ASSESSING THE OCEANOGRAPHIC CONDITIONS AND DISTRIBUTION OF REEF FISH ASSEMBLAGES THROUGHOUT THE GALÁPAGOS ISLANDS USING UNDERWATER VISUAL SURVEY METHODS

A Thesis

by

STEPHANIE MARIE DURKACZ

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Chair of Committee,	Douglas Biggs
Committee Members,	Niall Slowey
	Jay Rooker
Head of Department,	Deborah Thomas

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ABSTRACT

The Galápagos Islands are one of the most diverse marine ecosystems in the world because they lie at the confluence of several ocean currents in the eastern tropical Pacific Ocean (ETP). The Galápagos Marine Reserve (GMR) is a 138,000 km^2 area surrounding the archipelago that is divided into several zones based on the dispersal of fauna and marine resources. The goal of this thesis was to assess the distribution and abundance of reef fish assemblages throughout the GMR and to contribute to the existing knowledge of these assemblages. This project was performed during three visits to Galápagos: 16-30 May 2013, 16-19 November 2013, and 12-24 July 2014. Reef fish assemblage composition throughout the GMR was examined by collecting qualitative and semi-quantitative data using underwater visual survey techniques. Data on current and past oceanographic conditions around Galápagos were collected through *in situ* measurements and examining data collected by satellites.

Underwater surveys found a high species richness and wide range of trophic levels to exist across the Galápagos archipelago. Data were analyzed using several techniques including rank order of abundance (ROA), hierarchical cluster analysis, principal coordinates analysis, and regression. During 2013 surveys, 60 species from 32 families were recorded at 12 survey sites across the GMR. Through tests of similarity, it was found that fish assemblages across the GMR are not uniformly distributed and vary spatially. Ocean conditions such as temperature may influence fish assemblage composition at different islands. These results support previous studies that surveyed fish assemblages throughout the GMR and found that assemblages vary based on geographic location and that water temperature may play a role in how they are structured. In July 2014, data were collected around the northwest coast of Isla San Cristóbal at two sites previously surveyed in 2013. Fish assemblages around San Cristóbal showed little change from one year to the next in terms of species richness and diversity. Ocean temperatures were warmer and chlorophyll-a levels were lower in 2014 than in 2013, caused in part by El Niño climactic variations in the ETP during 2014. Information from this thesis may be used for a variety of applications including marine resource management and to support future zoning proposals in the GMR.

DEDICATION

I would like to dedicate this work to my family, in memory of my grandmother Emilia Durkacz.

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NOMENCLATURE

CCAR	Colorado Center for Astrodynamics Research
Chl-a	Chlorophyll-a
CPC	Climate Prediction Center
ENSO	El Niño Southern Oscillation
ETP	Eastern tropical Pacific
EUC	Equatorial Undercurrent
GMR	Galápagos Marine Reserve
HNLC	High-nutrient low-chlorophyll
INOCAR	Instituto Oceanográphico de la Armada del Ecuador
IUCN	International Union for Conservation of Nature
MODIS	Moderate Resolution Imaging Spectroradiometer
PAST	Paleontological Statistics software package
PCO	Principal coordinates analysis
REEF	Reef Environmental Education Foundation
ROA	Rank Order of Abundance
SCUBA	Self-contained underwater breathing apparatus
SSH	Sea surface height
SST	Sea surface temperature
UPGMA	Unweighted-pair group average

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Geologic and physical oceanographic setting

The Galápagos Islands lie about 600 miles (1000km) west of the Ecuadorian coast in a region of the Pacific Ocean known as the eastern tropical Pacific (ETP). The archipelago is comprised of thirteen major islands, six minor islands, and over forty islets and rock formations (Humann and DeLoach, 2003). The Galápagos archipelago lies in the Pacific Ocean between 01°40′N–01°25′S and 89°15′W–92°00′W (Okey et al. 2004). The Islands lie at the junction of three active oceanic plates; the Pacific, Cocos, and Nazca plates. Hotspot volcanism under the Cocos-Nazca spreading center formed the Islands (Sallares et al. 2005). Scientists infer that the islands are generally younger in the west and older in the east (Villagomez et al. 2010). The oldest island, Espanola, is estimated to be around 3.3 million years old, while the youngest islands, Fernandina, and Isabela, are only estimated to be 0.7 million years old (Woods 1987). There are still some active volcanoes in the archipelago on the islands of Isabela and Fernandina that are among of the most active in the world today (Amelung et al. 2000, Chadwick et al. 2006). Input of iron from weathering of volcanic basalt rocks into the Galápagos contributes to the high level of biological productivity of the region (Gordon et al. 1998).

Physical oceanographic variability within the ETP is high. The region lies between the two large subtropical gyres of the North and South Pacific oceans and is at the interface of several different water masses (Pennington et al. 2006). The physical oceanography of the ETP combined with the mixing of various equatorial and localized currents in Galápagos results in differences in surface temperature throughout the archipelago (McCosker and Rosenblatt, 1984). The archipelago is characterized by a strong and shallow thermocline and above this gradient depth the different water masses are distinguished based on temperature. In general, Galápagos has cool sea surface temperatures (SST), high surface salinities, and high near-surface nutrient concentrations (Fiedler and Talley, 2006). Seasonal water mass variability occurs within Galápagos and closely follows general patterns of seasonal variability in the ETP (Sweet et al. 2007).

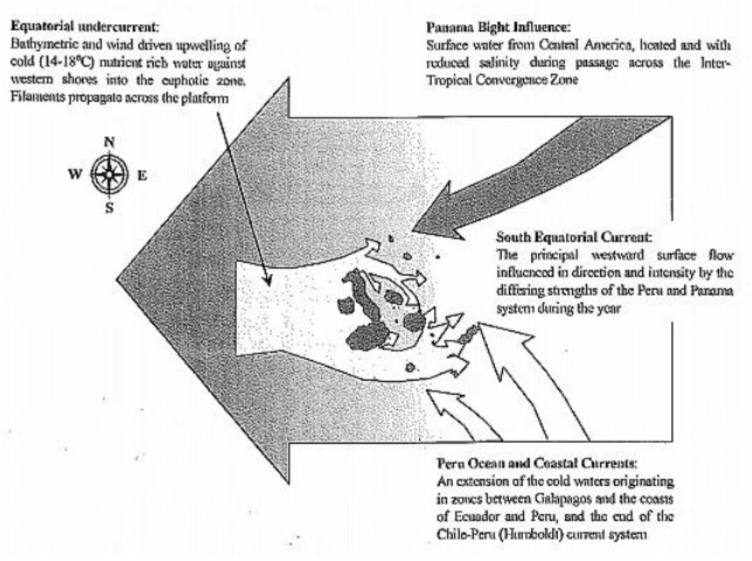


Figure 1. Major oceanographic currents around the Galápagos Islands. From Bustamante et al. 2008.

The Galápagos Islands are the only tropical archipelago that is found on the intersection of several warm- and cool-water ocean currents (Edgar et al. 2004a). The

Peru Coastal (Humboldt) and Peru Oceanic Currents flow northward from the coast of South America and bring cool water toward the islands (Figure 1). Combined, they form the South Equatorial Current, which flows westward and is influenced by the southeast trade winds. The tropical Panama current flows southwest from the Isthmus of Panama and brings warm waters to the islands (Humman and DeLoach, 2003, Bustamante et al. 2008).

The Equatorial Undercurrent (EUC) is a relatively narrow current that flows eastward towards Galápagos along the equator and bathes the islands in cool waters (Pak and Zaneveld, 1973). The cool water temperatures present on the western side of the Galápagos (west of Fernandina and Isabela Islands) reflect topographically induced upwelling of EUC water (Palacios 2004 and Kessler 2006). This upwelling brings cool, nutrient-rich deep water closer to the sea surface and can influence SST variations within the water masses in the archipelago (Wellington et al. 2001). The EUC bifurcates in Galápagos and is strongest at the western side of the archipelago but its influence is still felt in the easternmost island of San Cristóbal. The EUC is important because the strength and depth of the EUC is responsible for the water properties within the Galápagos archipelago (Sweet et al. 2007). These ocean currents are important to the Galápagos marine ecosystem not only because they provide an influx of macronutrients, but also because they transport larvae of coral and fish species to the area from other regions (Humann and DeLoach, 2003).

El Niño climactic variations

The ETP is a region of strong inter-annual climate variability due to the El Niño Southern Oscillation (ENSO) cycle (Fiedler and Lavin, 2006). ENSO is a large-scale climactic phenomenon that occurs about every 3-7 years (Hansen 1989). ENSO events are caused by anomalies in westerly wind patterns that decrease the strength of southeast tradewinds. Normally, wind curl from tradewinds acts to move warm surface waters west across the Pacific. When these tradewinds decrease, warm water masses spread east across the Pacific rather than west. This process introduces warmer water to the surface waters around Galápagos via disruption of normal surface currents and upwelling patterns. This results in the formation of a deeper thermocline, higher local sea levels, and increased precipitation (Cane 1983, Kessler 2006, Pennington et al. 2006). El Niño events in the ETP are strong drivers of the global carbon cycle, as decreased upwelling of CO_2 from deep waters during ENSO events has a large inter-annual variability (Murray et al. 1994).

Oceanographic warming associated with strong ENSO events can have a direct effect on species populations in Galápagos, as the archipelago sits near the center of intense ENSO events (Glynn and Ault, 2000). Without the cool, nutrient-rich waters delivered via upwelling, biological productivity decreases in warmer water (Chavez et al. 1999, Vinueza et al. 2006, Edgar et al. 2010). In particular, Galápagos saw severe changes during El Niño event of 1982-1983, which lasted approximately 1.5 years and raised SST up to 5°C (Glynn 1988). This event devastated coral, urchin, and algae populations (Glynn 1984). It is estimated that 95-99% of total coral reef cover was lost in Galápagos between the years of 1983-1985 due to El Niño (Edgar et al. 2010). This 1982-1983 ENSO event had far-reaching effects on nearly every trophic level in the marine ecosystem including fishes and marine mammals. The 1997-98 event heavily affected pinnipeds in Galápagos, causing an apparent decline of 50% due to increased mortality and migration away from habitats. Declines in the pinnipeds' main food sources (schooling pelagic fish families such as Serranidae, Sparidae, and Labridae, among others) are also thought to decline during these major ENSO events (Salazar and Bustamante, 2003). Endemic penguins, reptiles, seabirds, fishes, and macroalgal communities were also negatively impacted by either one or both of these major ENSO events in Galápagos (McCosker and Rosenblatt, 1984, Trillmich and Limberger, 1985, Boersma 1998, Chavez et al. 1999, Edgar et al. 2010).

Biological productivity

To examine the diversity of marine life in Galapágos, one must begin at the base of the marine food web with autotrophic phytoplankton. Phytoplankton use inorganic nutrients along with energy from sunlight to produce organic energy through the process of photosynthesis. Carbohydrate products of photosynthesis are utilized by the phytoplankton to fuel growth and reproduction processes. The amount of carbon converted to organic material by phytoplankton during a given time is termed biological productivity (Ivlev 1966). Key macronutrients such as nitrate and phosphate must be available to plankton in order to stimulate productivity. Phytoplankton are able to receive these nutrients via upwelling of colder, nutrient-rich waters from mid-depth to surface waters. Local wind-driven and topographical upwelling creates a shallow thermocline around Galápagos. This shallow thermocline is a crucial factor that allows macronutrients to become available to phytoplankton so that primary production may occur (Pennington et al. 2006). Production cycles for large pelagic fisheries in the Pacific Ocean are driven by bottom-up peaks in primary production in these upwelling areas (Caddy and Garibaldi, 2000).

The ETP is considered a high-nutrient low-chlorophyll (HNLC) region with lower productivity than might be anticipated based on the availability of nutrients via upwelling (Murray et al. 1994, Franck et al. 2005). Despite the availability of macronutrients, in many places there is insufficient iron to stimulate biological productivity (Palacios 2004). Iron is an important micronutrient that affects phytoplankton in several ways but is most important for facilitating photosynthesis by contributing to chlorophyll structure. Chlorophyll is the pigment used to capture sunlight for photosynthesis within plants and without it, the process is impeded. Several studies have confirmed the importance of iron for production to occur (Behrenfeld et al. 1996, Landry et al. 2000).

The Galápagos archipelago is a unique biological "hot spot" within this large HNLC region due to an influx of iron into the system, which comes from the islands themselves. This iron enhancement called the island-mass effect (Gordon et al. 1998, Palacios 2002, Pennington et al. 2006). The availability of iron enables phytoplankton to sustain high levels of productivity in the shallow-water marine ecosystem surrounding

Galápagos (Figure 2). When conditions are good and a large number grow and reproduce in a short time frame, seasonal phytoplankton blooms occur. Locally high production forms the basis of the marine food web and attracts organisms of all trophic levels to the area to feed including invertebrates, reef fishes, and apex predators. Presently, there are 128 families of fishes known in Galápagos, with approximately 13.6% endemic species (McCosker and Rosenblatt, 2010).

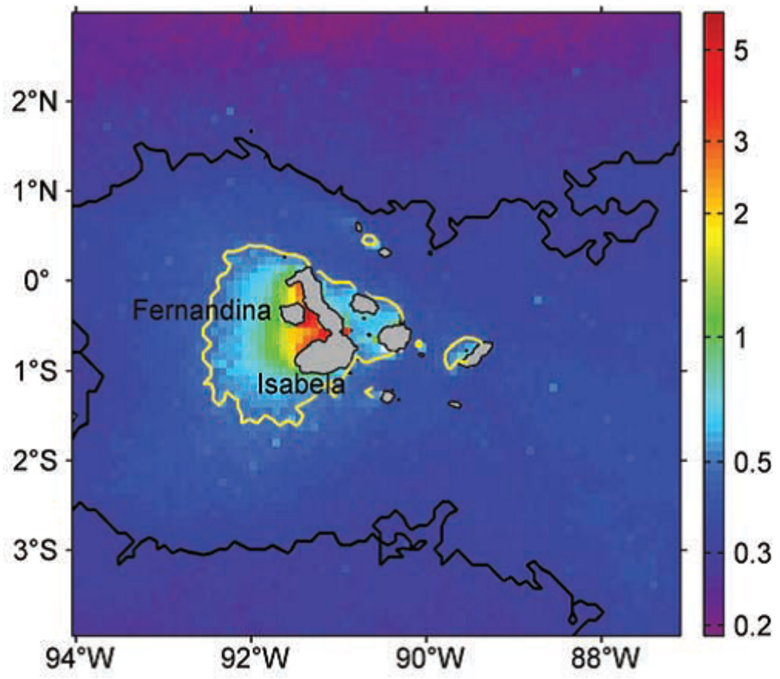


Figure 2. Average chlorophyll-*a* (chl-a) levels around the Galápagos Islands from September 1997 to June 2002 derived using SeaWiFS. From Palacios 2002.

The unique relationship between the ocean, land, and the diversity of life is the reason that the Galápagos Islands are one of the most unique ecosystems on Earth. A close relationship exists between the terrestrial and marine ecosystems in Galápagos. Many species that reproduce on land, such as seabirds, depend on food sources from the marine environment, and the high levels of marine productivity stimulate a healthy terrestrial ecosystem (Kenchington 1989). Historically, there has been much interest in Galápagos for its unique landscape and variety of exotic flora and fauna. The islands' most famous visitor, Charles Darwin, was so inspired during his 19th century visit that he used ideas and data collected from Galápagos while developing his theories of evolution and natural selection. He found that "the natural history of these islands is eminently curious, and well deserves attention" (p. 363, *Voyage of the Beagle*). Modern interest in the Galápagos has continued for tourism, economics, conservation, and scientific studies.

The Galápagos Marine Reserve

The Government of Ecuador established the Galápagos Marine Reserve (GMR) in 1998 to protect marine biodiversity around the archipelago. The GMR includes the islands and marine territory within forty nautical miles of a baseline drawn around the outermost points of the islands (Figure 3). It includes approximately 138,000 km^2 of marine protected area (Jennings et al. 1994, Edgar et al. 2004c, Edgar et al. 2008). Prior to the creation of the GMR in 1998, multiple qualitative studies were conducted on fish, coral, and invertebrate populations in the shallow waters around the Galápagos (Glynn and Wellington, 1983, McCosker and Rosenblatt, 1984).

Since the GMR was created, Ecuador has endeavored to manage the abundance and diversity of the marine ecosystem around the Galápagos and protect it against harm due to human activities. With the creation of the GMR came the need to implement an effective management scheme for the reserve. In 1999, a GMR Management Plan was created by members of the Ecuadorian government, the inhabitants of the Galápagos, and the international scientific community. Zones were established according to the amount of human activity they allowed: from general use zones for tourism to strict no-take zones where only scientific use is allowed (Kenchington 1989, Edgar et al. 2004c). This zoning plan is still considered preliminary until more data regarding the distribution of resources and biodiversity in the marine ecosystem can be collected and zones can be created that best represent conservation needs around the GMR. There exists a need to collect detailed data on the spatial distribution and abundance of faunal species around Galápagos to create the best policy possible (Edgar et al. 2008).

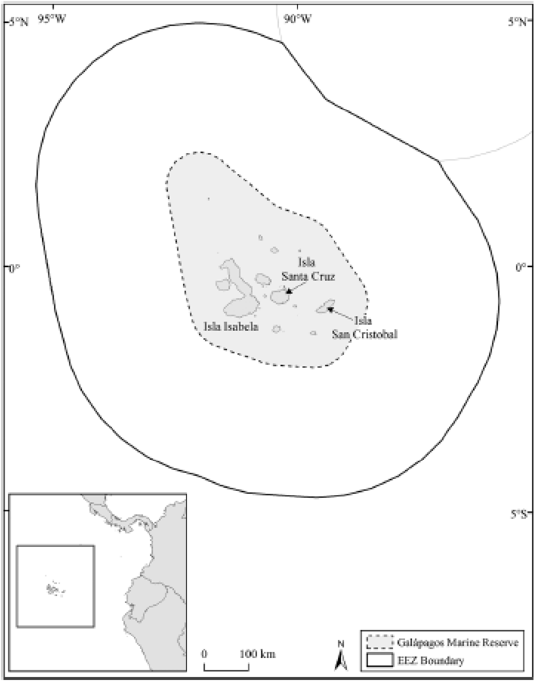


Figure 3. The Galápagos Marine Reserve includes inland waters of the islands and seas extending out to 40 nautical miles for a total area of approximately 138,000 km^2. Adapted from Schiller et al. 2014.

Underwater visual surveys

The advancement of the SCUBA (self-contained underwater breathing apparatus) technology in the second half of the 20th century allowed scientists access to many previously unexplored places in the ocean. Being able to use SCUBA systems revolutionized the way scientists were able to explore the ocean and allowed scientists to directly observe the behavior and ecology of underwater faunal species in their natural habitats (Witman et al. 2013). Conducting an underwater visual survey is a non-invasive and non-destructive method to gather data on fish assemblages in order to make estimates about density of underwater species (Sale and Sharp, 1983). In particular, SCUBA has been instrumental in broadening our knowledge of coral reefs and reef fish ecology. Much of the literature produced on reef fish ecology in the past few decades has been studies that incorporated SCUBA into data collection (Carr et al. 2013).

Underwater surveys and observations of various floral and faunal species in Galápagos have taken place since the mid-1940's. More detailed, quantitative surveys of ichthyofauna have been conducted within the last quarter century as the need to assess baseline conditions arose after the GMR was created (Edgar et al. 2008). In 1991, Jennings et al. sought to describe fish assemblages within specific areas proposed in the zoning scheme of the GMR (at time of the study, a zoning scheme had yet to be formally adopted by the GMR). They conducted visual surveys in ten sites around the archipelago and provided fish abundance estimates for diurnal species. Their results supported the zoning of the GMR as it was proposed at the time and they suggested future studies to examine whether factors such as temperature, productivity, or recruitment determine fish assemblage structure.

In 2004, Edgar et al. conducted a broad-scale ecological survey of reef fishes and macro-invertebrates at over fifty different islands and islets around Galápagos. One goal of this survey was to provide a baseline data set to assess long-term changes in different zone types in the GMR. From their data, they were able to map out regional fish biogeography and biodiversity as they varied within the archipelago. They identified five major marine bioregions around the islands and examined regional patterns of biodiversity of fish and invertebrates. They suggested that the GMR reconsider zoning efforts to focus on the five biogeographical regions that they identified.

As pointed out by Edgar et al. (2004a), there have been few similar studies conducted in Galápagos to examine fish assemblages using underwater visual survey methods. This thesis aimed to enhance this body of knowledge by performing a study similar in scope to Jennings et al. (1994) and to assess how fish populations around the islands may or may not have changed since Edgar et al. (2004a) published their results. This project was conducted over three visits to Galápagos: May-June 2013, November 2013, and July 2014. During 2013, data on fish assemblages were collected across fourteen islands so that spatial trends could be assessed. During 2014, data were collected on Isla San Cristóbal in two locations that were surveyed the year before in order that fish assemblage composition could be compared throughout time.

This thesis focused on fishes that live in rocky habitats near the bottom rather than pelagic species. It must be noted that "reefs" in Galápagos are unlike textbook coral reefs which may be dominated by hard and soft corals. Reefs in Galápagos are composed of scleractinian (hard) corals which often exist in scattered colonies with low species diversity. In general, coral reefs in the eastern Pacific are small and structurally simple compared to other reef systems due to isolation, extreme environments, frequent perturbances, and size of suitable habitats (Cortes 1997). Existing coral reefs in Galápagos are being destroyed by bioeroders such as sea urchins, and they are slow to recover due to low larval recruitment (Reaka-Kudla et al. 1996, Glynn and Ault, 2000). Therefore, this study examined fish species which live in assemblages at inshore rocky/sandy habitats near the seafloor rather than on traditional coral reefs. It is the hope that data from this thesis can contribute new information about fish assemblages around the GMR to be used for conservation purposes.

Satellite data

This thesis also describes physical and biological oceanographic conditions around Galápagos by collecting SST, ocean color, and sea surface height (SSH) data via satellites. Satellites in orbit around Earth are particularly useful in oceanography because of their ability to collect large spatial amounts of data. Using data collected from three satellites, information on ocean conditions around Galápagos during the time of survey were incorporated into analysis to gain a better understanding of ecosystem-wide processes that may affect fish assemblage composition.

SST can be measured via satellite through use of infrared sensors which measure the amount of infrared waves (wavelength = 11 microns) that reflect off of the ocean surface after visible light has been absorbed. The accuracy of this method depends on the level to which the sensors on the satellite are calibrated and corrections made for intervening effects of the atmosphere. Clouds are a prime problem for obtaining accurate SST data as they can block radiation from returning to the satellite. This can be solved by making a composite image using data from several passes of the satellite, as clouds are often temporary (Uddstrom and Oien, 1999, Emery and Thomson, 2001). SST and SST anomaly data for this thesis were generated by the Instituto Oceanográphico de la

Armada del Ecuador (INOCAR), who process weekly and monthly SST and SST anomaly data around the ETP from a variety of sources.

Biological productivity can be estimated with satellite data by looking at ocean color. Ocean color can give information about the amount of living organisms in the water. Chlorophyll-a (chl-a) can be used as an indicator for the amount of plankton in the ocean, as all phytoplankton incorporate chlorophyll pigments to perform photosynthesis. Satellites can collect data on ocean color by measuring the amount of, and several ratios among, backscattered green and blue wavelengths of visible light (wavelength = 0.4-0.6 microns) measured via radiometer. Data collected are also subject to problems such as backscatter and cloud cover. Composite imaging may help alleviate problems with the data (Thurman and Trujillo, 2003, Garrison 2006). Ocean color data for this thesis was collected from the MODIS (Moderate Resolution Imaging Spectroradiometer) Aqua 9km satellite using the GIOVANNI Interactive Visualization and Analysis tool from NASA’s Goddard Earth Sciences Data and Information Services Center.

Sea surface height (SSH), or ocean topography, can be measured by active satellites that bounce radar waves off the ocean surface immediately below their orbit. By measuring the speed at which electromagnetic waves return to the satellite, distance from the satellite to the ocean surface is measured. SSH is calculated by taking observed sea surface levels and subtracting them from an equilibrium surface called the geoid. The geoid is a surface that corresponds to the ocean surface at rest. Since the ocean has many dynamic processes occurring, geoid undulations occur. The deviation of sea level from the geoid is defined as ocean topography (Stewart 2005, Segar 2007).

Programmers are able to remove dynamic ocean and atmospheric processes from the data record to determine which differences in SSH may be caused by heating and cooling of water masses. Today's satellites have high enough resolution to measure small-scale ocean processes such as transport of warm surface waters during an ENSO event. If water masses below the satellite are warmer and less dense, they will have a higher SSH or topography then colder and more dense water masses. In this way, satellites calculate SSH and examine how much heat is being stored in the upper layers of the ocean. SSH anomalies indicate whether warmer or cooler water masses are present relative to average conditions in an area (Emery and Thomson, 2001, Steward 2005, Garrison 2006). SSH data were collected from a variety of satellite databases using the Colorado Center for Astrodynamics Research (CCAR)'s Global Historical Gridded SSH Data Viewer.

Objectives and hypotheses

Objectives

1) To collect data on the geographic distribution and relative abundance of fish species at areas around the GMR
2) To determine the relationship, if any, between the oceanographic conditions and the composition of fish assemblages

3) To compare data over time by sampling at repeated locations on Isla San Cristóbal and by comparing my results with those of Jennings et al. (1994) and Edgar et al. (2004a)

Null hypotheses

1) Different areas around the GMR will show no difference in the distribution and abundance of fish species (they do not vary spatially)
2) Distributions and abundances of fish assemblages do not change with time
3) There is no relationship between fish assemblage composition and oceanographic conditions

CHAPTER II

SPECIES RICHNESS AND OCEAN CONDITIONS AROUND THE GALÁPAGOS ARCHIPELAGO IN 2013

Survey sites and methods

To compare fish assemblage abundance and distribution throughout Galápagos, qualitative data on the distribution and relative abundance of fish species in Galápagos were collected during two periods: 16-30 May 2013 and 16-19 November 2013. With the cooperation and support of the Oceanographic Institute of the Ecuadorian Navy (INOCAR), fourteen sites at six islands of the archipelago were surveyed: Islas Santa Cruz, San Cristóbal, Floreana, Isabela, Seymour, and Wolf (Table 1 and Figure 4). Data were collected using underwater visual survey methods in inshore rocky reef habitats across the Galápagos Marine Reserve (GMR).

Table 1. 2013 underwater survey site locations across the Galápagos archipelago

Site Code	Location	Position		Date of Survey
FL1	Floreana	S 01°13.202'	W 90°26.861'	16-5-2013
FL2	Floreana (Punta Cormorant)	S 01°13.236'	W 90°25.80'	16-5-2013
FL3	Floreana (Post Office Bay)	S 01°27.963'	W 90°49.172'	17-5-2013
SZ1	Santa Cruz (Academy Bay)	S 00°74.832'	W 90°30.456'	20-5-2013
SZ2	Santa Cruz/Baltra (Itabaca channel)	S 00°28.861'	W 90°15.138'	21-5-2013
SZ3	Santa Cruz (Las Bachas)	S 00°29.250'	W 90°20.698'	21-5-2013
IS1	Isabela (Tortuga Island)	S 00°96.857'	W 90°97.078'	24-5-2013
IS2	Isabela (Puerto Villamil)	S 00°97.181'	W 90°95.603'	24-5-2013
SC1	San Cristóbal (Kicker Rock)	S 00°46.764'	W 89°31.098'	29-5-2013
SC2	San Cristóbal (Bahía Tijeretas)	S 00°53.255'	W 89°36.434'	30-5-2013
WF	Wolf	N 01°22.519'	W 91°49.074'	16-11-2013
SE	Seymour	S 00°23.599'	W 90°17.342'	18-11-2013

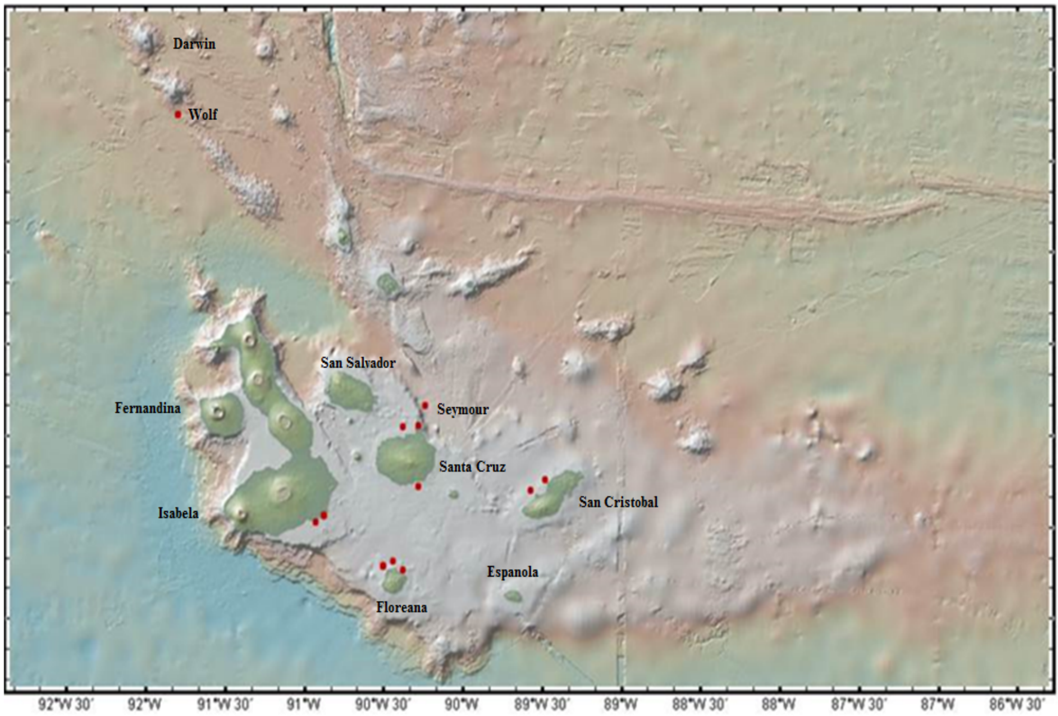


Figure 4. **2013 underwater survey site locations around Galápagos. Red dots indicate survey locations. Island names are written in black. Image created using GeoMapApp.**

The locations for underwater surveys were determined on an opportunistic basis while working with INOCAR. All surveys were conducted during daylight hours by two or more SCUBA divers. If the survey was performed where an Ecuadorian Navy buoy was present, divers began surveying where the buoy's mooring line was anchored to the seafloor. If no buoy was present, divers descended to the seafloor and began the survey at a chosen starting point.

Visual survey methods for this thesis were adapted from Jennings et al (1994), Bohnsack and Bannerot, (1986), Samoilys and Carlos, (2000), and Edgar et al. (2004a, b). Surveys were conducted using a point-count survey method where density of faunal species was estimated by a diver scanning 360° from a fixed point. This method allowed divers to estimate the number of fish in an area by counting individuals in the survey site (Sale and Sharp, 1983). A minimum of two divers were used to collect data for each survey; a primary diver who settled at the center point with an underwater notepad and a secondary diver who marked out a 7m radius around the center point with a retractable tape measure. This 7m radius gave each survey site an approximately 150m^2 survey area. The primary diver began the survey by visually identifying all fishes around the starting point while the secondary diver swam in a circle and maintained contact with the 7m survey line. This served to let the primary diver know where the boundary of the survey area was at all times. Once the primary diver identified all fishes around the starting point, she/he traded places with secondary diver and swam along the 7m edge of the survey area. Switching places and swimming along the periphery allowed the primary diver visual access to the entire survey area and all the fish species within it.

During surveys, species were identified by scientific nomenclature as well as common names as used in Humann and DeLoach, (2003). The relative abundances of fish species seen were recorded and abundance estimates were classified into four groups: One (one individual seen), Few (2-10 individuals seen), Many (11-100 individuals seen), or Abundant (100+ individuals seen). Abundance estimates were collected using the Reef Environmental Education Foundation (REEF) fish abundance classification system. Only fish species that could be positively identified were recorded. Juveniles and adults of identified species were recorded together during surveys.

When available, a third diver utilized a GoPro underwater video camera to collect images of the fish and benthic environment at some sites, providing permanent record of the fish and benthic environmental conditions that could be analyzed later to supplement data collected *in situ.* In addition to fish species and abundance estimates, qualitative ecological data were collected on the type of substrate at each site, as well as presence or absence of invertebrates. Salinity, depth, and temperature were also collected at each site using a YSI salinity meter and a Sherwood Amphos dive computer.

Presence/absence data for all fish species and relative abundance at each dive site were recorded into a spreadsheet using Microsoft Excel. The number of species seen at each dive site was totaled and the number of dive sites where each species occurred was counted. Rank Order of Abundance (ROA) summary rankings were assigned to the ten most commonly seen species across all survey sites. Video data were analyzed post hoc to ensure the survey data were accurate. Using the Paleontological Statistics software package (PAST), hierarchical cluster analysis and principal coordinates analysis (PCO) were performed using several similarity indices and clustering algorithms. These methods were used to explore similarity between sites and to visualize trends and groupings of fish assemblages at each site (Hammer et al. 2001) Abundance data for the ten most common species were used for tests of similarity (hierarchical cluster analysis and PCO). Satellite data were collected and analyzed to compare oceanographic conditions around Galápagos in May and November 2013.

Results

In total, 60 species from 32 families were identified at 12 survey sites across the GMR during the two survey periods in 2013 (Table 2). Most species seen were diurnally active, non-cryptic fishes. At each dive site, the number of species recorded ranged from 2-29. The site that had the most species seen was SE (Isla Seymour), where 29 different species were recorded. One dive at Isla Santa Cruz (Academy Bay) was removed from analysis due to the fact that no species were observed there and another dive at Isla Santa Cruz (Gordon Rocks) was removed from analysis because qualitative data were not able to be taken.

Table 2. **Presence-absence matrix of 60 fish species at twelve survey sites across the Galápagos archipelago. Survey sites listed under dive code as described in Table A.“1” indicates presence at dive site, blank space indicates absence at dive site.**

Family name	**Species name**	**FL1**	**FL2**	**FL3**	**SZ1**	**SZ2**	**SZ3**	**IS1**	**IS2**	**SC1**	**SC2**	**WF**	**SE**	**Total sightings**
Acanthuridae	*Prionurus laticlavius*					1	1	1	1	1		1		6
Aulostomidae	*Aulostomus chinensis*							1						1
Balistidae	*Canthidermis maculatus*											1		1
	Melichthys niger											1		1
	Sufflamen verres												1	1
	Pseudobalistes naufragium												1	1
	Balistes polylepis												1	1
Blenniidae	*Ophioblennius steindachneri*						1	1		1		1		4
	Plagiotremus azaleus								1					1
Carangidae	*Seriola rivoliana*											1		1
Carcharhinidae	*Triaenodon obesus*							1		1			1	3
Chaenopsidae	*Chaenopsis schmitti*		1											1
Chaetondontidae	*Johnrandallia nigrirostris*			1			1			1	1		1	5
	Chaetodon humeralis					1	1						1	3
Cirrhitidae	*Cirrhitichthys oxycephalus*							1						1
Congridae	*Taenioconger klausewitzi*						1					1	1	3
Dasyatidae	*Dasyatis brevis*										1			1
	Taeniura meyeri												1	1
Eleotrididae	*Eleotrica cableae*						1							1
Fistulariidae	*Fistularia commersonii*												1	1
Gobiidae	*Elacatinus nesiotes*						1							1
Haemulidae	*Anisotremus interruptus*								1		1		1	3
	Juveniles		1				1							2
	Orthopristis forbesi					1							1	2
	Orthopristus cantharinus					1							1	2
	Haemulon scudderii					1							1	2
Kyphosidae	*Kyphosus elegans*											1		1
Labridae	*Halichoeres dispilus*			1	1	1	1	1	1	1	1		1	9
	Bodianus diplotaenia			1	1	1		1		1	1	1	1	8
	Thalassoma lucasanum					1	1	1	1					4
	Halichoeres nicholsi					1			1		1		1	4
Labrisomidae	*Labrisomus dendriticus*			1				1						2
Lutjanidae	*Lutjanus viridis*			1							1		1	3
Mullidae	*Mulloidichthys dentatus*												1	1
Muraenidae	*Muraena argus*						1						1	2
Ophichthidae	*Myrichthys tigrinus*					1								1
Opistognathidae	*Opistognathus galapagensis*						1							1
Pomacanthidae	*Holacanthus passer*					1		1		1	1	1	1	6
Pomacentridae	*Stegastes beebei*			1	1	1	1	1	1	1	1		1	9
	Abudefduf troschelii	1	1		1			1			1		1	6
	Stegastes arcifrons				1				1		1			3
	Chromis atrilobata						1			1				2
	Microspathodon bairdii				1									1
Scaridae	*Scarus ghobban*					1		1				1	1	4
	Scarus compressus					1								1
Serranidae	*Paranthias colonus*			1	1	1	1	1		1	1	1	1	9
	Serranus psittacinus			1	1	1	1	1	1		1		1	8
	Epinephelus labriformis			1	1	1	1			1	1		1	7
	Alphestes immaculatus			1		1								2
Sparidae	*Calamus taurinus*					1	1							2
	Archosargus pourtalesii						1							1
Sphyraenidae	*Sphyraena idiastes*												1	1
Synodontidae	*Synodus lacertinus*					1								1
Tetraodontidae	*Sphoeroides annulatus*	1	1	1	1	1	1		1		1		1	9
	Sphoeroides angusticeps												1	1
Tripterygiidae	*Lepidonectes corallicola*										1			1
	Total	2	4	11	10	21	20	15	10	11	16	11	29	

Of the 32 families recorded, six families are considered to be predatory: Aulostomidae (Trumpetfish), Carangidae (Jacks), Carcharhinidae (Requiem sharks), Fistulariidae (Cornetfish), Lutjanidae (Snappers), and Sphyraenidae (Barracuda). Seven families are omnivorous consumers which graze on algae as well as other prey items: Scaridae (Parrotfish), Chaetodontidae (Butterflyfish), Acanthuridae (Surgeonfish), Pomacanthidae (Angelfish), Pomacentridae (Damselfish), Sparidae (Porgies), and Blenniidae (Blennies). Large strands of algae were found to be present at 75% of survey sites, so the presence of omnivores was expected. Most families fell in the category of secondary consumers which consume small fish or invertebrates. In addition to reef fishes, predatory sharks were seen at sites IS1, SC1, and SE. A sea turtle was seen at site SC1 and *Zalophus wollebaeki* (Galápagos sea lions) were present at site SC2. Herbivorous invertebrates such as sea stars and sea urchins were also seen at nine survey sites. Thus, a wide range of trophic levels in the marine food web was represented in survey sites.

Ten species were found to be present at six or more dive sites: *Sphoeroides annulatus* (Bullseye puffer), *Stegastes beebei* (Galápagos ringtail damselfish), *Paranthias colonus* (Pacific creolefish), *Halichoeres dispilus* (Chameleon wrasse), *Bodianus diplotaenia* (Mexican hogfish), *Serranus psittacinus* (Barred serrano), *Epinephelus labriformis* (Flag cabrilla), *Abudefduf troschelii* (Panama sergeant major), *Prionurus laticlavius* (Razor surgeonfish), and *Holacanthus passer* (King angelfish). From here on, these species will be referred to as the 10 most common species seen during the underwater surveys. Of these 10 common species, *S. annulatus, S. beebei, P.*

colonus, and *H. dispilus* were the most frequently seen, being recorded at 9 of 12 (75%) dive sites. Of the 10 common species, *P. laticlavius, H. passer, A. troschelii,* and *S. beebei* are omnivorous and eat both algae and small invertebrates. The rest of these species are carnivorous and feed on prey items such as plankton, invertebrates, or small fishes.

To examine abundance of different fish species in observed assemblages, ROA was assigned to each of the ten most common species seen for each dive site (Table 3). Average ROAs showed that of these ten most common species, some were more likely than others to be seen in larger numbers during surveying. The species with the highest average ROA was *P. laticlavius* with 2.3. This indicates that if *P. laticlavius* were seen at a dive site, they would most likely be seen in an aggregation of 2-10 individuals. Conversely, *E. labriformis* had the lowest average ROA with 0.8, indicating that, on average, only one individual of this species was seen at each site. Six species (*S. annulatus*, *S.beebei*, *H. dispilus*, *S. psittacinus*, *A. troschelii*, and *P. laticlavius*) were recorded to have mid-range average ROAs of 1.1-1.8 (Table 3), meaning that these species were seen at several dive sites during summer 2014. When these individuals were seen at dive sites, they were recorded as having ROA's from 1.0 (one individual) to 4.0 (groups +100 individuals).

Table 3. ROA of the ten most commonly seen species at each survey site in 2013. "blank" = no individuals seen, "1" = 1 individual seen, "2" = 2-10 individuals seen, "3" = 11-100 individuals seen, "4" = >100 individuals seen

Species	FL1	FL2	FL3	SZ1	SZ2	SZ3	IS1	IS2	SC1	SC2	WF	SE	Average
Paranthias colonus			3	2	3	2	3		3	4	4	4	2.3
Stegastes beebei			3	3	2	2	4	2	1	2		2	1.8
Prionurus laticlavius					3	2	3	4	3		4		1.6
Serranus psittacinus			2	2	2	2	3	2		2		2	1.4
Halichoeres dispilus			2		2	2	2		2	2		3	1.3
Sphoeroides annulatus	2	2	2	1	2	1		1		1		2	1.2
Abudefduf troschelii	3	2		2			2			2		2	1.1
Bodianus diplotaenia			1	1	1				3	1	2	2	0.9
Holacanthus passer					1		2		3	1	2	2	0.9
Epinephelus labriformis			1	1	1	2			2			2	0.8

To explore the data further in terms of spatial relationships, survey sites were grouped together to determine the similarity of their assemblages. First, hierarchical cluster analysis was used to identify groups in a dataset based on a given similarity measure. Figure 5 shows the result of site groupings based on cluster analysis using the unweighted pair-group average (UPGMA) clustering algorithm and Bray-Curtis similarity. Using these methods, clusters of similarity were joined based on the average of all possible distances between members of the groups. A dendrogram was created that visually depicts distances from the clustering algorithm and similarity measures. The closer to one another that two sites appear on the dendrogram, the more similar their assemblages were found to be. Branching points in the dendrogram indicate the degree of separation between clusters. The cophenetic correlation coefficient was reported to describe how completely the dendrogram represents actual similarities in the dataset compared to observed similarity (Michie 1982, Hammer et al. 2001).

The site groupings which had the highest similarity to one another were sites FL3/SZ2, SC2/SE, and FL2/FL1. All of these groupings had a similarity of 0.8 or higher on the dendrogram (Figure 5). The only pair of these groupings that were conducted at the same island was FL2/FL1. Several survey sites that were conducted in near geographic proximity to one another had a relatively high similarity on the dendrogram. These sites were still similar to one another, but branching points between them appeared further down on the dendrogram, indicating a lower value of similarity. As previously stated, sites FL1 and FL2 returned a similarity of 0.8 (Figure 5). Site SZ3 had a similarity of approximately 0.75 with the grouping of sites SZ2/FL3, and site SZ1had a similarity of 0.65 with the grouping of sites SZ2/SZ3 and other locations. Site IS2 had an approximate similarity of 0.45 with the grouping of site IS1 and other locations.

In other words, fish assemblages at the locations with higher similarity were more similar to one other than they were to other locations. Furthermore, the location of the branching point of Sites FL1 and FL2 away from the other sites implies that not only were their assemblages similar to one another, but that they were very different from dives conducted at other locations. These groupings suggest that most assemblages were different among geographically separated locations.

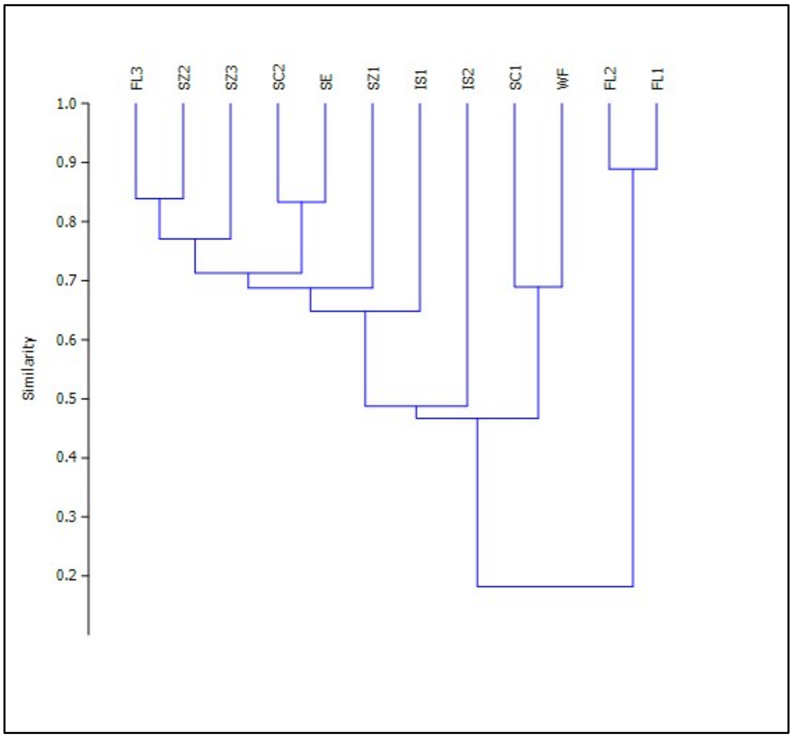


Figure 5. Dendrogram displaying survey site groupings as formed by cluster analysis using UPGMA clustering algorithm and Bray-Curtis similarity. Cophenetic correlation coefficient: 0.9063.

There were a few sites that did not cluster together as predicted in the dendrogram. Dives at sites SL1 (Isla San Cristóbal) and WF (Isla Wolf) were conducted in very different geographic locations yet were found to have an approximately similarity of 0.7. Site SL3 (Isla Floreana) clustered with site SZ2 (Isla Santa Cruz), rather than with the other two dives performed around Floreana. Sites SC2 (San Cristobel) and SE (Seymour) were also one of the groups found to have the highest similarity above 0.8. These way these groupings fall on the dendrogram suggest that factor(s) other than geographic location may be having an effect on fish assemblage composition.

PCO was also performed on the data to further examine similarity of fish assemblages between survey sites. This ordination method projects the dataset into multiple dimensions in order to visualize trends and groupings between survey sites. PCO uses distance between survey sites to reflect similarity of their assemblages and places them around two principal axes for visualization. The Bray-Curtis similarity index was again selected at the similarity index for consistency with the cluster analysis.

As seen in Figure 6, survey sites were clustered based on their similarity around two principal axes. The closer together that sites are clustered to one another on the PCO plot designates higher similarity in their assemblages. The farther away that a site is located from the center (0, 0) and the direction of the plot indicates the amount of variance in the data that can be seen by either coordinate axis. Each coordinate axis has an eigenvalue associated with it that indicates the amount of variation in the data explained by that axis (Hammer et al. 2001).

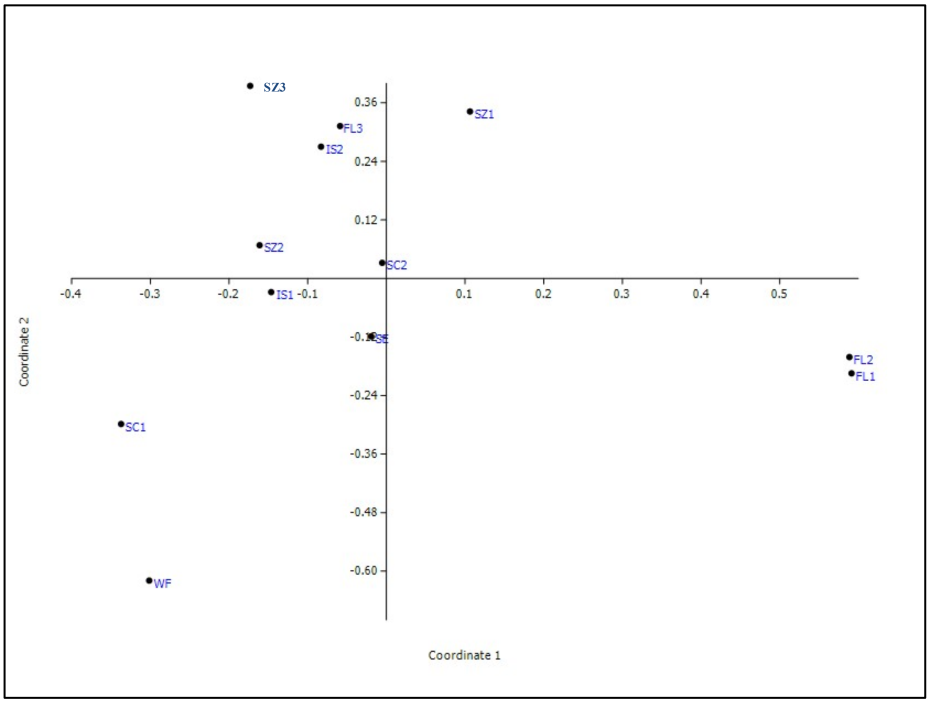


Figure 6. **PCO plot showing survey site groupings using Bray-Curtis similarity.**

As seen in the cluster analysis, several dive sites with close geographical proximity to each other emerge closely together on the PCO plot. Sites FL1 and FL2 (Isla Floreana) are clustered close together but are far apart from most of the other survey sites, which are relatively concentrated around the center and top axis (Figure 6). This suggests that sites FL1 and FL2 are different from all others and that a positive association with orthogonal coordinate axis 1 is leading to variation between sites. Site WF (Isla Wolf) plots far away from the center and is separated from the rest of survey locations by its strong negative association with orthogonal coordinate axis 1 and orthogonal coordinate axis 2, indicating fish assemblage at that location was found to be different from the other survey sites.

Oceanographic parameters were recorded along with fish identifications during each underwater survey. Dive sites ranged in bottom temperature from 17.8°C at Isla Wolf to 23.1°C at Isla Isabela. Dive sites ranged in depth from 7.0m at Isla San Cristóbal to 32.6m at Isla Wolf. Sites ranged in surface salinity from 34.8ppt to 35.8ppt (Table 4). All survey sites took place in habitats with substrate consisting of sand, rock, or a mixture of the two.

Linear regression models were calculated for bottom depth, bottom depth temperature, and surface salinity to examine functional relationships between oceanographic parameters and species richness at survey sites. The relationship between depth and species richness was not found to be significant with a p-value of 0.775 (Figure 7). The relationship between bottom temperature and species richness was not found to be significant with a p-value of 0.153 (Figure 8). The relationship between salinity and species richness was not found to be significant with a p-value of 0.113 (Figure 9). No relationships returned as significant, but positive functional relationships were found to exist between bottom temperature/surface salinity and species richness (Figure 7, 8).

Table 4. **Bottom temperature, bottom depth, surface salinity, and species richness for each survey location**

Site Code	Location	Species Richness	Bottom Temperature (°C)	Bottom Depth (m)	Surface Salinity (ppt)
FL1	Floreana	2	18.3	19.2	35.1
FL2	Floreana (Punta Cormorant)	4	19.4	17.7	35.2
FL3	Floreana (Post Office Bay)	11	21.1	13.1	35.3
SZ1	Santa Cruz (Academy Bay)	10	22.2	7.9	34.8
SZ2	Santa Cruz/Baltra (Itabaca channel)	21	22.2	16.2	35.4
SZ3	Santa Cruz (Las Bachas)	20	22.9	10.7	35.8
IS1	Isabela (Tortuga Island)	15	23.1	8.2	35.5
IS2	Isabela (Puerto Villamil)	10	22.8	7.3	35.5
SC1	San Cristóbal (Kicker Rock)	11	18.3	18.6	35.5
SC2	San Cristóbal (Bahía Tijeretas)	16	20.6	7	35.6
WF	Wolf	11	17.8	32.6	N/A
SE	Seymour	29	22.2	22.9	N/A

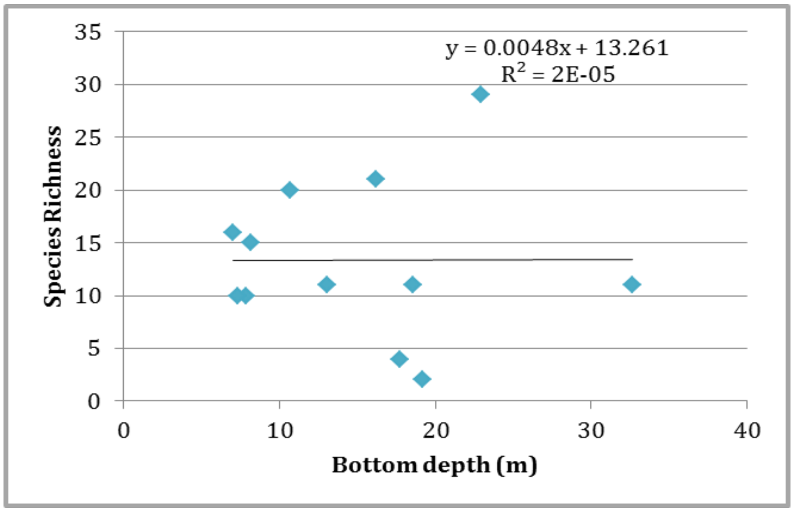


Figure 7. Relationship between bottom depth and species richness

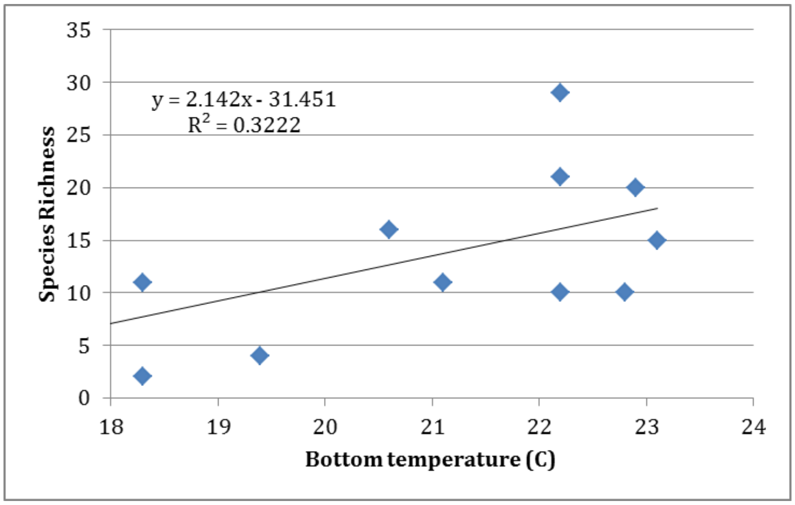


Figure 8. Relationship between bottom temperature and species richness

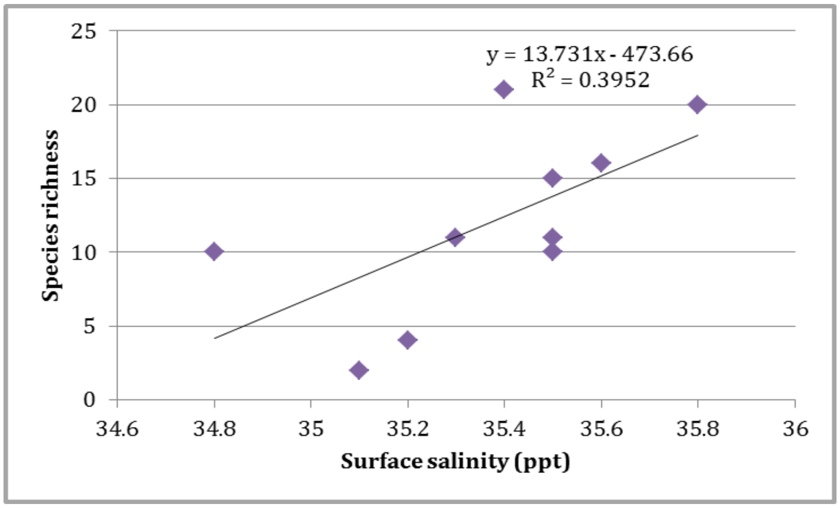


Figure 9. **Relationship between surface salinity and species richness**

Discussion

Spatial distribution of fish assemblages in 2013

The point-count visual survey method utilized for this study was the most effective strategy for collecting data over a wide spatial distribution while taking advantage of the time and resources made available to us by INOCAR. Biases associated with performing this type of survey include observer behavior, diver experience, accuracy of density estimates, and subjective identification of faunal species. Furthermore, fish behavior can have an effect on density estimates, due to the fact that some species may avoid divers underwater by hiding behind crevices or rock formations (Edgar et al. 2004b). Post hoc examination of video recorded during surveys helped to minimize errors in fish density estimates. Biases can almost never be completely eliminated, so it was the responsibility of the survey team to recognize that they exist and try to minimize their extent while performing surveys.

This 2013 survey recorded the presence of secondary consumers (omnivores), tertiary consumers (piscivores), and higher-order consumers (predators) in the marine ecosystem around the GMR. Our study recorded presence a range of trophic levels, including plants, invertebrates, herbivores, and marine mammals. Qualitative data were collected at all sites and quantitative data were collected whenever possible to calculate ROA for the ten most common species seen. Calculating ROA is important because it allows general conclusions about assemblages to be made based on abundance estimates from surveys. We seek to use ROA to predict which species could be more dominant than others in a particular geographic area. The species with highest average ROAs in this study, *P. colonus* and *P. laticlavius,* were the most abundant fishes seen at survey sites. Because ROA differed at every dive site, it is evident that species abundance was not uniform across all islands in the GMR.

My results showed that sites in geographic proximity sometimes clustered together in various tests of similarity. Figure 5 showed that some pairs of sites with surveys performed on the same island had relatively high values of similarity after being placed on a hierarchical cluster analysis dendrogram. Figure 6 highlighted several sites that showed difference in their assemblages from the other locations. In this figure, site WF (Isla Wolf) plotted far away from the rest of the survey locations. The fact that site WF is dissimilar to the other survey sites was expected due to Isla Wolf's northern geographic separation from the main Galápagos archipelago. It has been reported that fish assemblages at northern Islands Wolf and Darwin are unique from the rest of the islands (Grove and Lavenberg, 1997, Humann and DeLoach, 2003, Edgar et al. 2004a). Overall, these results do not support the null hypothesis that different areas across the GMR will show no difference in the distribution and abundance of fish species.

Using underwater transect surveys, Jennings et al. (1994) concluded that clearly identifiable and biologically distinct regions based on fish assemblage exist within the GMR. With their extensive underwater faunal surveys, Edgar et al. (2004a) divided marine ecosystems in Galápagos into three major biogeographical regions: 1) Far-northern (Darwin and Wolf) 2) Central, southern, and eastern 3) Western (Fernandina and Western Isabela) (Figure 10). Their study showed distinct assemblages at these three regions that enabled them to outline areas of highest conservation concern where endemic species are most abundant. This thesis confirms their findings that composition of fish assemblages varies by geographic location across the GMR.

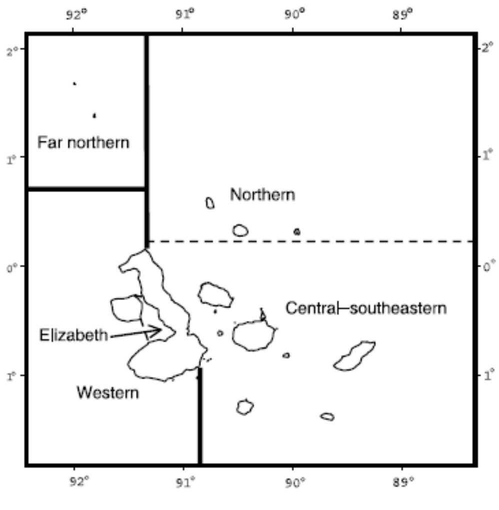


Figure 10. **Biogeographical regions in the GMR. From Edgar et al. (2004a).**

Oceanographic conditions, May 2013

During the three weeks during which the May 2013 surveys were conducted, the average SST in Galápagos was between 21-23°C (Figure 11). In terms of SST anomalies, conditions were normal to slightly cool conditions for May, ranging from 0 to -2°C (Figure 12). In May 2013 high chlorophyll-a concentrations were seen around most dive sites (excluding sites at Floreana), indicating increased levels of biological production across Galápagos (Figure 13). SSH anomalies (14cm) were more positive near the western end of the archipelago and more negative (-12cm) near the eastern end (Figure 14). This indicates less dense, warmer waters surrounding the western side of the archipelago and denser, colder waters surrounding the eastern side (relative to normal conditions). It must be noted that resolution on the Jason-2 satellite collecting SSH anomaly data were around 27.7km (15 nautical miles) while resolution on SST and ocean color and MODIS were around 4 and 9km. In Figure 18, SSH anomaly data are masked for some pixels at shallow locations among islands of the archipelago.

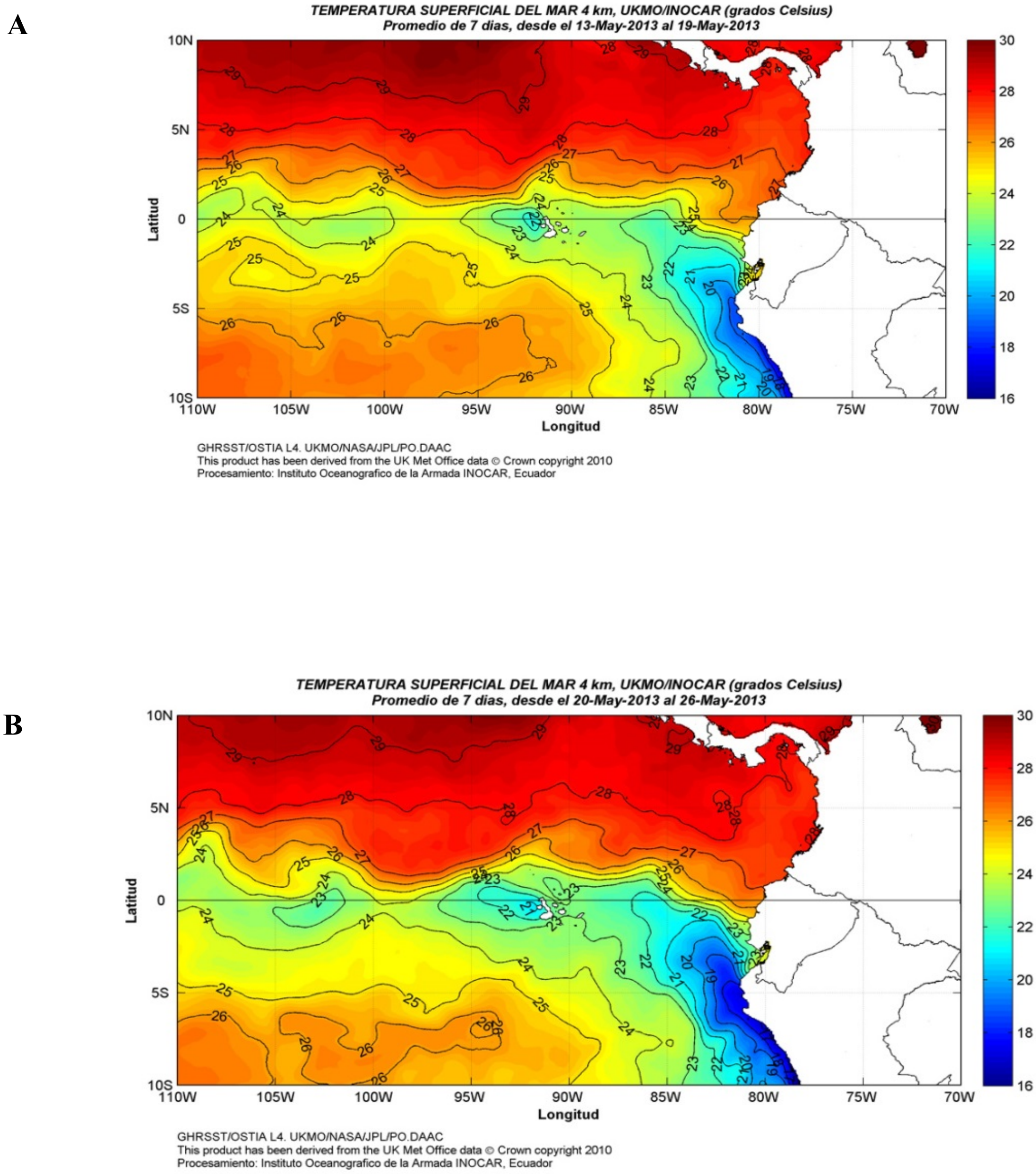
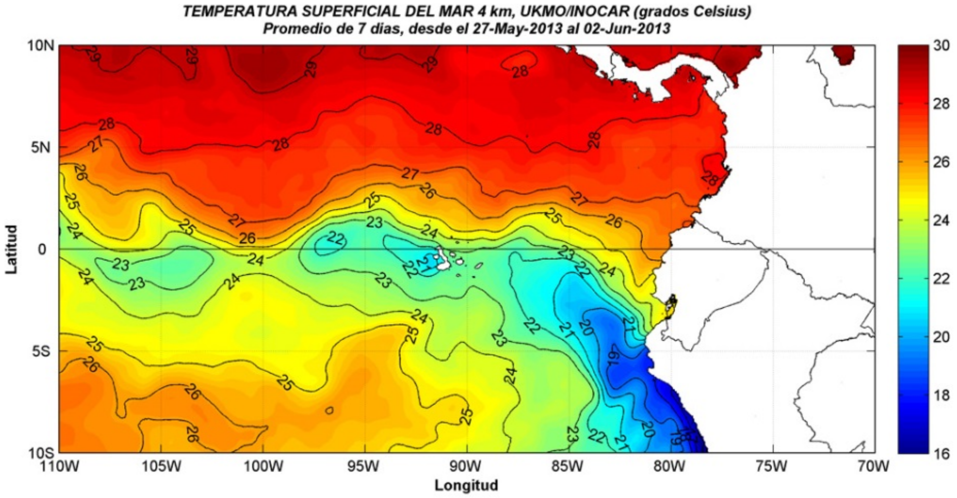


Figure 11. **Average SST around Galápagos in Summer 2013. (A) Week of 13-19 May 2013. (B) Week of 20-26 May 2013. (C) Week of 27 May-02 June 2013. Data displayed with 4km resolution. Satellite images courtesy of INOCAR.**

C

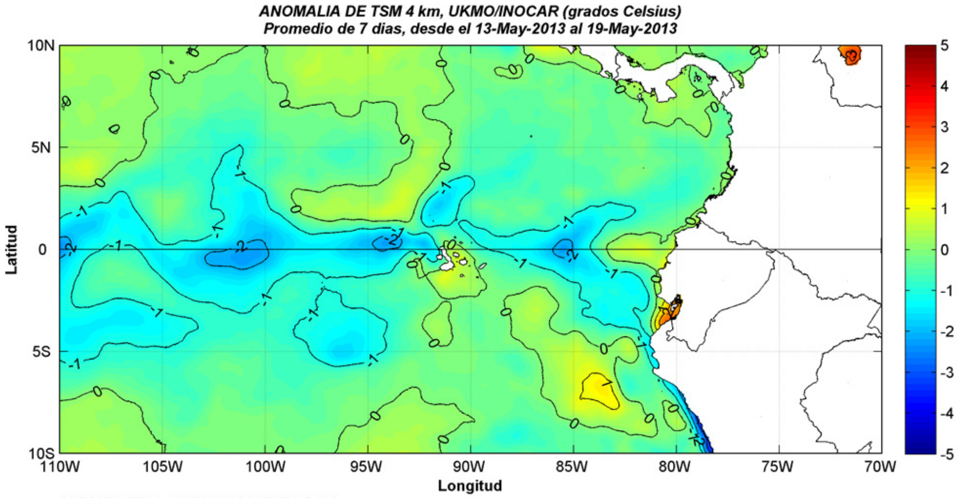


TEMPERATURA SUPERFICIAL DEL MAR 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 27-May-2013 al 02-Jun-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

Figure 11 Continued.

A



ANOMALIA DE TSM 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 13-May-2013 al 19-May-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
Anomalias de Temperatura segun Levitus/WOA-2005. Mes de definicion: Mayo
This product has been derived from the UK Met Office data © Crown copyright 2010
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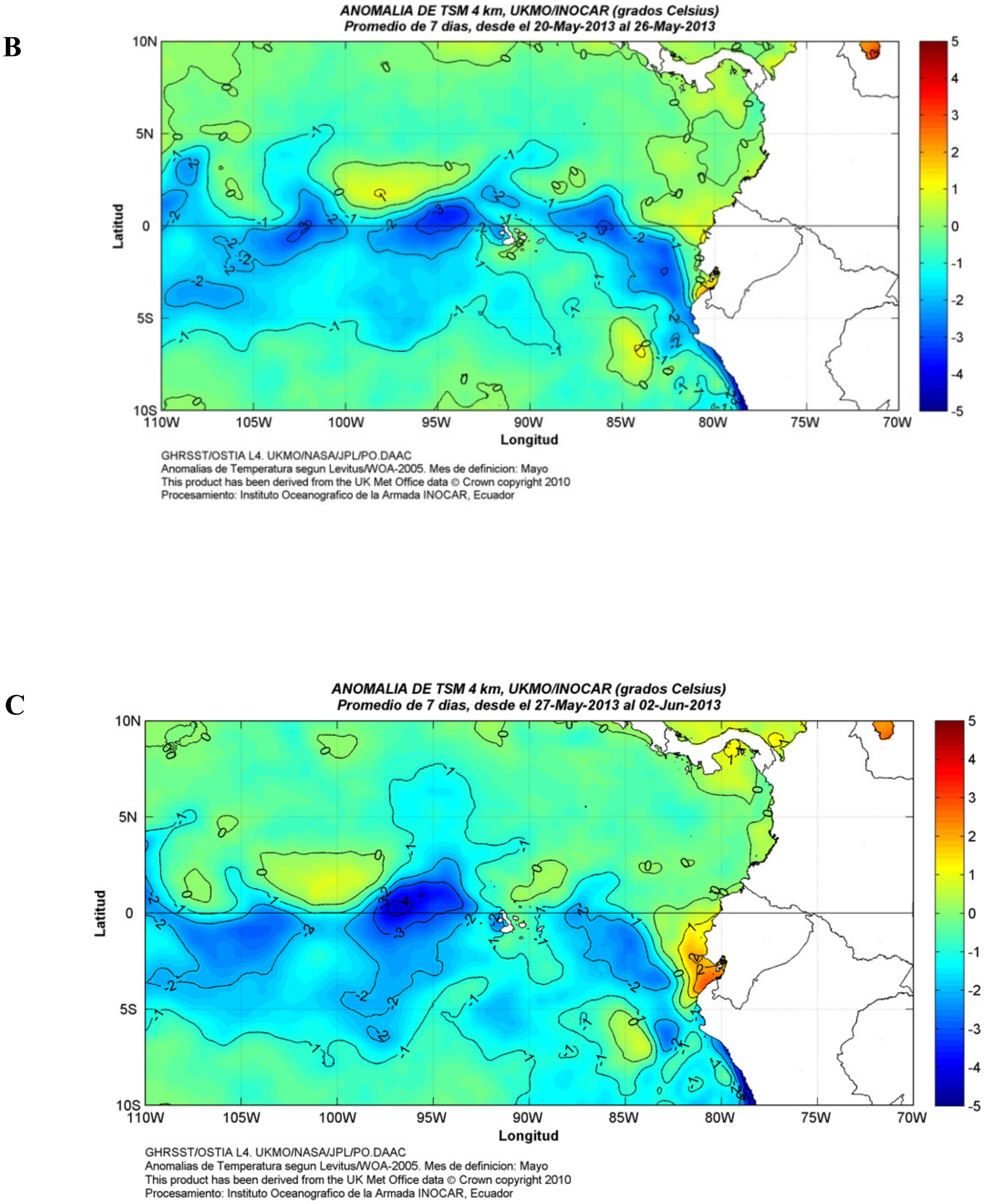
Figure 12. Average SST anomalies around Galápagos in Summer 2013. (A) Week of 13-19 May 2013. (B) Week of 20-26 May 2013. (C) Week of 27 May - 02 June 2013. Data displayed with 4km resolution. Satellite images courtesy of INOCAR.



B

ANOMALIA DE TSM 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 20-May-2013 al 26-May-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
Anomalias de Temperatura segun Levitus/WOA-2005. Mes de definicion: Mayo
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C

ANOMALIA DE TSM 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 27-May-2013 al 02-Jun-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
Anomalias de Temperatura segun Levitus/WOA-2005. Mes de definicion: Mayo
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Figure 12 Continued.

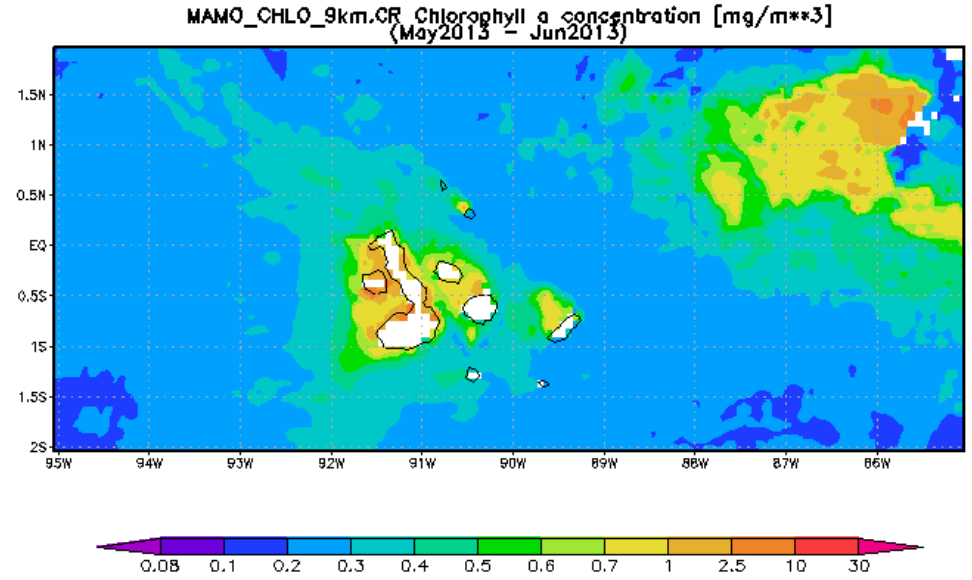


Figure 13. Chlorophyll-a concentration around Galápagos in Summer 2013. Data averaged from May-June 2013 and displayed with 9km resolution from MODIS-Aqua satellite. Image generated using GIOVANNI Interactive Visualization and Analysis tool.

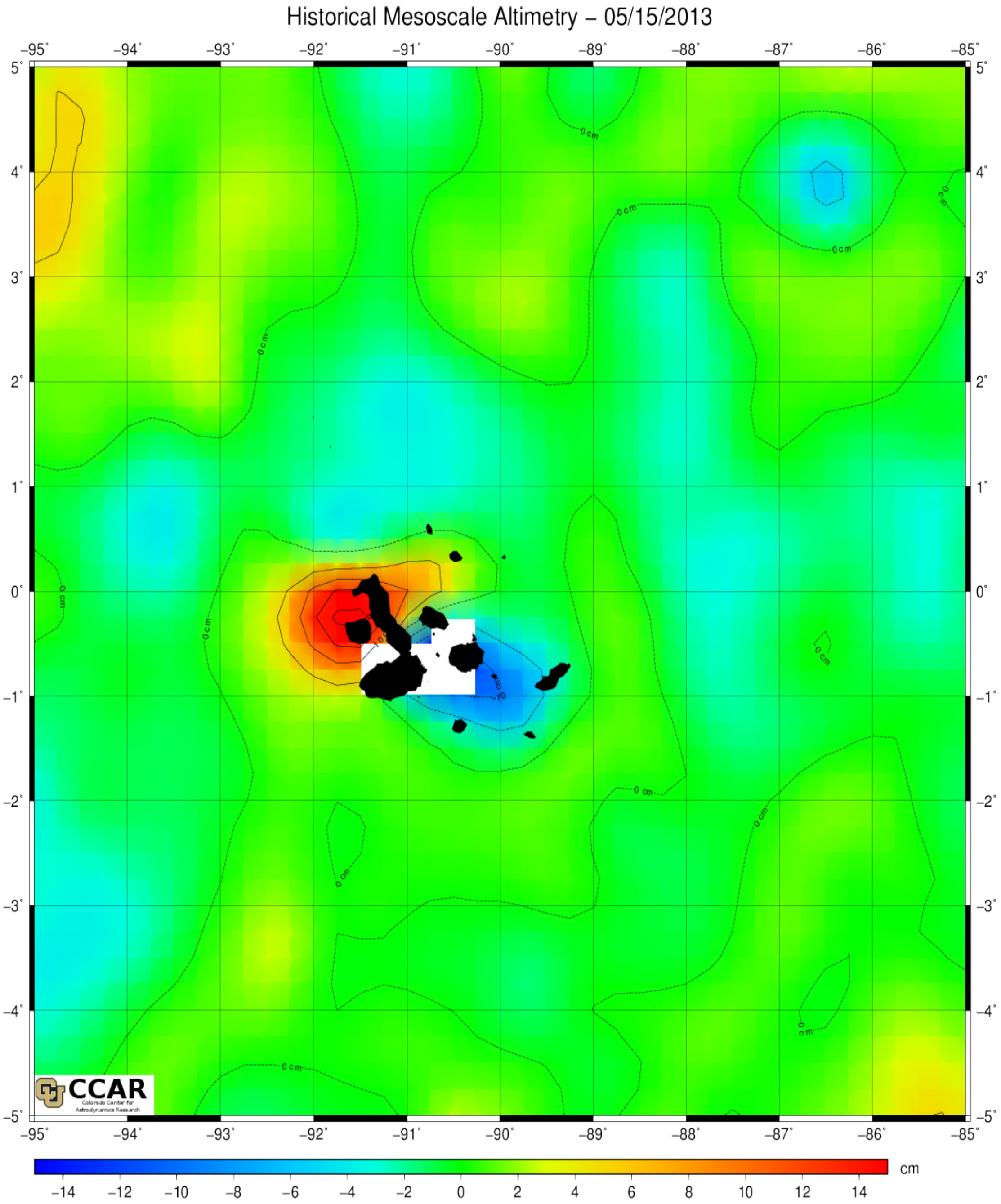
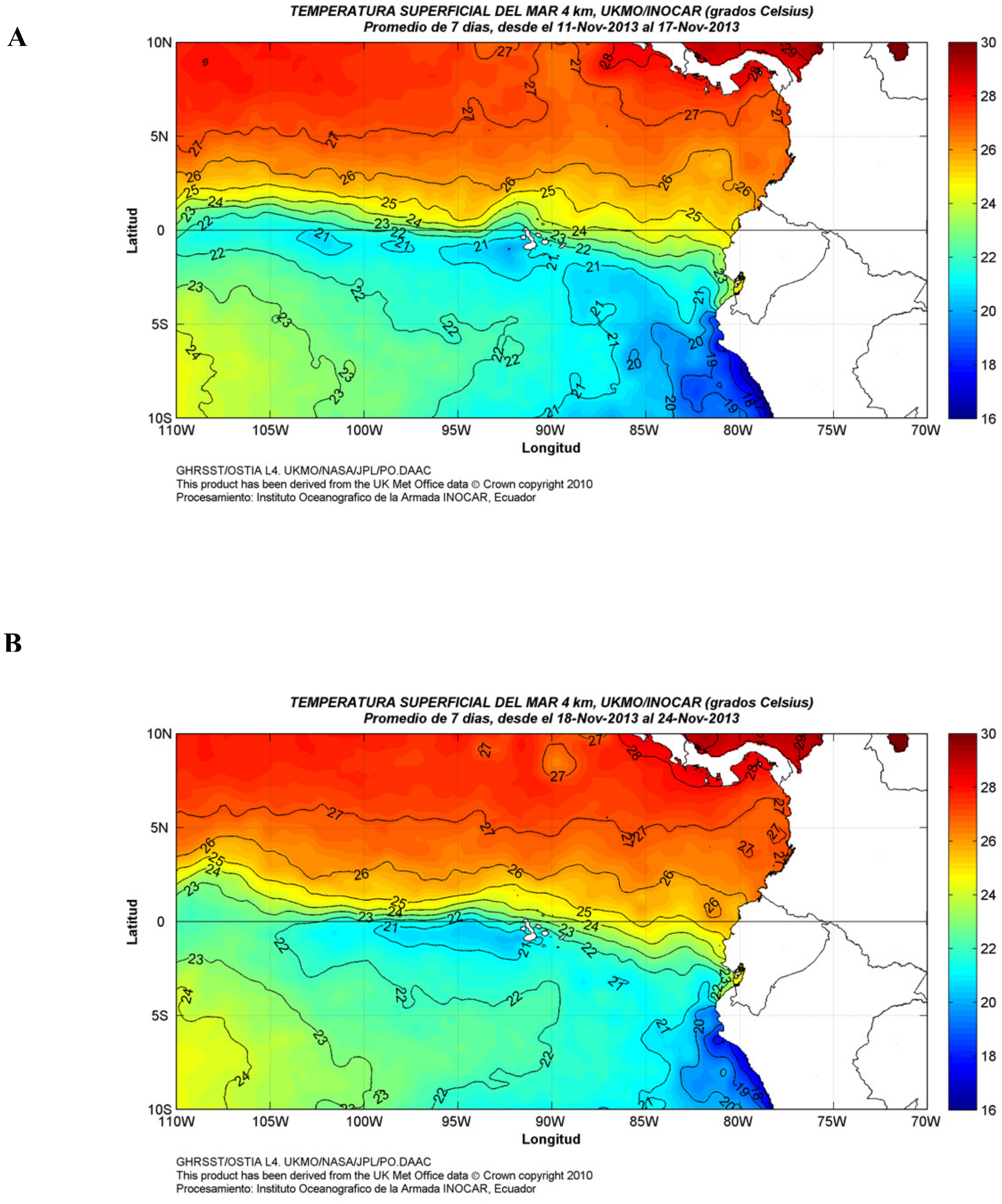


Figure 14. **SSH anomalies around Galápagos in Summer 2013. Data displayed with 22.5km resolution. Image generated using CCAR's Global Historical Gridded SSH Data Viewer.**

Oceanographic conditions, November 2013

During the middle of November 2013, the average SST in Galápagos was between 21-24°C (Figure 15). SST anomalies showed November temperatures were about average, ranging from -1 to -1°C (Figure 16). High chlorophyll-a concentrations were seen at the western end of the archipelago (around Isla Isabela and Fernandina) indicating biological production was undergoing a bloom at this time (Figure 17). In November, SSH anomalies (up to 5cm) were moderately positive near the northern end of the archipelago, but around 0 near the southern/eastern ends, and slightly negative (-1cm) near the western end (Figure 18). This indicates that slightly less dense, warmer waters were present near the northern end of the archipelago. The areas of higher SSH anomalies in Figure 24 match with Figures 19 and 20, which show warmer waters present in the northern and eastern parts of the archipelago. As was the case in the data collected for May, SSH anomaly data are masked for some pixels at shallow locations among islands of the archipelago.



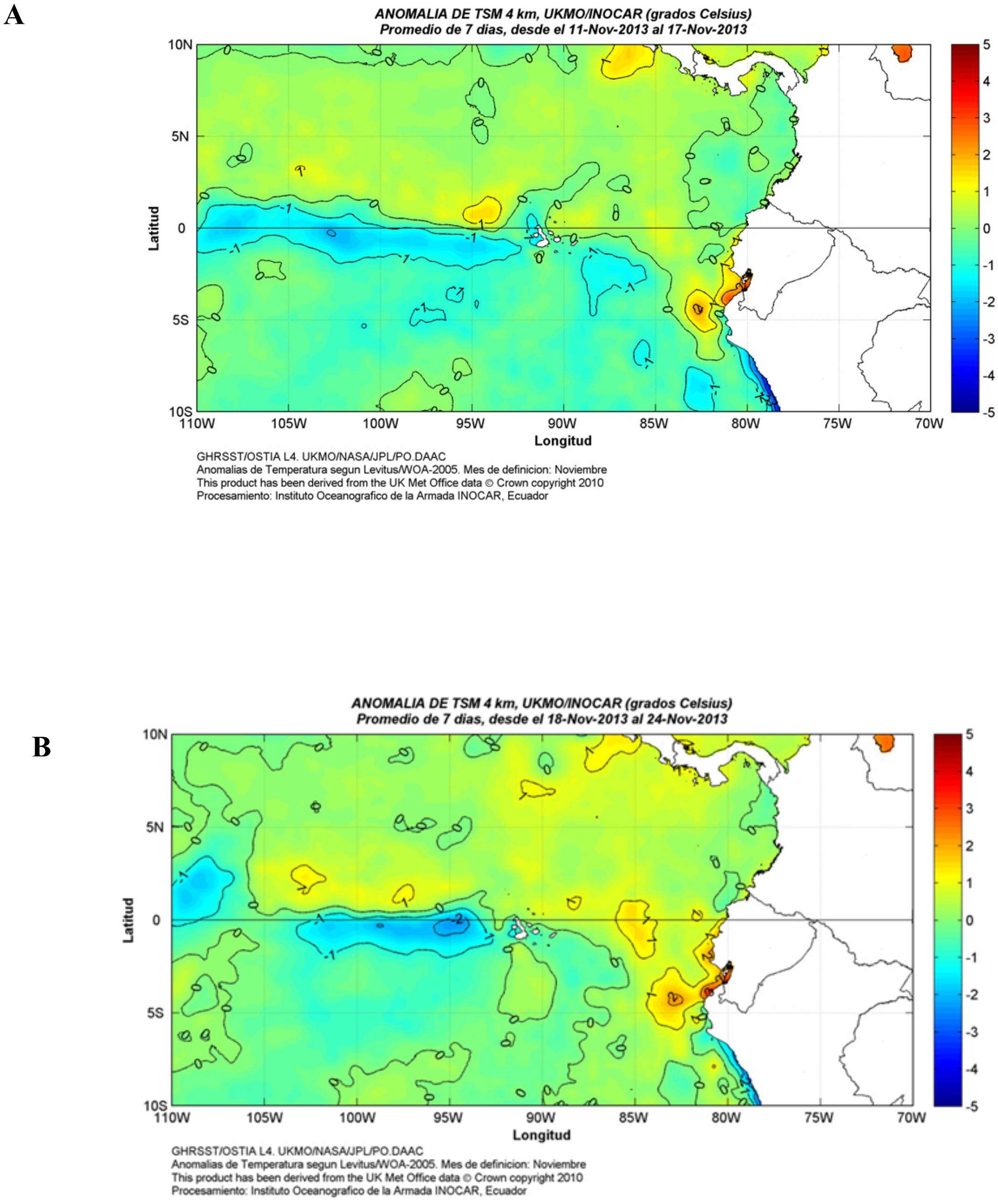
A: TEMPERATURA SUPERFICIAL DEL MAR 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 11-Nov-2013 al 17-Nov-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

B: TEMPERATURA SUPERFICIAL DEL MAR 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 18-Nov-2013 al 24-Nov-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

Figure 15. **Average SST around Galápagos in November 2013. (A) Week of 11-17 November 2013. (B) Week of 18-24 November 2013. Data displayed with 4km resolution. Satellite images courtesy of INOCAR.**



ANOMALIA DE TSM 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 11-Nov-2013 al 17-Nov-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
Anomalias de Temperatura segun Levitus/WOA-2005. Mes de definicion: Noviembre
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

ANOMALIA DE TSM 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 18-Nov-2013 al 24-Nov-2013

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
Anomalias de Temperatura segun Levitus/WOA-2005. Mes de definicion: Noviembre
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

Figure 16. Average SST anomalies around Galápagos in November 2013. (A) Week of 11-17 November 2013. (B) Week of 18-24 November 2014. Data displayed with 4km resolution. Satellite images courtesy of INOCAR.

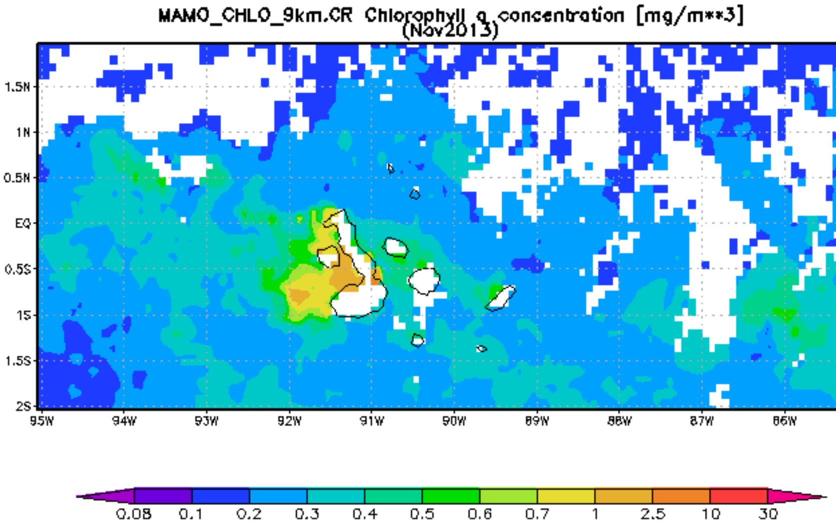


Figure 17. **Chlorophyll-a concentration around Galápagos in November 2013. Data averaged during November 2013 and displayed with 9km resolution using MODIS-Aqua satellite. White pixels indicate areas of cloud cover (no data). Image generated using GIOVANNI Interactive Visualization and Analysis tool.**

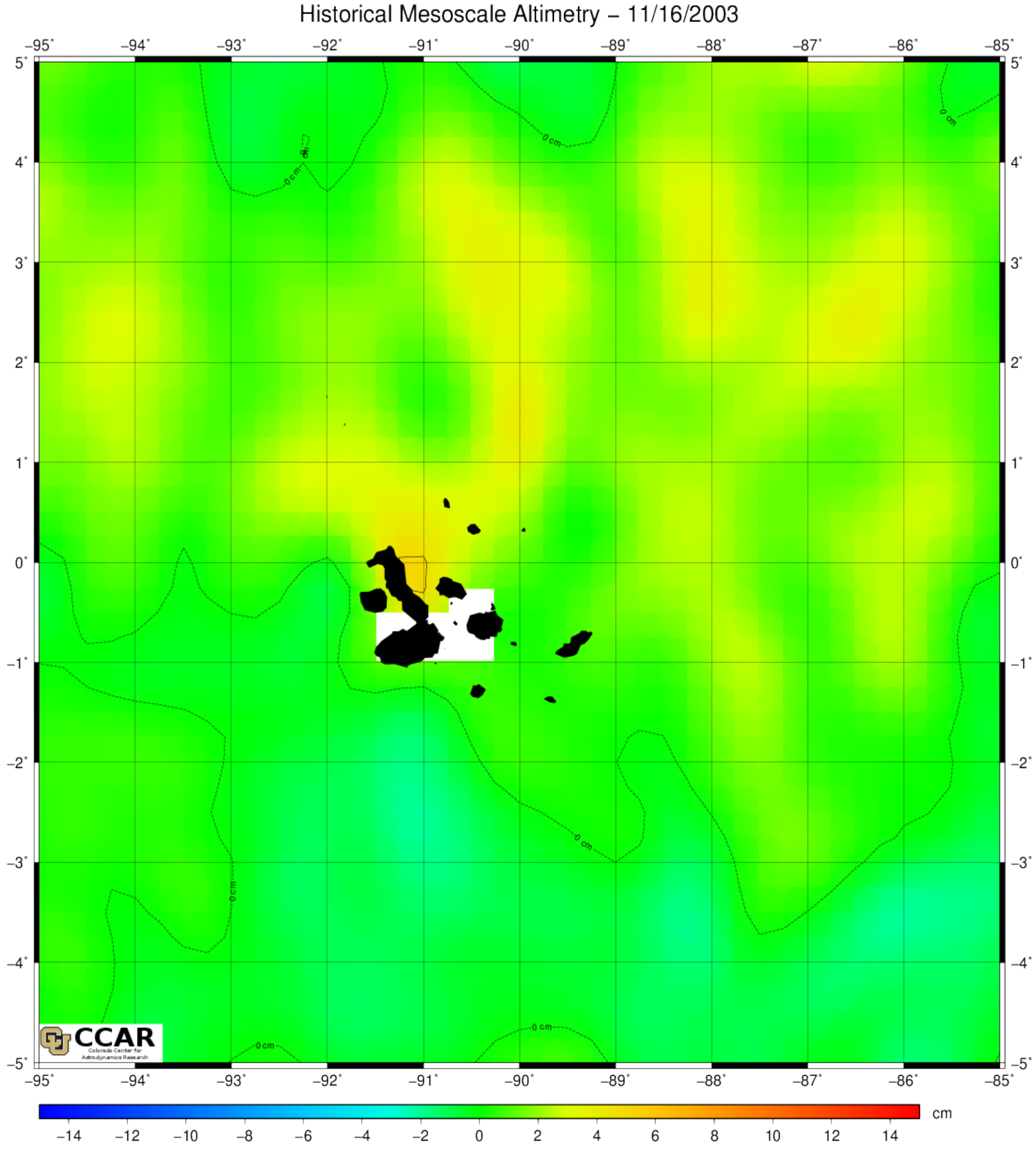


Figure 18. **SSH anomalies around Galápagos in November 2013. Data displayed with 22.5km resolution. Image generated using CCAR's Global Historical Gridded SSH Data Viewer.**

Ocean conditions and fish distribution

Some surveys that were conducted in close geographic proximity to one another did not cluster together during tests of similarity, while some surveys that were in different geographic areas appeared to group together (Figures 5, 6). The fact that assemblages in different geographic location grouped together suggests that something other than geography may have an effect on fish assemblage composition. Oceanographic data collected at dive sites were examined to see if regression might provide clues to the driving factor. As previously stated, data were collected on bottom temperature, bottom depth, and surface salinity, and linear regression models were calculated to examine the relationship between these environmental parameters and species richness at each dive site. None of these relationships were found to be significant, although bottom temperature/surface salinity returned positive R^2 values with species richness.

Interestingly, when examining survey sites by temperature, it was found that the four survey sites with the lowest recorded bottom temperature (Sites FL1, FL2, SC1, and WF) grouped together on the cluster analysis dendrogram and were also the four outliers from the rest of the survey site locations on the PCO plot (Figures 5 and 6). Clustering together indicates that these sites had similar assemblages, and plotting far away from other survey sites indicates that these four survey sites were different from the others on the basis of either coordinate axis. Based on data we were able to collect, it is suggested that temperature (or something that may co-vary with temperature) may be one of the orthogonal coordinates on the PCO plot and has an effect on the composition of fish assemblages at different locations.

Temperature may be an important driving factor for fishes for several reasons. In the Gulf of Mexico, seasonal trends in fish abundance are related to changes in water temperature and other factors, which serve as cues for spawning (Rooker et al. 1997). Temperature has been found to have effect on fish assemblages in estuaries and large-scale fisheries, both of which could have human economic impacts (Marshall and Elliott, 1998, Artrill and Power, 2002, Caddy and Garibaldi, 2000). Temperature also plays a large part in the recruitment, the process that occurs when larval fish (often pelagic) arrive to settlement habitats in which they will hopefully mature to juveniles and adults (Armsworth 2002). Jennings et al. (1994) determined that fish assemblage structure within their individual sites in Galápagos was variable and determined primarily by recruitment. Edgar et al. (2004a) agreed that regional faunal distribution patterns in Galápagos probably reflect local environmental conditions and ease of larval transport (recruitment) to the region. It is also possible that temperature may influence coral cover and type, which in turn may influence fish assemblage structured based on restricted food availability and habitat.

Results from this thesis complement the findings of the previous studies. Jennings et al. (1994) concluded that differences between fish assemblages from regions across Galápagos with characteristic temperature regimes can offer a sound basis for zoning of the GMR. Their results were the basis for zoning strategies in the GMR until Edgar et al. (2004a) offered more detailed evidence for further zoning based on biogeography (Figure 10). Even though this data did not find a statistically significant relationship between species richness and *in-situ* ocean conditions, the R^2 value between bottom temperature and species richness returned positive functional relationships. Additionally, several dive sites with low bottom temperatures clustered together during tests of similarity, and it is suggested that temperature (or some variable that co-varies with temperature) may be one of the orthogonal axes on the PCO plot (Figure 5, 6). These results do not support the null hypothesis that there is no relationship between fish assemblage composition and ocean conditions.

CHAPTER III

COMPARISON OF SPECIES RICHNESS AND OCEAN CONDITIONS BETWEEN SUMMER 2013 AND SUMMER 2014 AT ISLA SAN CRISTÓBAL

Survey sites and methods

To compare how fish assemblage composition at a location may differ through time, in July 2014 two survey locations that were previously surveyed in May 2013 were revisited. These two survey locations were located off of the northwest coast of Isla San Cristóbal: Playa Baquerizo/Bahía Tijeretas and Leon Dormido (Figure 19, 20, 21). With the cooperation and support of the Oceanographic Institute of the Ecuadorian Navy (INOCAR) and the Galápagos National Park (GNP), qualitative and semi-quantitative data on oceanographic conditions and the distribution and relative abundance of fish assemblages were collected from 15-19 July 2014.

Figure 19. **July 2014 survey site locations on Isla San Cristóbal. Map created using Google Earth.**

Figure 20. Bahía Tijeretas. Photo courtesy of Doug Biggs

Figure 21. Kicker Rock (Leon Dormido). Photo courtesy of Martin Narvaez.

Surveys were conducted using the visual survey methods described in Chapter 2 of this thesis adapted from Jennings et al (1994), Bohnsack and Bannerot (1986), Samoilys and Carlos (2000), and Edgar et al. (2004a, b, c). Detailed underwater survey methods are described in Chapter II of this thesis. Care was taken to ensure that survey methods were consistent between both years. The survey area was the same during both years (150m^2) and all underwater visual surveys were conducted during daylight hours. Surveys in 2014 were performed at the same locations as in 2013, but not at the same 150m^2 area. Species were identified by scientific nomenclature as well as common names as used in Humann and DeLoach, (2003). In addition to fish species and abundance estimates, qualitative ecological data were collected on the type of substrate at each site, as well as presence or absence of invertebrates. Oceanographic parameters (i.e., salinity, depth, and temperature) at each site were also collected *in situ* using a Seabird SeaCAT Profiler CTD, YSI salinity meter, and Sherwood Amphos dive computer.

In July 2014, four SCUBA divers were utilized to conduct surveys: one primary diver and three additional divers who were responsible for individual tasks. The primary diver was responsible for recording fish identifications and relative abundances (based on the REEF abundance classification system) on an underwater notepad while a second diver swam beside her and recorded video of the survey using a GoPro camera and underwater housing. Video was collected to provide a permanent record of the fish and benthic environmental conditions to supplement data collected *in situ.* As the primary diver switched positions from the middle of the survey area to circle the perimeter, the second diver continued to swim at her side and record video of the survey. The other two divers were responsible for laying out and maintaining the underwater line that defined the survey area, which sometimes proved complicated when *Zalophus wollebaeki* (Galápagos sea lions) would tug on the survey tape measure line.

In summer 2014, surveys were conducted in two locations that were previously surveyed in May 2013. Bahía Tijeretas is a shallow, rocky inshore bay along the northwest coast of San Cristóbal. Playa Baquerizo is an almost identical location located approximately 0.5 km east of Tijeretas on the same stretch of shoreline. Data from Bahía Tijeretas and Playa Baquerizo will be combined in analysis because of the similarity of their locations and these sites will be collectively referred to as the "inshore" locations. Kicker Rock is an offshore natural rock formation that has steeper bathymetry than the inshore locations and lies approximately 6.5km from shore (Table 5). Both sites were accessible via small boat. Sites were surveyed multiple times over a several days to ensure that the area was being appropriately surveyed and that species recorded accurately represented the entire population.

Presence/absence data for all fish species and relative abundance at each dive site were recorded into a spreadsheet using Microsoft Excel. The number of species seen at each dive site was totaled and the number of dive sites where each species occurred was counted. Video data were analyzed to ensure the survey data were accurate. Rank Order of Abundance (ROA) summary rankings were assigned to all species. 2014 data were compared to data from the same locations in 2013 to compare species richness through time. Species-area curves for both locations were plotted to show that the study site was sampled enough times to reliably represent the population. Satellite data were collected and analyzed to compare oceanographic conditions around San Cristóbal from 2013-2014.

Results

In total, 30 species from 19 families were identified on San Cristóbal in 2014 (Table 6). Most of the fish species seen were diurnally active, non-cryptic fishes. On any dive, the number of species recorded ranged from 6-13. An average of 11 species was seen at Playa Baquerizo and Bahía Tijeretas (sites IN1-IN5) and an average of 9 species was seen at Kicker Rock (sites KR1-KR4). Benthic habitats at all locations were either rocky reef or "mixed" sand and rocky reef substrate. Of the 19 families recorded, five are considered to be herbivorous/omnivorous and graze on algae: Blenniidae (Blennies), Chaetodontidae (Butterflyfish), Pomacanthidae (Angelfish), Pomacentridae (Damselfish), and Scaridae (Parrotfish). Algae and various genera of invertebrates such as urchins and sea stars were found to be present at all survey sites, so the presence of omnivorous consumers was expected. Three of the families seen are considered to be predatory: Carcharhinidae (Requiem sharks), Fistulariidae (Cornetfish), and Lutjanidae (Snappers). The rest of the families fell in the category of secondary consumers that consume small fish, plankton, or invertebrates as prey.

Table 6. **July 2014 presence-absence matrix. 30 fish species from 19 families were recorded at Playa Baquerizo/Bahía Tijeretas (sites IN1-IN5) and Kicker Rock (sites KR1-KR4). "1" indicates presence at dive site; blank space indicates absence at dive site. Total sightings indicates the number of dives on which each species was seen.**

Family name	Species name	IN1	IN2	IN3	IN4	IN5	KR1	KR2	KR3	KR4	Total Sightings
Apogonidae	*Apogon atradorsatus*	1		1							2
Balistidae	*Sufflamen verres*	1									1
Blenniidae	*Ophioblennius steindachneri*						1				1
Carcharhinidae	*Carcharhinus galapagensis*							1		1	2
Chaetondontidae	*Johnrandallia nigrirostris*		1	1			1	1	1		5
Cirrhitidae	*Cirrhitichthys oxycephalus*						1		1		2
	Cirrhitus rivulatus								1		1
Eleotrididae	*Eleotrica cableae*		1	1							2
Fistulariidae	*Fistularia commersonii*									1	1
Gobiidae	*Elacatinus nesiotes*	1		1							2
Haemulidae	*Anisotremus interruptus*				1	1					2
	Orthopristis forbesi							1			1
Labridae	*Halichoeres dispilus*	1	1	1	1	1	1		1	1	8
	Bodianus diplotaenia	1			1	1	1		1	1	6
	Halichoeres nicholsi	1	1	1	1	1		1			6
	Thalassoma lucasanum	1		1			1				3
	Semicossyphus darwini									1	1
Labrisomidae	*Labrisomus dendriticus*	1			1					1	3
Lutjanidae	*Lutjanus viridis*				1						1
Pomacanthidae	*Holacanthus passer*			1		1	1	1	1	1	6
Pomacentridae	*Stegastes beebei*	1	1	1	1	1	1		1		7
	Stegastes arcifrons		1	1	1	1					4
	Abudefduf troschelii				1	1					2
	Chromis atrilobata				1	1					2
Scaridae	*Scarus ghobban*						1				1
Serranidae	*Paranthias colonus*	1	1	1	1	1	1	1	1	1	9
	Epinephelus labriformis	1			1		1		1	1	5
	Serranus psittacinus		1		1					1	3
Tetraodontidae	*Sphoeroides annulatus*	1	1								2
	Total	12	9	11	13	10	11	6	9	10	

Table 5. **2014 underwater survey site locations around San Cristóbal**

Site Code	Location	Position		Date of Survey	Fish species counted
IN1	Playa Baquerizo	S 00°53.421'	W 89°36.736'	15-7-2014	12
IN2	Bahía Tijeretas	S 00°53.250'	W 89°46.683'	16-7-2014	9
IN3	Bahía Tijeretas	S 00°53.250'	W 89°46.683'	16-7-2014	11
IN4	Bahía Tijeretas	S 00°53.250'	W 89°46.683'	17-7-2014	13
IN5	Bahía Tijeretas	S 00°53.250'	W 89°46.683'	17-7-2014	10
KR1	Kicker Rock	S 00°46.764'	W 89°31.098'	18-7-2014	11
KR2	Kicker Rock	S 00°46.764'	W 89°31.098'	18-7-2014	6
KR3	Kicker Rock	S 00°46.764'	W 89°31.098'	19-7-2014	9
KR4	Kicker Rock	S 00°46.764'	W 89°31.098'	19-7-2014	10

To examine abundance of fish species in observed assemblages, ROA was assigned to each species seen during 2014 surveys (Table 7). Average ROAs showed that some species were more likely to be seen in larger numbers during surveying. The species with the highest average ROA in 2014 was *Paranthias colonus* (Pacific creolefish) with an average ROA of 4.0 This means that *P. colonus* were seen at every dive site, and they were recorded as Abundant (large group of over 100 individuals) each time. Two other species, *Stegastes beebi* (Galápagos ringtail damselfish) and *Halichoeres dispilus* (Chameleon wrasse), had average ROA's over 2.0 (2.8 and 2.7 respectively). These species were commonly seen in groups of 11-100 individuals, but several times were also recorded as Abundant at individual dive sites. Eighteen species were recorded to have mid-range average ROAs of 0.2-0.8 (Table 7), meaning that these species were seen at several dive sites during summer 2014. When these individuals were seen at dive sites, they were recorded as having ROA's from 1.0 (one individual) to 3.0 (groups of 11-100 individuals). Conversely, four species, *Cirrhitus rivulatus* (Giant hawkfish), *Orthopristis forbesi* (Galápagos grunts), *Semicossyphus darwini* (Galápagos sheepshead wrasse), and *Sufflamen verres* (Orangeside triggerfish), were recorded having the lowest average ROA of 0.1. This low ranking indicates that only one individual of these species was seen per site during summer 2014 surveys.

Table 7. **Bottom temperature, survey depth, surface salinity, and species richness for July 2014**

Site Code	Location	Species Richness	Bottom Temperature (°C)	Bottom Depth (m)	Surface Salinity (ppt)
IN1	Playa Baquerizo	12	22.2	7.62	34.5
IN2	Bahía Tijeretas	9	21	4	34.5
IN3	Bahía Tijeretas	11	21.1	7.3	34.5
IN4	Bahía Tijeretas	13	20.5	4.3	34.6
IN5	Bahía Tijeretas	10	20.5	8.2	34.6
KR1	Kicker Rock	11	21.7	12.5	34.8
KR2	Kicker Rock	6	20.3	24.4	34.8
KR3	Kicker Rock	9	20.5	13.8	34.9
KR4	Kicker Rock	10	20.1	22.9	34.9

Table 8. **ROA of all species recorded in 2014. "blank" = no individuals seen, "1" = 1 individual seen, "2" = 2-10 individuals seen, "3" = 11-100 individuals seen, "4" = >100 individuals seen**

Species name	IN1	IN2	IN3	IN4	IN5	KR1	KR2	KR3	KR4	Average ROA
Paranthias colonus	4	4	4	4	4	4	4	4	4	4.0
Stegastes beebei	4	4	4	4	3	3		3		2.8
Halichoeres dispilus	4	2	4	2	3	3		3	3	2.7
Bodianus diplotaenia	3			2	2	3		3	3	1.8
Halichoeres nicholsi	2	3	3	3	2		2			1.7
Stegastes arcifrons		4	3	4	2					1.4
Holacanthus passer			1		1	2	2	2	3	1.2
Johnrandallia nigrirostris		2	2			2	2	2		1.1
Thalassoma lucasanum	2		3			2				0.8
Epinephelus labriformis	2			1		2		1	1	0.8
Apogon atradorsatus	3		3							0.7
Abudefduf troschelii				3	2					0.6
Anisotremus interruptus				3	2					0.6
Chromis atrilobata				3	2					0.6
Serranus psittacinus		2		2					1	0.6
Cirrhitichthys oxycephalus						2		2		0.4
Sphoeroides annulatus	3	1								0.4
Labrisomus dendriticus	2			1					1	0.4
Fistularia commersonii									2	0.2
Lutjanus viridis				2						0.2
Ophioblennius steindachneri						2				0.2
Scarus ghobban						2				0.2
Carcharhinus galapagensis						1	1			0.2
Elacatinus nesiotes	1		1							0.2
Eleotrica cableae		1	1							0.2
Cirrhitus rivulatus								1		0.1
Orthopristis forbesi							1			0.1
Semicossyphus darwini									1	0.1
Sufflamen verres	1									0.1

Oceanographic parameters were recorded along with fish identifications during each survey. Dive sites ranged in bottom temperature from 20.1 to 22.22°C and bottom depth from 4 to 24.4m. Sites ranged in surface salinity from 34.5ppt to 35.9ppt (Table 8). All survey sites took place in habitats with substrate consisting of sand, rock, or a mixture of the two.

A linear regression model was calculated to examine if a relationship existed between bottom temperature and species richness for dives performed at the inshore locations in summer 2014. Dives performed at these inshore locations had bottom temperatures that varied from 20.5-22.2°C. In contrast, dives performed at Kicker Rock did not vary as much in bottom temperature (Table 8). Dives were probably more varied at inshore locations than at Kicker Rock because depth varied in the shallow water area around Playa Baquerizo and Bahía Tijeretas. The result was that colder water was present at some of the inshore dive sites. The relationship between bottom temperature and species richness was found have a p value of 0.558, thus there was no significant relationship between these two variables (Figure 22).

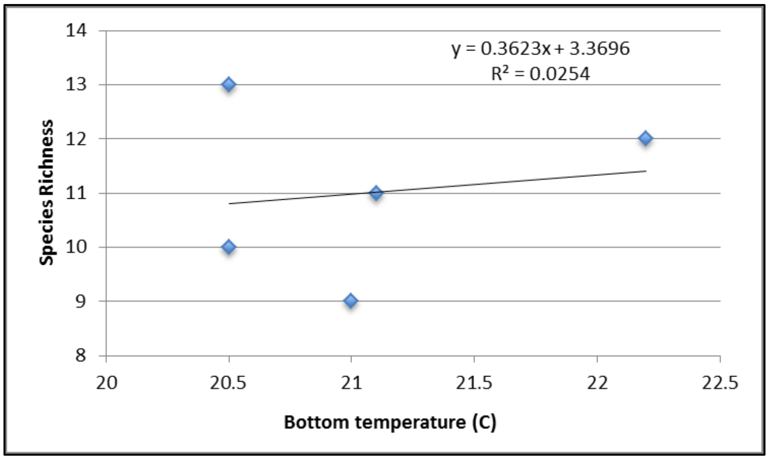


Figure 22. **Relationship between bottom temperature and species richness for dives performed at inshore locations in July 2014.**

Modified species-area curves were drawn to assess how thoroughly dive locations had been surveyed after multiple dives. In ecology, species-area curves are used to predict how the number of species may change based on the size of an area being surveyed (Watters 1992). Since this study focused on surveying the same sized area each time (~150m^2), curves were drawn that plotted the cumulative number of species recorded at each location (species richness) versus the number of times that the study site was sampled (Figure 23, 24). In theory, the more times a study site is sampled, species richness should also increase until it eventually reaches a plateau when the area is adequately surveyed. In this way, one can say that after a certain number of samples, the survey accurately represents the true population of the community being surveyed.

Curves drawn for Playa Baquerizo/Bahía Tijeretas and Kicker Rock showed that species richness increased each time the study site was surveyed. Cumulative species richness was plotted on the independent axis and the number of surveys performed was plotted on the dependent axis. For the inshore surveys, a plateau could be seen even after performing only four dives at the same location (Figure 23). At Kicker Rock, species richness continued to increase every time the location was surveyed, but began to plateau after four dives (Figure 24).

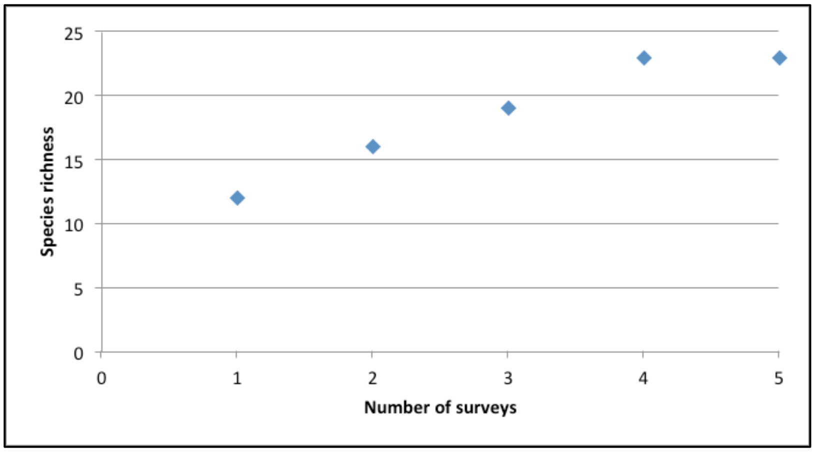


Figure 23. **Modified species-area curves for surveys performed at inshore locations.**

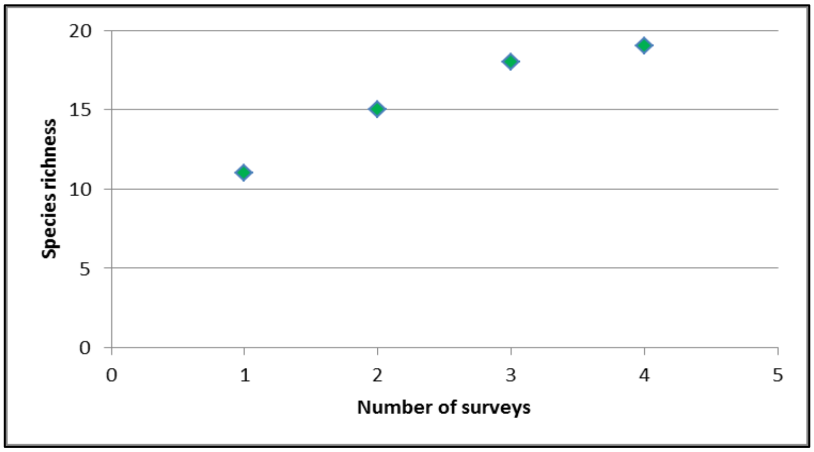


Figure 24. **Modified species-area curve for surveys performed at Kicker Rock.**

In 2014, 21 species were seen while surveying Playa Baquerizo/Bahía Tijeretas. In 2013, 16 species were seen at Tijeretas (Table 9). Fourteen species were repeat species that were seen in both years, so seven species recorded in 2014 were new species that were not present in 2013. Only two species seen in 2013 were not seen again in 2014.

Table 9. Total species seen at Playa Baquerizo/Tijeretas in 2013 and 2014. "*" denotes that species was unique to that location for that year.

2013 Tijeretas	2014 Tijeretas (cumulative)
Abudefduf troschelii	*Abudefduf troschelii*
Anisotremus interruptus	*Anisotremus interruptus*
Bodianus diplotaenia	*Apogon atradorsatus**
*Dasyatis brevis**	*Bodianus diplotaenia*
Epinephelus labriformis	*Chromis atrilobata**
Halichoeres dispilus	*Elacatinus nesiotes**
Halichoeres nicholsi	*Eleotrica cableae**
Holacanthus passer	*Epinephelus labriformis*
Johnrandallia nigrirostris	*Halichoeres dispilus*
*Lepidonectes corallicola**	*Halichoeres nicholsi*
Lutjanus viridis	*Holacanthus passer*
Paranthias colonus	*Johnrandallia nigrirostris*
Serranus psittacinus	*Labrisomus dendriticus**
Sphoeroides annulatus	*Lutjanus viridis*
Stegastes arcifrons	*Paranthias colonus*
Stegastes beebei	*Serranus psittacinus*
Total: 16	*Sphoeroides annulatus*
	Stegastes arcifrons
	Stegastes beebei
	*Sufflamen verres**
	*Thalassoma lucasanum**
	Total: 21

At Kicker Rock, 19 species were seen during surveys in 2014. In 2013, only 11 species were recorded during at Kicker Rock (Table 10). Eight species were repeat species that were seen in both years, so eleven species recorded in 2014 were new species that were not present in 2013. Only three species seen at Kicker Rock in 2013 were not spotted again in 2014.

Table 10. **Total species seen at Kicker Rock in 2013 and 2014. "*" denotes that species was unique to that location between years.**

2013 Kicker Rock	**2014 Kicker Rock (cumulative)**
Bodianus diplotaenia	*Bodianus diplotaenia*
*Chromis atrilobata**	*Carcharhinus galapagensis**
Epinephelus labriformis	*Cirrhitichthys oxycephalus**
Halichoeres dispilus	*Cirrhitus rivulatus**
Holacanthus passer	*Epinephelus labriformis*
Johnrandallia nigrirostris	*Fistularia commersonii**
Ophioblennius steindachneri	*Halichoeres dispilus*
Paranthias colonus	*Halichoeres nicholsi**
*Prionurus laticlavius**	*Holacanthus passer*
Stegastes beebei	*Johnrandallia nigrirostris*
*Triaenodon obesus**	*Labrisomus dendriticus**
Total: 11	*Ophioblennius steindachneri*
	*Orthopristis forbesi**
	Paranthias colonus
	*Scarus ghobban**
	*Semicossyphus darwini**
	*Serranus psittacinus **
	Stegastes beebei
	*Thalassoma lucasanum**
	Total: 19

Discussion

Overall ecosystem observations around San Cristóbal

San Cristóbal is one of the older and larger islands in the Galápagos archipelago (Woods 1987). In terms of island biogeography, larger and older islands should have a high diversity of species (MacArthur and Wilson, 1963, Diamond 1975). Oceanic islands have a high species-area relationship; that is, the curve between area and species richness is steep (Preston 1962). As seen in Results, modified species-are curves showed a high species richness for both inshore and offshore locations around San Cristóbal. The curve for inshore locations plateaued after five surveys in the area, thus indicating that five surveys there created an accurate representation of the population of fish assemblages at these inshore locations. The curve for Kicker Rock began to plateau after four dives in the area, indicating that our surveys were close to recording all fish species present. It is probable that more than four surveys are needed to represent the local population at Kicker Rock because it is a larger survey location than either Playa Baquerizo or Bahía Tijeretas. The possibility that more cryptic species are seen with each dive due to diver familiarity with the habitat also exists and could explain why species richness continues to increase. Overall, based on modified species-area curves, we can be confident that locations on San Cristóbal were thoroughly and accurately surveyed and data collected was truly representative of fish assemblages.

Looking at overall ecosystem diversity, a wide range of trophic levels was found to be present at San Cristóbal in both years. During 2014, this thesis documented the presence of several species of algae, corals, invertebrates, herbivores, carnivores, and apex predators. Various species of algae and invertebrate herbivorous consumers such as sea urchins, sea stars, and sea cucumbers were abundant at both locations in 2014. This year, several species of soft corals were noted at Kicker Rock that were not recorded previously. These may have not been seen in 2013 due to the fact that the area was only surveyed once that year, but their presence nevertheless confirmed that the area should be classified as a shallow rocky reef habitat.

In terms of higher order consumers, several families of seabirds populated the survey area including Fregitadae, Sulidae, and Laridae. Predatory sharks were present in the deeper habitat around Kicker Rock. Only *Carcharhinus galapagensis* was recorded during surveying, but several other species, including *Sphyrna mokarran*, were present in the area before and after surveys were conducted. Several species of sea turtles were present in reef habitats, and one came into the survey area and was recorded during survey of site IN2. Marine mammals were present near both survey sites. At Bahía Tijeretas, *Z. wollebaeki* were commonly seen in the shallow-water area interacting with divers as they were attempting to observe the survey area. Cetaceans were spotted in the vicinity near Kicker Rock during the week when surveys were taking place. Notably, a mother and calf *Megaptera novaeangliae* pair was spotted swimming between the shore and survey area over a period of several days. Another baleen whale was spotted just west of Kicker Rock on 19 July that was believed to be a Bryde's whale (*Balaenoptera brydei).*

The presence of these higher-order organisms is included to describe how the marine ecosystem around San Cristóbal remained diverse and robust between two years of survey. This is encouraging, as the number of tourists visiting Galápagos has been steadily increasing in recent years, and the trend shows no sign of slowing (Epler 2007). Overfishing, mismanagement of resources, and the illegal fishing trade also are newly emerging threats to the islands, in part due to an increasing human presence in the archipelago (Schiller et al. 2014). Future studies that examine the effects of fishing or tourism in protected areas could be misleading without proper baseline data from surveys (Edgar et al. 2004c). As tourism to the archipelago continues to increase, to better manage zoning and zone use around the GMR, it is important that the scientific community has strong baseline data to monitor changes. It is recommended that survey data of a similar nature to this thesis should continue to be collected to establish strong baseline data on the status of various faunal species around the islands.

Rank Order of Abundance

In both years of data collection, ROA was used to compile summary statistics for the abundance of fish present in assemblages around San Cristóbal. Calculating ROA is important because it allows general conclusions about assemblages to be made based on abundance estimates from surveys. In 2014, ROA was collected for every species that was seen, for predictions of which species could be more dominant than others in observed assemblages.

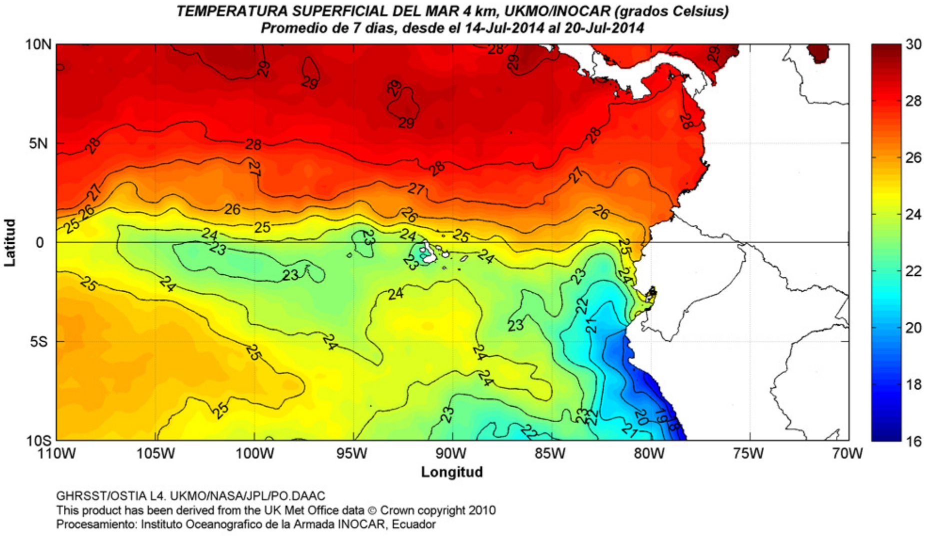
In the summer 2014 season, the species with the highest average ROA was *P. colonus,* which are some of the most abundant fish species in the entire GMR (Humann and DeLoach, 2003) and were recorded in large numbers at every survey site in 2014. *P. colonus* was tied for the highest average ROA in all of 2013 (Table 3), so abundance for this species was consistently high throughout both years. Conspicuously absent from 2014 surveys was *Prionurus laticlavius*, which tied with *P. colonus* for highest average ROA over all locations in Galápagos in 2013. This year, the survey team did not observe a single *P. laticlavius* at either location during surveys. With their bright yellow tails, they are an easy species for even novice divers to identify. The survey team is certain they were not present in survey areas this year. *P. colonus* may be an indicator species whose absence could signal changing conditions, thus more information about the species is needed to infer a reason for their absence in 2014.

Along with *P. colonus*, a few other species and families were found to dominate assemblages around San Cristóbal. As stated in Results, two other species, *S. beebi* and *H. dispilus*, had average ROA's over 2.0. There were five other species that had an average recorded ROA greater than 1.0; *Bodianus diplotaenia*, *Halichoeres nicholsi*, *Stegastes arcifrons*, *Holacanthus passer*, and *Johnrandallia nigrirostris* (Table 7). An average ROA above 1.0 means that these eight species were most likely to be found in groups versus individuals, and therefore were the most dominant families in assemblages in terms of estimated abundance. Serranidae and Labridae are carnivorous families while Pomacentrids, Pomacanthidae, and Chaetondontidae feed on algae, plankton, or small invertebrates. Thus, these shallow-water rocky reefs around San Cristóbal were found to be dominated by three omnivorous or piscivorous families.

Although three major families were found to dominate assemblages, there was still a large amount of diversity, with other families and individual species present at survey sites. The fact that seventeen species in this year's survey had low average ROAs ranging from 0.2-0.8 indicated that most assemblages were diverse and had high species-richness. The three families which all had average ROA's above 2.0 (Serranidae, Pomacentridae, and Labridae) were the clearly dominant families seen over all assemblages. Overall, summer 2014 data suggest that shallow-water rocky reefs surrounding San Cristóbal support diverse faunal assemblages that are dominated by several families.

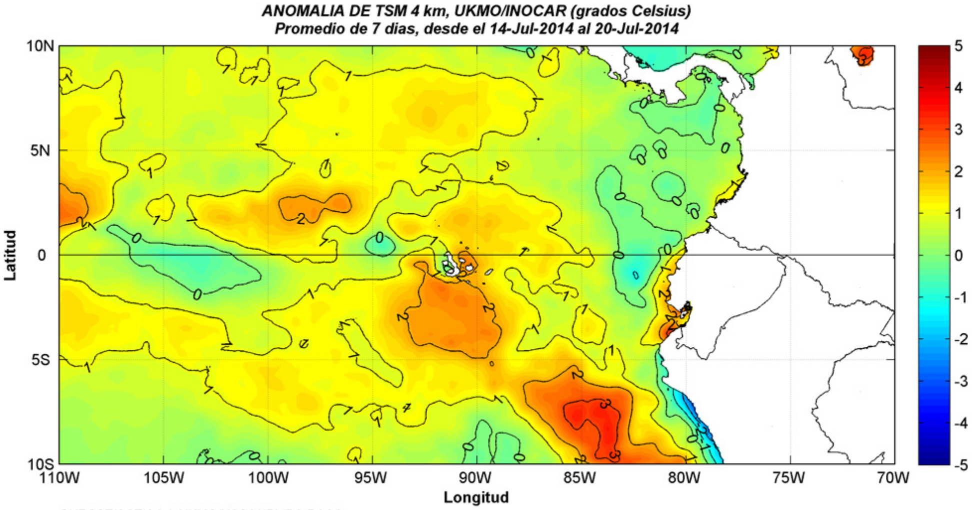
Oceanographic conditions, July 2014

During the week during which July 2014 surveys were conducted, the average sea surface temperature (SST) in Galápagos was between 23-24°C (Figure 25). These represented slightly warmer conditions than normal, with SST anomalies ranging from 2-3°C (Figure 26). In terms of ocean color, chlorophyll-a (chl-a) levels around the northwest coast of San Cristóbal ranged from 0.3-0.4mg/m^3 in July 2014 (Figure 27).


TEMPERATURA SUPERFICIAL DEL MAR 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 14-Jul-2014 al 20-Jul-2014

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

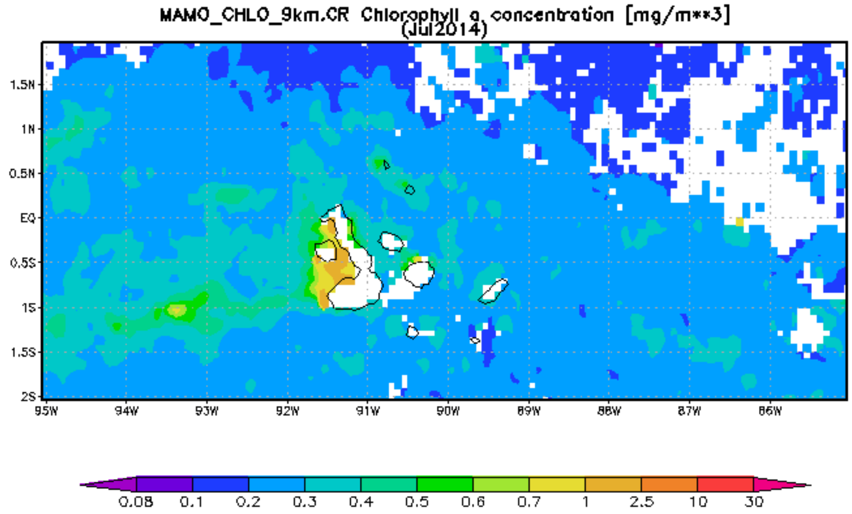
Figure 25. **Average SST around Galápagos for week of 14-20 July 2014. Data displayed with 4km resolution. Satellite images courtesy of INOCAR.**



ANOMALIA DE TSM 4 km, UKMO/INOCAR (grados Celsius)
Promedio de 7 dias, desde el 14-Jul-2014 al 20-Jul-2014

GHRSST/OSTIA L4. UKMO/NASA/JPL/PO.DAAC
Anomalias de Temperatura segun Levitus/WOA-2005. Mes de definicion: Julio
This product has been derived from the UK Met Office data © Crown copyright 2010
Procesamiento: Instituto Oceanografico de la Armada INOCAR, Ecuador

Figure 26. **Average SST anomalies around Galápagos for week of 14-20 July 2014. Data displayed with 4km resolution. Satellite images courtesy of INOCAR.**



MAMO_CHLO_9km.CR Chlorophyll a concentration [mg/m**3]
(Jul2014)

Figure 27. **Chlorophyll-a concentration around Galapágos. Data averaged during July 2014 and displayed with 9km resolution using MODIS-Aqua satellite. White pixels indicate areas of cloud cover (no data). Image generated using GIOVANNI Interactive Visualization and Analysis tool.**

Comparing survey sites between 2013-2014

In 2013, fish assemblage data were collected over a wide geographic range in Galápagos and covered fourteen sites across six islands. Summer 2014 data collection focused on fish assemblages around San Cristóbal by performing surveys at two locations that had previously been surveyed in 2013. This repetition gave the opportunity to create a more in-depth picture of fish assemblages in San Cristóbal than had been collected for any other island. It also allowed for the comparison of oceanographic conditions from one year to another on the northwest coast of San Cristóbal in order to see if any discernable differences may have an effect on the abundance of fish assemblages.

As stated in Results, at both the inshore and offshore locations, more species were recorded during 2014 surveys than in 2013. The number of species seen at Bahía Tijeretas increased from 16 in 2013 to 21 in 2014, and the number of species at Kicker Rock increased from 11 in 2013 to 19 in 2014 (Tables 9, 10). These numbers represent an increase in species seen in 2014, but the two years were not significantly different from one another in terms of species richness. As stated previously, only one survey at each area was able to be performed in 2013 whereas in 2014, several surveys were performed at each location.

The higher number of species recorded around San Cristóbal in 2014 likely reflects increased survey effort rather than any real changes in fish assemblages from one year to the next. The ability to dive a survey area multiple times gave divers more opportunities to see species that they may have missed on a previous dive and for data to be more accurate. Modified species-area curves support that the more times an area is surveyed, the more species are seen (higher species richness). There is also the possibility of bias; the more surveys a diver conducts, the more proficient in identifying various species he/she will become, resulting in an increase in the amount of species recorded. The probability of identifying rare and cryptic species also increases with diver experience (Sale and Sharp, 1983).

Aside from comparing fish assemblage composition, ocean conditions were also compared between years. Oceanographic conditions around San Cristóbal were different between 2013 and 2014. The most notable difference was the change in SST. As seen in Figure 28, 2013 was a typical year in for SST in Galápagos. There are two seasonal cycles in Galápagos: the warm and rainy “gaúra” season, which lasts from December through May, and the cool and dry season, which lasts from June through November. Long-range temperature data collected at Isla Santa Cruz (Academy Bay) recorded monthly mean temperatures ranging between 21.2-25.4°C over the past thirty years in Galápagos (Wellington et al. 2001).

In May 2013, average SST in Galápagos ranged from 21-23°C (Figure 11) and SST anomalies ranged from 0 to -2°C (Figure 12). In July 2014, average SST in Galápagos was higher, ranging from 23-24°C (Figure 25) and SST anomalies were as high as 3°C on San Cristóbal (Figure 26). The average *in-situ* temperature at all survey sites in 2014 was 20.9°C compared to 19.45°C in 2013 (Tables 4, 8). These data argue that 2014 was a year where higher than normal SSTs were present around Galápagos and San Cristóbal.

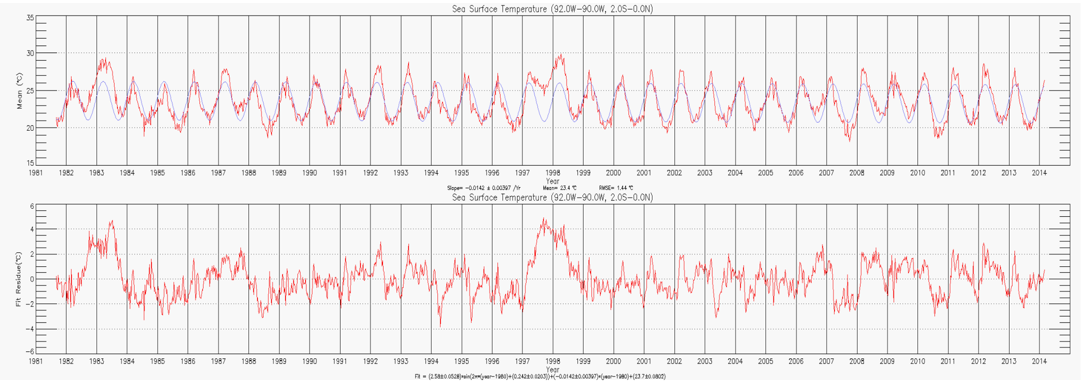


Figure 28. **Time-series graph of mean and residual SST in Galápagos from 1981-2013. Data assimilated from several satellite data sets including NCEP Reynolds SST and SeaWiFS SST. Figure produced from oceanmotion.org.**

Since 1981, Galápagos has experienced two major climatic variations, one in 1982-83 and another in 1997-1998 (Figure 28). Both were El Niño Southern Oscillation (ENSO) events that had ecosystem-wide effects as described in the Chapter I of this thesis. These two events were the largest of their kind in recent history and caused large-scale elevated ocean SSTs in the eastern tropical Pacific (ETP) and around Galápagos. As seen in Figure 34, these events resulted in increased SSTs of up to 5°C. Some of the largest effects of ENSO-related SST anomalies in the Pacific are seen around Galápagos (Wellington et al. 2001).

Warmer temperatures around San Cristóbal in 2014 reflect large-scale warming trends caused by increasing SSTs throughout the eastern tropical Pacific (ETP). The warmest part of the annual SST cycle in Galápagos typically peaks from February-April (Podesta and Glynn, 2001) but throughout 2014, the Pacific Ocean has been under watch for potential ENSO conditions developing. From March-June 2014, above-average SSTs (with anomalies greater than +0.5°C) were evident in the ETP, and current conditions remain elevated (Climate Prediction Center, 2014). According to NOAA Climate Prediction Center (CPC) reports, the ETP was experiencing positive SST anomalies during mid-August 2014. As of 18 August 2014, SST anomalies in the ETP have been persisting for the last four weeks and are currently experiencing an anomaly of +0.5°C (Figure 29). The CPC will continue to monitor these anomalies and changes to determine if ENSO warning conditions should develop, as they could have wide-reaching effects in Galápagos and the ETP.

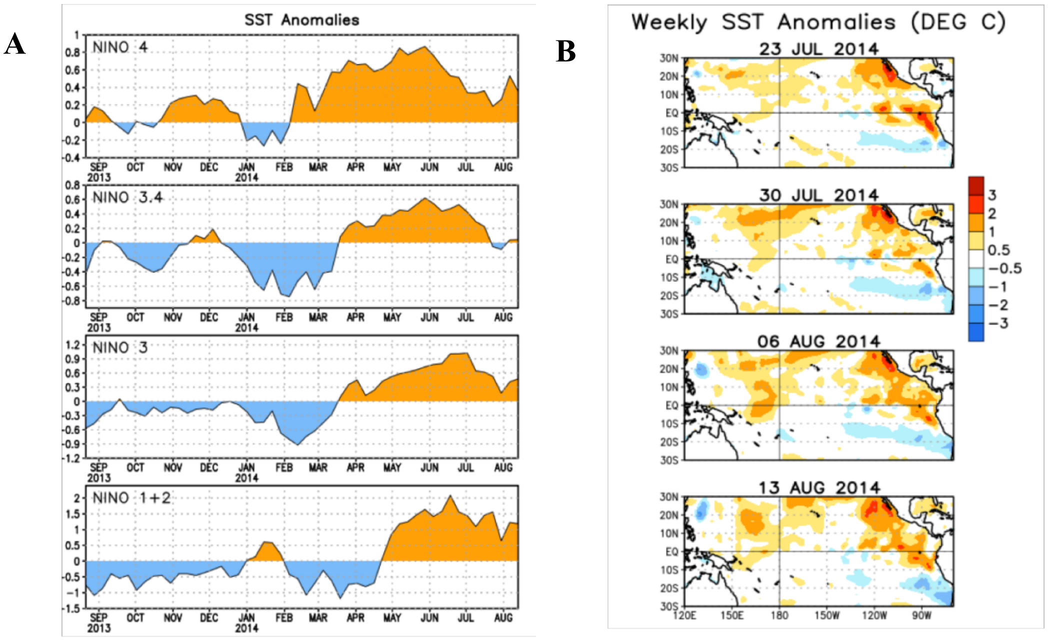


Figure 29. **SST anomaly data for Galápagos. (A) Galápagos is classified as crossing between NINO regions 1+2 and 3. (B) Weekly anomaly data from 23 July- 18 August 2014. Images from NOAA CPC.**

In addition to differences in SST, ocean color around San Cristóbal in July 2014 was found to be different than in summer 2013. As described in Chapter I of this thesis, chl-a data collected via satellite can be used as a proxy for lower-level (primary) productivity. The reef fish described in this thesis are primarily benthic feeders and will not feed directly on plankton, but chl-a can be used as a good indicator of biological conditions in the ecosystem.

In Galápagos, chl-a has two distinct annual cycles which peak around May and August each year (Palacios 2004). 2013 was a fairly typical year in Galápagos in terms of biological productivity. Chl-a levels peaked early in the year and then again around August-September (Figure 30). The average chl-a levels around San Cristóbal were 0.7-1.0mg/m^3 in May-June 2013 (Figure 13) compared to 0.3-0.4 in July 2014 (Figure 27). It should be noted that chl-a levels around San Cristóbal (the eastern-most island in Galápagos) are usually lower than in the western islands of the archipelago. In July 2014, a bloom occurred around Islas Isabela and Fernandina, where chl-a ranged from 1.0-2.5mg/m^3 (Figure 27). Levels of chl-a are typically higher in the western islands of Galápagos because the western islands are the first place that the equatorial undercurrent (EUC) reaches the archipelago as is travels west to east. The western islands also have the most topographically induced upwelling of macro- and micronutrients, which contribute to productivity (Palacios 2004).

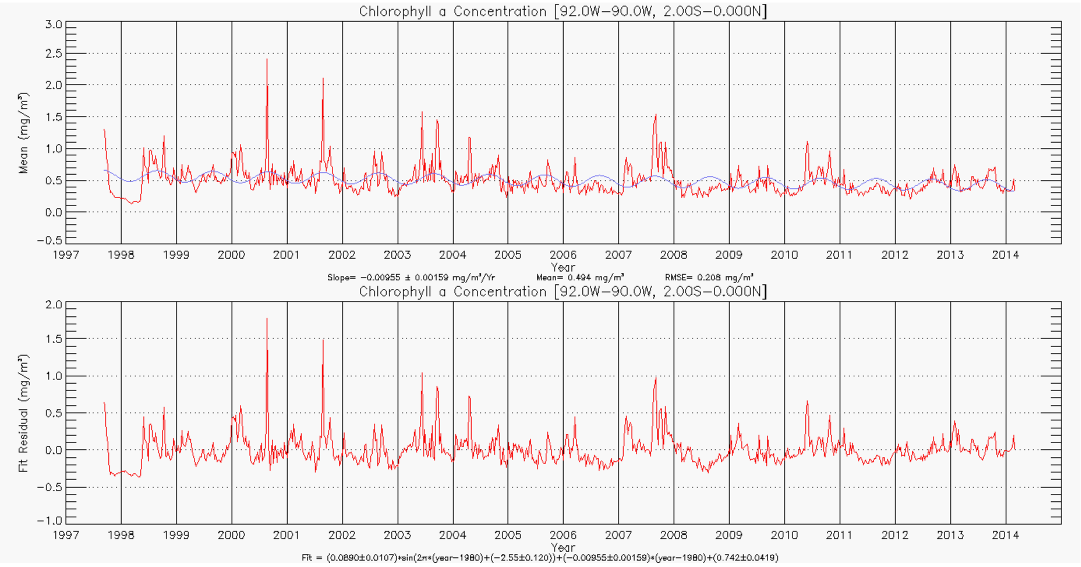


Figure 30. Time-series graph of mean and residual Chl-a concentration in Galápagos from 1997-2013. Data assimilated from satellite data sets including MODIS Ocean Surface Chlorophyll. Figure produced from oceanmotion.org.

Lower levels of chl-a in 2014 may be related to the warmer SST anomalies that have been present in the ETP. Ocean color is affected by changes in SST, as increased biological production (and therefore chl-a levels) typically occurs when cold, nutrient-rich water is present. As previously described, ENSO events in the Pacific Ocean act to alter patterns of southeast trade winds and bring anomalously warm surface waters towards the ETP. These actions also strengthen the thermocline in the waters surrounding Galápagos. A moderate ENSO event, which occurred in 1986-87 in the ETP, reduced surface chlorophyll and nutrient concentrations around Galápagos (Fiedler et al. 1992). Due to the fact that Figure 30 only includes data from mid-1997 until 2014, it is not possible to use this graph to explore how chl-a concentrations in the GMR reacted to the major 1982-83 or 1997-98 ENSO events.

Several studies performed in regions outside the ETP have examined the major 1997-98 ENSO event and its corresponding effect on chl-a levels. Studies in the Indian and Atlantic Oceans have shown that ENSO events may actually increase chl-a levels due to anomalous regional wind patterns that move warm water away from the study area (Susanto and Marra, 2005, Machado et al. 2013). While these studies confirm that a relationship exists between major ENSO events and chl-a levels, neither studied ENSO events in the Pacific Ocean. It is not probable that ENSO events surrounding Galápagos would increase chl-a concentrations as it has been documented in other ocean regions (Schaeffer et al. 2008). More data are needed to determine the mechanisms for exactly how chl-a levels around Galápagos respond to major ENSO events such as events of 1982-83 or 1997-98.

Even though SSTs were higher than normal and chl-a levels appear to have decreased from 2013-2014, more fish species were recorded at San Cristóbal in 2014 than in 2013. Even though differences in fish abundance from one year to the next are thought to be a consequence of increased survey effort in 2014, this trend suggests the opposite of would be expected from data presented in Chapter II. Data suggested that a relationship exists between temperature and the number of species seen at survey sites (Discussion, Ch. II). It is known that cooler waters retain higher micro and macronutrient concentrations than warmer waters and therefore foster a better environment for biological productivity to occur.

Temperature is likely not the only variable that can cause changes in abundance of fish assemblages between years. The most likely explanation for the increase in species richness from 2013-2014 is that other variables in the ocean are having a compounding effect with temperature to increase species richness. Fish populations are known to be affected by climactic variations and corresponding oceanic variations (Attrill and Power, 2002). With SSTs increasing globally due to anthropogenic climate change, this thesis suggests that the monitoring of SST, SST anomalies, chl-a, and other oceanographic conditions be continued around San Cristóbal and the GMR. Possible abiotic ocean factors that may affect species richness include dissolved oxygen concentration, nutrient concentration, current strength, salinity, and depth of survey area, among others. The more data are collected, the better the scientific community can begin to understand which oceanic variables may have the strongest effect on fish assemblages.

It is also important to consider that biotic factors in the marine environment may be influencing abundance in fish assemblages. Various studies have shown that body size, habitat selection, and interactions with other organisms, including but not limited to, competition, predation pressure, prey availability, and community structure have been shown to effect the composition of fish assemblages and benthic communities (Carr 1989, Anderson and Millar, 2004, Layman et al. 2005, Wells et al. 2009).

CHAPTER IV

SUMMARY AND CONCLUSIONS

Summary

2013 Data collection

During May-June and November 2013, data were collected on reef fish assemblages in Galápagos. 60 species from 32 families were recorded at 12 survey sites. Underwater visual surveys found a high species richness and wide range of trophic levels to exist across the Galápagos archipelago. Average Rank Order of Abundance (ROA) calculations for the 10 most common species seen in 2013 showed that relative species abundance was not uniform across all islands. Ocean conditions in 2013 were measured at dive sites (*in situ)* and via satellite (remote data). *In situ* data reported on conditions at each survey location: bottom temperature (°C), bottom depth (m), and surface salinity (ppt). Satellite data gave descriptive information about ocean conditions during both survey seasons in 2013; sea surface temperature (SST) and SST anomalies, ocean color/chlorophyll-a concentration (chl-a), and sea surface height (SSH). Regressions were performed to determine the strength of relationships between species richness and *in situ* conditions at survey sites. No significant relationships were found, but surface salinity and bottom temperature were found to have positive functional relationships with species richness.

Survey sites were tested for similarity using hierarchical cluster analysis and principal coordinates analysis (PCO). Generally, geographic locations in proximity to one another grouped together in cluster analysis. This means that most assemblages were different among geographically separated locations. Thus, results based on ROA and cluster analysis do not support the null hypothesis that fish assemblage composition does not vary spatially. Results from the PCO plot generally supported the cluster analysis dendrogram. Several outliers were different than other groupings on the PCO plot and lay further out on orthogonal coordinate axes. It was discovered that these four outliers were the survey sites with the lowest recorded bottom temperature. It is suggested that temperature, or something that co-varies with temperature, is likely orthogonal coordinate axis 1 on the PCO plot. Thus, temperature is likely the oceanic factor that affects fish assemblage distribution the most. Temperature is known in the literature to have an effect on fish assemblage distribution through several methods including recruitment and spawning.

Other studies performed via underwater visual surveys in the GMR (Jennings et al. (1994) and Edgar et al. (2004a)) found that distinct regions exist in terms of fish assemblage distribution. Both papers outlined regions throughout the GMR that were defined based on fish assemblages and geography. Edgar et al. (2004a) outlined special biogeographical regions to be used in zoning schemes and management of the GMR. This thesis supports the findings of these two studies; that composition of assemblages varies by geographic location across the GMR.

2014 Data collection

In July 2014, data were collected around the northwest coast of Isla San Cristóbal at two general locations; Playa Baquerizo/ Bahía Tijeretas (inshore) and at Kicker Rock (offshore). Both sites had been surveyed previously in 2013. During July 2014, five dives were performed at the two inshore locations and four dives were performed at Kicker Rock. Using the same underwater survey methods as in 2013, 30 species from 19 families were recorded during these nine dives. Presence/absence data and ROA were collected for all species in 2014. Calculated average ROA's found three families to dominate assemblages around San Cristóbal: Serranidae, Pomacentridae, and Labridae. Aside from these dominant species, data showed that shallow-water rocky reefs around the island support diverse fish assemblages. Many other families present had mid to low average ROA's, which indicates high species richness at survey sites.

Modified species-area curves were drawn to assess how thoroughly locations had been surveyed after multiple dives. Data showed that species richness increased each time site was surveyed. At both inshore locations and Kicker Rock, species-area curves began to plateau after 4-5 dives. Next, locations were compared between 2013 and 2014 to examine any changes in fish assemblage composition. At both locations in 2014, cumulative species richness increased from surveys performed in 2013. This may have been due to performing more repetitive dives at each location and from divers becoming more familiar with the dive site.

Ocean conditions surrounding San Cristóbal in 2014 were found to be different than in 2013 through examining remotely sensed data. SSTs were higher, SST anomalies were greater, and chl-a levels around San Cristóbal were lower in July 2014 than they had been the previous year. These conditions may have been due to positive SST anomalies in the ETP, which has been under watch by NOAA's Climate Prediction

Center (CPC) for an El Niño Southern Oscillation (ENSO) event since early 2014. Even though warmer SSTs and positive SST anomalies were present and chl-a levels were reduced, a higher species richness was seen at survey sites in 2014 versus 2013. It is possible that other variables in the ocean may be a compounding effect with temperature to have an effect on the reef fish assemblages around San Cristóbal. Likely, survey effort is the main factor that explains the increased species richness from one year to the next.

Conclusions

The objectives previously outlined were accomplished in this thesis. Using data collected with underwater visual survey methods, shallow-water reef fish assemblages around the Galápagos were surveyed. 2013 surveys focused on exploring spatial relationships while 2014 surveys focused on collecting data over time by sampling at repeated locations. The relationships between oceanographic conditions and fish assemblages were explored by collecting *in situ* and satellite data to provide an ecosystem-wide assessment. Results were consistent with previously conducted underwater visual surveys on reef fish assemblages in the Galápagos archipelago. No significant changes in abundance, no extinctions, no mass migration events, nor invasive species were found in reef fish assemblages from 2013-2014 that were not recorded in 1994 or 2004. This is encouraging news. Since the creation of the GMR, enforcement of the Management Plan's zoning schemes has proven to be effective in keeping diversity and species richness high, and must continue to be rigorously enforced to ensure that circumstances remain the same.

This thesis highlighted the need for strong baseline data regarding reef fish assemblages across the Galápagos Marine Reserve (GMR). Relatively few studies of this nature have been performed in Galápagos, so this work provides continuation of data collection from Jennings et al. (1994), and Edgar et al. (2004a). Information from this thesis may be used for a variety of applications including marine resource management and future zoning plans of the GMR. Data collected gave a general overview of fish assemblages across a wide geographic range in 2013 and recorded detailed data of reef fish populations around the northwest coast of San Cristóbal in 2014. Having these data allows for future comparisons to be made relative to the conditions and abundances that existed during the time of this study. Given the complex relationship between ocean conditions and anthropogenic climate change, it is more important than ever to have these data so changes due to these events can be tracked and resources inside the GMR may be preserved. The Galápagos Islands are one of the most unique marine ecosystems in the world and it is the hope that this work can be useful in providing evidence for its need of future conservation and care.

Suggestions for future studies

Future underwater visual surveys that can collect detailed quantitative data on fish abundance on a large geographic scale would help monitor reef fish assemblages throughout the GMR. Surveying Islands Darwin and Wolf would be of high interest, as they are geographically isolated from the main archipelago and have high diversity and species richness. Also, ocean conditions at these locations (i.e. temperature) are different from the main archipelago, so these data could provide insight on how different ocean conditions may affect fish assemblages. Surveying islands in the western region of the archipelago such as Fernandina and Isabela would also be important due to the fact that many species listed as “threatened” on the International Union for Conservation of Nature’s (IUCN) Red List in Galápagos are found in these locations (Edgar et al. 2008c). Performing multiple dives at each survey location is crucial to make sure that surveys accurately represent the populations present. Increasing effort to survey each location multiple times is likely the best way to ensure survey data is most accurate. The continued monitoring of oceanographic conditions in the ETP and around the GMR over time would beneficial to help quantify any relationships between conditions and reef fish assemblages. Additional data from surveying would aid in assessing which species are of highest risk from environmental and anthropogenic threats and would provide sound suggestions for practical zoning of the GMR based on areas of conservation concern.

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