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Navigating Shifting Currents:

A Decade of Marine Species Migration and Climate Change in the Eastern Pacific

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Acknowledgments

To the currents that never stopped moving,

and to the parts of myself that chose to stay.

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1. Introduction

A few weeks ago, I was drifting somewhere off the map, on a small fishing boat in the Pacific Ocean off the coast of El Paredón, Guatemala. The morning sun rose over the horizon while the boat swayed softly. A sea turtle surfaced beside me, its head barely breaking the water, when suddenly a flying fish shot past, silver flickering for a second before it vanished. One of the local fishermen turned to me and said the sea had been warmer than usual this year—and that some species weren't showing up the way they used to. His words stayed with me. At that moment, I wasn't just seeing the ocean. I was witnessing change.

This study examines how climate change has altered marine species' migration patterns over the past decade. While the topic of species movement on land has been widely studied, the shifting behaviors of ocean life remain comparatively understudied. Yet these shifts are undeniable, and their urgency grows by the day. Many species are moving earlier, moving toward cooler areas, or completely relocating. These changes are profoundly impacting livelihoods, traditions, and entire ecosystems for areas that live close to the sea, especially in regions like Central America.

Two species that are representative of this change are the subjects of my research: 1) The Eastern Pacific Green Turtle, whose breeding and migratory habits have been documented along Guatemala's beach; and, 2) Bull Shark, a wide-ranging species whose patterns are changing across the Pacific. By studying their movement patterns, we can begin to understand how altered habitats, shifting tides, and warming seas are reshaping marine biogeography as we know it.

To do this, I integrate NOAA's climate data with field observations from El Paredón and local ecological understanding from fishermen. I also incorporate animated storytelling visualizations as a way to bring these migration patterns to life, showing not just where species move, but what those movements feel like when seen through the eyes of someone at sea.

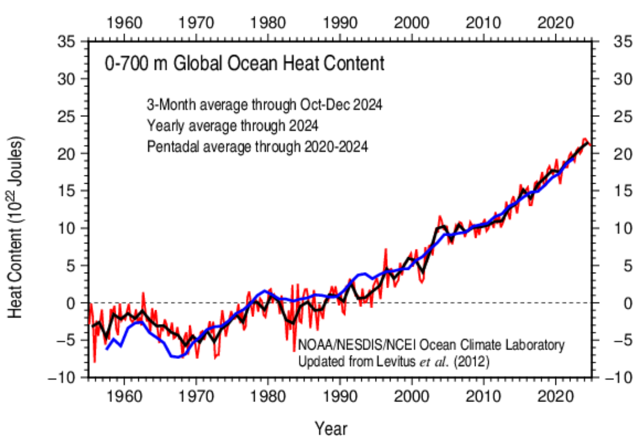
This paper is organized into ten sections. It begins with an introduction and background literature review, outlining existing research on marine migration under climate change and identifying key gaps. Next, the study examines large-scale ocean warming trends and regional variations in the Eastern Pacific. Two focused case studies then follow: the first analyzes migration pattern changes in the Eastern Pacific Green Turtle while the other on the Bull Shark. A methodology section describes the use of satellite datasets, field observations, and informal interviews. Visualization strategies, including geospatial mapping and interactive media, are then introduced to illustrate the movement patterns of some marine species. Finally, the paper presents key findings, and concludes with a discussion on the ecological and socioeconomic implications of shifting marine migration.

Diverging from conventional climate change narratives hidden in maps and policy bullet points, this paper blends data with lived experience, connecting scientific evidence to the textures of daily life along the ocean's edge. By combining datasets, field observations, conversations with local fishermen, and dynamic visualizations, I aim to make the shifting patterns of marine life a more tangible and visceral reality.

2. Background & Literature Review

2.1 Global Warming and Oceanic Change

Over the past decade, 90% of the excess heat created by greenhouse gas emissions has been absorbed by the oceans (Cheng et al. 2021). According to NOAA's climate reports, global ocean heat content has steadily increased since the 1970s, contributing to rising sea surface temperatures (SSTs) in nearly all major ocean basins (NOAA NCEI 2023). This warming disrupts the delicate physico-chemical equilibrium that marine ecosystems depend upon, affecting species from tiny plankton to massive migratory sharks and turtles (Poloczanska et al. 2013).



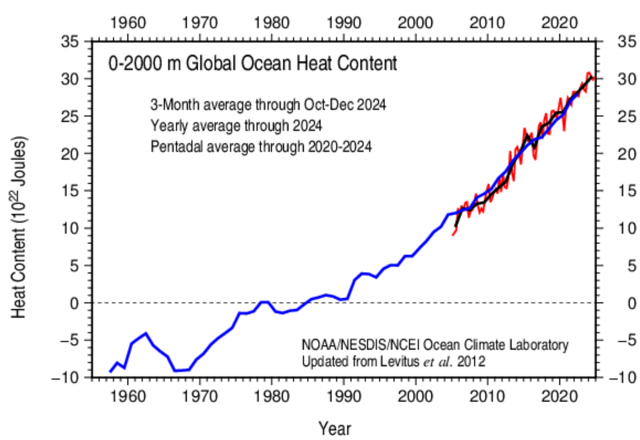


Figure 1a. Global Ocean Heat Content at 0–700 meters (1955–2023)

Source: NOAA National Centers for Environmental Information 2023.

Figure 1b. Global Ocean Heat Content at 0–2000 meters (1955–2023)

Source: NOAA National Centers for Environmental Information 2023.

In addition to surface warming, rising ocean temperatures have been shown to reduce mixed layer depth, intensifying vertical stratification and limiting nutrient mixing. This can lead to decreased phytoplankton productivity and impact food web dynamics (Behrenfeld et al. 2006).

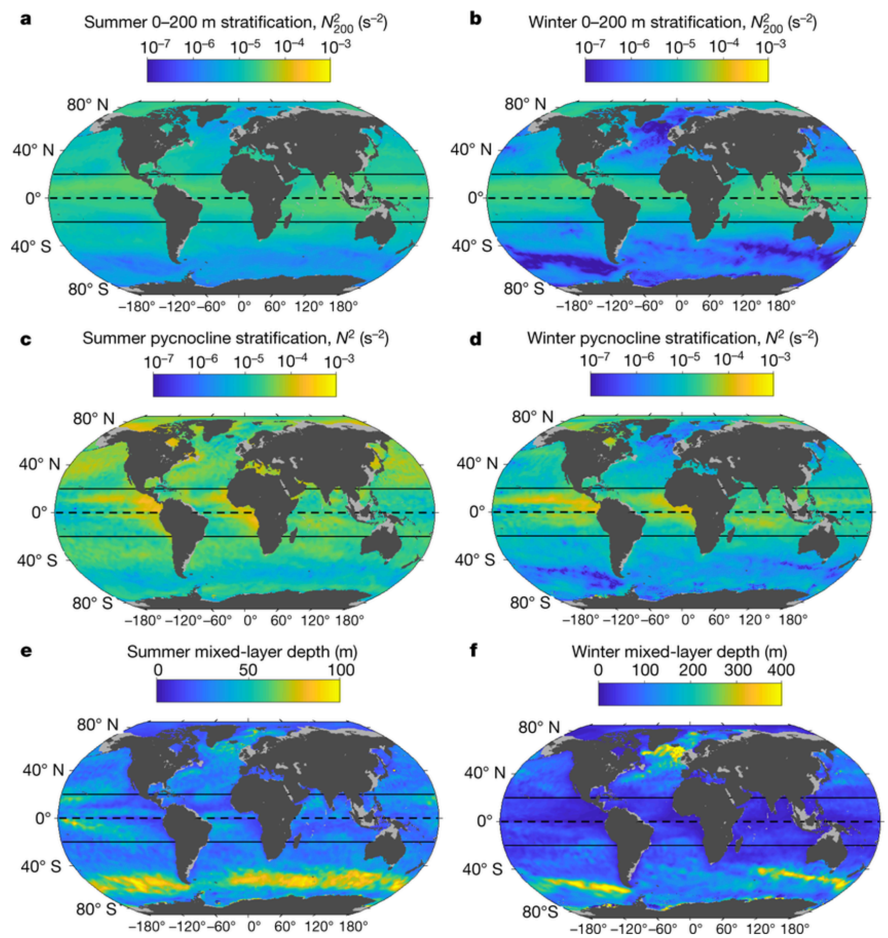


Figure 2. Climatological Upper-Ocean Stratification and Mixed-Layer Depth

Source: Sallée et al. 2021.

Among the most visibly impacted systems, coral reefs, plankton populations, and marine turtles stand out for their high sensitivity to thermal stress. The diversity and distribution of plankton, essential to the marine food web, have sharply decreased (Boyce, Lewis, and Worm 2010). Parallel to this trend, the incidence of coral bleaching displays marked increases in both occurrence and intensity (Hughes et al. 2018). These interconnected modifications propagate through marine ecological networks and have an impact on a variety of marine ecosystems and some specialized species.

2.2 Migration Pattern Research in Marine Species

The study of marine species movement in response to climate change is a comparatively new area despite the long-standing focus on terrestrial species migration. Some typical challenges such as the tracking of mobile species across large and deep sea environments, have previously limited research efforts. However, developments in satellite tagging, acoustic telemetry, and remote sensing technologies have expanded our ability to observe and monitor the movements of marine life with greater accuracy (Block et al. 2011).

Different species respond to oceanic climate shifts in various ways, according to studies on marine migration. Whales may alter their seasonal migration timing by several weeks, while turtles establish new nesting beaches up to 150 km poleward from the historic site (Poloczanska et al. 2013). Some fish species have been observed moving into cooler water. However, some studies still face restrictions due to data gaps, particularly in remote coastal areas with limited funding for research and equipment (Maxwell et al. 2015). Additionally, migratory species frequently cross international borders, which adds to the difficulty of organized conservation efforts and standard monitoring.

Learning marine migration requires not only biological knowledge but also professional knowledge of oceanography, climatology, and even policies. The dynamic characteristics of the ocean add another layer of complexity. Unlike landscapes, ocean currents, temperature layers, and nutrient distribution are constantly changing, creating a flowing environment where the "range" is not fixed (Deutsch et al. 2015).

2.3 Regional Studies: Central America & Pacific Ocean

Regional experiments in Central America and the Pacific have begun to show how certain marine species adjust to climate changes. In the Eastern Pacific, which runs along the shores of countries like Guatemala, Costa Rica, and Panama, many migratory species find places to breed, feed, and move through. Yet, the same waters are particularly exposed to changing climate patterns, especially shifts tied to events like the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (McPhaden et al. 2006).

Central America's Pacific coast now witnesses marine migrations governed by rising temperatures and altered currents. Considering Costa Rica's sharks and billfish, research confirms their movement patterns have shifted, forcing fisheries managers and conservationists to rethink long-standing approaches. Meanwhile on Guatemalan beaches, sea turtles' nesting calendars no longer match the previous experience, with nests appearing weeks earlier or failing altogether when sands grow too hot. These aren't isolated cases but connected symptoms of a system in flux, where each shifted migration sends ripples through fisheries and protection plans alike.

In general, ecological observations in the Pacific Ocean are often hampered by its vastness and environmental complexity. Large-scale events like ENSO occasionally hit vast ocean regions, causing ecosystem disruptions across thousands of kilometers. When there are strong El Niño years, species that typically migrate along predetermined routes may fail to reach crucial habitats (Cheung et al. 2009). To better anticipate future adjustments under continued global warming, understanding how migration patterns respond to local climatic events is essential.

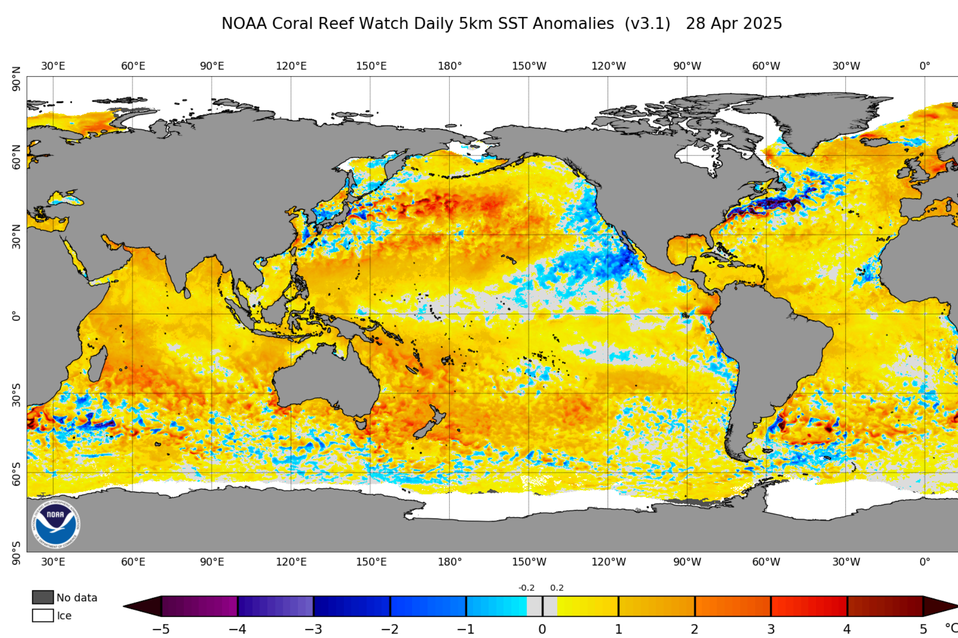


Figure 3. Sea Surface Temperature Anomalies in the Equatorial Pacific (April 2025)

Source: NOAA Climate Prediction Center 2025.

2.4 Evolution of Data Collection Methods

The methods for studying marine migration have evolved considerably in recent years. Before the mid-20th century, sailors and fishermen primarily relied on direct sources of information such as catch records, shoreline surveys, and anecdotal observations (Pauly 1995). These methods provided critical insight but lacked broad spatial and temporal resolution.

Today, scientists use satellite-based devices to track individual wildlife across waters for months or years. Acoustic telemetry devices provide in-depth analysis of local activities (Hussey et al. 2015). Environmental DNA (eDNA) sampling has emerged as a non-invasive method for detecting the presence of specific marine species through genetic material left behind in water (Bohmann et al. 2014). Geographic Information Systems (GIS) further facilitate the creation of unified, visualized migration maps that incorporate various data streams, including temperature, currents, and species locations (Roberts et al. 2023).

Interestingly, community-based monitoring initiatives are now recognized as reliable sources of biological information. Local anglers often notice shifts in species presence, unusual behaviors, and seasonal changes that might otherwise go unreported, particularly in areas like El Paredón. These efforts advance our understanding of marine migration patterns under the influence of climate change and strengthen biological stories grounded in lived knowledge.

3. Climate Change & Ocean Temperature Trends

3.1 Global Ocean Warming Patterns

The heat distribution has been unequal, both vertically and horizontally, despite the ocean acting as the main heat sink for Earth. IPCC data confirm increasing heat absorption in deeper ocean layers (700-2000 meters), driving changes in oxygen availability, nutrient cycling processes, and vertical migration corridors for marine organisms (IPCC 2019).

Some areas of the Southern Ocean have warmed more slowly than the global average, such as the eastern Pacific Warm Pool and the North Atlantic. However, even these relatively "cooler" zones are projected to experience accelerated warming under ongoing emissions scenarios. This process starves surface waters of upwelled nutrients, directly impairing the phytoplankton productivity that sustains marine food webs.

The frequency and intensity of marine heat waves have substantially increased alongside the background trend of continuous ocean warming. Recent research indicates that events once considered rare are now twenty times more common compared to pre-industrial conditions (IUCN 2021). Activating ecosystem-wide responses that cannot be measured by normal temperature metrics only, marine heatwaves can quickly destroy migrant schedules, prey availability, and breeding success (Smale et al. 2019).

3.2 Regional Impacts: Eastern Pacific and Caribbean

The Eastern Pacific's coastal waters particularly along Guatemala, Costa Rica, and Panama now exhibit unprecedented thermal patterns. Analysis of NOAA's ERSST data demonstrates a clear trend: tropical Eastern Pacific surface temperatures have climbed roughly 0.15°C each decade since the early 1980s (Cheng et al. 2024) . However, these warming trends interact complexly with the region's dominant climate driver—the ENSO cycle—which creates temperature fluctuations that sometimes mask the underlying heating signal.

During strong El Niño events, surface temperatures in the Eastern Pacific may rise several degrees above seasonal norms. This heat causes a decrease in nutrient upwelling, alters the thermocline depth, and which causes cascading effects on migratory species ' food availability. For example, tuna, billfish, and sharks ' migration corridors become less predictable, and sea turtle mating patterns are increasingly decoupled from traditional annual signals. Emerging research suggests that the frequency of extreme El Niño events may increase under future warming scenarios (Cai et al. 2014).

The Caribbean's weakened currents and intensified gyres create persistent heat accumulation zones. Coral reefs across the region now face annual thermal stress surpassing historical records according to PLOS Climate, driving recurrent mass bleaching (NOAA 2024). These prolonged heat exposures disrupt critical life stages—juvenile fish lose nursery habitats while young turtles abandon degraded reef shelters, altering migratory populations at ecosystem scales (Eakin et al. 2010).

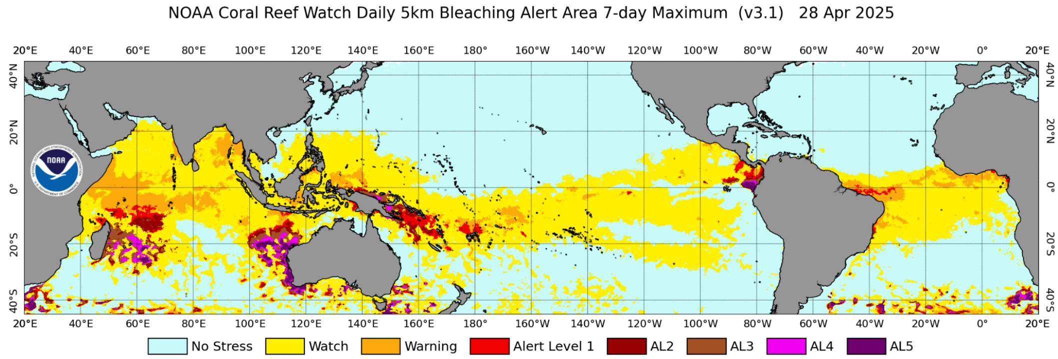


Figure 4. Coral Bleaching Alert Levels in the Caribbean

Source: NOAA Coral Reef Watch 2025.

Beyond temperature increases, regional warming has altered fundamental oceanographic conditions, including salinity gradients, OMZ expansion, and current system modifications, particularly the North Equatorial Countercurrent's weakening. These transformations are driving measurable ecological consequences: shrinking species distributions and displacement into less suitable habitats.

3.3 Data-Driven Insights and Visualization

Comparative analyses using NOAA's Coral Reef Watch SST anomaly charts and PLOS Climate local analyses show a widening difference between historical and contemporary SST patterns. SST anomalies exceeding 1°C above the annual mean have become increasingly frequent in the Eastern Pacific, particularly during the strong ENSO seasons of 2015, 2016, and 2019–2020 (NOAA Coral Reef Watch 2024; PLOS Climate 2023).

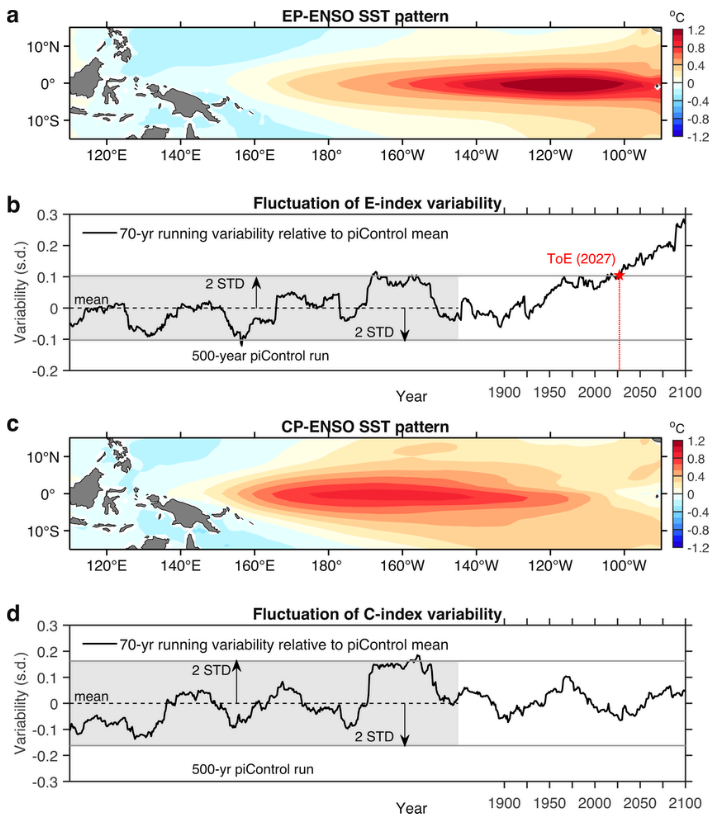


Figure 5. Spatial Patterns and Variability Trends of Eastern and Central Pacific ENSO Events

Source: Cai et al. 2022.

Time-series visualizations based on NOAA data illustrate the rising frequency and intensity of marine heatwaves (Smale et al. 2019). These ocean warming events have been increasingly linked to disruptions in migratory behaviors among marine species. During periods of extreme sea warming, data suggest that large coastal sharks, such as the bull shark, may encounter range shifts or habitat contractions in response to thermal stress. In addition, empirical studies have shown that Eastern Pacific Green Turtles prefer cooler beach areas as standard locations become thermally unsuitable (Fuentes et al. 2011).

A broader understanding of how subtle ocean changes influence species movement and behavior can be explored through a combination of satellite-based SST data and movement tracking studies. The animated part created for this project visualizes these invisible dynamics, offering a narrative perspective that connects scientific insight with broader community and policy awareness.

4. Case Study 1: Eastern Pacific Green Turtle (Guatemala)

Figure 6. Hatchling Green Turtles Departing the Shoreline in Guatemala

Source: Johnny's Place Hotel 2024.

4.1 Changing Migration Patterns

The Eastern Pacific Green Turtle has long been recognized for its broad migratory behavior, traveling between nesting beaches and remote foraging grounds across the eastern Pacific Ocean (Seminoff et al. 2008). Communities nestled along Guatemala's coasts, especially near El Paredón and Sipacate, previously had relatively stable migrant corridors that regularly return to known feeding locations in coastal grass beds and deep reef systems (Mongabay 2013).

However, these long-established patterns now face disruption from contemporary ocean changes, particularly increasing surface heat, modified circulation patterns, and growing hypoxic regions (NOAA Fisheries 2023). Recent studies suggest that green turtles are now changing their migratory timings, finding unique foraging sites, and, sometimes, shortening or fragmenting their migrations. Satellite tracking data from local conservation groups indicate that some individuals, instead of migrating north along traditional routes toward Mexico and Baja California, remain in offshore Guatemalan waters for longer or divert west toward less conventional sites (Procrea n.d.).

These observed changes are strongly correlated with local thermal anomalies and habitat degradation, such as the warming and bleaching of seagrass meadows (IFAW n.d.). Field observations and reports from local fishers corroborate these patterns, indicating broader environmental disruptions across the eastern Pacific.

4.2 Coastal Environmental Changes and Policy

Spanning approximately 254 miles along the Pacific, Guatemala's coastline provides essential ecological sites for Eastern Pacific Green Turtles, featuring both sandy nesting grounds and adjacent coastal feeding zones. These vital ecosystems now face compounding threats from marine heat accumulation, shoreline degradation, and deteriorating seagrass conditions—all contributing to diminished turtle habitats and declining population figures.

These challenges are made worse by human influences. Aquaculture activities, agricultural runoff, and uncontrolled coastal expansion all put stress on marine ecosystems. For example, sedimentation from inland operations degrades the quality and purity of the water, disrupting crucial nearshore habitats that are essential to turtles of all ages.

Conservation efforts are ongoing, but significant challenges remain. Local organizations such as NGOs and local efforts have worked to shield nesting beaches and track turtle populations, particularly focusing on Eastern Pacific Green Turtles along Guatemala's coastline. Many conservation initiatives rely heavily on community participation and external financing support, even though national parks like Sipacate Naranjo National Park provide some legal frameworks for habitat protection (Tico Times 2006). Broader, integrated coastal management approaches are needed to address these challenges.

4.3 Field Observations and Community Perspectives

In April 2025, I spent several days at El Paredón, walking along the beach and talking with local residents about the sea and the animals they see around it. The coastline stretched out in dark sweeps of volcanic sand, with small lines of foam left by the waves breaking onto the shore. On some mornings and toward the end of the day, the beach seemed almost empty. Now and then, I noticed scattered shells half-buried in the sand, and once or twice, faint turtle tracks leading up from the water.

There was a stillness to the place that was both peaceful and unsettling. Without formal conservation infrastructure visible on the beaches, the presence of the turtles seemed vulnerable, left to the rhythms of the tides and the growing pressures of human encroachment. I saw no official patrols or marked nesting zones there.

Talking with people from the town added a deeper stillness to the quiet landscape. Some residents shared changes they had noticed over the years: turtles arriving at unusual times, fewer nests during some seasons, and shifts in foraging patterns offshore. One elderly fisherman told me, “You used to walk at night and almost trip over turtles,” but now, he said, such situations have become rare and dispersed. Another local resident, who ran a small tour service and also served as my guide, pointed out toward the open sea as we sat on a boat together. He explained that these days, visitors often get excited just to see a single nesting turtle, a moment that used to be so common it hardly drew any attention.

What stayed with me most was the tone of the conversations. In fact, when I had conversations with many local residents, we couldn't fully understand what they were saying, as I do not speak Spanish. But I could always hear that people were proud of the historical connection between this community and sea turtles, there was also a silent sense of loss, because they realized that the ways of life they grew up with is slipping away. Turtles remain a part of their world, but no longer with the same certainty and abundance. Obviously, for many residents, sea turtles are not merely an ecological symbol; They are also the memories of individuals and collectives.

These observations made it clearer to me that conservation cannot rely on scientific data or government policies alone. It also needs to consider the lived realities and emotional connections of the people who share their environment with these species. For the Eastern Pacific Green Turtle, protecting migration routes and nesting sites is not just about managing environmental threats; it is equally about keeping alive the cultural and historical bonds that give these animals meaning within the community.

Figures 7-10. Field observations in El Paredón, Guatemala.

Photo by author, April 2025.

5. Case Study 2: Bull Shark (Pacific Ocean)

5.1 Shifts in Migration Routes

The Bull shark is a predatory species that lives in coastal seas and is the shark with the best ability to move into freshwaters, particularly large, coastal waters and freshwater systems (Oceana n.d.). They are able to move back and forth between saltwater and freshwater with ease (National Geographic 2022). In the past, they moved seasonally between estuaries and offshore feeding sites along well-defined migration patterns in the northern Pacific Ocean (Rider et al. 2021). But throughout the last ten years, these trends have started to change (Matich et al. 2024).

Based on satellite and acoustic tagging over the last decade, bull sharks are moving farther north and into deeper waters. The 2015-2016 El Niño provided a clear example, when researchers documented these sharks reaching unprecedented northern locations including Baja California and southern California's coastal waters. This behavior suggests that bull sharks actively shift toward cooler nearshore waters to avoid the thermal stress caused by unusually high sea surface temperatures. These areas act as “thermal refuges” where water temperatures remain within the sharks’ physiological tolerance range, allowing them to maintain stable metabolic functions and access prey that may also be displaced by warming.

5.2 Food Chain and Ecological Niche Impacts

According to the Smithsonian Environmental Research Center and the National Marine Sanctuaries, bull sharks, as primary predators, govern the population of its prey and affect the behavior of other species (NOAA National Marine Sanctuaries 2022). It is essential to the integrity of the coastal ecology.

The local food web's stability will decrease when bull sharks depart from their original homes. They would have to change their diet in recently colonized regions due to increased competition or a decline in prey. In addition to altering ecological dynamics, such disruption may also have an effect on human populations and coastal fisheries (NOAA Fisheries 2023).

5.3 Broader Implications and Future Outlook

The documented northward migration of bull sharks in the Pacific Ocean may serve as an early indicator of broad ecosystem shifts occurring due to elevated water temperatures and more changing current dynamics. As oceanic conditions evolve, bull sharks may establish permanent populations in previously colder waters, increasing the potential for conflict with native predators and unintended consequences for local prey species.

To determine whether these migration shifts represent short-term responses to periodic phenomena like El Niño or enduring range changes caused by oceanic warming, ongoing long-term monitoring will be important. Implementing progressive conservation strategies, like adaptive marine reserves and regional fisheries policies, might mitigate downstream impacts on ecological stability and coastal populations reliant on marine resources.

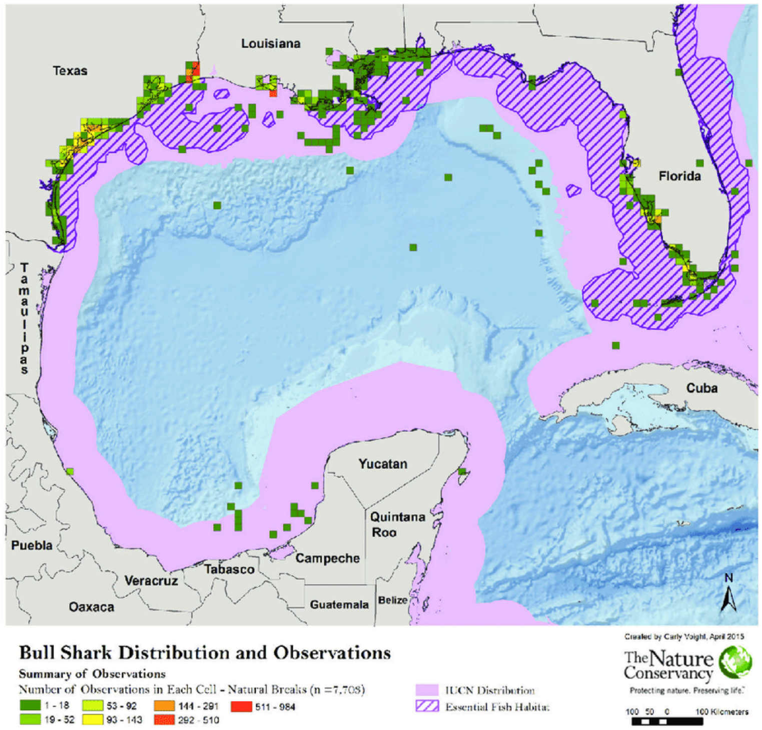


Figure 11. Bull Shark Distribution and Habitat Observations in the Gulf of Mexico

Source: Brenner et al. 2016.

6. Methodology

This study used a mixed-methods approach to investigate how migratory movements in marine species are influenced by climate change, integrating field observations, secondary data analysis, and visual communication strategies.

6.1 Data Sources

This paper integrated both secondary data and firsthand field observations. At its core were two NOAA datasets: the Extended Reconstructed Sea Surface Temperature (ERSST) program, maintaining decades of global and regional temperature records, and Coral Reef Watch products, monitoring marine heatwaves and thermal anomalies (National Oceanic and Atmospheric Administration 2023). These combined datasets revealed how steadily warming oceans have disrupted traditional migration pathways of marine species since the late 20th century.

Peer-reviewed studies from PLOS and other journals have strengthened the data evidence and provided more research directions regarding how species distribution and ecosystem behavior adapt to the warming ocean.

Meanwhile, during the field visit to El Paredón, Guatemala in April 2025, informal conversations with local residents and fishermen collected more information about the environmental conditions of the Green Turtles, the characteristics of nesting beaches, and anecdotal evidence.

6.2 Semi-Structured Interviews

As previously stated, during the field visit to El Paredón, informal semi-structured conversations were held with local residents and fishermen. These open discussions provided qualitative insights into the research.

Despite not being statistically representative, these narratives supplement quantitative environmental data and provide important depth to understanding the local socio-ecological context.

6.3 Visualization Strategy

Visualization in this research focused on presenting spatial and temporal patterns of species migration in an accessible format. Geospatial mapping was used to illustrate the shifting migration routes of Eastern Pacific Green Turtles and bull sharks, based on satellite data and regional temperature trends.

Collectively, these methodologies offer a comprehensive insight into the impact of climate change on marine species movement in the Eastern Pacific and surrounding coastal ecosystems.

7. Finding & Visualizations

To synthesize the research findings and communicate both ecological patterns and their experiential implications, this section is divided into two parts. Part 1 focuses on comparative migration maps developed using geospatial reasoning and data-informed design, illustrating species distribution shifts over time. Part 2 presents an experimental visualization built with TouchDesigner to explore the affective dimensions of environmental change.

7.1 Migration Maps: Green Sea Turtles and Bull Sharks

Figure 12. Changes in Eastern Pacific Green Sea Turtle Migration Routes (2010 vs. 2023)

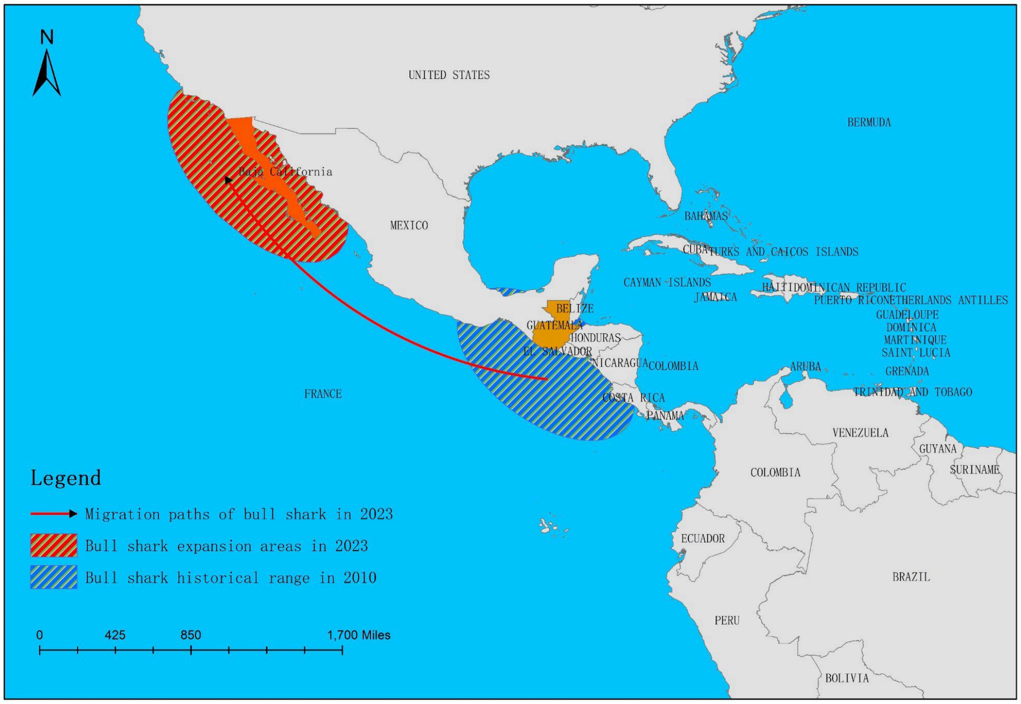


Figure 13. Bull Shark Range Expansion and Migration Shift in the Eastern Pacific (2010–2023)

To illustrate the spatial shift in green sea turtle migration over the past decade, I created **Figure 12**, a comparative map of two estimated routes from Guatemala into the Eastern Pacific. The green arc shows the dominant 2010 path, moving steadily north along the coast toward Baja California. This route reflected long-established ecological rhythms, predictable temperatures, stable nesting sites, and reliable feeding grounds along the continental shelf.

The red arc, representing 2023, shows a clear deviation. Rather than continuing north along the coast, the path veers west into deeper offshore waters. This shift is not based on a single dataset, but on a synthesis of satellite tracking studies, regional SST trends, and field observations from my time in El Paredón. The altered route reflects growing disruption in coastal habitats, rising temperatures, reef decline, and increasing unpredictability, all influencing instinctive movement.

Figure 12 is not a precise tracking record, but a conceptual visualization meant to reflect a broader ecological reality: that migration is no longer a return to the familiar, but a continuous response to environmental instability. What was once a clear path has become fragmented. The sea is warmer, the signals are different, and the movement continues, but in new and uncertain directions.

To further explore how marine species are responding to these shifting oceanic conditions, I created **Figure 13**, a map visualizing the recent northward expansion of bull sharks in the Eastern Pacific. The blue area represents their estimated historical range around 2010, concentrated in the tropical coastal waters of Central America. These zones once provided ideal thermal and ecological conditions: warm estuaries, shallow bays, and relatively stable food chains.

In contrast, the red shaded area shows their observed and projected distribution in 2023, extending up through Baja California and into regions not historically associated with bull shark presence. The migration path illustrated here traces a new movement pattern: away from familiar equatorial zones and toward cooler, higher-latitude waters. While the exact data remains limited, this visual is based on a synthesis of acoustic tracking studies, NOAA species records, and predictive modeling from recent literature.

Like **Figure 12**, **Figure 13** is not meant to represent precise telemetry data, but rather to show a broader ecological tendency: one where movement is driven not by repetition, but by response. In a changing ocean, even apex predators are no longer following fixed cycles. Their routes are adapting, bending toward thermal refuges and prey migrations, reflecting a deeper shift in marine ecosystems.

8. Discussion

8.1 Ecological Impacts

These migrations not only represent biological adaptation, but also serve as an ecological alarm.

The departure of green turtles from their original feeding areas or the invasion of bull sharks into unfamiliar coasts are obvious distress signals. Apparently, changes in the movement patterns of marine species will trigger a cascading effect throughout the entire ecosystem (Estes et al. 2011). This kind of damage undermines the stability of the food web. Think of the bull sharks moving northward, their presence threatens the local fish species that are not adapted to this new threat. Meanwhile, the sea turtles' migration may destroy important seagrass habitats, which have historically maintained ecological balance.

8.2 Human Activity and Policy Responses

Human activities both exacerbate and respond to these ecological shifts.

Human activities in coastal areas have exacerbated these ecological damages. The combined pressure formed by coastal development, pollution and overfishing is together squeezing the living conditions of marine species with climate-driven migration stress (Halpern et al. 2008). When animals move to areas with less protection, they often meet greater human impacts. Despite the adoption of local conservation policies for national parks in Guatemala, limited budgets and weak regional cooperation still make this work extremely difficult. Although treaties like the Inter-American Sea Turtle Convention provide a policy framework, there are still inconsistencies in their implementation (Inter-American Convention for the Protection and Conservation of Sea Turtles 2001). Actively adjusting protection strategies to adapt to the constantly changing migration routes is crucial for protecting fragile ecosystems.

8.3 Economic Implications

As marine species move, economies that once depended on their predictability must learn to move too.

The changes in the movement of marine species can also have economic chain reactions. When fish change their routes, fisheries built on predictable movements face volatile harvests and endangered incomes (Cheung et al. 2010). Meanwhile, tourism operators related to the ocean are confronted with uncertainties, such as the operating hours and strategies of tours. On the contrary, new ecotourism opportunities may emerge in areas experiencing an influx of species. Policymakers must invest in flexible, ecosystem-based approaches to adapt to the mobility of species and the changing relationship between humans and wildlife.

9. Conclusion & Recommendations

Thinking back to a few weeks ago, when I was sitting on a small boat in El Paredón. At the time, it felt like witnessing a small, isolated shift.

Today's migration is no longer simply governed by the natural laws of seasons and ocean currents. Instead, it has become a biological compass. Its shifting tracks mapping ecosystem transformations, its altered routes revealing life's struggle to navigate a changing world. These migrations are not isolated events, but fragments of broader transitions, ecological, cultural, and political, that unfold slowly, powerfully, and with increasing inevitability.

Migration patterns today are maps not only of where species move, but of how human systems must evolve alongside them.

This study explores the impact of ocean warming caused by climate change on the migration patterns of marine species, especially in the eastern Pacific. The two case studies, green sea turtles and bull sharks in the Eastern Pacific, using a combination of satellite data, literature reviews and field observations. These two species represent a broader trend that migration is becoming increasingly unpredictable and is affected by climate change, habitat deterioration and coastal human development. They also show that species that once followed relatively stable migration routes are now responding to abnormal temperatures, habitat degradation and increased human stress. Along the El Paredon coast of Guatemala, green turtles now stay in shallow water for a longer time and have changed their traditional nesting behavior. Meanwhile, bull sharks crossed historical boundaries and recorded their advance northward towards Baja California for the first time during the 2015-2016 El Nino.

The migration pattern changing of marine species has disrupted the existing ecological balance: the food web is shaken, the predator-prey ratio is unbalanced, and the coastal economy based on fishery and tourism is facing unprecedented pressure. Current conservation strategies need to shift from rigid management frameworks toward dynamic, adaptive approaches with greater flexibility. For instance, marine protected areas should be adapted to species migration patterns, with enhanced regional collaboration to address spatiotemporal changes in migration corridors and improved science communication to strengthen conservation consensus.

These shifts call for more than conservation—they make us rethink our place within the living systems that sustain us, and to confront the futures already unfolding before us.

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