LOGGERHEAD SEA TURTLE (*CARETTA CARETTA)* INTERACTIONS IN PELAGIC LONGLINE SWORDFISH FISHERIES: A COMPARISON OF THE NORTH PACIFIC AND NORTH ATLANTIC TRANSITIONS ZONES

by
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Abstract

While many factors have contributed to the decline of worldwide sea turtle populations, longline fishing, in particular, has received a significant amount of attention in the past decade. However, there are still many areas where bycatch composition and rates are largely unknown. Using observer data from the N. Atlantic and N. Pacific longline swordfish fisheries from 1994-2000, this study analyzes the underlying oceanographic conditions that occur when loggerhead sea turtles (*Caretta caretta*) are caught in longline gear. Using geospatial and statistical analysis, these events are compared to fishing activities that did not result in loggerhead interactions. Within each study area certain predictors emerged, however significant differences were apparent in five of the six variables analyzed. While these differences may be the result of limitations in the data used, it may be attributed to utilization of habitat by loggerheads in the areas studied. In gaining a greater understanding of when bycatch is likely to occur, more effective management can be enacted to help reduce both the frequency of interactions with endangered species and the socioeconomic impacts on fishermen.

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Introduction

Interactions between sea turtles and longline fisheries have been a well documented problem in many fisheries (Lewison et al, 2004). Different management strategies have been proposed and implemented to help reduce the number of interactions with varying success. The goal of this study was to determine if the spatial and temporal distribution of bycatch was similar within two comparable oceanographic regions, and determine if there are predictive oceanographic variables that increase the likelihood of a bycatch event. This information could then be used to help assess the extent of bycatch in areas of similar oceanographic composition that are currently data deficient.

While there have been an increasing number of studies examining the influence of oceanographic conditions on the rate and composition of sea turtle bycatch, it has been predominantly focused within the Atlantic Ocean, most likely due to the availability of data. This research seeks to expand on previous spatial analysis of bycatch within the Pacific by Crowder and Myers (2001) by providing a more in depth examination of bycatch of loggerhead sea turtles within the Hawaii longline swordfishery. Additionally, comparisons of the management and practices of the two fisheries can offer insight into why some policies work and others fail, which can hopefully lead to more effective management, with the end goal of increasing both economically viable sustainable fishing as well as loggerhead sea turtle populations.

Sea Turtles

Despite their worldwide distribution, sea turtles have been shown to utilize only a portion of the vast ocean, congregating in nutrient-rich hotspots to forage and using specific migration corridors to reach nesting grounds. As a result of their highly migratory nature, sea turtles are particularly susceptible to population declines when management and conservation efforts do not take into account the cumulative impacts from regional activities that directly affect the survival of these species. Population of the seven species of sea turtles are all believed to be greatly reduced as a result of anthropogenic causes. The World Conservation Union (IUCN) Redlist lists green, loggerhead and olive ridley turtles as endangered and hawksbill, kemp's ridley and leatherback turtles as critically endangered, with the status of the remaining species, the Australian flatback, considered data deficient.

Life History of Sea Turtles

All sea turtles are slow growing, late reproducing, and long lived. Their life history can be separated into three phases: hatchling, juvenile and adult (Figure 1). Turtle hatchlings emerge from nests on the beach and wait until night to enter the ocean. Once male hatchlings enter the water they will never again return to land. Hatchling swim into the waves, which direct them toward deeper waters, and then the hatchlings navigate by using the Earth's magnetic field when they get far enough offshore that there are no longer waves (Spotila, 2004). Little is known about sea turtles in this stage compared to other stages, which has been described by Carr as the "lost years" (1967) until they reappear as juveniles.

All species have a juvenile pelagic phase, except the flatback (Bowen, 2007). It is believed that juveniles swim with prevailing ocean currents, near frontal zones where they can feed, and also among seaweed to decrease predation (Dutton, 2003). Upon reaching sexual maturity, sea turtles will migrate from their foraging ground to their mating beaches, which can be separated by thousands of miles (Dutton, 2003). Mating occurs offshore and females exhibit natal homing, nesting on the beaches that they once emerged from (Spotila, 2004).

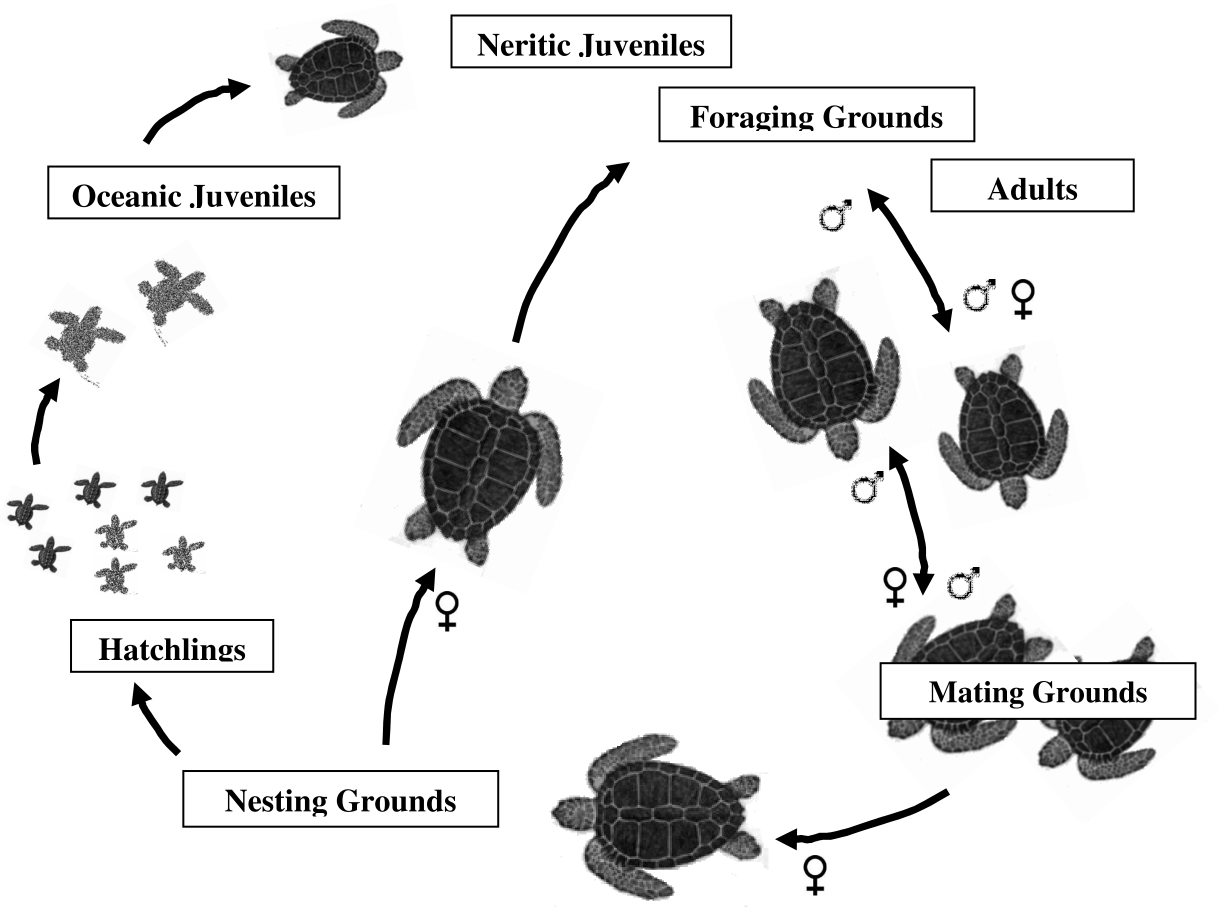


Figure 1: Generalized life cycle of sea turtles.

Sea Turtle Conservation and Management

Sea turtles are protected under a number of agreements, treaties and laws on a national and international scale. Within the US these include the Endangered Species Act (ESA), the National Environmental Policy Act (NEPA), and the Magnuson's-Stevens Fishery Conservation and Management Act (MSA). Internationally, sea turtle conservation is coordinated under the Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC). Since sea turtles are a highly migratory species, and spend different stages of their lives within the waters and lands of different countries, multilateral management plans are necessary for conservation to be effective.

Within the US, sea turtle are managed jointly by the National Marine Fisheries Service (NMFS) and the US Fish and Wildlife Service (USFWS). NMFS has authority over the management of sea turtles when they are foraging and migrating within state and federal waters, while the USFWS is responsible for the management of female sea turtles when they come ashore to nest on US coastal beaches. All species of sea turtles that migrate through US waters or nest along US beaches are classified as threatened or endangered, and therefore are protected by the ESA. This protection prohibits the "taking" of sea turtles. The action of taking is defined by the ESA as to "harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect or to attempt to engage in such conduct" (16 U.S.C. § 1532). Incidental taking of specifically any species of sea turtle is permitted in fishing activities when an incidental take permit has been issued by NMFS (50 C.F.R 223.206d). Under the ESA, NMFS is required to prepare Biological Opinions (BiOp) on actions affecting protected species, specifically if the action places the protected species in jeopardy (16 U.S.C § 1536c). The ESA states that jeopardy occurs "when an action is reasonably expected, directly or indirectly, to diminish a species' numbers, reproduction, or distribution so that the likelihood of survival and recovery in the wild is appreciably reduced" (50 C.R.F 402.02). If the action does not impose jeopardy on the species, then recommended incidental take levels are determined.

Additionally, sea turtles are given further protection by NEPA. Under NEPA, any governmental actions that significantly affect the environment are required to issue an Environmental Impact Statement (EIS) (42 U.S.C. § 4321-4327). The purpose of these statements is to develop a reasonable range of alternative management plans that minimize the environmental impact of the proposed action, including a no action alternative (42 U.S.C. § 4321-4327). When any governmental action has the possibility of impacting sea turtles (i.e. changes in fisheries regulations or the reopening a fishery), an EIS must be prepared.

Sea turtles are also protected under the MSA, which guides the management of commercial fishing within the US Exclusive Economic Zone (EEZ). Commercial fishing produces a significant amount of bycatch, which is the incidental catch of non-targeted species and also the catch of undersized targeted fish. The MSA created eight regional fishery management councils (FMC) within NMFS that are responsible for developing commercial fishery management plans (FMP) that "shall, to the extent practicable, minimize bycatch and to the extent bycatch cannot be avoided, minimize the mortality of such bycatch" (16 U.S.C § 1801c).

The IAC is an inter-governmental treaty ratified in 2001 by Mexico, Guatemala, Belize, Honduras, Costa Rica, Venezuela, Ecuador, Peru, Brazil and the US, with Uruguay and Nicaragua as signatories (IAC, 2001). The treaty was created to better facilitate multilateral coordination of conservation efforts between the nations (IAC, 2001). Requirements of the treaty include the complete restriction on the capture (incidental or otherwise) or commerce of sea turtles, restrictions on human activities that may impact sea turtles at any point in their life, protection of critically designated habitat, environmental education, and the reduction of sea turtle bycatch in fishing gears (IAC, 2001).

While these agreements and policies may have slowed the decline of some populations, declines are still occurring that still place some species at risk for extinction. Threats that sea turtles face are both natural and anthropogenic, and include the destruction of beach nesting habitat through hurricanes, global warming and coastal development; hunting and consumption of turtles and turtle eggs; nest predation by native and non-native species; ship strikes; ingestion of marine pollution; and interactions with commercial and small-scale fishing (Lewison et al 2007). Pelagic longlining, in particular, has received an increased amount of attention as a result of the industries interactions with sea turtles in the past decade.

Loggerhead Sea Turtles

Loggerheads have become one of the most well studied species of sea turtles, especially in the Atlantic Ocean, because they are considered generalist species (Bowen, 2003). They have the greatest geographic range of nesting beaches and have the least specialized diet (Bowen, 2003). As a generalist species, loggerheads can offer insight into other more specialized sea turtles species.

Loggerhead Biology

Nesting areas for loggerheads are focused in the western North Atlantic, the Mediterranean and the Indo-Pacific. Once hatchlings emerge, they face many threats in moving from land to sea, including predation and disorientation from light pollution. Once in the water, loggerheads will actively swim away from shore in a period known as the “swim frenzy” (Bolten, 2003). As soon as the turtles begin feeding the hatchlings enter into the post-hatchling stage (Bolten, 2003). During this time they will seek cover from predation, feed opportunistically on plants and animals, remain in surface waters and swim with the prevailing oceanic currents to the open ocean (Spotila, 2004), which can take many months depending on the favorability of current and winds (Bolten, 2003). Once the post-hatchlings reach the oceanic zone they move into the juvenile stage (Bolten, 2003).

The juvenile stage can be broken up into two phases, the oceanic and neritic, or coastal, phase. It is estimated that the transition between the two occurs when juvenile loggerheads are approximately 44 - 67 cm in straight carapace length, depending on the region (Bolten, 2003). Oceanic juveniles spend approximately 75% of their time in the top five meters of the water column, with the majority of dives above 100 meters and only rarely diving to depths up to 200 meters (Bolten, 2003). The duration of the oceanic phase is estimated to be between 6.5 and 11.5 years with Pacific juveniles believed to remain in this phase longer (Bolten, 2003).

The neritic stage is marked by a shift in habitat from oceanic to coastal waters. It is believed that loggerheads will transition when it becomes more advantageous for growth to enter coastal waters that contain more abundant food sources, despite the increased risk of predation (Bolten, 2003). During the neritic stage loggerheads are feeding actively on the bottom and throughout the water column (Bolten, 2003) often in the area of their natal rookery (Bowen, 2007). Juveniles from genetically different rookeries have been found to mix on coastal foraging grounds (Bowen, 2007). During this time, juvenile loggerheads may be sharing the same habitat as adult loggerheads that are foraging.

Loggerheads do not reach maturity until they are between 12 – 30 years (Spotila, 2004) when turtles are generally greater than 80cm in straight carapace length (Hopkins-Murphy et al, 2003). Adult females exhibit not only fidelity toward nesting beaches, but also toward foraging grounds (Luschi, 2003), swimming at times against prevailing currents or using currents to help them to arrive at foraging grounds faster after nesting (Schroeder et al, 2003), and may remain at the foraging ground for the entire inter-nesting period (Luschi, 2003). Females departing from the same nesting beaches and traveling to the same foraging grounds may not necessarily use the same migration route (Schroeder et al, 2003). Adult males also exhibit site-fidelity to foraging grounds after mating (Schroeder et al, 2003).

A study on loggerheads within the Great Barrier Reef found that there was no sex-specific difference in survival probabilities and the expected annual survival probability for adults was 0.875 (95% CI: 0.84-0.91) (Chaloupka, 2002). A difference in shark predation frequency of between male and female loggerheads was seen by Heithaus (2002), suggesting that males face greater predation risk than females and may take more risks.

Genetic differences between the Pacific and Atlantic populations

Loggerheads are descendant from two separate lineages, representing the Atlantic-Mediterranean and Indian-Pacific populations, which diverged three million years ago (Bowen, 2003). These populations have been separated since then, with little mixing occurring (Bowen, 2003). However, recent genetic evidence has revealed that some mixing of loggerhead populations from the Indian-Pacific and Atlantic regions has occurred via migrations around southern Africa (Bowen, 2003).

Atlantic Loggerheads

Population Status

There are five genetically different nesting regions within the western North Atlantic located in the southeastern US, from North Carolina to the Dry Tortugas, Florida, and also include a population on the Yucatan peninsula in Mexico. These populations contain, at highest estimations, 56,000 nesting females (NMFS/USFWS, 2007). Although comprehensive and consistent monitoring has not been completed annually at all of these locations, those sites that have data available show a general decrease in the number of nesting females, ranging from 3.1% in North Carolina to 22.3% in southeastern Florida (NMFS/USFWS, 2007). These different groups are considered highly vulnerable, due to the fact that females exhibit high site fidelity to nesting beaches which leads to little genetic flow between the populations (Bowen, 2003).

Preferred Habitat

Hatchlings from US beaches emerge from nests and head offshore, follow oceanic currents to the Sargasso Sea, in the center of the North Atlantic subtropical gyre. Hatchlings are found near large conglomerations of surface Sargassum seaweed, and located near convergence zones (Carr, 1987). Oceanic juveniles were once thought to make multiple loops within the North Atlantic subtropical gyre, but studies have revealed that the main oceanic population is found around the Azores, an area which is considered prime habitat because it is comprised of many seamounts and banks (NMFS/USFWS, 2007). After 7 to 12 years oceanic juveniles will transition to coastal waters.

During the neritic phase juveniles can be found from as far north as Cape Cod Bay in Massachusetts all the way to Cuba (NMFS/USFWS, 2007). During this period they are feeding actively on the ocean bottom and throughout the water column on benthic invertebrates and fish (NMFS/USFWS, 2007). A recent study by Lewison et al (2007) on Atlantic juvenile loggerheads has revealed that juvenile loggerheads in the neritic stage will sometimes return to the open ocean, a shift which could not be attributed to size, age or sex and puts them at increased risk of interactions with fisheries fleets on the high seas.

The neritic zone provides crucial foraging habitat, inter-nesting habitat, and migratory habitat for adult loggerheads in the western North Atlantic (NMFS/USFWS, 2007). The major foraging areas for western North Atlantic adult loggerheads are found on the relatively shallow continental shelf waters of the U.S. (NMFS, nd). Migration routes between foraging habitats to nesting beaches for some population are within the continental shelf, while other population are undertake longer migration, crossing oceanic waters to and from the Bahamas, Cuba, and the Yucatán Peninsula (NMFS, nd).

Management and Conservation

In 2000, an area approximately 56,000 square miles due east of New Jersey known as the Northeast Distant Statistical reporting area (NED) was shut down to longline swordfishing, as a result of increasing awareness over the high rates of interactions between longline gear and sea turtles, predominately loggerhead and leatherbacks (NMFS, 2004b). During the closure, NMFS worked to developed methods to reduce bycatch in longline gear (NMFS, 2004b). Working with longline fishermen, NMFS scientists conducted research on the impacts of different gear on rates of sea turtle bycatch (NMFS, 2004b). They concluded that the combined use of 18/0 circle hooks (Figure 2) with fish bait decreased bycatch rates more than other combinations tested (NMFS, 2004b).

Figure 2: The difference between circle hooks: 16/0 (left) and 18/0 (right).

This area was subsequently reopened in 2004, however management suggestions based on research conducted in the NED to reduce bycatch were not followed. Fishermen were allowed to continue to fish with either squid or fish bait (50 C.F.R 635.21). Additionally, the entire US

Atlantic longline fleet was required to use either 18/0 circle hooks or 16/0 circle hooks (figure 2), which are smaller (50 C.F.R 635.21). This change was allowed, even though no research was conducted by NMFS on the effect of 16/0 circle hooks, as a result of pressure by the fishing industry who preferred the smaller hooks (Griffen, personal communication). Only fishing within the NED was required to use the 18/0 circle hooks (50 C.F.R 635.21).

In November 2007, Oceana, along with Center for Biological Conservation, petitioned NMFS to consider changing the status of Atlantic loggerheads from threatened to endangered (Oceana, 2007). Despite the findings that the 2004 BiOp determined that the existence of the longline fishery would not jeopardize loggerhead populations, this appears to have been the case. The most recent review of the recovery plan for Atlantic loggerheads found that there was a "steep decline in the nesting populations along the southeastern US coasts," which is where the majority of nesting occurs (Oceana, 2007). The Florida Fish and Wildlife Service reported "the fewest loggerhead nests in nearly two decades" (Oceana, 2007).

Pacific Loggerheads

Population Status

The main nesting grounds for Pacific loggerheads are located in Japan and Australia (NMFS/USFWS, 2007). Nesting beaches in Japan are slightly larger and a recent study found a slight increase in the number of nests per year, although it was inconclusive if this corresponded to a similar increase in population (NMFS/USFWS, 2007). Nesting beaches in Australia have decreased by 86% in just 23 years (Limpus et al, 2003) It was once believed that loggerheads foraging in Mexico were nesting in undiscovered beaches along the eastern Pacific coast (Bowen, 2007). However, in the early 1990s genetic analysis first revealed that these the turtles seen foraging in the eastern Pacific were the same turtles later observed nesting in the western pacific, and this has since been confirmed via satellite tracking (Bowen, 2007).

Preferred Habitat

The migration of the Pacific juvenile oceanic loggerhead between Japan and Mexico, covering more than 1/3 of the Earths surface, has been described as one of the "greatest navigational feats in the animal kingdom." (Bowen, 2007). Studies by Polovina found that oceanic juvenile (2-8 years) loggerheads in the Pacific traveling westward from Baja to Japan prefer SST from 15°C-25°C, as well as chlorophyll concentrations of 0.2 mg m^{-3}, which represents the Transition Zone Chlorophyll Front (TZCF). The loggerheads moved against weak currents toward the Kuroshio Extension Bifurcation Region, while also moving vertically between 30°N and 40°N latitude as a result of seasonal influences (2000, 2004, and 2006). The earlier study by Polovina originally found that juvenile loggerheads (n=9) displayed bimodal distribution between SST of 17C and 20C, corresponding to frontal systems (2000). While these results fall within the findings of the later studies, they clearly suggest a more limited habitat preference. This highlights the need to utilize tagging data as part of overall strategy to define habitat preferences for management practices, especially in studies with small sample sizes and until satellite tracking technology can provide the ability to conduct longer studies.

In Japan, polymorphic behavior has been observed in adult females (Hatase, 2007). Smaller adult females were observed diving between 0 -25 meters, with dives recorded longer during the night (Hatase, 2007). In contrast, larger adult females stayed near the continental shelf and routinely dove to depths of 100-150 meters during the day, but remained at 0-25 meters during the night, and were believed to be resting (Hatase 2007).

Management and Conservation Status

Loggerheads do not nest or come ashore anywhere along the Pacific coast of the US, so therefore management of pacific loggerheads falls exclusively under NOAA. The Hawaii-based longline swordfishery has come under intense scrutiny in the past decade due to high levels of interactions with sea turtles, predominately loggerheads and leatherbacks. In 2000, a lawsuit by the Center for Biological Biodiversity (CBD) and the Sea Turtle Restoration Project (STRP) was filed against NOAA for not being in compliance with the NEPA by allowing the Hawaii-based longline swordfishery to operate without the completion of an Environmental Impact Statement. As a result, in 2001 the Hawaii-based longline swordfishery was essentially shut down by the court until the EIS could be completed. This fishery was reopened in 2004, under new management guidelines including mandatory 100% observer coverage, real-time reporting of protected species interactions, and a limit of 17 and 18 interactions with loggerheads and leatherbacks allowed each year (NMFS, 2004a). Since it reopened, this fishery has been described as one of the best managed fisheries in the US (Griffen, personal communication).

Swordfish (*Xiphias gladius)*

Biology and Habitat

Swordfish are highly migratory, and can be found in every ocean, except the Arctic, which is a wider distribution than other billfish or tuna. Females mature slower, grow faster and live longer than males (DeMartini, 2007). They are a pelagic species, typically found at depths of between 180 - 580 m where the surface temperature is above 15°C, although they can tolerate temperatures as low as 5°C (Ward and Elscot, 2000). Juveniles are more abundant in tropical and subtropical waters (DeMartini, 2007). Adults move from temperate areas for feeding to warmer areas for spawning in the summer, with spawning occurring in water temperatures above 24C (Ward and Elscot, 2000). There appears to be a correlation between size and temperatures, with only larger individuals recorded in water temperatures as low as 10°C, and the majority of fish less than 90 kg found in waters warmer than 18°C. (Ward and Elscot, 2000)

Diet studies suggest opportunistic feeding on available surface-dwelling prey with preference for squid (Seki, 2002) Swordfish exhibit diurnal movements, moving from deeper water during the day to surface waters at night to feed, triggered by light cues. Migration is typically with the prevailing currents. In the Pacific large congregations can be found along fronts (Seki, 2002), while in the Atlantic the Charleston Bump region is an important area for spawning and feeding (Sedberry et al, 2001).

Atlantic Swordfish Population Status

There are three different swordfish stocks in the Atlantic Ocean: the North Atlantic stock, the South Atlantic stock, and the Mediterranean stock (Ward and Elscot, 2000). The North Atlantic swordfish was classified by IUCN as endangered in 1996. Biomass of this population is considered to be overfished, but are recovering and increasing with size estimates at 65% of maximum sustainable yield (MSY) (NMFS, 2003). Within the United States several time/area closures have been implemented to protect important habitat areas for juveniles (NMFS, 2003).

Pacific Swordfish Population Status

In this region there are two to four distinct genetic populations (Ward and Elscot, 2000). Stock assessments found that North Pacific swordfish populations are relatively stable and are only very lightly exploited by fisheries, specifically longlines and gillnets, with fishing pressure below MSY (Kleiber and Yokawa, 2000).

Longline Fishing

Longline fishing in the Pacific was developed by the Japanese in the mid-1800's and was first used by Hawaii fishermen in 1917 (Watson et al, 2006). In the Atlantic, Mediterranean fishermen began to use this method in the early 1900's, and it was adopted by New England tuna fishermen in the 1940's (Watson et al, 2006). Expansion of the fleet was propagated by the development of freezing technology, an increase in market demand and a relaxation of trade regulations (Watson et al 2006).

Longline gear consists of a mainline, branchlines and baited hooks, all of which can be modified for different targeted species (Watson et al, 2006). Commercial longliners typically target highly migratory species (HMS) such as tuna (bluefin, bigeye, yellowfin and albacore) and swordfish. The mainline and branchlines are made of a monofilament line. Baited hooks are attached to the mainline via the branchlines which are generally 250 – 300 feet apart (Watson, 2006). In 2000, global longline fishing vessels set an estimated 1.4 billion hooks (Lewison et al, 2004). Lightsticks are also often attached to the hooks in order to lure different species (Hazin and Hazin, 2005).

The deployment and retrieval of gear is referred to as a set. The time between deployment and retrieval is dependant on the targeted species, but generally lasts from a few hours up to a day. The number of sets during the course of a fishing trip can range from five to twenty-five, depending on the duration of the trip. Shallow set longline gear is set above 100 feet and predominately targets swordfish, while deep-set longline gear is set below 100 feet and is more commonly used for tuna fishing (Figure 3). Gear in both fisheries is usually set at dusk and allowed to soak overnight before retrieving it, in response to movements by the targeted species.

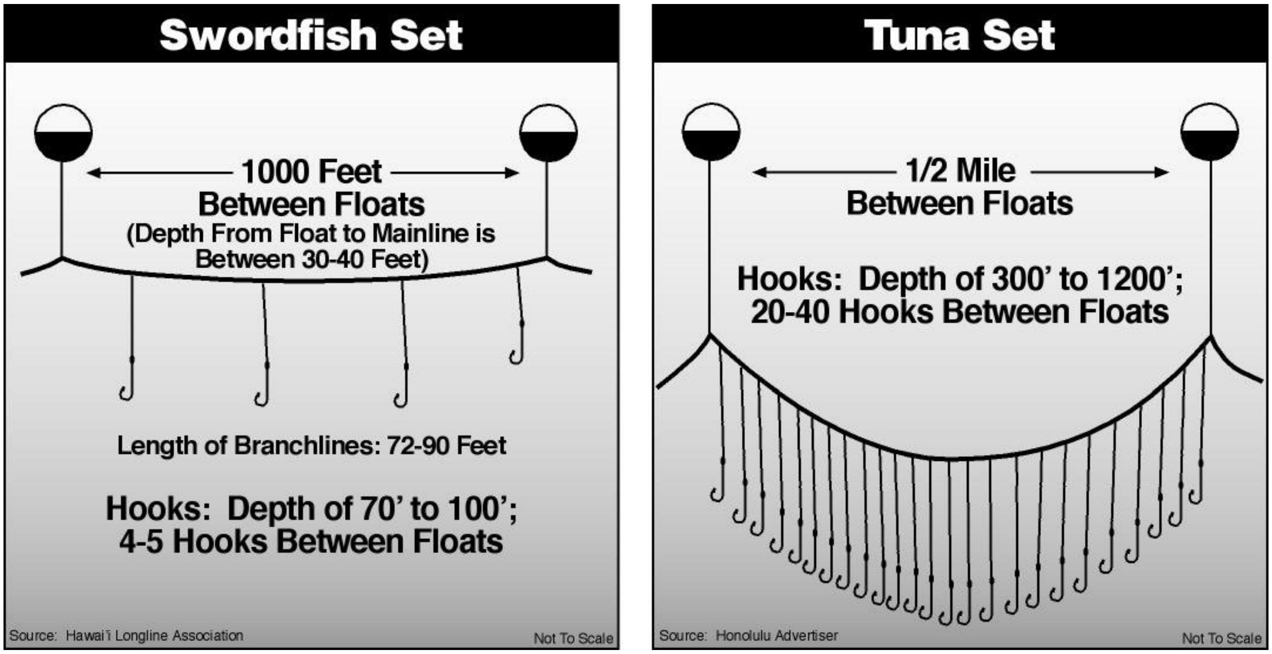


Figure 3 Differences in Swordfish gear targeting swordfish (left) and tuna (right). Source: Hawaii Longline Association and Honolulu Advertiser

US Longline Swordfishery Management

In the Atlantic, fishing for tuna and swordfish is managed by the International Convention for the Conservation of Atlantic Tuna (ICCAT) and NMFS Division of Highly Migratory Species (DHMS). ICCAT sets the annual quotas for all tuna and swordfish fishing within the Atlantic Ocean. Under the Atlantic Tuna Conventions Act, NMFS is required to implement the quotas determined by ICCAT (16 U.S.C. § 971). The DHMS is the agency responsible for the development of the Atlantic HMS FMP. This FMP determines the allocation of the fishing quota among different fishing sectors (commercial, charter and recreational) and includes methods for reducing bycatch.

This fishery operates under limited access and is capped at 247 vessels, however less than half of those that hold permits actively fish (Witzell, 1999). Landings peaked in the late 1980's but subsequently have been reduced as a result of reductions in quotas by ICCAT (Figure 4).

While there is considerable difference in the configuration of longline gear used in the region, on average mainlines set are 47 km long, with 429 hooks sets at a depth of 54 m (Witzell, 1999).

In the Pacific, the management of HMS is under the Western Pacific (WestPac) Fisheries Management Council. The WestPac is responsible for commercial fisheries within the federal waters of the Hawaiian Islands and the Pacific Island territories of the US. In addition, vessels fishing in this area also fall under the jurisdiction of the Inter-American Tropical Tuna Commission (IATTC). Both FMC have developed their own HMS FMP.

The Hawaii-based longline fishery is the largest producer of swordfish of all the U.S. North Pacific swordfish fisheries, accounting for about two thirds of U.S. swordfish production and about 15% of all Pacific swordfish landings (Witzell, 1999). Growth in the longline fishing industry in Hawaii occurred in the early 1990s when converted shrimp trawlers from the Gulf of Mexico and longliners from California and the East Coast arrived to a relatively unexploited market (Wagner, 2000). Vessels fishing for swordfish in the Pacific typically

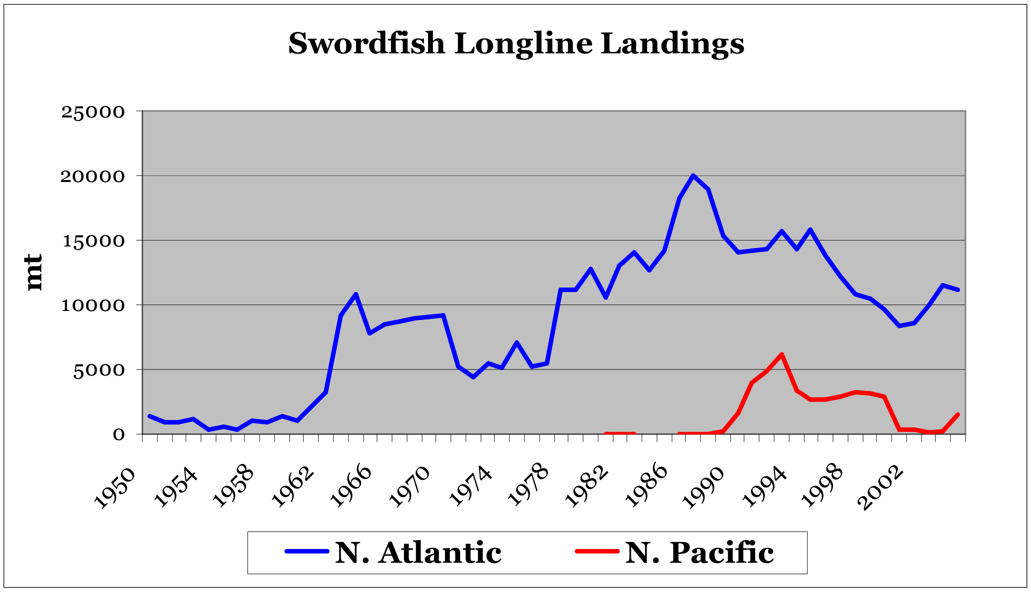


Figure 4: Historical landings within the North Atlantic and North Pacific longline swordfisheries. From ICCAT and NOAA.

range in length from 56 – 74 feet and the fishery is currently capped at 164 vessels (Watson, 2006).

Logbook and Observer Reporting

The Atlantic pelagic longline logbook program was initiated in 1986 and became mandatory for all fishermen in the industry in 1992. Within the Pacific the program began in 1991. Logbooks may not be appropriate if there are restrictions placed on a fishery, such as quotas or time/area closures. Problems include inadequate attention to accuracy, misidentification of species, omission of catch (Cotter, 2007).

The observer program started in 1992 in the Atlantic and Pacific in 1994. Currently, there is a target of 8% observer reporting within the Atlantic fishery, while within the Hawaii fishery mandatory observers are required on all longline swordfish vessels. The amount of observer coverage needed will vary depending on the fishery, and on what species is of critical importance to observe (Babcock, 2003). It is estimated the 20% coverage is needed to adequate estimate bycatch in common species, and up to 50% is needed to adequately estimate bycatch in rarer species (Babcock, 2003).

Bycatch in Longline Fisheries

The impact of longline fisheries bycatch is a problem faced not just by the United States, but of all countries with active longline fisheries. In 2000, it is estimated that at least 50,000 leatherbacks and 220,000 loggerheads worldwide were caught in longline gear (Lewison, 2004). Capture includes sea turtles that are lightly hooked or entangled and subsequently successfully released, sea turtles hooked or entangled more severely, and also sea turtles that are killed. The impact of longline gear varies depending on the type of gear used and with the species of sea turtle. Shallow set longline fishing, which targets swordfish, creates the greatest impacts to sea turtle since it is set in the same stratum of the water column that these species frequent (Crowder and Myers, 2001). During these sets loggerheads are typically drawn to the bait and are hooked on the mouth or on a flipper. Individuals that are unable to reach the surface to breathe will drown. Post-hooking effects have been largely hypothesized in the past decade. A study conducted in the Atlantic revealed that incidental capture in longline gear resulted in shallower dives and a greater tendency to move with the current, possibly drifting (Bolten, 2003). However, studies by Polovia in the Pacific seem to indicate that there is minimal effect on behavior (2000, 2004, 2006). Additionally, a recent study conducted by Sasso (2007) compared the post-hooking movement of ten turtles that were caught on longline gear in the Atlantic to that of seven "control" turtles and found that there was no difference in the probability of survival between the two groups, suggesting that in cases where turtles are lightly hooked and the gear is removed successfully there may be no further impact.

There has been an increasing focus on longline fleet interactions with sea turtles in the Mediterranean. Caminas (2006) found that within the Spanish longline fleet, operating in the western Mediterranean, boats targeting bluefin tuna had the highest number of loggerhead interactions, while boats targeting swordfish had the highest mortality, based on fishing effort. Mortality was low, at approximately 1.32%, but there was a significant inter-annual difference in both effort and bycatch rates (Caminas, 2006). In another study on the Spanish longline fleet, Baez et al (2007) found that bycatch was better predicted by ecogeographical variables, rather than fishing effort. Specifically, the occurrence of loggerhead bycatch increased significantly with relation to an increase in the distance fishing effort occurred from the coast and fishing ground depth (Baez et al 2007). This highlights that managements policies which aim to limit the amount of fishing effort might not produce the greatest possible desired outcome. Additional studies in the Ionian Sea have yielded catch per unit effort (CPUE) for each fishing trip of sea turtles between 0.06 and 0.27 (DeMetrio et al, 1983; DeFlrio et al, 2005). CPUE is determined by the number of catches for a given species divided by the number of hooks set and normalized to 1000 hooks. An additional study by Baez (2003) in the Spanish longline fleets concluded that swordfish captures are independent of retrieval time, but bycatch of loggerheads occurs mainly during daytime, attributing this to the fact that loggerheads use vision to locate baits.

Within the Western Atlantic there has been a considerable amount of studies conducted on the interactions of sea turtles and longline fishing. In the Atlantic, the mid-Atlantic Bight and the Northeast Distance (NED) area, off the coast of New England, accounts for 89% of loggerhead bycatch, with 88% of bycatch occurring from June to November (Witzell, 1999). CPUE values for loggerheads was highest within the NED, with most effort closely related to the shelf break and associated with major oceanographic currents and thermally active areas (Witzell, 1999).

There has been less attention given toward sea turtle bycatch in the Southern Atlantic Ocean than the Northern Atlantic Ocean. Brazil is an important nesting location for loggerheads, but also has small populations of olive ridley and leatherback turtles. With an increase in longline effort targeting swordfish in the past ten years, sea turtles populations, particularly loggerheads, in the region are becoming increasingly vulnerable (Pinedo, 2004). The longline fishery targeting swordfish has an estimated CPUE of 1.5 sea turtles, with subadult loggerheads comprising over 80% of the total sea turtle bycatch (Pinedo, 2004). Fishing generally occurred in water less than 75 m, with recorded water temperature ranging from 14 to 25C; however sea turtle interactions occurred predominately in sets that were set above 50m, as well as above the thermocline (Pinedo, 2004). Kotas et al (2004) assessed longline fishing operations off southern

Brazil, and calculated a CPUE of 4.31 for loggerheads, with higher CPUEs occurring during the late spring and with lower sea surface temperatures when compared to summer and fall.

Research on loggerheads in the Pacific has mainly been on behavior and movements, and those studies that focus on the issue of longline bycatch frame it primarily in terms of strategies to reduce interactions with longline gear, with a few notable exceptions (Lewison, 2004; Crowder and Myers, 2001; and Ovetz, 2005). The most comprehensive study on bycatch specifically in the Pacific was conducted by Ovetz, who found that 4.4 million non-targeted marine species, such as sea turtles, seabirds marine mammal and sharks, were caught in longlines each year, resulting in up to 40% of catches being composed of bycatch (2005). Lewison estimates that up to 33% of global bycatch of loggerheads occurs in the Pacific Ocean (2004).

Within the Pacific coast of the Baja peninsula the greatest cause of mortality and injury to juvenile loggerheads is the incidental capture in small-scale fisheries (Koch et al 2006). Juvenile loggerheads in this area spend 70% of their time at one specific hotspot, before beginning the migration west toward Japan. Analysis by Crowder and Myers (2001) of loggerhead bycatch concluded that occurrences were higher in areas of greater depth and flatter terrain.

Study Areas

Bycatch of loggerheads was examined in both the North Atlantic transition zone and the North Pacific transition zone (figure 5). Predominately fishing effort in these two areas is by US longline vessels (Lewison 2004). The transition zone is defined as the area between a subpolar and subtropical gyre and which has characteristics of both oceanographic regions (Seki, 2006). The position of the transition zone is highly variable depending on the season and the year (Seki, 2006).

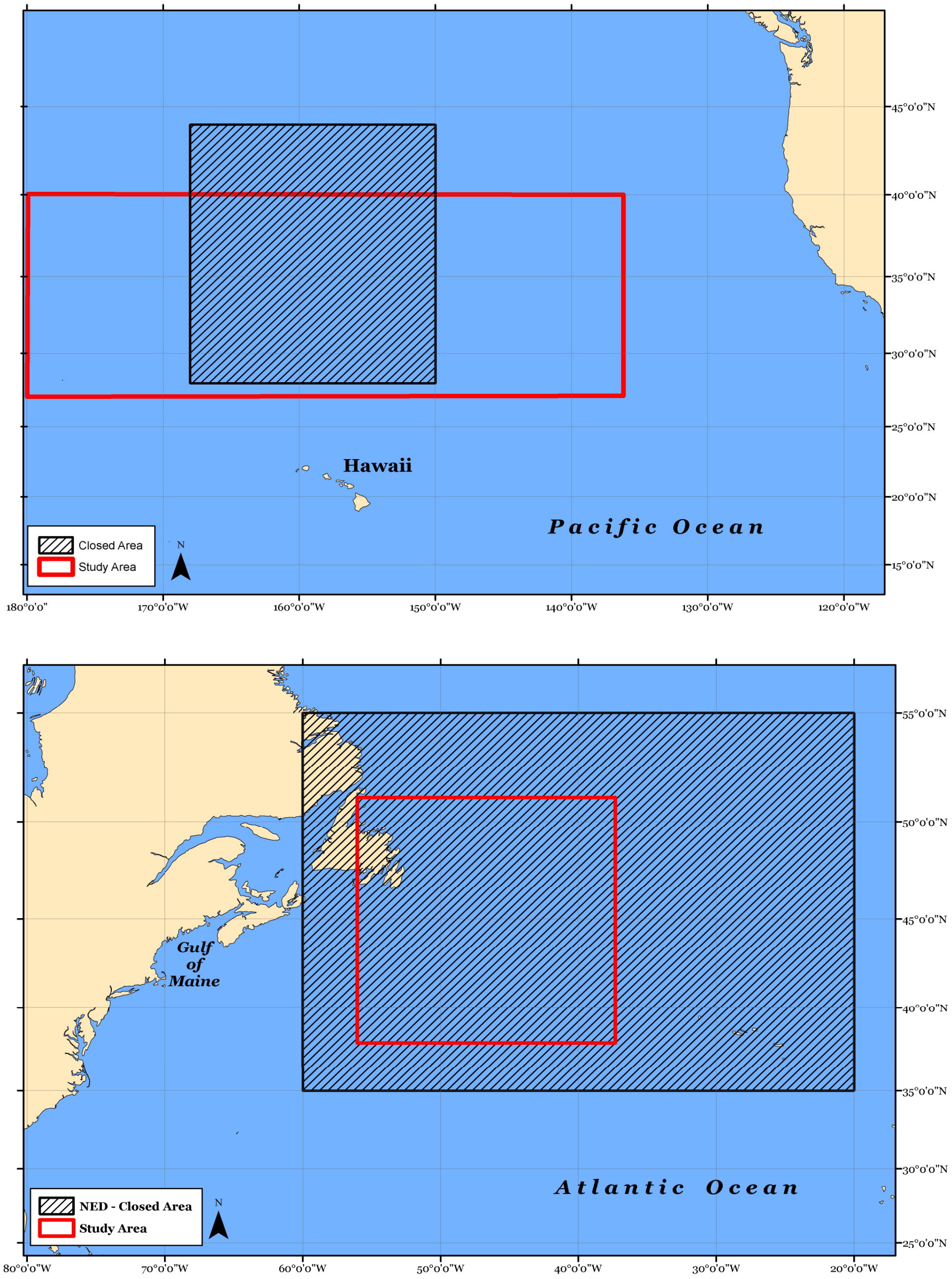


Figure 5: Study areas in the North Pacific (top) and North Atlantic (bottom) denoted in red, with shaded area showing areas where swordfishing was prohibited due to excessive interactions with loggerhead and leatherback sea turtles.

In the Atlantic the transition zone falls between 40N and 50N. It receives warm water from the Gulf Stream, which represents the western boundary current of the north Atlantic subtropical gyre, and cold water from the Labrador current, which represents the western boundary of the North Atlantic subpolar gyre. The study area falls entirely within the Northeast Distant fishing area (NED). The complex circulation and thermodynamics in this region create a unique and highly productive system (Witzell, 1999).

In the Pacific the transition zone falls between 27N and 40N and falls between the subarctic front and subtropical front (Roden, 1980). It receives cold water from the Alaska current and warm water from the Kuroshio Current. Salinity and temperature increase from north to south and the concentration of nutrients falls between the low levels in the subtropic gyre and the higher levels within the subpolar gyre (Seki, 2006).

Methods

Observer Records

Observer records were obtained from NOAA's Southwest Fisheries Science Center - Honolulu Laboratory and Southeast Fisheries Science Center. Since swordfish fishing generally has the highest interactions with sea turtles, only those sets that targeted swordfish were used in this analysis. However, while observers are required to list the targeted species for each haul in the reporting of catch data this field is not necessarily reported accurately. Confounding this problem is also the fact that in many of the sets the targeted species is listed as "MIX", representing sets that are targeting a mix of species, most likely tuna and swordfish. Therefore, only sets that caught at least one swordfish were included in this study in order to determine if there was difference in sets that contained swordfish to those that contained both swordfish and loggerheads. Data from seven years, spanning 1994 to 2000, were examined.

Observer data records differed in both the data recorded and codes used in reports. Variables examined as a predictor for sea turtle bycatch included longitude, latitude, number of hooks set, number of lightsticks set, season and number of swordfish caught.

From the number of hooks set it was possible to calculate the CPUE. Additionally, the F index, which measures the number of catches divided by the number of sets, could also be determined. Both measures are compared and used as a measure of the overall impact of the fishery. Logbook data was only available for the Atlantic longline fishery, and was used to compute the amount of observer effort for each year.

Oceanographic Variables

The oceanographic variables examined included sea surface temperature (SST), chlorophyll concentration, distance to frontal systems, bathymetry, seafloor slope and distance to shore, with the first three variables sampled on a monthly time scale. Geospatial analysis was preformed in ESRI ArcGIS 9.2.

Sea Surface Temperature

SST rasters were obtained from NOAA's Advanced Very High Resolution Radiometer (AVHRR) Pathfinder v5 dataset. The rasters were converted into geophysical units using the following equation: SST = Raster Value * 0.075 - 3.0.

Chlorophyll-a Density

Chlorophyll density rasters were obtained from the Sea-viewing Wide Field-of-View Sensor (SeaWIFS) onboard the SeaStar polar orbiting satellite, which was launched on August 1, 1997 and provided 4km resolution. Chlorophyll-a density has been related to loggerhead movement in the Atlantic (McCarthy, 2006) and Pacific (Polovinia 2004, 2006).

Frontal Systems Location and Strength

The distance to frontal systems was determined from SST rasters using focal statistic analysis in GIS. Focal statistic analysis looks at a specified area, here a 3 cell by 3 cell square, and calculates a desired metric, for this analysis it was the range in temperature. That value is then applied to the center cell within the specified area. This analysis is repeated until the entire study area has been analyzed in this manner. Larger ranges in temperature represent frontal systems, which are the zones where high temperature systems meet low temperature systems. Fronts were classified from the focal statistics analysis as those cells that had a value of five or greater. The Euclidean distance from the front was then calculated for each month during the study period.

Additionally, the strength of frontal systems was also assessed. The change in temperature was reclassified into five different classification designations, depending on the change in temperature: none (0), weak (1-4), low (5-9), medium (10-14) and high (15 and greater).

Bathymetry, Slope, Distance to Shore and Distance to Shelf Break

The bathymetry, slope and distance to shore was obtained for each study area. The S2004 global 1-minute bathymetric grid was used to determine ocean depth (Smith 2004). Two other types of high resolution sonar data were available, ETOPO2 and GEBCO, but S2004 has been determined to be superior to these other alternatives because it provides a finer resolution and better definition of bathymetry features (Marks and Smith, 2005). Slope was calculated from the S2004 bathymetry data. Distance from shore was determined by Euclidean distance. In the Atlantic, due to the close proximity to the continental shelf, the distance to the shelf break was also used as an oceanographic variable.

Limitations

The main limitation to this research is the reliance on fisheries data for analysis. While easily available, the use of this data to understand bycatch occurrences can only partially begin to do so. Incorporating this data with long-term satellite tracking studies of both loggerheads and swordfish will provide a better understanding of how habitat is being utilized by each species and the extent of overlap between the two, which would be the most valuable information for marine conservation managers. Additionally, the use of bycatch data in the prediction of habitat preferences for sea turtles is not necessarily appropriate, as it is biased in the preferences on swordfish.

Statistical and Geospatial Analysis

Statistical analysis was preformed in R statistical software using a binominal and poisson distributed generalized linear regression. Using Akikie Information Criterion (AIC) the best predictors for each seasonal model within the two study areas were established and then transformed back into a spatial layer in GIS using the model:

$$Y_i = \beta_0 + \beta_1 \mathrm{OCEAN}_1 + \ldots\ \beta_x \mathrm{OCEAN}_x$$

Here, β represents the coefficient and OCEAN represents the different oceanographic conditions used in the model. Predictors were determined for each season that interactions occurred, with three models created for the Atlantic fishery and four models created in the Hawaii fishery. A probability grid was calculated through the inverse logistic link function:

$$P = \frac{e^{a+bX}}{1+e^{a+bX}}$$

Comparisons between the two regions were based on the nonparametric Mann-Whitney test.

Results

Atlantic Loggerhead Interactions

Between 1994 and 2000 there were 244 observer recorded interactions between longline fishing activities and loggerheads within the NED (Figure 6). This represents 97 different sets with the target species recorded as “swordfish”, except for five which listed “mixed” as the target species. Every set that caught a loggerhead also caught at least one swordfish. The total number of hooks deployed during these sets was 81,777, with a mean of 843 hooks deployed per set. The resulting CPUE (catch per unit effort) for loggerheads during these sets was 2.98. Taking into account all longline sets in the period, the CPUE for loggerheads was 1.15 and the F-index was 0.97. The maximum number of loggerheads caught on any one set was 9, with 60% of the sets catching more than one loggerhead and an average of 2.51 loggerheads caught per set. The majority of the interactions occurred during the third quarter, which represented July, August and September.

Atlantic Swordfish Catches

Between 1994 and 2000 there were 6,813 observer recorded swordfish caught by longliners within the NED during 251 sets with 211,671 hooks deployed (CPUE = 32.18). There were only six sets deployed during this period under observer observation that failed to yield any swordfish. The total number of sets deployed during this time in this area by longline fishermen was 5,024, as recorded in logbook data, resulting in an average observer coverage for this time period in the NED of 5%.

The mean number of swordfish caught per set was 27 with a standard deviation of 19. The maximum number of swordfish caught was 123 and the minimum was 1. As many as 11 different types of species were caught during a set, with the mean being 6 different species. Swordfish comprised an average of 39% of the total catch. Catches averaged 72 animals per set, and the average number of hooks deployed per set was 843. This works out to be, on average, one species landed at every eleventh hook. In total, 18,243 animals were recorded being brought onboard during this period.

Sets were recorded beginning between 14:45 and 00:42 and were left to soak for an average of 7.1 hours. All sets were deployed with lightsticks, with a mean of 676 lightsticks per set and 43% of the sets having complete lightstick coverage.

Pacific Loggerhead Interactions

Between 1994 and 2000 there were 165 observer recorded loggerhead interactions in the longline swordfish fishery during 137 separate sets (Figure 6). The size of loggerheads caught ranged from 50 – 90 cm curved carapace length, with the majority ingesting the hook and subsequently released injured (Figure 7). At this size, it is estimated that bycatch is occurring on both sub-adults and mature adults. The average number of loggerheads caught per set is 1.2, with a maximum of 3 loggerheads caught in 4 sets. All but four of the sets that caught a loggerhead as bycatch were listed as targeting swordfish. The total number of hooks deployed during these sets was 112,325, which translates to a CPUE for loggerheads of 1.46. The CPUE for loggerheads for all sets deployed during this time is 0.26, with an F-index of 0.17. Loggerhead catches were spatially dispersed throughout the entire area where swordfish were caught.

Of the sets that had interactions with at least one loggerhead, the average number of lightsticks and hooks used was 413 and 819 respectively, with 64% having at least half of the hooks deployed with lightsticks. 55% of the sets caught at least one swordfish, with a mean of 4.5 swordfish caught per set for sets that had at least one interaction with a loggerhead.

Pacific Swordfish Catches

There were 802 trips which caught swordfish between 1994 and 2000, with a total of 618,412 hooks deployed and 6 549 caught. The total number of swordfish caught per set varied from 1 to 37 (sd = 7.1) with an average of 9 swordfish caught in a set and up to 28 sets per trip and a CPUE of 10.29. Sets begin between 1400h and 900h, with the median 1800h, and a mean soak time mean of 20h. An average of 382 lightsticks and 842 hooks were used per set. Swordfish comprised on average 64% of the total catch of targeted species (Swordfish, Bluefin, Yellowfin and Albacore Tuna). Numbers were not available for species other than the four main targeted species, so therefore the composition of the catch could not be examined further.

Logbook data was unavailable to determine observer coverage, but during the period of this study observer coverage is estimated between 5-22% (Overtz, 2005). Since it reopened in 2004 the fishery has been operating under 100% coverage.

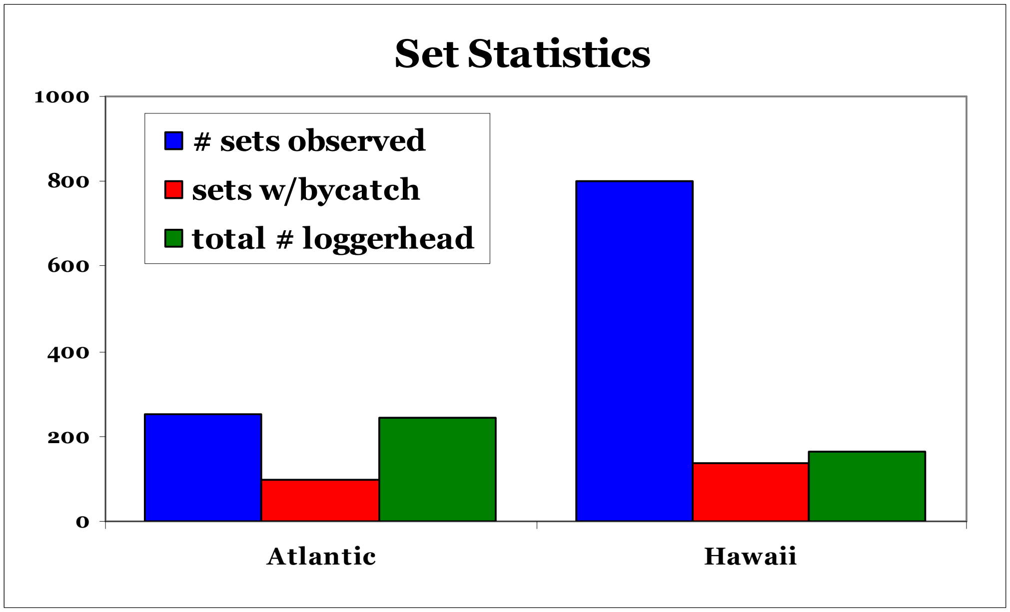


Figure 6: Summary of sets used in analysis of research and loggerhead interactions for each region.

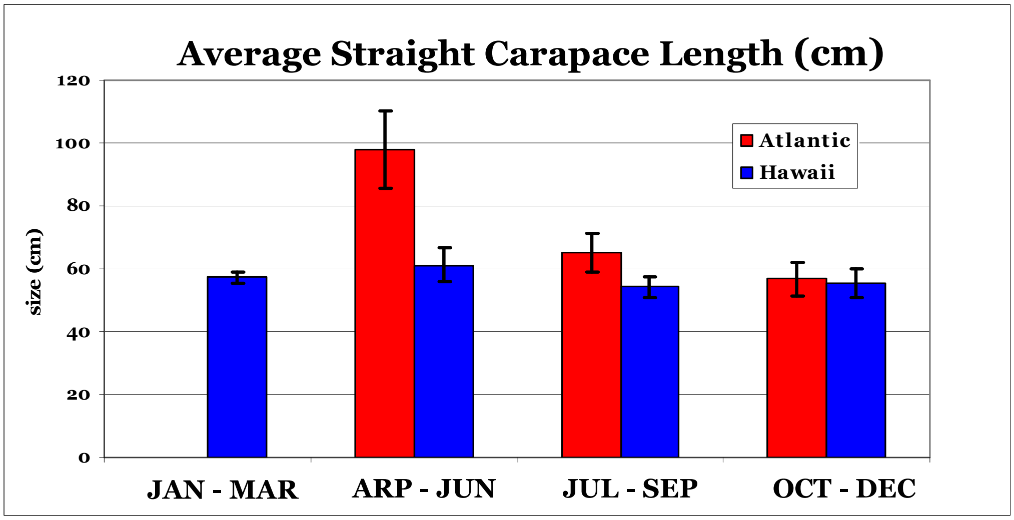


Figure 7: Average size of loggerhead sea turtles caught in each fishery by season.

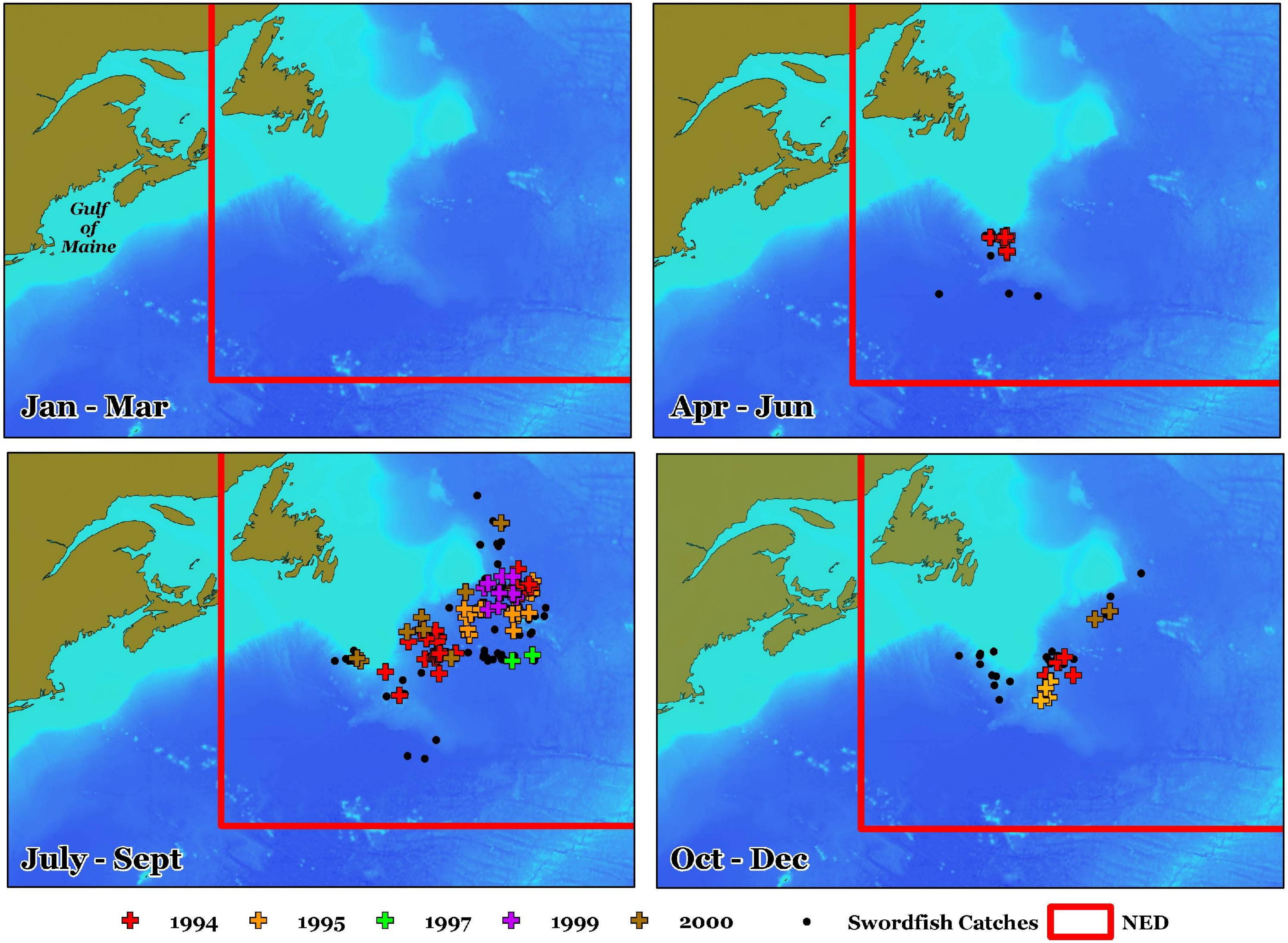


Figure 8: Spatial and temporal distribution of bycatch events (colored circles) and non-bycatch events (black circles) within the North Atlantic transition zone

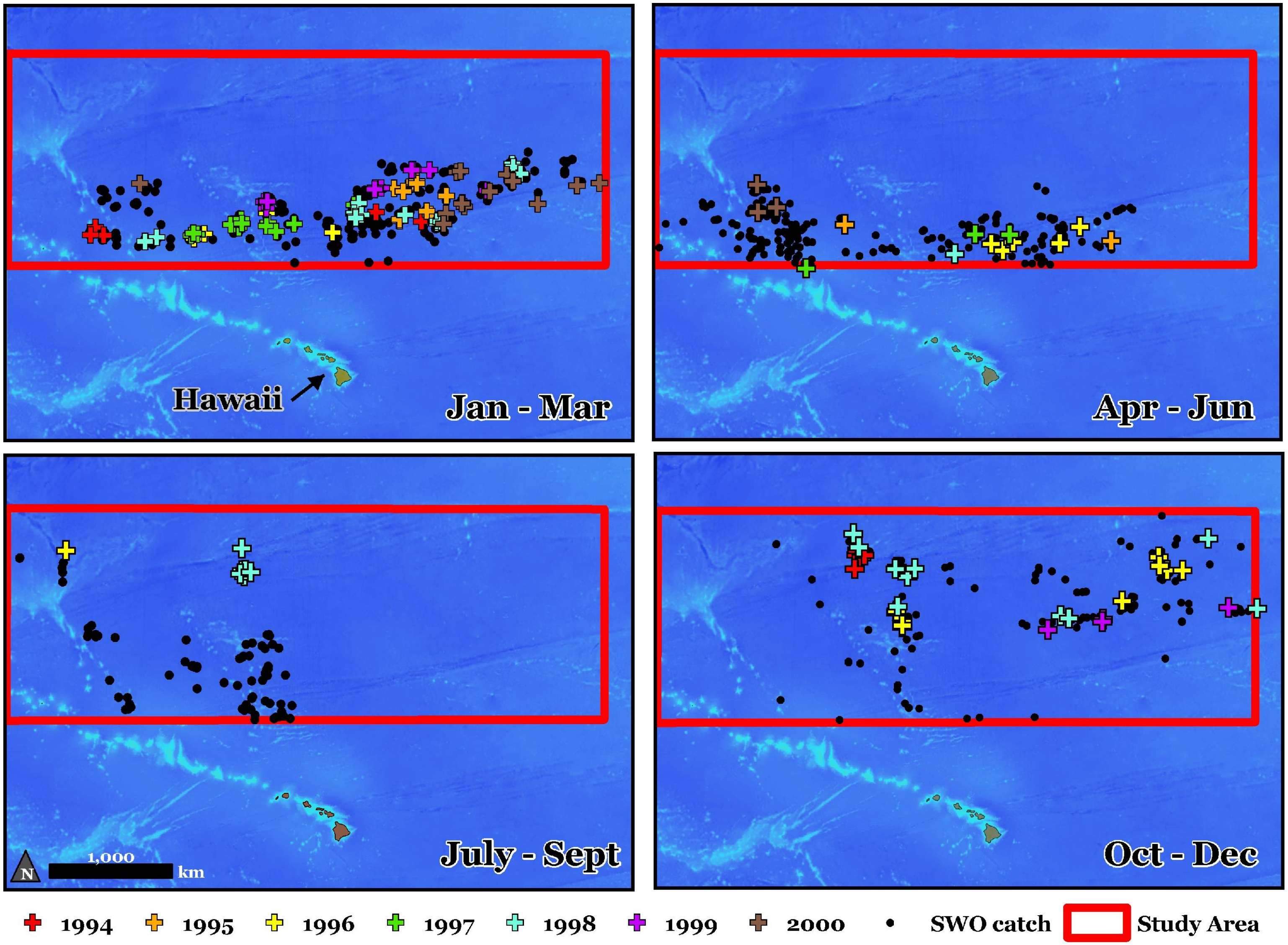
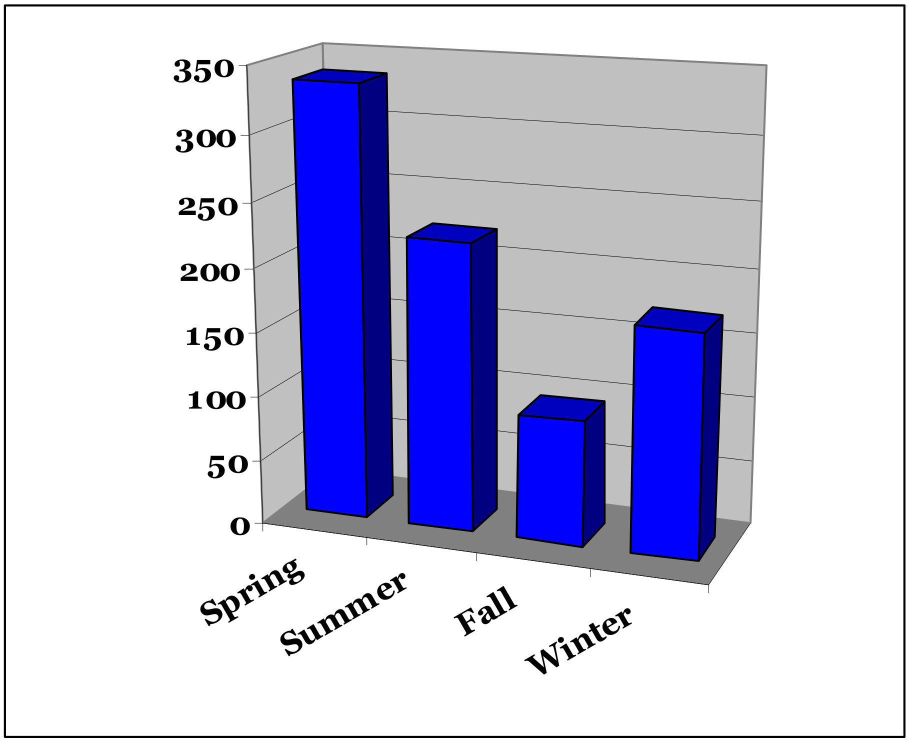


Figure 9: Spatial and temporal distribution of bycatch events (colored circles) and non-bycatch events (black circles) within the North Pacific transition zone



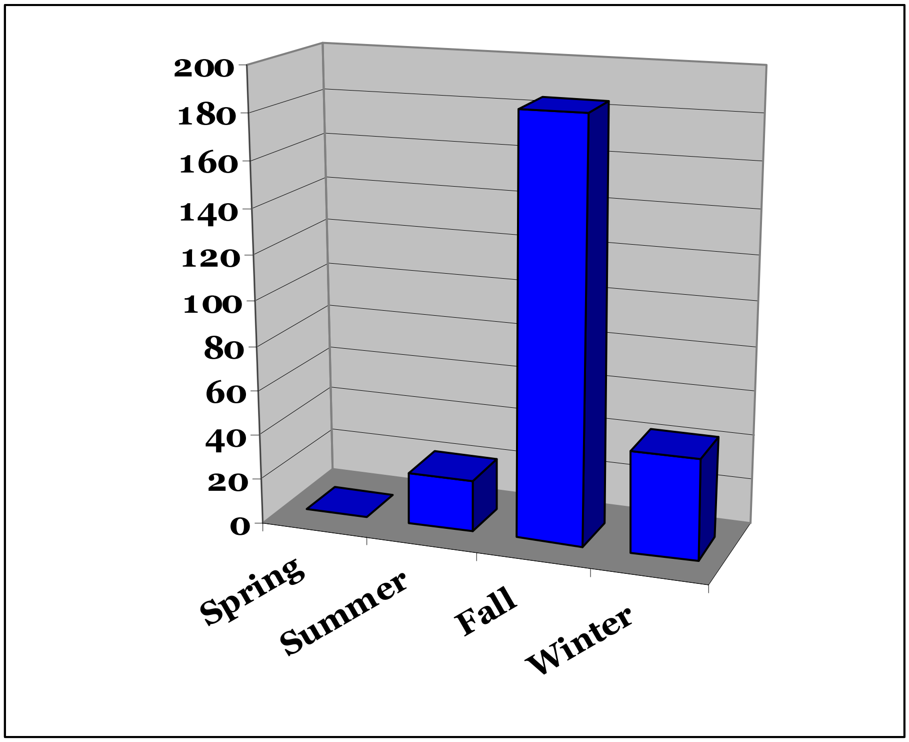


Figure 10: Distribution of bycatch sets by season for the North Pacific transition zone (top) and North Atlantic transition zone (bottom). Fishing effort was year round within the North Pacific region, while fishing effort only occurred in the summer, fall and winter within the North Atlantic study regions.

Correlation between Oceanographic Variables

Spatial correlation is inherent in nature and occurs when the value of one attribute can give you an estimate of another attribute. Within each study area, SST is significantly correlated to almost every oceanographic variable (Table 1). It is negatively correlated to chlorophyll and front strength, and positively correlated to frontal systems in both the Pacific and the Atlantic study. Within the Atlantic, as SST increased in the fall, chlorophyll-a increased slightly in at the locations of bycatch sets (Figure 11). Within the Pacific, as SST increased through the fall, chlorophyll-a decreased at the locations where bycatch occurred (Figure 7). There was a statistical difference when comparing chlorophyll-a between the two regions, while there was no difference in SST (Mann-Whitney, $p < 0.05$).

Table 1: Correlation of environmental variables at bycatch and non-bycatch events in each region

Atlantic

	SST	FRONT	CHLO	BATHY	SHORE	SLOPE	SHELF	STRENGTH
SST	1							
FRONT	**0.29**	1						
CHLO	**-0.269**	0.061	1					
BATHY	**-0.169**	-0.102	0.044	1				
SHORE	**0.296**	**0.2**	0.073	**-0.749**	1			
SLOPE	-0.001	-0.098	-0.034	**0.538**	**-0.287**	1		
SHELF	**0.352**	**0.30**	**-0.247**	**-0.663**	**0.783**	**-0.259**	1	
STRENGTH	**-0.425**	**-0.361**	-0.15	-0.018	**-0.128**	-0.05	-0.093	1

Bold numbers represent significant (P<0.05) correlation using Pearson's Correlation Test

Hawaii

	SST	FRONT	CHLO	BATHY	SHORE	SLOPE	STRENGTH
SST	1						
FRONT	**0.314**	1					
CHLO	**-0.266**	**-0.207**	1				
BATHY	**0.168**	0.0657	**-0.17**	1			
SHORE	-0.023	**-0.203**	0.037	**0.068**	1		
SLOPE	**0.121**	**0.116**	**-0.2**	**0.671**	-0.008	1	
STRENGTH	**-0.418**	**-0.32**	**0.096**	**-0.13**	0.0473	**-0.08**	1

Bold numbers represent significant (P<0.05) correlation using Pearson's Correlation Test

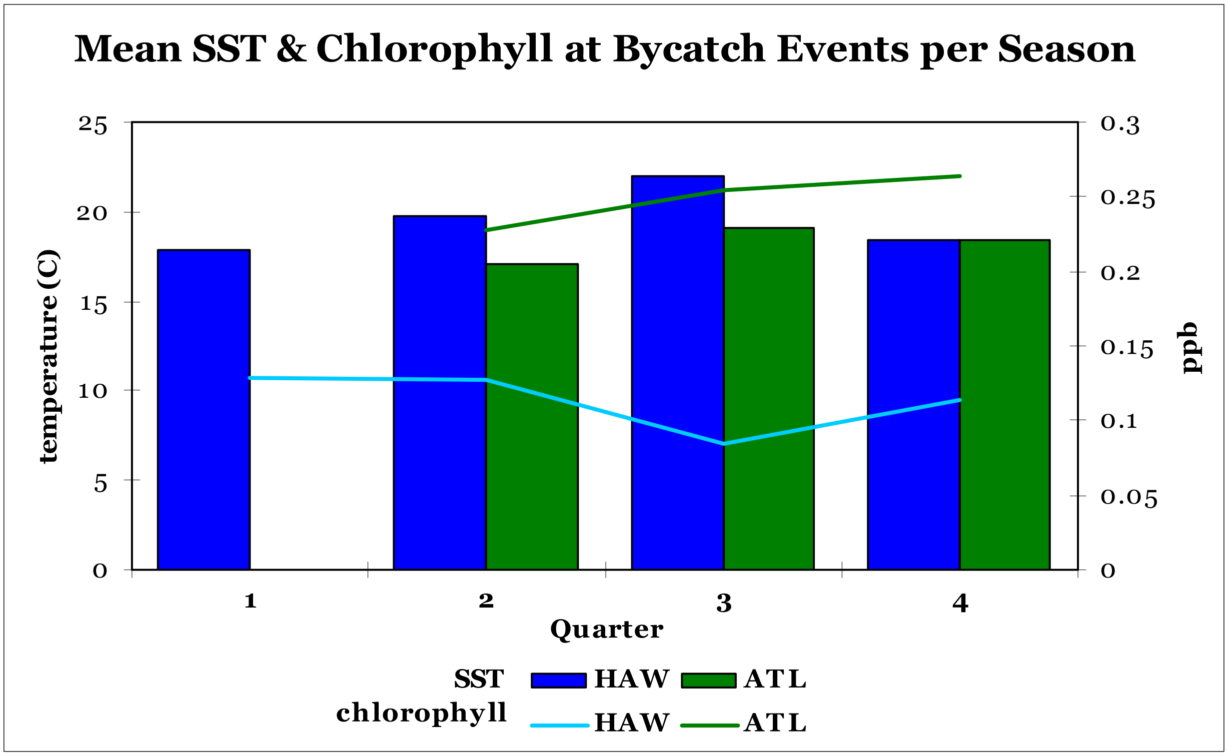
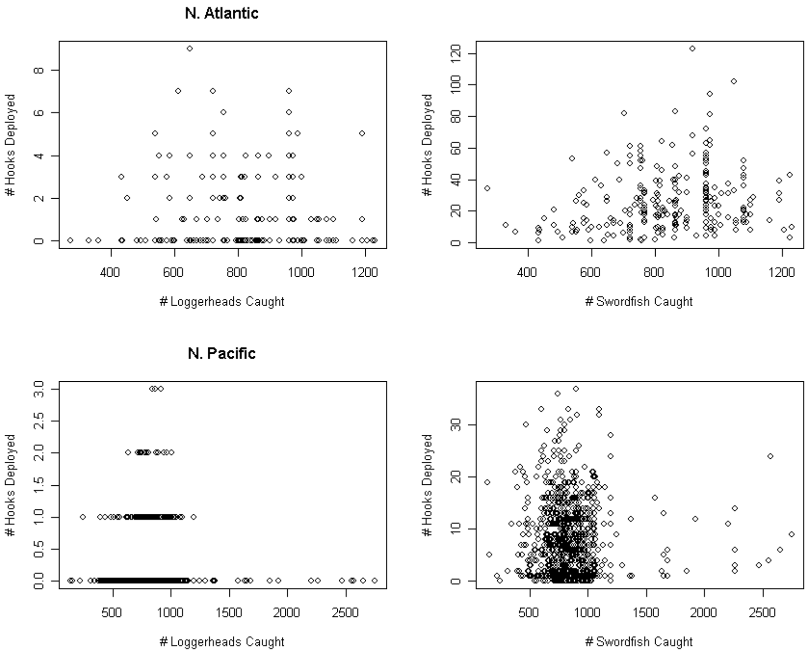
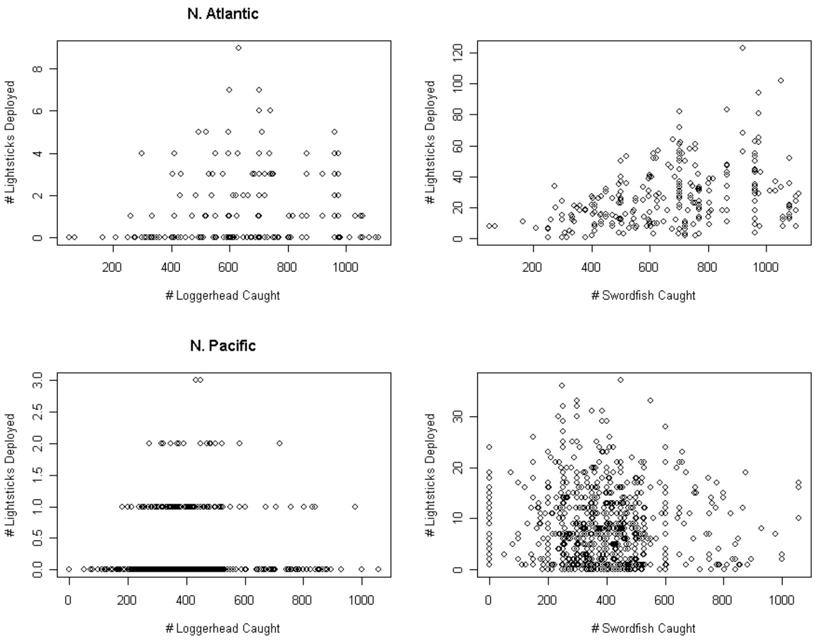


Figure 11: Mean SST and chlorophyll-a at bycatch events by season between the two regions. There was a statistically significant difference in chlorophyll-a between the two regions, while there was not a statistically significant difference in SST between the two regions.

Correlation between Gear and Catch

In the Atlantic there was a statistically significant correlation between the number of swordfish caught and the number of hooks deployed, the number of lightsticks used and the percent lightstick coverage, while in the Hawaiian fishery this was not observed (figure 12). The correlation between lightstick counts may be attributable to the fact that Atlantic longline fishermen were more likely to set hooks with 100% lightstick coverage, with a mean occurring at 80%, while in the Hawaiian fishery fishermen had a preference to set hooks with 50% coverage (mean = 48%). In the Atlantic there was a significant correlation between the percent lightstick coverage and the number of loggerheads caught, while in the Hawaiian fishery the number of loggerheads caught was correlated to the number of lightsticks used and the amount of lightstick coverage.





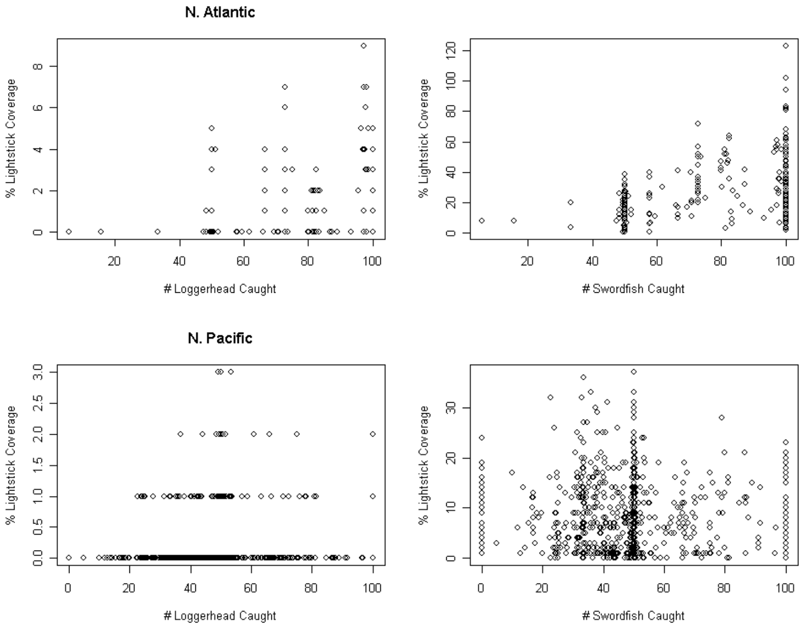


Figure 12: Comparison of fisheries variables against loggerhead and swordfish catch by region. Top right: Number of hooks deployed. Top Left: Number of lightsticks deployed. Bottom: Percent lightstick coverage.

Comparison of Oceanographic Conditions

Evaluation of bycatch and non-bycatch events in the Atlantic and Pacific yielded different results. Statistically significant difference between non-bycatch and bycatch events (Mann-Whitney test, $p<0.05$) in Hawaii were seen in four of the seven variables examined: SST, bathymetry, slope and chlorophyll-a (Figure 14). Loggerheads seemed to move to stay within their preferred SST range, with SST being correlated to chlorophyll-a, slope and bathymetry, with bycatch events most likely to occur between 17C and 20C, which is consistent with findings by Polovina (2006). Additionally, loggerheads favored deeper and flatter regions, which is consistent with previous findings by Crowder and Myers (2001). Non-bycatch events exhibited a weak bimodal temperature distribution, with occurrences peaking at 17°C, as well as 25°C.

Within the Atlantic significant differences (Mann-Whitney test, $p<0.05$) between bycatch sets and non-bycatch sets were observed in three of the eight variables examined: distance to fronts, strength of front and bathymetry (Figure 15). Again, bycatch was more prevalent when fishing activities took place in deeper water. 56% of the total sets occurred in water deeper than 4km. When separated by the occurrence of bycatch, 67% of bycatch sets occurred in equally deep water, while only 50% of non-bycatch sets occurred at locations where depths were greater than 4km. Bycatch was also more likely to occur closer to fronts, with 64% of bycatch sets occurring within one-third a kilometer from a defined front.

Comparison of bycatch events between the Pacific and Atlantic yielded significant differences in five of the seven comparable environmental variables: distance to fronts, bathymetry, chlorophyll-a, distance to shore, and front strength (Mann-Whitney test, $p<0.05$). Despite differences in the actual depth of bycatch events between the two regions, which can be attributed to the different oceanographic characteristics of the basins, bycatch was more likely at deeper locations within both study areas. There was no significant difference in SST and slope between bycatch events in the study areas.

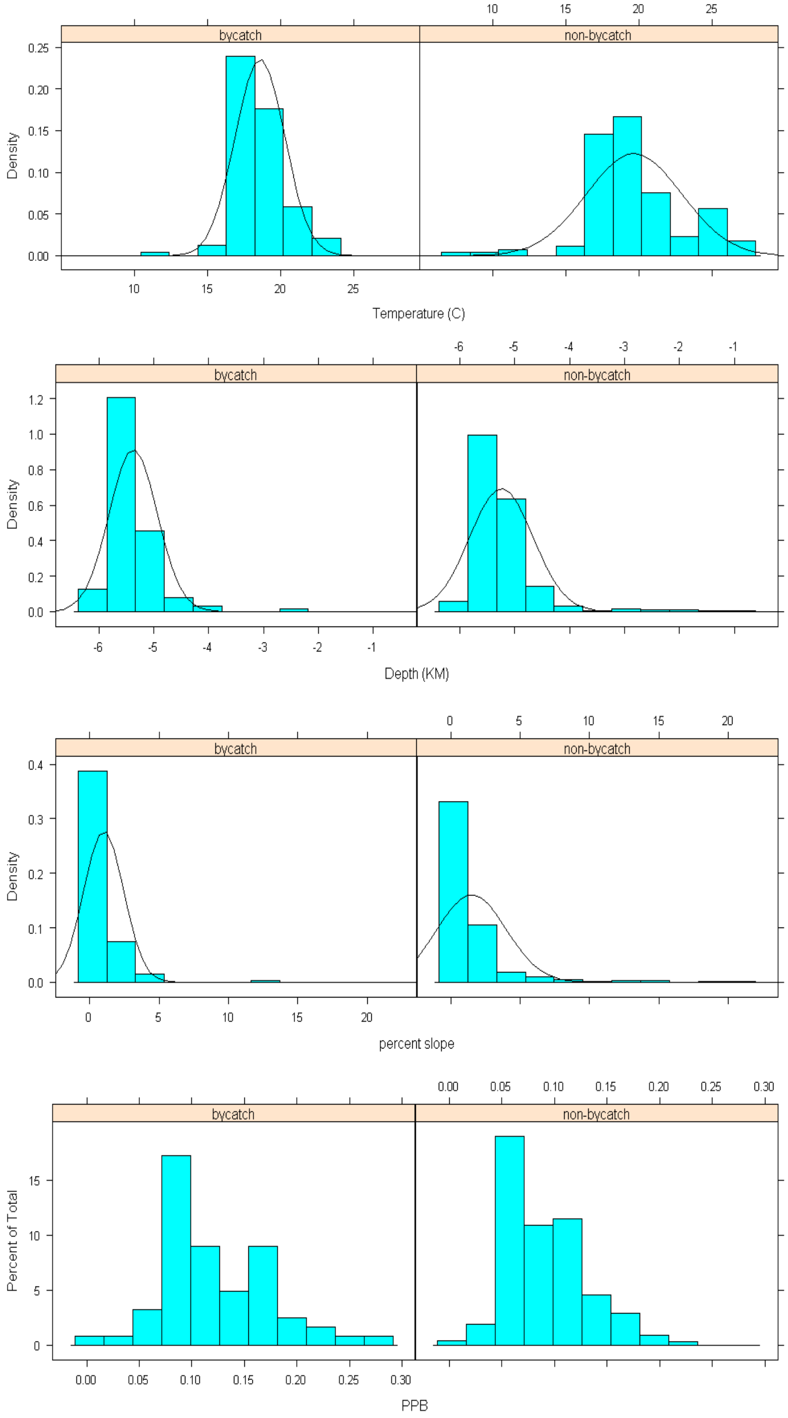


Figure 13: Comparison by oceanographic variables that were significantly different in bycatch sets vs. non-bycatch sets within the North Pacific transition zone. From top to bottom: SST, bathymetry, slope, and chlorophyll-a.

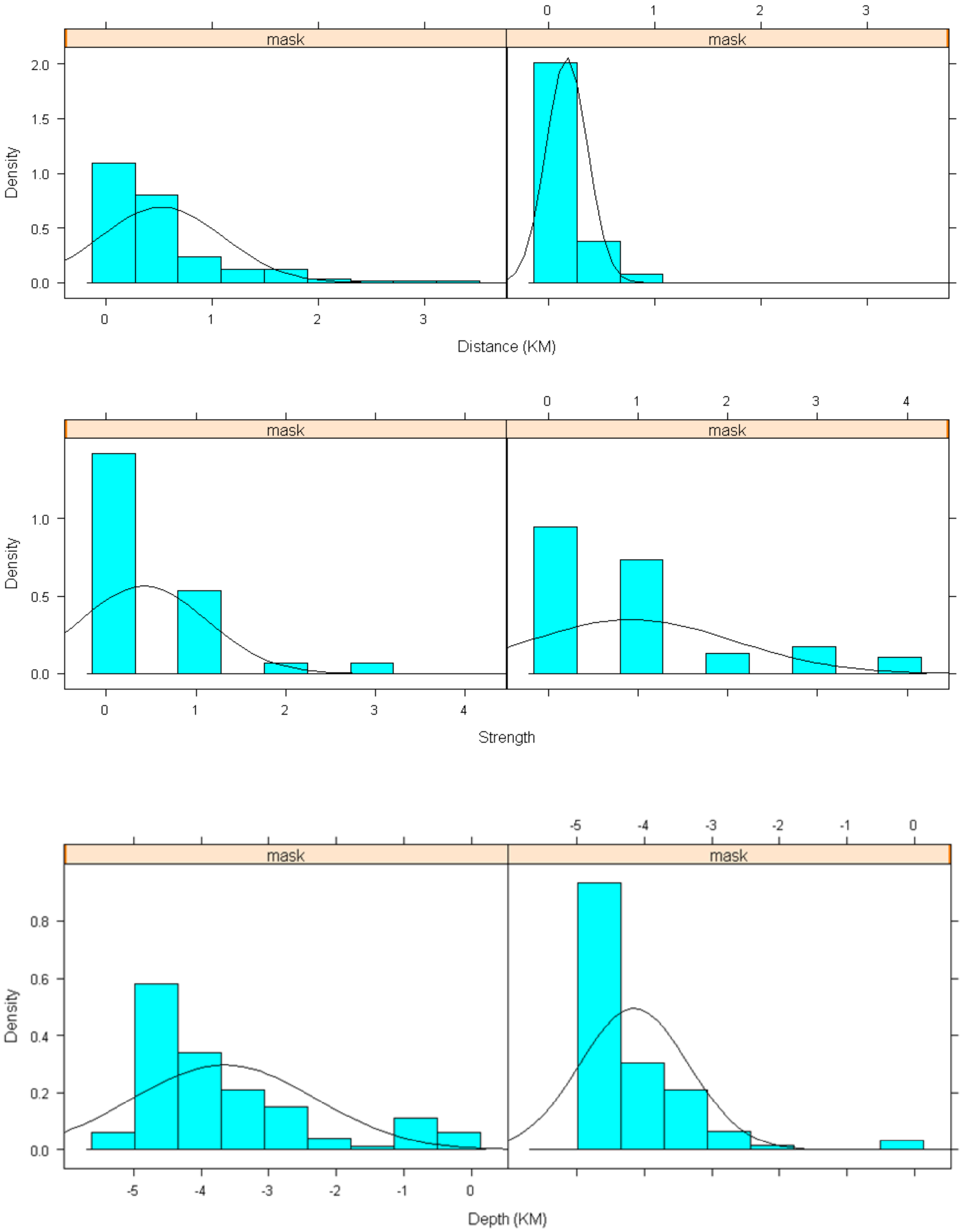


Figure 14: Comparison by oceanographic variables that were significantly different in bycatch sets vs. non-bycatch sets within the North Atlantic transition zone. From top to bottom: distance to fronts, strength of fronts and bathymetry.

Comparison of Fishing Variables

Significant differences in fishery characteristics between non-bycatch and bycatch events (Mann-Whitney test, $p<0.05$) in Hawaii included the number of lightsticks deployed, the soak time, season, latitude and longitude. Within the Atlantic, only latitude, longitude and the number of swordfish caught varied significantly between bycatch and non- bycatch sets (Mann-Whitney test, $p<0.05$). Comparison of bycatch sets between the Pacific and Atlantic yielded significantly differences in five of the six fisheries variables: latitude, longitude, season, number of lightsticks deployed and number of swordfish caught (Mann-Whitney test, $p<0.05$).

Bycatch Hotspots

Predictors of bycatch varied between each study area and between seasons. Within the Hawaii study area, the best predictors for bycatch were chlorophyll-a, strength of front and season (binominal GLM, $p < 0.05$). Taking the season into account, the significant predictors for bycatch were chlorophyll-a and distance to shore (January – March); bathymetry (April – June); and SST (July – September); and distance to shore, distance to fronts, and front strength (October – December) (binominal GLM, $p < 0.05$). Bycatch probability grids were developed using the most parsimonious models developed through stepwise regression. The models included chlorophyll-a , distance to shore and front strength (January – March); bathymetry and distance to fronts (April – June); SST, distance from shore, bathymetry and slope (July – September); and bathymetry and distance to front (October – December).

When applying the model to the spring, when the majority of bycatch occurs, the areas of high probability of bycatch moves northerly as the months move from January to March. January was shown to have the highest probability of bycatch. The probability decreased slightly through February and March.

Within the Atlantic study area the best predictors for bycatch were distance from shelf break and season (poisson GLM, $p < 0.05$). Taking the season into account, the significant predictors for bycatch were distance from shore and distance from shelf break (April – June); bathymetry, distance from shore, distance from front and front strength (July – September); and distance from shelf break and front strength (October – December) (poisson GLM, $p < 0.05$). Oceanographic variables included in bycatch probability models developed through stepwise regression included SST, distance to shore and distance to shelf (April – June); bathymetry, distance to shore and distance to front (July – September); and distance from shelf break and front strength (October – December).

When applying the model to the fall, when the majority of bycatch occurs, the area of high probability of bycatch stays within the same area from August to October. However, as the months progress, the probability of bycatch increases substantially, peaking in October.

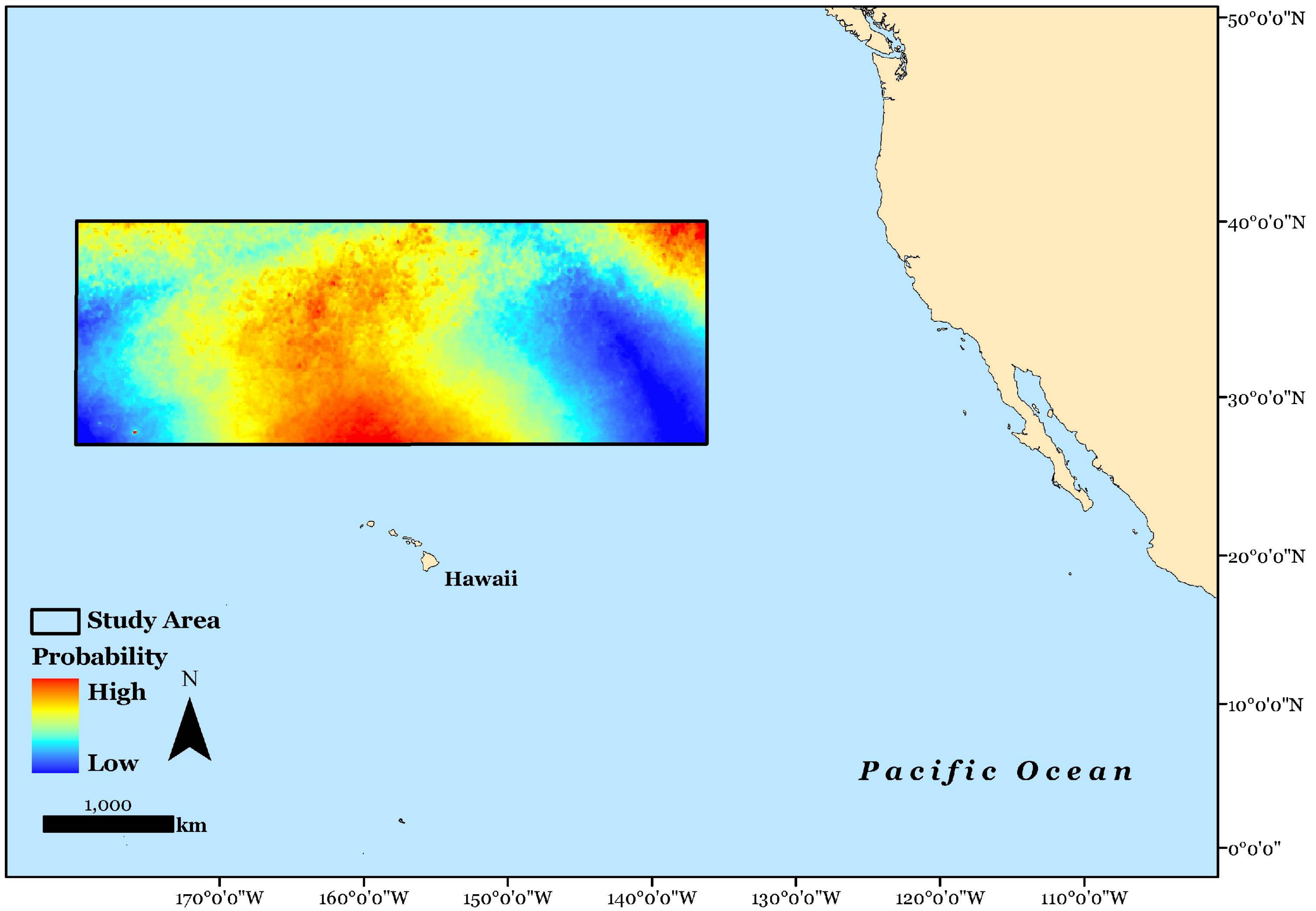


Figure 15: Probability of bycatch of loggerheads in pelagic longline swordfish gear in January within the North Pacific transition zone. The oceanographic variables used in the creation of the grid included chlorophyll-a and distance to shore

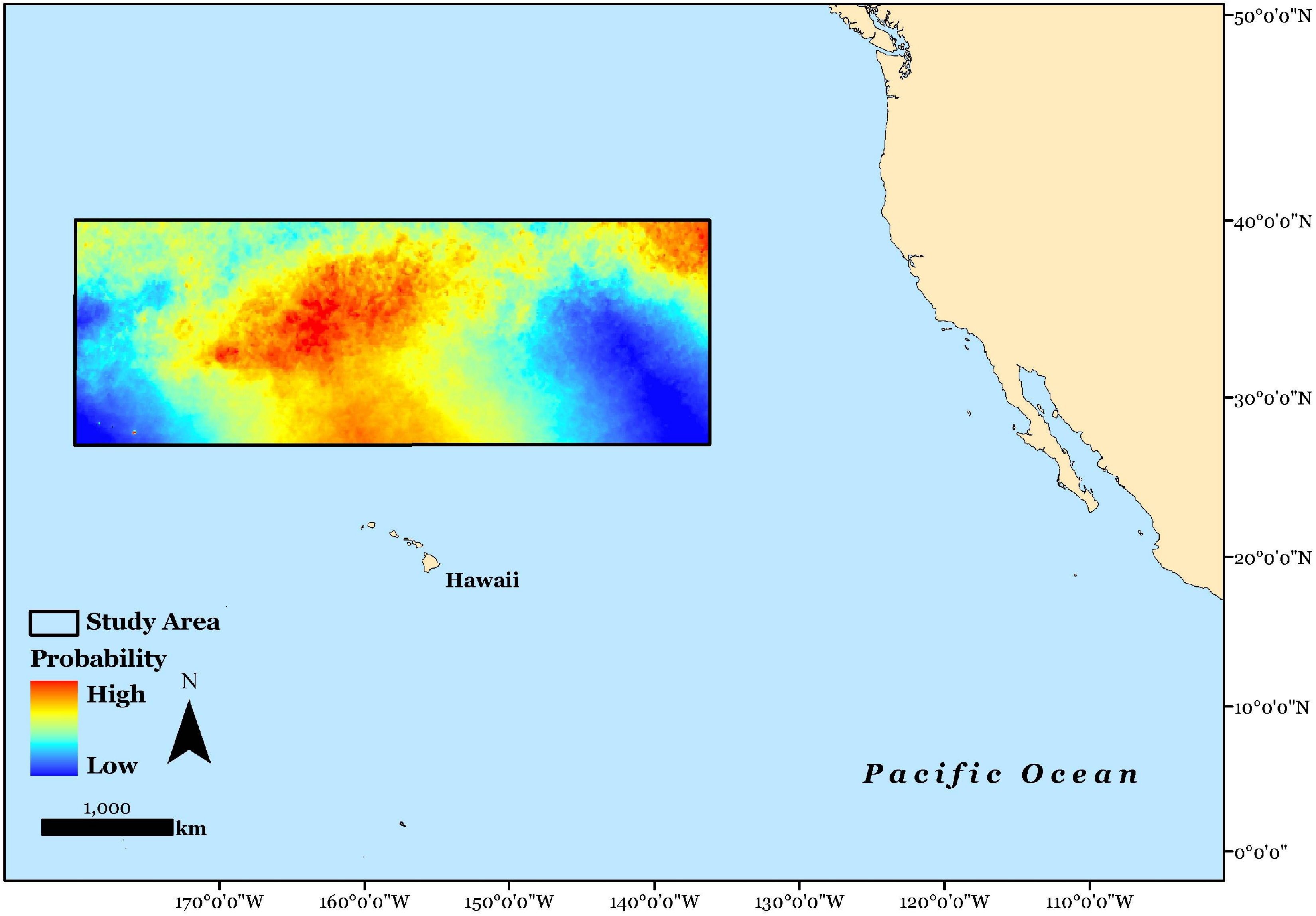


Figure 16: Probability of bycatch of loggerheads in pelagic longline swordfish gear in February within the North Pacific transition zone. The oceanographic variables used in the creation of the grid included chlorophyll-a and distance to shore

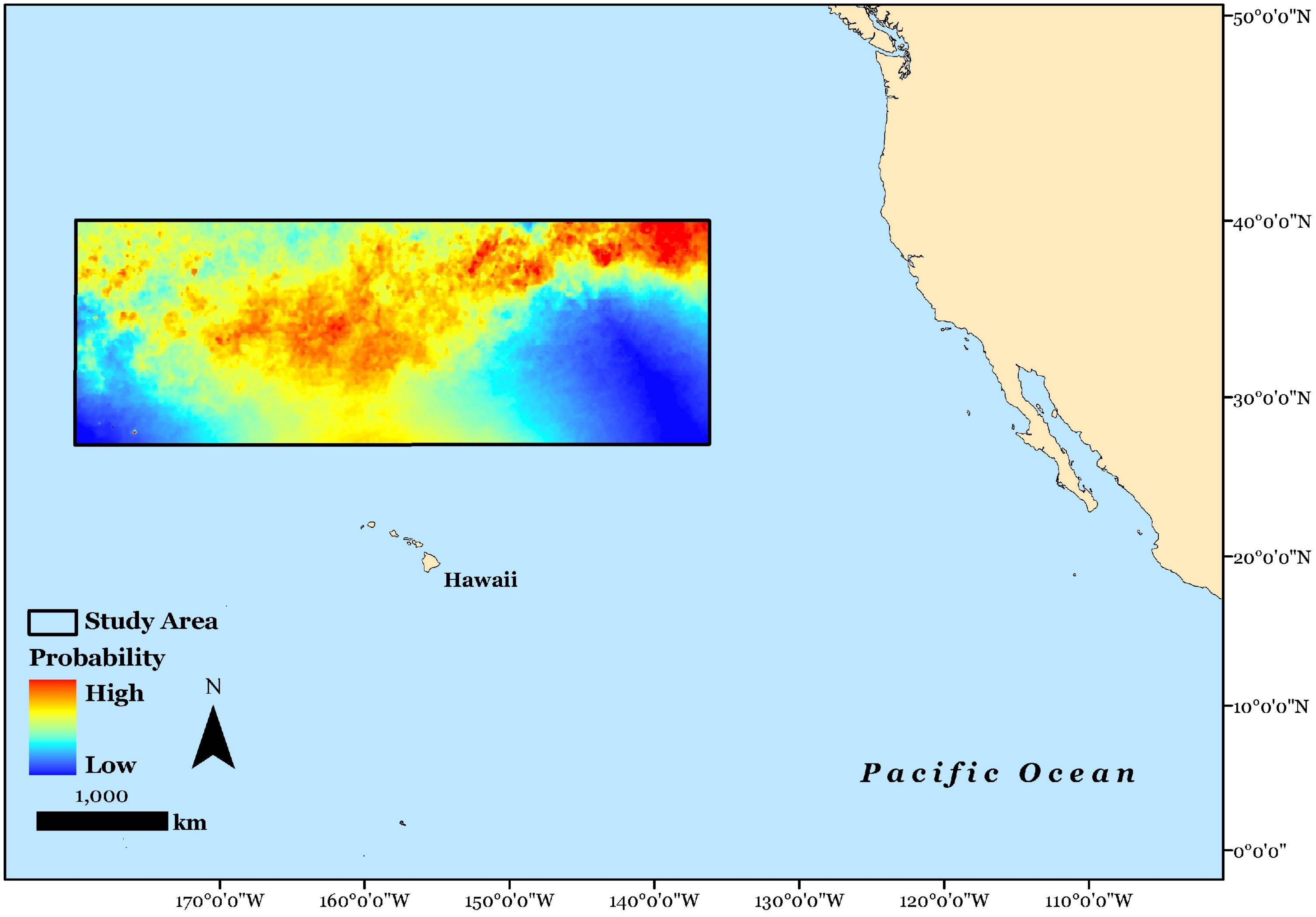


Figure 17: Probability of bycatch of loggerheads in pelagic longline swordfish gear in January within the North Pacific transition zone. The oceanographic variables used in the creation of the grid included chlorophyll-a and distance to shore

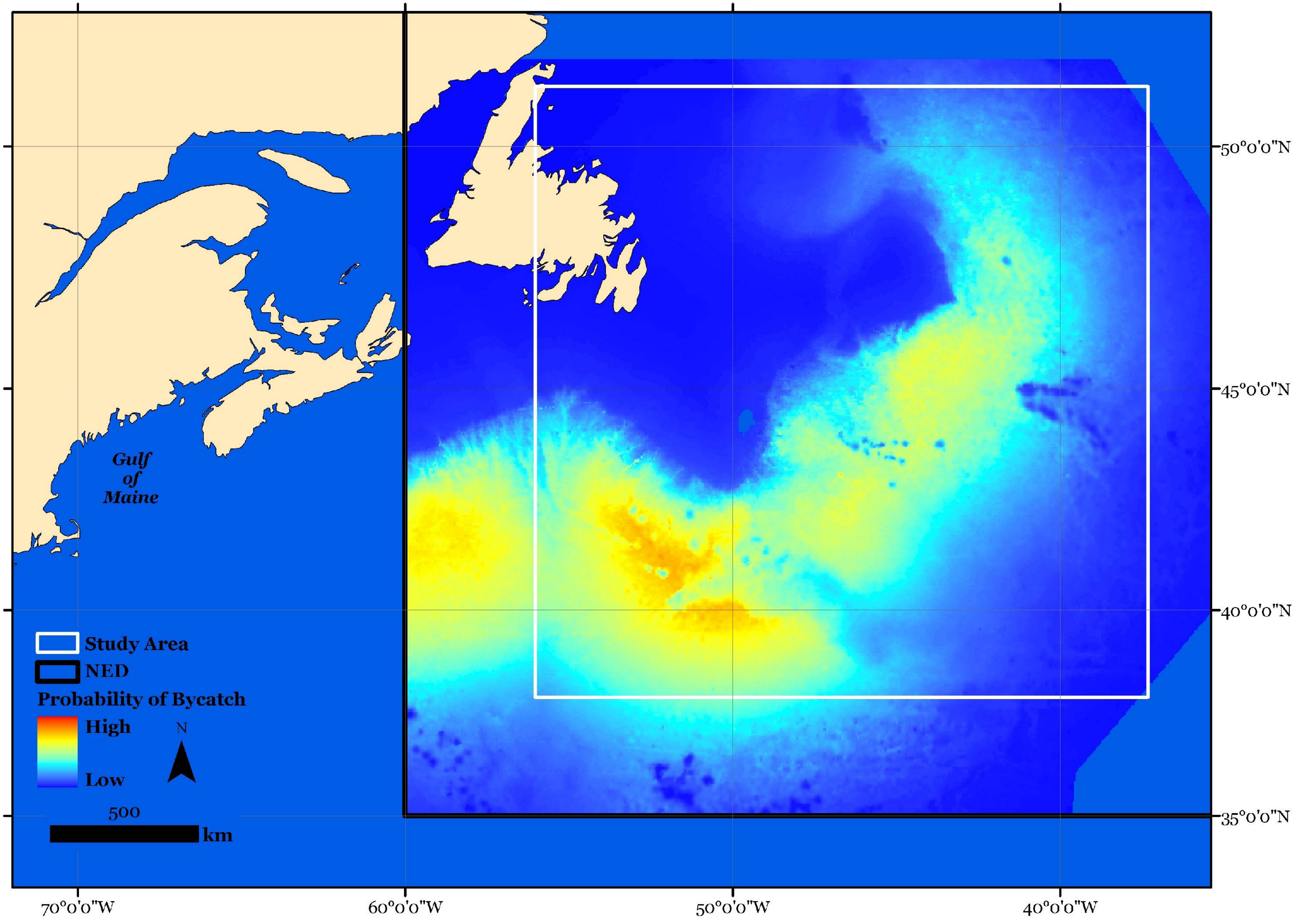


Figure 18: Probability of bycatch of loggerheads in pelagic longline swordfish gear in August within the North Atlantic transition zone. The oceanographic variables used in the creation of the grid included chlorophyll-a and distance to shore

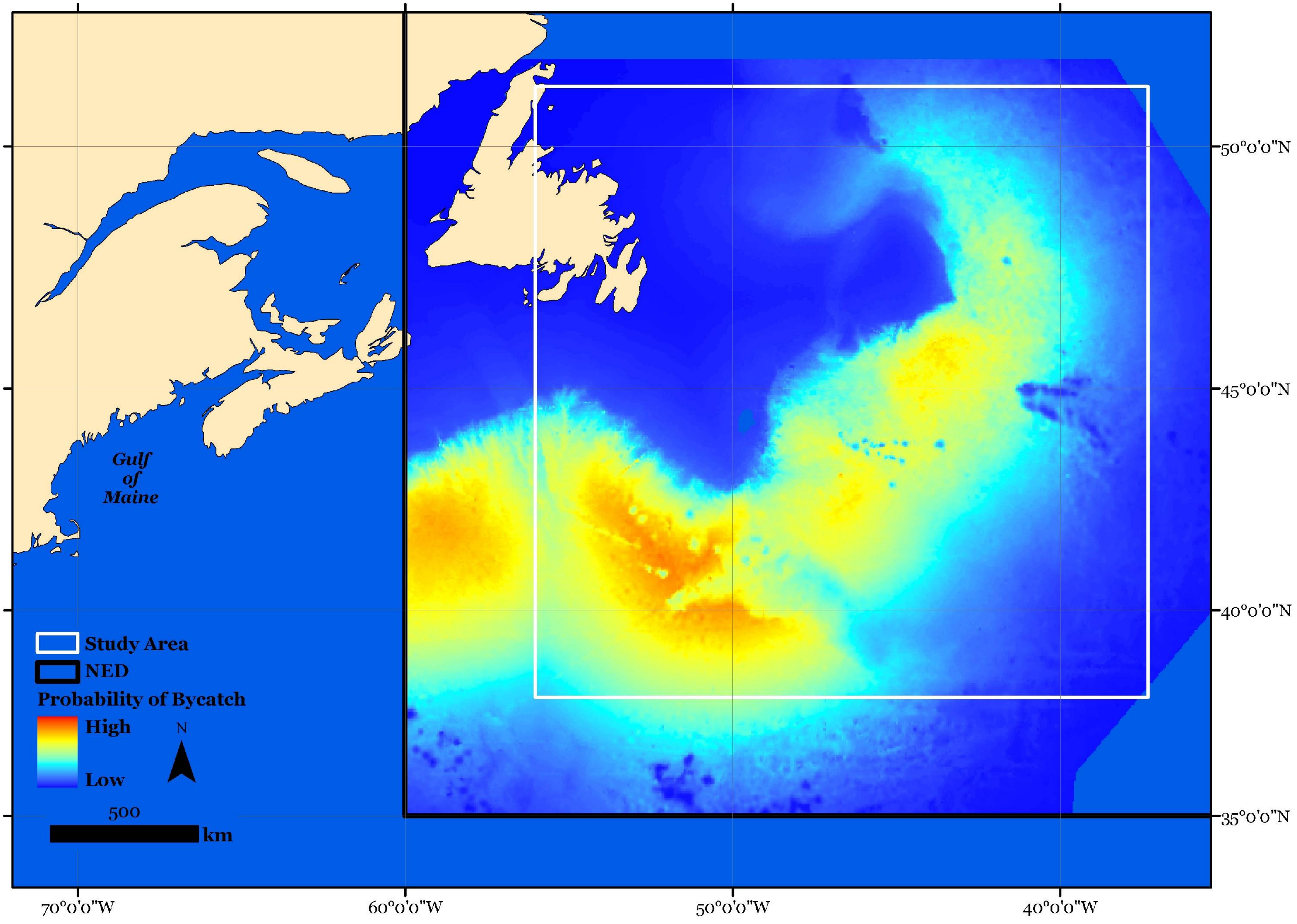


Figure 19: Probability of bycatch of loggerheads in pelagic longline swordfish gear in September within the North Atlantic transition zone. The oceanographic variables used in the creation of the grid included chlorophyll-a and distance to shore

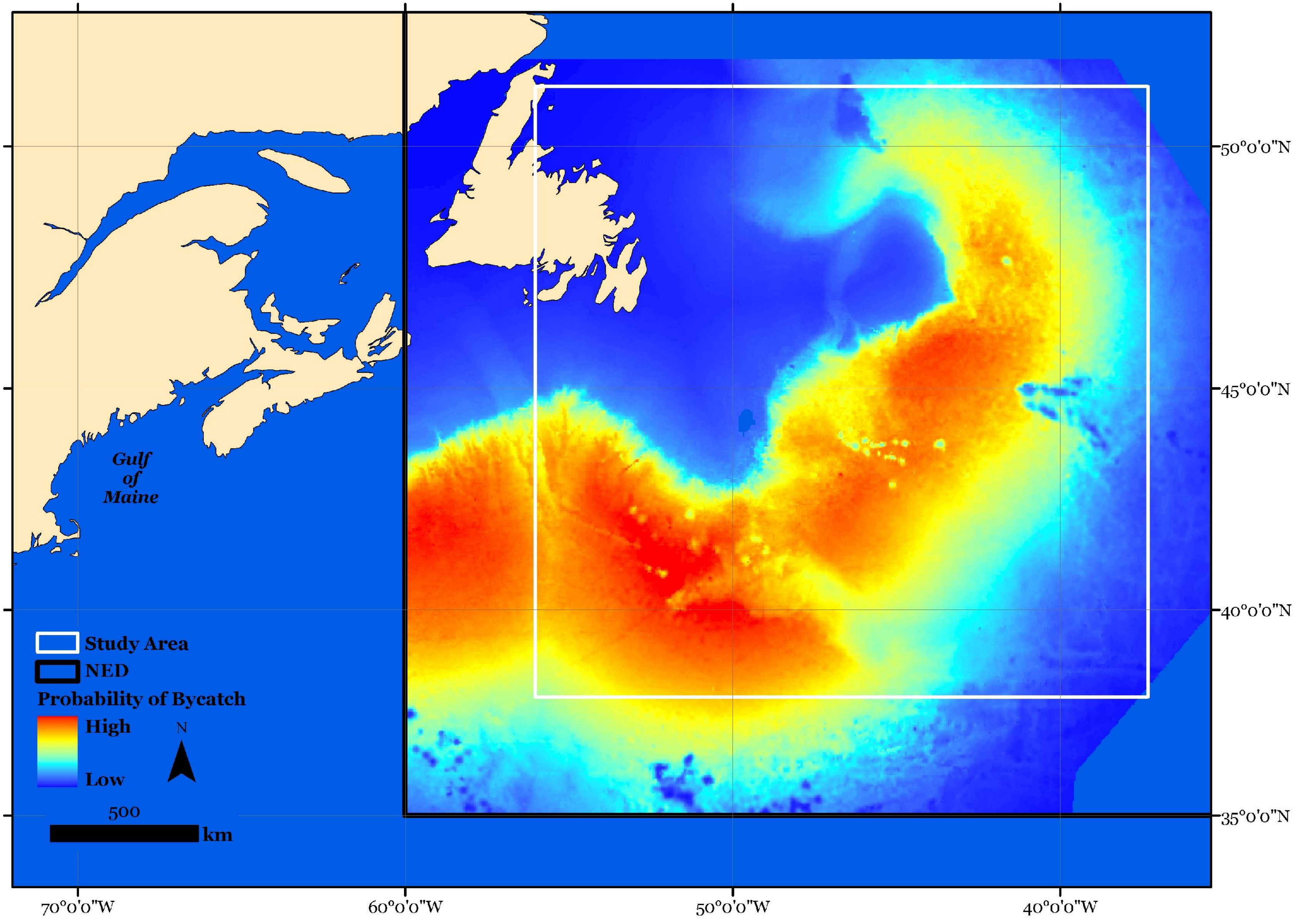


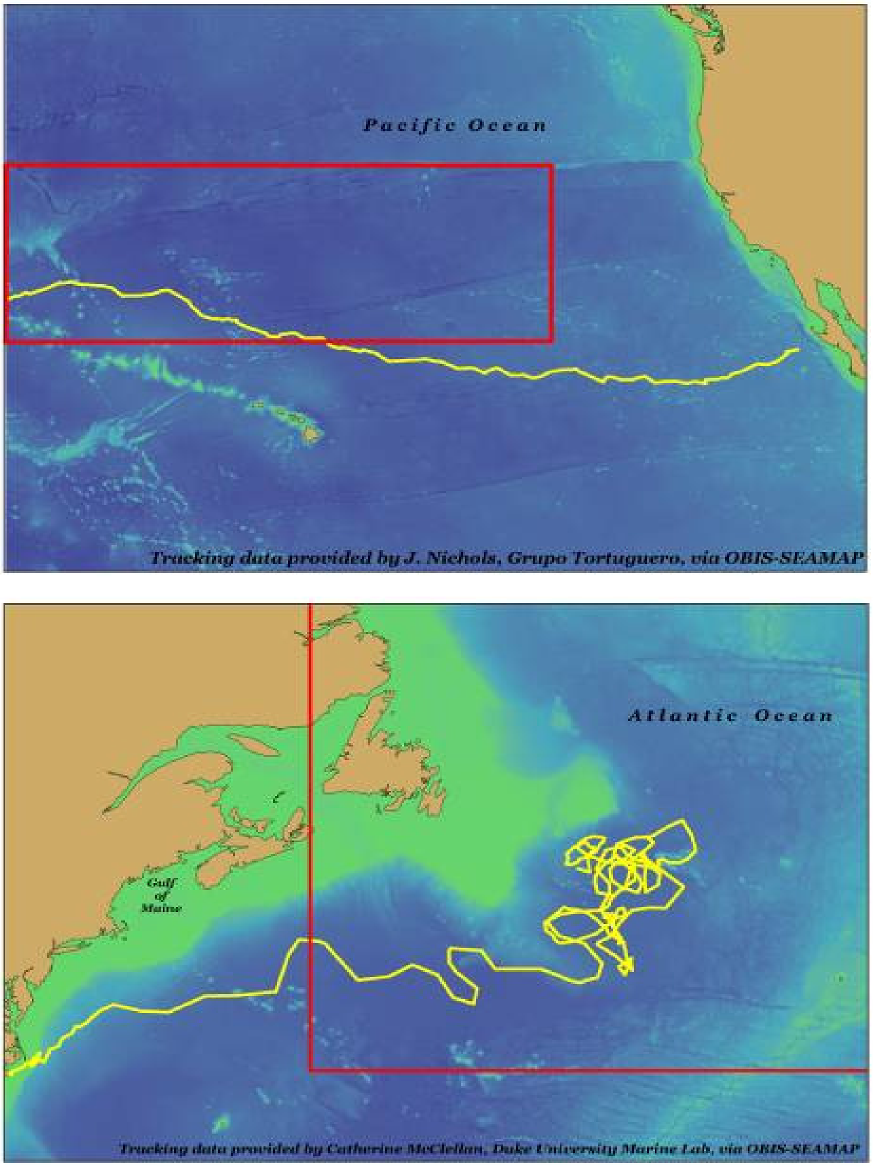
Figure 20: Probability of bycatch of loggerheads in pelagic longline swordfish gear in October within the North Atlantic transition zone. The oceanographic variables used in the creation of the grid included chlorophyll-a and distance to shore

Discussion

The most notable difference between the two study areas is the temporal composition of bycatch. Bycatch events within the Atlantic study area occurred only during April – December and peaked from July – September, when 82% of interactions were reported. Fishing did not take place from January – March, when SST was below the general range of both swordfish and loggerheads. Within the Hawaii study area, bycatch interactions were year-round and peaked from January – March, with 69% of bycatch interactions for the year occurring during this period.

When comparing the underlying oceanographic conditions where bycatch occurred between the two study areas, five of the six variables available for comparison were statistically different. While this may be attributed to the use of monthly data, which may not adequately capture the dynamic conditions that occur when a bycatch event happens, it may also be influenced by how the loggerheads are utilizing the habitat within each study area. In the Pacific, the area north of Hawaii is a migration corridor for loggerheads as they head to the western Pacific, which can be seen in Figure 21, which shows an example of a loggerhead turtle moving in a relatively straight line from east to west in the Pacific. Conversely, in the Atlantic study area, loggerheads are using the area more for foraging activities, as seen in Figure 21, where the loggerhead is frequently turning and the track is very sinuous. Since foraging activities will increase the residency time within the study area, the likelihood that a loggerhead will encounter a longline will increase as well, which may account for the higher CPUE and F-index within the NED as compared to the Hawaii study area.

The main problems with basing management on dynamic environmental conditions are those of enactment and enforcement. For example, it would be logistically difficult to implement a closure of fishing grounds in the Atlantic based on the development of



Tracking data provided by J. Nichols, Grupo Tortuguero, via OBIS-SEAMAP

Tracking data provided by Catherine McClellan, Duke University Marine Lab, via OBIS-SEAMAP

Figure 21: Loggerhead satellite tracking data shows the use within each region is different. In the N. Pacific loggerheads are primarily migrating through the region, while in the N. Atlantic loggerheads are foraging.

specific frontal conditions and located a certain distance from such a system. Fishermen headed out to sea at the time of a closure would be forced to either return to port or wait it out, both of which would increase operating costs, through the added fuel consumption or unproductive days at seas, in an industry that is already operating at margin (Crowder and Myers 14). Would fishermen that already had gear set be allowed to retrieve it? If not, it could lead to increased waste of marine recourses, as the increase in soak time results in species falling off hooks or being predated upon (Myers et al, 2004). Additionally, there could be an increase in ghost gear if fishermen leave gear deployed. If fishermen were allowed to retrieve their gear it creates an incentive to always have gear deployed, encouraging derby-style fishing practices. Attempting to create such a system would require increased support on the part of NMFS, whose resources are already stretched. It would also require a flexibility that is not inherent in the current system.

If the logistic behind enactment could be overcome, enforcement will still pose many challenges, although it may be possible to utilize technologies already in place within the fisheries. Almost all fishing vessels today operate with the assistance of high-tech marine electronics, which help to improve navigation and communication, as well as increase catch (Watson, 2006). Vessels are equipped with an array of devices including fish-finders, GPS, radar, real-time SST and ocean color imagery, sonar, and Doppler current meters (Watson, 2006). Having such technological vessels out at sea has might be more of a hindrance, for example if closures were enacted in a particular area, but fishermen disagreed based on the information given by their electronics. A solution to this may be to have fleet-calibrated equipment. Vessels are also required to carry Vessel Monitoring Systems (VMS) onboard, which transmits the geographic location of the vessel via satellite to regulating authorities, may assist with enforcement. By knowing exactly where vessels are located it would be possible to determine which vessels were in prohibited areas.

Management Strategies for Reducing Loggerhead/Sea Turtle Bycatch

Since different species of sea turtles are impact in different ways, there is no one clear solution to reducing or preventing injury or mortality from longline gear. From this research the following recommendation are proposed to help reduce bycatch and promote more effective bycatch management within the US:

- The use of oceanographic cues can be incorporated into an overall strategy of bycatch management through the utilization of oceanographic forecasting models to help deal with the dynamic nature of the marine environment.
- Increasing communication between Pacific and Atlantic longline programs. Specifically standardizing data collection and reporting will help to create a more cohesive bycatch management program within the US.
- The Atlantic longline fleet fishing within the NED should be required to have 100% Observer coverage, as well as real time reporting of protected species interactions. Implementation of these new regulations has successfully reduced sea turtle interactions within the Hawaii longline fishery (Gillman et al, 2006). While successful management practices in one area should not necessarily be applied to other areas and does not guarantee future success in other areas, due to the high rates of interactions within the Atlantic longline fishery it should be enacted.
- Satellite tagging studies on swordfish should be conducted to help better understand how they are utilizing ocean habitats, which can then be compared to recent satellite studies on sea turtle movement.

Conclusion

With the increasing availability of remote sensing data and ability to track animals, it has become possible to analyze the correlation of animal movement and activities with environmental factors. As technologies improve and longer studies are conducted it will be possible to further increase our awareness of where animals are at different time of the year and at different points in their life. Hopefully such research will not only lead to a greater understanding of where animals are choosing to be, but will lead to insight into why they are choosing these locations as well.

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