Title

Potential Applications for Remote Sensing of Chlorophyll-a in the Coastal Waters of Belize in Support of SDG 14

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by

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ABSTRACT OF THE THESIS

Potential Applications for Remote Sensing of Chlorophyll-a in the Coastal Waters of Belize in Support of SDG 14

by

Katie Perkins Osborn
Master of Science in Civil Engineering
University of California, Los Angeles, 2022
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Standard Development Goal (SDG) 14, which targets monitoring water quality and reducing marine pollution, is especially relevant to vulnerable coastal communities and ecosystems like Belize. To quantitatively assess progress toward SDG 14, measurement of chlorophyll-a concentrations via satellite data could be used as an effective way of monitoring coastal water. The remote sensing of chlorophyll-a has been successfully used in other regions of the world but has yet to be applied to Belize. This paper assesses chlorophyll-a algorithms for 145 studies determined in a relevant criteria literature search. These papers are narrowed down to 12 studies based on the factors such as coefficient of determination, algorithm accessibility, and relevance. Seven different algorithms are suggested for potential use on coastal waters in Belize, and one of these algorithms is tested to demonstrate seasonal trends in algae blooms in Belize. The results of this study suggest that there is potential in monitoring water quality in Belize through remote

sensing of chlorophyll, and that further research validating chlorophyll-a algorithms with in-situ data is necessary.

The thesis of Katie Perkins Osborn is approved.

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Part 1: Assessing the need for more quantitative indicators of SDG 14 such as the remote retrieval of Chlorophyll-a in Belize

Introduction to SDG 14

SDG 14 is part of the Sustainable Development Agenda, which was formed by the United Nations in 2015 as a call to end poverty and protect the planet. As stated in the by the UN, SDG 14 functions to "conserve and sustainably use the oceans, sea and marine resources for sustainable development" (*Sustainable Development Report 2022).* This goal was created in response to increasing plastic and marine pollution, ocean warming, eutrophication, acidification, and fishery collapse (*SDG Report 2021 - Goal 14 - Video*). As of 2021, 80% of world merchandise trade is administered throughout the sea, and over 3 billion people rely on the ocean to make a living (Guterres, 2020). However, of the SDG 14 indicators that were set to be reached by 2020, there is little evidence that any have been attained on a global scale, and SDG 14 goals set for 2030 also risk not being met if further progress isn't made (*Goal 14: Life below Water - SDG Tracker*, *Sustainable Development Report 2022*, Guterres, 2020).

Water quality is a crucial part of SDG 14 and is directly related to at least half of the UN's proposed indicators of SDG 14. While some goals of SDG 14 focus on policy-based on economic approaches, this paper will target water quality related objectives of SDG 14. Relevant SDG 14 targets to this study and their proposed indicators are shown in **Table 1.**

Goal	**Indicator**
14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	14.1.1 (a) Index of coastal eutrophication; and (b) plastic debris density

14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans Indicators	14.2.1 Number of countries using ecosystem-based approaches to managing marine areas
14.3 Number of countries using ecosystem-based approaches to managing marine areas	14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations
14.5 By 2020, conserve at least 10 percent of coastal and marine areas, consistent with national and international law and based on the best available scientific information Indicators	14.5.1 Coverage of protected areas in relation to marine areas
14.A Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries	14.a.1 Proportion of total research budget allocated to research in the field of marine technology

Table 1: SDG 14 as documented by the UN. (*Goal 14 | Department of Economic and Social Affairs*)

Quantitative Parameters for Measuring SDG 14 Progress

When SDG 14 was first published in 2015, many studies concluded that these indicators were not nearly enough to adequately assess global and national progress toward SDG 14 (Recuero Virto, 2018, Rickels et al., 2016, Reimer et al., 2020). Furthermore, most of the proposed indicators are not quantitatively measurable, making it difficult to evaluate tangible progress (Recuero Virto, 2018). Additional indicators for SDG 14 have been suggested by some studies, such as gross nitrogen balance, plastic waste generation, natural products, etc. (Rickels et al., 2016). However, for some of these indicators, information is not available on a global scale. For example, material produced in the Our World in Data SDG14 tracker, which shows all data available from their database pertaining to each indicator, is limited to countries that have that data accessible and available (*Goal 14: Life below Water - SDG Tracker*). In some instances, such as for indicator 14.2.1 in which "Number of countries using ecosystem-based approaches to managing marine areas" is displayed, only a handful of countries have data available. In this case, only 18 countries, mostly located in eastern Asia, had data available in 2021 (*Goal 14: Life below Water - SDG Tracker*).

In 2021, the United Nations Environment Programme (UNEP) published an updated manual on measuring various indicators of SDG 14 (*Understanding the State of the Ocean*, 2021). This manual provides a comprehensive guide to implementing indicators via a subsection of monitoring parameters and methods under each indicator. It also categorizes these parameters into 3 levels: global, national, and supplementary or recommended (*Understanding the State of the Ocean*, 2021, pg 15). For example, under SDG indicator 14.1.1a, parameters such as dissolved oxygen (Level 2), chlorophyll-a deviations (Level 1), chlorophyll-a concentrations (Level 2), dissolved Oxygen (Level 3), and total organic carbon (Level 3) are proposed (*Understanding the State of the Ocean*, 2021, pg 16). Some of these parameters are given a step-by-step guide for implementation, such as chlorophyll-a deviations (Level 1), where data is through readily available remote sensing techniques and calculated through a step-by-step deviation model (*Understanding the State of the Ocean*, 2021, pg 19-23). However, for other parameters, such as the measurement of chlorophyll-a and other nutrients on a *national* scale (Level 2), the UNEP states that these measurements should be taken when "national capacity to do so exists," but does not provide any available data or methods on the parameter (*Understanding the State of the Ocean*, 2021, pg 24).

For this study, the parameters relevant to water-quality measurement **without** a step-by-step guide for data extraction and implementation are listed in **Table 2.**

Goal	**Indicator**	**Parameter(s)**	**Level**
14.1	14.1.1a	• Chlorophyll-a concentration (remote sensing and in situ) • National modeling of ICEP • Total Nitrogen of DIN (dissolved inorganic nitrogen) • Total Phosphorus or DIP (dissolved inorganic phosphorus) • Total silica	2
14.1	14.1.1a	• Dissolved oxygen • Biological/chemical oxygen demand (BOD/COD) • Total organic carbon (TOC) ✕ Turbidity (remote sensing) • River parameters from SDG 6.3.2 • Other water parameters (O2 % saturation, Secchi depth, river discharge, salinity, temperature, pH, alkalinity, organic carbon, toxic metals, persistent organic pollutants) • Microalgal growth, harmful algal blooms, submerged aquatic vegetation coverage, biodiversity and hypoxia	3
14.2	14.2.1	• Ecological parameters (e.g. state of biodiversity, water quality, habitat quality, ecosystem health)	3
14.5	14.5.1	• Management effectiveness of protected areas	3

Table 2. List of parameters relevant to monitoring water quality that do not currently have any step by step plan for measurement. (*Understanding the State of the Ocean*, 2021)

Due to the lack of comprehensive information publicly available to measure the above SDG 14 parameters, there is a need for further research addressing feasible tactics for measuring these SDG 14 indicators on a national, and in some cases, global scale. To address this data gap, this study explores the feasibility of remote sensing applications in support of the SDG 14 indicators mentioned in **Table 2.**

Chlorophyll-a as an indicator of SDG 14

Chlorophyll-a is a quantified parameter in indicator 14.1.1a, and as noted earlier, the UNEP has outlined a step-by-step guide for measuring chlorophyll-a deviations on a global scale

(*Understanding the State of the Ocean*, 2021). However, because the resolution of the data extracted in this process is from 2-4km, it is not an adequate way of measuring chlorophyll-a concentrations on a national scale, where contaminated lakes, rivers, and bays could start from a minimum of around 15m² in area. Determining the most effective way of measuring chlorophyll-a concentrations on a localized scale can not only target the chlorophyll-a concentration (Level 2) parameter of SDG 14.1.1a, but it can also help access microalgal growth, harmful algal blooms, ecosystem health, and water quality parameters (Level 3) outlined within SDG indicators 14.1.1a and 14.2.1.

Although there is a large database of recent literature on the remote sensing approaches to monitoring water quality, there is a lack of research studying the application of using remotely sensed chlorophyll-a data as an SDG indicator. A literature search of studies related to the water sensing of water quality is shown in **Table 3**, with added parameters and corresponding number of results shown below.

Search Criteria	# of results for all fields	# of results for topic
• remote sensing OR satellite OR Earth Observation OR EO OR Google Earth Engine OR GEE • water quality OR coastal OR recreational water OR marine • monitoring OR sampling OR measurement OR measuring	40,663	18, 728
+		
• sustainable development goals OR sustainable development goal OR SDGs OR SDG	126	68
+		
• chlorophyll OR chlorophyll-a	9	6

Table 3: Search criteria for literature review. This search was done through Web of Science.

Although there are tens of thousands of papers discussing the monitoring of water quality via remote sensing, adding SDGs to the search criteria reduces resulting studies by a factor of ~300. When factoring in chlorophyll-a to the criteria, those results decrease by another factor of ~10. Of the 9 papers fitting all search criteria for all fields, only the 6 papers that fit all criteria for "topic" were relevant using the remote sensing of chlorophyll-a as an SDG indicator.

In one of these six studies, satellite-derived chlorophyll-a data and Google Earth Engine are used to assess global coastal eutrophication potential at 4km resolution, showing the potential of remote sensing applications on a global scale, especially with relation to 14.1.1a (de Raús Maúre et al., 2021). Although it doesn't mention the UNEP parameters under 14.1.1a, it essentially validates the chlorophyll-a parameter in Level 1, and supports the potential for further research in this field. Another study showed the feasibility of using remote sensing chlorophyll-a data to infer the presence of Vibrio pathogens and cholera outbreaks, supporting SDG 3, 6, 13, and 14 (Racault et al., 2019). This study also focused on remote sensing on a global scale.

The remaining four papers were case studies of varying locations. In the first study, Sentinel 2 satellite data validated in-situ samples showing decreased water quality in Vembanad Lake, India, after the demolition of four high rise buildings on the shore of the lake (George et al., 2021). The study suggests the potential in using remote sensing to support SDG 3, 6, and 14. In another study, the Copernicus Marine Environment Service uses Earth Observation data and in-situ measurements to indicate SDG 14.1.1.a in the Iberia-Biscay-Ireland Seas (Sykas et al., 2018). The mythology of the study uses Phosphate-Nitrates-Silica-Chlorophyll and Water-Transparency models to calculate indicators in four tiers of eutrophication risk, demonstrating the potential to apply remote sensing to SDG 14.1.1a in other locations (Sykas et al., 2018). In a third study, Landsat 8 and Sentinel 2A imagery were used to map chlorophyll-a and total suspended solids over large bodies of surface waters in Zambia, Senegal, and Peru to support the idea that satellite data can be used to inform countries on their Indicator 6.6. Reporting (Hakimdavar et al., 2020). The final paper demonstrated the potential for applying field data and Sentinel-3 Ocean and Land Color Instrument (OLCI) imagery to SDG 6.3.2 indication was assessed in Eastern China (Shen et al., 2020).

The way that data is collected for the above parameters, whether remote or situ, can vary drastically by country depending on water properties, instruments available, amount of funding toward water quality research, and policy on water management. To give an accurate assessment of parameters on a national level, this paper will focus on a case study of a single country. However, as the results above have shown, there is a large data gap in using the remote sensing of chlorophyll-a as a direct indicator of SDG 14 metrics on a regional level. Therefore, the resulting methods can potentially be applied to other countries with further research and validation.

Area of Study: Belize

This study chooses to focus on the country of Belize for this case study for the following reasons:

1. Belize has a high risk of increased algae blooms and eutrophication that threaten the quality of coastal reefs and water resources in the country(*Nutrients | The Caribbean Environment Programme (CEP)*, *Efforts to Improve Water Quality in Belize*).
2. Research on water quality in Belize is scarce, and some areas may lack the instruments and technology necessary to take and process accurate samples (Young, 2008).

3. There is a large data gap on remote sensing applications in Belize, and a validated chlorophyll-a algorithm for monitoring water quality remotely in Belize has yet to be developed.

Characteristics of Belize's land, climate, and water play an important role in water quality issues such as algae blooms. Belize contains two main ecosystems: marine, and terrestrial. Belize's terrestrial ecosystem is dominated by broadleaf and fine forests, several lakes, and an extensive river system. Its marine system includes the largest barrier reef in the Northern Hemisphere, which is also the 2nd largest in the world (*National Climate Change Office, 2020*). The Belize Barrier Reef is a habitat for many threatened marine species, but has faced a number of local threats in recent years including overfishing, coral bleaching, coastal development, and invasive species (*Great Barrier Reef Foundation Launches Resilient Reefs Initiative in Belize - Great Barrier Reef Foundation*).

Climate in Belize varies seasonally and regionally. The northern region of Belize is characterized by a subtropical climate, with annual rainfall amounting to 1500 mm or 60 in. In the southern region of Belize, the climate is more tropical, and annual rainfall is around 3800 mm, or 150 in. Belize has both dry and wet seasons throughout the year. 60% of rainfall in Belize occurs from June to November during Belize's hurricane season. From November to February, there is a cool transition period in which rainfall declines, and 12 cold fronts cross Belize. February to April marks Belize's truly dry season, and in April-June Belize transitions back to the wet season (*National Climate Change Office, 2020*).

In recent years, the warmer months of Belize's dry season from April to May have been characterized by algae blooms, with sargassum accounting for most algae in Belize. Sargassum has been flowing through the Caribbean since 2011, when ocean currents brought an influx of sargassum into the area. Studies have suggested that increasing nutrients due to warming waters and upwelling caused by climate change have facilitated the growth of Sargassum in the past decade (Fortune & Gervais, 2017 & Langin, 2018). This research has also indicated that the source of sargassum lies south of the Caribbean and to the east of Brazil in the Atlantic Ocean, where sea surface temperature is warmest (Fortune & Gervais, 2017 & Langin, 2018). Ocean currents move the sargassum upward into the Caribbean, where it floats along the coasts of countries like Belize.

In addition to increasing masses of sargassum polluting the coastal waters of Belize, inland water in Belize is also at risk. New River, the longest river Belize, has seen an increase in pollution over the past few years due to issues such as agricultural companies dumping waste, effluent ponds overflowing, and increased tourist attractions and lodging near the water (*National Plan of Action*, 2008 & *Crisis at Belize's Northern New River, 2019*). In 2017, there were numerous reports describing dead fish and ill crocodiles around New River, which has led researchers to investigate the state of the river's ecosystem (*Crocodile Research Coalition*, 2021). Researchers found increased chlorophyll levels leading to little to no dissolved oxygen in some areas of the river, which has hindered the river's ability to sustain fish and other aquatic organisms vital to both the ecosystem, and local fisheries (*Almost No Dissolved Oxygen in Parts of the New River | Amandala Newspaper*, 2021).

Current State of Research on Remote Sensing Chlorophyll-a in Belize

Creating a thorough method for remotely measuring chlorophyll-a concentrations in Belize would not only allow progress toward SDG 14 to be quantitatively measured, but it would also help communities in Belize monitor water quality hotspots and potential threats to ecosystems. However, a literature search in all fields for the remote sensing of chlorophyll-a in Belize indicates zero results. A few studies have sought to assess topographical change in Belize via remote sensing, such as modeling future forest cover change in Belize (Voight et al., 2019 & Emch et al., 2005) monitoring neotropical savannas (Stuart et al, 2006), and measuring land-cover change (Emch et al., 2005). Another handful of studies have used remote sensing to assess aspects of water quality in Belize, such as the change in the attenuation coefficient at 490nm, Kd(490) during COVID-19 (Callejas et al., 2021), assessment of temperatures on coral reefs (Castillo & Lima, 2010), and prediction of structural complexity of fish and reefs (Bejarano et al., 2011). Despite the existence of studies exploring other remote sensing applications in Belize, no papers have yet documented the use of remote sensing to measure chlorophyll-a in Belize waters.

The lack of data on this topic is likely due to the complexity of Belizean waters, and in turn the difficulty of finding a chlorophyll-a algorithm that can accurately extract satellite reflectance data from Belize. Chlorophyll-a is a key indicator of phytoplankton biomass, which can be used to assess the eutrophic status of water bodies, or the level of nutrients enriched within the water. It has photoactive pigments that change water color, which is why heavily eutrophic water bodies appear green (Camuffo, 2014). Chlorophyll-a absorbs most energy from blue-violet and red wavelengths (Camuffo, 2014). Typically, blue-green ratio chlorophyll-a algorithms work well in the open ocean where phytoplankton dominate any variation in optical water properties, otherwise known as “case-1” waters (Morel & Prieur, 1977). However, in coastal waters where colored dissolved organic matter (CDOM) and suspended sediments strongly influence the optical properties of the water, these blue-green ratio algorithms tend to fail to retrieve accurate chlorophyll-a data. Additionally, areas in which chlorophyll-a reaches extremely high values are also not suitable for these algorithms. These optically-complex mostly coastal waters are categorized as “case-2” waters (Morel & Prieur, 1977). A variety of algorithms have been developed for case-2 waters, such near infrared (NIR) - red band ratios, but in many cases, algorithms will fit different case-2 waters differently based on water properties (Lavigne et al., 2021). Over 80% of global waters can be classified as case-1 throughout the year, and that case-2 waters exist mainly along the coast (Matsushita et al., 2012). However, the area and distribution of case-1 and case-2 waters do shift seasonally, making it more difficult to find a single algorithm that works best for a larger water body region (Matsushita et al., 2012). Studies indicate that the Belize coastal lagoon can be classified as case-1 water (Callejas et al., 2021). However, evidence also suggests that lagoonal waters can alternate between case-1 and case-2 depending on factors such as rainfall, fresh and saltwater exchange, and part of the lagoon being analyzed (Ecol et al., 1996). Therefore, the coastal waters of Belize could be classified as either case-1 or case-2 waters depending on the location and season, and it is important to consider algorithms for both cases while trying to determine the best algorithm for detecting chlorophyll-a in Belize.

Part 2: Literature Review of Relevant Chlorophyll-a Algorithms

To determine algorithms that could be useful in estimating chlorophyll-a measurements in Belize waters, this study performs a literature review of remote sensing applications for other regions. The goal of this review is to compare algorithms used in studies that sufficiently validated chlorophyll-a retrieval via remote sensing within situ data in areas with water properties similar to the coastal waters of Belize.

Literature Search and Screening

Using the Web of Science Core Collection database criteria search, this study assessed the availability of criteria stated in **Table 4**.

Criteria	**Restrictions**
remote sensing OR satellite OR Earth Observation OR EO OR Google Earth Engine OR GEE	All Fields
water quality OR coastal OR recreational water OR marine	All Fields
monitoring OR sampling OR measurement OR measuring OR validation	All Fields
chlorophyll OR chlorophyll-a	Title
algorithm OR algorithms	Title

Table 4: Literature Review search criteria and corresponding restrictions.

The literature review criteria presented in **Table 4** resulted in 145 papers. After reviewing each paper, studies that fell in any of the following categories were removed for the next phase:

1. Irrelevant to topic
2. Machine-learning or neural network-based algorithms
3. The highest observed coefficient of determination (R^2) value between in-situ and estimated chlorophyll-a was <.7
4. No R^2 value was given
5. No regional study area was assessed
6. There was a problem accessing the paper (out of date, not available from any publisher, etc.)

Machine learning and neural network-based algorithms were neglected because they are site-specific and cannot be replicated accurately for a region different from the sample area.

Although machine learning applications could be promising for Belize waters considering its complexity, this study chose to focus on ratio-based algorithms as part of a larger analysis. Additionally, because this study is contingent on comparing R^2 values to assess accuracy of algorithms, the few papers that did not include their R^2 values were not used.

After filtering out papers that fell into the above categories, 47 papers remained. The remaining papers were then categorized by water type:

Type 1	**Type 2**
Coastal	Inland
Estuary	Lagoon
Bay	Lake
Ocean	Reservoir

For this study, only Type 1 waters were used as this paper focuses on assessing chlorophyll retrieval on the coast of Belize rather than any inland waters. However, the data from the Type 2 waters could be used in a future assessment that targets inland waters in Belize, such as New River or Progresso Lagoon.

Of the 48 papers, 28 fell into the category of Type 1 waters. The regions that these papers targeted are shown below in **Figure 1**, with Belize shown as a locational reference.

Figure 1: All 28 remaining papers that assessed Type 1 waters, along with an indicator for the location of Belize. Paper locations are shown by the blue indicators, while Belize is shown with the yellow indicator.

From the 28 remaining papers, 12 papers were chosen for a deeper analysis and comparison to the coastal waters of Belize. These 12 papers were chosen solely for their proximity to the latitude of Belize. Although climate across water in similar latitudes is not always the same due to factors such as proximity to land and ocean currents, all twelve papers include sample sites close to coastlines in tropical regions, meaning that they may be more prone to algae blooms in the warmer months. Therefore, these locations may still offer some insight into algorithms effective for certain water properties inherent to tropical waters. The locations of the 12 papers, as well as their corresponding sample area ranges, are shown below in **Figure 2.**

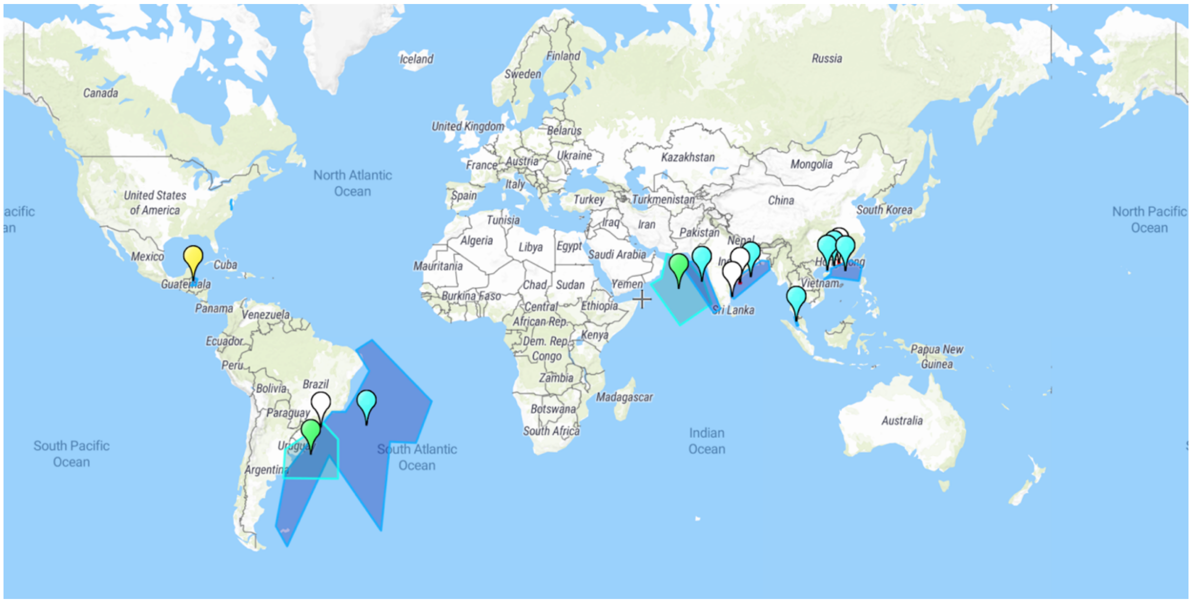


Figure 2: Regions assessed by the 12 remaining papers located in the tropics. Green, turquoise and white indicators show general areas of study, while blue and turquoise areas show a full range of samples for each paper. The location of Belize is shown with a yellow indicator.

Regional Algorithms from 12 Papers

Three areas were categorized from the sampling points shown in **Figure 2**: Area #1: Coast of India, Area #2: Southeastern Asia coastal areas, and Area #3: Coastal areas around Southeastern South America. Each area is assessed individually in **Figures 3, 4, and 5** with corresponding **Tables 5, 6, and 7.**

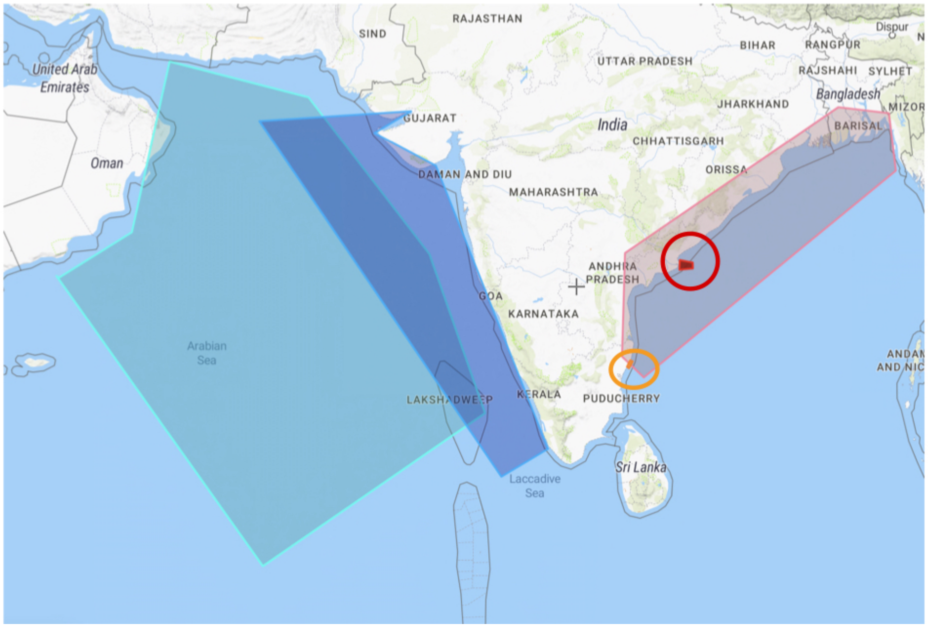


Figure 3: Area #1: Coast of India. Different studies and their respective sampling areas are indicated in different colors, which correspond to the colors in **Table 5** below.

Color	Location	Paper	R2	Algorithm	Water Properties
🟦	Arabian Sea	Nagamani et al., 2008	.96	OCM-2	upwelling along southern coast during summer monsoon = nutrient-rich waters brought to surface; oligotrophic/mesotrophic in winter
🟦	Arabian Sea	Tilstone et al., 2013	.73	OC3M	See above
🟪	Bay of Bengal	Tilstone et al., 2011	.74	OC4v6	turbid; seasonal reversal of monsoon winds; high SST; large influx of freshwater and sediments
🟧	Kalpakkam, India	Natesan et al., 2015	.92	OCM-2	influenced by winter monsoon
🟥	Kakinada and Yanam, India	Shaik et al., 2021	.94	S2MCI	turbid; extremely influenced by CDOM and suspended matters; high SST; large influx of freshwater and sediments

Table 5: Papers corresponding by color to their respective sampling areas on the map of **Figure 3.** R^2 values, algorithms, and water properties for each study are also shown. Water properties are pulled solely from each paper to reflect characteristics specific to that area of study.

Figure 3 and **Table 5** show the different chlorophyll-a algorithms that were effectively used to remotely measure chlorophyll-a off the coasts of India, in the Arabian Sea, and in the Bay of Bengal. Four out of five algorithms are based on ocean color (OC) chlorophyll algorithms.

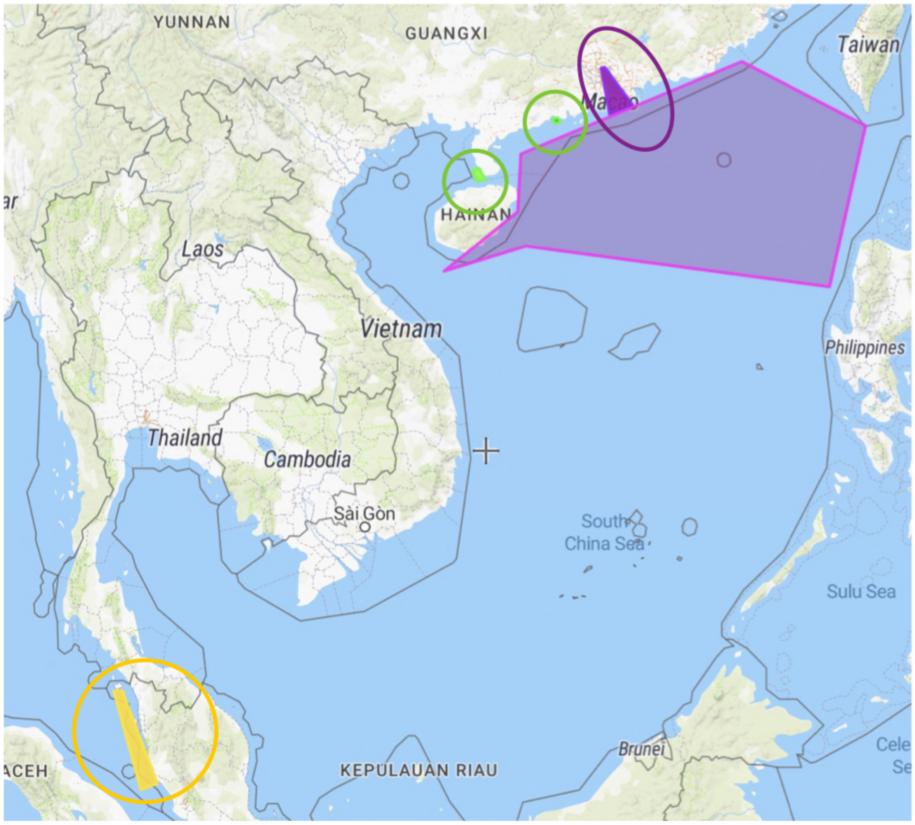


Figure 4: Area #2: Southeastern Asia coastal areas. Different studies and their respective sampling areas are indicated in different colors, which correspond to the colors in **Table 6** below.

Color	**Location**	**Paper**	**R2**	**Algorithm**	**Water Properties**
🟨	Malacca Straits	Ab Lah et al., 2014	.88	OC3M	High productivity, high nutrient outputs from rivers
🟩	Western Guangdong, South China	Chen et al., 2021	0.9	3-band	increasing eutrophication, water quality issues, case-2 waters

🟪	Pearl River Estuary	Liu et al., 2019	.74	PEA	Lots of phytoplankton blooms In wet season (April-Sep); increasing blooms with urbanization of Pearl River delta
🟪	Northern South China Sea	Pan et al., 2010	.84	OC4_TP	tropical-subtropical area; predominantly oligotrophic and ultra-oligotrophic; monsoons year-round

Table 6: Same as table 5 but for **Figure 4.**

Figure 4 and **Table 6** show the different chlorophyll-a algorithms that were effectively used to remotely measure chlorophyll-a off the coasts surrounding the South China Sea and Malacca Strait. Based on the water properties, all areas seem to have increasing eutrophication except for some of the areas in the central locations of the Northern South China Sea.

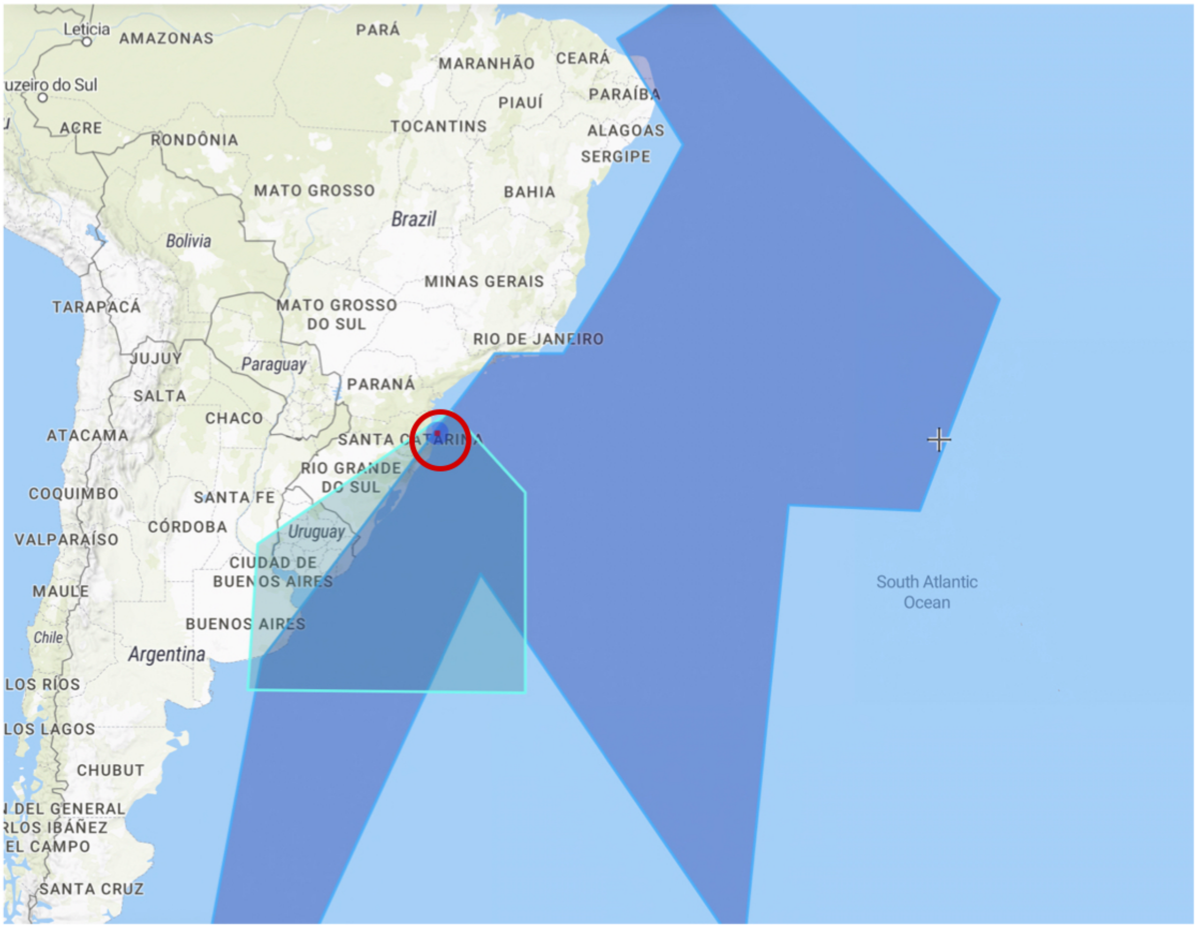


Figure 5: Area #3: Coastal areas around Southeastern South America. Different studies and their respective sampling areas are indicated in different colors, which correspond to the colors in **Table 7** below.

Color	**Location**	**Paper**	**R2**	**Algorithm**	**Water Properties**
🟥	Southern Brazilian	Silva et al., 2021	.96	OC3M	humid subtropical mesothermal climate
🟦	Southwestern Atlantic Coastal Region	Garcia et al., 2006	.86	GSM01	case-2 waters
🟦	Southwestern Atlantic	Garcia et at., 2005	.89	FURG OC4	case-2 waters

Table 7: Same as **Table 5** and **Table 6** but for **Figure 5.**

Figure 5 and **Table 7** show the different chlorophyll-a algorithms that were effectively used to remotely measure chlorophyll-a off the southeastern coast of South America. **Table 8** displays all the papers and their corresponding algorithms in a single table to compare the different processes used for each location.

	Paper	**Algorithm Name**	**Algorithm Process**	**R2**
Western Guangdong, South China	Chen et al., 2021	3 Band Model	Generally known as$[R(\lambda 1)^{-1} - R(\lambda 2)^{-1}] \times R\ (\lambda 3)$ Specifically used for this paper: (1/R689)-(1/695)xR727	.9
Southwestern Atlantic	Garcia et at., 2005	FURG OC4	Revision of NASA's OC4v4 algorithm using *R*=[max (*R*555/443, *R*555/490, and *R*555/510)]	.89
Southwestern Atlantic Coastal Region	Garcia et al., 2006	GSM01	Garvel, Siegel and Maritorena algorithm, which uses model parameters derived through statistical optimization (Maritorena et al. 2002)	.86
Arabian Sea	Tilstone et al., 2013	OC3M	$log[Chl] = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4$ Where $X = log[\frac{max(R_{rs}(443), R_{rs}(489)}{R_{rs}(555)}]$ (Campbell & Feng, 2005)	.73
Southern Brazilian	Silva et al., 2021	OC3M	See above	.96
Malacca Straits	Ab Lah et al., 2014	OC3M	See above	.88
Northern South China Sea	Pan et al., 2010	OC4_TP	$log[Chl] = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4$ Where $X = log[\frac{R_{rs}(443) > R_{rs}(490) > R_{rs}(510)}{R_{rs}(555)}]$	.84
Bay of Bengal	Tilstone et al., 2011	OC4v6	Using in situ data from NOMAD version 2, this algorithm describes the best fit polynomial relating the log ratio of reflectances $log[Chl] = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4$ Where $X = log[\frac{R_{rs}1}{R_{rs}2}]$; $R_{rs}1$ = blue wavelength, $R_{rs}2$ = green wavelength (443>489>510) *(NASA Ocean Color)*	.74
Arabian Sea	Nagamani et al.,	OCM-2	Using maximum band ratio:	.96

	2008		$log[Chl] = a_0 + a_1X + a_2X^2 + a_3X^3$ $X = log[\frac{R_{rs}1}{R_{rs}2}]$; $R_{rs}443/R_{rs}555$, $R_{rs}490/R_{rs}555$, and $R_{rs}510/R_{rs}555$	
Kalpakkam, India	Natesan et al., 2015	OCM-2	$log[Chl] = a_0 + a_1X + a_2X^2 + a_3X^3$ $X = log[\frac{R_{rs}1}{R_{rs}2}]$; $R_{rs}490/R_{rs}555$	.92
Pearl River Estuary	Liu et al., 2019	PEA	Red-peak envelope area near 700 nm: $PEA = \int_{\lambda1}^{\lambda2} R'(\lambda)d\lambda$ where λ1 & λ2 indicate the wavelength range of the reflectance peak determined by the 1st derivative	.74
Kakinada and Yanam, India	Shaik et al., 2021	S2MCI	Using the maximum chlorophyll index, $MCI = L_2 - L_1 - (\frac{\lambda2 - \lambda1}{\lambda3 - \lambda1})(L_3 - L_1)$ λ1 = 665nm, λ1 = 705nm, λ3 = 740nm	.94

Table 8: Papers and their corresponding algorithms, algorithm processes, and R2 values.

Chlorophyll-a algorithm OC3M is the most frequently used algorithm between the 12 papers, used by 25% of the studies. OCM-2 is used by 17%, and different variations of OC4 account for 25% of the studies. The sensor used the most in these studies is MODIS.

Part 3: Applied OC2 Algorithm Assessment of Chlorophyll-a Patterns in Belize

Methods

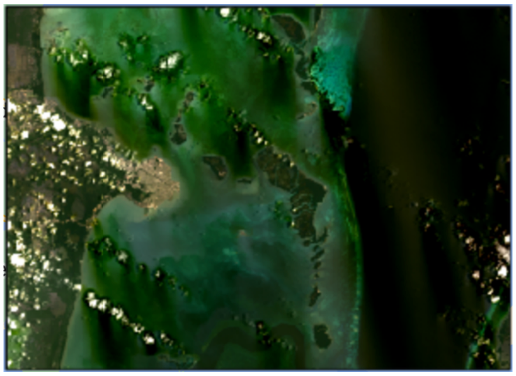
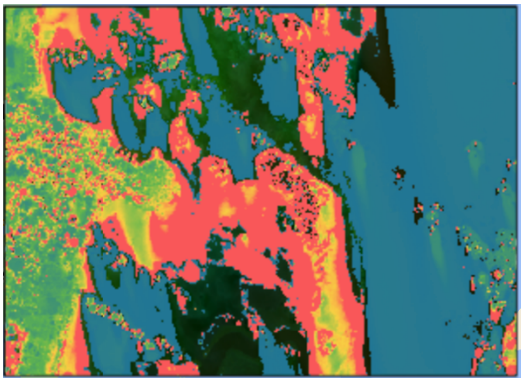
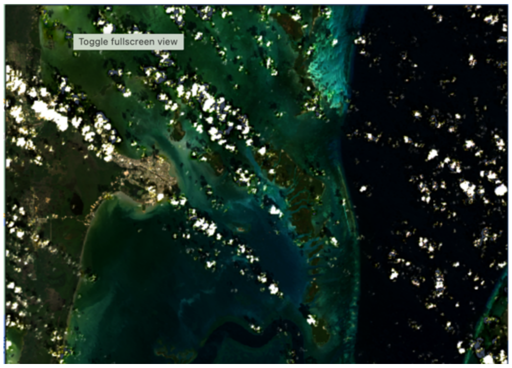
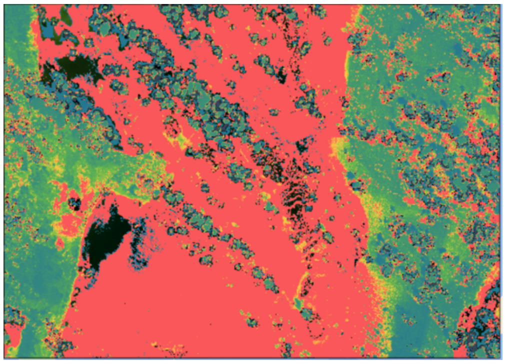
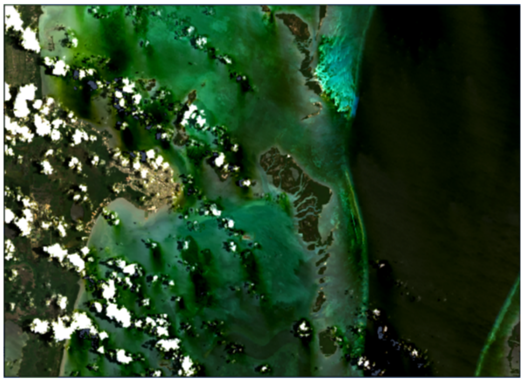
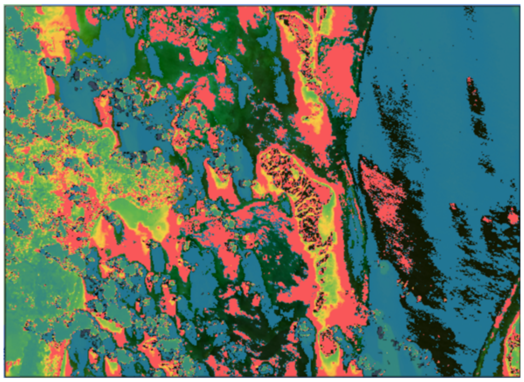
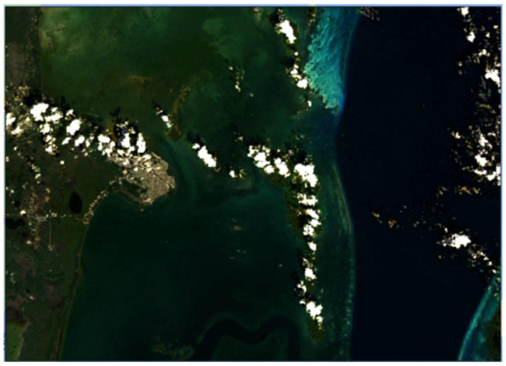
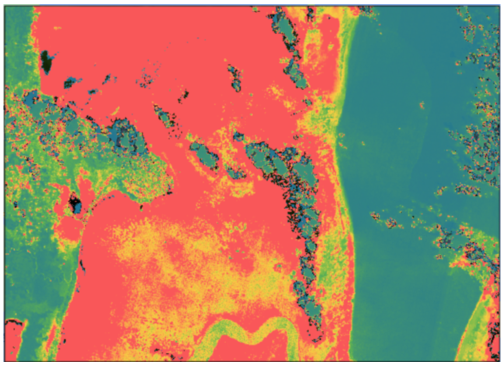
To properly assess the effectiveness of various chlorophyll-a algorithms on the coast of Belize, remote sensing data needs to be validated with in-situ data. However, since in-situ data is not currently available, this paper will only assess algorithms based on expected seasonal changes in chlorophyll-a from algae blooms. Ideally, all algorithms from the 12 remaining papers would be assessed for applications in Belize since each location embodied some type of similarity to the waters off the coast of Belize. However, for the purpose of this study, only one of the common algorithms from the above section is used.

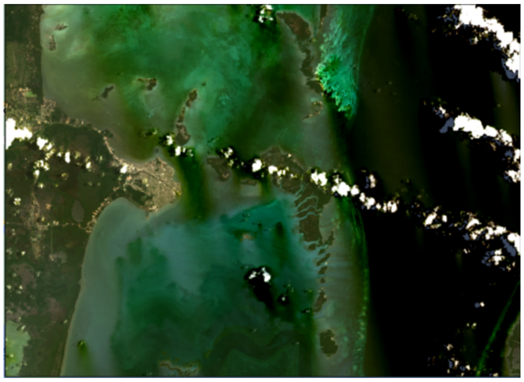
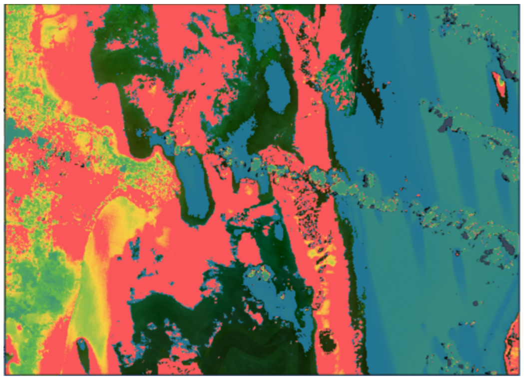
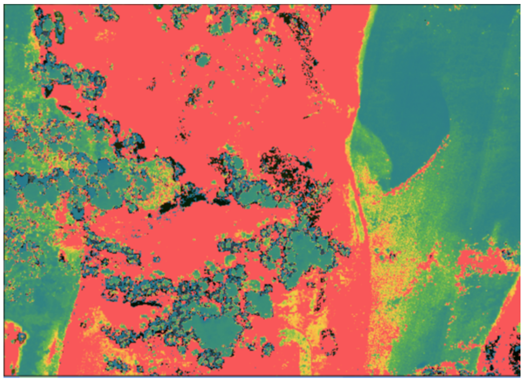
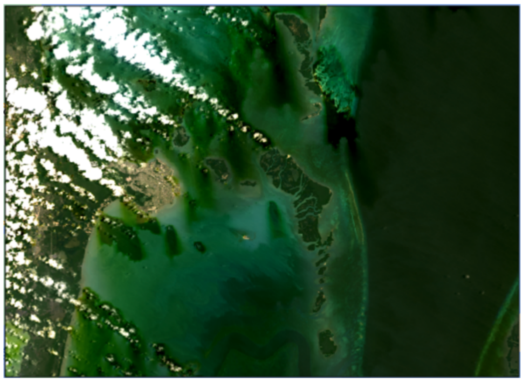
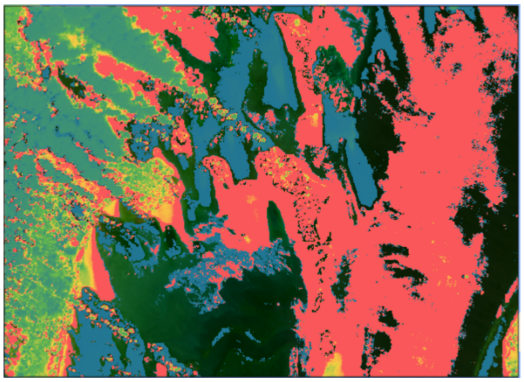
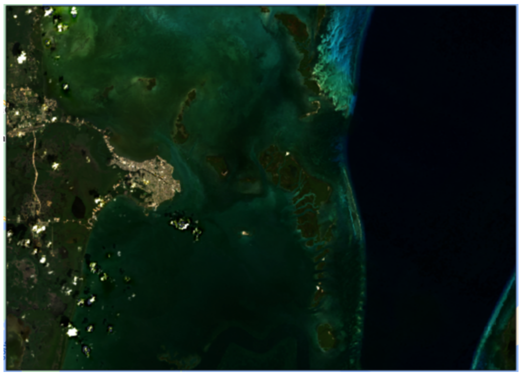
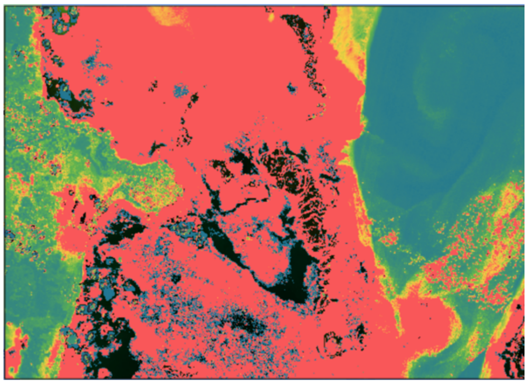
The above literature review illustrated the effectiveness of OC3M and OCM-2 algorithms in tropical coastal waters across multiple regions. In response, this study uses the OC2 algorithm to look for indicators of algae blooms in Belize. OC2 is chosen over OC3 for easier replicability, and Landsat 8 data is used instead of MODIS because of its higher spatial resolution which is more conducive to the smaller coastal zones of Belize. Landsat 8 provides a spatial resolution of 30m while MODIS has a spatial resolution of 250m in the bands used.

This study used the coastal area surrounding Belize city to look at seasonal differences in algae blooms with the OC2 algorithm. This area was chosen because it encompasses a Marine Protected Area (MPA), Swallow Caye, and because it may be prone to more eutrophication due to increased urbanization. The assessment used 2 seasons: April-August, which experience warmer, wetter conditions, and November-February, which experience colder, dryer conditions. Cloud cover was set to less than 30% or less. The results are shown below in **Table 9.**

Results

Date	**April-August**	**November-February**

2016- 2017	 	 
2017- 2018	 	 

2018-2019	 	 
2019-2020	 	 

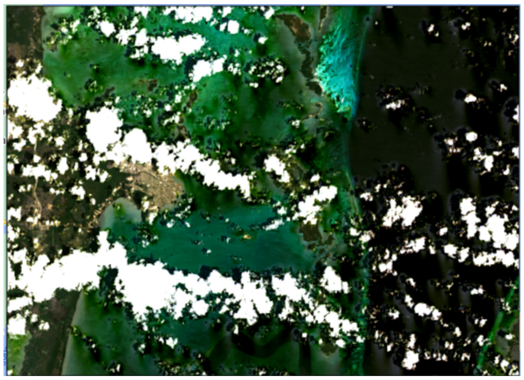
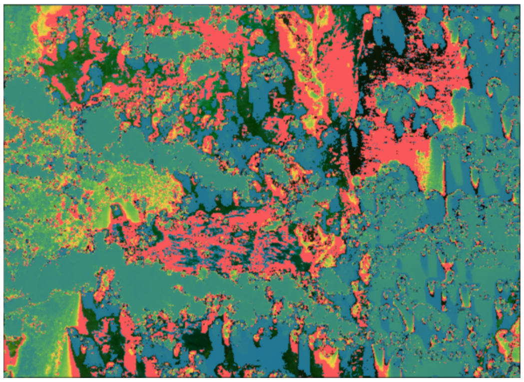
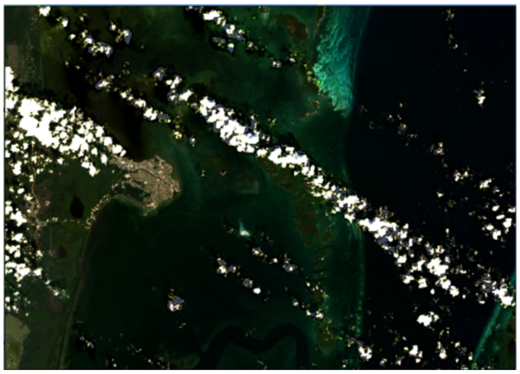
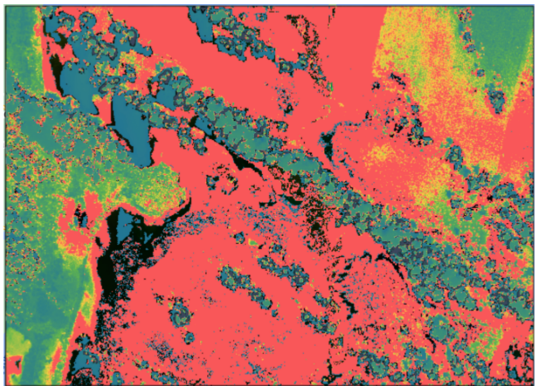
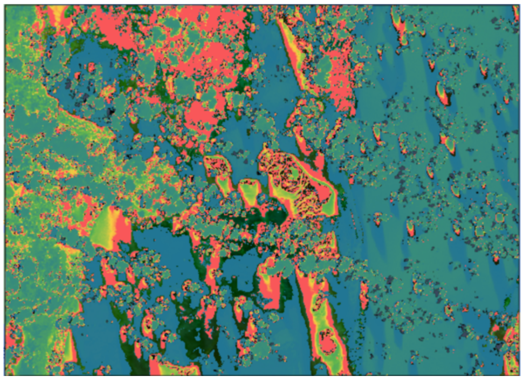
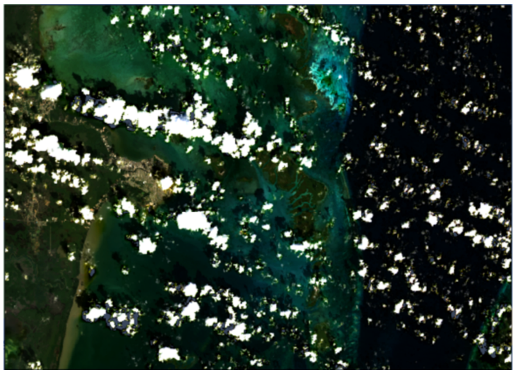
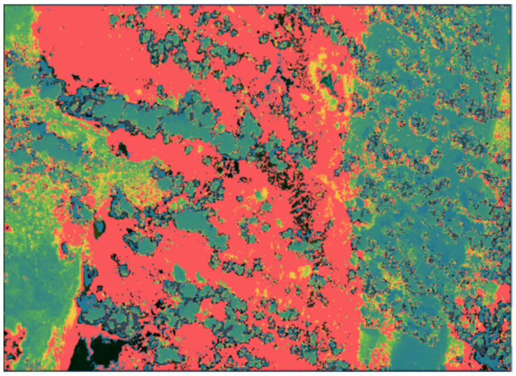
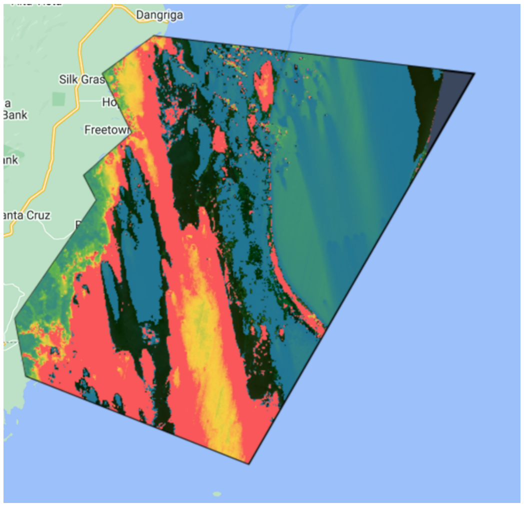
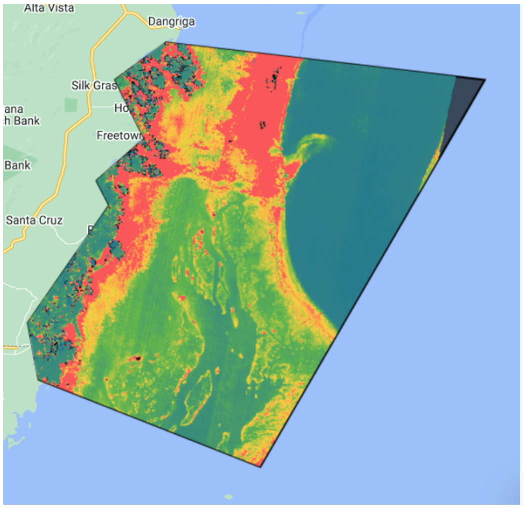
2020-2021	 	 
2021-2022	 	 

Table 9: Comparison of seasonal differences in chlorophyll-a off the coast of Belize city using the OC2 algorithm. True color images are shown first, and then chlorophyll-a images are shown below them. The palette used to indicate chlorophyll-a goes is a rainbow palette, where red designates higher chlorophyll concentrations and blue designates lower concentrations.

The results in **Table 9** tend to show an increase in chlorophyll-a concentrations during the winter months, indicating that those months experience more eutrophication. This could be explained by several processes, one of which could be the dry period experienced from November-February leading to less dilution of nutrients.

To validate these results, the same assessment was done farther down the coast of Belize between Hopkins and Placencia. This area has been especially prone to Sargassum blankets in recent years during the summer season. The results are shown in **Table 10.**

Date	**April-August**	**November-February**
2019- 2020		

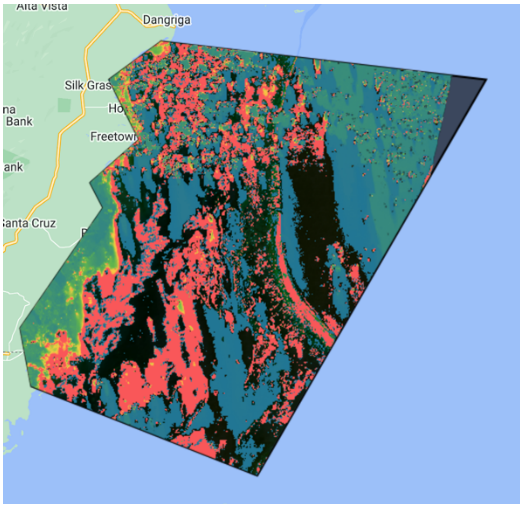
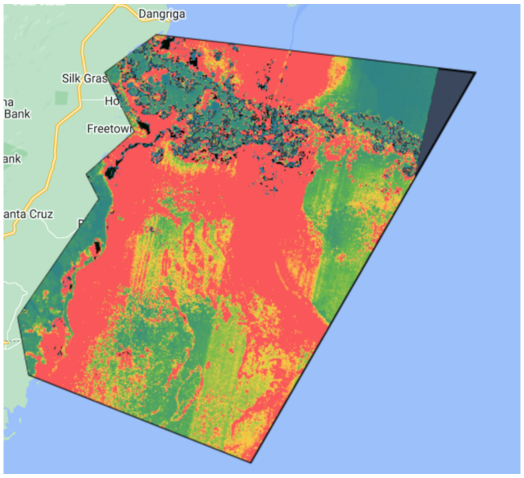
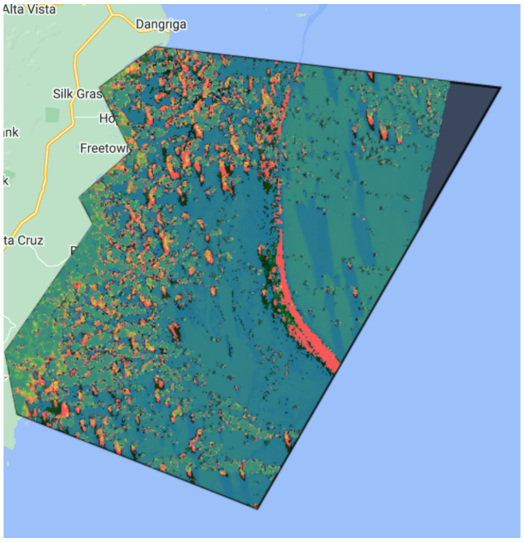
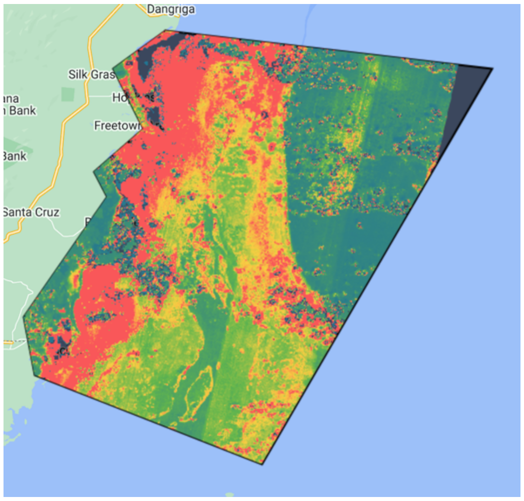
2020- 2021		
2021- 2022		

Table 10: Comparison of seasonal differences in chlorophyll-a off the coast of southern Belize using the OC2 algorithm.

The results in **Table 10** display a similar trend to that shown in Table 9: chlorophyll-a concentrations increase during the winter season using the OC2 algorithm. This difference is even more noticeable in the most recent year, 2021-2022.

These results pose an interesting question about why chlorophyll-a concentrations appear higher in the winter than the summer, when algae blooms and sargassum migration are expected during the summer. Because it is not clear whether the OC2 algorithm is effective, it is necessary to further investigate various chlorophyll-a algorithms for the coast of Belize, as well as obtain in situ data that can validate these types of results. As the OC2 algorithm did show consistent changes in chlorophyll-a concentrations seasonally, it could have potential for further applications in Belize. However, since it did not fit the predictions of the algae blooms, there is need for further research.

Conclusion

SDG 14, which strives to conserve the oceans and coastal regions for sustainable development, is an important measurement for the coastal waters of Belize, which are threatened by eutrophication, pollution, and algae blooms. Belize's marine ecosystem is home to many endangered species, but in recent years an increase in overfishing, urbanization, and coral bleaching has decreased water quality in Belize. However, SDG 14 does not offer a comprehensive plan for monitoring changes in water quality. Instead, the UNEP has suggested parameters for assessing water quality. Chlorophyll-a concentrations and algal blooms are two of the most significant parameters listed in these suggestions; however, there is currently no large-scale and effective way of quantifying and monitoring eutrophication in the coastal waters of Belize.

The remote sensing of chlorophyll-a has been successfully used in other regions of the world but has yet to be applied to Belize. By assessing chlorophyll algorithms used successfully in other tropical regions of the world, this study determined a handful of algorithms that have potential to measure chlorophyll-a in Belize. The application of one of these algorithms (OC2) to assess seasonal variation in chlorophyll-a on the coast of Belize demonstrated a clear trend between winter and summer seasons. However, the chlorophyll variations were not as predicted, and indicated a clear need for further research on chlorophyll-a algorithms effective for Belize.

Although multiple algorithms were determined to have potential for monitoring chlorophyll-a in Belize, this study only studied seasonal variation in two small coastal regions for a single algorithm. Additionally, this data was not validated with in-situ samples. For future research, more algorithms need to be tested as well as compared to in-situ values in Belize for validation. Other types of algorithms not explored in this paper, such as machine learning and neural network algorithms, should also be assessed and compared to original band ratio algorithms. The potential that applications of remote sensing of chlorophyll-a in Belize have for SDG 14 present a unique opportunity for standardizing the monitoring of water quality on a national level, and future research in this realm of research could be incredibly valuable to conserving ecosystems and water bodies under the increasing threat of climate change.

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