of pelagic species (tunas, mackerels, sardines), demersal fish (groupers, snappers, emperors, etc.), as well as crustaceans and mollusks (shrimps, lobsters, cuttlefish) and others. Pelagic fish, especially tunas and small pelagics, form the largest share of the catch by volume (Shaher, 2007) (FAO). Among tuna, species like yellowfin, skipjack, and kawakawa/ bonito are common. The estimated distribution is shown in Figure 12. The Red Sea coast has supported valuable fisheries for shrimp and rock lobster, while the Gulf of Aden is known for tuna, kingfish, and large jacks. The estimated figures for the Red Sea are shown in Figure 13. It is worth noting in those estimates that confidence is rated a 1.9 out of 4, so the general distribution is the most notable aspect.

Yemen's fisheries are predominantly artisanal (small localized), with thousands of fishers operating dhow boats and skiffs. There was some industrial fishing (including foreign fleets) especially in the Red Sea for shrimp and demersal fish, but much of that has reduced in recent years due to conflict and regulations. According to catch reconstructions, Yemen's total marine catch was historically under-reported – actual catches from 1950–2010 were estimated to be about 1.9 times higher than the official FAO-reported figures for the Red Sea coast, and about 1.3 times higher for the industrial fishery component (Tesfamichael et al., 2016).

This implies a substantial subsistence and artisanal catch not fully captured in official data. Nonetheless, FAO statistics and local surveys show that pelagic fish consistently make up the bulk of landings, followed by demersal and smaller proportions of crustaceans. For example, one assessment noted that kawakawa and kingfish (Spanish mackerel) are year-round staples in coastal catches, whereas oceanic tunas (yellowfin, skipjack) appear seasonally (Shaher, 2007, 1984).

In recent years, Yemen's fisheries sector has faced challenges beyond environmental variability, including overfishing of some stocks, piracy and conflict limiting offshore access, and economic hardships. Yet, climate and ocean changes remain a significant and growing concern, as they directly affect fish habitat, migration, and productivity. There is evidence of shifts in fish distribution (some pelagics appearing further north or at different times) and anecdotal reports of declining catches for certain species which may relate to the environmental trends outlined in Part 1 (Al-Mowafak 2023).

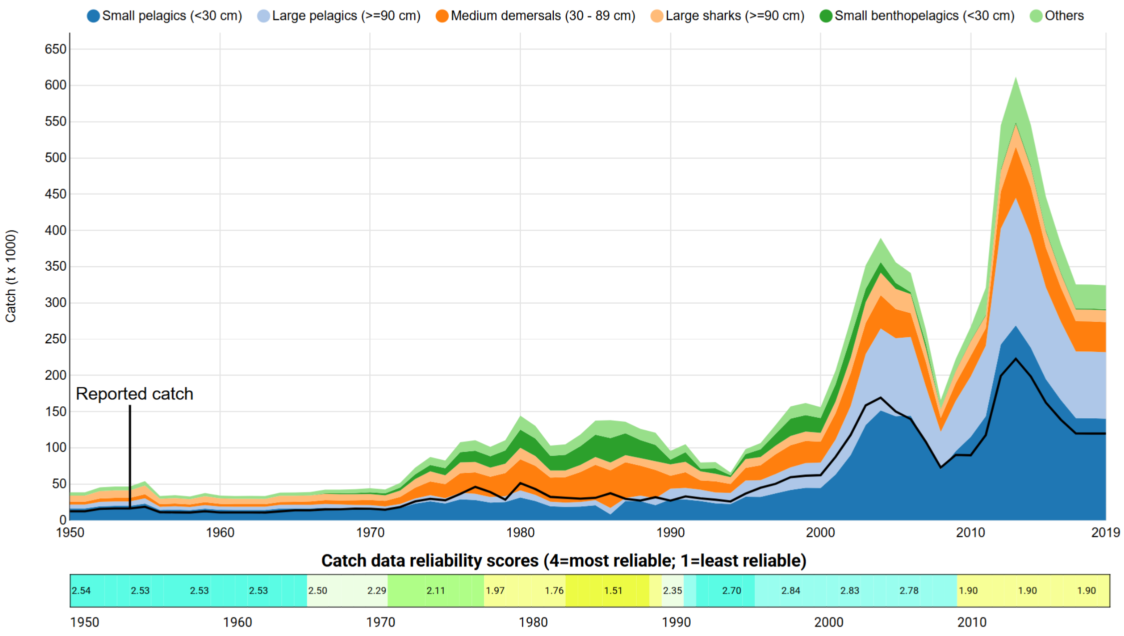

Figure 12: FAO Estimated Catch by Type: Gulf of Aden and Arabian Sea

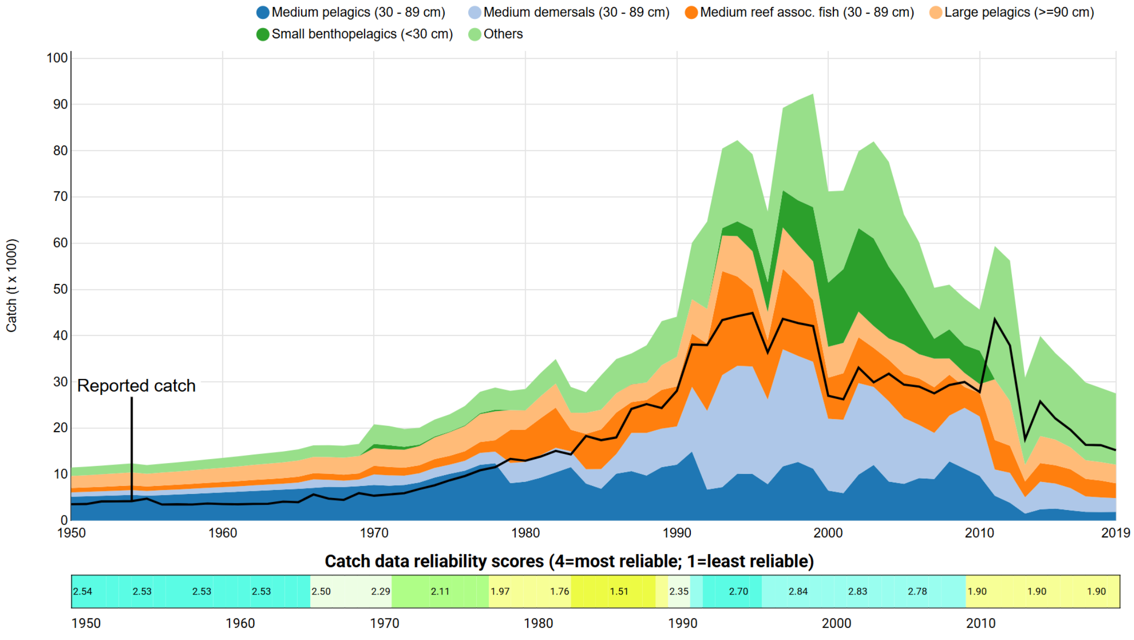

Figure 13: FAO Estimated Catch by Type: Red Sea

2.3. Decline in Data and Research Post-2014

The beginning of the civil war in 2014 led to a collapse of fisheries monitoring and data collection in Yemen. Government institutions responsible for fisheries (i.e., MoAIF and MSBRA) were severely disrupted. Official catch reporting largely ceased after 2014, creating a major gap in knowledge. For example, data from western Red Sea fishing ports became unavailable when those areas fell outside the Internationally Recognized Government (IRG) government control (Al-Fareh, A. M. 2018). The Ministry lost access to fisheries offices in Taiz and Hodeida, meaning no catch or effort statistics were gathered from those governorates after 2015. Table surveys show that records for Taiz and Hajjah governorates simply became nonexistent because authorities could no longer operate there (Al-Fareh, A. M. 2018). Nationally, Yemen stopped signing new international fisheries agreements and could not participate in regional science efforts post-2014. Research surveys and stock assessments that were urgently needed became impossible due to insecurity. The war also interrupted routine monitoring such as port sampling, patrols, and fishery surveys. Projects by international agencies (FAO, World Bank, Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA)) that had been working on Red Sea and Gulf of Aden fishery management were put on hold or canceled. As a result, there has been a steep decline in peer-reviewed research and reports on Yemen's fisheries since 2014. A literature search shows far fewer publications in the past decade, and those that exist often rely on pre-war data or anecdotal information. For instance, one of the only comprehensive post-2014 fisheries studies focused on Socotra used reconstructed data rather than new field data (Derrick, B. 2023). Local scientists faced displacement and damage to laboratories; the MSBRA in Aden struggled to continue any field studies, lacking funding and security.

2.4. Conflict Impacts on Fisheries and Coastal Communities

Beyond data issues, the war has directly disrupted fishing operations and the health of the fishery sector. The conflict had severe consequences for fishermen, significantly impacting their livelihoods due to damaged equipment and altered routes. In 2015, Yemen's fish catch in waters near Somalia plummeted to just 25% of its pre-war level, largely due to a decrease in port access and fuel supplies for Yemeni vessels operating in those distant waters (Cashion, T et al., 2018). Coastal fishing was also curtailed by security threats as only about 50% of fishermen were still able to go to sea by 2017. Infrastructure critical to the fishery sector including landing sites, cold storage, roads, and fuel supply have been extensively damaged in conflict zones and fishing cooperatives and ice factories were not spared, undermining the value chain.

These war impacts have had cascading effects on fishery health and outputs. With fuel scarce and expensive, fishermen cannot venture to richer offshore grounds, concentrating effort in nearshore waters. This increases pressure on coastal fish stocks, which were already stressed pre-war. Indeed, humanitarian assessments note that more people in Yemen's coastal communities turned to fishing for subsistence during the conflict (as agriculture and other jobs declined), intensifying overfishing of easily accessible species. Important demersal and pelagic stocks have shown signs of severe decline, fishers report catching smaller sizes and fewer high-value species than before (FAO). The disruption of exports also meant a loss of income for maintenance and gear, reducing fishing efficiency. By 2017, Yemen's total fish production had dropped dramatically to an estimated 50,000 tonnes/ year, barely 25% of pre-war levels (UNDP 2019). Export revenues similarly shrank to a fraction of their former value (only USD 74 million by 2018, down from nearly USD 300 million in 2013 (UNDP 2019). Coastal poverty has consequently deepened. Before the war, the fisheries sector employed approximately 0.5 million people and indirectly supported 1.7 million (Elayah, M. et al., 2019). Those who continued to fish faced longer trips and higher risks. There is also evidence of illegal fishing by foreign boats taking advantage of Yemen's instability. This likely exacerbates overfishing of shared stocks. Satellite-based analyses by Global Fishing Watch documented nearly 200 foreign driftnet vessels operating illegally in Somali and Yemeni waters, underscoring the governance vacuum and the external pressures facing artisanal fishers (Global Fishing Watch 2020). The conflict has devastated the fishing industry's infrastructure and capacity, altered who fishes and where, and likely impacted fish populations through unchecked exploitation in some areas and reduced pressure in others.

2.5. Regional Trends and Insights from Neighboring Waters

Yemen's fisheries are part of the broader Red Sea and northwest Indian Ocean ecosystems, and regional studies can shed light on trends affecting Yemen. In the Red Sea, studies from neighboring countries corroborate the findings that fish stocks were under heavy pressure before the conflict. For example, KSA's Red Sea fisheries experienced declining catch per fisher and signs of reef fish depletion in the 2000s, similar to Yemen's pre-war trajectory. A regional review by PERSGA noted that coastal fish stocks across the Red Sea were either fully exploited or over-exploited by the early 2010s and called for stricter management in all bordering nations. This regional overfishing context implies that Yemen's fishery health issues were not isolated. Furthermore, the migratory nature of species like tuna, mackerel, and sharks create compounding effects for neighboring countries within similar migration patterns. A catch reconstruction for Somali waters (Cashion et al. 2018) found that Yemeni vessels had been responsible for a notable portion of catches there, but those catches dwindled after 2015 due to Yemen's war and related naval blockades. In this way, the conflict not only affected Yemen's own waters but also the broader regional fishing patterns. Conversely, piracy off Somalia in the late 2000s had previously reduced foreign fishing in that area, possibly displacing more effort into Yemeni waters; when piracy waned and Yemen's war began, foreign fleets (legal or not) may have shifted into Yemen's zone, as hinted by reports of foreign boats during the conflict.

In the Gulf of Aden and Arabian Sea, oceanographic phenomena such as monsoons drive nutrient upwelling that supports fisheries for small pelagics (sardines, anchovy) and large pelagics (tuna). Yemen's Al-Mahra and Hadramaut coasts border Oman's productive waters, and environmental trends there likely affect Yemen. Recent studies off Oman have observed fluctuations in sardine stocks possibly linked to climate variability (for e.g., El Niño events) (Al Julaili S, et al., 2019). While direct data from Yemen's side are missing post-2014, it is plausible that the same fluctuations occurred in Yemeni waters. Climate change and warming waters are a concern in the region as the Red Sea is one of the fastest-warming marine areas. The new incursion of skipjack tuna into the Red Sea in 2021 (first recorded in Egyptian waters) is believed to be a result of such changes, opening the Bab-el-Mandeb corridor to species that previously rarely passed through (Adel, M. et al. 2022). Neighboring countries like Djibouti and Eritrea also have minimal fisheries data, but the limited information indicates those coasts saw reduced fishing during periods of regional conflict (Djibouti's civil war, Eritrea's restrictions), often followed by resource depletion when effort resumed. By analogy, Yemen's enforced fishing hiatus in some areas might have allowed slight recovery of certain stocks as hinted by the modest uptick in Socotra's catches post-2015 (Derrick, B, 2023), but any rebound is likely temporary if governance is not restored.

Overall, regional research underscores common challenges: unreliable data reporting, overfishing by both local artisanal and distant-water fleets, and emerging climate-driven shifts in marine ecosystems. Many Red Sea and Gulf of Aden fish species are shared, migrating along the coast or across the strait, so Yemen's lack of data post-2014 also hinders regional assessments. Studies from the KSA Red Sea and Omani waters can provide some proxy indicators of stock status (for e.g., trends in tuna catches by the regional tuna commission, or coral reef fish surveys in KSA waters) and most show either plateauing or declining catches in the 2010s, suggesting broad stress on marine resources. This regional perspective highlights that Yemen's fisheries stress is part of a wider pattern, though amplified by the acute shock of war. Rebuilding Yemen's fishery will require cooperation with neighbors on managing migratory stocks and combating Illegal, Unreported, and Unregulated (IUU) fishing that has likely increased in Yemeni waters during the lawless war period.

2.6. Key Research Gaps Due to Conflict

The conflict in Yemen has created significant research and data gaps regarding the country's fisheries. Firstly, the lack of recent catch and effort data and variable degrees of landing data makes it difficult to quantitatively assess the status of fish stocks or the total yield of Yemen's fisheries. Secondly, scientific surveys and monitoring programs were disrupted. Research vessels that once conducted trawl surveys or coral reef assessments are inactive; remote sensing and marine research stations in Yemen ceased most operations for a long period of time. As a result, marine ecological research (on fish spawning grounds, migration routes, habitat condition) is lagging. The status of critical habitats like mangroves and coral reefs that support fisheries is not well documented under war conditions. While pre-war studies identified nursery areas and seasonal migration patterns (for e.g., for shrimp and pelagic fish) in Yemeni waters; there is now a deficit of data as to whether these patterns have changed or if those areas have been damaged.

Another gap is understanding the socio-economic impact of conflict and climate change on fishing communities and how they have adapted. While some limited surveys (for example, interviews in Al-Hodeida in 2017–2018) have been conducted, there is still a lack of comprehensive data on fisher migration, changes in local fish consumption, or the resilience of coastal economies. Still, efforts are underway in this area and some progress has been made. Comparable work on this topic, such as the World Bank's PROBLUE-supported frame surveys in Somalia, demonstrate the feasibility of low-cost, standardized data collection systems that could be replicated in Yemen to establish robust management baselines (World Bank 2023). In parallel, UNDP-led fisheries value chain assessments (UNDP 2020; UNDP 2024) show how systematic mapping of actors, infrastructure, and market flows can generate insights into vulnerabilities and opportunities across the sector an approach that remains absent in Yemen since the onset of war. Economic valuation of the fishery post-2014 is also lacking, making it difficult to assess the full cost of the conflict. Moreover, the war's effect on IUU fishing and regional stock distribution remains poorly documented. Satellite analyses by Global Fishing Watch revealed nearly 200 foreign driftnet vessels operating illegally in Somali and Yemeni waters, highlighting the governance vacuum and external pressures facing artisanal fishers (Global Fishing Watch 2020). Finally, management and governance studies are urgently needed: institutional capacity for fisheries oversight has deteriorated, and research on how to rebuild monitoring, control, and surveillance post-conflict is scant. Filling these gaps will require restoring stability and engaging both local researchers and international partners in comprehensive surveys.

3. Framework for Creating a Dynamic Model for Environmental Conditions and Vessel Presence

3.1 Overview of Value Chain Analysis

This report aims to further provide a comprehensive understanding of Yemen's fishing value chain by integrating environmental indicators, satellite-based vessel detection methodologies, and ground-based data collection. The expected outcome of this framework is the creation of a dynamic model to be implemented in collaboration with MoAIF and MSBRA. Previously, this report focused on the climatological drivers and pressures affecting the Yemen coastal environment and fisheries. We then identified the lack of available catch data and the absence of reliable monitoring as a result of the ongoing conflict. The following aims to fill these gaps.

We first construct a fishing conditions metric, derived from satellite-based SST and Chl-a data, which will identify spatial and temporal patterns in the coastal ecosystem conducive to fishing. Additionally, an object identification model trained with computer vision techniques will monitor and estimate boat activity in Yemeni ports, effectively bridging the gap between environmental conditions and fishery operations. We will combine these analyses to create a framework for monitoring the coastal ecosystem and fishery sector.

3.2. Fishing Conditions Metric Construction

To quantify marine productivity and optimal habitats for pelagic fish, remote sensing data is leveraged. SST data, aggregated at a 0.25° resolution, will highlight areas where surface temperatures lie between 26 °C and 30 °C, a range commonly associated with favorable pelagic fish habitats in the region. Simultaneously, optimal Chl-a concentrations will be constructed, where the chosen optimal range of 0.3–1.0 mg/m³ indicates moderate to high productivity. These datasets will be further refined and verified using in situ observations leveraging the support of MSBRA. By overlaying SST and Chl-a within these thresholds, a discrete "fishing conditions" index will generated, pinpointing areas most likely to yield substantial fish stocks. This comprehensive approach acknowledges not only the seasonal variability of productivity, driven by phenomena like the monsoon cycle, but also the spatial heterogeneity of Yemen's extensive coastline. Figure 14 displays a sample of desirable fishing conditions.

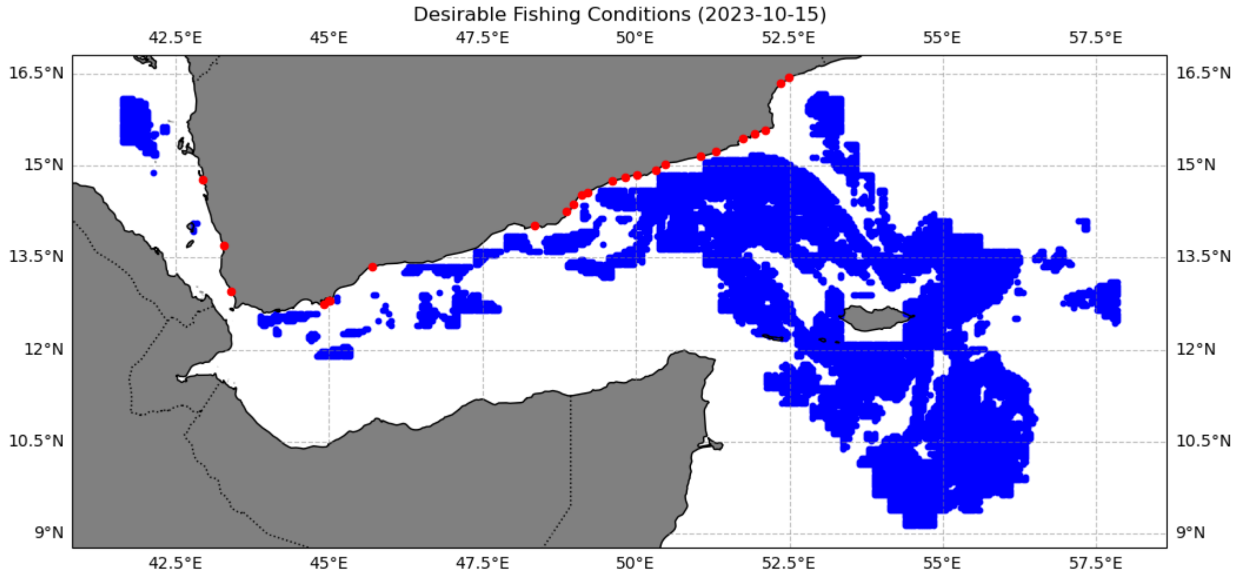

Figure 14: Example of Desirable Fishing Conditions Map

3.3. Computer Vision for Vessel Detection and Capacity Estimation

Parallel to assessing environmental conditions, the study will employ You Only Look Once (YOLO) version 8, a convolutional neural network (CNN)-based model known for its real-time object detection capabilities. YOLO's CNN architecture processes entire images in a single forward pass, enabling it to predict bounding boxes and class probabilities simultaneously. To test the applicability of this global model to Yemeni fisheries, a training dataset of over 600 satellite images was compiled, including specific examples tailored to Yemen's ports with manual bounding box annotations. This localization ensures high precision when detecting the smaller, often uniquely shaped vessels found in Yemeni waters. In a validation test at Shuqrah port, the model achieved 98% accuracy in identifying vessels. Furthermore, once a boat is detected, its bounding box dimensions, coupled with information on image resolution, viewing angle, and sensor altitude, allow for an estimation of the vessel's length. By correlating boat size with official catch records from the MoAIF, we can infer the likely capacity of each vessel, thereby approximating port-wide catch potential in near real time (Figures 15, 16 and 17).

Figure 15: Satellite Image at 250m of Boats in Shuqra

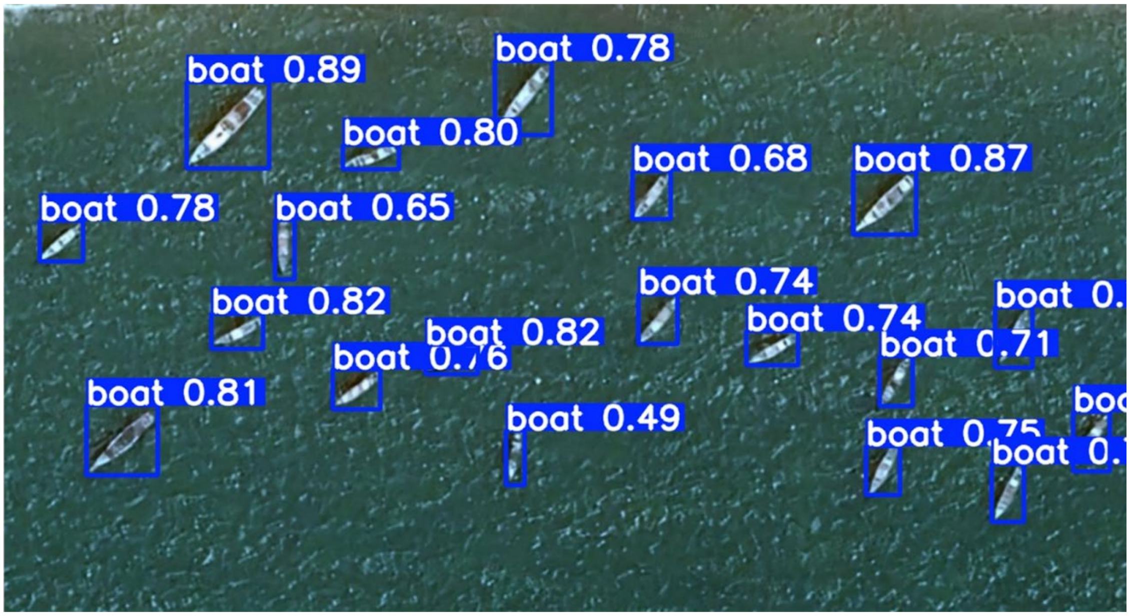

Figure 16: CNN Prediction of Boat Identification

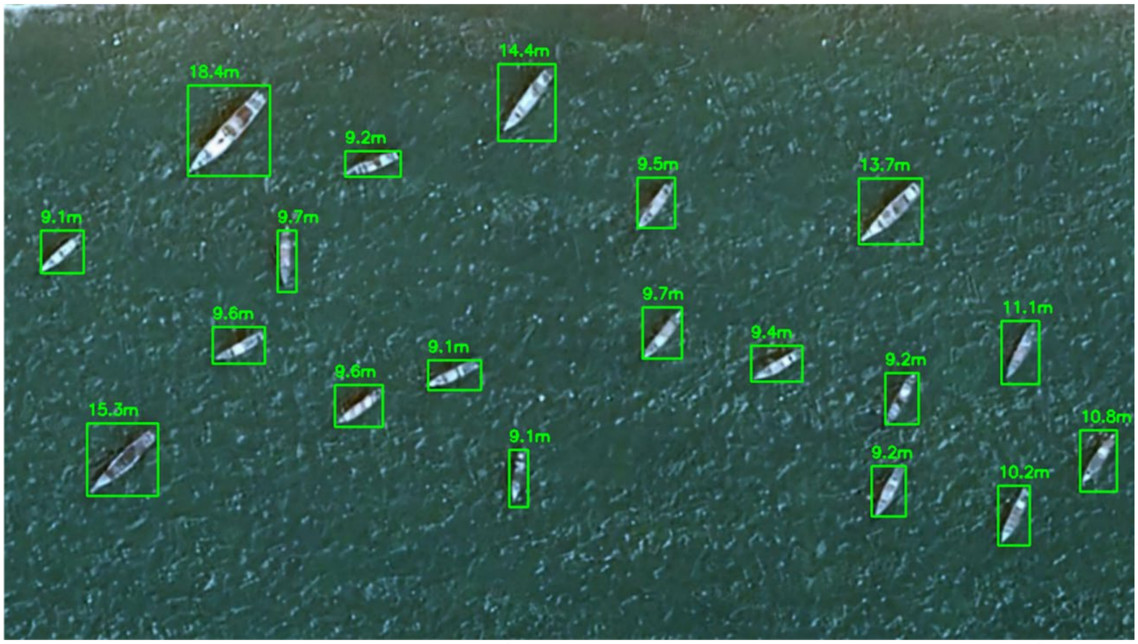

Figure 17: CNN Boat Length Estimates

3.4. Data Integration and Collaborative Framework

To ensure rigorous validation and long-term feasibility, the project aims – in order to ensure verification accuracy and long-term feasibility – to deploy additional sensors (such as for temperature, salinity, and nutrients) at strategic port locations. This effort is expected to be supported by the MSBRA with backing from MoAIF. The integrated datasets, remote-sensed SST/ Chl-a, in situ measurements, automated vessel counts, and official Ministry records on catch volume will provide a multi-dimensional perspective of the fisheries value chain. Furthermore, the initiative includes monitoring international fishing activity via transponder data from Global Fishing Watch, aiming to quantify the impact of foreign fleets on local fish stocks. Initially, the focus will be on ports such as Aden (Dockyard, Sira), Shabwah (Balhaf, Bir Ali), Hadhramaut (Al-Shihr, Mukalla), Al-Mahra (Nashtoon, Al Ghaydah), Socotra (Hadibu), and Abyan (Shuqrah), chosen for their historically significant catches and strategic value to Yemen's fisheries. Seasonal analyses will also play a critical role, recognizing how monsoon-driven wind patterns and productivity cycles shape fishing activities across the year.

3.5. Applications and Expected Outcomes

By harmonizing environmental suitability metrics with vessel detection and capacity estimates, this study will create a dynamic model of Yemen's fishery sector. Ministries and local stakeholders can utilize these findings to allocate resources effectively, identify high-potential fishing zones, and regulate fishing efforts to prevent overexploitation. Equally important, the approach can provide near-real-time alerts about shifts in environmental conditions or external fishing pressures. Ultimately, the work aims not only to fill existing data gaps but also to support data-driven policy decisions, encourage sustainable fishing practices, and enhance the resilience of Yemen's fishery-dependent communities.

3.6. Fisheries Dynamic Model Framework

1. **Introduction**
    - Objective: Integrate environmental indicators (SST, Chl-a, Ocean Ph) with vessel detection to support a robust value chain analysis.
    - Scope: Focus on Yemen's key fishing ports, recognizing seasonal wind and productivity patterns.

2. **Fishing Conditions Metric**
    - Data Sources
        - NASA SST (MODIS): Filtered to 26–30 °C for optimal pelagic fish habitats.
        - Chlorophyll-a (NASA Ocean Color): Concentrations between 0.3–1.0 mg/m³ to indicate moderate-to-high productivity.
        - SEABASS In Situ: Ground-truth data (temperature, nutrients) for calibration.
    - Resolution and Overlap:
        - 0.25° grid cells where both SST and Chl-a thresholds are met.
        - Gridded "fishing conditions" index assigned to each cell.
    - Seasonal Variation:
        - Weekly composites to capture short-term anomalies.

3. **Computer Vision for Vessel Detection**
    - YOLOv8 Model
        - CNN Architecture: Allows single-pass detection of bounding boxes and class probabilities.
        - Training Dataset: 600+ satellite images including Yemen-specific ports; manual bounding boxes ensure localized accuracy.
        - Evaluation: Achieved 98% accuracy in vessel detection at Shuqrah.
    - Boat Length Estimation
        - Bounding Box Geometry: Uses image resolution, altitude, and diagonal lengths for approximate vessel sizes.
        - Catch Capacity: Linking vessel dimension to average catch data (via Ministry inputs).

4. **Collaboration and Ground-Based Monitoring**
    - MoAIF
        - Provide records on vessel registration, active boats, and catch data.
        - Support policy decisions based on integrated model outputs.
    - MSBRA
        - Deploy sensors for temperature, salinity, and nutrient measurements.
        - Maintain local calibration and validation efforts.

  - Global Fishing Watch
    - Transponder data to identify foreign fishing vessel activity.
    - Allows quantification of non-Yemeni impact on local fish stocks.

5. **Geographic Focus**
   - Target Ports:
     - Aden (Dockyard, Sira)
     - Shabwah (Balhaf, Bir Ali)
     - Hadhramaut (Al-Shihr, Mukalla)
     - Al-Mahra (Nashtoon, Al Ghaydah)
     - Socotra (Hadibu)
     - Abyan (Shuqrah)
   - Justification: Historically significant and representative of Yemen’s diverse coastal environments.

6. **Integration and Analysis**
   - Data Fusion: Combine fishing condition grids with vessel detection counts and in situ observations.
   - Temporal Analysis: Track monthly/seasonal changes, highlight monsoon impact on fishing opportunities.
   - Policy/Management Relevance: Identify potential hotspots for overfishing, forecast catch potential, and guide enforcement.

7. **Next Steps and Outcomes**

Immediate actionable steps recommended within the next 6-12 months include:

- Establishing key monitoring stations for SST, Chl-a, and Ocean Acidification parameters in key fishing ports.
- Initiating targeted regional research partnerships for direct acidification and ecological response studies.
- Scaling vessel detection technology deployments in strategic fishing ports to quantify and regulate fishing capacity.
- Strengthening regional collaboration to monitor migratory fish stocks and combat illegal fishing.

The outcomes to be achieved are:

  - Dynamic Fisheries Model: Near-real-time updates on environmental conditions and vessel presence.
  - Sustainability and Policy: Inform stakeholders on capacity limits, optimize fishing efforts, and reduce IUU fishing.
  - Future Expansion: Extend to additional ports, refine YOLO training for diverse vessel types, integrate more frequent satellite imagery, and incorporate long-term climate projections.

Addressing these priorities will significantly advance Yemen’s marine resource management, promote sustainable fisheries, and enhance coastal community resilience in the face of ongoing climate change and conflict challenges. These efforts can also provide evidence to design and evaluate targeted climate adaptation interventions.

There is a significant role for international organizations to play to support the development of an evidence-based dynamic fisheries model through financial and capacity building initiatives. Climate funds, in particular, play a vital role in unlocking finance for supporting such adaptation projects. For reference, attached in the appendix is a non-exhaustive list of fisheries adaptation projects from all four major climate funds. Many focus on building capacity for the sustainable management of fisheries as well as leveraging technology to improve data collection and dissemination.

3.7. Conclusion

Rebuilding structure and monitoring of Yemen’s fisheries amid ongoing challenges necessitates a multi-pronged strategy that restores effective data collection, applies advanced analytical tools, and drives evidence-based policy decisions. This proposed methodology, featuring fishing conditions metric grounded in satellite-derived oceanic data, coupled with a cutting-edge computer vision model for vessel detection, directly addresses many of the gaps left by the conflict. Crucially, it re-establishes routine monitoring through partnerships with national agencies, ensuring that the MoAIF and MSBRA can expand their data and validate remote-sensing products with on-the-ground measurements.

The recommendations outlined here chart a path toward a more adaptive fisheries management paradigm, in which local authorities and international stakeholders have access to up-to-date information on both environmental conditions and fishing practices. By linking vessel size to estimated catch capacity, managers will have a clearer view of the sector’s operational scale, enabling more balanced regulation of fishing effort. Efforts to track foreign vessel activity through transponder data can further mitigate the risk of overexploitation by non-Yemeni fleets. In tandem, ongoing sensor deployment and data-sharing initiatives will strengthen collaboration among researchers, policymakers, and local communities, reinforcing the sector’s resilience. As additional field data become available and sensor coverage grows, these methods can be refined, extended to other ports or marine habitats, and integrated with broader climate projections, ultimately helping Yemen’s fisheries recover and thrive in a post-conflict landscape.

Policy Recommendations

Considering this report’s analysis on Yemen’s changing marine environment and the state of current data gaps for monitoring Yemeni fisheries, several policy and management recommendations emerge to help adapt to and mitigate the impacts of climate change on marine ecosystems while rebuilding infrastructure. These are as follows.

Integrated Monitoring of Key Indicators

- Establish a robust, long-term program to monitor SST, Chl-a, sea SSS, and pH (for Ocean Acidification) in Yemen's Red Sea, Gulf of Aden, and Arabian Sea waters.
- Combine satellite data (for e.g., MODIS, SMAP) with locally deployed buoys and research cruises to provide both broad-scale and in situ observations.
- Develop an integrated database, managed jointly by the MSBRA and MoAIF to correlate changing environmental conditions with fisheries data.

Ecosystem-Based Fisheries Management

- Adopt an ecosystem-based approach that factors in climate-driven changes to habitat and species distribution.
- Adjust fishing quotas and seasonal closures if indicators (for e.g., declining Chl-a or intensifying MHWs) suggest stressed fish populations.
- Enhance enforcement to curb IUU fishing, especially in ecologically sensitive or overfished areas.

Climate Adaptation for Coastal Communities

- Provide small-scale fishers with timely climate information particularly on extreme weather events along with training on adaptive gear and fishing strategies.
- Invest in cold storage and value-adding facilities to reduce post-harvest losses and create alternate income streams during climate-induced fishing downtimes.
- Strengthen safety-at-sea programs to address increasingly unpredictable weather patterns.

Regional Collaboration and Research

- Work with international bodies (for e.g., PERSGA, FAO) to share data, harmonize stock assessments, and coordinate management of migratory species (tuna, mackerel, sharks).
- Pursue joint oceanographic surveys in the Red Sea and Gulf of Aden with neighboring countries to track transboundary fish stocks and oceanographic trends.

- Develop research partnerships to study the long-term ecological impacts of cyclones, MHWs, and Ocean Acidification on Yemen’s coastal ecosystems.

Rebuild Fisheries Governance and Data Systems

- Reestablish port-level data collection (catch records, fishing effort, landing surveys), ensuring secure, conflict-sensitive operations.
- Leverage remote-sensing (for e.g., vessel detection with computer vision) and local catch reporting to create near-real-time monitoring of fishing activities.
- Reinstate stock assessments and habitat surveys that were disrupted by conflict, focusing on key species (tuna, lobster, shark) and critical habitats.

Facilitate Access to Finance and Insurance

- Collaborate with development agencies and private-sector partners to design microfinance and insurance products for fishers vulnerable to climate shocks (for e.g., cyclones, failed monsoons).
- Encourage climate adaptation funding (via Green Climate Fund, Adaptation Fund, etc.) to support technology upgrades, sustainable gear, and training programs.

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Appendix: List of Fisheries Projects Funded by Climate Funds

	Project Name	Entity	Countries	FA Financing	Summary of project
Green climate Fund					
1	Improving the resilience of vulnerable coastal communities to climate change related impacts in Viet Nam	United Nations Development Programme	Viet Nam	29,523,000	Strengthening storm and flood protection for coastal communities in Viet Nam through resilient housing, planting and rehabilitation of mangrove forests, and systematized climate risk assessments for the public and private sectors.
2	Climate Information Services for Resilient Development Planning in Vanuatu (Van-CIS-RDP)	Secretariat of the Pacific Regional Environment Programme	Vanuatu	18,106,905	Using science to better prepare Vanuatu's policy makers and public for a changing climate. This project will expand the use of Climate Information Services (CIS) in five targeted sectors: tourism, agriculture, infrastructure, water management and fisheries. Specific project goals include building technical capacity to harness and manage climate data, developing practical CIS tools, fostering their use and disseminating tailored climate information.
3	Vanuatu community-based climate resilience project (VCCRP)	Save the Children Australia	Vanuatu	26,182,878	This project will support highly vulnerable rural and coastal communities to increase their resilience to climate change, through targeted community and local adaptation activities in the agriculture and fisheries sectors. The project will also provide access to climate information and early warning systems at the local level. Key activities include establishing local disaster risk reduction committees; protecting and restoring 11,600 hectares of agricultural and fisheries sites; and training smallholder farmers in climate-resilient agriculture techniques and fishers in effective coastal resource management.

4	Climate Resilient Fishery Initiative for Livelihood Improvement in the Gambia (PROREFISH Gambia)	Food and Agriculture Organization	Gambia	17,200,000	The project aims to support vulnerable and poor fishing communities in building resilience to climate change and in diversifying livelihoods through technology improvements, processing techniques, climate-proofing of the local fishery infrastructure, and diversification of local food systems.
5	Adapting tuna-dependent Pacific Island communities and economies to climate change	Conservation International	Cook Islands, Fiji, Kiribati, Marshall Islands, Micronesia (Federated States of), Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu	107,449,716	This project will build resilience in tuna-dependent economies and communities by addressing food insecurity and economic risks caused by climate change. It will achieve this by enhancing access to tuna for coastal and urban communities, strengthening national fisheries systems, and improving forecasting to manage tuna redistribution effectively. Key activities will include technical support for Fish Aggregating Devices (FADs) deployment, fisher training, post-harvest improvement; policy development, improved handling, and market opportunities; and using science-based forecasts and projections to reduce uncertainty in climate change-driven tuna redistribution.
Adaptation Fund					
1	Resilient Coastal Fisheries and Aquaculture in Nauru	The Pacific Community	Nauru	7,999,493	This project strengthens institutional structures at the national and local level, conducting awareness raising campaigns for local communities, improve food security through increased farmed fish supply, technical and financial assistance to fishers, increase resilience of ecosystems through availability of data and knowledge sharing.

2	Strengthening the Adaptive Capacity of Coastal Communities of Fiji to Climate Change through Nature-Based Seawalls	The Pacific Community	Fiji	5,707,100	Coastal adaptation remains a top priority for the Government of Fiji (GoF) given the proportion of the population living in coastal areas. However, cost-effective solutions remain challenging to implement and scale up due to financial, capacity and other constraints. This proposed project seeks to deliver impact at scale by facilitating cross-ministerial cooperation, institutional capacity building and knowledge sharing to build nature-based seawalls using mangrove forests, locally sourced boulders, and vetiver grass to protect 16 coastal communities in Fiji highly vulnerable to impacts of climate change. These interventions will enable critical capacity building and institutionalise the engineering expertise required to design and implement innovative Nature-based Solutions (NbS) at local level.
3	Adaptation to the Impacts of Climate Change on Peru's Coastal Marine Ecosystem and Fisheries	Peruvian Trust Fund for National Parks and Protected Areas	Peru	6,950,239	The overall objective of the project is to reduce the vulnerability of coastal communities to impacts of climate change on the coastal marine ecosystems and fishery resources. This will require the implementation of a group of adaptation measures that include: 1. Implementation of a group of activities that contribute to the enhancement of current adaptive capacity of artisanal fishing communities living along the Peruvian coast, and reduce the vulnerability of coastal ecosystems, while increasing the income of the communities and their participation in managing and protecting their natural resources; 2. Deployment of a modern and efficient surveillance, prediction and information system of climate and environmental key factors at regional and local scales, supporting fishing, aquaculture and ecotourism activities, as well as fisheries adaptive management based on long-term prevision under climate change scenarios; 3. Development of a knowledge

					framework to facilitate capacity building at different levels and the dissemination of project's lessons learned; 4. Adjustment of the institutional framework (legal, regulatory and organizational) to facilitate EBA for the coastal marine domain at country-level and to implement an Ecosystem Approach to Fisheries (EAF) including artisanal fishing.
Global Environment Facility					
1	Promoting sustainable fisheries management in the Red Sea Large Marine Ecosystem (RedSeaFish project)	Food and Agriculture Organization	Djibouti, Egypt, Eritrea, Jordan, Yemen, Regional	6,192,694	The objectives of this project are to: 1. Identify lessons from past and ongoing related efforts to improve fisheries governance and regulatory enforcement at regional and national scales, and ensure these are integrated into project design explicitly. 2. Address incentives for proposed shifts in behaviour with specific reference to the socio-economic drivers and governance context. 3. Consider how future scenarios could impact project implementation and outcomes, and demonstrate how these considerations have influenced design. In addition to climate futures, which does feature in design, it is useful to consider the role of conflict risk and stability, particularly in light of the civil unrest in Sudan and ongoing conflict in Yemen. Information on how changing price of fish and fishing operations might impact the behaviour of fishermen would be useful as this seems to be a major reason behind overfishing. 4. Claims to innovation focus on the newness of effective regional cooperation and application of multi-stakeholder dialogue approaches in this particular geography.
2	Sustainable management of fisheries, marine living resources and their habitats in the Bay of Bengal region for the benefit	Food and Agriculture Organization	Bangladesh, India, Indonesia, Malaysia, Maldives, Sri Lanka, Thailand, Regional	9,478,899	This project includes technical assistance to build the capacity of national government to sustainably manage fisheries, to restore and conserve critical marine habitats, and to manage coastal and marine pollution, and improve coordination.

	of coastal states and communities				
3	Strengthening Adaptative Capacities to Climate Change through Capacity Building for Small Scale Enterprises and Communities Dependent on Coastal Fisheries in The Gambia	United Nations Industrial Development Organization	Gambia	2,200,000	This project includes the improvement of national capacities to mainstream Climate Change Adaptation, increased resilience and adaptative capacities of enterprises and communities along the coastal fisheries value chain, strengthening the institutional and community capacities to develop and utilise integrated fisheries data.
4	FishAdapt: Strengthening the Adaptive Capacity and Resilience of Fisheries and Aquaculture-dependent Livelihoods in Myanmar	Food and Agriculture Organization	Myanmar	6,000,000	The objectives of this project are to: To enable inland and coastal fishery and aquaculture stakeholders to adapt to climate change by understanding and reducing vulnerabilities, piloting new practices and technologies, and sharing information, 2. Enhanced capacity of DoF, Gov and private sector stakeholders to address climate change issues through improved relevant national policies and strategies facilitating a climate resilient fisheries and aquaculture sector; 3. Increase knowledge and reduce vulnerability of fishers
5	Marine Science and Aquatic Biology Research Infrastructure Upgrade Project	FAO-Yemen	Research activity extension along the coasts of the Red Sea, Gulf of Aden, and Arabian Sea	10,235,000	To enhance and strengthen scientific research in fisheries management, update data on the impacts of climate change on the growth and reproduction of fishery resources

6	Lakes Edward and Albert Integrated Fisheries and Water Resources Management Project	African Development Bank	Congo DR, Uganda, Regional	8,100,000	The sector goal of the LEAF II Project is poverty reduction and sustainable livelihoods for men and women (in the local fishing communities) and global environmental benefits in sustainable management of the natural resources. The principal project objective is to *sustainably utilize the fisheries and allied natural resources of the Lakes Edward and Albert Basin through harmonized legal framework and policies*, through three components: i) *Fisheries resources development and management*; ii) *Integrated water resources management*; and iii) *Project management and coordination*.
Climate Investment Funds					
1	Enhancing the Climate Resilience of Coastal Resources and Communities	International Bank for Reconstruction and Development	Samoa	14,270,000	This project includes measures to manage climate and disaster-related threats near the coastlines, strengthening climate information services, and institutional strengthening for climate and disaster resilience, project coordination and monitoring.
2	Promoting Community-based Climate Resilience in the Fisheries Sector of Jamaica	International Bank for Reconstruction and Development	Jamaica	4,820,000	The Project development objective is to enhance community-based climate resilience among targeted fishing communities of Jamaica. This would be achieved by investing in (i) strengthening the fisheries policy and regulatory framework including making it climate-smart, (ii) viable alternative livelihoods that enhance sustainable fisheries, and (iii) capacity building and awareness raising among the fishing communities. These measures would be implemented in a participatory approach with the targeted fishing communities. While national and international best practices will inform the design and implementation of the supported activities, the use of local knowledge will be crucial to the success of the Project.

3	Coastal Climate Resilient Infrastructure Project	Asian Development Bank	Bangladesh	27,170,000	This project aims to improve road connectivity, improve market services, upgrade climate disaster shelters, enhance knowledge management, and capacity of local government.

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