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Surviving Under the Reign of El Niño Southern Oscillation: An analysis of the effects of extreme El Niño events on the oceanographic and biological environment of the Galápagos Islands

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Abstract

El Niño Southern Oscillation (ENSO) is commonly known as the atmospheric and oceanographic powerhouse of the Southern Pacific Ocean. From phytoplankton to apex predators, ENSO controls the stability of species' populations within this biodiverse ocean environment. El Niño's 9-15 month alteration of the heat storage in the tropical Pacific drastically shifts the temperature, nutrient, and circulation gradient its marine life is accustomed to. A single degree change in the ocean's surface layer temperature can have large consequences for marine species, and El Niño is commonly associated with Sea Surface Temperature Anomalies (SSTAs) between 2°- 6° Celsius. The potential danger El Niño poses to the ETP's trophic structure is especially high in the Galápagos Islands. Positioned almost perfectly on the equator, the Galápagos Islands are located at the epicenter of this phenomenon. The Galápagos Islands' unprecedented rate of endemism creates a dynamic and sensitive environment to analyze the interactions between abiotic and biotic factors altered by ENSO. Satellite imagery and computer models of the Sea Surface Temperatures (SSTs), SSTAs, and chlorophyll concentrations (mg/m^3, milligram per cubic meter) of the three most powerful El Niños ever recorded: 1982-83, 1997-98, and 2015-16 were examined in this study to investigate ENSO's oceanographic influence. Secondary research was analyzed to examine ENSO's effect on plant and animal populations in the Galápagos and ETP. This study concluded that there was a causal relationship between the SSTAs and chlorophyll concentrations observed across the ETP during El Niño Events. It also found that marine organisms suffered greatly during El Niño events that reached a SSTA threshold of +2°C and below chlorophyll concentrations of 0.12 mg/m^3.

Resúmen

El Niño Oscilación del Sur (ENSO) es bien conocida como la fuerza motriz de la atmosférica y oceanográfica del Océano Pacífico Sur. Desde el fitoplancton hasta los depredadores del ápice, ENSO controla la estabilidad de las poblaciones de especies dentro de este entorno oceánico biodiverso. La alteración de 9-15 meses por El Niño en el almacenamiento de calor en el Pacífico tropical cambia drásticamente el gradiente de la temperatura, los nutrientes y la circulación al que su vida marina está acostumbrado con. Un cambia de un solo grado en la temperatura de la capa superficial del océano puede tener grandes consecuencias para las especies marinas y El Niño se asocia comúnmente con anomalías de temperatura de la superficie del mar (SSTAs) entre 2°- 6° Celsius. El peligro potencial que El Niño se representa para la estructura trófica del PTO es especialmente alto en las Islas Galápagos. Situadas casi perfectamente en el ecuador, las Islas Galápagos se encuentran en el corazón del cambio de este fenómeno. La tasa sin precedentes de endemismo de las Islas Galápagos crea un entorno dinámico y sensible para analizar las interacciones entre factores abióticos y bióticos alterados por ENSO. En este estudio, se examinó las imágenes de satélites y los modelos informáticos de las temperaturas de la superficie del mar (SST), SSTAs y las concentraciones de clorofila (mg/m^3, miligramo por metro cúbico) de los tres El Niños más poderosos jamás registrados: 1982-83, 1997-98, 2015-16 para investigar la influencia oceanográfica del ENSO. Además, se analizó la investigación secundaria para examinar el efecto de ENSO en las poblaciones de plantas y animales en las Galápagos y el PTO. Este estudio concluyó que había una relación causal entre las SSTAs y las concentraciones de clorofila observadas en todo el PTO durante los eventos de El Niño. También, lo encontró que los organismos marinos sufrieron mucho durante los eventos de El Niño que alcanzaron un umbral de SSTA de +2°C y por debajo de las concentraciones de clorofila de 0,12 mg/m^3.

Acknowledgments
From the bottom of my heart, I would like to thank Xavier Silva (Ph.D.), Ana María Ortega (M.S.), and Diana Serrano (M.S.) for their profound kindness and understanding during this unprecedented and difficult time. Your steadfast dedication and determination throughout this process assured that each of your students would be able to carry out an Independent Study Project online, regardless of our rapid departure from the beautiful country of Ecuador. I am truly inspired by you all and further wish to thank you for the extra time you took to speak with our class, both as groups and as individuals, to ease our general stress and anxiety. Xavier, your genuine passion for a wide breadth of topics and guidance during the semester and the ISP kept our program connected across hemispheres. Diana, your unwavering support and preparedness during these extraneous circumstances is beyond commendable and made the ISP possible. Ana María, I cannot begin to thank you enough for your kindness and for always going the extra mile to help your students. I am also very grateful to our professors for connecting us with wonderful advisors in Ecuador that kept us grounded during this research process. To my advisor Lenin Villacis, I wish to thank you for your support and generosity during my research journey. Your counsel made this process both enjoyable and manageable. Finally, to my advisor Branwen Williams, I cannot possibly thank you enough for your counsel during this time and for inspiring me to pursue my interest in oceanography.

Introduction

Context

El Niño Southern Oscillation (ENSO) is one of the most dynamic and impactful climate phenomena on Earth. Its oscillation across the equatorial Pacific has the power to create changes on both regional and global scales, altering global circulation patterns and regional population demographics. ENSO has gained great attention from the climate science community due to its unpredictable patterns, high amplitude, and shocking alteration of the tropical Pacific Ocean's energy gradient (Yu & Kao, 2007). The warm phase of ENSO, known as El Niño, is characterized by a 9-15 month period of anomalously warm water in the Eastern Tropical Pacific Ocean (ETP) (Figure 1B) (Lian et al., 2014). The counterpart to El Niño is a cold La Niña phase, which is best understood as an amplification of normally cold conditions in the ETP and increased upwelling along the Peruvian coast (Yu et al., 2011) (Figure 1A). The upwelling, or rise of nutrient-rich deep-water (> 80m) near Peru, is responsible for the prosperous marine life of the ETP (Stenseth et al., 2002). El Niño's disruption of this upwelling dramatically alters the oceanographic, atmospheric, and ecological conditions of the Pacific basin (Newman et al., 2011). Regionally, the Galápagos Islands have been credited for having complex interactions with ENSO's major effects, as the archipelago's near-perfect equatorial positioning in the ETP has placed it at the center of El Niño's tropic anomalies (Figure 2)(Trueman & d'Ozouville, 2010). The Galápagos Islands offer a unique opportunity to better understand the major impacts of this climate event on local oceanic conditions, trophic level stability, marine species population dynamics, and coral reef ecosystems (McClanahan et al., 2011). The focus of this research will be on the impacts of the most intense El Niños in recorded history: 1982-83, 1997-98, and 2015-16 on the oceanographic and biological conditions of the Galápagos Islands using satellite imagery, computer modelling, and secondary research.

Background

A. The Tropical Pacific Ocean's Climate System

El Niño Southern Oscillation is defined as irregular variations in the Sea Surface Temperature (SST) and atmospheric circulation of the Equatorial Pacific Ocean that occurs every 2-7 years (Appendix A). The National Oceanic and Atmospheric Administration have quantitatively defined ENSO as a phenomenon that exhibits positive SST anomalies of at least +0.58°C in the Niño 3.4 region (58S–58N, 1708–1208W) averaged over three or more consecutive months (Kug et al., 2009;NOAA, 2020)(Appendix B for Niño regions). The most important climatological and biological aspect of ENSO is its shift in the energy storage and decrease of chlorophyll concentrations in the tropical Pacific (McPhaden et al., 2011). Chlorophyll levels are the clearest indicator of the degree of nutrient supply to the surface ocean. Chlorophyll is a green pigment that plants and cyanobacteria use to absorb light energy essential for photosynthesis (OceanTracks, 2017). In oceanography, chlorophyll is used as a proxy to measure the average concentrations of phytoplankton and rates of primary productivity occurring in the surface layer of the ocean. The tropical Pacific normally stores warm, nutrient-poor water along its western boundary, but El Niño events completely reorganize the basin's temperature and nutrient gradient causing a measurable decrease in phytoplankton biomass.

a. High and Low Pressure Systems

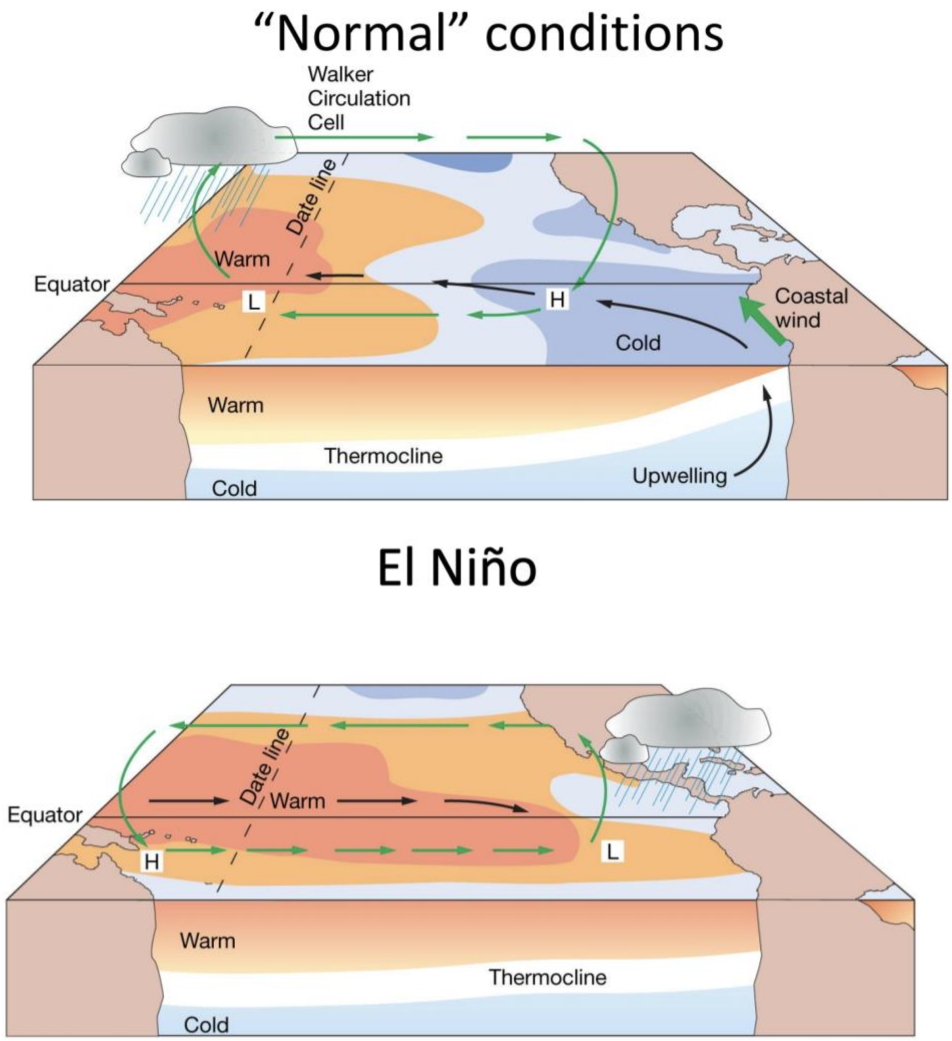
The normal surface pressure gradient of the tropical Pacific has a low-pressure system on the western side and high-pressure system on the eastern side, known as the Walker Circulation Cell (Kodama & Burls, 2019)(Figure 1, Appendix C). In the Walker Circulation Cell, wind and precipitation are continuously exchanged in a cycle of warming and cooling air. Warm air from the west travels to the eastern high-pressure system where it cools and is drawn back to the low-pressure center, rotating counterclockwise above the South Pacific Gyre (Appendix C). Winds flowing from east to west across the tropical Pacific are called the easterly trade winds (Appendix E). As they travel back across the equator, surface tension between easterly trade winds and the sea pulls water up from below the thermocline and supplies crucial nutrients to South America's western coast (Kodama & Burls, 2019). The thermocline is a distinct layer that separates the calm deep-water from the upper mixed layer of the ocean (Kao et al., 2009;Yeh et al., 2009) (Appendix D). In addition to the initial upwelling, trade winds distribute this collection of nutrients and cold water (known as the "Cold-Tongue") out into the central Pacific (Kug et al., 2009) (Appendix A). Without upwelling, organisms in the ETP's surface layer would experience severe nutrient limitation (Stenseth et al., 2002).

b. Oceanic and Atmospheric Gradients

The Walker Circulation Cell also creates an east-west thermocline gradient. Nutrient-rich deep-water is drawn up higher on the eastern side directly due to easterly trade-wind upwelling. The thermocline in the western Pacific is depressed by the nutrient-poor warm pool, creating a nutrient imbalance across the basin compared to the Cold-Tongue (Figure 1A). The sea level is also higher in the western Pacific where more water is being pushed up against the continental shelf (Appendix D). Once these trade winds return to the west, they warm and lose their moisture above the low-pressure system as they rise higher in the atmosphere. This creates a similar precipitation gradient as more rain is concentrated in the western Pacific.

c. El Niño's Reversal

At the onset of an El Niño event, trade winds begin to slow as the latitudinal temperature gradient (responsible for the creation of these winds) weakens (Cai et al., 2014). Warm wind and water are then propagated eastward from the western Pacific as the Walker Circulation Cell starts to reverse. The large warm water cap normally concentrated in the western Pacific shifts across the basin, depressing the high thermocline critical to marine life in the eastern Pacific and eliminating surface-layer mixing (50-100m)(Chavez et al., 1999)(Appendix E). At the peak of El Niño, upwelling is halted along the coasts of Peru and Ecuador, and the Walker Circulation Cell is reversed (Figure 1B)(Chavez et al., 1999). This causes changes in global and regional atmospheric circulation as El Niño upends the precipitation pattern, temperature profile, and nutrient distribution that marine ecosystems in the tropical Pacific are accustomed to (Lian et al., 2014). Oceanic primary productivity is also severely limited as the nutrient supply to the ETP phytoplankton community is halted, sending cascading effects up the trophic levels (Glynn et al., 2001).



A.

B.

Figure 1. Represents a reverse of the climate system in the tropical Pacific Ocean (A is normal conditions, B is El Niño conditions). El Niño switches the location of the low and high-pressure systems to east and west respectively. Sourced from Pearson Williams, 2019.

B. ENSO's Impact on the Galápagos Islands

Located in the heart of the Eastern Pacific Cold-Tongue, the Galápagos Islands' rich ecosystems are created by the confluence of three major currents in the ETP: the Cromwell, Humboldt, and Panama Currents. The archipelago forces deep, rich waters from the Cromwell current up to the surface and fuels high rates of photosynthesis and large phytoplankton populations (Fundación Charles Darwin, 2017). El Niño conditions have serious consequences for this unique region as the phenomenon disrupts the upwelling Cromwell and Humboldt currents, limiting the nutrient supply to the region, increasing SSTs, and destabilizing local marine ecosystems (Manzello, 2010)(Figure 2). The ENSO warm cap's replacement of the EP Cold-Tongue causes extreme Sea Surface Temperature Anomalies (SSTA = the departure of the water from mean sea surface temperatures, anywhere from 2-5°C) that make it difficult for sensitive marine organisms like phytoplankton, corals, and fish to survive in (NOAA, 2020). Major changes to the Galápagos' nutrient supply and sea surface temperature are clearly seen in satellite imagery of past El Niños, and biological records explain how these changes affected the archipelago's species composition (Lee & McPhaden, 2010).

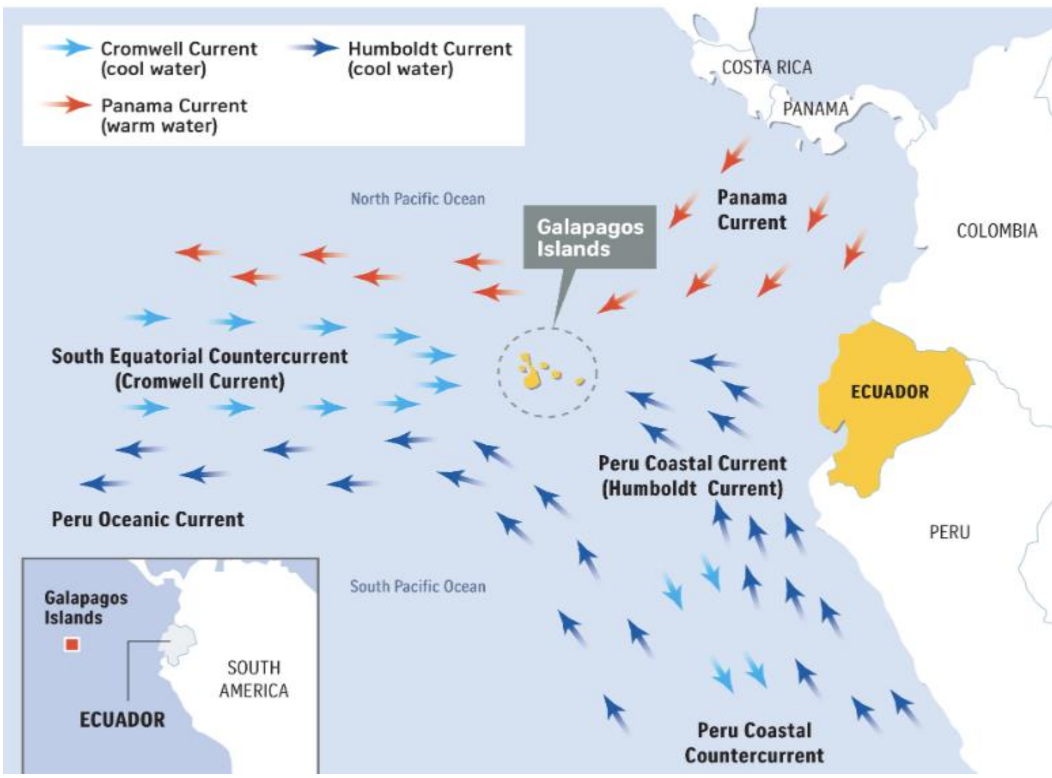


Figure 2. Map representing the three main currents and their intersection with the Galápagos Islands. Source from The Straits Times, 2019.

Objectives

The main objective of this paper is to synthesize a comprehensive body of research to better understand how El Niño Southern Oscillation impacts the Galápagos Island ecosystem. Based on the current research available on this topic, it is predicted that ENSO will negatively relate to marine life survival. In order to meet this study's overall objective, the research process was conducted with the following goals,

1. Analyze satellite imagery and computer models to quantify the dynamic oceanographic conditions of the most powerful ENSO events from the past 50 years using SSTs, SSTAs, and chlorophyll
2. Connect the environmental changes associated with these events to the response seen in the biological communities of the Galápagos Islands
    a. Highlight trends in marine species population fluxes, species interactions, and coral reef health during El Niño
3. Posit this climate phenomenon in a dynamic context where global climate change may be changing the intensity and frequency of these events, leading to more uncertainty for the Galápagos Islands and other biodiverse ecosystems, emphasizing the importance of future research in this topic

Methods and Materials

Online Resources

- ❏ GISTEMP Team
- ❏ NOAA View
- ❏ Earth Null School
- ❏ NASA Observatory
- ❏ NASA SeaWiFS
- ❏ Data from Scientific Articles
- ❏ Excel: calculation of SSTA/SST values

Data Collection: Image Analysis

Satellite imagery and computer models of the 1982-83, 1997-98, and 2015-16 El Niño periods were analyzed to visualize the changes these events had on the oceanographic and atmospheric conditions of the Galápagos Islands. Secondary research available on fish, seabird, marine animal, and coral populations were also analyzed to gauge the archipelago's biological response to El Niño's environmental changes. The data for this analysis was principally collected using online geo-mapping services to evaluate the spatial patterns, temperature anomalies, and chlorophyll concentrations of the 1982-83, 1997-98, and 2015-2016 El Niño events. Multiple data visualization resources were used as each mapping tool only had access to a set number of ENSO years. Satellite Images of Sea Surface Temperature Anomalies were taken directly from the NOAA View Data Exploration Tool and Earth Null School for the 1997-98 and 2015-16 El Niños respectively. No satellite images of the SSTAs for the 1982-83 El Niño were available, thus the GISTEMP Team's (v4) online computer-modeling system was used to reconstruct the estimated SSTAs. The data for the model comes from a recent study by Lenssen et al., 2019 and uses similar methods to generate the photos as the satellite visualization tools. To create these images, filters for the desired Year, Factor, and Map size were inputted and a screenshot was taken of the final image.

The direct observation of chlorophyll values for the 1982-83 El Niño were not available and a digital reanimation by the NASA Earth Observatory and NASA SeaWiFS project was used instead (1982-83). Satellite images of the chlorophyll concentrations were taken from the NASA SeaWiFS Project for the 1997-98 El Niño and from NOAA View for the 2015-16. Each image was first taken as a screenshot of the data visualization tool and later cropped to focus only on the tropical Pacific Ocean. Satellite images and modelling seen in Results Section I and II should be credited to the respected scientists and organizations involved in their creation.

Sea Surface Temperature, Sea Surface Temperature Anomalies, and Chlorophyll Concentrations

The Sea Surface Temperature (SST) and Sea Surface Temperature Anomaly (SSTA) average values were calculated in Excel using the “Monthly Atmospheric & SST” indices provided online by The National Weather Service (Table 1) (NOAA Monitoring, 2020). The values for both El Niño and La Niña conditions were chosen by averaging the three months with the highest SSTs/SSTAs observed in the Niño-3.4 region together (Appendix B). For chlorophyll, satellite images and model reconstructions are only able to estimate the concentration in the surface ocean. When possible, chlorophyll concentration values reported in relevant scientific articles were used to help quantify the values more accurately (1997-98 El Niño). Values for the 1982-83 and 2015-16 El Niño’s were estimated from the legends and descriptions of the computer-models and satellite images (Table 2).

Secondary Research on Biological Implications

In addition to firsthand analysis of the satellite imagery, strictly relevant peer-reviewed articles, theses, and reports by reliable organizations were used to support the trends seen in the satellite imagery (Table 3). These resources supplement the data and regional context missing from the satellite images and specify the impacts that El Niño had on the Galápagos’ marine life, ocean chemistry, and overall ecosystem.

Ethics

The research for this study was conducted in accordance with the SIT Study Abroad Statement of Ethics. No people were directly involved in this study, no fieldwork was completed, and no environmental sampling occurred. Therefore, this paper did not require approval from an International Review Board. The main ethical concern of this study was to ensure the proper and constant attribution of the satellite images, computer-generated models, and research data to their respective scientists and organizations. The methodologies of each research study were also taken into account, and all were deemed ethical.

Results

Oceanographic Conditions of 1982-83, 1997-98, and 2015-16 El Niños

The three strongest El Niños were divided into three sections to qualify their general oceanographic patterns and trends. The first section focused on a comparison between the peak Sea Surface Temperature Anomalies (SSTA in ° C) in the Equatorial Pacific Ocean during the specified El Niño and its transition into normal (La Niña) conditions. The second section utilized satellite imagery of chlorophyll concentrations (estimates in mg/m^3) to capture the primary production profile of the three El Niños during the peak SSTA. The final section includes secondary research from 33 biological studies that recorded the response of the marine community to these events. Appendix entries F-I contain the scales and legends for each satellite image.

<u>Section I: Sea Surface Temperature Anomalies (SSTA) with Sea Surface Temperatures (SST)</u>

1. The peak SSTAs for the 1982-83 El Niño are shown as being highly concentrated in the eastern Pacific. Peak SSTA in the Niño-3.4 region was reported as a three-month average of November-January 1983 of +2.17° C with an SST of 28.79° C. Small quantities of heat were still stored near the coasts of the western Pacific. The Galápagos Islands were located in a region of high SSTAs of approximately +2.0° Celsius (Figure 3).

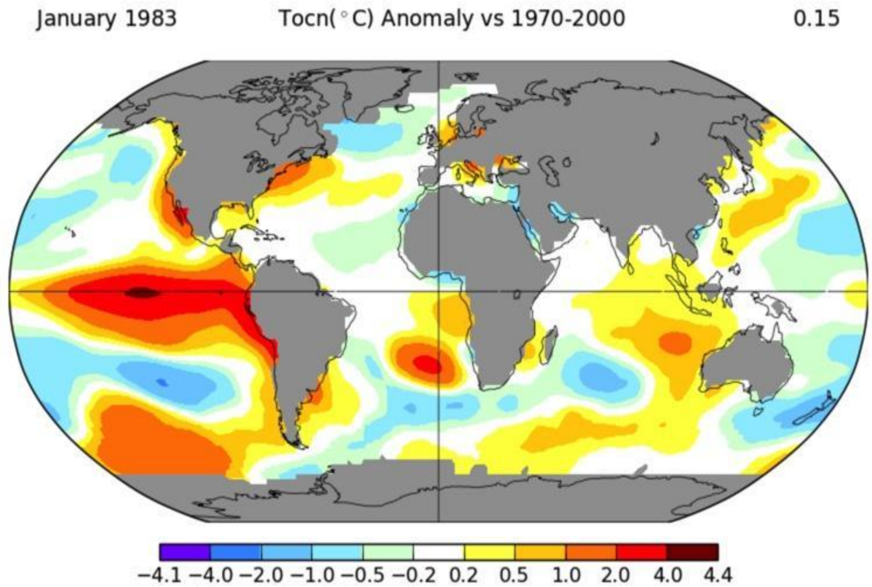


Figure 3. Spatial pattern of the SSTAs of the 1982-83 El Niño. Computer-generated for January 1983, no satellite imagery available (GISTEMP Team, 2020)

The 1982-83 El Niño reversal to a La Niña phase shows some visible recovery of the Eastern Pacific Cold-Tongue reforming/reformed in the ETP region (Figure 4). The strength of SSTA of the 1982-83 El Niño caused a long delay in recovery to the La Niña phase but some concentration of the warm pool was still collected near Peru and Ecuador. The Niño-3.4 region's SSTA was reported as an average of the November-December months of -1.11° C with an average SST of 25.50° C.

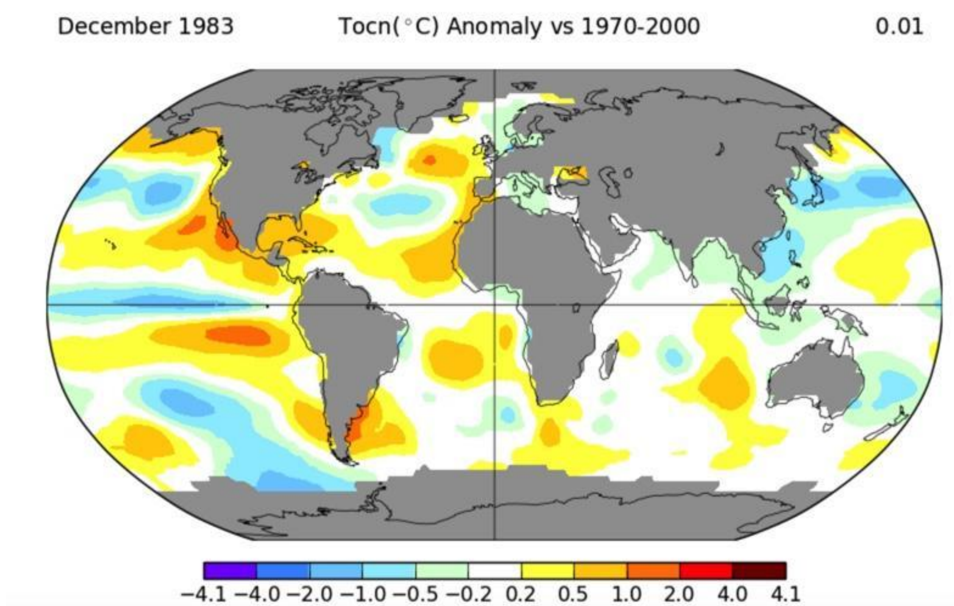


Figure 4. Recovery of the 1982-83 El Niño to La Niña conditions. Computer-generated for December 1983, no satellite imagery available (GISTEMP Team, 2020).

2. The peak SSTAs observed for the 1997-98 El Niño. The main heat distribution pattern can be seen concentrating in the eastern Pacific with high SSTAs also in the central area. There appears to have been some leftover circulation still pushing the warm water out into the eastern and central areas. The Galápagos Islands were located in an area of small circulation of anomalously warm water, approximately +3°C- 4°C (Table 3). The highest SSTA in the Niño-3.4 region was reported as the average of October-December 1987: +2.41°C with an average SST of 29.03°C.

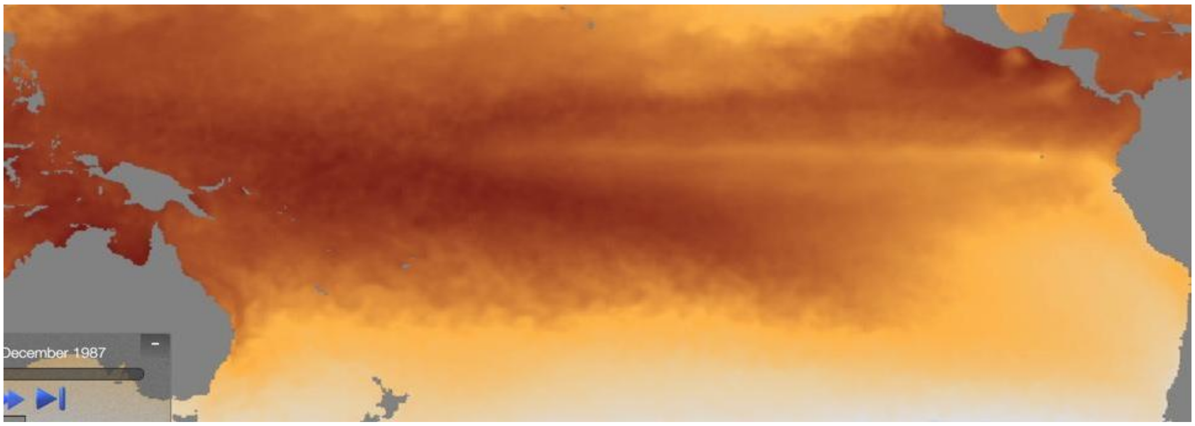


Figure 5. Main SSTA concentration pattern of the 1997-98 El Niño in the Southern Pacific Ocean. Satellite image captured from December 1987 (NOAA View, n.d).

The reversal to Cold-Tongue stratification in the Eastern Tropical Pacific occurred rather rapidly after the 1997-98 El Niño. Strong circulation is seen along the coast of Peru fueling a quick development of the Cold-Tongue. The Cold-Tongue also reached far into the western Pacific, slightly farther than the 1982-83 El Niño. The Niño-3.4 region's highest SSTA was reported as the average of May-July: -0.80° C with an average SST of 26.40° C.

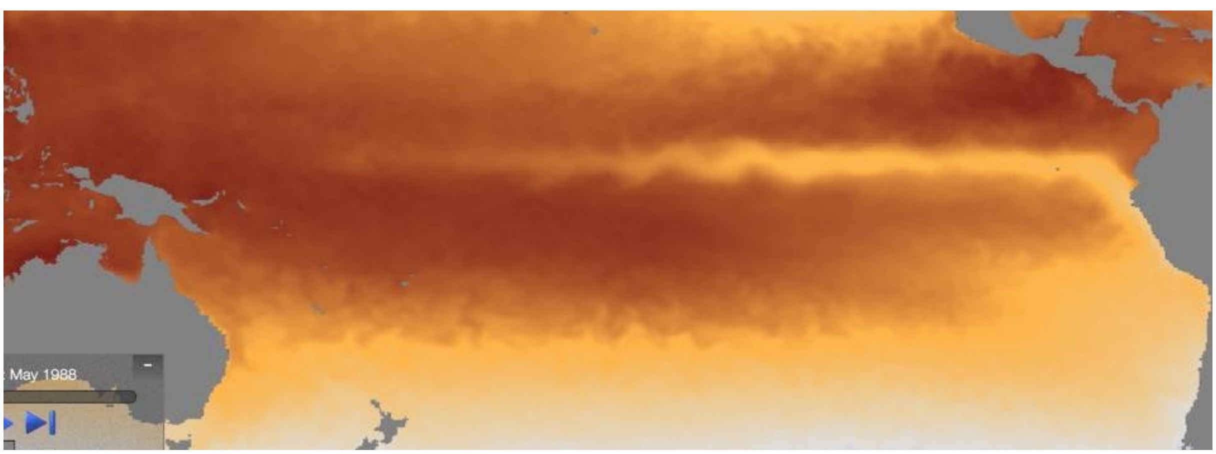


Figure 6. Recovery of the 1997-98 El Niño to La Niña conditions and a strong Cold-Tongue circulation pattern. Satellite image captured from May 1988 (NOAA View, n.d).

3. The peak SSTAs observed for 2015-16 El Niño. This satellite image shows a thick warm pool concentrating on both sides of the equator, mostly in the central and eastern Pacific. The warm

pool still reached far into the western Pacific and may have caused greater environmental impacts across the Pacific with the highest SSTAs. The Galápagos Islands were located in an area of high SSTAs with water approximately +3°C-4°C. The highest SSTA in the Niño-3.4 region was reported as the average of October-December 2015 as +2.64° C with an average SST of 29.25°C.

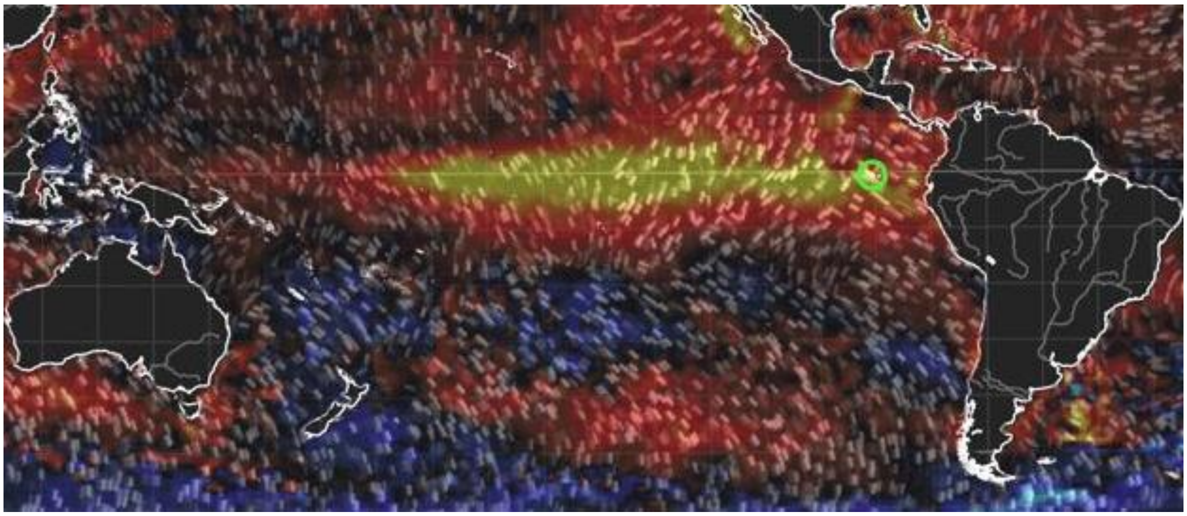


Figure 7. Peak conditions of the 2015-2016 El Niño. Satellite image captured from November 2015 (green circle around Galápagos Islands)(Earth Null, n.d).

The near-complete reversal to La Niña conditions from the 2015-2016 El Niño took longer than the 1997-98 El Niño but shorter than the 1982-83 El Niño. The Cold-Tongue had nearly reformed by July 2016 and upwelling restarted along the coast of Peru. The Cold-Tongue reaches out into the central Pacific but not as far into the western Pacific as 1997-98. The highest SSTAs in the Niño-3.4 region was reported as the average of July-September 2016 as -0.65° C with an average SST of 26.02° C.

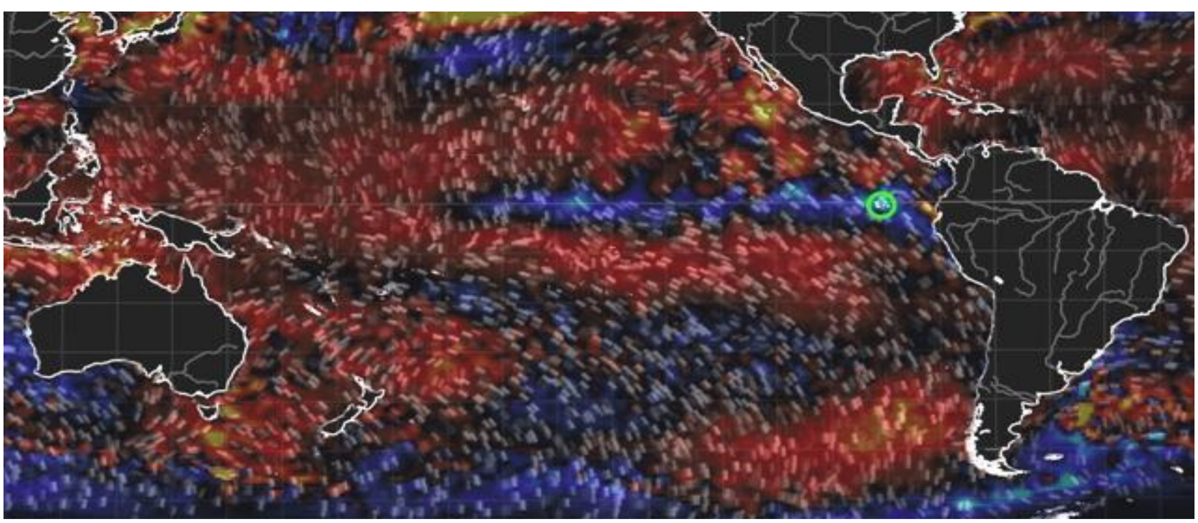


Figure 8. Return of the 2015-16 El Niño to La Niña conditions. Satellite image captured from July 2016 (Earth Null, n.d.).

Section I: Summary Table

Out of the three El Niños, the ETP experienced the lowest average SSTA and SST during the 1982-83 El Niño (2.17°C and 28.79°C respectively). The ETP experienced the second-highest SSTA and SST during the 1997-98 El Niño (2.41°C and 29.03°C). The highest SSTA and SST experienced in the ETP were during the 2015-16 El Niño (2.64°C and 29.25°C). El Niño tended to reach peak SSTA and SST between the end of October and the beginning of January. Data available for the return to La Niña conditions showed that the average SST during Cold-Tongue conditions was 25.97° C. The 1982-83 El Niño had the longest recovery process to a normal SST of 25.5°C by Nov/Dec of 1983. The 2015-16 El Niño had a shorter recovery time and returned to a normal SST of 26.02°C by July-Sept of 2016. The 1997-98 El Niño recovered to a normal SST the fastest reaching 26.4° C by May-July 1998.

Table 1. The Sea Surface Temperature Anomalies and Sea Surface Temperatures for the three El Niño events. SSTA and SST were averaged across the indicated peak months for an average of the anomalies experienced across the general Eastern Tropical Pacific region. These averages are an estimate of the SSTA and SST close to the shores of the Galápagos Island.

El Niño Year	Peak Months (avg.)	SSTA (° Celsius)	SST (° Celsius)	Value sources
1982 - 83	Nov '82 - Jan '83	2.17	28.79	GISTEMP, 2020
post 1982 - 83	Nov '83 - Dec '83	-1.11	25.50	GISTEMP, 2020
1997 - 98	Oct '87 - Dec '87	2.41	29.03	NOAA View, n.d.
post 1997 - 98	May '88 - Jul '88	-0.80	26.40	NOAA View, n.d.
2015 - 16	Oct '15 - Dec '15	2.64	29.25	Earth Null, n.d.
post 2015 - 16	Jul '16 - Sept '16	-0.65	26.02	Earth Null, n.d.

Section II: Chlorophyll Concentrations as a proxy for Marine Primary Productivity

Satellite images below show the distribution and average concentration of chlorophyll in the ETP during El Niño and La Niña conditions. For the purposes of this paper, chlorophyll concentrations above 0.3 mg/m^3 are considered nutrient-rich waters and below 0.3 mg/m^3 are nutrient-poor (Barber & Chavez, 1983).

1. The change in chlorophyll concentrations for the 1982-83 El Niño was significant. This model shows a high depression and dispersal of chlorophyll concentrations normally found in the EP Cold-Tongue. Some higher concentrations of chlorophyll were still seen along the coasts of Peru and Ecuador. The Galápagos Islands are classified as being in nutrient-depleted waters. The model reconstructed chlorophyll values to be at estimated concentrations below 0.01 mg/m^3 for the ETP.

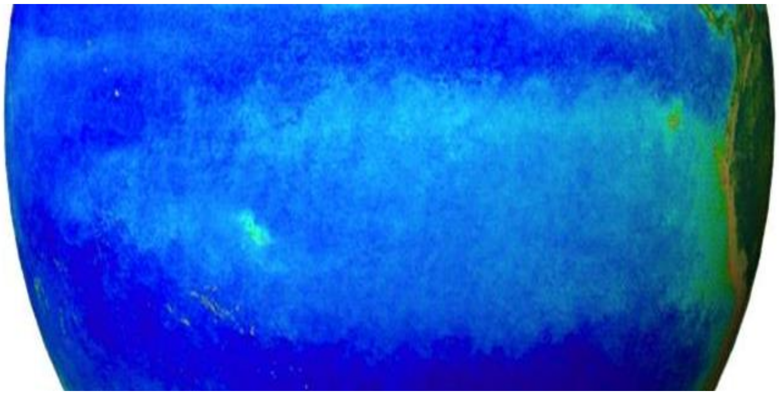


Figure 9. Chlorophyll pattern in the Southern Pacific Ocean during the 1982-83 El Niño. A computer-generated model of January 1983 (NASA Observatory, 2017; NASA SeaWiFS, n.d.).

Chlorophyll concentrations showed a large algal bloom in recovery from 1982-83 El Niño. The chlorophyll concentrations were especially high in the central and coastal regions of the ETP with increased upwelling and rapid restart of primary production. The computer-generated model for July 1983 reconstructed chlorophyll values at estimated concentrations greater than 0.10 mg/m^3 (NASA Observatory, 2017). No direct-observations were available for chlorophyll values during 1982-83 (NASA Observatory, n.d.;NASA SeaWiFS, n.d.).

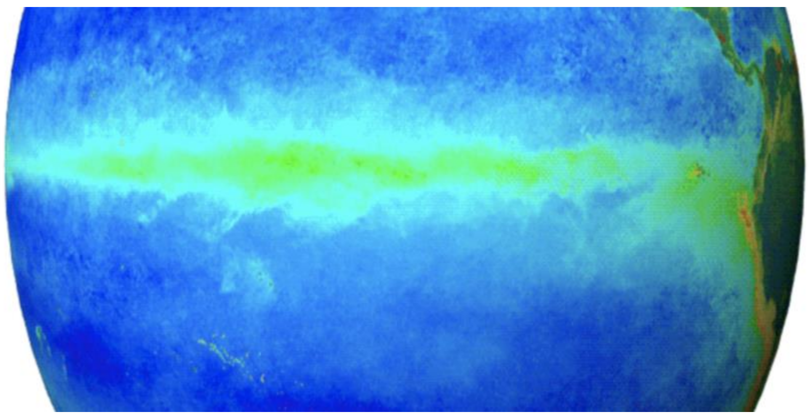


Figure 10. Recovery of upwelling and primary production in the Southern Pacific Ocean after the 1982-83 El Niño. A computer-generated model of chlorophyll concentrations for June 1983 (NASA Observatory, 2017; NASA SeaWiFS, n.d.).

2. The pattern of chlorophyll concentrations in the Eastern Tropical Pacific for the 1997-98 El Niño was widely dispersed. Pattern shows a high depression of normal Cold-Tongue chlorophyll concentrations in the central and eastern Pacific. Low amounts of chlorophyll seen along the Peruvian coast. The Galápagos Islands were classified as being in heavily nutrient-depleted waters. Reported chlorophyll values from Chavez et al. (1999) in the Niño-3.4 region reported at less than 0.05 mg/m^3.

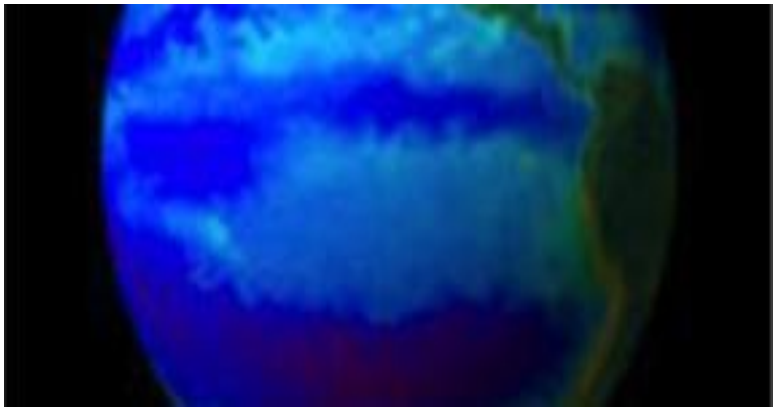


Figure 11. Chlorophyll concentrations in the Southern Paciifc Ocean during the 1997-98 El Niño Satellite image captured from November 1997 (NASA SeaWiFS, n.d.).

The recovery of Eastern Tropical Pacific chlorophyll concentrations occurred rapidly after the 1997-98 El Niño. A large algal bloom was seen in eastern and central Pacific regions with rapidly increasing rates of primary productivity over the summer months. Recovery of chlorophyll values in the Niño-3.4 region reached very rich values of 1.40 mg/m3 and the Galápagos Islands experienced levels up to 3.0 mg/m3.

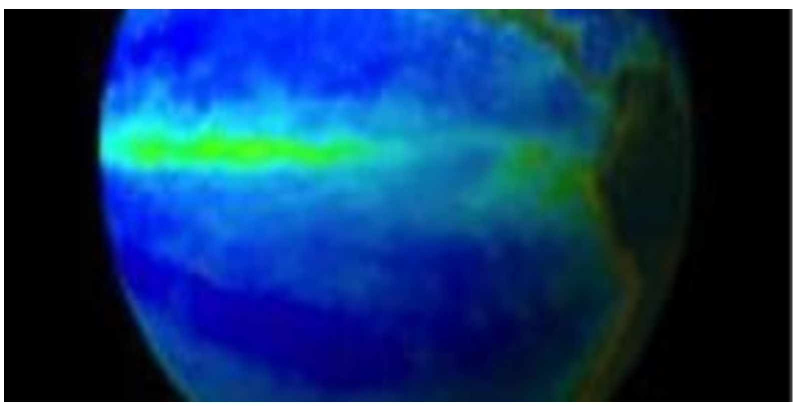


Figure 12. Recovery of primary productivity in the surface ocean of the Southern Pacific Ocean after the 1997-98 El Niño. Satellite image captured from June 1998 (NASA SeaWiFS, n.d.).

3. Low levels of chlorophyll were observed during 2015-16 El Niño, though not as low as the 1982-83 or 1997-98 El Niños. Dark blue areas above and below the normal Cold-Tongue region show there was a high depression and narrowing of the chlorophyll concentrations across the eastern pacific. Even lower chlorophyll levels were found in the central area where there appeared to be large regions of almost no chlorophyll. Chlorophyll concentrations in the Niño-3.4 were estimated to be at 0.12 mg/m3.

Figure 13. Chlorophyll concentrations in the Southern Pacific Ocean during the 2015-16 El Niño. Satellite image captured from November 2015 (NOAA View, n.d.).

Chlorophyll concentrations recovered rather quickly after the warm pool of the 2015-2016 El Niño. Large algal blooms were observed in the central Pacific with smaller but more concentrated amounts in the eastern areas. A greater recovery was found along the coasts where more upwelling occurred at the beginning of the recovery of the Eastern Pacific Cold-Tongue. The average chlorophyll concentrations in the Niño-3.4 region were estimated to be 1.20 mg/m^3.

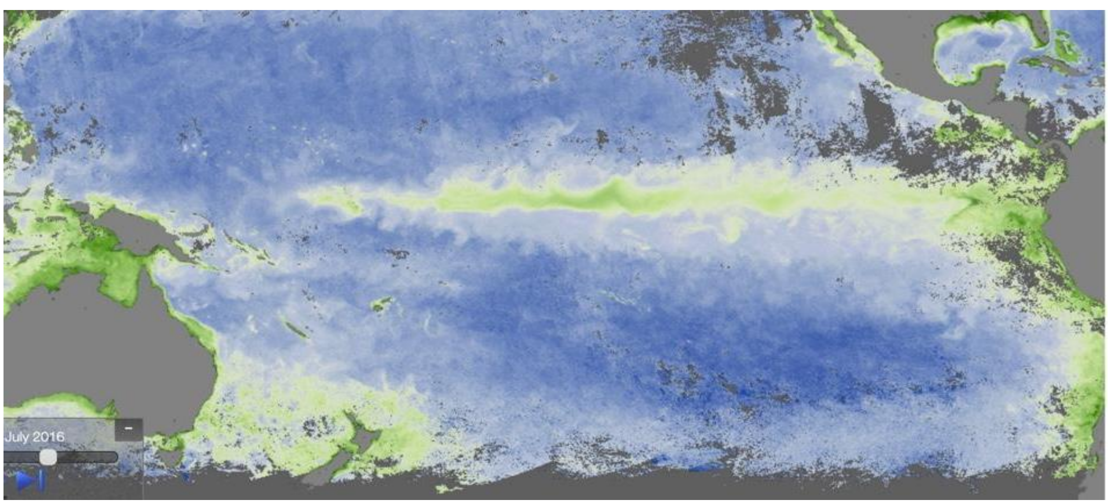


Figure 14. Recovery of chlorophyll concentrations in the Southern Pacific Ocean after the 2015-16 El Niño. Satellite image captured from July 2016 (NOAA View, n.d.).

Section II: Summary Table

The lowest reported chlorophyll values for the three El Niños were found during the 1997-98 El Niño. This event also experienced a high recovery from the warm pool and experienced a large algal bloom in nutrient-rich conditions (1.40 mg/m^3)(Glynn et al., 2017). The 1982-83 ETP chlorophyll values were estimated from a computer-generated model to also be very nutrient-poor, but only threshold values were available. The 2015-16 El Niño also reached low levels of chlorophyll (0.12 mg/m^3) though not as low as the other two extreme El Niños. The

2015-16 experienced a large chlorophyll recovery after peak conditions like the 1997-98 El Niño, reaching 1.20 mg/m^3.

Table 2. The chlorophyll concentration values for three El Niño events and their corresponding values during post-El Niño conditions. Chlorophyll concentrations were averaged across the indicated peak month periods. Note that direct-observation of chlorophyll values was not available before 1997; values for 1982-83 El Niño were reconstructed using computer-modeling visualizations from NASA Observatory, 2017.

El Niño Year	Peak Months (avg.)	Chlorophyll Conc. Estimates (mg/m3)	Value Sources
1982 - 83	Nov '82 - Jan '83	reconstructed, <0.10	NASA Observatory, 2017
post 1982 - 83	Nov '83 - Dec '83	reconstructed, >0.10	NASA Observatory, 2017
1997 - 98	Oct '87 - Dec '87	0.05	Chavez et al.,1999
post 1997 - 98	May '88 - Jul '88	1.40	NASA Observatory, 2017
2015 - 16	Oct '15 - Dec '15	0.12	NOAA View, n.d.
post 2015 - 16	Jul '16 - Sept '16	1.20	NOAA view, n.d.

<u>Section III: Research Articles on El Niño and its impacts on the marine species populations near the Galápagos Islands and the ETP region</u>

In this section, 33 scientific articles were analyzed to understand the biological impacts of the 1982-83, 1997-98, and 2015-16 El Niños events on the Galápagos Islands and overall effects of ENSO in the Eastern Tropical Pacific. Out of the 33 articles, 15 key species were chosen to exemplify the gravity and wide-spread dispersion of El Niño's biological consequences. Out of the 15 species, 100% experienced some kind of reproductive failure, breeding season adaptation, or mortality event. Fish were shown to respond the fastest to El Niño's alteration of SSTAs and chlorophyll levels. Seabirds, corals, and marine iguanas experienced some of the highest rates of mortality events (over 90%) across the analyzed species. El Niño also caused approximately 60% of these species to have to relocate or modify their amount of time spent hunting to accommodate for losses in food availability from lower trophic levels. Some of the highest mortality rates across species were seen during the 1997-98 El Niño, but more information is not yet available on the true extent of the 2015-16 El Niño which had higher average SSTAs in the ETP. Though the effects of El Niño were seen throughout the ETP, the Galápagos Islands experienced abnormally high rates of biological damage.

Table 3. Summary from biological reports of the most drastic impacts of extreme El Niños from the past 50 years (1970s-2020) on the marine communities in the ETP and the Galápagos Islands. The major environmental changes (SSTA, SST, chlorophyll concentrations) associated with these impacts are also summarized.

Marine Species	**Effects on Organisms**	**Environmental Impacts**	**Citation**
Sardines	-more resistant to warmer temps but still a majority of populations	- depressed thermocline	Barber & Chavez (1983), Jarrin & Salinas-

	disappeared from surface waters, esp. during 1997-98 El Niño - remainder of populations were restricted to the phytoplankton zones pushed up against the coasts and vulnerable to fishing or moved south down the Americas - loss of juvenile members from population - After the 2015-16 El Niño, catch composition of artisanal fin-fish fishery became dominated by predatory benthic fish species	- warmer surface waters, decreased upwelling, and therefore less phytoplankton available in the surface layer - nitrate concentration dropped from rich levels to depleted levels (<0.1μm) - higher predation by more temperate species - fish emaciation more frequent in shallower dwelling fish, indicative of smaller composition of the artisanal catch	de-León (2018), Velarde et al. (2004)
Anchovy	- next to zero fish were found in normal fishing habitats or in deeper waters (some found at ~80m) - complete redistribution of population or high mortality events - loss of juvenile members from population - collapse of some local populations due to overfishing exacerbated by El Niño	- warmer water particularly affected anchovy populations, decreasing their overall biomass from nearly 20 million tons in 1960 to below 6 million after intense 1982-83 El Niño - some regions could experience +2 - 6°C anomalies - 20-fold decrease in primary productivity near Galápagos Islands -ENSO conditions increased benthic predator fish pop. (seabass, snapper) and overpowered sensitive small fish populations	Ñiguen & Bouchon (2004), Sharp & McLain (1993), Quispe-Ccalluari et al. (2018), Barber & Chavez (1983)
Jack and Pacific Mackerel	- migratory resource that was often heavily overfished when sardine and anchovy pops. Disappeared - eggs can sometimes survive through El Niño events to repopulate after -food shortages as all fish are pushed up against the shoreline, high competition -juveniles dominated populations during El Niño events	- Warm water perturbations shocked populations along shorelines and near off the coast -response to environmental changes occurred about one-year after El Niño peak anomalies -prefers a 15°C isotherm that was heavily depressed and moved south -restoration of ideal nursery habitat conditions can take up to 3-4 years to recover after anomalies	Sharp & McLain (1993,) Pacheco et al. (2012), Arcos et al. (2001), Peña-Torres et al. (2017), Dioses et al. (2002),
Corvina	- mortality event in corvina fish and anchovy populations	- quick rise in SST at the onset of events, ~5°C in some coastal regions	Barber & Chavez (1983), Valdivia & Wolf (1985)

	-40% to 80% reduction in some populations during El Niño	which shocked many surface layer species - disappearance of bottom-dwelling fish heralds the arrival of quick temp. change for these species	
Blue-footed booby	- reproductive failure of blue-footed booby common - high rates of nest and colony failure - more birds seen visibly exhausted and emaciated - blue-footed booby's response to ENSO occurred within a few months - 87% of blue-footed booby pairs delayed by warmer SST during ENSO conditions	- Extreme food shortage - large dispersal of marine prey - Increase in precipitation shown to have a positive relationship with disease and parasite abundance - 1 degree of atmospheric pressure change (hPa) lead to 7-day reproductive delay -1 degree of SST warmer (°C) reduced avg. nest success by 0.45 fledglings	Barber & Chavez (1983), Gibbs et al. (1987), Champagnon et al. (2018), Jones & DuVal (2019), Ancona et al. (2011), Meraz et al. (2013), Castillo-Guerrero et al. (2014), Kiere & Drummond (2016)
Nazca booby	- 30% of Nazca booby juvenile survival explained by ENSO oscillation indices - 23% of Nazca booby adult survival dictated by larger decadal oscillation patterns in the ETP ^ a proxy for changes in inter-annual upwellng rates, nutrient supply, and fish populations	- climate indices (ENSO) had a pronounced effect on bird survival rates -probability of adult survival depended on year and sex	Champagnon et al. (2018), Ancona et al. (2011), Clifford & Anderson (2001)
Galápagos penguins	- overall smaller clutch and brood sizes during ENSO conditions - many emaciated and/or dying birds seen in colonies -loss of juvenile population - reduction of adult population - increased diminution in population since 2014	- ENSO SSTA affected breeding participation, timing, nest success, and fledgling success	Champagnon et al. (2018), Ancona et al. (2011), Fundación Charles Darwin (2017)
Flightless cormorants	- nest and colony collapse common events - relocation of colonies to new areas causes great stress on the community - juvenile population is often the	- increases in Sea Surface Temperatures over 7° Celsius in some cormorant habitats - stress on bird population to find food for farther and longer amounts of distance and time	Wolff et al. (2012), Fundación Charles Darwin (2017),

	first to die off		
Great frigate birds	-reproductive failure common in great frigate birds - population relocation or colony collapse often observed -experienced up to 95% mortality in some colonies	- many dead birds found along the coast of Peru - evidence of climate change and anthropogenic effects exacerbating ENSO threats to the stability of seabird habitats and populations	Fundacion Charles Darwin (2017), Barber & Chavez (1983)
Albatross	-reduced nesting of albatross communities with high nest abandonment - emaciated or exhausted birds often observed	- pollution also exacerbating ENSO's effects - food limitation and overly competitive environment to survive	Fundacion Charles Darwin (2017), Barber & Chavez (1983)
Marine Iguanas	- some islands in Galápagos experienced 90% mortality of marine iguanas - every Islands reported at least 10% mortality - Severe mortality events delayed the species reproduction and recovery - large territorial male iguanas suffered the highest mortality during El Niño	- Marine Iguana populations dictated by cyclical famine from ENSO food shortages, warm temperatures, and over intertidal algal loss - marine populations threatened by loss of genetic data from ENSO-caused population crashes - higher the population density, higher the mortalities from ENSO	Steinfartz et al. (2007), Wikelski & Nelson (2004), Wikelski et al. (1997), Wikelski & Thom (2000), Galápagos (1987)
Sea lion and fur seals	- reproductive failure and loss of juvenile/young from population due to emaciation - reduction in adult population as they try to provide for young as well - wide population dispersal due to food shortage, seen in colonies from Chile to Mexico	- Extreme food shortages - habitat limitation - increased intra and interspecies competition for resources - widespread temperature effects along the western coast of South America	Guzman & Siefeld (2002), Barber & Chavez (1983), Fundación Charles Darwin (2017), Moraga et al. (2015)
Corals	- low number of coral reefs that experienced bleaching/ mortality in 1982 survived the 1997-98 El Niño anomalies - coral mortality does not end with the phasing out of an El Niño ($\geq$1 year) -higher coral mortality in ETP during 1982-83 than 1997-98 (52-	- main dangers to corals increased solar insolation, altered storm activity, sedimentation, global warming - bleaching and coral mortality have been increasing with ENSO over time - coral reefs in Galápagos region experienced 3-4°C SSTA anomalies - SSTs $\geq$28ºC are potentially	Glynn et al. (2001), Rossi & Soares (2017), McClanahan et al. (2019), Zapata et al. (2010), Fundación Charles Darwin (2017), Galindo et al. (2012)

	97%) (2-3°C lower than peak SST during 1997-98 El Niño) - 70-90% of all zooxanthellate corals were bleached - 26.2% mortality of corals in Galápagos (Isla Española had 75.5% mortality) - G. planulata coral experienced local extinctions after species barely survived 1982-83 El Niño	dangerous to archipelago's corals - unprecedented rates of near-shore sea warming - corals experienced mortality events within weeks of high SSTAs - first observed coral bleaching event Dec 1997 (Eisenhardt, 1997) - Galápagos corals experience the highest rates of mortality and bleaching of the entire ETP	

Analysis

Trends between SSTA, SST, Chlorophyll concentrations, and the health of key marine species

No direct linear relationship was found between the amplitude of Sea Surface Temperature Anomaly and the amount of decline in chlorophyll concentrations (proxy for phytoplankton biomass) in the Eastern Tropical Pacific. Though the 2015-16 El Niño experienced the highest amount of SSTA (+2.64°C), it did not reach the lowest chlorophyll concentrations (only 0.12mg/m^3). The 1997-98 El Niño had the lowest average amounts of chlorophyll (0.05mg/m^3) and the 1982-83 El Niño could only be estimated to reach a significantly nutrient-poor threshold (<0.10 mg/m^3)(Table 2). Despite this, an overall trend was observed across all three El Niño events between an increase in SST (high SSTA) and a decrease in chlorophyll concentrations (Table 1 and 2). This means that any presence of the El Niño warm pool over the ETP reduces the overall primary productivity of the region by decreasing upwelling and nutrient availability (Wolff et al., 2012). Furthermore, chlorophyll concentrations below the nutrient-rich threshold (0.3mg/m^3) were easily observed during all three El Niño events (Appendix J)(Barber & Chavez, 1983). These chlorophyll estimates show that pelagic (open ocean) fish species, and the upper trophic levels that rely on them, had to try to survive in waters with dangerously low levels of available food (Appendix K). Though marine species suffered during each El Niño period, there appeared to be a higher frequency of mortality events in mammals after the 1997-98 El Niño (Table 3). The 1982-83 El Niño also had high mortality rates in corals, seabirds, and pelagic fish but the extent of these impacts and the exact drop in chlorophyll concentrations experienced by Galápagos' marine species is less well-known (estimate <0.10 mg/m^3). The effects of El Niño can be delayed and thus studies in the coming years may find more biological effects from the 2015-16 El Niño, but from this research it appears that chlorophyll concentration is a more direct indicator of the survival of marine animals than SSTAs. However, SSTAs may be stronger indicators of the survival of intertidal algae and coral reef ecosystems as these submerged areas are more directly affected by sea water temperature than seabirds or marine iguanas. Additionally, high rates of coral bleaching, mortality, and algal loss were seen during all three El Niños (SSTA range of 2.17°C-2.64°C) and may signify that Galápagos' marine plants cannot survive over a certain threshold of SSTA (Fundación Charles Darwin, 2017). Each El Niño event reached a SSTA threshold of at least +2°C and below chlorophyll levels of 0.12 mg/m^3. These values can serve as important thresholds for predicting the survival of marine species in the Galápagos Islands after powerful El Niño events.

Chlorophyll: Pelagic Fish and Seabird Populations

A serious reduction in the overall biomass of phytoplankton destabilizes the bottom of the food chain and sends rippling effects throughout the trophic levels (Appendix K). Since pelagic fish species like sardines (S*ardinops sagax*) and anchovies (*Engraulis ringens*) rely on phytoplankton populations to survive, they suffered great declines in population due to food shortages during El Niño (Barber & Chavez, 1983;Ñiguen & Bouchon, 2004). Recent studies have also found that temperate predatory fish like the Grape eye seabass (*H. macrophthalmus*) and Pacific dog snapper (*L. novemfasciatus)* became more prevalent during warm El Niño conditions and further diminish small pelagic fish (Jarrin & Salinas-de-León, 2018). Moving up the food chain, smaller anchovy and sardine populations spell disaster for seabirds and marine mammals (Wikelski & Nelson, 2004;Ancona et al., 2011). Exceptionally high rates of habitat abandonment, population dispersal, juvenile failure, and overall population loss were observed in both seabirds and marine mammals as the fish populations decreased (Glyn et al., 2001;Ancona et al., 2011). The research articles from each El Niño event showed that extreme changes to the stable oceanographic conditions of the Eastern Tropical Pacific and the Galápagos Islands led to intense declines in the fitness and stability of marine organisms (Table 3)(Appendix K). Though satellite images showed the ETP recovered to high chlorophyll levels and normal SSTs within a year of peak El Niño conditions, seabird and marine mammal populations declined quickly during the 9-15 month climate perturbation (Stenseth et al., 2002).

Most studies have focused on seabirds as they respond the fastest to destabilized marine food webs (after pelagic fish populations) and can be an important bioindicator of the severity of El Niño's impacts on larger animals (Barber & Chavez, 1983). For example, seabirds' reproductive success and overall fitness was significantly reduced by the middle of extreme El Niño periods, much sooner than other marine organisms (Champagnon et al., 2018). Food shortages commonly led to delays in breeding time as birds had to spend longer times hunting just to feed themselves. Adult seabirds also suffered quickly if trying to provide for their young and lead to mortality events within small populations that often caused island-wide colony failure (Ancona et al., 2011). In the Galápagos Islands, the health of the Blue-footed booby (*Sula nebouxii*) and Nazca booby (*Sula granti*) populations were often endangered during El Niño conditions (Clifford & Anderson, 2001;Huyvaert & Anderson, 2004;Gibbs et al., 1987). Flightless cormorants and Galápagos penguin populations also declined directly with the loss of pelagic fish populations and have frequently skipped breeding seasons to survive (Fundación Charles Darwin, 2017). Reproductive failure is common throughout marine species during El Niño periods, and has been routinely documented in the Galápagos fur seal (*Arctocephalus galapagoensis*) and California sea lion (Zalophus wollebaeki) (Barber & Chavez, 1983). Disrupted population demographics can be seen in species across the Pacific Ocean. In 1983, a colony on Christmas Island in the Indian Ocean of over 20,000 Great frigate birds (*Fregata minor)* was reduced to fewer than 100 birds in a matter of months (Barber & Chaves, 1983). In addition to El Niño's decrease in overall fish populations, it also redistributes prey to new locations in the Pacific. Pelagic fish must follow the scarcely available phytoplankton concentrations which can make them harder to find (Section II chlorophyll images)(Appendix K). Birds and other marine mammals thus have to travel farther in search of food or relocate altogether (Jarrin & Salinas-de-León, 2018;Ancona et al., 2011).

SSTA: Marine Iguana and Algal Communities

In addition to the threat El Niño poses to seabirds and marine mammal species through fish limitation, it similarly threatens herbivorous species like the endemic Galápagos marine iguana (*Amblyrhynchus cristatus*)(Wikelski & Nelson, 2004;Steinfartz et al., 2007). The marine iguanas' only food source is intertidal algae growing in the rocky-shore zone around the Galápagos Islands (Wikelski et al., 1997). In anomalously warm temperatures, algal growth declines rapidly throughout the Galápagos region and marine iguanas have to adapt dramatically to survive (Wikelski et al., 1997). Marine iguanas' body size is limited by food intake and can shrink to 35% their normal size to accommodate for lower algae concentrations. The large SSTA associated with El Niño conditions, especially during the 1997-98 event (+2.41°C), were shown to decrease algal biomass to scarce concentrations in rocky-shore communities (Vinueza et al., 2006). Marine iguanas can only adapt to so many environmental changes. Some islands in the Galápagos have lost up to 90% of their marine iguana populations after El Niño events (Steinfartz et al. 2007).

El Niño also raises the sea level and intensifies wave action along rocky-shore habitats (Glynn et al., 2017). Higher sea levels and increased wave erosion endanger many different types of plant life in these sensitive tidal habitats. Some plants are unable to survive the perturbations in temperature and erosion, like the brown macroalgae *Sargassum* and endemic *Bifurcaria* algae that both went extinct in the Galápagos after the 1982-83 El Niño (Vinueza et al., 2006). In addition to these changes in oceanic conditions, algal communities are also at risk from predation by the sea urchin *E. galapagensis* (Glynn et al., 2017). Grazers like this echinoid normally maintain healthy coral reefs and intertidal habitats but El Niño disrupts this balanced predator-prey relationship. Warmer temperatures seem to favor sea urchin abundance, or they may potentially be less affected by the high SSTAs of El Niño events (Glynn et al., 2017). Overgrazing by sea urchins can destroy delicate algal and coral reef communities as they try to survive El Niño's impacts (Glynn et al., 2017). Additionally, algal communities rely on upwelled nutrients to buffer environmental changes and suffer alongside phytoplankton communities in El Niños' warm, nutrient-depleted waters (Randall et al., 2020). The impacts on primary producers quickly cascades up the marine ecosystem's tropic levels, as demonstrated by El Niño's effects on fish, seabird, and marine iguana populations (Appendix K).

SST and SSTA: Coral Reef Ecosystems

Coral reefs are another essential component of healthy marine ecosystems alongside phytoplankton. Coral reefs are some of the most productive regions in the ocean and also provide key habitats for thousands of different species (Glynn et al., 2001). Coral reefs share an intimate connection with algal communities and both are jeopardized during extreme El Niño events (Appendix L). Coral reefs are resistant 3-D structures but are quickly and devastatingly affected by anomalously warm sea temperatures (Fundación Charles Darwin, 2017). Coral bleaching occurs when corals become overly stressed due to changes in temperature, light, or nutrients in the water and react by expelling the symbiotic algae in their tissues (NOAA, 2020)(Appendix M). Coral reefs can recover from short and intermittent bleaching events, but ENSO-induced bleaching is intense and prolonged. During the 1997-98 El Niño, corals exposed to SSTs greater than or equal to 28ºC experienced reef-wide bleaching events. The corals that survived the 1982-

83 El Niño were either eliminated or threatened by the later 1997-98 event (Glynn et al., 2001). Approximately 70-90% of all corals in the Galápagos were bleached by the 1997-98 El Niño as the region experienced the highest coral mortality event in the entire ETP (26.2%) (Appendix N). For coral reefs, SSTs over 28ºC or SSTAs of + 2ºC are considered severe conditions (Glynn et al., 2017). These conditions were observed in all three El Niño periods (28.79ºC, 29.03ºC, 29.25ºC) for an average of three months. It is no surprise that after these recurring perturbations only one true coral reef, located just off the coast of Darwin Island, remains in the Galápagos (Fundación Charles Darwin, 2017)(Appendix N). ENSO's amplification of regional temperature levels has lethal effects on Galápagos corals and species recovery after each event does not appear to be robust. As coral and algal communities suffer, so too do the higher trophic levels that rely on their stability and production for survival (Appendix K, Appendix L).

Discussion

A. Spatially Defining the Three Most Powerful El Niños

The biological impacts of El Niño are undeniable. The scientific literature used in this study confirmed that the 1982-83, 1997-98, and 2015-2016 El Niño's are truly some of the most powerful climate events on record. In addition to their similar SSTAs, SSTs, and chlorophyll profiles, these forceful events have also all been classified as Eastern Pacific El Niños (Yu & Kim, 2013). Eastern Pacific El Niños, or EP El Niños, concentrate the majority of their changes in the Niño-3 region (Appendix B). The Galápagos Islands are located in the easternmost part of the Niño-3 region (approximately 0° 47' S and 91° 8' W) and have thus experienced heightened biological repercussions during these events.

a. *Central Pacific and Eastern Pacific El Niño*

ENSO is driven by ocean-atmosphere interactions, and therefore the severity of its impacts is closely related to the amplitude and location of change experienced by the ETP. Specifically, not all El Niño events are the same, and the categorization of different ENSO events over the past 100 years is an ongoing debate in the scientific community (Ashok et al, 2007). There are two main types of El Niño events that have been widely agreed upon: the Central Pacific El Niño (also known as Warm-Pool El Niño [Kug et al., 2009], El Niño Modoki [Ashok et al., 2007] or dateline El Niño [Larkin & Harrison, 2005]) and the Eastern Pacific El Niño (canonical events known as Cold-Tongue El Niño [Kug et al.,, 2009]) (Appendix O).The most important delineation between the two ENSO types is that the EP El Niño is defined by SST anomalies that originate in the Niño 1+2 region and eventually concentrate in the Niño 3 region. This ENSO has greater oceanographic and atmospheric effects across the Southern Pacific (Kao et al., 2009). The Central Pacific El Niño (CP) is characterized by SST and surface wind anomalies in the Niño-4 region (Kug et al., 2009;Lee & McPhaden, 2010). As seen in the SSTA images for the three El Niños, these events all had strong warm pool concentrations in the eastern Pacific (Niño-3 region)(Section I). It is important to understand the difference between these two types of El Niños as the Galápagos Islands have experienced greater consequences during EP El Niños.

b. *Concentration of effects*

The dichotomous spatial concentrations of these two types of ENSO cause variations in basinwide impacts (Kao et al., 2009). CP El Niño events tend to develop and decay in situ (Niño-4) whereas EP El Niño anomalies have a longer origination and decay system (Appendix P). EP El Niños experience a western propagation where their anomalies generally begin in the Niño 1+2 in March, then Niño-3 in April, Niño-3.4 in May, and finally reaching the Niño-4 region in

September (Kao et al., 2009; Kug et al., 2009). CP El Niño events concentrate the majority of surface wind, SST, and subsurface anomalies to the central Pacific (Kao et al., 2009). The impact of ENSO's atmospheric circulation also varies since CP El Niños exhibit a more westward location of the rising branch of Walker Circulation and EP El Niños have stronger anomalies over central and eastern Pacific (Hu et al., 2016). Furthermore, EP El Niños generate higher amounts of atmospheric water vapor and warmth in the eastern Pacific and have greater impacts on Galápagos Island ecosystems. (Hu et al., 2016).

c. *Duration of Event*

On the other hand, both events have similar oscillation periods, developing in the boreal summer months and reaching their peak anomalies during the boreal winter (December - January) (Kao et al., 2009). Within this time frame, CP El Niños tend to have a shorter duration of 8 months with more concentrated SST and westerly wind anomalies (winds reach from western to central tropical pacific) whereas EP El Niños last longer (15 months) with more widespread and drastic environmental effects. EP El Niños rely on air-sea interactions driven by a strong discharge of equatorial heat and greater thermocline gradient depression in the eastern Pacific (Hu et al., 2016). Therefore upwelling is more depressed during EP El Niños than CP El Niños and takes longer to recover to rich La Niña conditions. Not only have EP El Niños been the most powerful ENSO events in history, they have also consistently concentrated their SSTAs and depleted nutrient concentrations around the Galápagos archipelago. The 1982-83, 1997-98, and 2015-16 Eastern Pacific El Niños exhibited great power over the oceanic and biological stability of the Galápagos Islands. These three climate events alone warrant further investigation into the dynamic impacts of EP El Niños on the Galápagos Island and their potential to increase in the future.

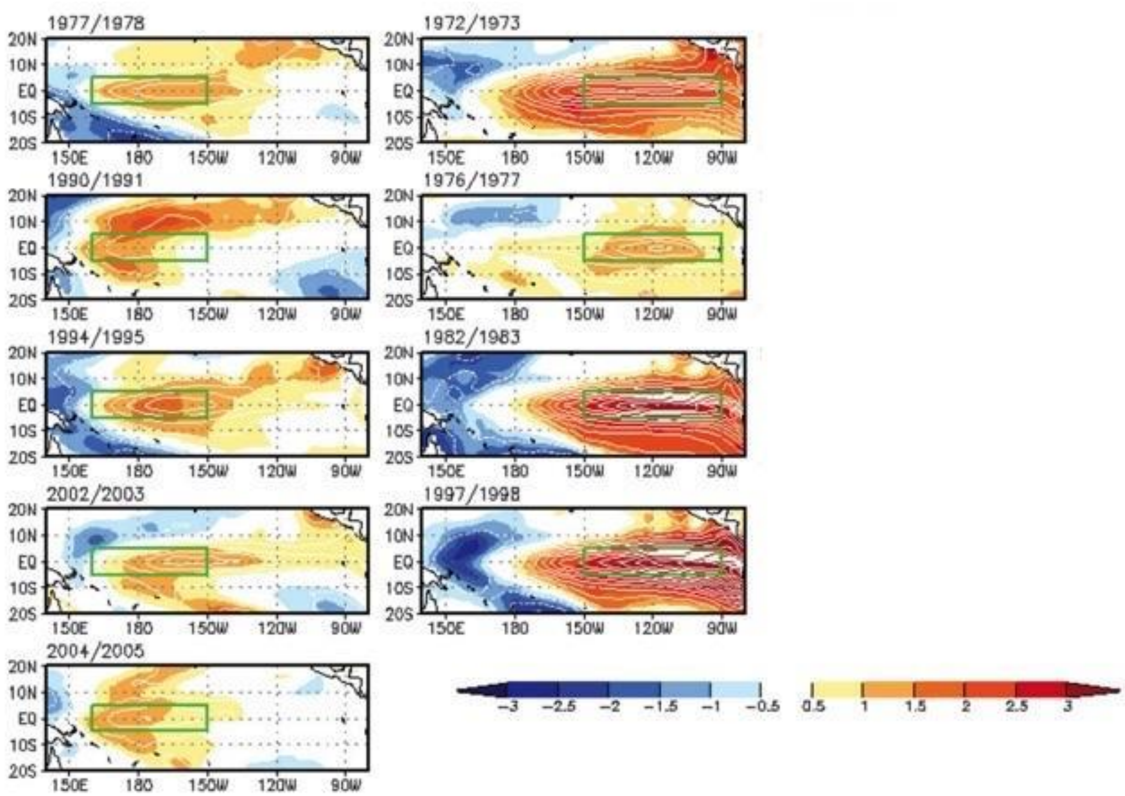


Figure 15. SST anomalies of the two types of ENSO events from 1970-2005 (averaged from September-February). Central Pacific El Niño is shown to the left and Eastern Pacific El Niño is shown to the right. Green boxes show theNiño-4 region (left) and Niño-3 (right). Sourced from Kug et al., 2009.

B. A Growing Threat: the implications of global climate change for El Niño

El Niños intimate coupling with the atmospheric system means global climate change will have important implications for the frequency, severity, and duration of all major climate patterns (Henson, 2007). The frequency of CP El Niños have increased over the past few decades but it appears that the severity of EP El Niños may also be increasing alongside them, bringing even greater SSTAs to fragile ecosystems like the Galápagos Islands (Yu et al., 2011). Though the Galápagos Islands are an especially important region to focus future research on, the impacts of El Niño Southern Oscillation are global. El Niño's displacement of the Walker Circulation Cell increases the likelihood of drought in Australia, India, Indonesia, southeast Africa, and northern South America (Henson, 2007). Many of these areas have not yet recovered from recent wildfire devastation and will be placed at even greater risk in the future. Some studies have also suggested that increased cloud cover over the Pacific Ocean could trap heat around the center of the globe, creating a positive feedback loop with greenhouses gasses that would warm the planet to even greater degrees (Kerr, 2010). In the context of this paper, climate change is expected to raise global base ocean temperatures by at least 2ºC (IUCN, 2016). Powerful events like EP El Niños already warm regions of the eastern Pacific to dangerously high SSTs. The severity of these types of El Niños would potentially be amplified by higher underlying SSTs in the Pacific Ocean and most importantly, cause even greater biological damage to marine ecosystems than before.

Conclusion

The Galápagos Islands' marine ecosystem is at the mercy of the Cromwell and Humboldt upwelling currents (Figure 2). The concentration of El Niño's warm pool in the eastern Pacific can stop these currents completely and limit the supply of cold, nutrient-rich water to the Galápagos archipelago. This ecosystem is full of resistant and adaptive species, but El Niño's temperature and chlorophyll anomalies have often proven to overwhelm these marine organisms. There are three important conclusions to take away from this paper. Firstly, the geographic positioning of the Galápagos Islands have made them a crucial and reliable model to witness the gravity of El Niño's impacts. Secondly, the three most powerful El Niños of the past 50 years were all Eastern Pacific El Niños whose SSTAs, SSTs, and low chlorophyll concentrations destabilized the trophic food web of the Galápagos Islands and ETP region. Thirdly, the joint analysis of satellite imagery, computer models, and secondary research revealed important SSTA and chlorophyll concentration thresholds that can be used as dynamic predictors of marine life survival under future El Niño conditions.

Limitations and Future Research

The data in this project was limited as direct-observations of some Sea Surface Temperatures and chlorophyll values had to be estimated or reconstructed completely (1982-83 El Niño). More accurate and detailed comparisons could have been made between the environmental and biological impacts of the 1982-83, 1997-98, and 2015-16 El Niño if the values for the first event were precise. An additional limitation is the available scientific research was often focused on the 1997-98 or 1982-83 El Niño and there was surprisingly little information on the consequences of the 2015-16 El Niño. Future research should focus on investigating the effects of this recent El Niño to better compare the severity of its impacts to its predecessors. The importance of future in-depth research into El Niño Southern Oscillation’s interaction with global climate change and its potentially increasing severity cannot be stressed enough.

Bibliography

Ancona, S., Sánchez-Colón, S., Rodríguez, C & Drummond, H. (2011). El Niño in the Warm Tropics: local sea temperature predicts breeding parameters and growth of blue-footed boobies. *Journal of Animal Ecology 80*(4), 799-808.

Arcos, D. F., Cubillos, L. A., & P. Núñez Sergio. (2001). The jack mackerel fishery and el niño 1997-98 effects off chile. *Progress in Oceanography*, *49*(1), 597–617. https://doi.org/10.1016/S0079-6611(01)00043-X

Ashok, K., Behera, S., Rao, A.S., Weng, H. &Yamagata, T. (2007). El Niño Modoki and its teleconnection. *Journal of Geophysical Research* 112: C11007, DOI: 10.1029/2006JC003798.

Barber, R.T. & Chavez, F.P. (1983). Biological Consequences of El Niño. *Science, 222* (4629), 1203–10.

Cai, W., Brolace, S., Lengaigne, M., Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L, England, M.H., Wang, G., Guilyardi, E. & Jin, F.F. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change, 4*, 111-116

Castillo-Guerrero, J. A., González-Medina, E., & Mellink, E. (2014). Adoption and infanticide in an altricial colonial seabird, the blue-footed booby: the roles of nest density, breeding success, and sex-biased behavior. *Journal of Ornithology*, *155*(1), 135–144. https://doi.org/10.1007/s10336-013-0995-7

Champagnon, J., Lebreton, J.D., Drummond, H. & Anderson, D.J. (2018). Pacific Decadal and El Niño oscillations shape survival of a seabird, *The Ecological Society of America, 99*(5), 1063-1072.

Chavez, F. P., Strutton, P. G., Friederich, G. E., Feely, R. A., Feldman, G. C., Foley, D. G., & McPhaden, M. J. (1999). Biological and chemical response of the equatorial pacific ocean to the 1997-98 El Niño. *Science (New York, N.y.)*, *286*(5447), 2126–31.

Clifford, L. D. & Anderson, D. J. (2001). Food limitation explains most clutch size variation in the nazca booby. *Journal of Animal Ecology*, *70*(4), 539–545. https://doi.org/10.1046/j.1365-2656.2001.00521

Dioses, T., Dávalos Rosa, & Zuzunaga, J. (2002). El niño 1982-1983 and 1997-1998: effects on peruvian jack mackerel and peruvian chub mackerel. *Investigaciones Marinas*, *30*(1 Suppl Symp), 185–187. https://doi.org/10.4067/S0717-71782002030100077

Earth Null School. (n.d.). EarthWindMap. *Earth community*, Retrieved from https://earth.nullschool.net/

Fundación Charles Darwin. (2017). Reporte Anual 2016, avances 2017, para Las Islas Galápagos. *Fundación Charles Darwin,* Retrieved from https://www.darwinfoundation.org/images/pdf/InformeAnual20162017_ES.pdf

Galápagos marine iguanas threatened by ‘el niño’ now recovering. (1984). *Marine Pollution Bulletin, 15*(3), 87–87. https://doi.org/10.1016/0025-326X(84)90428-4

Galindo, M., Haiek, G., Mónaco Carlos del, & Narciso, S. (2012). Massive bleaching of coral reefs induced by the 2010 enso, puerto cabello, venezuela. *Revista De Biología Tropical*, *60*(2), 527–538.

Gibbs, H. L., Latta, S. C., & Gibbs, J. P. (1987). Effects of the 1982-83 el niño event on blue-footed and masked booby populations on isla daphne major, galápagos. *The Condor, 89*(2), 440–442.

GISTEMP Team. (2020). GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies. Dataset accessed 2020-04-20, at https://data.giss.nasa.gov/gistemp/.

Glynn, P.J., Glynn, P.W., & Riegl, B. (2017). El Niño, echinoid bioerosion and recovery potential of an isolated Galápagos coral reef: a modeling perspective. *Marine Biology, 164*(7), 146-164

Glynn, P.W., Maté, J.L., Baker, A.C. & Calderón, M.O. (2001). Coral bleaching and mortality in Panama and Ecuador during the 1997–1998 El Niño-Southern Oscillation event: spatial/temporal patterns and comparisons with the 1982–1983 event. *Bull Marine Science, 69*, 79–109

Guzmán Ana, & Sielfeld, W. (2002). Effect of el niño 1997/98 on a population of the southern sea lion (otaria flavescens shaw) from punta patache/punta negra (iquique, chile). *Investigaciones Marinas, 30*(1 Suppl Symp), 158–160. https://doi.org/10.4067/S0717-71782002030100059

Henson, R. (2007). Rough Guide to Climate Change: Climate Change & El Nino. *Weatherwise, 60*(1), 32-38.

Hixon, M.A. (2015). Coral Reefs in the Anthropocene. *Department of Biology, University of Hawaii at Manoa, Honolulu,* Retrieved from https://manoa.hawaii.edu/biology/sites/manoa.hawaii.edu.biology/files/users/hixonm/hixon_15_in_birkeland_book.pdf

Huyvaert, P.K. & Anderson, J.D. (2004). Limited dispersal by nazca boobies *sula granti*. *Journal of Avian Biology*, *35*(1), 46–53. https://doi.org/10.1111/j.0908-8857.2004.03131

IUCN. (2016). IUCN Issues Brief: Ocean Warming. *IUCN THEMES*, Retrieved from https://www.iucn.org/resources/issues-briefs/ocean-warming

Jarrin, J.R.M. & Salinas-de-León, P. (2018). Effects of the 2016 El Niño on the Galápagos artisanal coastal fin-fish fishery. *PeerJ [thesis],* Retrieved from https://peerj.com/preprints/26773/

Jones, B.C. & DuVal, E.H. (2019) Direct and indirect effects of the EL Niño Southern Oscillation on development and survival of young of a tropical passerine. *Ecosystem Ecology- Oecologia, 190,* 485-496

Kerr, R. El Niño lends more confidence to strong global warming. *Science*, *330,* 1465

Kiere, L. M., & Drummond, H. (2016). Female infidelity is constrained by el niño conditions in a long-lived bird. *Journal of Animal Ecology*, *85*(4), 960–972. https://doi.org/10.1111/1365-2656.12537

Kodama, K & Burls, N.J. (2019) An empirical adjusted ENSO ocean energetics framework based on observational wind power in the tropical Pacific. *Climate Dynamics*, *53, 3271-3288*

Kug, J.S., Jin, F.F. & An, S.I. (2009). Two types of El Niño events: Cold tongue El Niño and warm pool

El Niño. *Journal of Climate* 22: 1499– 1515.

Larkin, N. K., & Harrison, D. E. (2005). On the definition of el niño and associated seasonal average u.s. weather anomalies. *Geophysical Research Letters*, *32*(13). https://doi.org/10.1029/2005GL022738

Lee, T. & McPhaden, M.J. (2010). Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters* 37: L14603, DOI: 10.1029/2010GL044007.

Lenssen, N.,Schmidt,G., Hansen, J., Menne, M., Persin, A., Ruedy, R. & Zyss, D. (2019). Improvements in the GISTEMP uncertainty model. J. Geophys. Res. Atmos., **124**, no. 12, 6307-6326, doi:10.1029/2018JD029522.

Lian, T., Chen, D., Tang, Y. & Wu, Q. (2014). Effects of Westerly Wind Bursts on El Niño: A new perspective. *Geophysical Research Letters, 41*(10) , 3522-3527

McClanahan, T. R., Darling, E. S., Maina, J. M., Muthiga, N. A., D'agata, S., Jupiter, S. D., Arthur, R., Wilson, S.K., Mangubhai, S., Nand, Y., Ussi, A.M., Humphries, A.T., Patankar, V.D., Guillaume, M.M.M., Keith, S.A., Shedrawi, G., Julius, P., Grimsditch, G., Ndagala, J., & Leblond, J. (2019). Temperature patterns and mechanisms influencing coral bleaching during the 2016 el niño. *Nature Climate Change*, *9*(11), 845–851. https://doi.org/10.1038/s41558-019-0576-8

McPhaden, M.J., Lee, T., McClurg, D. (2011). El Niño and its relationship to changing background conditions in the tropical Pacific Ocean. *Geophysical Research Letters* 38: L15709, DOI: 10.1029/2011GL048275.

Meraz, J., Ancona, S., Rodriguez, C., & Drummond, H. (2013). Reproduction of the blue-footed booby predicts commercial fish abundance in the eastern tropical pacific. *Ices Journal of Marine Science*, *70*(6), 1263–1272. https://doi.org/10.1093/icesjms/fst076

Moraga, R., Muñoz Lily, Olea, D., Santos, M., Sepúlveda Maritza, Sielfeld, W., & Veas, R. (2015). Annual, seasonal and daily variation in the abundance of the south american sea lion otaria flavescens in two breeding colonies in northern chile. *Revista De Biología Marina Y Oceanografía*, *50*(2), 205–220. https://doi.org/10.4067/S0718-19572015000300001

NASA Observatory. (2017). Impacts and Teleconnections. National Aeronautics and Space Administration: Earth observatory, Retrieved from https://earthobservatory.nasa.gov/features/ElNino/page4.php

NASA SeaWiFS. (n.d.) SeaWiFS Views the Whole Worlds with Three Years of Data. National Aeronautics and Space Administration: Scientific Visualization Studio, Retrieved from https://svs.gsfc.nasa.gov/stories/elnino/gallery/index.html

NCAR UCAR. (2018). NINO SST INDICES (Niño 1+2, 3, 3.4, 4) ONI and TNI. *NCAR Climate Data Guide,* Retrieved from https://climatedataguide.ucar.edu/climate-data/nino -sst-indices-nino-12-3-34-4-oni-and-tni

Newman, M., Shin, S.I. & Alexander, M.A. (2011). Natural variation in ENSO flavors. *Geophysical Research Letters* 38: L14705, DOI: 10.1029/2011GL047658.

Ñiquen Miguel, & Bouchon Marilú. (2004). Impact of el niño events on pelagic fisheries in peruvian waters. *Deep-Sea Research Part Ii*, *51*(6-9), 563–574. https://doi.org/10.1016/j.dsr2.2004.03.001

NOAA Monitoring and Data. (2020). Climate Prediction Center: Monthly Atmospheric & SST Indices. *National Oceanographic and Atmospheric Administration*, Retrieved from https://www.cpc.ncep.noaa.gov/data/indices/ersst5.nino.mth.81-10.ascii

NOAA View Data Exploration Tool. (n.d.) Global Data Analysis map. *National Oceanographic and Atmospheric Administration*, Retrieved from https://www.nnvl.noaa.gov/view/globaldata.html#SURF

NOAA. (2020). What Is Coral Bleaching? *National Oceanographic and Atmospheric Administration*, Retrieved from *https://oceanservice.noaa.gov/facts/coral_bleach.html*

Ocean Tracks. (2017). What is Chlorophyll? *Ocean Tracks Library*. Retrieved from https://oceantracks.org/library/oceanographic-factors/chlorophyll

Pacheco, A. S., Riascos, J. M., Orellana, F., & Oliva, M. E. (2012). El niño-southern oscillation cyclical modulation of macrobenthic community structure in the humboldt current ecosystem. *Oikos*, *121*(12), 2097–2109. https://doi.org/10.1111/j.1600-0706.2012.20257

Peña-Torres, J., Dresdner, J., & Vasquez, F. (2017). El niño and fishing location decisions: the chilean straddling jack mackerel fishery. *Marine Resource Economics*, *32*(3).

Peterson, J.F., Sack, D., & Gabler, R.E. (2011). El Niño Southern Oscillation. *Physical Geography*, Retrieved online from https://books.google.com/books?id=bfVCKu_rxxUC&pg=PT162&lpg=PT162&dq=brooks/cole+cengage+learning+el+nino &source=bl&ots=Zw5n4vlb55&sig=ACfU3U2lPuYfrAPDBva4o1Imu572mDfrrw&hl=en&sa=X&ved=2ahUKEwj0z4ys86fpAhUjFTQIHTwUDsQQ6AEwAHoECAoQAQ#v=onepage&q=brooks%2Fcole%20cengage%20learning%20el%20nino&f=false

Quispe-Ccalluari, C., Tam, J., Demarcq, H., Chamorro, A., Espinoza-Morriberón D, Romero, C., Oliveros-Ramos, R. (2018). An index of coastal thermal effects of el niño southern oscillation on the peruvian upwelling ecosystem. *International Journal of Climatology*, *38*(7), 3191–3201. https://doi.org/10.1002/joc.5493

Randall, C. J., Toth, L. T., Leichter, J. J., Maté Juan L, & Aronson, R. B. (2020). Upwelling buffers climate change impacts on coral reefs of the eastern tropical pacific. *Ecology*, *101*(2). https://doi.org/10.1002/ecy.2918

Rossi, S., & Soares, M. de O. (2017). Effects of el niño on the coastal ecosystems and their related services. *Mercator (Fortaleza)*, *16*. https://doi.org/10.4215/rm2017.e16030

Schreiber, R.W. & Schreiber, A. (1984). Central Pacific seabirds and the El Niño Southern Oscillation: 1982 to 1983 perspectives. *Science*, *225*, 713-716

Science Learn. (2020). Marine Food webs. *Science Learn Organization*, Retrieved from https://www.sciencelearn.org.nz/resources/143-marine-food-webs

Sharp, G. D., & McLain, D. R. (1993). Fisheries, el niño-southern oscillation and upper-ocean temperature records: an eastern pacific example. *Oceanography*, *6*(1), 13–22.

Steinfartz, S., Glaberman, S., Lanterbecq, D., Marquez, C., Rassmann, K., & Caccone, A. (2007). Genetic impact of a severe el niño event on galápagos marine iguanas (amblyrhynchus cristatus). *Plos One*, *2*(12), 1285.

Stenseth, N.C., Mysterud, A., Ottersen, G., Hurrell, J.W., Chan, K.S. & Lima, M. (2002). Ecological Effects of Climate Fluctuations. *Science, 297* (5585), 1292-1296

Trueman, M & d'Ozouville, N. (2010). Characterizing the Galápagos terrestrial climate in the face of global climate change. *Galápagos Research Articles*, 67, 26-37

Velarde, E., Miguel F. Lavín, Ezcurra, E., & Cisneros-Mata, M. A. (2004). Seabird ecology, el niño anomalies, and prediction of sardine fisheries in the gulf of california. *Ecological Applications*, *14*(2), 607–615.

Valdivia, E. & Wolf, A.E. (1985). Cambias en Los Recursos Costeros y su Incidencia en la Pesquería Artesanal durante El Niño 1982-83. *IMARPE: Boletín Extraordinario, 0378-7699*

Vinueza, L. R., Branch, G. M., Branch, M. L., & Bustamante, R. H. (2006). Top-down herbivory and bottom-up el niño effects on galápagos rocky-shore communities. *Ecological Monographs*, *76*(1), 111–131.

Wikelski, M., Carrillo, V., & Trillmich, F. (1997). Energy limits to body size in a grazing reptile, the galapagos marine iguana. *Ecology*, *78*(7), 2204–2217. https://doi.org/10.1890/0012-9658(1997)078[2204:ELTBSI]2.0.CO;2

Wikelski, M. & Nelson, K. (2004). Conservation of Galápagos Marine Iguanas (*Amblyrhynchus cristatus). Iguana, 11*(4), 191-197

Wikelski, M., & Thom, C. (2000). Marine iguanas shrink to survive el niño. *Nature*, *403*(6765), 37–38. https://doi.org/10.1038/47396

Williams, B. (2019). Oceanography: El Niño Southern Oscillation Lecture. *Keck Science Department*, Claremont, CA.

Wolff, M., Ruiz, D. J., & Taylor, M. (2012). El niño induced changes to the bolivar channel ecosystem (galapagos): comparing model simulations with historical biomass time series. Marine Ecology Progress Series, 448, 7–22.

Yeh, S.W., Kug, J.S., Dewitte, B., Kwon, M.H., Kirtman, B.P. & Jin, F.F. (2009). El Niño in a changing climate. *Nature, 461*, 511-514

Yu, J.Y. & Kao, H.Y. (2007). Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958–2001. *Journal of Geophysical Research* 112: D13106, DOI: 10.1029/200JD007

Yu, J.Y., Kao, H.Y., Lee, T. & Kim, S.T. (2011). Subsurface ocean temperature indices for Central-Pacific and Eastern-Pacific types of El Niño and La Niña events. *Theoretical and Applied Climatology* 103: 337– 344, DOI: 10.1007/s00704-010-0307-6.

Zapata, F. A., Caro-Zambrano, C., Garzón-Ferreira Jaime, & Rodríguez-Ramírez Alberto. (2010). Mid-term coral-algal dynamics and conservation status of a gorgona island (tropical eastern pacific) coral reef. *Revista De Biología Tropical*, *58*(Suppl 1), 81–94.

Title Page Image sourced from Galápagos Islands Yacht Charter, (2020). Retrieved from https://www.charterworld.com/index.html?sub=Galapagos-Islands-Yacht-Charter