TUNA-DOLPHIN-BIRD FEEDING ASSEMBLAGES IN THE GALAPAGOS ISLANDS AND THEIR RESPONSE TO THE PHYSICAL CHARACTERISTICS OF THE UPPER WATER COLUMN

A Thesis

by

MICHELLE LYNN JOHNSTON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Oceanography

Tuna-Dolphin-Bird Feeding Assemblages in the Galapagos Islands and Their Response
to the Physical Characteristics of the Upper Water Column

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Approved by:

Chair of Committee,	Douglas Biggs
Committee Members,	John Wormuth
	William Neill
Head of Department,	Piers Chapman

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ABSTRACT

Tuna-Dolphin-Bird Feeding Assemblages in the Galapagos Islands and Their Response
to the Physical Characteristics of the Upper Water Column. (August 2011)
Michelle Lynn Johnston, B.S., Westminster College
Chair of Advisory Committee: Dr. Douglas Biggs

Tuna-dolphin-bird feeding assemblages are unique to the Eastern Tropical Pacific Ocean (ETP). These multiple species groups are believed to forage together in response to the physical properties of the near surface ocean as these constrain the distribution of prey. In the Galapagos Marine Reserve (GMR), intra-annual and interannual changes affect the properties of the water column, inducing mesoscale and fine scale temporal variability. Four three-week oceanographic surveys took place, in September 2008, April 2009, October 2009, and September 2010, between the coast of Ecuador and the Galapagos Islands and one small boat survey took place in June 2010 within the GMR. Marine mammal surveys were conducted during daylight hours and Conductivity, Temperature, Depth (CTD) sensor casts were taken throughout the survey. Data were analyzed to determine the types of water masses present and the strength and depth of the thermocline layer. These data were compared with the sightings of marine mammals, bird feeding groups, and tuna-dolphin-bird assemblages. Additionally, these data were used to predict where tuna would be likely to associate with dolphin groups.

Results show Equatorial Surface Water was the dominant water mass throughout the archipelago, regardless of season or ENSO index. High salinity, cold water west of Isla Isabela indicated topographic upwelling of the Equatorial Undercurrent. Tropical Surface Waters from the Panama Current were detected north of the Equatorial Front to the east of the islands. Obvious changes in the water column properties were observed between El Niño and La Niña events in the GMR.

Most mixed groups were sighted west and south of Isla Isabela during the four oceanographic surveys, as well as north and west of Isla San Cristobal in June 2010. Most sightings were in cool, high salinity waters, and high chlorophyll concentrations. There were a greater number of sightings during the April 2009 survey (ENSO-neutral conditions) than during any of the three fall surveys. Additionally, tuna-dolphin-bird groups were more likely to be seen near Isla Isabela, with the majority of them sighted during the April 2009 survey and a few sighted in each of the September 2008 and October 2009 surveys. No tuna-dolphin-bird groups were sighted during the September 2010 surveys. Results show that the presence and location of these multi-species groups may be controlled by the inter-annual cycles, the intra-annual cycles, or a combination of both types of changes seen within the Galapagos.

I would like to dedicate this thesis to my family and friends for all of their support in my studies.

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NOMENCLATURE

A09	April 2009
CTD	Conductivity Temperature Depth Instrumentation
DW	Deepwater
ECC	Equatorial Countercurrent
EF	Equatorial Front
ENSO	El Niño Southern Oscillation
ESW	Equatorial Surface Water
ETP	Eastern Tropical Pacific
EUC	Equatorial Undercurrent
GMR	Galapagos Marine Reserve
GNP	Galapagos National Park
HNLC	High nutrient low chlorophyll
IATTC	Inter-American Tropical Tuna Commission
INOCAR	Instituto Oceanográfico de la Armada del Ecuador
J10	June 2010
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
O09	October 2009
PaC	Panama Current
PC	Peru Current

S08	September 2008
S10	September 2010
SEC	Southern Equatorial Current
SSH	Sea surface height
SSS	Sea surface salinity
SST	Sea surface temperature
T-S plot	Temperature-Salinity plot
TSW	Tropical Surface Water

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CHAPTER I

INTRODUCTION – TUNA-DOLPHIN-BIRD ASSEMBLAGES IN THE EASTERN TROPICAL PACIFIC OCEAN

Introduction

The tuna fishery is an important worldwide commerce, with an average of 1.2 million metric tons of yellowfin tuna fished from the world's oceans every year (Ely *et al.* 2005). With this large tuna fishery comes a large number of problems. Since tuna is so popular in the world market, especially in Asian countries, the increased demand for tuna has increased the amount of fishing in the oceans. There are a variety of ways to fish for tuna: purse seine, trolling, pole and line gear (longline), and gillnet fishing (Au & Perryman 1985). However, with every method of catching tuna, a variety of other species, called bycatch, are also caught. Sharks, turtles, and many species of marine mammals are caught along with tuna in longline and gillnet fishing, and purse seining is threatening the dolphin populations in the Eastern Tropical Pacific Ocean (ETP).

In the late 1960s it was noticed that large numbers of dolphins were being killed as bycatch from the tuna fishery, and worry grew that their populations were threatened with extinction (Ferguson *et al.* 2006). In the ETP tuna and dolphins often travel together in mixed schools, and the dolphins are easier to spot than tuna (Edwards 1992). Due to this, purse seiners began targeting dolphin populations to catch the tuna associated with them (Ferguson *et al.* 2006). The National Marine Fisheries Service (NMFS) has been monitoring dolphin abundances in the ETP since the early 1970s. It is

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This thesis follows the style of Marine Mammal Science.

estimated that the number of dolphins in the ETP have been reduced to approximately 20% of their pre-1959 population size, before the purse seining fishery was prevalent (Oxenford 2002). This sparked interest and management concerns about the dolphin species that were being affected by the purse seining fishery (Polacheck 1987).

Since then, the Inter-American Tropical Tuna Commission (IATTC) has imposed strict regulations on the purse seining industry, and “dolphin-safe” tuna became an important regulation for tuna sold in the United States. However, dolphins are still being caught and killed as bycatch. Due to this, it is important to understand where these groups form and why they occur so that better fishing management strategies can be used to protect the Pacific Ocean dolphins.

Previous Research

Most studies on cetacean habitats are performed by comparing empirical associations between population density and physical, and occasionally biological, variables. These studies also try to predict cetacean habitat based on known species-habitat relationships and determine which ecological mechanisms are most important in determining distribution and density patterns (Ballance *et al.* 2006).

However obvious the patterns in the data may be, the statistical correlations between cetaceans and habitat defined by physical variables are often much weaker than those of their prey. In one study, only 14.7% of the variation in the dolphin's habitat preferences could be explained by different oceanographic variables; those measured were sea surface temperature, salinity, chlorophyll concentration, and thermocline depth and strength (Ballance *et al.* 2006). This is because the relationship of dolphins to these physical conditions may not be direct. Rather, their relationship could be controlled by the responses of their prey to these physical features. This leads to the need of cetacean habitat research to include biological parameters such as prey density, availability, and productivity along with the previously mentioned physical parameters (Ballance *et al.* 2006). In addition, research on tuna-dolphin-bird groups has often been focused on the entire ETP, with coarse resolution. However, within the Galapagos Marine Reserve (GMR), there are large changes in physical oceanographic conditions on small scales that may be "averaged out" in coarse resolution studies (Palacios 2004). This presents the need for fine-scaled investigation of these areas.

Tuna Fisheries

Purse Seining

The tuna targeted in the purse seining fishery are yellowfin tuna, *Thunnus albacores*; these are a surface schooling species of tuna that are often associated with several different species of dolphins. During purse-seining fishing boats chase these mixed species groups until the dolphins tire and the whole group is surrounded with nets, catching both the tuna and the dolphins (Edwards 1992). These nets have two "drawstrings" attached to the bottom and top of the nets. First the bottom string is pulled to keep the tuna from escaping then the top string is "pursed" to pull the catch onto the boat. This captures the tuna and anything with which they are traveling, namely the associated dolphins (Brill & Lutcavage 2001). In order for purse seining to be effective, the thermocline and oxygen minimum zone must be close enough to the surface so that the fish cannot escape out the bottom of the net before it is pursed (Brill & Lutcavage 2001). Because of this practice, the species of dolphins impacted have begun to avoid boats when encountered, rather than approaching the boats as they might do in other areas of the ocean. Whenever a purse seine boat, helicopter, or other boats which sound like purse seiner boats approach, dolphins in the ETP have been observed to increase their speed and aerial activity and move to avoid the boat (Scott & Chivers 2009).

Artisanal Fisheries

Although large industrial fleets have been the main focus of the IATTC to reduce cetacean bycatch, recent studies on artisanal fisheries suggests that the cetacean bycatch from the coastal seas of western South America might be another significant source of cetacean mortality as bycatch (Mangel *et al.* 2010). In a study of gillnet fisherman in the coastal town of Salaverry, Peru, it was found that in the early 1990s, the mortality of cetaceans as bycatch from fisheries was between 15,000-20,000 animals (Mangel *et al.* 2010). The average number of cetaceans killed each year was 2,400 in an average of only 520 fishing trips. The gillnet fishery in this small town is responsible for as much cetacean mortality as the total number in all fisheries in the US and this small coastal town has one of the largest cetacean bycatch mortalities in the world (Mangel *et al.* 2010). This bycatch is often used as bait in Peru, as well as in many other coastal communities in Columbia, Argentina, Chile, Mexico, and the Philippines, along with many other countries around the world (Mangel *et al.* 2010). In order to effectively reduce the amount of cetacean bycatch from tuna fisheries, these smaller artisanal fisheries must be better understood and as efficiently managed as their larger, industrial counterparts.

Cetacean bycatch has also been reported in the Ecuadorian artisanal fisheries (Castro & Rosero 2010). The gillnet fisheries observed caught an average of 0.18 dolphins a day, catching mainly Risso's dolphins, bottlenose dolphins, and pygmy sperm whales (Fig. 1). Additionally, humpback whales, who breed off the coast of Ecuador, have been reported breaking through gillnets used by fisherman, although they are not generally caught by the nets (Castro & Rosero 2010). This rate, estimated from three fishing ports in the Machililla National Park in southwest Ecuador, has increased from those estimated in the 1990s. In the 1990s, the main dolphin species caught was common dolphins while no common dolphins were caught in the duration of the study in 2009 (Castro & Rosero 2010). It is suggested that this is because of changes in the fishermen's behaviors, fishing areas, and the decrease in the population of common dolphins in the area due to high fishing pressures (Castro & Rosero 2010).

The artisanal fishery in the Galapagos Marine Reserve is strictly managed, with very specific regulations on the type of fishing gear used, the total catch allowed, and the use of fishing permits. There are four types of fishing permitted in the GMR: experiential artisanal fishing, commercial artisanal fishing, domestic fishing, and scientific fishing (Ecuador Ministry of the Environment 2008, CTPJMP 2009). There are currently 24 boats permitted for experiential artisanal fishing, where tourists accompany artisanal fishermen on a day trip to learn about their trade. All fish caught during these trips are released alive, and generally have little impact upon the environment. Commercial artisanal fishing allows fishermen to sell their catch at the local fish markets (Fig. 2). Domestic fishermen are those who fish to support their families, but are not allowed to sell their fish for commercial gain. Domestic and commercial fishing has the greatest impact upon the ecosystem. Scientific fishing permits scientists to catch fish in order to assess the status of the stock (Ecuador Ministry of the Environment 2008, CTPJMP 2009). The types of fishing gear used in the artisanal fisheries in the GMR are limited to rod and reel, trawling with a line, handnets, beach seines for herring, Red Lisera or gillnets, and Hawaiian Vara (for lobster). The gillnets are responsible for the majority of the cetacean bycatch in the Peru fisheries, the coastal (mainland) Ecuadorian fisheries, and presumably, the GMR fisheries (Ecuador Ministry of the Environment 2008, CTPJMP 2009, Castro & Rosero 2010).

Figure 1. Photos of cetacean bycatch captured with gillnets in an Ecuadorian artisanal fishery during the study by Castro and Rosero (2010). Photo on left is a juvenile bottlenose dolphin, photo on right is a Risso's dolphin in a gillnet.

Figure 2. Typical size of *y*ellowfin tuna caught by the GMR artisanal fishermen, cleaned and ready to be sold at the Puerto Ayora, Santa Cruz fishing market (Photo by Douglas Biggs, December 2010).

Multi-species Associations

The dolphins associated with tuna schools are mostly small pelagic dolphins: primarily spotted and spinner dolphins, *Stenella attenuata* and *S. longirostris*, respectively, but occasionally striped or common dolphins, *S. coeruleoalba* and *Delphinus delphis*, respectively (Perrin *et al.* 1973, Au & Perryman 1985, Reilly 1990, Silva *et al.* 2002). Even Fraser's dolphins, *Lagenodelphis hosei*, are occasionally affected by the purse-seining industry as well; however they are rarely found in association with yellowfin tuna.

Tuna, cetaceans, and the associated birds all eat close to the top of the food chain, and many are apex predators (Ballance *et al.* 2006). The majority of seabirds in the ETP are surface-feeders which allow them to rely on predators such as dolphins or tuna to drive small fish or squid to the surface (Au & Perryman 1985, Mills 1998). This means they will have a close relationship to surface schooling tuna and aid in the location for these schools; their presence is often noted by marine mammal observers (Au & Perryman 1985, Au 1991). Birds have been found with approximately 80% of the log-fish (associated with floating logs, algae and seaweed, etc.) and school-fish (single species of schooling fish) tuna, and almost every dolphin-fish school in the ETP (Au 1991). The birds generally associated with tuna often have diets similar to those of the tuna, and are generally far ranging birds such as frigate birds, boobies, petrels, shearwaters and terns, the latter of which are only occasionally found with these groups (Au 1991, Ballance *et al.* 2006). Flocks of these birds can feed independently from the tuna, but they will feed with them whenever the opportunity presents itself, due to the ease of reaching shallower prey schools (Au 1991). The birds have not been observed to feed with dolphins that are not associated with tuna, although the reasons for this are unknown (Au 1991).

The tuna-dolphin-bird association is unique and important to the ETP (Ballance et al. 2006, Reilly 1990). It is similar to the poly-specific associations found among primates and terrestrial birds who also seem to forage together without strong interactions (Au 1991). This association could be driven by the circumstances related to open sea foraging. It can become considerably ecologically complex, and involve strategies not only in group foraging but also predation reduction (Silva *et al.* 2002). There are a variety of hypotheses for why these associations are only found in the ETP. The ETP is characterized by a sharp, shallow thermocline and a thick O_2 minimum layer just below it (Scott & Cattanach 1998). This thermocline is also believed to be a primary factor in explaining the prevalence of these interactions (Ballance *et al.* 2006). Many species of marine fish show responses to temperature changes as small as 0.03ºC/m and are able to determine the thermocline, preferentially staying in the warmer surface waters (Green 1967).

Also, the shallow thermocline may induce vertically migrating prey to aggregate, and account for nighttime prey abundance often being closely related to thermocline depth (Green 1967, Reilly 1990, Saltzman & Wishner 1997, Fielder *et al.* 1998, Spear *et al.* 2001, Ballance et al. 2006). In addition, thermal ridges may concentrate aggregations of vertically migrating organisms while discontinuities in horizontal gradients in water density will cause weakly swimming prey to aggregate (Yen *et al.* 2004, Scott & Chivers 2009). The thermocline and shallow (20-100 m deep) O_2 minimum layer may be responsible for keeping prey species in larger groups in shallower, warmer surface waters where they are more available to predators, rather than deeper cooler waters where they are more likely to escape from predation (Scott & Cattanach 1998, Yen et al. 2004, Ballance et al. 2006). In summary, the associations of large mixed species groups has two main causes, prey distribution and predation pressure, and the size of the group is often a compromise between the pros and cons of aggregation (Scott & Cattanach 1998).

If these interactions are based on the availability of prey, it is thought to be because of one or more common prey items between the species. Spotted and spinner dolphins and yellowfin tuna eat several of the same types of prey (Perrin *et al.* 1973, Silva *et al.* 2002). However, correlation does not imply causation, and one cannot assume they are together because of a common diet. Yellowfin tuna usually feed during the day, and spotted and spinner dolphins generally prey at night (Fielder *et al.* 1998, Scott & Cattanach 1998, Silva *et al.* 2002). Spotted and spinner dolphins usually prey upon an ommastrephid squid that migrates vertically to feed near the surface at night and other epipelagic and mesopelagic fish and squid (Scott & Cattanach 1998, Scott & Chivers 2009).

There are various arguments on whether or not spotted dolphins are diurnal or nocturnal feeders, however a recent study by Scott and Chivers (2009) on spotted dolphins in the ETP showed that their dive patterns implied they were primarily nocturnal feeders. They found that the dolphins traveled relatively deep during the day without the characteristic rapid changes in depth that indicate prey pursuit, but their dive depths followed the rise and fall of the deep scattering layer at dawn and dusk. This suggests that they tend to feed upon the vertically migrating species that rise to the surface at night (Scott & Chivers 2009). In addition spotted dolphins tended to spend less time at the surface at night and have faster ascent and descent times, with more time chasing prey at depth (Scott & Chivers 2009). This study supports others on food-habitat and radio-tracking studies that indicate spotted dolphins as nocturnal feeders. In comparison, yellowfin tuna gut analyses have shown that they feed rarely at night, when their associated dolphins tend to feed (Brill *et al.* 1999). There is evidence that the aggregations of these species are not competing with each other for the same prey species. It is believed that these species have specialized in prey items, time of the day for feeding, and maybe even the maximum feeding depth, allowing the species to interact without competing for the same resource (Perrin *et al.* 1973).

These associations may be loosely based and sporadic or tight and last a long time, and tuna and dolphins may not feed on the same things at the same time (Perrin *et al.* 1973, Au 1991). It has been noted that occasionally when spotted and spinner dolphins are associated with tunas that are actively feeding in the daytime, the dolphins are not actively participating, but rather remain on the edges of the group. Also, fishermen in Hawaii have noticed that tuna often scatter at dusk and regroup at dawn (Scott & Cattanach 1998). This has led to hypotheses that the tuna-dolphin associations are primarily diurnal, they disperse at night and reform just before dawn. Spotted dolphin groups often break up in the late afternoon, and may be the driving factor for breaking up the association for the night (Scott & Cattanach 1998). In addition, tuna tend to remain above the thermocline in the daytime and below the thermocline during the night, increasing the probability that these groups are primarily diurnal (Schaefer *et al.* 2009). This strategy is one that may reduce predation risks during the day with a large herd, while decreasing competition at night for food by decreasing their population density.

Vertically migrating prey species also tend to scatter at night, making feeding in dense, large groups on low density prey less effective than feeding independently (Scott & Cattanach 1998). Therefore, tuna-dolphin associations should be more prevalent where prey is strongly clumped, possibly due to oceanographic conditions, and less prevalent where the prey distribution is more uniform (Edwards 1992). The observed associations are probably a time-varying combination of both tight groups and loosely affiliated groups. The species may join and leave the groups in response to changes in foraging situations. When the prey is clumped, they will forage together, when it is dispersed, they forage independently. These groups may only last a few hours, or they may last up to a few years (Au 1991).

The nature of these associations and which species takes the role of the leader and the follower are both still unknown. In multispecies interactions, the more behaviorally versatile species will often exploit the other species although there appears to be some mutual benefits in this particular case (Au 1991). Some argue that it would probably be disadvantageous for dolphins to follow tuna searching for food due to dolphins' superior ability to find distant food via echolocation (Edwards 1992, Silva *et al.* 2002). It has also been shown that tuna seek out dolphins of a particular size range, those that travel approximately 100-130 cm/second. Large, mature yellowfin tuna travel at an average speed of 120 cm/second, so finding these smaller dolphins to travel with would not require the tuna to lose speed by slowing down, or energy by speeding up (Edwards 1992). For this reason, the larger tuna would follow the smaller dolphins in order to locate food patches more efficiently (Silva *et al.* 2002).

Purpose and Hypotheses

The purpose of this study is to investigate the presence of tuna-dolphin-bird feeding assemblages in the Galapagos Marine Reserve using physical *in situ* data to further characterize the habitat of these groups along with other cetacean and bird-tuna groups. The objectives are to:

1.) Collect and review information already known on tuna-dolphin-bird assemblages in the Eastern Tropical Pacific and specifically in the Galapagos Marine Reserve;

2.) Characterize the upper 50 m of the water column using in situ data collected via a hand-deployed CTD in areas of cetacean and bird-tuna sightings along with areas of no sightings;

3.) Determine the relationship, if any, of the tuna-dolphin-bird assemblages, cetacean groups, and bird-tuna assemblages to the strength and depth of the thermocline.

The null hypotheses for this study are:

1.) Areas within in the Galapagos Marine Reserve will show no difference in upper water column properties.

2.) There will be no difference in thermocline properties in areas where there are tuna-dolphin-bird assemblages compared to areas where there are just bird-tuna assemblages, cetacean groups, or no sightings.

CHAPTER II

PHYSICAL PROPERTIES OF THE SURFACE WATERS IN THE GALAPAGOS MARINE RESERVE AND SURROUNDING AREA

The Galapagos Marine Reserve

The Galapagos Marine Resources Reserve (GMR) was established by the Ecuadorian government in 1986 to protect the marine diversity that can be found around the already established terrestrial Galapagos National Park (GNP). In area, it extends 40 nautical miles outside of a baseline drawn from the outermost points of the Galapagos Archipelago (Jennings *et al.* 1994). This area is considered a biological "hot spot" despite its position in the Equatorial Pacific Ocean, an area typically characterized by high-nutrient low chlorophyll (HNLC) waters and low biological productivity.

This low productivity, despite the high nutrient concentrations, is due to iron limitation; iron is a necessary ion for chlorophyll's structure (Palacios 2004). Typically, the tropical waters around the Equator are well stratified with very low nutrient concentrations. However, west of the archipelago, the Equatorial Undercurrent (EUC) collides with the islands of Fernandina and Isabela, upwelling cold, nutrient rich water (Sweet *et al.* 2007). In addition, iron is provided to the waters from the island platform (Palacios 2004). This gives the Galapagos Islands a distinction as an "oasis" of phytoplankton in an otherwise chlorophyll poor area. This, in turn, leads to the congregation of marine species of all trophic levels around the archipelago, including high trophic level and apex predators such as sharks, cetaceans, and marine pinnipeds (Palacios 2004, Palacios *et al.* 2006, Sweet *et al.* 2007, Alva 2009).

North of the archipelago, the warmer tropical waters of the Panama Current (PaC) approach the archipelago, creating a transition zone clockwise through the islands as the water transitions from the warm tropical waters of the north to the cold upwelling waters of the west (Fig. 3). These waters combine to form the weakly flowing South Equatorial Current (SEC) that flows westward across the archipelago occupying the surface waters up to depths of 20-50 m below the sea surface, depending on the season (Sweet *et al.* 2007).

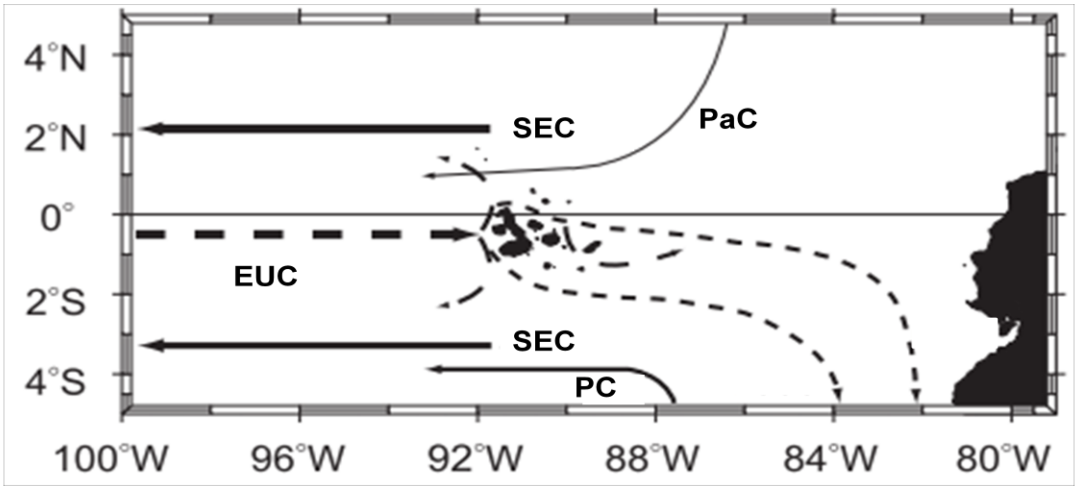


Figure 3. Schematic of major surface and subsurface currents impacting the Galapagos Islands. SEC = Southern Equatorial Current; EUC = Equatorial Undercurrent; PaC = Panama Current; PC = Peru Current. Solid lines indicate surface flows, dashed lines indicate subsurface flows, and arrows indicate primary direction of flow. Adapted from Palacios (2004).

Due to this clockwise transition zone within the islands, the physical characteristics of the water vary considerably throughout the archipelago. In addition, the strength and depth of the EUC flowing to the archipelago varies depending upon the time of year (Sweet *et al.* 2007). This causes the thermocline to also vary depending upon the time of year. The thermocline has been found to be shallowest in March (average 16 m deep), and deepest in June (average 44 m) within the archipelago (Sweet *et al.* 2007).

El Niño Southern Oscillation Cycle

The physical characteristics of the water are also affected by the El Niño Southern Oscillation (ENSO) cycle. This natural ocean-atmospheric cycle creates interannual variability around the Equator in the ETP to be as high or higher than the season variability in this area; often cycling every 2-10 years (Fielder 2002, Cane 1983). There are three possible conditions during the ENSO cycle, a warm El Niño period, a cool La Niña period, and ENSO-neutral conditions. The El Niño period is characterized by unusually warm SST in the ETP, sometimes up to 5°C warmer than normal conditions. This is caused by a decrease in the strength of Southeast trade winds, which weakens the surface currents, such as the SEC and the Peru Current, and reduces the strength of the upwelling of cooler, deeper water (Cane 1983). Additionally, the thermocline deepens, and any water that is upwelled is warmer than average. The warmer SST results in higher sea levels for this area, decreased chlorophyll concentrations, and increased precipitation (Cane 1983, Fielder 2002, Conroy *et al.* 2009). El Niño has a positive effect on terrestrial organisms in the Galapagos with the increased precipitation increasing the available freshwater, but marine organisms can be severely negatively affected, with little food available mass mortality can occur (Conroy *et al.* 2009).

La Niña is characterized by opposite conditions. Southeast trade winds are stronger than average, the thermocline is shallow, SST are cooler than average, and upwelling is enhanced, resulting in higher chlorophyll concentrations. La Niña has a positive effect on marine species, with plentiful food, but terrestrial species must endure a drought, often resulting in negative effects on those species (Fielder 2002).

Water Mass Types

There are two distinct types of water found in the surface waters around the Galapagos Islands: Equatorial Surface Waters (ESW) and Tropical Surface Waters (TSW). ESW are defined in Sweet, *et al.* (2007) as waters with a salinity of >34; this water mass is most prominent in the archipelago when there is a strongly developed EUC in the west with strong upwelling. TSW are waters with salinities <34 and are present when there is an increase in local rainfall during the wet season or the Panama Current is strongly developed in the east (Sweet *et al.* 2007). Below the surface, the EUC is often within the 14-20°C isotherms, characterized by high salinities (34.9 - 35.2), and generally detected below 30 meters deep (Sweet *et al.* 2007). However, studies on the physical properties of the waters within the Galapagos Archipelago are few and focus mainly upon remote sensing data, such as ocean color or surface wind speed, which offer coarse scale resolution (Reilly *et al.* 2002, Palacios 2004, Ballance *et al.* 2006, Redfern *et al.* 2008). Moreover, ocean color is a proxy for the first trophic level of marine food webs, primary production. Fine scale resolution investigations of the Galapagos are important in determining the large amount of variability that occurs within the Galapagos on seasonal, annual, and inter-annual time scales.

Survey Methods

Marine mammal surveys were completed in the southern part of the Galapagos Islands during two weeks in June 2010. From June 4-6, observers recorded marine mammal, sea turtle, and bird-fish assemblages between Puerto Ayora, Isla Santa Cruz, Isla Floreana, and Puerto Villamil, Isla Isabela. Observers stood on the captain's pit on the top of a 50ft fishing vessel called *Lancha Cucaracha*. At each tuna-bird-dolphin assemblage, bird-tuna group, and dolphin group sighting a CTD was taken shortly after the sighting in the vicinity of the sighting location. In addition, “non-sighting” CTD data were collected as a control. CTDs were taken using a Sun and Sea Technology CTD M48 Memory Probe. It was hand-deployed to depths between 12-35 meters. Depths were estimated at time of collection based upon the amount of line released, however strong currents often pulled the lightweight CTD horizontal rather than vertical, often resulting shallower drops than anticipated. Temperature, conductivity, and pressure were recorded four times a second and data were downloaded to Sun and Sea Technology's Standard Data Acquisition software (SST-SDA) to determine drop depth each evening and the amount of line released was modified to obtain drops of at least 20 meters of depth. A total of 6 drops were made during the 3-day survey. An INOCAR officer recorded the survey track on-board using the GPS/laptop system HYPACK 2.0

and ArcGIS software 9.2.

The marine mammal survey continued June 8-14 on-board the 65ft fishing vessel *Niño Ronny Jesus*. Observations were made for two days around Isla Española, and four days around Isla San Cristobal. CTD casts were made when bird-tuna groups or cetacean groups were sighted, along with non-sighting control stations. A total of 17 CTD casts were made in the six days of survey to depths between 23-66 m. An INOCAR officer recorded the survey track again using the GPS/laptop system as noted above.

In addition, data from oceanographic surveys by the *B.A.E. Orion*, a 70 m oceanographic research vessel, in September 2008, April 2009, October 2009, and September 2010 were used. Hydrographic data were collected on board a cruise from the port of Guayaquil, Ecuador to Puerto Ayora, Galapagos Islands. CTD casts were made at various locations during each of the surveys. CTD cast locations used in this analysis are shown in Figure 4. The CTD was cast to 500 meters of depth using a Seabird Technology CTD. Data were then averaged in either one meter bins for the first 100 m and 5 m bins for the rest of the cast or 5 m bins for the entire cast. CTD data from June 2010 were averaged into one meter bins for analysis.

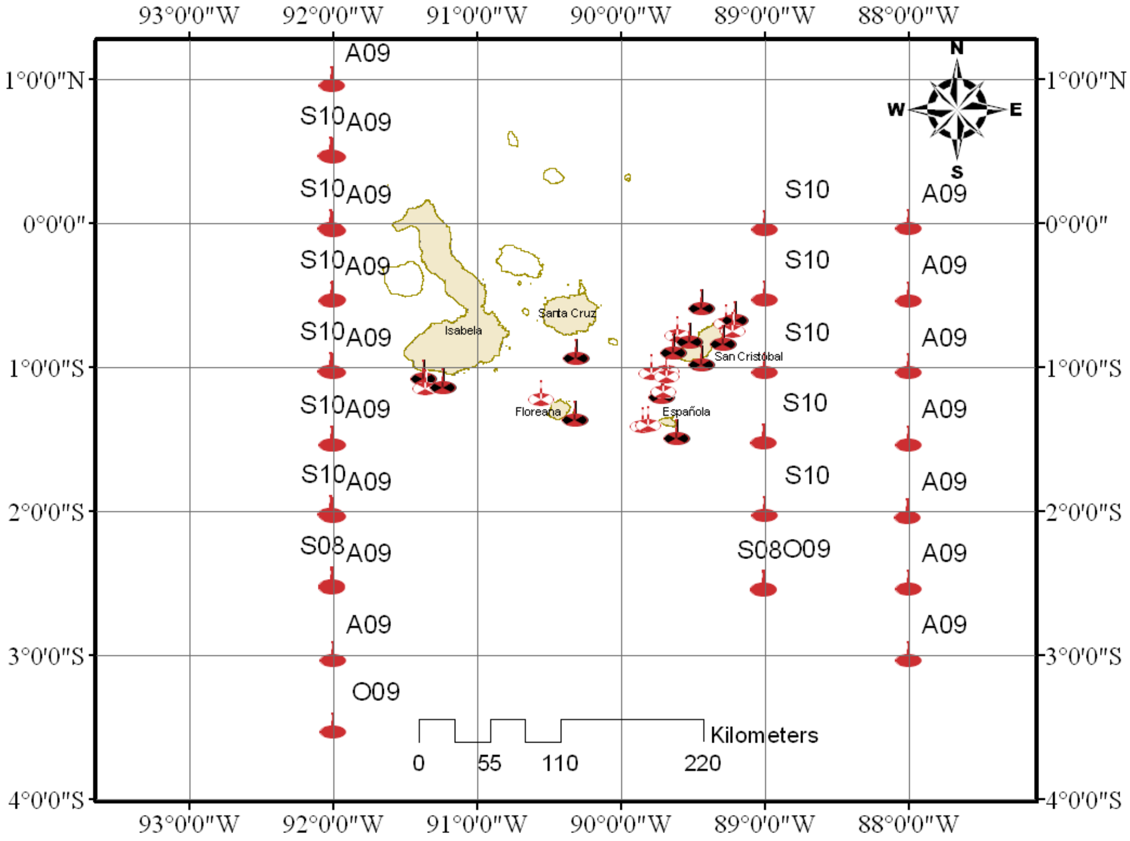


Figure 4. Map of CTD locations for each survey. Oceanographic CTD stations labeled by survey. CTD stations from J10 are red/white when associated with a sighting and red/black when not associated with a sighting.

Data Analysis

Physical oceanographic data were analyzed to determine thermocline depth and strength (represented by the degree of stratification of the water column), upwelling areas, and water mass characterization and mixing. Temperature-salinity plots were created using MAT-LAB software, most statistical analysis was performed using Excel

2007 ©. For simplicity, surveys are labeled by the first letter of the month in which they occurred, and the last two digits of the years (Table 1). ENSO cycle conditions were determined based upon NOAA ENSO indices for Regions 1&2 (Figs. 5 & 6), which have been show to correlate with SST around the Galapagos Islands (Conroy *et al.* 2009). Conditions for each survey are also listed in Table 1.

Table 1. Abbreviations for survey names and ENSO conditions during each of the surveys in this study.

Survey	**Label**	**ENSO Conditions**
September 2008	S08	Weak El Niño
April 2009	A09	Weak El Niño/Neutral
October 2009	O09	Moderate La Niña
June 2010	J10	Transition/Weak La Niña
September 2010	S10	Strong La Niña

Water masses were determined using modified definitions by Sweet, *et al.* (2007), as described above. TSW and ESW were temperature independent, however EUC only included water warmer than 14°C. Any water colder than 14°C was referred to as “deepwater” (DW). Upwelling areas were defined as areas where Equatorial Undercurrent Water was present at the sea surface.

Thermocline depths were determined by estimating the depth of the 20°C isotherm (Donguy & Meyers 1987, Kessler 1990, Kessler *et al.* 1995, Fiedler 2010). This method has been compared to Wyrtki’s (1964) method of determining the thermocline boundaries based on a temperature change of greater than 0.3°C/10 m with the thermocline depth defined as the depth with greatest temperature change and has resulted in approximately similar depths (two tailed t-test assuming unequal variances, t = 1.28, p = 0.20). Therefore for this study, the depth of the 20°C isotherm is the depth of the thermocline. The stratification of the water column was represented by the greatest change in temperature in °C per meter of depth (*dt/dz*). Drops with *dt/dz* less than 0.04°C/meter were given a stratification value of 0 (Palacios *et al.* 2004, Fiedler 2010).

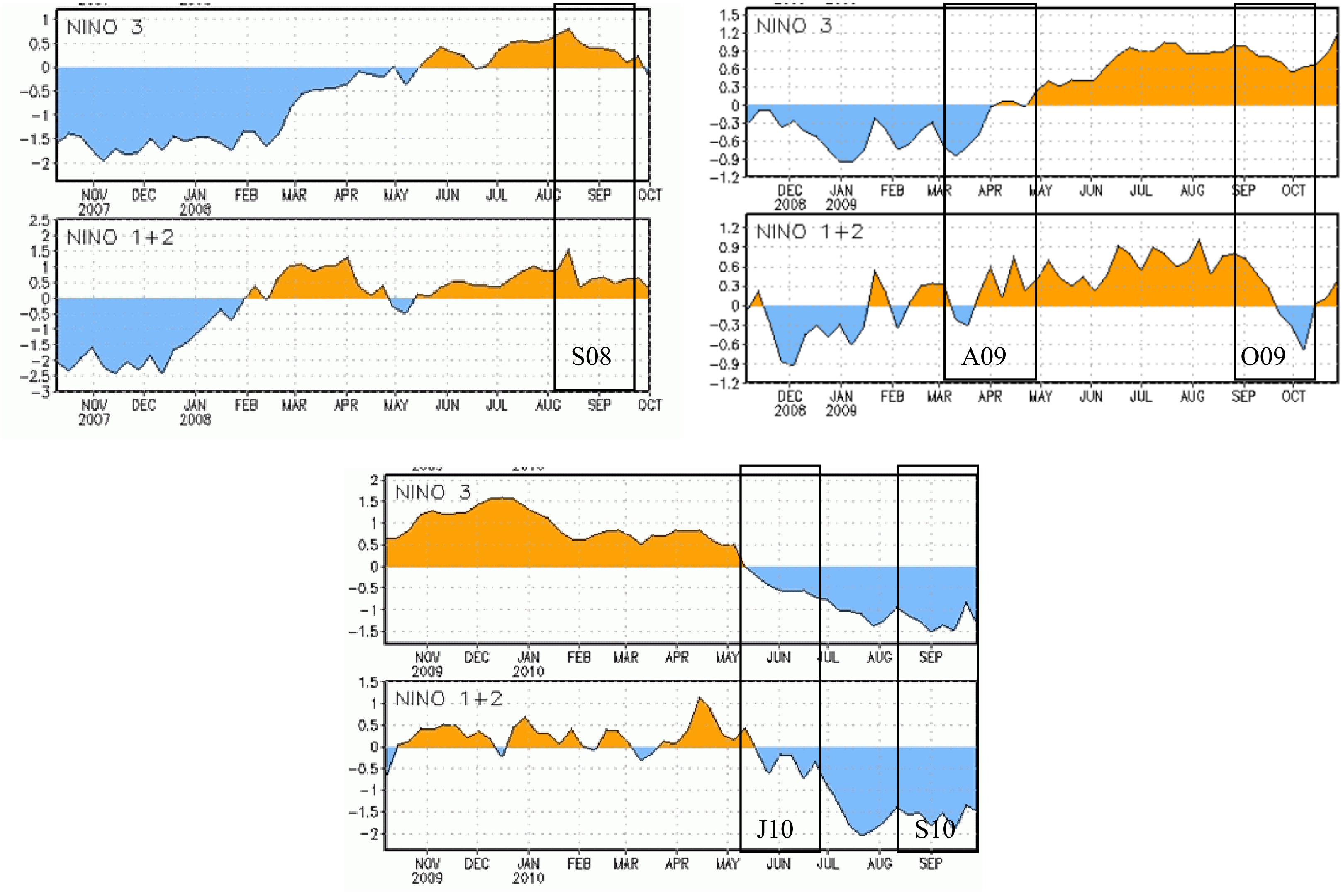


Figure 5. Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño regions: Niño-1+2 (0°-10°S, 90°W-80°W), Niño 3 (5°N-5°S, 150°W-90°W) for each survey. SST anomalies are departures from the 1971-2000 base period weekly means (CPC/NWS 2011).

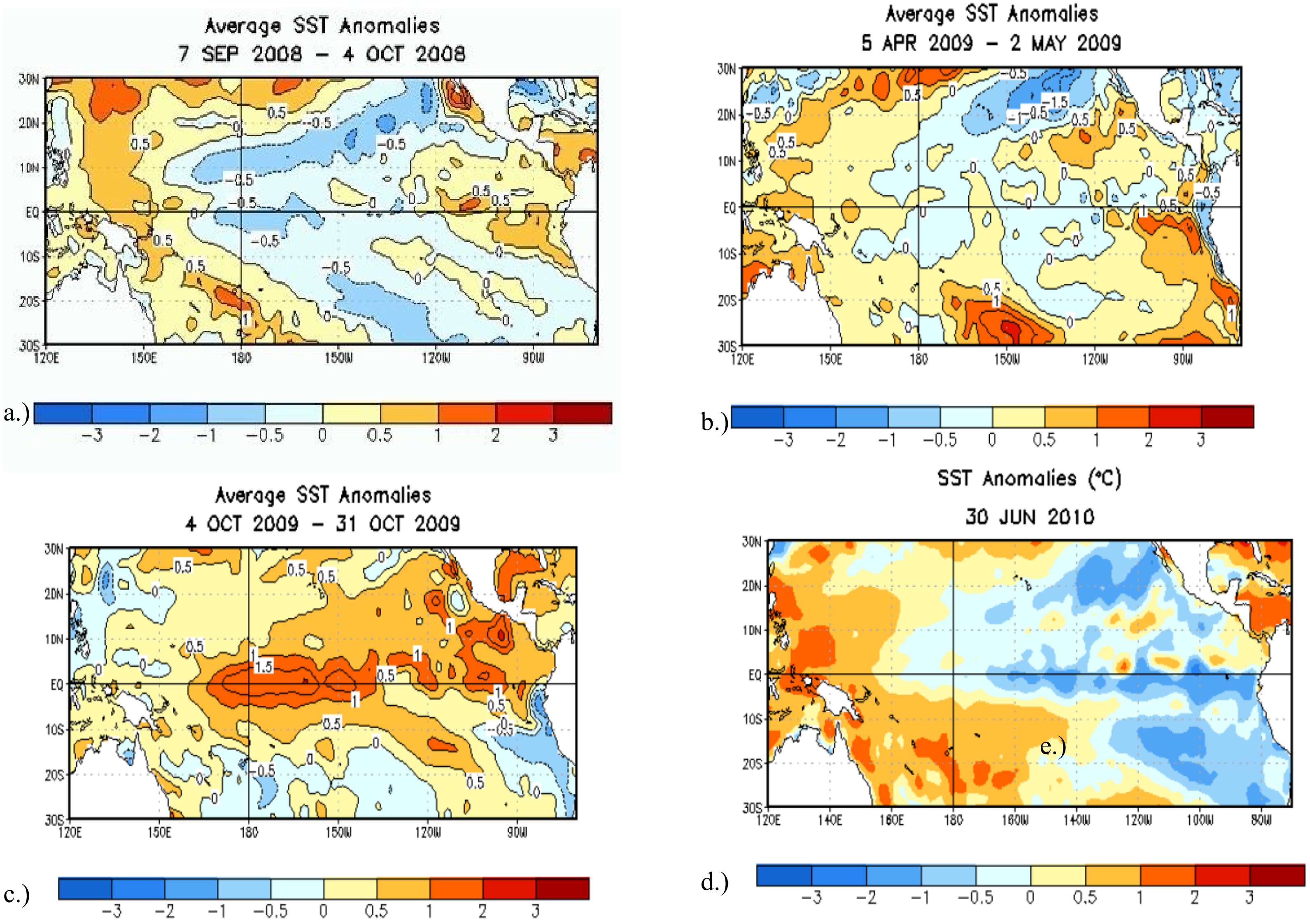
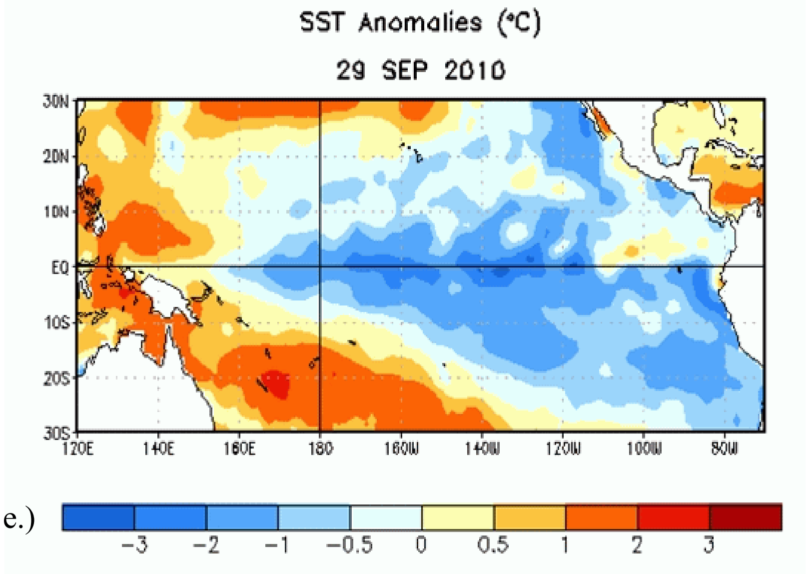


Figure 6. SST anomalies (in °C) in the Equatorial Pacific during each survey: a.) S08; b.) A09; c.) O09; d.) J10; e.) S10 (CPC/NWS 2011).



e.)

Figure 6 Continued.

Results

All three major water masses in the Eastern Equatorial Pacific are found within the Galapagos Archipelago throughout the survey based upon the sea surface salinities (SSS). The temperature-salinity plot shows the distribution, and any mixing along isopycnals, of the water masses within all the CTD from the surveys (Fig. 7). SSS ranged between 33.1 and 35.6 with an average salinity of 34.7 (sd = 0.4) over all the surveys (Fig. 8).

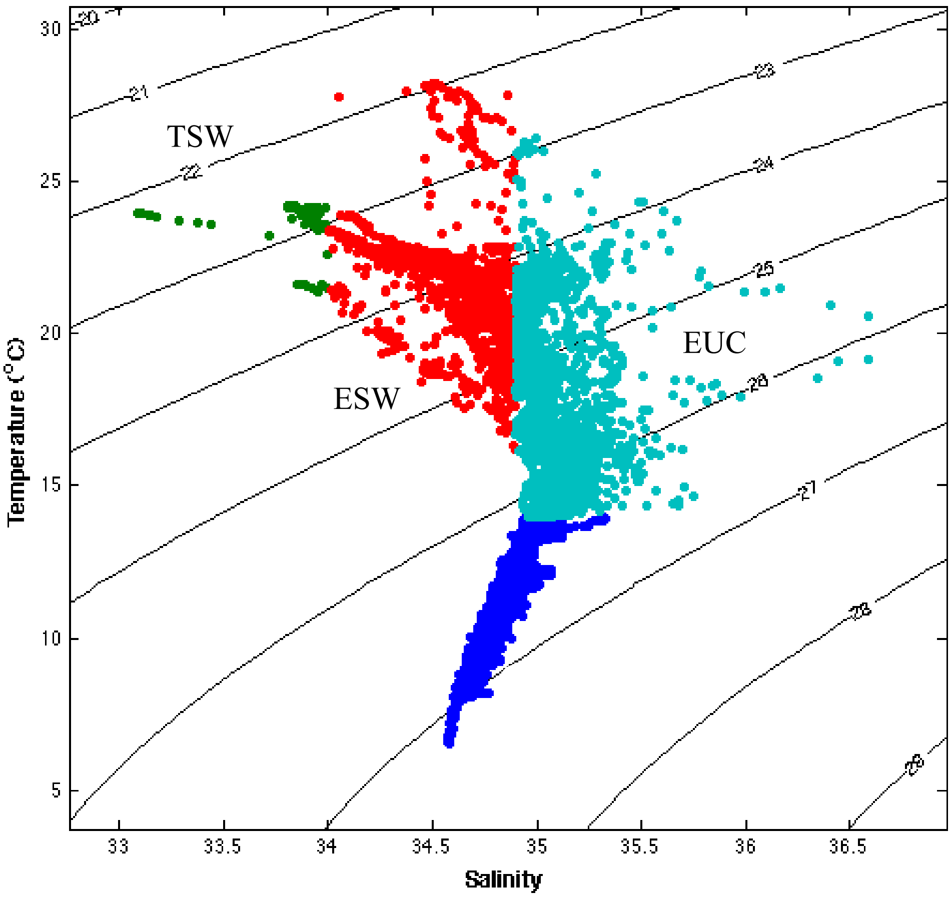
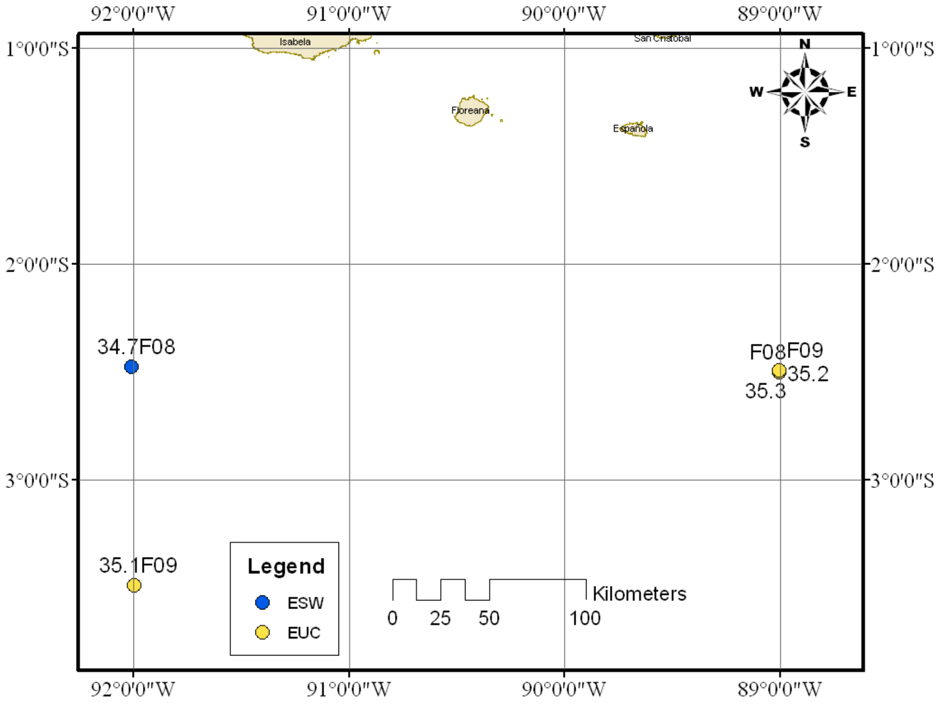


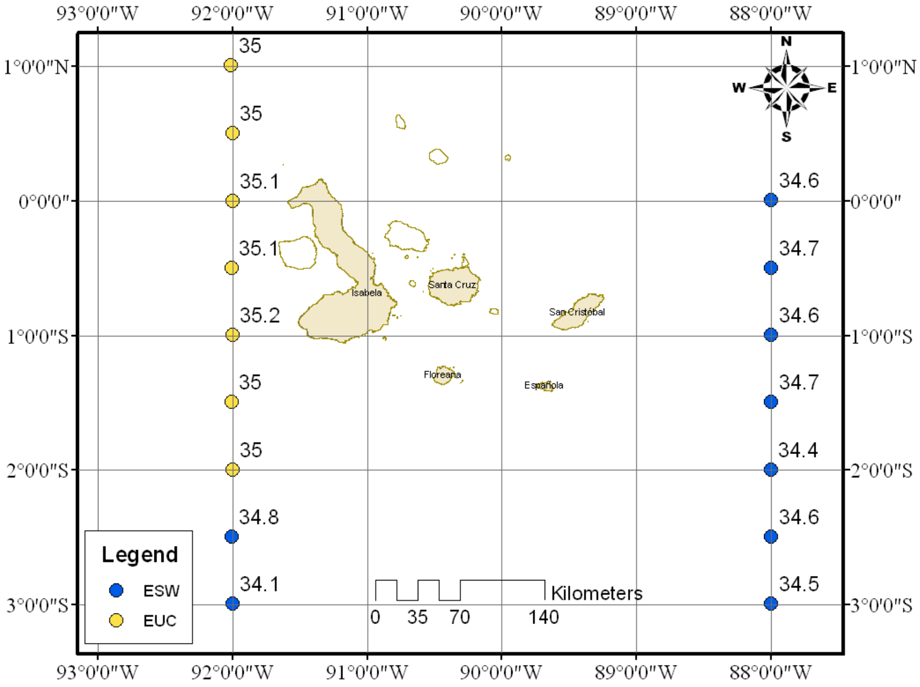
Figure 7. T-S plot of oceanographic CTD data and CTD data from the small boat survey in June 2010. TSW is green, ESW is red, EUC is light blue, and DW is dark blue.

In general, salinities were lowest in the western part of the archipelago around Isla Isabela where the EUC upwells; on average, two-thirds of the current travels south around the island with the other one-third traveling north around the island (Steger *et al.* 1998). The EUC was detected north of 2°S along 92°W in A09 with the highest salinity surface water, with all other data being lower salinity ESW (34.9; Fig. 8b). Occasionally high salinity EUC remained far south (S08, O09, and S10) and was detected at the southernmost stations along both 92°W and 89°W (Fig. 8a, d). In the J10 survey, unlike all other surveys, highest salinities (EUC) were found around the northern part of Isla San Cristobal in the eastern part of the archipelago and near the shore of Isla Santa Cruz.

Lowest salinities (TSW) were found in the central part of the archipelago, between Isla Santa Cruz and Isla Floreana. Furthermore, EUC was not present in the surface waters south of Isla Isabela, where salinities were around 34-34.5 (Fig. 8c). The majority of the survey area was ESW during the S10 survey, with EUC only detected around three stations, 92°W 2°S, 92°W 1°S, and 89°W 1°S (Fig. 8d). In addition, TSW was detected in the farthest northeast station, 89°W 0°, with the salinity greater than one lower than the next station at 89°W 0.5°S (33.1 and 34.3, respectively). EUC was detected at the furthest south station along 89°W in the same survey, resulting in a change in salinity of almost 2 in only 120 nautical miles.

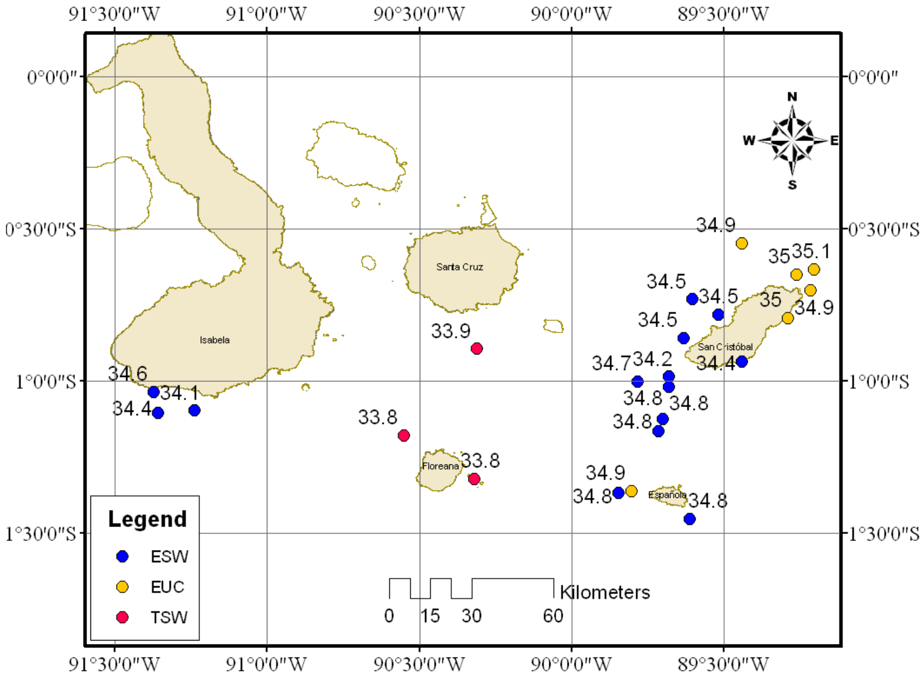


a.)



b.)

Figure 8. Water mass types with salinity values for each of the five surveys: a.) S08 and O09, b.) A09, c.) J10, d.) S10. Dot color signifies water type: blue = ESW, yellow = EUC, red = TSW; Labels denote SSS.



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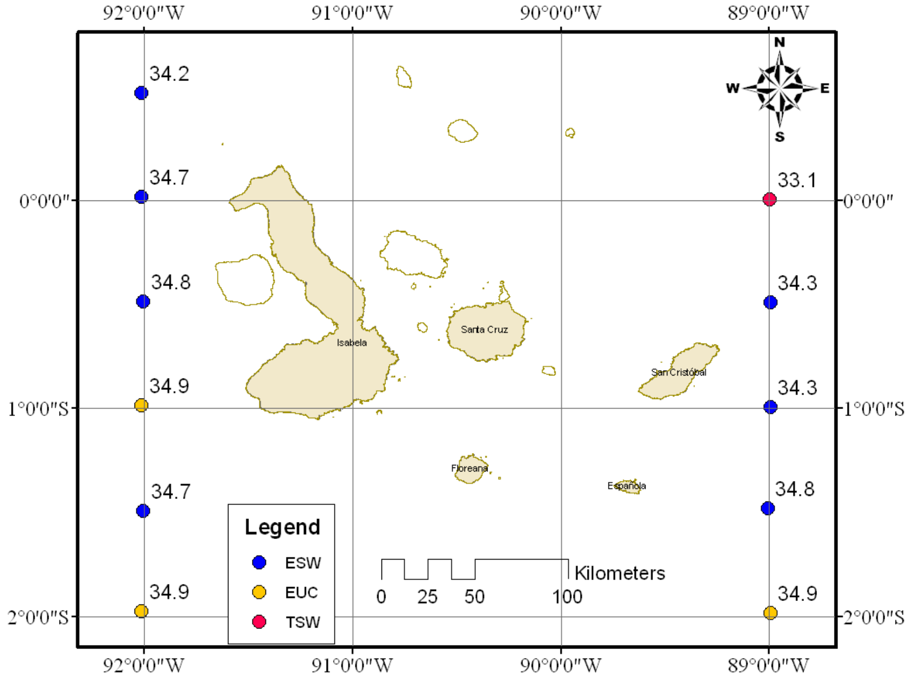

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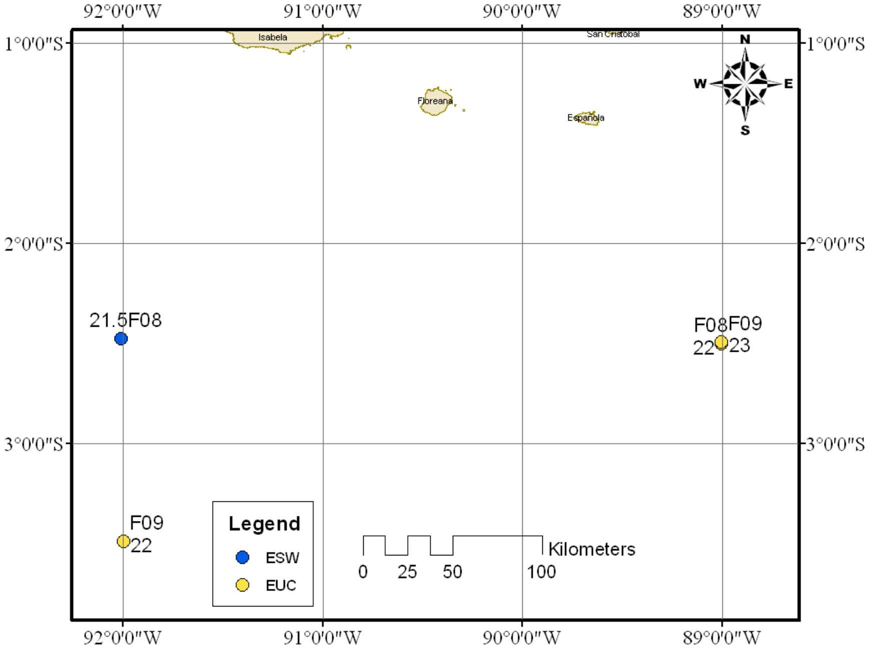
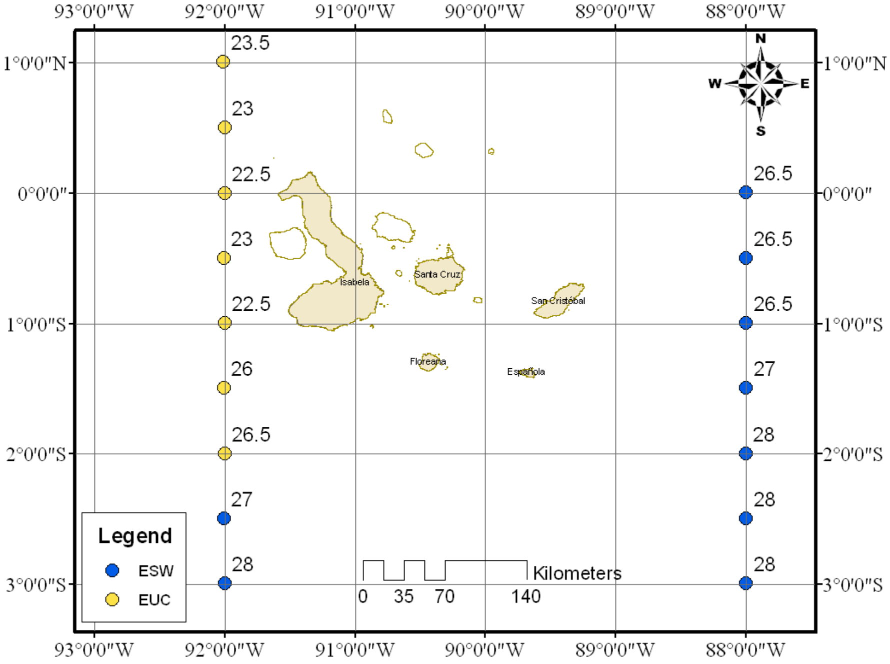
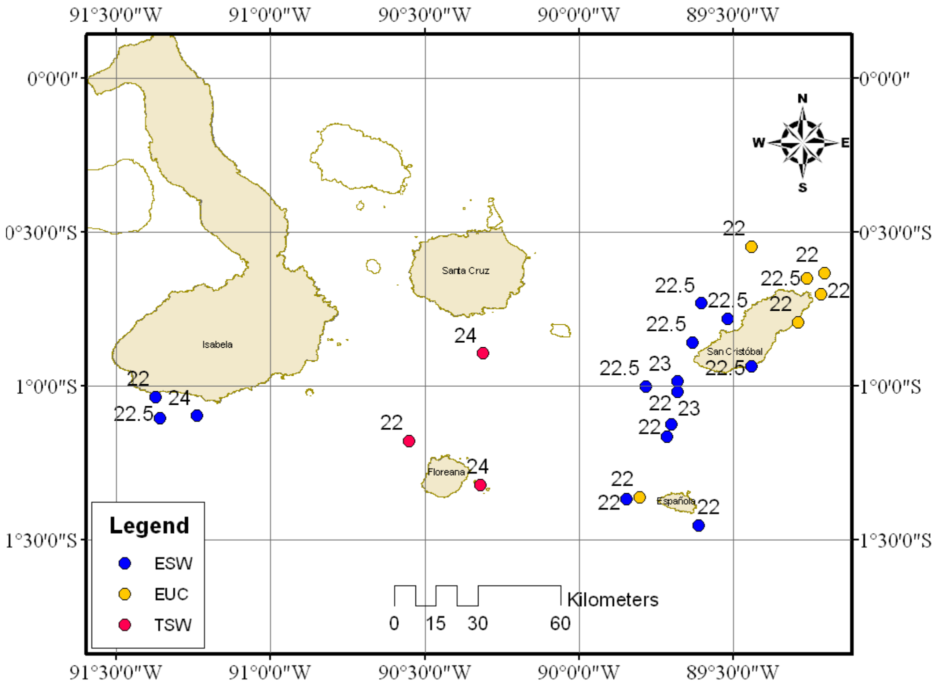


a.)



b.)

Figure 9. Map of water types and SST determined for each of the 5 surveys: a.) S08 and O09, b.) A09, c.) J10, d.) S10. Colored dots signify water types, blue = ESW, Yellow = EUC, Red = TSW, Labels denote SST.



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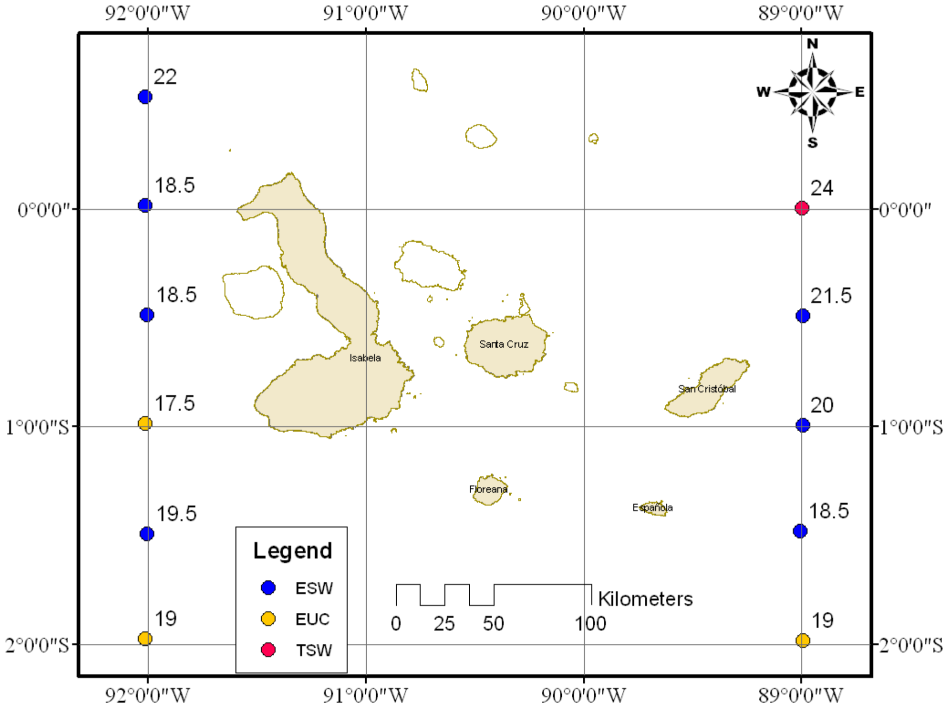


d.)

Figure 9. Continued.

SST varied between 17°C and 28°C with an average temperature of 22.9°C (sd = 2.6) throughout the surveys (Fig. 9). In general, temperatures were warmest in the eastern part of the archipelago and coldest west of Isla Isabela. In A09, temperatures were coldest around Isla Isabela, but warmed south of 2°S (Fig. 9b). The colder waters corresponded to lower salinities shown by the EUC upwelling in that region. East of the archipelago, SST were the warmest recorded in this study; however they were still primarily higher salinity ESW. SST were warmest in the center of the archipelago in J10, with cooler temperatures in the east around Isla Española and Isla San Cristobal, in the west around Isla Isabela, and along the coast of Isla Santa Cruz (Fig. 9c). These warmer waters corresponded with the lower salinity TSW, whereas the cooler temperatures were primarily ESW and EUC. The coldest SST recorded were in the S10 survey (Fig. 9d). Both the east and west areas of the archipelago had cooler waters than even those found four months earlier in the J10 survey. Warm water was only found in the far northeastern part of the survey where SST was warm (24°C) and was classified as TSW.

The depth of the thermocline was on average 33 m deep (sd = 15 m) with a maximum measured depth of 50 m. Three of the sites within the archipelago in the J10 survey have a thermocline deeper than the depth of the CTD cast: site 2-2 >13 m, site 3-3 >16 m, and site 8-1 >44 m (Table 2). In addition, at site 4-4, the cast was in a shallow area (25 m depth) and reached the bottom. The entire drop was well mixed and did not have a thermocline and is labeled N/A. Thermoclines near Isla Isabela were generally shallowest with the deepest thermocline depths around Isla San Cristobal. Thermocline depths from the oceanographic surveys show deeper thermoclines in A09 and very shallow in S10. Many of the sites in S10 had water colder than 20°C at the surface, and are noted as NP in Table 2. The stratification of the water was strongest around the northern tip of Isla San Cristobal and weakest around Isla Española. *Dz/dt* labeled with ND were casts where the thermocline was deeper than the depth of the cast or the thermocline was at the bottom of the cast and there were not sufficient data to accurately determine the full area of the thermocline. Drops where the depth of the thermocline was deeper than the maximum depth of the drop were labeled N/A, indicating insufficient data available. In the oceanographic surveys, the stratification of the water was generally weakest along 92°W and strongest along 89°W. An exception is between 0.5°N and 0.5°S along 92°W in the S10 survey, which had strongly stratified waters, while no thermocline was recorded for the remainder of the sites along that longitude and the waters were weakly stratified. Thermocline depth and thermocline strength were poorly correlated ($R^2 = 0.017$).

Table 2. Thermocline depth and stratification of the water column for each CTD cast.

Station	Depth of 20°C Isotherm (m)	*dz/dt*
June 2010 Isla Isabela		
2-1	9	0.32
2-2	+13	N/A
2-3	14	0.56
Isla Floreana/Isla Santa Cruz		
3-1	13	1.02
3-2	31	1.86
3-3	+16	N/A
Isla Espanola		
5-1	23	1.26
5-2	13	0.45
5-3	33	0.41
6-1	30	0.26
6-2	31	0.75
6-3	39	0.51
6-4	24	0.34
Isla San Cristobal		
4-1	30	0.78
4-2	N/A	0
7-1	15	0.69
7-2	40	0.28
7-3	19	0.65
7-4	20	1.52
8-1	+44	N/A
8-2	30	0.65
9-1	42	1.69
9-2	37	3.52
Oceanographic Cruises September 2008		
-89°W -2.5°S	40	0.27
-92°W -2.5°S	30	0.33
October 2009		
-89°W -3.5°S	49	0.73
-92°W -3.5°S	32	0.33
April 2009		
-88°W 0°	40	0.47
-88°W -0.5°S	50	0.31

Table 2 Continued.

Station	Depth of 20°C Isotherm (m)	*dz/dt*
April 2009		
-88°W -1°S	50	0.65
-88°W -1.5°S	45	0.46
-88°W -2°S	42	1.61
-88°W -2.5°S	35	0.86
-88°W -3°S	47	1.77
-92°W 1°N	50	0.19
-92°W 0.5°N	50	0.25
-92°W 0°	45	0.19
-92°W -0.5°S	50	0.23
-92°W -1°S	36	0.53
-92°W -1.5°S	40	0.35
-92°W -2°S	45	0.90
-92°W -2.5°S	45	0.48
-92°W -3°S	46	0.91
September 2010		
-89°W 0°	27	1.43
-89°W -0.5°S	21	1.25
-89°W -1°S	20	0.27
-89°W -1.5°S	ND	0.38
-89°W -2°S	ND	0.32
-92°W 0.5°N	14	2.34
-92°W 0°	ND	0.95
-92°W -0.5°S	ND	0.70
-92°W -1°S	ND	0.29
-92°W -1.5°S	ND	0.23
-92°W -2°S	ND	0.43

Discussion

This study presents results that are a snapshot of the water column properties in different seasons both within the Galapagos Archipelago and surrounding it. Three distinct types of water masses were detected within the archipelago: TSW, ESW, and

EUC. While the definitions of these water masses were based on salinities alone, the temperature of the water also tended to correspond with the types of water mass (Wyrtki 1966, Sweet *et al.* 2007). TSW is low salinity water from the Panama Current which flows south, turning slightly west near the Equator from Central America (Palacios 2004). The Panama Current reaches the Galapagos seasonally, from February to April, when the Equatorial Countercurrent (ECC) and Peru Current (PC) are relatively weak (Wyrtki 1966). TSW was found in the interior of the archipelago during the Garuá season (J10), however, it was also detected along the Equator in the S10 survey, when the ECC and SEC are strong.

This anomaly can be accounted for by the Equatorial Front (EF). The EF separates the tropical water (TSW) characterized by high temperatures and low salinity in the north from the cooler higher salinity water in the south, the ESW (see the appendix for regional maps showing the EF). This front is strong during May to November, and begins along the Peruvian coastline around 4°S, cuts across the Equator east of the Galapagos, and continues north of the Equator throughout the remainder of the Pacific Ocean (Wyrtki 1966). This front is also characterized by large horizontal temperature and salinity differences, like those we see along 89°S in S10. Steger *et al.* (1998) also found the EF along 89°W in November 1993. During a survey along 89°W and 92°W with normal sea surface conditions, Steger noted that SST was 3°C warmer and SSS was 1 greater at 1°N compared to 2°S. These values are similar to those in the A09 survey, with SST 5°C warmer and SSS 2 greater at the Equator compared to 2°S. These changes in values are indicative of the EF's presence slightly below the Equator east of the archipelago (Steger *et al.* 1998).

Both the sea surface temperature and salinities were somewhat anomalous in the J10 survey. Salinities were lower than expected and temperatures higher than expected around Isla Isabela, with opposite conditions around Isla San Cristobal. The high salinities around Isla San Cristobal indicate that there may be some kind of localized upwelling in the region. To support this, there were high chlorophyll concentrations to the northwest of Isla San Cristobal at the time of the survey (Fig. 10). Additionally, strong surface currents were observed around this area, indicating that a current may be upwelling due to topographic blockage from the island. This would bring nutrients to the surface, accounting for the high salinity, lower temperatures, and high chlorophyll concentrations in the area. However, the strong and deep thermoclines in the northern part of Isla San Cristobal surveyed suggest this upwelling maybe occurring downstream of the area with the horizontal transport of nutrients. It is well documented that primary productivity is enhanced around islands, an effect called the “island mass effect” (Hasegawa *et al.* 2004, Hasegawa *et al.* 2009). It has been shown in the Western Pacific Ocean that islands with deep waters around them often have high primary productivity around them due to a variety of processes. These include the formation of eddies that occur on the lee side of the island and cause localized upwelling that contributed deepwater nutrients to the surface waters around the island (Hasegawa *et al.* 2004, Hasegawa *et al.* 2009). This water can then be transported horizontally through the surface currents (Gargett 1991).

The upwelling in these eddies can be seen as areas of low sea surface heights compared to the rest of the area (Espinosa-Carreon *et al.* 2004). In Figure 10 an area of low sea surface height (SSH) is present between Isla Santa Cruz and Isla San Cristobal, suggesting the presence of a small eddy from the island mass effect of the SEC flowing around Isla San Cristobal from the east to the west. However, caution must be used when drawing conclusions from this figure; the composite is an optical interpolation of eight days of data with resolution on an x-y scale of only about 100 kilometers. Though an area of low SSH is indicated, the geometry of the low SSH region shown in Fig 10 is an interpolation. A monthly composite shows that there is a persistent area of high productivity in the lee of Isla San Cristobal, with respect to the SEC (Fig. 11).

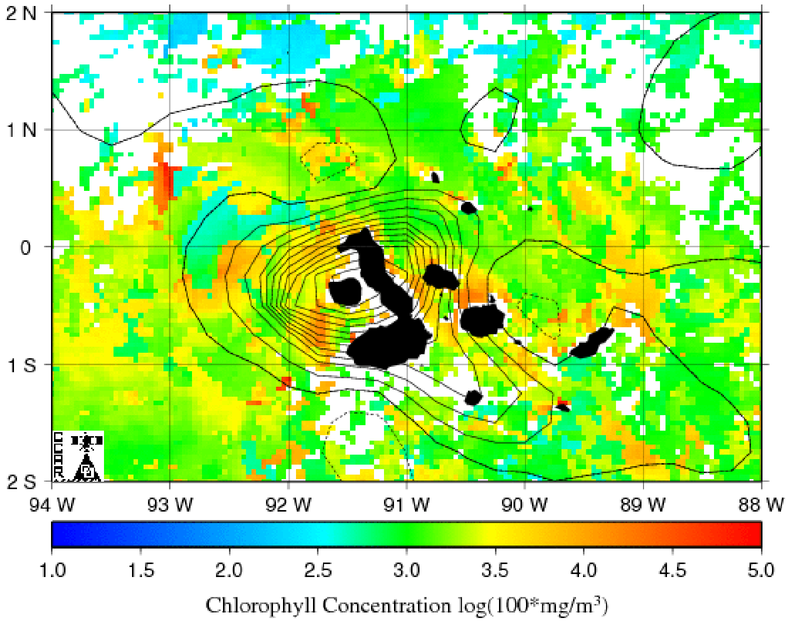


Figure 10. 8-day composite of chlorophyll concentrations around the Galapagos Islands, centered on June 5, 2010. Sea surface height contours (5cm) show positive anomalies with solid lines and negative anomalies with dashed lines.

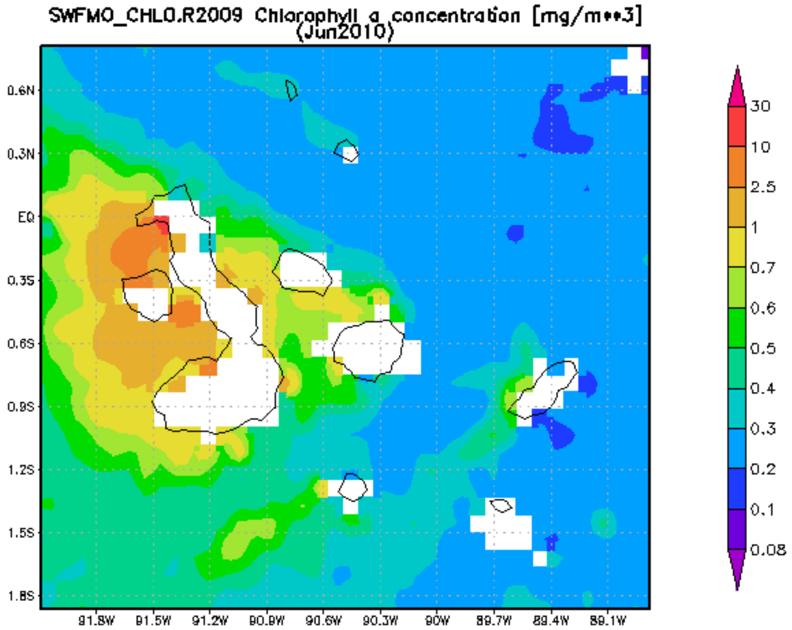


Figure 11. Monthly composite for June 2010 for chlorophyll concentrations around the Galapagos Islands.

Sweet *et al.* (2007) did a hydrographic survey around the Galapagos Islands in 2005-2006, with similar data collected (Morrison *et al.* 2009). One of the three surveys occurs in the same month as the survey in this study, a June 2006 survey. In the current study, thermocline depths were relatively shallow, less than 40 m, and shallowest in the west while deepening eastward. However, Sweet found deep thermoclines throughout the archipelago (>50 m) with the shallowest areas in the central archipelago rather than a west to east gradient. Interestingly, the T-S plots from each of the surveys are similar; both studies show there is very little TSW within the archipelago during this month and the area is covered primarily by ESW. The most probable reason for the deeper thermocline depths in J10 than in June 2006 is the ENSO cycle. June 2006 was characterized by SST anomalies between +0.2 to +0.3°C above normal as an El Niño began to develop, which caused a deepening of the thermocline and warmer SST with relatively constant SSS. June 2010 was a transition period between an El Niño and a La Niña with temperature anomalies -0.2 to -0.6°C below normal (Figs. 5 & 6). This period was between a moderate El Niño in October 2009-Spring 2010 to a moderately strong La Niña, through September 2010 (CPC/NWS 2011). This accounts for the differences in thermocline depths and the similar salinities between the two surveys.

Additionally, the ENSO cycle likely accounts for the large variation in SST between the A09 and S10 surveys. A09, with ENSO-neutral conditions, has SST up to 10°C greater than those in S10, with moderate La Niña conditions. SSS were also up to 1 greater in A09, than during the La Niña in S10. The sea surface conditions found in A09 along 92°W are similar to those found in November 1993 by Steger *et al.* (1998), a time of neutral sea surface conditions as well. Steger noted the EUC core around 0.5°S, indicated by the coolest SST (19.5°C) and highest SSS (34.9). The EUC at this time was turning predominately northeast, although high temperature and low salinity waters (25.2°C and 33.8, respectively) were measured north of the Equator. In this study, however, warmest temperatures were recorded south of the Equator, between 2°S and 3°S. SST were coolest between 1°S and the Equator which, along with high SSS, indicates near surface EUC upwelling. It is important to note that the patterns in our A09 survey and Steger's November 1993 survey do not completely overlap. This is probably due to the seasonal variations between the Garuá season (May – November) and the wet season (December-April). During the Garuá season, upwelling is enhanced, with cooler SST throughout the archipelago due to the Inter-tropical Convergence Zone (ITCZ) reaching its northern most position. The wet season has warmer SST coinciding with decreased upwelling and the ITCZ is near the Equator (Sweet *et al.* 2007). This likely accounts for the differences in SST and SSS between Steger's November 1993 survey and our A09 survey.

CHAPTER III

RELATIONSHIP OF TUNA-DOLPHIN-BIRD DISTRIBUTIONS TO THE VARIABILITY OF WATER CONDITIONS IN THE ETP

Introduction

Tuna-dolphin-bird groups are unique the Eastern Tropical Pacific (ETP), an area that includes everything from the western coast of the Americas to approximately 140°W and between 20°N and 20°S (Edwards 1992). These associations are apparently a result of the unique oceanographic features seen in this area (Au & Perryman 1985, Au 1991, Ballance *et al.* 2006). Only in areas where the preferred habitats of yellowfin tuna and their associated dolphins (common, striped, spotted or spinner) overlap in the ETP, however, might one expect to find these mixed species groups of marine predators. Therefore it is important to not only describe and analyze the oceanographic conditions that are present in the Galapagos Islands, as in chapter two of this thesis, but also determine how the distribution of tuna, dolphins, and seabirds are affected by those oceanographic conditions.

Seasonal Variations in the Eastern Tropical Pacific

Since tuna tend to be more widespread than dolphins (Collette & Nauen 1983), determining the dolphin habitat preferences allows us to locate tuna-dolphin assemblages more easily. Smaller cetaceans do not typically undertake extensive pole to pole migrations like the larger baleen species (Reilly 1990). Also, while dolphins can change their distributions based on seasonal changes of water masses, there is little seasonal change in the ETP, leading to little change in dolphin habitat (Reilly 1990). In general, upwelling will supply nutrients to the upper water column, which occurs along the equator, the countercurrent thermocline ridge, west of the Galapagos Islands, and along the coast of South America. In the ETP, the thermocline is usually shallower in the east and deepens westward. Also, the Equatorial Front (EF) is unstable and distorted west of the Galapagos Islands due to high shear between the currents, but the EF is generally better defined east of the Galapagos. The EF begins at the coast of Peru at about 4°S, rising towards the equator as it reaches the Galapagos (Ballance *et al.* 2006).

The ETP in general is not often affected by strong seasonal changes, although the area immediately around the Galapagos can experience strong seasonal variation (Sweet *et al.* 2007). In addition, on the interannual scale, the El Niño-Southern Oscillation (ENSO) cycle causes inter-annual and decadal changes in the water masses (Ballance *et al.* 2006, Redfern *et al.* 2008). Since upwelling west of the Galapagos tends to be a seasonal occurrence, seabirds and cetaceans will follow their preferred habitat conditions as those conditions move spatially during the seasonal and interannual changes (Ballance *et al.* 2006). Also, some coastal species of dolphins move in response to seasonal movements of their prey, following their food source as it changes its distribution (Reilly 1990).

However, various features of the ETP can fluctuate in strength or prevalence and are not all synchronized. The southeast trade winds, the Peru Current, and the Southern Equatorial Current all change seasonally with weak periods during the winter and strengthening during the summer (Fielder 2002). From July to December there is greater equatorial upwelling and more horizontal transport in the Peru Current (Reilly 1990). The Equatorial Cold Tongue is strongly developed from August through October; however, it is weak from February to April (Ballance *et al.* 2006).

ENSO Cycle

The ENSO cycle is mainly responsible for the moderately strong inter-annual variations in the ETP. This cycle causes marked changes in the “typical” oceanographic conditions of the area. These changes are believed to affect prey densities, which in turn would affect the density and distribution of their predators (Ballance *et al.* 2006, Redfern *et al.* 2008). However, the relationship between the ENSO cycle's effect of oceanographic conditions and the prey-predator interactions are not well understood (Redfern *et al.* 2008). As mentioned previously, the warm cycle of ENSO, or El Niño, results in significantly warmer sea surface temperatures (SST) and reduced upwelling, causing the decrease in food availability due to resource limitation. The cold cycle, or La Niña, increases the productivity of the oceans with enhanced upwelling, cold SST and abundant food resources (Cane 1983, Fielder 2002).

Cetacean Habitat

Cetacean habitat is often defined by oceanographic variables; however, their movements may not be directly related to these characteristics (Redfern *et al.* 2008). Most studies use variables such as SST, SSS, and thermocline depth to determine areas where cetaceans are more likely to be observed, or as a proxy for predicting where their prey may be located. These physical variables are believed to influence prey availability and density, thereby controlling where the cetaceans might aggregate (Redfern *et al.* 2008).

Since tuna are mainly associated with spotted, stripped, spinner, and common dolphins, their preferred habitats are most important to finding tuna-dolphin aggregations. Each species of dolphin seems to prefer general characteristics of habitat that sometimes overlap between the species. The difference between habitat preferences in each of these species of dolphins is probably not directly related to the physical variables themselves, but rather the prey that reside in each of these areas (Ballance *et al.* 2006).

Common dolphins, along with pilot whales, bottlenose dolphins, Risso's dolphins, and Bryde's whales prefer areas of upwelling. Food chains tend to be shorter in upwelling modified waters, which usually results in common dolphins feeding low on the food chain. Common dolphins tend to occupy the coldest, most saline waters of the ETP: areas east and west of the Galapagos where they appear with striped dolphins (Au & Perryman 1985, Wade & Gerrodette 1993, Reilly *et al.* 2002, Ballance *et al.* 2006).

Striped dolphins tend to be more widespread and usually aggregate in smaller schools than common dolphins. They often inhabit the eastern boundary current's coastal upwelling regions where they may occur as part of a mixed species group with common dolphins (Ballance *et al.* 2006). In addition, stripped dolphins are typically distributed where the other types of dolphins are not found (Wade & Gerrodette 1993, Reilly *et al.* 2002) including areas where the water is shallow (<300 m), and where the thermocline is strong and shallow (Redfern *et al.* 2008). Where common dolphins and stripped dolphins occur as mixed groups, the ocean is usually characterized by highly variable oceanographic features that are upwelling modified (Au & Perryman 1985). This upwelling modified area has weak thermoclines, cool surface temperatures (<25ºC), high salinities (>34.5), and high chlorophyll concentrations (Ballance *et al.* 2006, Redfern *et al.* 2008). These mixed groups are frequently found along the equatorial waters out to 100ºW, with higher abundances west of the Galapagos (Au & Perryman 1985, Reilly 1990).

Spotted dolphins are also found occasionally in the cooler, upwelling modified waters, but generally they prefer areas with deep thermoclines (>70 m) (Reilly 1990). Spotted dolphins often join schools of spinner dolphins, forming multispecies pods of dolphins that can number in the thousands. These groups are most abundant in areas of warm tropical waters with low salinities (<34), deep, sharp thermoclines (>2ºC/10 m), strong water column stratification, very warm, stable surface water (>25ºC), and low surface chlorophyll concentrations (Wade & Gerrodette 1993, Reilly 1990, Reilly *et al.* 2002, Ballance *et al.* 2006, Redfern *et al.* 2008). While common dolphin habitat is centered on the equator, spotted/spinner groups are rarely observed near the equator (Au & Perryman 1985). Instead, these groups live north and south of the equator, along the warm edge of the Peru Current, and near the Costa Rica Dome (Au & Perryman 1985, Reilly 1990, Ballance *et al.* 2006). They have low abundances between the South American Coast and the Galapagos Islands (Reilly 1990).

Yellowfin Tuna Habitat

Also important in analyzing tuna-dolphin-bird distributions are the habitat requirements of the yellowfin tuna. These tuna prefer areas with gradual thermocline gradients that are shallow rather than a sharp, deep thermocline (Green 1967). Shallow thermoclines along with areas of high chlorophyll concentrations can result in the aggregation of a high abundance of potential prey, compared to areas with a deep thermocline and low chlorophyll concentration (Ballance *et al.* 1997). These are areas where the tuna prefer to feed, presumably because there is more food available.

Furthermore, the shallow thermocline may act as a vertical barrier and keep the squid and fishes the dolphin and tuna prey upon from a quick escape to deeper water. These areas allow successful foraging for both tuna and dolphins alike, and by keeping the prey close to the surface, birds can join in the feeding frenzy (Reilly 1990). The O_2 minimum zone is often close to the shallow thermocline and will also keep prey from escaping to deeper water (Green 1967).

Most tuna tend to occupy the warmest water available; yellowfin tuna have acclimated to the cooler surface temperature waters in the ETP compared to other tropical waters. Tuna have the ability to maintain their body temperature higher than the ambient water temperature; yellowfin tuna are often 1.4-4°C warmer than the surrounding water (Block *et al.* 1997). Their depth distribution is determined by the relative change in water temperature rather than a specific temperature (Brill *et al.* 1999, Brill & Lutcavage 2001) and the depth of the oxygen minimum zone (Gooding *et al.* 1981). Yellowfin tuna are not found at depths where the temperature is more than 8°C cooler than the surface waters for long periods of time, although they may dive deeper occasionally. In areas where there is a very shallow thermocline, this constrains tuna to the upper 20-30 meters of the water column where they are more likely to associate with dolphins (Brill *et al.* 1999, Brill & Lutcavage 2001).

Bird Assemblage Distribution

The distribution of bird assemblages in the ETP is generally believed to be influenced primarily by the environmental characteristics of the area, including water mass types and current systems (Ribic & Ainley 1997). Additionally, these bird groups can be found associated with these same characteristics regardless of the ENSO stage, with ENSO events having very little impact on the distribution of these birds (Ribic & Ainley 1997). Generally, storm petrels are associated with the ESW, following the SEC, and shearwaters are associated with the warmer, low salinity TSW with deep thermoclines. It has been suggested that the depth of the thermocline is an indicator for the amount of productivity in an area. If this is the case, then areas of high productivity may be a predictor for bird assemblage presence (Ribic & Ainley 1997). Bird assemblages are found associated with tuna-dolphin groups primarily in the TSW, north of 5°N, with the majority of the tuna-dolphin-bird groups between the Equator and 5°S comprised of shearwaters and boobies (Au & Pitman 1988). Whenever TSW are within the Galapagos, generally December through February, these bird assemblages can be found associated with tuna-dolphin groups (Au & Pitman 1988).

Tuna-dolphin-bird Groups: Working Hypotheses

1.) In the Galapagos Marine Reserve, tuna-dolphin-bird groups would be found where their respective habitats overlap, including around the western side of the archipelago where there are upwelling modified waters with shallow, gradual thermoclines and abundant food resources.
2.) These groups would also tend to form in the middle of the archipelago where the cooler subsurface water is close to the sea surface and a shallow thermocline with warm surface waters is predominant.
3.) There would be a greater occurrence of these groups during normal conditions, rather than during El Niño with deep thermoclines or La Niña with cold SST.
4.) The tuna in the GMR would associate with common and/or striped dolphins which are most likely to be found around the Galapagos Islands.

Survey Methods

Marine Mammal Surveys

Marine mammal surveys were completed in the southern part of the Galapagos Islands during two weeks in June 2010. From June 4-6, observers recorded marine mammal, sea turtle, and bird-fish assemblages between Puerto Ayora, Isla Santa Cruz, south and west to Puerto Villamil, Isla Isabela (Fig. 12). Observers stood on the captain's pit on the top of a 50ft fishing vessel called *Lancha Cucaracha*. For each sighting the position, time, species, and an estimate of abundance was recorded if the group was close enough for observation. Photos were taken of each sighting to verify species identities. Every half-hour the position, weather conditions, and sea state were recorded. The sea state was a Beaufort 4 on average, making observation with 7x50 hand-held binoculars difficult; therefore most observations were carried out with the naked eye.

The marine mammal survey continued June 8-14 on-board the 65ft fishing vessel *Niño Ronny Jesus*. Observations were made for two days around Isla Española, and four days around Isla San Cristobal. Two observers stood 30 minute watches, rotating with two other observers resting. Observers used 7x50 hand-held binoculars while sitting in the captain's pit. The recording observer recorded marine mammal, bird, and sea turtle sighting data as described above, along with environmental conditions every 30 minutes.

In addition, data from oceanographic surveys by the *B.A.E. Orion*, a 70 m oceanographic research vessel, in September 2008 (S08), April 2009 (A09), October 2009 (O09), and September 2010 (S10) were used. Marine mammal surveys were conducted during daylight hours from the port of Guayaquil, Ecuador to Puerto Ayora, Galapagos Islands (Fig. 12). Two to three observers were on watch for 30 minute rotations, with the port observer watching from 0° at the bow to 90° to the port and the starboard observer watching from 0° at the bow to 90° to the starboard. Surveys were conducted using 7x50 binoculars and recording position, speed, ocean conditions, and meteorological conditions every 30 minutes. The third observer, when available, served as the note taker and watched for sea lions, sharks, and sea turtles in the waters directly around the boat.

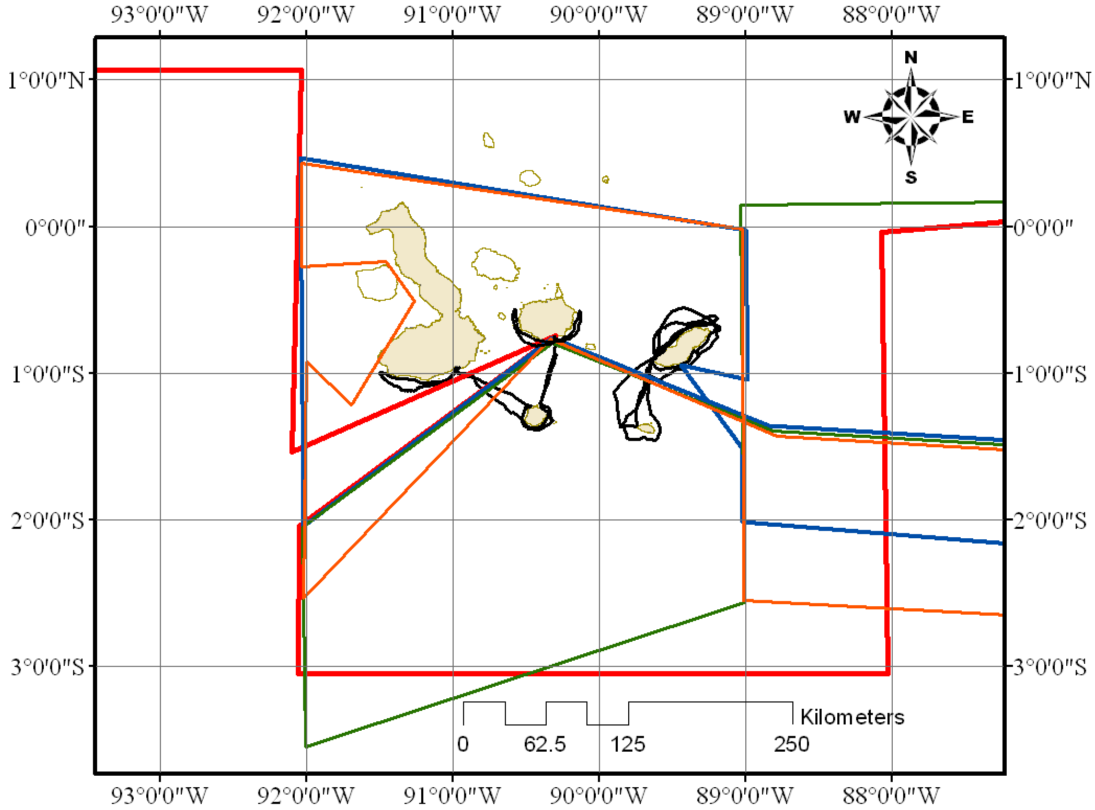


Figure 12. Approximate routes taken during oceanographic and small boat marine mammal surveys. Line colors denote survey tracks as follows: Orange denotes S08; Green denotes O09; Red denotes A09; Black denotes J10; Blue denotes S10.

Data Analysis

Maps of cetacean, bird, and tuna group sightings were plotted in ArcGIS software 9.2. Data were plotted for each cruise individually with identifying labels for tuna-dolphin-bird groups, birds, single species cetacean groups, and multiple species cetacean/cetacean or cetacean/pinniped groups. The range of yellowfin tuna was determined by finding the depth at which there was a greater than 8°C difference in temperature from the sea surface temperature (Brill *et al.* 1999). Statistical significance of the data was determined using a two sample t-test assuming unequal variances.

Results

Sightings of groups within the GMR area were limited in the S08 survey, with only five sightings recorded: one bird group near Isla Isabela, three dolphin groups, and one tuna-dolphin-bird group in the Bolivar Canal between Isla Isabela and Isla Ferdindina (Table 3). Dolphin species sighted were all unable to be identified (un-ID) due to distance from ship or limited visibility. Bird species sighted with dolphin groups were nazca boobies and shearwaters. The majority of the sightings in the GMR in were west of Isla Isabela, with one group of dolphins east of Isla San Cristobal and one group of dolphins south of Isla Santa Cruz (Fig. 13a).

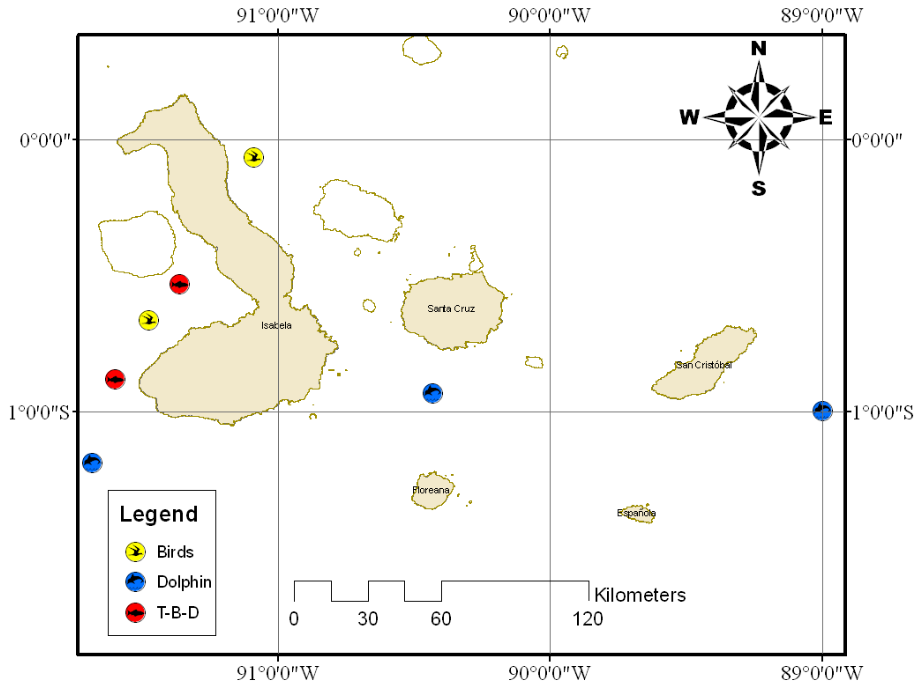
Table 3. List of cetacean and tuna group sightings during each marine mammal survey.

Season	**Sighting type**	**Species**	**Number of Sightings**
S08	Cetacean	Un-ID Dolphins	3
S08	Tuna-Dolphin-Bird	Un-ID Dolphins	1
A09	Cetacean	Bottlenose Dolphins and Pilot Whales (*Tursiops truncatus, Globicephala macrorhynchus*)	1
A09	Cetacean	Common Dolphins (*Delphinus delphis*)	2
A09	Tuna-Dolphin-Bird	Common Dolphins	1
A09	Cetacean	Un-ID Dolphins	5
A09	Tuna-Dolphin-Bird	Un-ID Dolphins	8
O09	Cetacean	Common Dolphins	3
O09	Cetacean	Bottlenose Dolphins	1
O09	Cetacean	Un-ID Dolphin	2
O09	Bird-Tuna	Un-ID Birds	3
J10	Cetacean	Bottlenose Dolphins and Pilot Whales	1

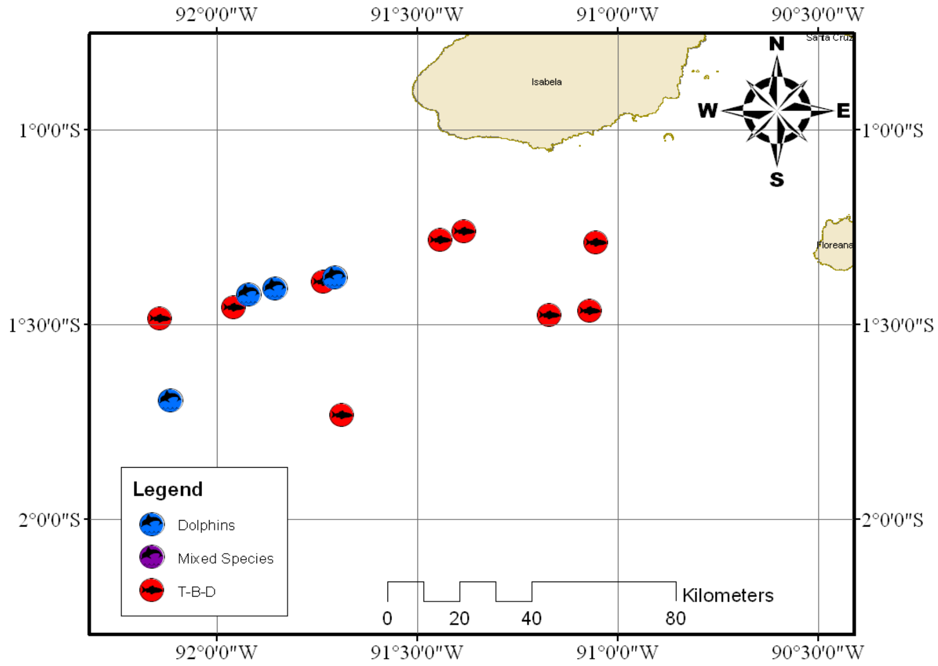
Table 3 continued

Season	Sighting type	Species	Number of Sightings
J10	Cetacean	Bottlenose dolphins and Sperm Whales (*T. truncates, Physter macrocephalus*)	2
J10	Cetacean	Common Dolphins	2
J10	Cetacean	Bottlenose Dolphins	1
J10	Tuna-Dolphin-Bird	Common Dolphins	1
J10	Cetacean	Un-ID Dolphins	7
J10	Cetacean	Whales (Various Species)	15
S10	Cetacean	Bottlenose Dolphins	2
S10	Cetacean	Common Dolphin	1
S10	Cetacean	Striped Dolphin (*Stenella coeruleoalba*)	1
S10	Cetacean	Un-ID Dolphin	1
S10	Bird-Tuna	Un-ID Birds	1

Out of 19 groups sighted in A09, nine were tuna-dolphin-bird groups with only one group of positively identified species, the common dolphin. All of these groups were sighted south of Isla Isabela near Isla Floreana. Additionally, there was one mixed species group of bottlenose dolphins and pilot whales, two groups of common dolphins, and five unidentified dolphin groups. Bird species were boobies (various species), shearwaters, storm petrels (various species), and un-ID birds. There were only two groups sighted south east of Isla Española, all other sightings were either west or south of Isla Isabela (Fig. 13b).

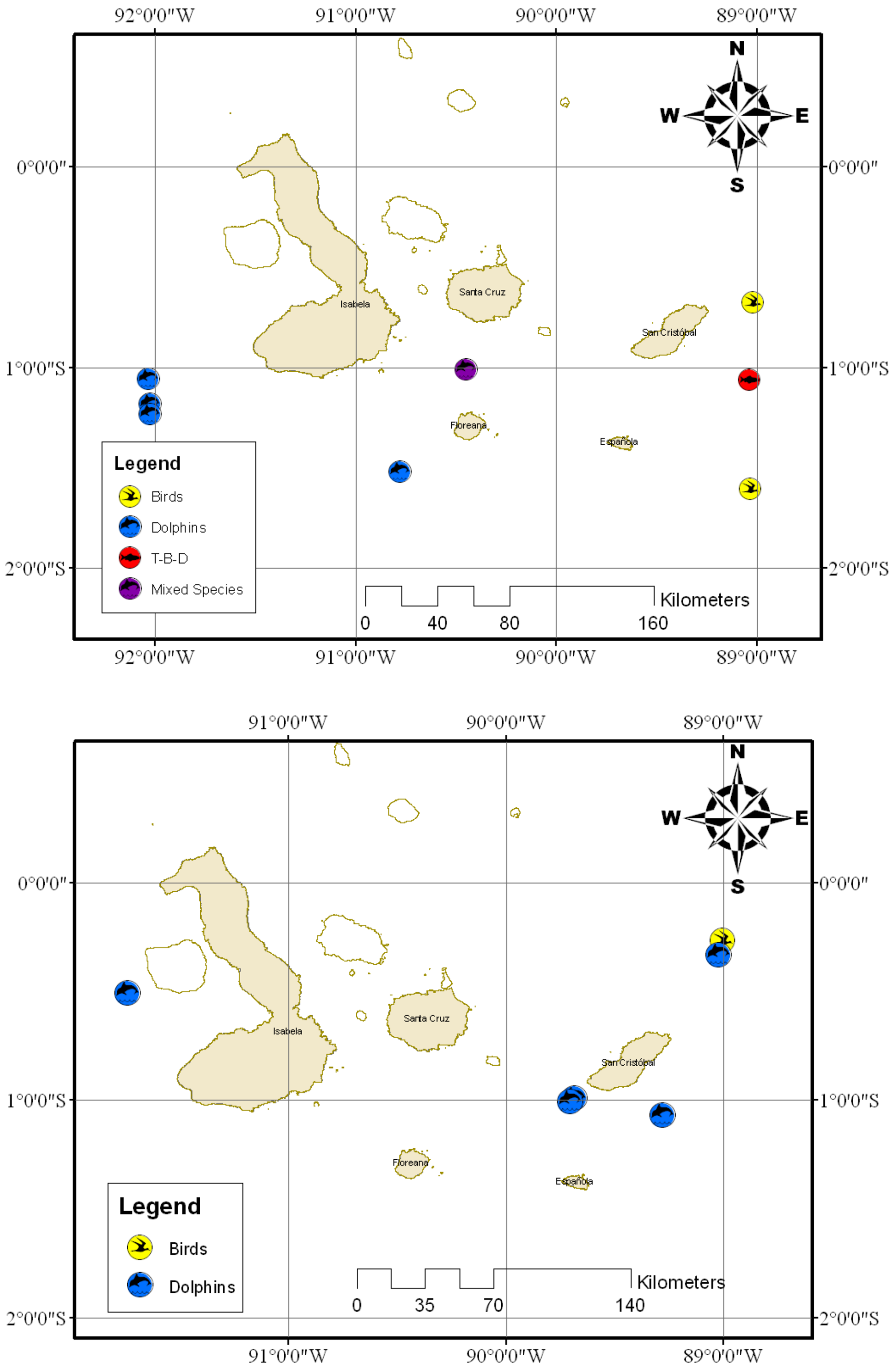


a.)



b.)

Figure 13. Distribution of groups sighted near the Galapagos (92°W-89°W and 0.5°N-2°S) from all the oceanographic surveys: a.) S08, b.) A09, c.) O09, and d.) S10. Yellow birds represent bird group sightings; blue dolphins represent single species dolphin groups; red fish represent tuna-dolphin-bird group sightings. Sightings are labeled by the oceanographic survey during which they were sighted.



c.)

d.)

Figure 13. Continued.

There were a total of eight O09 groups sighted: three bird groups, three common dolphin groups, one bottlenose dolphin group, and two groups of un-ID dolphins. Bird species indentified included blue-footed and nazca boobies and shearwaters. Three of these sightings were west of Isla Isabela, two were within the center of the archipelago around Isla Floreana and Isla Santa Cruz, and four sightings were east of Isla San Cristobal (Fig. 13c).

The 39 sightings in J10 included 15 whale species, one group of common dolphins, one bottlenose dolphin group, and seven groups of un-ID dolphins. Additionally, there were three mixed species groups, two of bottlenose dolphins and sea lions and one of bottlenose dolphins and pilot whales, and one tuna-common dolphin-bird group. The tuna-dolphin bird group was the only sighting south of Isla Isabela, with the rest either between Isla Isabela, Isla Floreana, and Isla Santa Cruz or around Isla San Cristobal and between Isla San Cristobal and Isla Española. There were no sightings south and east of Isla Española, with the only sightings to the west (on two different days) around a frontal boundary, an area marked with visible convergence or divergence at the surface, where there were large groups of cetaceans sighted and large groups of sea lions sighted (Fig. 14).

There were few sightings during the S09 survey, with only one bird group and five cetacean sightings. Most of the sightings were around Isla San Cristobal, with three of the sightings south of the island: two bottlenose groups and a common dolphin group. There was one striped dolphin group and the bird group northeast of the island. The only other cetacean sighting was west of Isla Isabela, un-ID dolphins (Fig. 13d).

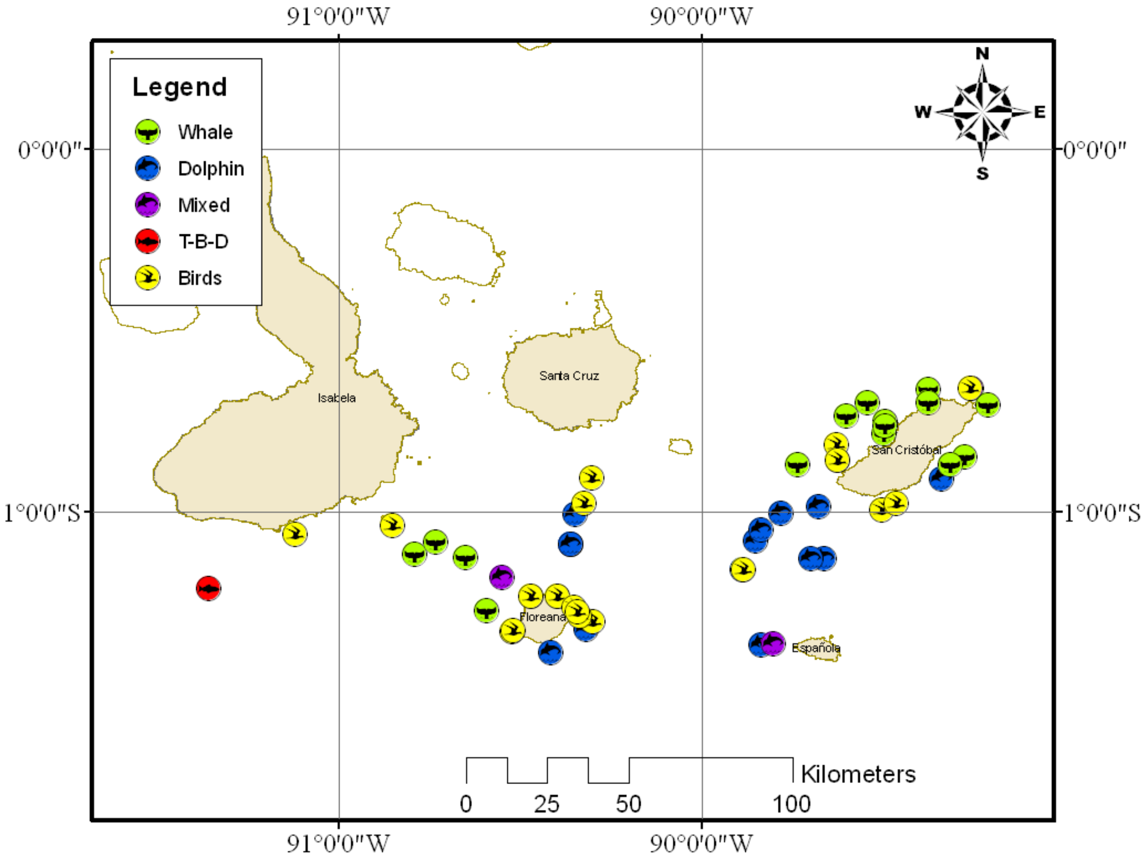


Figure 14. Distribution of groups sighted from the J10 near shore survey around the Galapagos Islands. Blue dolphins represent single species groups of dolphins; purple dolphins represent mixed species groups of marine mammals (cetacean/cetacean or cetacean/pinnipeds); Green whales represent individual or group whale sightings; red fish represent tuna-dolphin-bird assemblages; yellow birds represent bird groups.

The maximum depth of the distribution of yellowfin tuna, referred to as their vertical limit, around the Galapagos (88°W, 89°W, and 92°W) are shown in Figure 15. General trends show a deepening of their vertical limit to the north in April 2009, a deepening of their limit to the south in September 2010, and generally deeper vertical limits along 92°W compared to 89/88°W. There were no significant differences between depths for the pooled data 92°W and 88/89°W (Table 4). However, there were significant differences between longitudes in September 2010 but not in April 2009. There were also differences between pooled data from April 2009 and September 2010. Data from September 2008 and October 2009 were not analyzed for significance due to a small sample size. Data from June 2010 were not included in this analysis because CTD casts were not deep enough to reach water 8°C colder than the surface temperature. The maximum temperature difference recorded between the surface and bottom of cast was 7°C, with an average temperature difference between the surface and bottom of cast of 4°C.

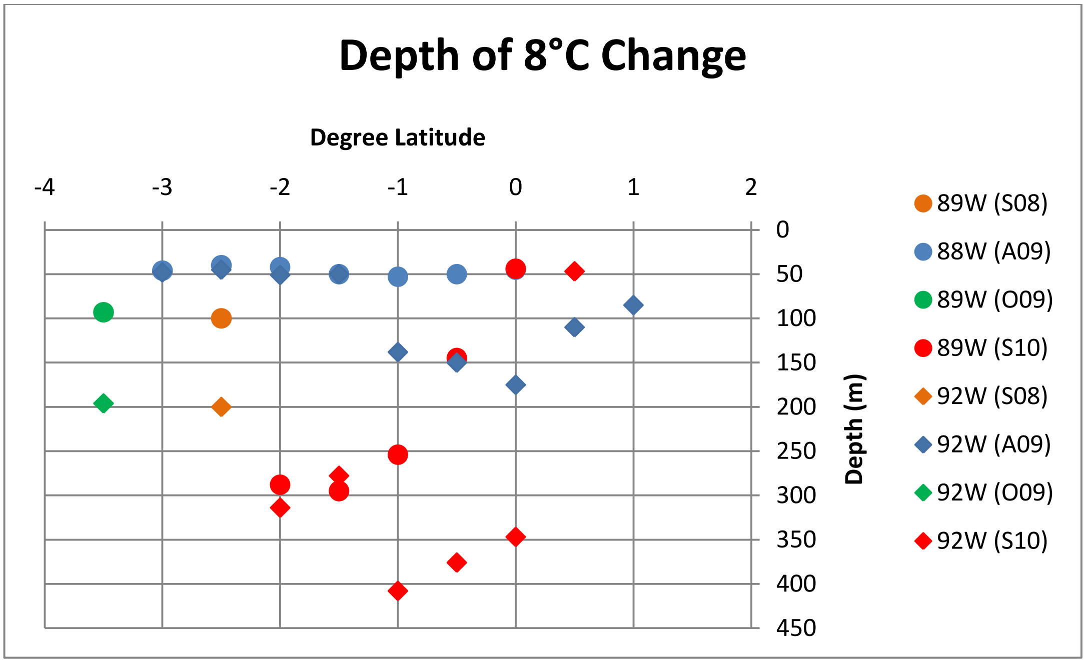


Figure 15. Maximum depth of tuna distribution at each oceanographic CTD station based on a difference of ≥8°C from SST. Circles represent stations along 88°W or 89°W (east of the archipelago); diamonds represent stations along 92°W. Same color markers are from the same survey with orange markers from S08, blue from A09, green from O09, and Red from S10.

Table 4. Average depth of vertical limit for yellowfin tuna and statistical comparisons between groups. Significance in pairs tested for using a two sample t-test assuming unequal variances. Statistically significant pairs are in red

Data set	Average (m)	Standard Deviation	Degrees of Freedom	T-stat	P value
88/89°W (all)	178	96	29	-1.69	0.10
92°W (all)	110	125			
S10 89°W	205	108	9	-2.85	0.02
S10 92°W	295	130			
A09 88°W	46.6	4.7	8	-1.25	0.24
A09 92°W	94.7	50.3			
A09 (all)	74	44	12	4.63	<0.01
S10 (all)	254	124			

Discussion

Marine Mammal Sightings

The majority of the marine mammal sightings on the oceanographic surveys were west and south of Isla Isabela. This area is highly productive with high chlorophyll a concentrations due to the topographic upwelling of the EUC, supplying the waters with abundant nutrients (Palacios 2004). Additionally, almost all of the tuna-dolphin-bird assemblages were found around Isla Isabela. This area has shallow thermoclines due to the near surface upwelling of the EUC and high abundances of prey so that these groups can form without unfavorable competition between the different species. The majority of the sightings east of Isla San Cristobal were recorded in the fall surveys, during the Garuá season when upwelling is enhanced and SST are cool. Cooler SST allow for more mixing of the surface layer and potentially make more nutrients available to support more prey for cetaceans. Tuna-dolphin-bird groups are less often present east of the archipelago because of the deeper thermocline does not promote formation of these groups (Au 1991).

Sightings were generally lower in the three fall surveys than the one spring survey. The fewest sightings were recorded in the fall survey S08. The low number of sightings in S08 can be attributed to the El Niño conditions that were present at this time. El Niño has significant negative impacts on marine life due to the decrease in upwelling and the low chlorophyll a concentrations, which cannot support the prey the marine mammals rely upon (Cane 1983, Fielder 2002). The high number of sightings in A09 can be attributed to both the water conditions due to the ENSO cycle and the annual season. The spring survey took place during the hot season, when SST are warm; additionally, NOAA cites A09 as a weak El Niño/neutral conditions (CPC/NWS 2011). The difference in the distribution of sightings between the spring and fall surveys may be the result of the marine mammals adjusting their distribution to remain in the warmer waters as the distribution of the warm water changes from the cooler Garuá season to the warmer hot season. While not generally recorded, tuna may also change their distribution to stay in the warmer surface waters in this area, accounting for the low numbers of tuna groups seen in the fall surveys.

The one summer survey, J10, found opposite trends than those of the oceanographic surveys. The majority of the sightings were around Isla San Cristobal, with only a few recorded while in transit between Isla Santa Cruz and Isla Floreana and between Isla Floreana and Isla Isabela. There was only one sighting south of Isla Isabela during the survey. This lack of sightings around Isla Isabela may be accounted for by the proximity of the survey track to the coast of the islands (Fig. 12). Except when traveling from island to island, the survey was within sight of the coastline the majority of the time. Furthermore, the large number of sightings around Isla San Cristobal may be due to the greater amount of time spent surveying around the island. While only three days were spent surveying between Isla Santa Cruz, Isla Floreana, and Isla Isabela, eight days were spent surveying Isla San Cristobal and Isla Española. Additionally, high chlorophyll concentrations north of Isla San Cristobal may be due to local upwelling or mixing of surface waters, allowing for greater food availability north and west of Isla San Cristobal, possibly due to the island mass effect (Hasegawa *et al.* 2009).

North of Isla San Cristobal, large groups of feeding birds were spotted, along with baleen whales and mixed species groups of marine mammals, including a group of bottlenose dolphins and pilot whales, surrounded by a group of feeding birds. While the cetaceans were not actively feeding, the boobies that surrounded them have similar diets, implying that there was food available for the group to eat if necessary. East of Isla San Cristobal the surface waters were chlorophyll poor, and few marine mammal sightings were recorded there.

The large number of sightings between Isla San Cristobal and Isla Española may be due to a frontal boundary sighted west and northwest of Isla Española. This boundary was sighted in this area on several non-consecutive days, implying that it may be found there on a time scale of at least a few days or longer. CTD data collected in this area also suggest that this boundary may promote mixing of nutrients from deeper in the water column, with lower SST and SSS east of the boundary than west of the boundary. Along this boundary, large groups of sea lions (approx. 30-40 in one sighting) were found jughandling, a behavior involving floating in the surface waters with one fore fin grasped between their back fins, held out of the water, generally believed to be for body temperature maintenance (Riedman 1990). Additionally, large groups of cetaceans were spotted around the boundary, including a group 200-400 bottlenose dolphins and a group of common dolphins.

Tuna Vertical Distribution

Yellowfin tuna have been found to be limited in their vertical distribution by a temperature difference of 8°C colder than the surface temperature of the water, regardless of the sea surface temperature (Brill *et al.* 1999, Brill & Lutcavage 2001). Around the Galapagos Islands, this temperature difference is controlled significantly by the upwelling of the EUC west of Isla Isabela. Where the EUC upwells, the SST will be colder than elsewhere around the archipelago making the vertical limit of the tuna much deeper because the colder deeper water is now at the surface. During the Garuá season, when upwelling is enhanced and sea surface temperatures are cool, fewer aggregations of tuna and dolphins were observed. Upwelling of the EUC occurs primarily around 92°W and the cold water tends to move north and south around Isla Isabela.

In all oceanographic cruises, the tuna's vertical limit was significantly lower along 92°W between 2°S and the equator, the main area influenced by the upwelling. Along 88°W and 89°W, east of the archipelago, the vertical limit of the tuna is not as much impacted by the upwelling, and the limit is much shallower than along 92°W. However, when all data were pooled, there was no significant difference between the two latitudes (Table 4). In general, we would expect to see more tuna dolphin assemblages along the eastern side of the archipelago if their presence was due solely to the vertical limitation by temperature and their distribution would change as the annual season changes the water temperature. However, because we observed more groups along 92°W, there may be additional influences on tuna distribution in the GMR.

The ENSO cycle conditions were different during each oceanographic survey, and may help explain the changes in tuna-dolphin-bird distribution. For example, the vertical limit is significantly shallower in April 2009 during ENSO-neutral conditions than in September 2010 during a strong La Niña event. These neutral conditions had slightly deeper 20°C isotherm depths, but warmer SST, making the depth at which there is an 8°C difference in temperatures shallower than during the La Niña when the SST is much cooler, at times less than 20°C, resulting in the increase in water depth needed to reach the 8°C threshold. This is because the ENSO cycle generally only impacts the upper 150-200 m of the water column in the ETP (Fielder 2002, CPC/NWS 2011) and the water beneath this layer maintains its temperature structure of ENSO-neutral conditions. Conditions in the archipelago during neutral conditions are favorable to the formation of tuna-dolphin-bird groups, many of which were observed during the A09 survey. These groups formed due to the shallow and sharp thermoclines, forcing the yellowfin tuna in the highly productive surface waters where the EUC shoals towards the surface, bringing nutrient rich water into the photic zone.

The La Niña (S10) increased the difference in vertical limits between the eastern and western side of the archipelago due to the increased upwelling and the greater extent of the surfaced cold water along 92°W. More tuna-dolphin-bird groups were observed throughout the archipelago during normal conditions and the hot season in A09 (nine reported) than in any of the Garuá season and/or La Niña events (two tuna-dolphin-bird groups and three bird-tuna groups reported, in total).

Additionally, in the summer survey, J10 a tuna-dolphin-bird group was spotted south of Isla Isabela while several bird-tuna feeding assemblages were spotted around Isla Española, south east of the archipelago. Since the J10 survey was during a transition period between a strong El Niño and a strong La Niña, there were shallower thermoclines across the entire archipelago, increasing the likelihood that where the tuna fed close to the surface, dolphins and/or birds fed with them.

Most literature does not cite significant horizontal limits to the biogeographic distribution of yellowfin tuna except that they are only found in tropical waters with warm SST, generally between 18°C and 31°C (Collette & Nauen 1983). Obviously, events such as ENSO events, which can change the SST in an area by several degrees, may influence the horizontal distribution of the tuna. During the La Niña in S10, SST along 92°W ranged from 22°C to 17°C, a difference of five degrees. The same CTD stations during the A09 cruise had a SST range of 27 to 22°C. In only 18 months, the temperature of the water varied by 10°C. Assuming the 8°C limit of the tuna's distribution, we would expect tuna to be horizontally restricted in their distributions on an annual to interannual scale when the SST changes significantly in response to the

ENSO cycle.

Brill *et al.* (1999) and Brill and Lutcavage (2001) estimated the vertical distribution of yellowfin tuna based on their movements in Hawaii, a tropical area with little seasonal change in SST. Around the Galapagos, there are significant annual and interannual changes in SST, making the horizontal changes in SST important to the tuna's distribution as well. This is not unexpected, though since many organisms (pelagic cetaceans and seabirds in particular) are known to change their distributions in response to the movement of water masses (Ballance *et al.* 2006). Similarly , it has been shown that in the Eastern Pacific Ocean, yellowfin tuna will travel north and south of the tropics as the subtropical water warms in the summer months and return to the tropics as the water cools in the fall and winter months (Broadhead & Barrett 1964). Tuna altering their distribution would be similar to the movement of those cetaceans, resulting in less tuna-dolphin-bird groups present during the periods when SST were cooler.

CHAPTER IV

CONCLUSIONS

Conclusions

There are distinct contrasts between the physical oceanographic characteristics of the Galapagos Marine Reserve intra-annually (between the Garuá and hot seasons) and inter-annually (between El Niño, La Niña, and ENSO-neutral periods). These changes may affect the distribution of marine mammals and change the possibility of the formation of tuna-dolphin-bird assemblages. The intra-annual changes within the GMR occur when warm SST, high rainfall, and low salinities during the hot season shift to cooler SST, enhanced upwelling, higher SSS, and low rainfall during the Garuá season (Sweet *et al.* 2007). The lower frequency interannual changes can disrupt this cycle to cause abnormally warm SST and suppression of upwelling during El Niño events, to enhanced upwelling with abnormally cool SST during La Niña events (Fielder 2002). Intra- and interannual cycles combine to create a unique environment around the Galapagos Islands.

These changes in the physical characteristics of the water column in the GMR are much stronger than in other parts of the ETP where the major factor in changes is the ENSO cycle and there are only small annual changes. It is believed that marine mammals adjust their distribution to compensate for the changes in the water properties (Ballance *et al.* 2006) and that they generally follow their preferred habitat as it changes spatially throughout the year in response to both the annual and interannual cycles.

Physical Oceanography of the GMR

Three types of surfaces waters commonly found in the ETP were identified in the GMR during the surveys: TSW, ESW, and EUC. Generally, the cooler upwelling modified waters (ESW and EUC) were detected around Isla Isabela and to the north and west of Isla San Cristobal. These areas are also characterized by high chlorophyll concentrations. TSW waters were generally detected north of the Equatorial Front in spring (A09) or within the central archipelago in summer (J10).

The differences in the characteristics of the upper water column correlate to both the annual seasonal cycle and the interannual ENSO cycle. While it is difficult to separate the influences of each cycle with the present limited data, additional surveys during April, June, and September/October during various ENSO events should allow for the determination of how much each cycle influences the water column properties. In this study, upwelling modified waters were most prominent west of Isla Isabela during the ENSO-neutral and La Niña events and during the Garuá season.

Marine Mammal Surveys

There were a greater number of sightings and larger groups of marine mammals during the surveys in both the hot season (A09) and during ENSO-neutral conditions (A09, J10). These waters, characterized by warm SST, moderate SSS (34-35), and shallow, sharp thermoclines, presumably promote greater success in predation for marine mammals, as food should be generally abundant (Cane 1983). During A09 and J10, the majority of sightings were west and south of Isla Isabela and north and west of Isla San

Cristobal. Additionally, the majority of the tuna-dolphin-bird groups were sighted south of Isla Isabela.

In contrast, a sharp decrease in the amount of sightings was noticed in for the three Garuá season cruises (S08, O09, and S10). For these cruises in the Garuá season, the S08 cruise took place during an El Niño, the O09 cruise took place during ENSO-neutral conditions, and the S10 took place during a La Niña. When the sightings for each of these cruises are compared, they are similar, suggesting marine mammals tend to move away from the islands during periods of cool SST. However, since there was only one data set available to me from the hot season (April), it is not feasible to determine if the high number of sightings was a consequence of the season or the ENSO-neutral conditions of spring 2009.

While the distribution of marine mammals appears to be correlated with the physical water properties, there are of course more factors that may influence their distributions including biological factors like prey availability, and factors affecting the observers: the survey effort, the time of day, the sea state, and visibility, among others (Fielder *et al.* 1998, Reilly *et al.* 2002, Ballance *et al.* 2006). Nevertheless, tuna-dolphin-bird groups are believed to form primarily in response to the physical properties of the water column (Au 1991, Edwards 1992). These groups are only found in the ETP because the ETP has a unique combination of water column properties: shallow, sharp thermoclines and warm SST. Since these properties ultimately determine if tuna and dolphin will associate with each other, understanding how these water properties change over time will aid in the management of fisheries that target the dolphins in order to catch the tuna.

My thesis data sets show an increase in the observation of tuna-dolphin-bird groups during periods when SST were warm and the thermoclines were shallow and sharp (i.e. when prey is assumed to be abundant (A09). Additionally, the ENSO cycle plays a significant role in controlling the depth of the thermocline, although the current data are too limited for any conclusive evidence. It is expected that additional fieldwork should show that there are greater numbers of tuna-dolphin-bird groups during ENSO-neutral periods than during El Niño (deep thermoclines) or La Niña (cool SST) events.

Additionally, yellowfin tuna may be limited both horizontally and vertically within the GMR as large (+10°C) temperature fluctuations occur from year to year. When these occur, tuna should change their distribution to follow the warmer water. If the formation of tuna-dolphin-bird assemblages were determined solely on the depth of their limitation, then most groups would form east of the GMR. However, very few groups were observed here. Rather they were concentrated around southern Isla Isabela. With only limited CTD data from this region, it is difficult to determine what the typical depth of the thermocline in the area is. However, future work may show that south of Isla Isabela the thermoclines are shallow (i.e. the EUC should be close to the surface). This, along with the high prey abundance indicated by high chlorophyll concentrations, may indicate this area should have optimal conditions for the formation of these multispecies groups.

Future Work

Additional Surveys

It is difficult to ascribe any statistical significance in the trends observed in this study due to the limited amount of data. Additional surveys are required during each combination of the months observed in the GMR (April, June, and September/October) and the different possible ENSO conditions. These surveys should include not only the present stations occupied in the oceanographic surveys along the outer limits of the GMR, but also within the archipelago such as CTDs of opportunity done in the J10 survey. If these surveys continue to support the observations made in this study, the analytical trends noted in this these could be statistically supported.

Applications

The data from this survey could be used to reduce the amount of dolphin bycatch in small artisanal fisheries by arranging the gillnet fishing season around periods when the conditions are unfavorable for the formation of these assemblages. The other fishing methods permitted in the GMR would not need to be subject to the same closures because they have a low potential for dolphin bycatch. For example, within the GMR, the artisanal gillnet tuna fishing season could be limited to periods when the SST are cooler than average such as during the Garuá season and La Niña events. This would require a dynamic method of managing the fishery, rather than a static method of arbitrary area closings, etc that is generally used. This method of fishery management has been shown to be successful in other areas that experience strong annual and interannual changes (Bakun *et al.* 2010). In this way, the bycatch of marine mammals in artisanal tuna fisheries may be more effectively managed, and eventually reduced.

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APPENDIX

SST FIGURES

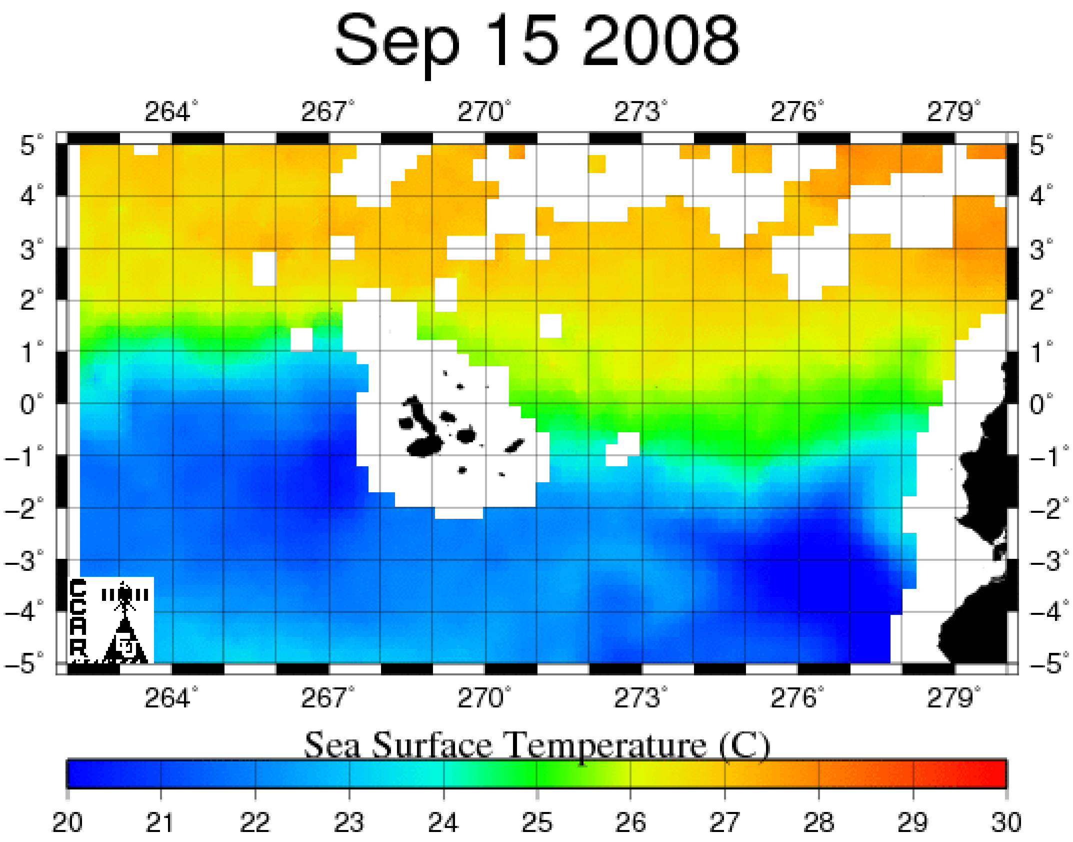

Figure A-1. Sea surface temperatures of the area between the Ecuador mainland and the Galapagos Islands, showing the location of the Equatorial Front in September 2008. Map based on values on September 15, 2008, the approximate mid-point of the survey.

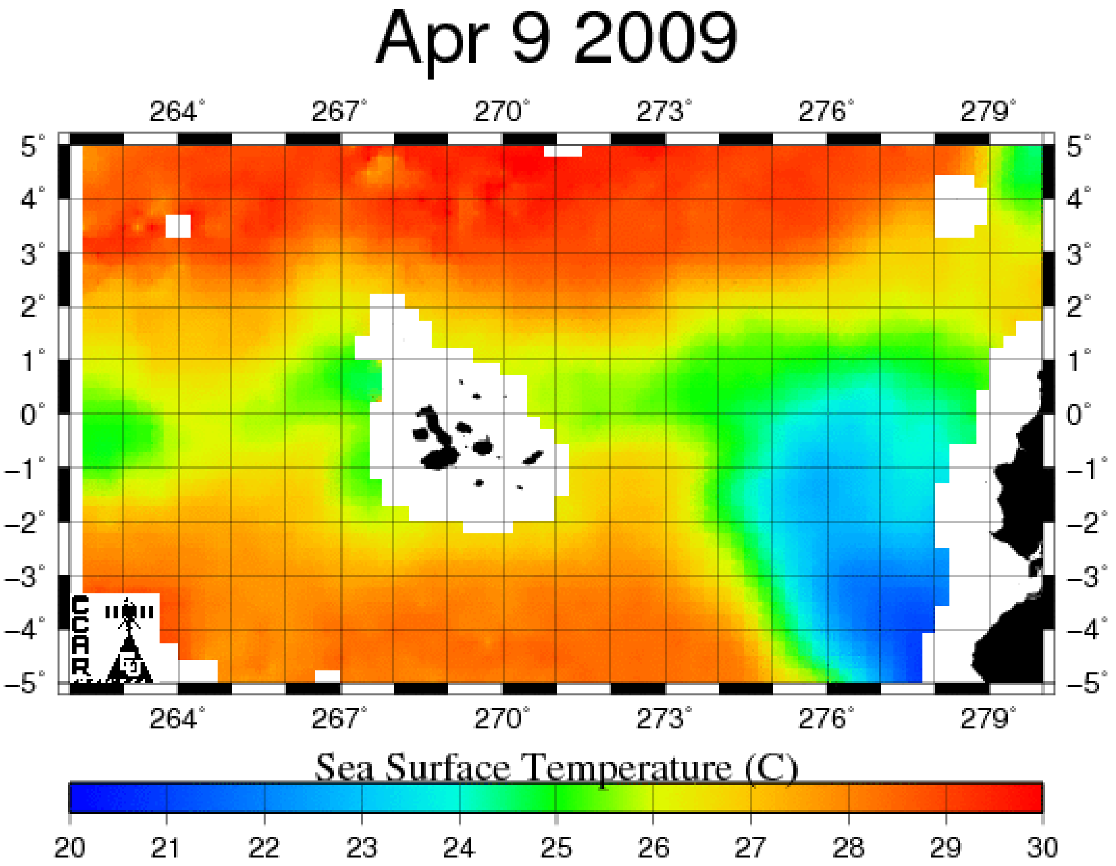

Figure A-2. Sea surface temperatures of the area between the Ecuador mainland and the Galapagos Islands, showing the absence of the Equatorial Front in April 2009. Map based on values on April 9, 2009, the approximate mid-point of the survey.

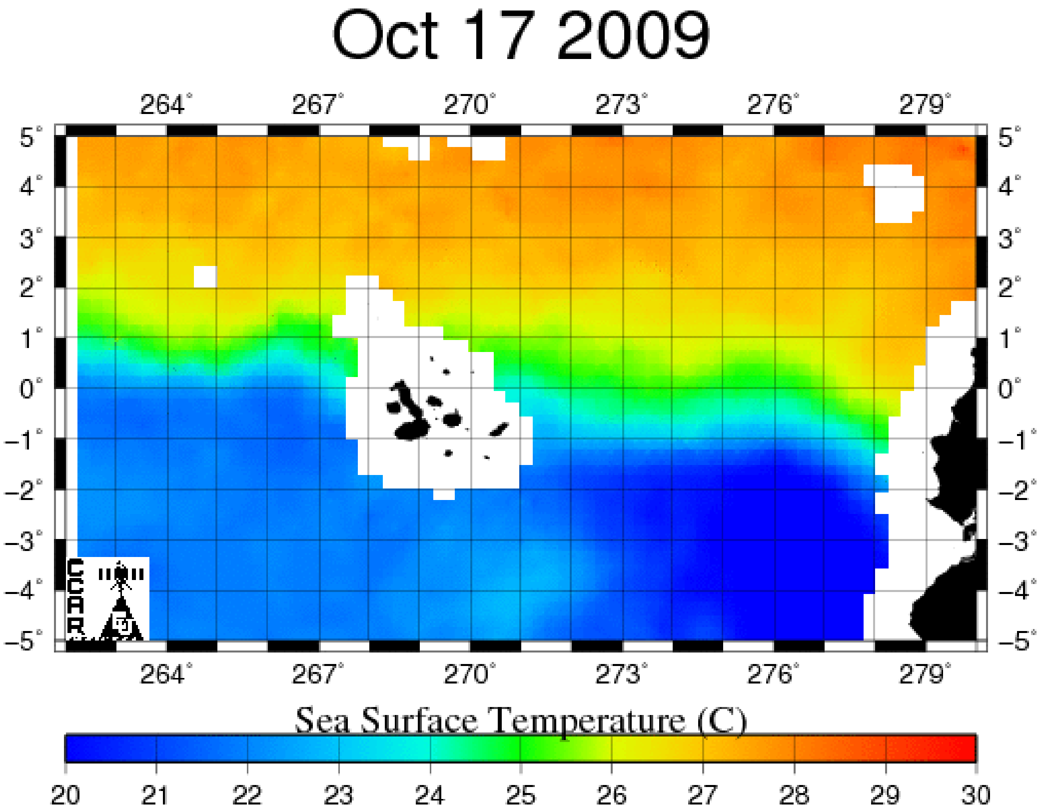

Figure A-3. Sea surface temperatures of the area between the Ecuador mainland and the Galapagos Islands, showing the location of the Equatorial Front in October 2009. Map based on values on October 17, 2009, the approximate mid-point of the survey.

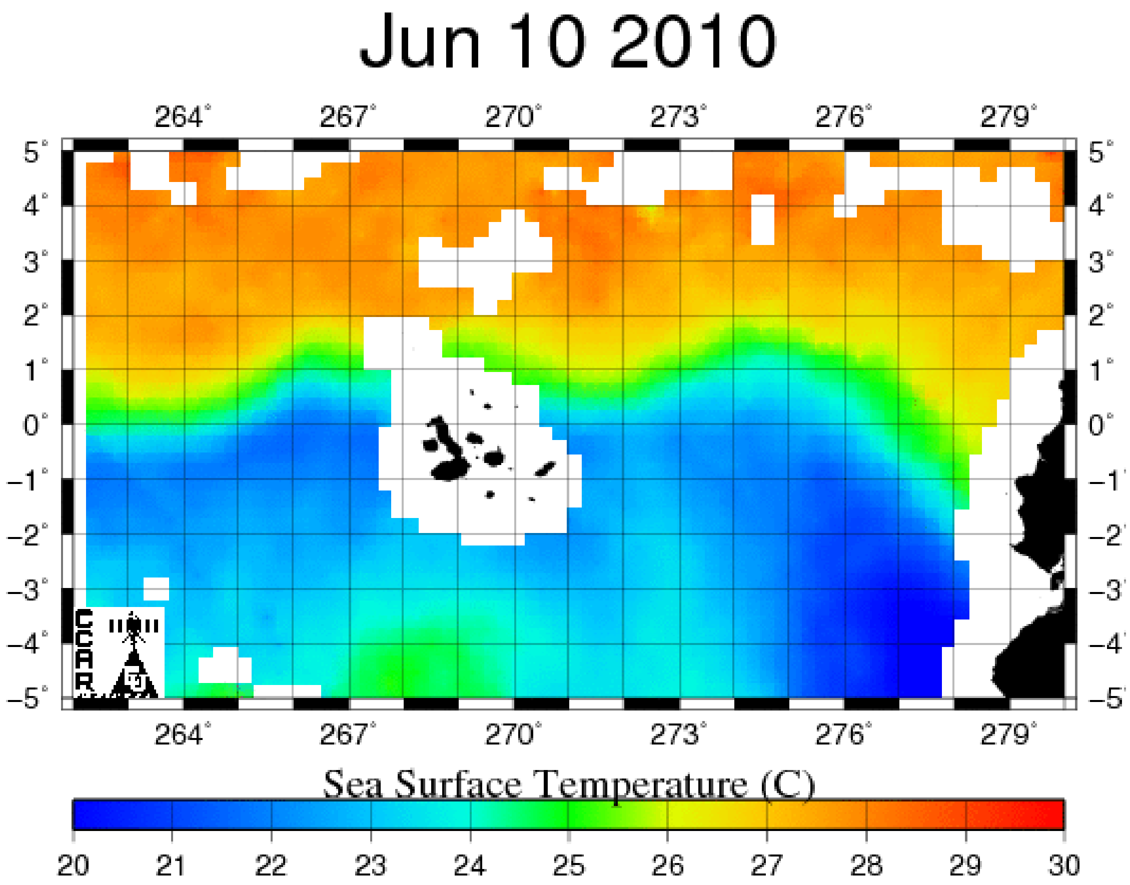

Figure A-4. Sea surface temperatures of the area between the Ecuador mainland and the Galapagos Islands in June 2010. Map based on values on June 10, 2010, the approximate mid-point of the survey.

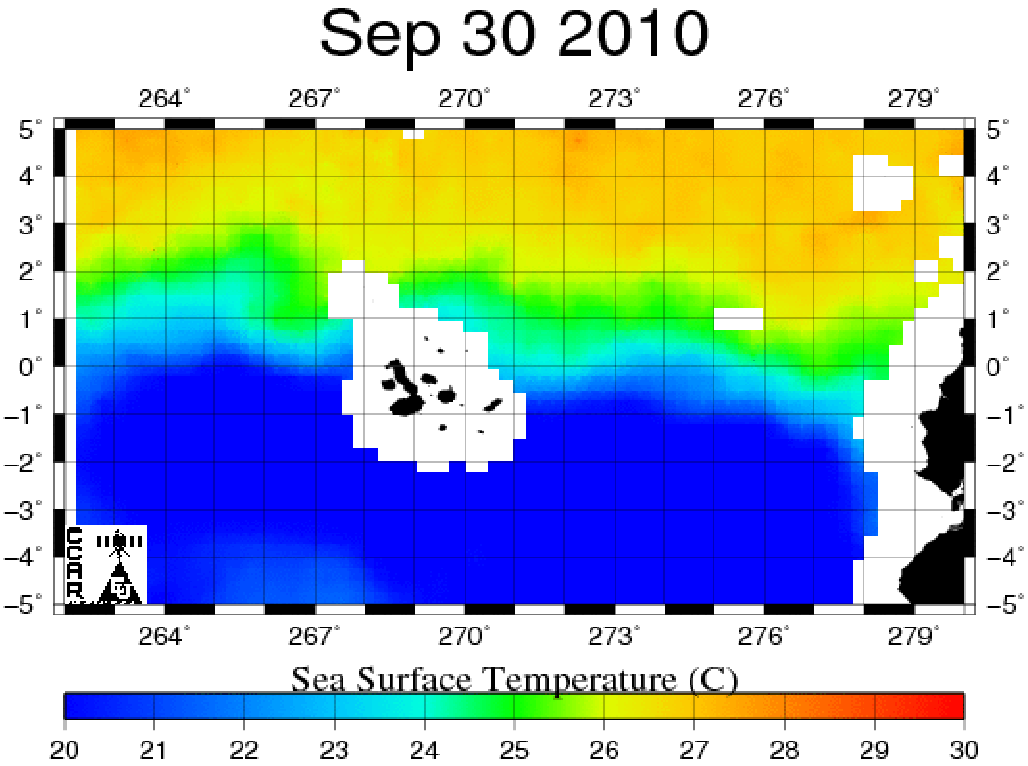

Figure A-5. Sea surface temperatures of the area between the Ecuador mainland and the Galapagos Islands, showing the location of the Equatorial Front in September 2010. Map based on values on September 30, 2010, the approximate mid-point of the survey.

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