ESCUELA SUPERIOR POLITÉNICA DEL LITORAL

Facultad de Ingeniería Marítima y Ciencias del Mar

How is primary productivity affected by the Island Mass Effect (IME) in the Galapagos Island?

CAPSTONE PROJECT

Prior to obtaining the Title of:

OCEANOGRAPHIC ENGINEER

Presented by:

Elisa Beatriz Toro Yerovi

GUAYAQUIL – ECUADOR

YEAR: 2022

DEDICATION

I dedicate this project to my parents, grandparents, and brother who throughout my years at university supported me in good times and bad. Thanks for being with me.

I also want to dedicate this work to my friends Julio, Maritza, Julissa who taught me how beautiful life can be despite the sad moments because they knew how to make me happy, and they were with me in many moments inside and outside the university. Thanks for being part of my life.

GRATITUDE

This project could not be executed without the support of Oc. Leonor Vera, Oc. Sonia Recalde, and Oc. Freddy Hernandez because they opened the door for me and gave me the opportunity to do this song, thank you very much for this.

I also thank all the FIMCM professors, who throughout my university time taught me all their knowledge and support, have made me love my career much more beautiful.

And last but not least, my tutor, Dr. María José Marín, who was my guide, and she did not let me give up despite everything, thank you for having been my tutor.

EXPRESS DECLARATION

"The rights of ownership and exploitation correspond to me in accordance with the intellectual property regulations of the institution; Elisa Beatriz Toro Yerovi and I give my consent for ESPOL to make the public communication of the work by any means in order to promote the consultation, dissemination and public use of the intellectual production."

Elisa Beatriz Toro Yerovi

EVALUATORS

Firmado electrónicamente por:
JORGE WASHINGTON
ESPINOZA AMAGUANA

MSc. Jorge Washington
Espinoza Amaguaña
SUBJECT TEACHER

Firmado electrónicamente por:
MARIA JOSE MARIN
JARRIN

Ph. D. María José
Marín Jarrin
TUTOR

RESUMEN

El Efecto de Masas de Islas (EMI) es un proceso que describe el aumento de la productividad primaria alrededor de islas. En este estudio se analizaron los impactos del océano-atmósfera sobre el oeste de la Reserva Marina de Galápagos (RMG). Se usó información satelital de Clorofila a, Temperatura Superficial del Mar (TSM) y estrés de vientos, entre septiembre y octubre del 2022, los cuales fueron procesados en MATLAB para su posterior análisis. Este análisis consistió en determinar la correlación entre clorofila a y TSM. El análisis semanal de la información permitió encontrar áreas, de hasta 102.68 m^2, con una correlación positiva significativa, que se produce cuando la TSM y Clorofila a aumentan o disminuyen conjuntamente. En la séptima semana se encontró una masa de agua fría con poca concentración de Clorofila a dentro del área de estudio; lo que coincidió con vientos de mínimas velocidades hacia el norte. Para la primera semana de octubre se obtuvo una correlación negativa significativa en un área de 38.50 m^2, la cual ocurre cuando la TSM disminuye y la Clorofila a aumenta, o lo opuesto, lo que indica que existen surgencias o en el primer caso existe otro proceso que genere el cambio en la concentración de Clorofila a. La información aquí analizada permite demostrar que, en las Islas Galápagos, se produce un aumento en productividad primaria por EMI. Se recomienda obtener datos in-situ (cruceros oceanográficos o estaciones fijas) para la validación de los datos satelitales y el análisis continuo del IME en las islas.

Palabras claves: Efecto de Masas de Islas (EMI) Clorofila a, TSM, Reserva Marina de Galápagos, estrés de vientos.

ABSTRACT

The Island Mass Effect (IME) is a process that describes the increase in primary productivity around islands. In this study, the impacts of the ocean-atmosphere on the west of the Galapagos Marine Reserve (GMR) were analyzed, for this, satellite information on Chlorophyll-a was used, Sea Surface Temperature (SST) and wind stress, between September and October 2022, which were processed in MATLAB for further analysis. This analysis consisted of determining the correlation between chlorophyll-a and SST. The weekly analysis of the information made it possible to find areas, up to 102.68 m^2, with a significant positive correlation, which occurs when the SST and Chlorophyll-a increase or decrease together. In the seventh week, a mass of cold water with a low concentration of Chlorophyll-a was found within the study area; which coincided with winds of minimum speeds to the north For the first week of October, a significant negative correlation was obtained in an area of 38.50 m^2, which occurs when the SST decreases and Chlorophyll-a increases, or the opposite, which indicates that there are upwellings or there is another process that generates the change in chlorophyll a concentration. The information analyzed here allows demonstrating that, in the Galapagos Islands, there is an increase in primary productivity due to IME. It is recommended to obtain in-situ data (oceanographic cruises or fixed stations) for the validation of the satellite data and the continuous analysis of the IME on the islands.

Keywords: Island Mass Effect (IME), Chlorophyll a, SST, Galapagos Marine Reserve, wind stress.

GENERAL INDEX

ABBREVIATIONS

ESPOL	Escuela Superior Politécnica del Litoral
INOCAR	Instituto Oceanográfico y Antártico de la Armada
ENSO	El Niño Southern Oscillation
EUC	Equatorial Undercurrent
SDGS	Sustainable Development Goals
IME	Island Mass Effect
CTD	Conductivity, Temperature and Depth
SST	Sea Surface Temperature

SYMBOLOGY

$°C$	Celsius
deg	Degrees
$mg\ m^{-3}$	Milligrams / cubic meter
m	Meter
Km	Kilometer

FIGURE INDEX

TABLE INDEX

CHAPTER 1

1. Introduction

1.1 Problem Statement

The Galapagos Marine Reserve located in the World Heritage Galapagos National Park, is one of the marine reserves that contains natural habitats and a large amount of biodiversity in both fauna and flora, including species that feed on phytoplankton (Ministry of the Environment, Water and Ecological Transition, 2014). The great biodiversity that the RMG has is mainly due to constant interaction with important ocean currents such as the South Equatorial Current, that moves from east to west bringing water; the equatorial Subsurface Current (Cromwell Current), that goes from west to east, causes upwelling along the continental coast, on the western side of the Galapagos Islands, especially in Fernandina, Isabela and Floreana Island (Feingold & Glynn, 2014). It is worth mentioning that the Galapagos Islands tend to vary in surface temperatures due to the ENSO, El Niño and La Niña phases (Feingold & Glynn, 2014).

There are other atmospheric-oceanic physical processes that cause upwelling on the coasts of the islands, including the Island Mass Effect (IME). IME is a mesoscale oceanographic event and refers to an increase in primary production that it is visible around the islands and is often ignored in biological oceanography. The most common way to analyze it is by understanding the spatial and temporal relationship between chlorophyll-a concentration and sea surface temperature (Elliott, et al., 2012).

Chlorophyll-a is a photosynthetic pigment that is present in phytoplankton, an autotrophic organism presents throughout the ocean, The concentration of chlorophyll-a in the ocean allows us to determine concentration of phytoplankton, therefore, the biological activity (Salgado Costa, 2014). The study of its behavior in the water column must be carried out with specialized instruments such as the fluorometer or laboratory analysis, while the ocean temperature is carried out using the Conductivity Temperature Depth (CTD) or thermos-salinometers (Elliott, et al., 2012). In general, these studies are carried out in Oceanographic Cruises that last a few months due to the great cost that these demands. Due to this high cost, there is a lack of analysis of primary production and the IME in the Galapagos Islands, causing the studies that link the physical and biological parameters present in this and other islands in Ecuador to be minimal. Through this project, the ocean-atmosphere impacts on primary productivity in the western part of the Galapagos Marine Reserve are studied, which are the first step to evaluate the impacts of ENSO events and climate change in the future. Decision makers within Ecuadorian institutions, and consequently compliance with SDG 14 "Underwater life".

1.2 Justification

The GMR is mainly known for its great diversity of both terrestrial and marine fauna and flora, in addition to receiving the influence of four prevailing currents, which generated species from warm and cold environments to concentrate on its multiple islands. It has unique oceanographic and meteorological conditions compared to other parts of the world, which is why they are under constant study and analysis by public and private entities, and even international organizations (Directorate of the Galapagos National Park, 2014).

In Ecuador is the “Ley Orgánica de Navegación, Gestión Seguridad y Protección Marítima” (LOTAIP) promulgated on June 14, 2021, which indicates that the “Instituto Oceanográfico y Antártico de la Armada” (INOCAR) in article 18 section 8 must:

> "*Carry out oceanographic, geophysical and marine science exploration and research work marine environment, as well as coordinate and control the execution of the mentioned works that are authorized by other competent authorities, within the scope of this Law*" (NATIONAL ASSEMBLY, 2021).

1.3 Objectives

1.3.1 General objective

To estimate the Island Mass Effect (IME) of the Galapagos Islands using remote sensors by determining the behavior of Primary Productivity and physical variables from September to November 2022.

1.3.2 Specific objectives

- Establish the relevant variables for the analysis of Primary Productivity in the Galapagos Islands.
- Select the remote sensor that allows the generation of the database with the least number of information gaps.

- Develop a code that allows the identification of relationships between the chosen variables: Sea Surface Temperature (SST), Chlorophyll-a, Wind Stress.

1.4 Theoretical framework

1.4.1 Description of the study area

The Galapagos Islands, one of the twenty-four provinces of Ecuador, is located on the equator in the Pacific Ocean, at 972 km from the Ecuadorian continental coast (Figure 1.1) (Governing Council of the Special Regime of Galapagos, 2016). The islands that make up the Galapagos Islands are divided into 19 larger islands and more than 200 islets and rocks, which make up a total area of almost 8,010 km^2 and are scattered around 70,000 km^2. 96.7% of the land surface belongs to the National Park which is Natural Heritage of Humanity (Governing Council of the Special Regime of Galapagos, 2016).

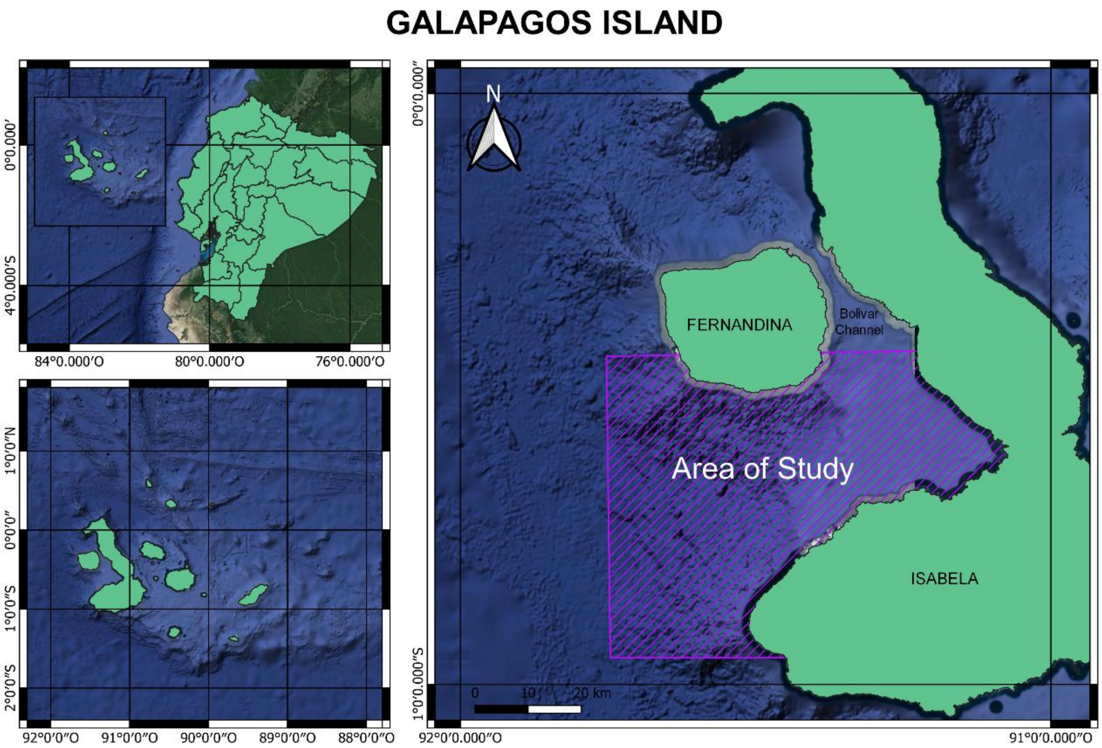

Figure 1.1: Area of Study

1.4.2 Antecedent

1.4.2.1 Ocean Currents

The Galapagos Islands are in the middle of the convergence of different ocean currents, which carry both warm and cold waters (Figure 1.2): Subsurface Equatorial Current

(Cromwell Current), South Equatorial Current, Panama Current, and The Humboldt Current.

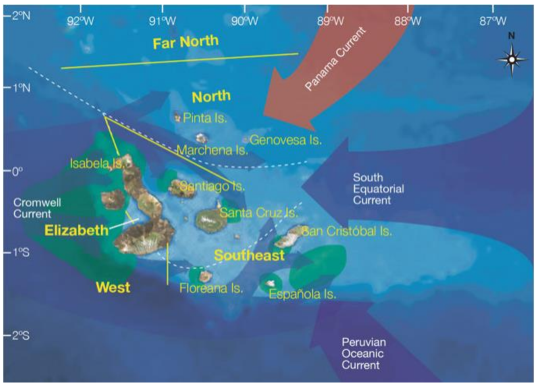

Figure 1.2: Current system in the Galapagos Islands. Source: (Sonnenholzer, et al., 2012).

The currents influence the Galapagos Islands in different ways, since they have different properties and prevail at different times of the year.

1.4.2.1.1 The South Equatorial Current (SEC)

Current which has a westward flow generally north of 1°N, and is predominant most of the time, however it is pushed northward when the EUC is wide (Rudnick, et al., 2021). Generates the dominant flow that is present during the rainy season, that corresponds to the months of May to November. During December to May the front and the temperature becomes more homogeneous (Sonnenholzer, et al., 2012).

1.4.2.1.2 Subsurface Equatorial Current (Cromwell Current)

This current is characterized by having cold surface temperatures (average of 17°C), a thickness of 300 m and a width of 400 km, in addition to transporting a large amount of nutrients, plankton, which allows the island's biodiversity to flourish (Sonnenholzer, et al., 2012). In addition, the SEC causes upwelling on the island's coasts since it hits the platform with a depth of less than 1000 m on the west side of the Galapagos Islands (Feldman, 1986).

1.4.2.1.3 The Panama Current

This current is characterized by having temperatures ($> 25°C$) and low salinity and nutrients. This current reaches the Galapagos coasts around January, when the southeasterly winds and currents weaken. This physical process allows the masses of warm water from the Intertropical Convergence Zone (ITCZ) to flow south along the northwestern coast of South America (Sonnenholzer, et al., 2012).

1.4.2.1.4 Equatorial Undercurrent (EUC)

A current that carries cold, nutrient- and oxygen-rich waters in the Pacific Ocean, this current flows eastward along the equator. The EUC is influenced by the variability of the global climate, in addition they strengthen the primary productivity due to two processes: (1) thermocline convergence in the subtropical meridional overturning cells; (2) waters rise to the surface in the EUC and diverge from the equator in the Ekman layer and plunge back into the thermocline in the subtropics; regularized by equatorial easterly winds in the central and eastern Pacific, this current causes cold water to rise to the surface to supply the wind-driven Ekman divergence (Stellema, et al., 2022).

1.4.2.2 IME

In the mid-1950s, an increase in primary production was observed around the coasts of the Hawaiian Islands, which was called the "Island Mass Effect" (IME) (Doty & Oguri, 1956). There are six different ways in which the IME is formed through physical processes in the vicinity of the coasts (Figure 1.3): (1) tidal mixing which modifies the vertical column of water breaking down the pycnocline and nutricline, (2) unidirectional or bidirectional flows across the island, (3) presence of fresh runoff near the islands, (4) wind stress on the water surface around the island causing local upwelling, (5) presence of internal waves that alter the thermocline, and (6) geostrophic flow processes and Ekman drift interacting with the bathymetry of the area (Elliott, et al., 2012).

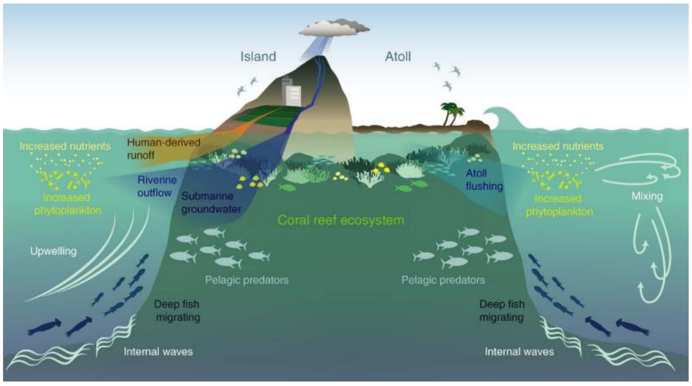

Figure 1.3: The Island Mass Effect. Source: (Gove, et al., 2016).

The dynamics of the IME results in higher nutrient concentrations near the coasts, aiding the ecosystem processes of coral reefs, consequently, nitrogen fixation or decomposition processes also improve (Figure 1.3). IME can influence the dynamics of the food web so that the species approach the coasts to be able to feed, therefore, there is a greater biomass of fish in the reef (Gove, et al., 2016).

Because of this, the study of phytoplankton biomass in the Galapagos Islands began to gain relevance, demonstrating that the upwelling of the Equatorial Undercurrent (EUC) causes an increase in biomass, that is, the presence of IME (Palacios , 2002). Additionally, the relationship of the topographic upwelling of EUC with the high productivity of phytoplankton in the western region is due to the natural enrichment of iron that the platform of the islands possesses (Kislik, et al., 2017). On the other hand, northerly winds are almost permanent west of the Galapagos, which also regularize upwelling in the Galapagos (Forryan, et al., 2021).

These results are the basis for evaluating the ecological resilience of the Galapagos system, since they are an adequate representation of localized atmosphere-ocean interactions and help the effectiveness of climate change mitigation strategies.

CHAPTER 2

2 Methodology

The identification of the most appropriate methodology that allowed finding the expected answer within this project arose from the following research question:

"How is primary productivity affected by the Island Mass Effect (IME) in the Galapagos Island?"

Which generated the following hypothesis:

"If there is an increase in primary productivity in the vicinity of the Galapagos Islands, then the correlation between chlorophyll-a, SST and wind stress is important to analyze."

2.1 IME calculation

The IME calculation is conducted mainly with in-situ data using CTD and fluorometer that measure the structure of the water column at different points, in addition to the use of Doppler profilers (Hasegawa, et al., 2007); mainly in cruises and oceanographic campaigns that are usually expensive (Appendix A). Due to the limitations of the project, it was considered to use a method using remote sensors, which consists of downloading NetCDF files of the variables that directly influence the obtaining and calculation of the IME,

- Sea Surface Temperature (SST),
- Concentration of chlorophyll-a (Chlor-a) (Elliott, et al., 2012);
- Wind stress (Kislik, et al., 2017).

The presence of IME was determined by obtaining areas with both positive and negative correlations between the variables. This correlation was obtained by processing the data in the MATLAB version R2020b program, since it has the "Climate Data Toolbox" version 1.01 created by Chad Greene and contains more than 100 functions to process the data obtained from satellites, and then comparing them with the wind stress data within the study area. This process is detailed below.

2.2 Data Collection

2.2.1 SST data collection

The SST files were obtained from the NASA Ocean Color website (https://oceancolor.gsfc.nasa.gov/), these files had the following specifications:

Table 2.1:SST data properties (NASA Goddard Space Flight Center, Ocean Ecology Laboratory, 2022).

Processing Level	L3 Mapped
Product Status	Standard
Sensor	Aqua – MODIS
Product	Sea Surface Temperature (4μ nighttime)
Period	8-day
Resolution	4 km
Real Resolution	4.64 km
Start Date	2022_08_29
End Date	2022_10_31
Type:	Mapped
Data Retrieval Method	Extract: • northernmost latitude = 0 • southernmost latitude = -1 • westernmost longitude = -92 • easternmost longitude = -91

Up to the date of writing this project, the end date represents the last time files with NetCDF data updated to the website.

2.2.2 Chlor-a data collection

The Chlor-a files were obtained from the NASA Ocean Color website (https://oceancolor.gsfc.nasa.gov/), these files had the following specifications:

Table 2.2: Chlor-a data properties (NASA Goddard Space Flight Center, Ocean Ecology Laboratory, 2022)

Processing Level	L3 Mapped
Product Status	Standard
Sensor	Aqua – MODIS
Product	Chlorophyll concentration
Period	8-day
Resolution	4 km
Real Resolution	4.64 km
Start Date	2022_08_29
End Date	2022_10_31
Type:	Mapped
Data Retrieval Method	Extract: • northernmost latitude = 0 • southernmost latitude = -1 • westernmost longitude = -92 • easternmost longitude = -91

Up to the date of writing this project, the end date represents the last time files were uploaded to the website.

2.2.2.1 Data Reading

The reading of all the files was carried out using MATLAB, where the location of the file was indicated, and read with the "ncdisp" function of the program itself. After opening the data contained in the files downloaded from the satellites, we proceeded to assign a variable to all the data we used.

2.2.3 Correlation between SST and Chlor-a

Once the files were read and the value assigned to the SST and Chlor-a data to be used for the correlation, the CCORR function was used. The CCORR function returns a matrix with correlations between two variables, based on the code of Lippmann (1999); which goes through each value located in the corresponding latitude and longitude, to finally create a matrix with correlation values between these two variables. This correlation produces negative and positive correlations, from -1 to 1 respectively. For this project the correlation established by Pearson was considered, which defines significance from ±0.6. Two areas of oceanographic importance were obtained: the first was Significant Negative Correlation (SNC), the second Significant Positive Correlation (SPC). The SNC indicates that there is water with low temperatures, and high Chlor-a, indicative of upwelling (REF). SNC also could indicate high temperatures and low Chlor-a, which is an expected relation between productivity and temperature (REF). The SPC indicates that both the SST and Chlor-a variables increased or decreased in the same proportion.

2.2.3.1 Variable and Correlation plots

SST and Chlor-a were plotted using the CMOCEAN function that allows to give the appropriate color to the processed products (Thyng, 2016), along with bathymetry of the area, using GEBCO bathymetry, obtained through the Nippon Foundation-GEBCO Seabed 2030 Project was used with the following specifications:

Table 2.3: Bathymetry data properties (GEBCO through the Nippon Foundation-GEBCO Seabed 2030 Project, 2022)

Grid version	GEBCO 2022
Geospatial bounds crs	WGS84
Product	Elevation relative to sea level
Units	m
File size (estimated)	4 MB
Grid	netCDF

TID grid	None
Grid dimensions	W960 H1440
Data Retrievial Method	Extract: • West: -92 • East: -88 • South: -3 • North: 3

The correlation matrices between SST and Chlor-a were plotted onto maps to find areas of SNC and SPC.

2.3 Obtaining correlation areas

The areas with SPC and SNC were obtained by extracting the values from the CCORR correlation matrix, for this, a double run had to be made in MATLAB with "for" and a conditional, which converted the values that did not meet the condition of being greater than 0.6 in 0. Using the "$trapz$" function, which calculates the area under the curve, in this case from the matrix for both the column and row, we obtained the total area with SPC or SNC. In this way, the behavior of the IME over time is obtained, which is compared with the stress of the winds.

2.4 Wind Stress data collection

NetCDF files of wind velocity were obtained from the website Copernicus Marine Service, with the following specifications:

Table 2.4: Winds data properties (Copernicus Marine Service, 2022)

Processing Level	L4
Product ID	WIND_GLO_PHY_L4_NRT_012_004
Format	NetCDF-4
Variables	Eastward wind (WIND) Northward wind (WIND)
Period	Hourly
Resolution	4 km
Real Resolution	4.64 km
Start Date	Since 5 Jul 2020
Data Retrieval Method	All

Due to the fact that the data is in a different period (hours) than the correlation obtained previously (weekly), the days with all the hours obtained from the NetCDF wind files were averaged.

In order to obtain wind stress, the WINDSTRESS function was used, which returns the estimate of wind stress in the ocean from the wind speed (Greene, 2013). The function returned matrices with the calculated values and these matrices were assigned the name of Taux (northward_wind) and Tauy (eastward_wind). Once these two matrices were obtained, we proceeded to take the average of all the data per week of both variables to obtain two values per week, that is, Average Taux and Average Tauy. We compare these values with the correlation of SST and Chlor-a previously obtained.

2.4.1 Relationship between Wind Stress, Chlor-a, and SST

With all the variables obtained, we determine if the IME that we obtained is influenced by the wind stress in the area. To do so, time series comparisons between SPC, SNC and wind stress were performed. If the wind stress is high and the SNC is also high in the study area, the presence of IME due winds is confirmed, otherwise, the IME is not caused by winds.

2.5 Alternative Solution

Two alternatives were established to solve the research question:

- Option 1: Data of the main variables collected through fixed stations involved in the primary production process through oceanographic equipment that anchored within the study area.
- Option 2: In-situ data taken at least twice a year through oceanographic campaigns.

These two options, together with the proposal, were subjected to a feasibility index, and due to the cost and time limitations of the project, they were not considered for the results obtained (Appendix B).

CHAPTER 3

3 Results and Analysis

Once all the data was processed for the first week from August 29 to September 05, values of SST, Chlor-a and Wind Stress were obtained (Figure 3.1a and 3.1c) within the study area (delimited by the magenta square). Figure 3.1(a) shows Chlor-a values between 1 [mg/m^3] and 2 [mg/m^3], with the presence of an SST of 20 [$°C$] isotherm at the end of the Bolívar channel. The correlations obtained for this week (Figure 3.1(b)) show the presence of SPC (delimited by yellow lines) with an area of 26.18 [m^2] at the end of the Bolívar channel and the west of Isabela Island. SNC (delimited by blue lines in Figure 3.1(b)) with an area of 4.28 [m^2] was limited to being coastal. This does not seem to be related to Wind stress (Figure 3.1(c)), with an average of 0.008 [m/s], indicating that the IME is formed by other factors that are necessary to confirm, for example with cruises and stations.

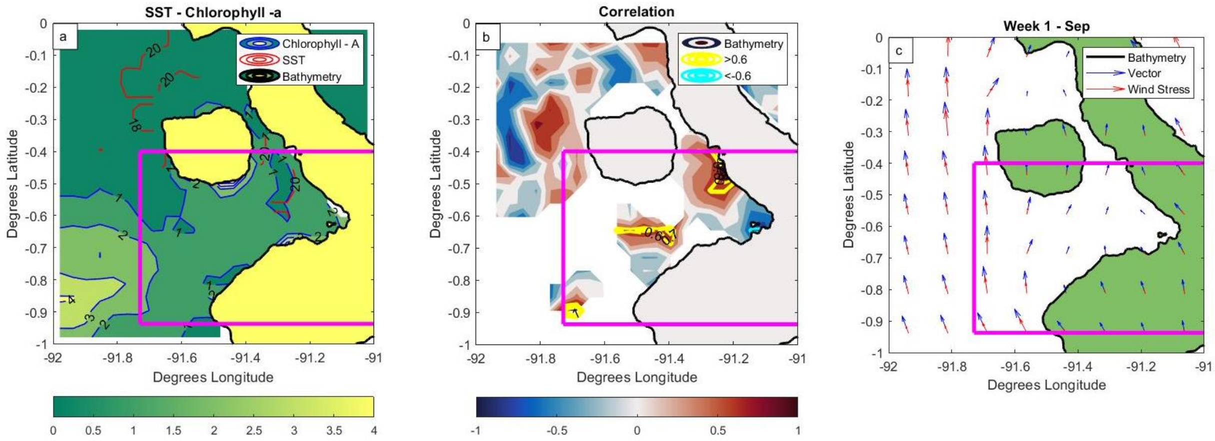

Figure 3.1: Oceanographic conditions around the Galapagos Islands during August 29 and September 05. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

Values of SST, Chlor-a and Wind Stress for the second week (from September 05 to 13), are shown in Figure 3.2a-c within the study area. The Chlor-a values (Figure 3.2 (a)) are between 1 [mg/m^3] and 4 [mg/m^3] around longitude 91.2° W, with the presence of an 18 [$°C$] isothermal SST that goes from Fernandina to Isabela Island. Correlations shown in Figure 3.2 (b) shows the presence of SPC with an area of 47.6 [m^2], more present west of Isabela Island around 91.6° W. The presence of SNC was very reduced, with an area of 14.73[m^2], indicative of weak IME, with average wind stress of 0.007 [m/s] (Figure 3.2 (c)).

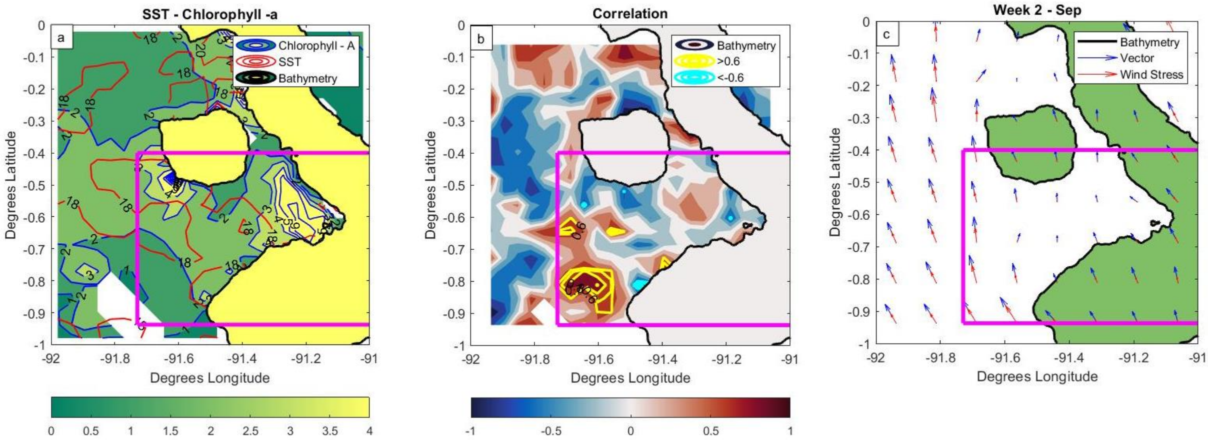

Figure 3.2: Oceanographic conditions around the Galapagos Islands during September 05 and September 13. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

In the third week from September 14 to 21, Chlor-a values were between 1 [mg/m^3] and 4 [mg/m^3] in the southwest of the coast of Isabela Island (Figure 3.3 (a)), while the SST isotherm 18 [$°C$] is observed from Fernandina Island to Isabela Island. In Figure 3.3 (b) correlations show the presence of SPC with an area of 71.74 [m^2], more present in the west of Isabela Island around 91.2° W and 91.6° W. A weak presence of SNC with an area of 15.47[m^2], indicative of a weak IME, with average wind stress of 0.007 [m/s] (Figure 3.3 (c)).

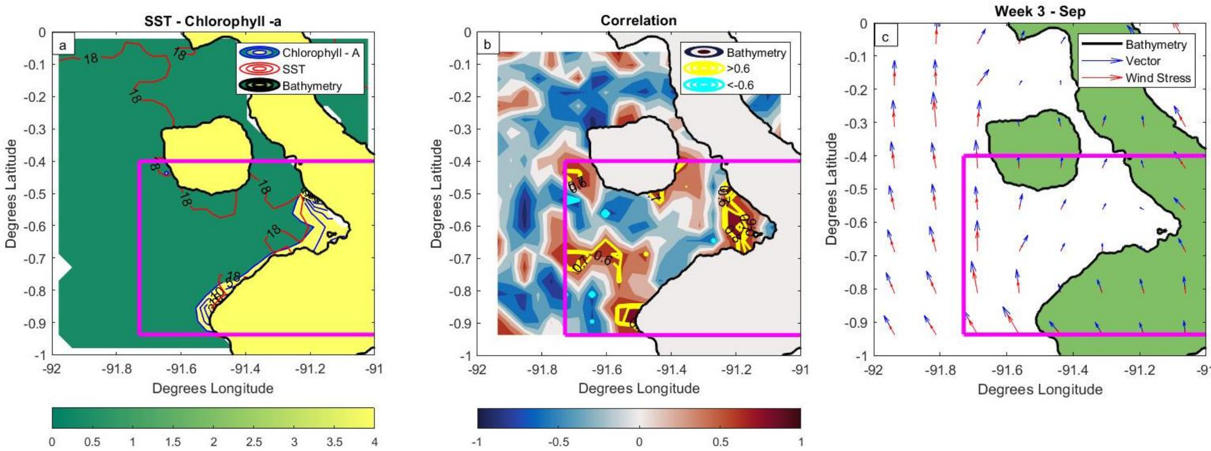

Figure 3.3: Oceanographic conditions around the Galapagos Islands during September 14 and September 21. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

On the fourth week, from September 22 to 29, Chlor-a values were 0.5 [mg/m^3] between latitudes 0.5°S and 0.6° S. The SST had two well-distinguished isotherms of 16[$°C$] and

18[°C] from Fernandina to Isabela Island. Figure 3.4(b) shows correlations, where the presence of SPC with an area of 60.17 [m^2] was more present at the west of Isabela Island around 91.2° W and 91.6° W; while there was a presence of SNC with an area of 13.46 [m^2], only at 91.6° W. The SNC is indicative of IME, however, we expect that the it did not have a larger area because the surface wind stress were the lowest recorded in all the weeks analyzed, with an average of 0.006 [m/s].

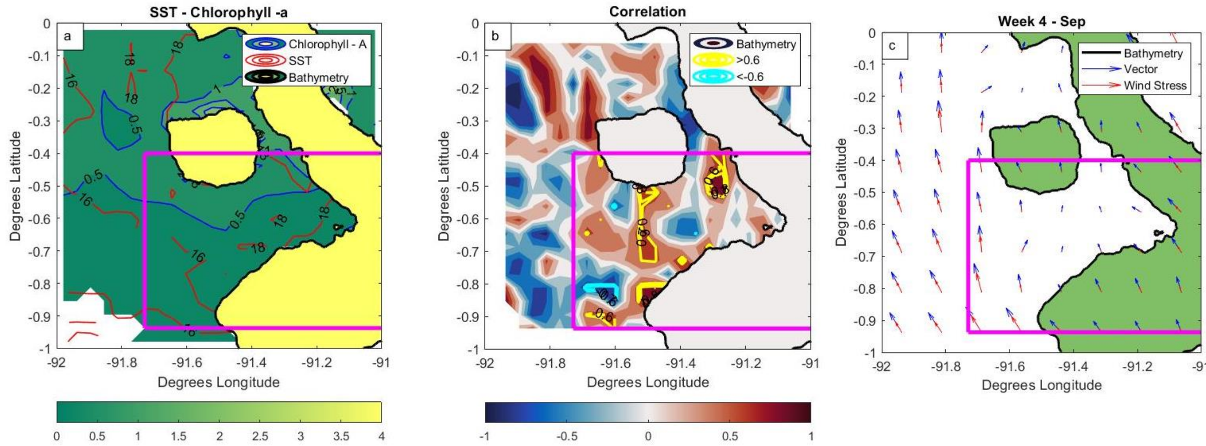

Figure 3.4: Oceanographic conditions around the Galapagos Islands during September 22 and September 29. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

In the fifth week, from September 30 to October 07, Chlor-a ranges from 1 [mg/m^3] to 4 [mg/m^3] covering the entire distance between Fernandina Island and Isabela Island. The SST has two well-distinguished isotherms of 16 [°C] and 18[°C] (Figure 3.5 (a)). In Figure 3.5(b) that corresponds to the correlations, the presence of SPC with an area of 38.2 [m^2] was more present in the west of Isabela Island around from 91.4°W and 91.6°W. There was a large area of SNC, unlike the other weeks, of 38.5 [m^2], related to wind stress (Figure 3.5(c) average of 0.025 [m/s]), being the highest value recorded in the analyzed timeseries.

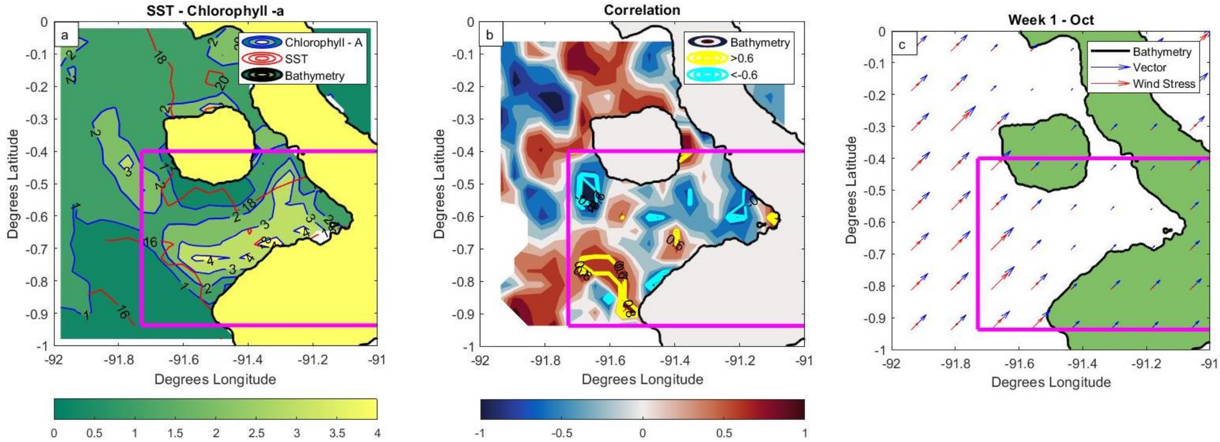

Figure 3.5: Oceanographic conditions around the Galapagos Islands during September 30 and October 07. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

In the sixth week from October 08 to October 15, Chlor-a values were between 1 $[mg/m^3]$ to 2 $[mg/m^3]$ on the coast of Isabela Island (Figure 3.6(a)). The SST had an isotherm of 18 $[°C]$ that goes from Fernandina Island to Isabela Island. Correlations shown in Figure 3.6(b), the presence of SPC with an area of 77.9 $[m^2]$ was more present on the entire west coast of Isabela Island; while there was a presence of SNC with an area of 28.92 $[m^2]$, between Fernandina and Isabela Island, therefore, a relatively strong IME, in the middle of the islands, not close to the coasts. Wind stress distribution shows that the IME was partly helped by wind, Figure 3.6(c), where it was an average of 0.007 $[m/s]$.

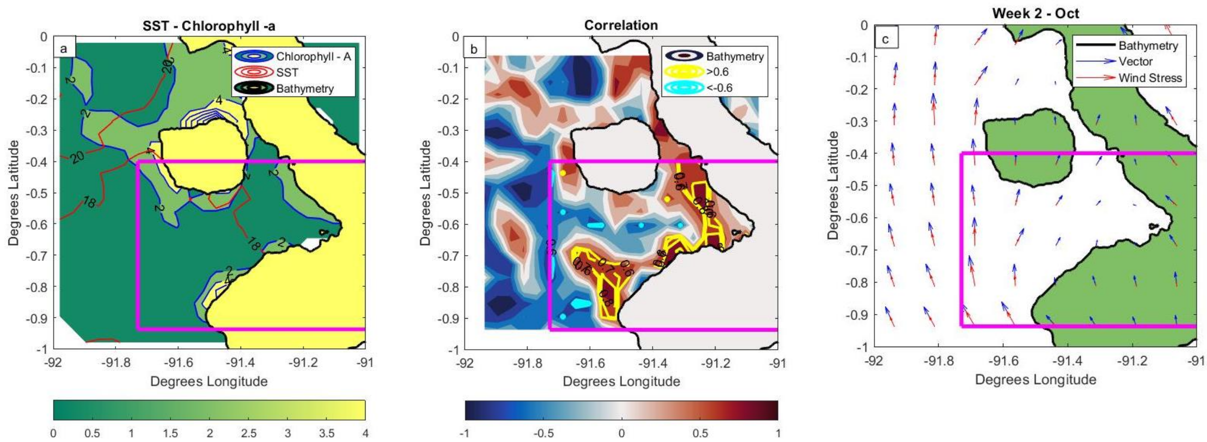

Figure 3.6: Oceanographic conditions around the Galapagos Islands during October 08 and October 15. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

In the seventh week from October 16 to 23, Chlor-a values were between 1 $[mg/m^3]$ to 2 $[mg/m^3]$ on the coast of Isabela Island (Figure 3.7(a)). The SST had two isotherms of

16[°C] and 18 [°C], the latter being predominant in the vicinity of the Isabela coast. In Figure 3.7(b), the presence of SPC with an area of 102.68 [m^2] is observed, mostly between longitudes 91.8 W to 91.4 W and at the end of the Bolivar Channel. There was presence of SNC with an area of 15.1 [m^2] around longitude 91.4 W, therefore, there was relatively weak IME. The wind stress, Figure 3.7(c), obtained in average was 0.007 [m/s].

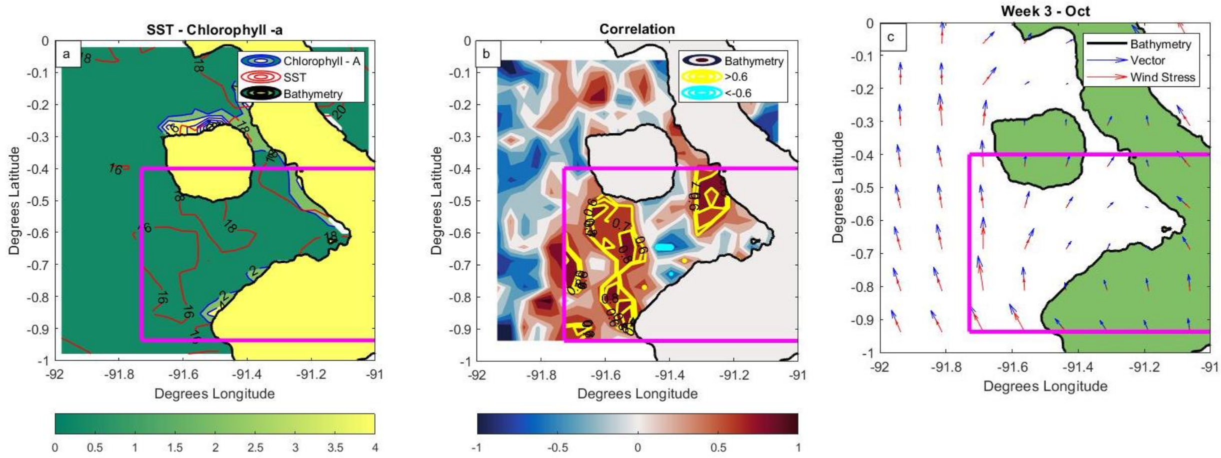

Figure 3.7: Oceanographic conditions around the Galapagos Islands during October 16 and October 23. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

In the eighth week from October 24 to 31, the Chlor-a values are 0.5 [mg/m^3] between Fernandina Island and Isabela Island (Figure 3.8(a)). The SST has an isotherm of 18 [°C] that goes from Fernandina Island to Isabela Island. Correlations in Figure 3.8(b), show the presence of SPC with an area of 28 [m^2], mostly on the entire west coast of Isabela Island. There was presence of SNC with an area of 44.83 [m^2], on longitude 91.6 W and 91.2 W very close to the coasts, possibly, two strong IME, one oceanic and the other coastal. During this week, the IME is not influenced by the weak winds, Figure 3.8(c), of an average of 0.01 [m/s]. This is the second highest value in the record, indicating that IME is formed by other factors such as currents, and to confirm them, in-situ analysis is necessary.

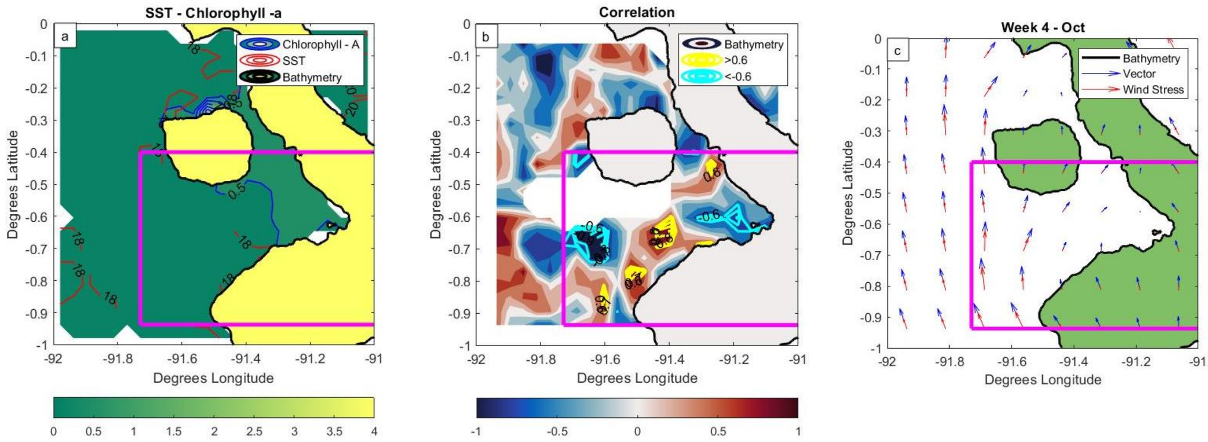

Figure 3.8: Oceanographic conditions around the Galapagos Islands during October 23 and October 31. (a) Surface image of Chlorophyll-a and SST, (b) Correlation between Chlorophyll-a and SST, (c) Winds and Surface Wind Stress

3.1 Change of IME through time

The variability of both SPC and SNC is shown in Figure 3.9, were an increase in SPC during the first three weeks is observed, from 26.18 $[m^2]$ to 71.74 $[m^2]$. The SNC area increases in the second week and remains at values around 15 $[m^2]$. In the first week of October, the SPC and SNC areas are almost the same, with the difference that the stress of the winds present in the area had its highest peak, that is, it influenced the areas of surface correlations in the area. During the following two weeks, the SPC areas increase until reaching a maximum area of 102.68 $[m^2]$, while the SNC areas decrease to a minimum area of 15.1 $[m^2]$. This maximum area of SPC is produced by the decrease in wind stress in the area, in addition to the variables that were not considered in the study, such as ocean currents.

At the end of October (Figure 3.9), the areas of the SNC tripled while the areas of the SPC decreased, that is, the upwelling that occurred on this occasion with respect to the 1st week of October was much higher, and even the wind stress increased compared to the average it had in the eight weeks of the study with 0.01 $[m/s]$. Further research, including in-situ data comparison, is required to understand this event.

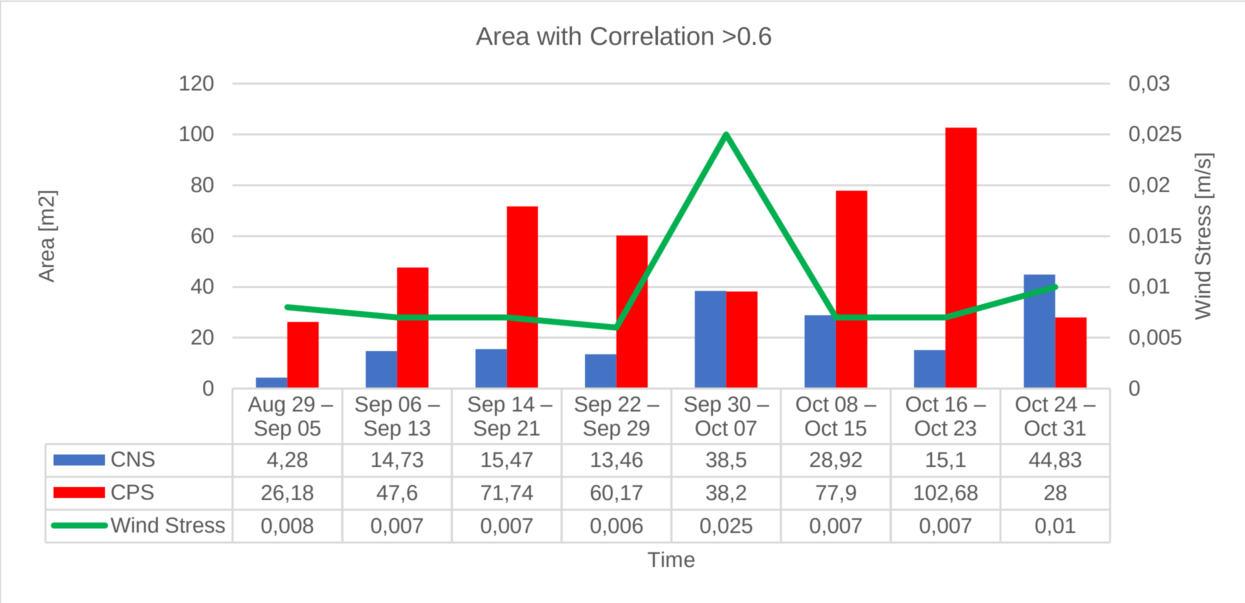

Figure 3.94: SPC, SNC areas [m^2] and Wind Stress [m/s] in the study time

CHAPTER 4

4 Conclusions and Recommendations

4.1 Conclusions

- The IME is a mesoscale oceanographic process, which describes an increase in primary activity (chlorophyll a) near an island. This process can be caused by local upwelling induced by winds or by the presence of islands in the way of a current. This modifies the pycnocline and nutricline of the area, allowing primary productivity to be more abundant for the species that inhabit nearby the island.
- IME is a crucial factor in the development of the biodiversity of the Galapagos Islands, since it was shown that it has an influence on primary productivity, due to the interaction with the winds towards the North. This happens mainly to the geographical location of the islands, since they are on the equator and are affected by Coriolis.
- The verification of IME based on the relationship between SST, Chlor-a and wind stress, determined that October had greater areas where upwelling existed. It is necessary to increase the number of variables analyzed, such as nutrients, considering that Galapagos is influenced by 5 currents that carry nutrients that directly affect the island.
- The cost of implementing other variables is very high compared to the costs of the project, however, it is important to analyze the study of the behavior within the water column and the components of the ocean floor in-situ since the method described here uses satellite data. This satellite data either due to cloudiness, or problems with the server, are not always available (as in our case) and are only superficial.

In conclusion, the presence of IME was determined in the west of the Galapagos Islands, through correlations between SST, Chlor-a and Wind stress. This area is important because different marine species, such as giant tortoises, flamingos, penguins, marine iguanas, among others, inhabit it. In addition to having a great biodiversity of corals, which contribute to the use of primary productivity activity in their diet. Although only one of the many factors that cause IME was studied here due to time and budget considerations, it is necessary to mention that the initiation of this topic in the future may help researchers, governments and decision makers to choose on the correct management in the ocean health.

4.2 Recommendations

- It is recommended to obtain in-situ data (oceanographic cruises or fixed stations) for the validation of satellite data and the continuous analysis of the IME in the islands of Ecuador, including Isla de la Plata, Salango, Los Ahorcados, El Pelado. These sites, with high biodiversity and tourism, could be affected by changes in wind patterns under future scenarios due to climate change.
- The study of the change in the IME should be analyzed in periods where climatic events such as La Niña and El Niño were present, which are very drivers of change in the waters of the Galapagos Islands.
- Another methodology that could be done is to calculate the IME using monthly averages, however, the data must always be validated.

BIBLIOGRAPHY

Copernicus Marine Service. (2022). *Global Ocean Hourly Sea Surface Wind and Stress from Scatterometer and Model*. Retrieved from Copernicus Marine Service: https://data.marine.copernicus.eu/product/WIND_GLO_PHY_L4_NRT_012_004/description

Directorate of the Galapagos National Park. (2014). *Management Plan for the Protected Areas of Galapagos for a GOOD LIVING.* Retrieved from https://www.galapagos.gob.ec/wp-content/uploads/downloads/2016/07/DPNG_Plan_de_Manejo_2014.pdf

Doty, M., & Oguri, M. (1956). *The Island Mass Effect* (Vol. 22 (1)). ICES Journal of Marine Science 22 (1). doi:https://doi.org/10.1093/icesjms/22.1.33

Elliott, J., Patterson, M., & Gleiber, M. (2012). Detecting "Island Mass Effect" through remote sensing. Australia: Proceedings of the 12th International Coral Reef Symposium, Cairns.

Feingold, J. S., & Glynn, P. W. (2014). Coral Research in the Galápagos Islands, Ecuador. In J. Denkinger, & L. Vinueza, *The Galapagos Marine Reserve: A Dynamic Social - Ecological System* (pp. 3-23). New York: Springer Science+Business Media New York. doi:10.1007/978-3-319-02769-2

Feldman, G. C. (1986). Patterns of Phytoplankton Production around the Galapagos Islands. In M. J. Bowman, R. T. Barber, C. N. Mooers , & C. M. Yentsch, *Lecture Notes on Coastal and Estuarine Studies* (pp. 77-106). New York: Springer-Verlag.

Forryan, A., Naveira Garabato, A. C., Vic, C., George Nurser, A. J., & R. Hearn, A. (2021). Galapagos upwelling driven by localized wind front interactions. *Scientific Reports*.

GEBCO through the Nippon Foundation-GEBCO Seabed 2030 Project. (2022). *GEBCO GRIDDED BATHYMETRY DATA DOWNLOAD* . Retrieved from GEBCO GRIDDED BATHYMETRY DATA DOWNLOAD : https://download.gebco.net/

Gove, J. M., McManus, M. A., Neuheimer, A. B., Polovina, J. J., Drazen, J. C., Smith, C. R., . . . Williams, G. J. (2016). Near-island biological hotspots in barren ocean basins. *Nat. Commun. 7:10581*. doi:10.1038/ncomms10581

Governing Council of the Special Regime of Galapagos. (2016). *Galapagos Plan 2015-2020. Sustainable Development and Territorial Planning Plan of the Special*

Regime of Galapagos. Retrieved from Galapagos Plan 2015-2020. Sustainable Development and Territorial Planning Plan of the Special Regime of Galapagos: https://unidosporgalapagos.files.wordpress.com/2021/05/resumen-educomunicativo-plan-galapagos-2015-2020.pdf

Greene, C. A. (2013). Function windstress. Retrieved from http://www.chadagreene.com

Hasegawa, D., Yamazaki, H., Ishimaru, T., Nagashima, H., & Koike, Y. (2007). Apparent phytoplankton bloom due to island mass effect. *ScienceDirect*, 238-246.

Kislik, E., Mantilla Saltos, G., Torres, G., & Borbor-Córdova, M. (2017). Biological Hotspots in the galapagos islands exploring seasonal trends of ocean climate drivers to monitor alga. Retrieved from International Sholarly and Scientific Research & Innocation.

Ministry of the Environment, Water and Ecological Transition. (2014, september 8). *Galapagos celebrates 36 years as a World Heritage Site*. Retrieved from Ministry of the Environment, Water and Ecological Transition: https://www.ambiente.gob.ec/galapagos-celebra-36-anos-como-patrimonio-natural-de-la-humanidad/

NASA Goddard Space Flight Center, Ocean Ecology Laboratory. (2022). *NASA Ocean Color*. Retrieved from NASA Ocean Color: https://oceancolor.gsfc.nasa.gov/l3/order/

NATIONAL ASSEMBLY. (2021, june 14). ORGANIC LAW OF NAVIGATION, MANAGEMENT SECURITY AND MARITIME PROTECTION. Quito, Pichincha, Ecuador .

Palacios , D. M. (2002). *Factors influencing the island-mass effect of the Galápagos Archipelago.* Oregon : Geophysical Research Letters. doi:https://doi.org/10.1029/2002GL016232

Rudnick, D. L., Brechner Owens, W., Shaun Johnston, T., Karnauskas, K. B., Jakoboski, J., & Todd, R. E. (2021). The Equatorial Current System West of the Galápagos Islands during the 2014–16 El Niño as Observed by Underwater Gliders. *Journal of Physical Ocenaography, 55*, 3-17. doi:https://doi.org/10.1175/JPO-D-20-0064.1

Salgado Costa, L. (2014). *Chlorophyll a variability in the coastal waters of the Iberian Peninsula between 1998 and 2007 using SeaWifs data.* Facultade de Ciencias de Ourense. España: Universidad de Vigo. Retrieved from https://ephyslab.uvigo.es/wp-content/uploads/2019/04/TFG_LorenaSalgado-1.pdf

Sonnenholzer, J., Brandt, M., Francisco, V., Hearn, A., Luzuriaga, M., Guarderas, P., & Navarro, J. C. (2012). Chapter 6: Echinoderms of Ecuador. In J. J. Alvarado, & F. A. Solís-Marín, *Echinoderm Research and Diversity in Latin America* (pp. 183-234). Berlin: Springer-Verlag. doi:10.1007/978-3-642-20051-9_6

Stellema, A., Gupta, A. S., Taschetto, A. S., & Feng, M. (2022, august 08). Pacific Equatorial Undercurrent: Mean state, sources, and future changes across models. *Research Topic, 4*. doi:https://doi.org/10.3389/fclim.2022.933091

Thyng, K. ,. (2016). True colors of oceanography: Guidelines for effective and accurate colormap selection. Oceanography 29(3):9?13. Retrieved from http://dx.doi.org/10.5670/oceanog.2016.66.

APPENDIX

Appendix A

The costs involved in carrying out an oceanographic campaign in Ecuador are detailed in the following table.

Table: Budget for an oceanographic cruise in Ecuador

Element	Unit Value	Cost for 1 month of cruise
Use of the Vessel without considering maintenance	$20 thousand	$600 thousand
Sample Analysis	$25.00 per sample	$22,200
CTD	$80 thousand	$80 thousand
D-type batteries (minimum 40) for the CTD and AFM	$3	$120
Rosette with 24 Niskin bottles	$300 thousand	$300 thousand
Total		**$1,002,320**

Appendix B

The methodology that was used and developed within the project was put to the test and compared with the other two options mentioned in the document; for this, they were compared among themselves following 4 selection criteria.

The selection criteria were Cost, Time, Data Obtainment and Ease of processing, described in the following table.

Table: Project selection criteria: Option 1: Fixed stations; Option 2: Take data in situ; Option 3: Processing with satellite data.

Parameters	Score	Option 1	Option 2	Option 3
Cost	0.25	0.10	0.10	0.25
Time	0.25	0.20	0.15	0.23
Data Obtainment	0.25	0.25	0.25	0.15
Ease of Processing	0.25	0.21	0.20	0.20
Total	1	0,76	0,70	0,83

The option 3 was the best option due to the time and cost limitations of the project.

Appendix C : MATLAB CODE