DEVELOP Technical Report

Trinidad & Tobago Climate

Using Earth Observations to Monitor Sea Level Rise and Identify Vulnerable Areas for Restoration Strategy in Trinidad & Tobago

Spring 2025 | Alabama – Marshall
April 4th, 2025

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Abstract:
This study, in partnership with the Institute of Marine Affairs (IMA), investigated the use of Earth observations to analyze shoreline change and to estimate relative sea level rise (SLR) in Trinidad and Tobago. The IMA has relied on outdated shoreline data from 2014, which has become increasingly unreliable for current decision-making and future planning. This project utilized Landsat 8 OLI and Sentinel-2 MSI data to assess the efficacy of optical imagery for shoreline delineation to illustrate relative shoreline change. Additional commercial imagery from PlanetScope Dove was used for finer resolution analyses of partner-selected case study areas of Caroni Swamp (Trinidad), Mayaro (Trinidad), and Pigeon Point (Tobago). The project team then explored changes in relative sea surface levels, as a key factor affecting overall shoreline change, using tidal gauge data to project sea level change to 2050 and satellite altimetry data to capture relative regional and seasonal anomalies in sea surface height. Tidal gauge data was compiled and analyzed using linear regression models. A digital elevation model (DEM) derived from a LiDAR scan was used to project potential flood impacts to low-lying areas imposed by potential future sea level rise. Hence, a replicable and accessible methodology was designed to support the IMA in their development of environmental and community resilience strategies. The end products include an overlay map of delineated shorelines produced by public and commercial satellites, visualizing the movement of shoreline in 2015, 2020, and 2024, along with an estimate of SLR within Trinidad and Tobago for the year 2050.

Key Terms: Shoreline change, sea level rise, Earth Observation, observation-based extrapolation, altimetry, coastal vulnerability

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1. Introduction

As sea level rises within the Caribbean region, safeguarding both human and non-human life along the coastline remains a critical task for government organizations and advocacy groups. Coastlines are at the center of community and economic life, as are sites of ecological importance such as mangroves, tidal marshes, and sea grass meadows. Current sea level rise projections at a global scale are estimated to range between 0.10 meters to 0.27 meters until 2050 (IPCC, 2023). In the Caribbean, sea levels are predicted to rise at equal or higher rates (Maitland et al., 2024). For countries like Trinidad and Tobago, understanding the impacts of sea level rise at scale can provide key opportunities to develop environmental and community resilience strategies in critical ecological zones. However, small island states like Trinidad and Tobago face considerable barriers in accessing accurate and applicable data to capture sea level rise as a phenomenon. This includes satellite data for shoreline estimation and ground-level data to measure the impacts of sea surface height. Furthermore, resource constraints often faced by small islands underscore the need for replicable and feasible sea level rise estimation procedures. Given these limitations, Trinidad and Tobago benefits from systematic approaches that leverage Earth observation data to overcome resource constraints and accurately measure and estimate the impacts of sea level rise. This feasibility study examined sea level rise in Trinidad and Tobago while considering both data accessibility and process replication, to facilitate applicability to other Small Island Developing States (SIDS). The study incorporated remote sensing methods to monitor sea level changes, which can benefit the project partners as well as other organizations in SIDS concerned with coastal planning and ecological monitoring.

The objectives for this study were to estimate current and future sea level rise through changes in sea surface height, to analyze shoreline variations in shoreline extent over study period, and model the future impacts of sea level rise in 2050 on the shoreline using current estimates. This feasibility analysis was grounded in Earth observation (EO) research and utilized remote sensing optical data from both public and commercial satellites. Existing methods to assess sea level rise and detect shoreline change over time include aerial photography, aerial LiDAR, and satellite photogrammetry (Boak and Turner, 2005; Gens, 2010; McAllister et al., 2022). Sea surface heights, a key signal of sea level rise, were measured through observational tidal gauge data and remotely derived coastal altimetry data to capture long-term trends in relative sea surface levels (Cazenave et al., 2022; Adebisi et al., 2021). The goal of this feasibility study was to create replicable methods to capture sea level rise using remote sensing, which address capacity and data gaps experienced by the project's partner organization. This goal aims to support methodologies that can generate outputs that are integrated into evidence-driven policy and decision-making for the country of Trinidad and Tobago.

The island country of Trinidad and Tobago is characterized by a compact, complex topography with low-lying coastal areas and mountainous terrains located along a series of fault lines in the Caribbean region (Figure 1). The region sits at the convergence of the subducting South and North American plates (Escalona and Mann 2011). The project study area is significant because Trinidad and Tobago's coastal areas are changing due to the impacts of sea level rise and other environmental factors. Some factors include sediment and water discharge from the Amazon and Orinoco rivers, which raise sea surface levels, as well as increased vertical land motion in the Gulf of Paria on Trinidad's Western coast (Subrath-Ali, 2014).

This project examined a ten-year period between 2015 and 2024, a period chosen to complement previous Earth observation work in 2014 (Asmath & Gooding, 2022). Therefore, this study incorporates a ten-year period which is not captured by existing research. Sea surface height at a global scale has steadily increased from a rate of 1.8 mm per year between 1950 and 2009 (Church & White 2011) to a reevaluated rate of 3.40 $\pm$ 0.3 mm/year between 1993 to 2019 (Maitland et al. 2024). In the last five years, sea level rise has continued to increase with 2024 marking some of the highest rates on record (Lee 2025). The study period partially captures a broader trend of rising sea levels that are affecting the study area as well as the broader Caribbean region (Vousdoukas et al. 2023). The study period accounts for the highest sea surface levels as well as seasonal dry periods characterized by low precipitation that span from December to May (Martinez et al. 2019; Tide Forecast). The seasonal dry period from January to June and December constitutes the subsection of each epoch included within the study period. The months of July through November are excluded from the shoreline change analysis because of seasonal weather phenomena on image quality, notably tropical storms and hurricanes (Appendix 1). Tropical storms and humid pressure systems create extensive cloud cover (Flores-Anderson et al., 2023) and thus reduce the usability of images accessed during this period.

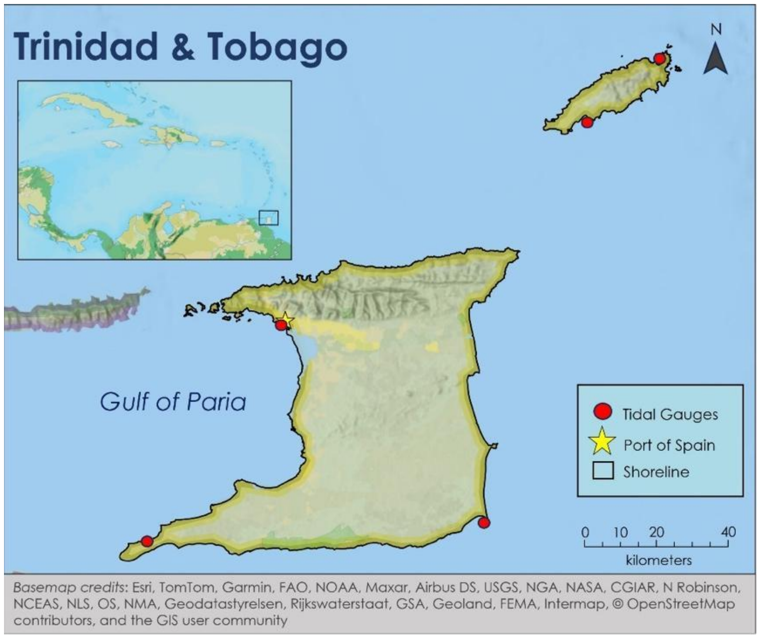

Figure 1. Trinidad and Tobago is located within 10° 2' and 11° 12' N latitude and 60° 30' and 61° 56' W longitude.

This feasibility study was conducted in partnership with the Institute of Marine Affairs (IMA). As an environmental and research organization, the IMA collects, analyzes, and communicates environmental information relating to oceanic and coastal environmental impacts. To conduct their work, the IMA uses Earth observations, notably remote sensing, to sustainably manage coastal resources, sensitive ecosystem areas, monitor and manage disaster impact zones, as well as support general planning and development on the island. For the purposes of this study, the IMA partnered with DEVELOP to use Earth observations to inform decision-making and strategic policies addressing rising sea levels and their impacts on human and non-human coastal communities. Current global and regional tools depicting sea level rise are insufficient for decision-making by excluding the major extents of the Trinidad and Tobago's shoreline. To respond to such insufficiencies, this joint DEVELOP-IMA study adopted a methodological framework that evaluated, analyzed, and estimated the localized impacts of sea level rise on human and non-human communities in Trinidad and Tobago both today and in the future.

2. Methodology

2.1 Data Acquisition

2.1.1 Measuring Sea Surface Height

Both tidal gauge and altimetry data were acquired to measure changes in sea surface height. Tidal gauge data were aggregated into spreadsheets from the Sea Level Station Monitoring Facility platform of the Intergovernmental Oceanographic Commission (IOC) of United Nations Educational, Scientific and Cultural Organization (UNESCO). Altimetry data were downloaded from NASA's Physical Oceanography

Distributed Active Archive Center (PO.DAAC) to complement the tidal gauge data (see Section 2.1.3). Both data sources were leveraged to better understand the variation in sea level height and how it varied between shorelines due to both seasonal differences and variability generated by vertical land motion along the fault line running through Trinidad (Willis et al. 2025; Miller, 2005). The aggregated tidal gauge data was composed of observations across multiple times within a day, downloaded by month for each year that data was available. Data was selectively available for five of the seven tidal gauges listed for Trinidad and Tobago, and only two of the seven gauges — Scarborough and Port Spain — had data covering over 60% of study period (Table 1). The data from these two tidal gauges were subsequently processed and analyzed for trends in sea surface height.

Table 1
Details of tidal gauge data available within Trinidad and Tobago, Source: IOC/UNESCO

Tidal Gauge	**Island**	**Latitude, degree**	**Longitude, degree**	**Epochs Gathered**
Cedros Bay	Trinidad	10.09405	-61.8655	2013, 2014, 2015, 2021
Charlottesville	Tobago	11.31667	-60.55	2013, 2015, 2015
Galeota	Trinidad	10.13873	-61.002	2021, 2022, 2023, 2024
Point Fortin	Trinidad	10.1833	-61.42	No epochs available
Point Galeota	Trinidad	10.13806	-60.9919	No epochs available
Port of Spain	Trinidad	10.65	-61.5767	2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024
Scarborough	Tobago	11.1667	-60.7333	2014, 2015, 2017, 2018, 2019, 2020

2.1.2 Shoreline Delineation

To determine the extent of shoreline changes from sea level rise, this study applied a shoreline delineation method to process raster images from public and commercial satellites (Table 2). Public satellites were prioritized due to their accessibility for any subsequent feasibility studies inspired by this research. Private satellites were acquired as complements to public satellites due to their finer resolution. Raster images collected from public satellites were from Landsat 7 Enhanced Thermatic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Sentinel-2 MultiSpectral Imager (MSI). The Near-Infrared (NIR) band consists of electromagnetic waves (750-2500 nm) which are absorbed by water and vegetation. As such, it can act as a means of distinguishing land from water, thereby yielding the shoreline. Landsat 7 and Landsat 8 have an NIR band resolution of 30 m and a revisit period of 16 days at nadir. Sentinel-2 imagery has an NIR band resolution of 10m and a revisit period of approximately 5 days at nadir. Commercial optical imagery from PlanetScope Dove was acquired from NASA's Commercial Satellite Data Acquisition (CSDA) program. Planet imagery has a finer NIR band resolution of 3 m and a revisit period of 5.5 days at nadir. Finer optical imagery was examined to consider opportunities to distinguish land from water with greater accuracy compared to coarser resolution imagery from public satellites. Commercial satellite data was acquired in subsets within the study area due to overall data volume and computational cost of processing large image repositories for a short-term feasibility study. The boundary of the imagery was set between 10° to 11° North and -62° to –60.5° West to capture both islands of Trinidad and Tobago. In addition to resolution, differences in temporal resolution for each satellite's revisit periods were important to the study because they impacted the total images acquired within each year.

Table 2

Details of satellite image and data acquisition for shoreline delineation and altimetry

Sensor	Platform	Type	Purpose	Processing Level	Spectral Bands	Spatial Res. (m)	Acquisition Dates
Landsat 7 ETM+	EarthExplorer	Public	Shoreline Delineation	Collection 2 Tier 1	NIR Band (Band 4)	30	2015/01/28 - 2024/01/19
Landsat 8 OLI	EarthExplorer	Public	Shoreline Delineation	Collection 2 Tier 1	NIR Band (Band 5)	30	2015/01/01 - 2024/12/29
Sentinel-2 MSI	Copernicus	Public	Shoreline Delineation	2A	NIR Band (Band 8)	10	2020/01/01 - 2024/12/31
PlanetScope Dove	CSDA	Commercial	Shoreline Delineation	3B	NIR Band (Band 4 or Band 8)	3	2020/01/01 - 2024/12/31

2.1.3 Altimetric Data for Monitoring Sea Level Trends

Altimetric data is preprocessed by PO.DAAC in the NASA-SSH Simple Gridded Sea Surface Height from Standardized Reference Missions Only to make satellite radar data more accessible. PO.DAAC provides data granules searchable through Earth Explorer (Table 3) and consists of data compiled from combined imagery and satellite instrumentation. The altimetry data was used to examine daily sea surface height and regional sea surface height anomalies (SSHA) in the Caribbean which may contribute to relative differences in rates of sea level change. Once the study area and period were determined, we searched for granules that fit our parameters and downloaded them. The geographic parameters determine coverage, as the satellite collects new imagery in an area every 7 days. Data products from PO.DAAC, which harmonize a variety of altimetric data sources (Appendix 2) , allow for both downscaled data downloads for specific geographies, and large-scale batch downloading of data for regional trend observations of sea surface height. Despite this capacity for large-scale downloading, we downloaded them individually.

Table 3

PO.DAAC satellite altimetry data details and use, Source: NASA Earthdata

Dataset / Source	Type	Purpose	Processing Level	Spatial Resolution	Acquisition Dates
NASA-SSH Simple Gridded Sea Surface Height from Standardized Reference Missions Only Version 1 dataset/ PO.DAAC	Public	Altimetry	4	0.5-degree latitude and longitude grid	2015/01/07 - 2024/12/28

2.2 Data Processing

2.2.1 Tidal Gauge Processing for Sea Surface Height Trends

Tidal gauge data was compiled from 2015 to 2024 and analyzed for trends within the data to consider the need to account for cyclical variability from tides, seasonal warming/cooling, and vertical land motion within the observational data. Trinidad, to greater extent than Tobago, is known to experience seasonal variation in sea surface height between the dry season and the tropical storm season, due to heavy rain fall from tropical storm systems and higher sea surface levels from river outflows from the Orinoco and Amazon rivers in South America pouring in towards Trinidad's Western Gulf of Paria (Subrath-Ali et al., 2013). Vertical land motion is also known to contribute to over 40% of Trinidad and Tobago's sea level change, causing shorelines to change unevenly due to proximity to fault line (World Bank, 2021). Difference in vertical land motion was also accounted for by processing tidal gauges separately, notably Port of Spain on the Western shore of Trinidad subject to land subsidence and river inflows at the Gulf of Paria, and Scarborough in Southwestern Tobago where both seasonal variation and vertical land motion are known to have lesser impacts. In Port of Spain in Trinidad and Scarborough in Tobago (Figure 2), the plotted tidal data indicates an increase in overall sea surface height over time, including cyclical variation which can be attributed to seasonal perigean spring tides, or yearly highest tides.

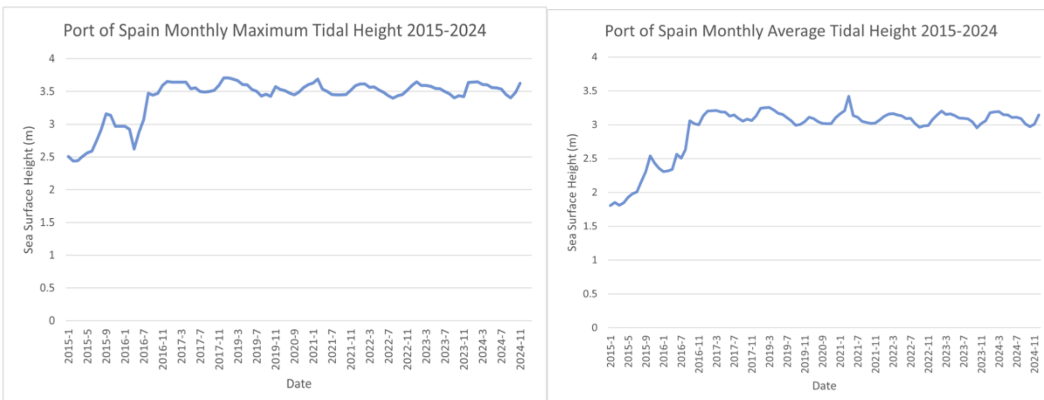

Figure 2. Monthly maximum and average tidal height data over study period 2015-2024 at Port of Spain .

Seasonal variation was addressed by conducting a deseasonalization process (Figure 3), which entailed average monthly maximum or average mean sea level was normalized by subtracting a monthly ten-year average maximum or mean sea level height (Ansari et al., 2024; Collini et al., 2022). The equation for deseasonalization creates a normalized trend represented by the variable Tidal Gauge (TG_{New}) trend by subtracting the yearly monthly ten-year average from the monthly average (TG_m) for each year in the ten years:

$$TG_{New} = TG_m\text{-monthy mean TG(2015-2024)} \quad (1)$$

Plots of deseasonalized tidal gauge data (Figure 3) for monthly average and maximum sea surface height illustrated a continued upward trend at the Port of Spain, as well as Scarborough. These plots suggested sea level rise does impact overall sea surface height between 2015 and 2024 in Trinidad and Tobago.

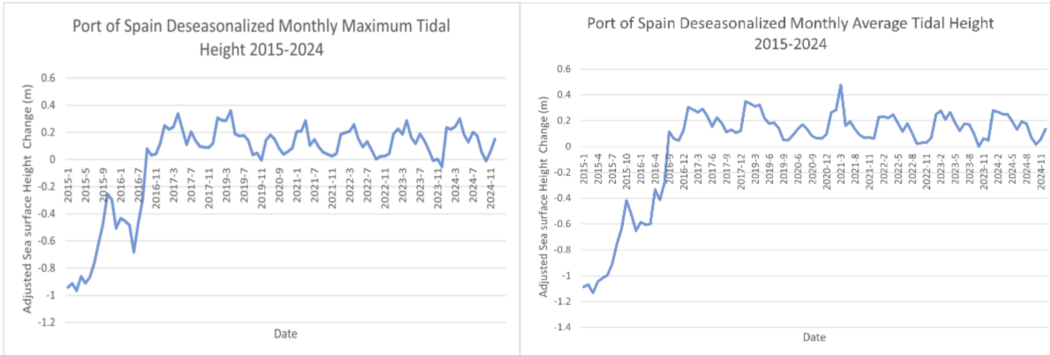

Figure 3. Deseasonalized tidal gauge data plotted by monthly maximum and monthly average tidal height over study period 2015-2024.

2.2.2 Satellite Data Processing for Shoreline Delineation

To create an estimated shoreline, satellite imagery was processed in four steps (Appendix 3). First, cloud masks were applied using ArcGIS Pro 3.4.0 to account for cloud coverage across our imagery. Cloud coverage must be handled in processing because clouds obstructed areas along the shoreline of Trinidad and Tobago and made it difficult to delineate the coastline. For Planet and Sentinel-2, cloud masks were available and downloaded concurrently with the NIR bands. For Landsat 8 imagery, cloud masks were generated utilizing Quality Assessment (QA) bands and using the remap tool within ArcGIS Pro. Cloud masks were resampled to the same resolution as the source imagery and assigned no data values where high-confidence clouds and cloud shadows were identified (Figure 4). Second, cloud-masked images were mean-mosaicked spatially, across imagery tiles, and temporally, across months into annual mosaics for the years 2015, 2020, and 2024. Outputs from these steps were aggregated and a cloud-minimized raster image for our study area within the three epochs (where applicable) for each satellite. Third, images were classified to distinguish

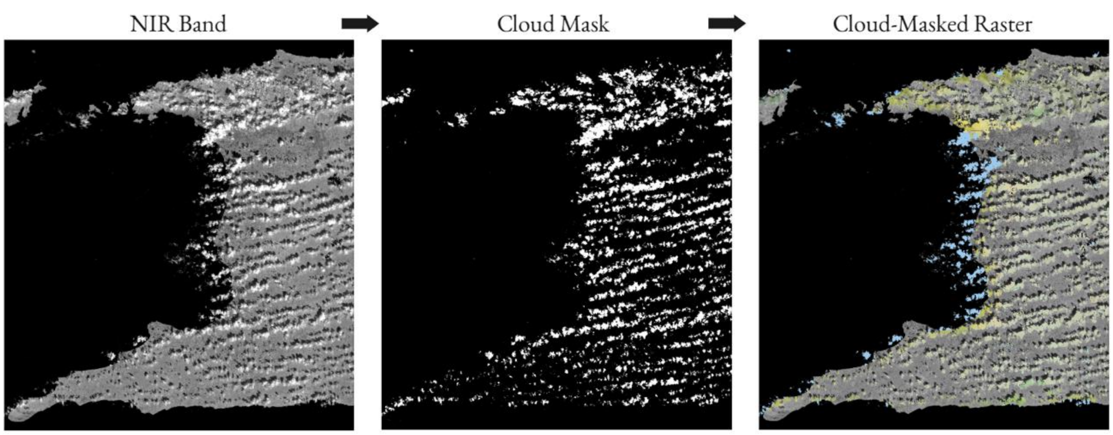

Figure 4. Geoprocessing tools to create a cloud-masked raster in ArcGIS Pro 3.4.0 using the NIR band and the cloud mask. Left: NIR band with water (black) and land (gray). Middle: cloud mask (white = cloud). Right: cloud-masked raster with null values (removed clouds) and preserved NIR reflectance for land (gray) and water (black). Image Credit: ESA Sentinel-2 MSI

between land and water. This process used binary thresholding to assign one of two values (e.g. 2-class Natural Jenks) to each cloud-masked aggregate image. In this classification, water had a value of zero and land had a value of one. To isolate the land values from the sea we clipped by raster value, which resulted in a clean land raster image. We converted the clean land raster image into a polygon and filled remanent gaps with the union tool, followed by the dissolve tool in ArcGIS Pro. This generated a clean polygon boundary of the study area. For each year, clean polygons were converted to a yearly shoreline, represented as an aggregated yearly shoreline for 2015, 2020, and 2024 (Figure 5).

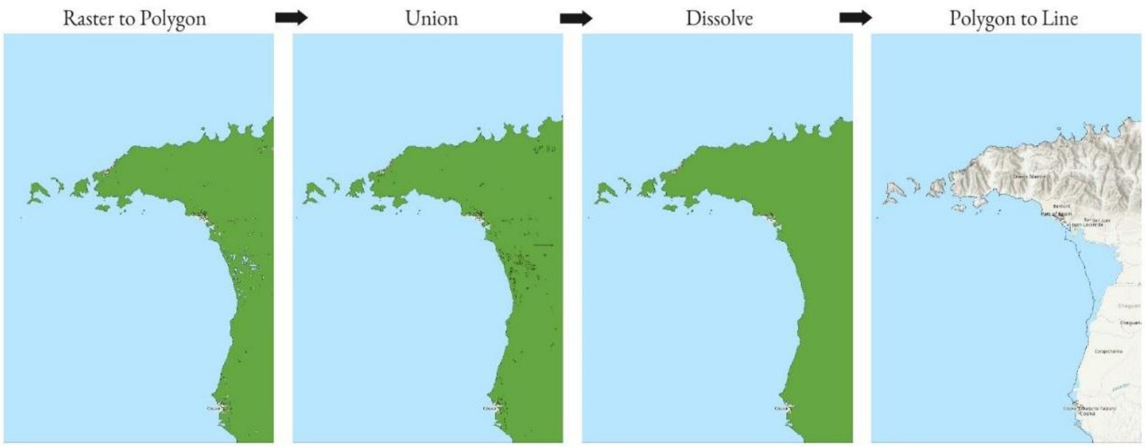

Figure 5. Geoprocessing tools used to create a visualization of shoreline in ArcGIS Pro 3.4.0. The leftmost image is the result of the raster to polygon tool, followed by the union and dissolve tool that results to create the shoreline visualization after transforming polygon to line. Image Credit: Ersi, NASA, NGA, USGS, TomTom, Garmin, FAO, NOAA, USGS, OpenStreetMap contributors, and the GIS User Community.

2.2.3 Altimetry Data Processing

Altimetric data used for this study focused on monitoring sea level rise through sea surface height anomalies, which reflect the difference in current sea surface height from the 30-year averaged mean sea level (Wilis, 2025). Using Jupyter Notebooks, altimetric data was aggregated to plot the temporal aspect of the data and show changes to sea level over time (Appendix 5). Through data processing, the data then became usable in the form of a Network Common Data File (NetCDF), and the files were visualized in Panoply to observe the file contents and structure of the contents in a user-friendly manner. Once we determined that the files were readable, we moved to plot them using Python in Jupyter Notebooks. We created a 2D plot of the Sea Surface Height Anomaly (SSHA) (Figure 6) data over the duration of the study timeframe to best represent the change.

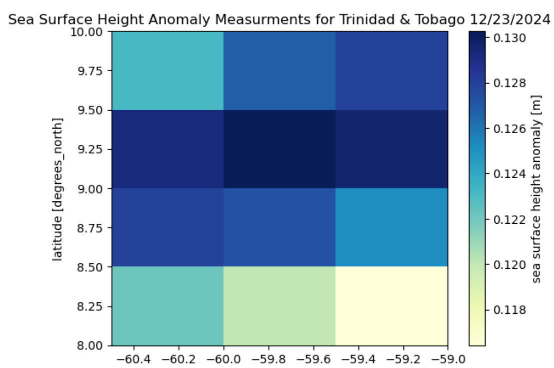

Figure 6: Plotted data of one day of Sea Surface Height Anomaly data over Trinidad and Tobago. Land data is masked in the data, so that only water surface levels are reflected in the data.

2.3 Data Analysis

2.3.1 Changes in Sea Surface Height

To assess the relationship between recorded sea surface height, temporal extent, and area change, linear regressions were conducted to capture the statistical relationship between sea levels over time (Zerbini et al., 2017). To generate each regression, a deseasonalized average rate of sea surface height was calculated for the monthly average and monthly maximum of every year for each tidal gauge where recorded observations were available. In R-Studio, linear regressions were calculated in R using the deseasonalized tidal gauge data. The independent variables of years (Y) and months (M) were compared against the dependent variable of sea surface height (SSH):

$$SSH_i = \beta_0 + \beta_1 Y_i + \beta_2 M_i + e_i \tag{2}$$

Where SSH_i represents the sea surface height of i_{th} observation, Y_i and M_i are year and month, β_0 is the regression intercept, β_1 and β_2 are the coefficients of average change by year and month, and e_i is the error term. Each linear regression was assessed for the yearly and monthly coefficient, statistical significance (p-value), and coefficient of determination (R^2). Projected changes in sea surface height for Trinidad and Tobagowere defined by extending the slope of the line of the 2020 coefficient (β) over a thirty-year period between 2020-2050 for Port of Spain and Scarborough tidal gauges, respectively. The data was then plotted against projected global and regional averages from the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) published in the Global Sea Level Change Sea Level Explorer (National Oceanography Centre, n.d.).

2.3.2 Shoreline delineation

The team calculated the total area (in square kilometers) of delineated land surface polygons for each year from each satellite instrument. To interpret temporal shoreline changes, the team then calculated percent area change over time (PercentAreaChange) to analyze loss of land area as a result of sea level rise.

$$PercentAreaChange_{(y1,\ y2)} = \frac{Area_{y2} - Area_{y1}}{Area_{y1}} * 100 \tag{3}$$

where $y1$ and $y2$ refer to reference years within our study period. Validation efforts, such as confusion matrices or spatial autocorrelation, were considered but not used in this study. Due to a lack of reference data within our study period, the team could not calculate the margin of error that would be used to validate this shoreline model.

2.3.3. Sea Surface Height & Regional Anomalies

The Mean Sea Level (MSL) was calculated from data spanning from 1993 to 2012 (Andersen, 2022) and represented a sea surface height that can be used to observe changes from that baseline, giving PO.DAAC users the resulting Sea Surface Height Anomaly (SSHA) measurements.

3. Results & Discussion

3.1 Analysis of Results

3.1.1 Sea Level Rise

The coefficients for two low-confidence linear regressions for the deseasonalized monthly average maximums from both Port of Spain and Scarborough (Appendix 4) were plotted against the relative rates of sea level change estimated IPCC AR6 model and observations (Figure 7). IPCC AR6 considers different future societal development pathways and corresponding emission scenarios, including very high (Shared Socioeconomic Pathways 5-8.5, i.e., SSP5-8.5), intermediate (SSP2-4.5), and low emissions (SSP1-2.6) (IPCC, 2023). The observations combined tidal gauge and altimetry model (NASA et al., 2024). From this plot, we found that the rate of change derived from deseasonalized monthly maximums matched the relative rate of sea level change from the complex IPCC AR6. These results were low-confidence, meaning the strength of the correlation (r-squared) was below 0.7 and was calculated using limited factors. Linear regressions completed on monthly maximums and monthly averages had much higher rates of change, indicating that deseasonalized trends point to a general rate of change, which may be lower than the true relative rate of change for Trinidad and Tobago. The discrepancies in overall rates of change point to the non-linear nature of sea level change, and the more complex modelling often required to capture this non-linearity (Boon & Mitchell, 2015).

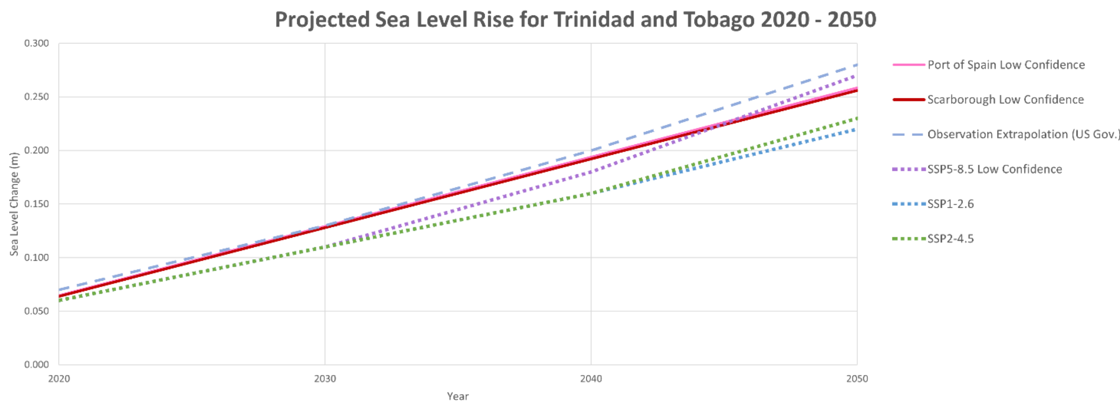

Figure 7. Projected sea level rise from tidal gauge observation extrapolation from Port of Spain in pink (low confidence) and Scarborough in red (low confidence) linear regression.

3.1.2 Shoreline Delineation

The outputs, or shorelines for each sensor, within the study period (2015, 2020, 2024), created a baseline to analyze changes in Trinidad and Tobago's shoreline. Annual area change was calculated by examining the five-year area change for both islands of Trinidad and Tobago (Table 4). Discrepancies existed within the detected shorelines (Figure 8) and created challenges in capturing accurate rates of change to both islands' coasts. Large discrepancies between delineated shorelines from each of the three satellite data sources can be measured by joining shorelines for a given year within a distance threshold of 12-meters, or spatial margin of error (i.e. the largest average geolocation accuracy of the three satellite sensors) (NASA; Copernicus; NASA NTRS). Areas joined within the distance threshold would then be considered successfully mapped using an optical imagery shoreline delineation method. Areas that fall outside the 12-meter margin of error will not be joined and are considered areas in need of further study or alternative treatment. Alternative treatment can include post-processing image verification and manual tracing, as well as additional automated image classification methods (Abdelhady et al., 2022). Segmenting images into case areas or sections in shoreline delineation can potentially facilitate validation methods. Area change, as calculated, indicates an increase in area over time for the polygon areas derived from Landsat 8 and Sentinel-2. However, this increase remains inconclusive and may be due to anomalies generated by residual cloud-cover (Appendix 6) and image processing steps.

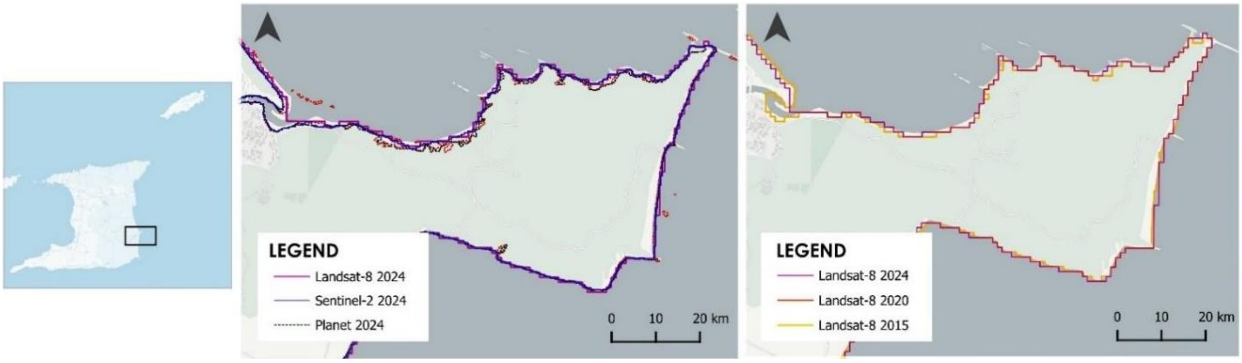

Figure 8. Map depicting variation in shoreline estimation comparing detection across one year between Planet, Sentinel-2, and Landsat 8 in 2024, and across one satellite, Landsat 8, over three epochs within study period.

Table
Estimated Area Change from Shoreline Delineation in Trinidad and Tobago over study period between 2015-2024

Area Change Between 2015-2024						
Year	**2015**	**2015 - 2020**	**2020**	**2020 - 2024**	**2024**	**2015 - 2024**
Landsat 8	4987.277 km²	2.472%	5110.574 km²	0.476%	5134.888 km²	2.960%
Sentinel-2	N/A	N/A	5129.157 km²	0.029%	5130.629 km²	N/A

3.1.3 Altimetry-derived Sea Surface Anomalies and Sea Surface Trends

Sea level rise can be observed as the sea surface height anomalies recorded deviate further from Mean Sea Level (MSL) measured over 1993-2012 (Figure 9). Differences between the months of November and July reflect seasonal patterns, notably river flux during the rainy season from the Orinoco and Amazon to the south of Trinidad and Tobago. Seasonal deviations, however, are not a signal for an overall increase in sea surface height over five-year increments. Rather, the increase in sea surface height is illustrated by an increased coloration from blue to yellow and orange, notably in July, where sea surface heights are highest. The trends observed with the altimetric data, both from the data plotted in Panoply and in Python scripting, support conclusions found by the tidal gauge data that sea levels have risen over time (Appendix 7). Altimetry data allows this conclusion to be drawn from over four decades of data, as opposed to the 10-year study period examined for the tidal gauge data.

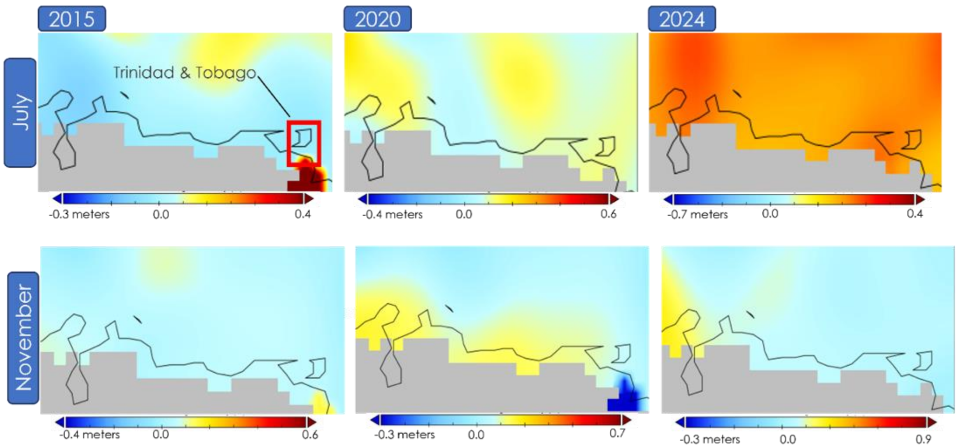

Figure 9. Diagram of simple maps of sea surface height anomalies over three years, taken from similar dates in July and November. Scaling on the graphs is not consistent, but sea level rise can still be observed.

3.1.4 Potential Flood Vulnerability Assessment

A one-meter Digital Elevation Model (DEM) derived from a high-resolution 2014 LiDAR scan of Trinidad and Tobago was utilized to illustrate the potential flood zones created by an estimated 0.25 meters of sea level rise by 2050 (Figure 10). Contour lines between 0.25 and 0.5 meters were classified to illustrate potential flood zones. This map neither represents increased risk for flood from seasonal high tides, nor does it include temporary increases in sea surface levels from storm surge or high river outflows from the nearby Oronoco River and Amazonian River basins. Rather, the map points to the likelihood that the impacts of future sea level rise stand to be unequally distributed across Trinidad and Tobago. Low-lying areas such Caroni Swamp will risk submersion, whereas areas with relatively higher elevations may experience concentrated coastal erosion. Ultimately, the uneven and still-evolving upward trend in sea level rise that has been observed, measured, and visualized over the course of this project signals a continued need for research methods and studies to facilitate continued assessments of coastal change in Trinidad and Tobago.

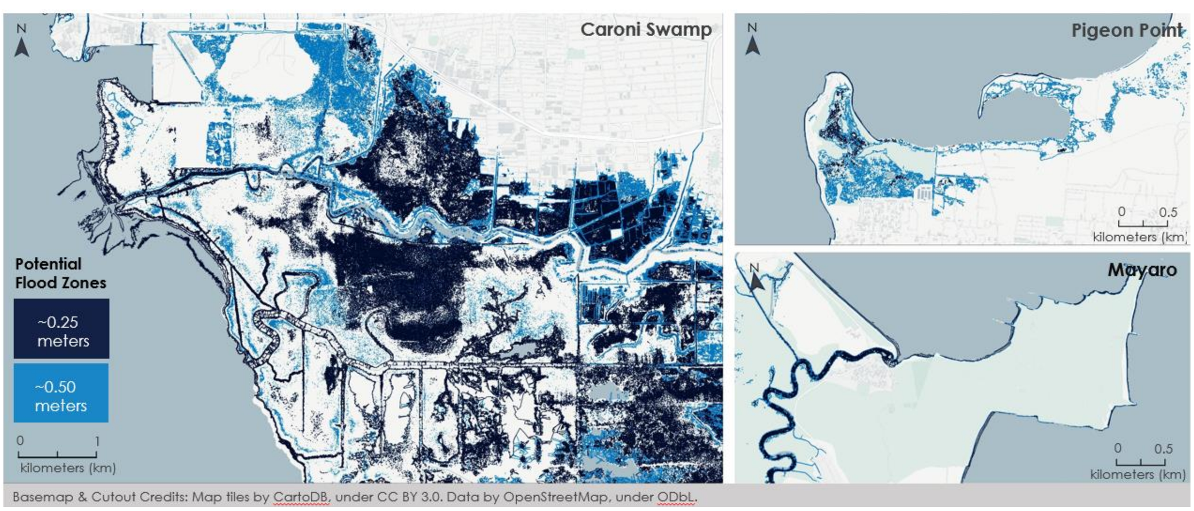

Figure 10. Potential flood zones at Caroni Swamp, Pigeon Point, and Mayaro based on projected sea level rise in 2050

3.2 Errors & Uncertainties

Temporal, seasonal, and geographic variation were central to errors and uncertainties in this study and stand to impact future study replication. The first limitation we encountered was deviation across processing steps for satellite-based optical imagery. These discrepancies between satellites impeded a more systematic or code-driven approach to process the satellite data acquired. Differences across satellite imagery used for shoreline delineation presented two central challenges. The first challenge was related to cloud contamination across our three satellite data sources. Low-lying clouds were, at times, falsely identified as land, and smaller islands were difficult to distinguish from clouds (Appendix 8). Synthetic Aperture Radar (SAR) and LiDAR imagery are promising alternatives to optical imagery, as they are cloud-penetrating data sources that avoid underlying issues with cloud contamination. The second challenge was due to temporal and seasonal variability in the satellite data. This variability embedded differences created by tidal cycles and river outflow into the Gulf of Paria during the rainy seasons. However, harmonized Landsat 8 and Sentinel-2 imagery offer potential opportunities to account for daily variation and seasonality. A preliminary analysis of harmonized imagery suggests that a more accurate shoreline can be derived after processing (Appendix 9).

Furthermore, optical imagery validation was limited within this study. This is due to limited access to reference data within our study period which can be used to calculate a margin of error between predicted and actual detected shoreline and island area, which validation processes, such as confusion matrices or spatial autocorrelation, are dependent upon (Griffth & Chun, 2016). Though the project partners initially provided land surface polygons and delineated shorelines derived from a 2014 LiDAR survey of Trinidad and Tobago, the team ultimately could not consider the datasets as validation data for the project's shoreline outputs. The provided 2014 land surface polygons were generated based on an NDVI-defined vegetation boundary rather than a NIR-defined water/land boundary. Owing to a lack of available 2014 imagery from the utilized satellite instruments, Landsat 8 and Sentinel-2, the team was unable to perform statistical validation of its delineated shorelines and land surface polygons. Nevertheless, the team acknowledges an overestimation of shoreline change was calculated for its outputs due to uncalculated errors and lower resolution of sensors (Sunny et al. 2022).

Gaps in historic tidal gauge data became a major limitation in identifying sea surface height trends and predicted increases in sea levels. The absence of tidal data narrowed the trends which could be observed between different coasts in Trinidad and Tobago. Furthermore, offsets in tidal gauge reference levels may have also impacted the sea level trends in Figure 2 and Figure 3. Methods using satellite radar altimetry data remain a critical avenue to assess gaps in tidal gauge reference levels generated by human error or vertical land motion (Ray et al., 2023) as well as estimate future changes in sea surface height.

Currently, available altimetry datasets include infrared data from ICESat-2 a NASA mission, and SWOT interferometry data from the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO+) program, a joint mission between NASA, French Space Agency (CNES), Canadian Space Agency (CSA), and United Kingdom Space Agency (UKSA). Additional engagement with sea level rise estimations from physics-based modelling (e.g. IPCC AR6 report) for future forecasting remain an important consideration given current climate dysregulation stands to outpace trends established by historic data (NASA, 2016). Combined estimations from historical and model-based estimations remain important to evaluate relative trends in sea level rise, where global models often fail to downscale to make data relevant for small island states like Trinidad and Tobago.

Photon based altimetry data poses limitations primarily in the form of data availability posed by cloud cover and 91-day measurement intervals for the ICESat-2 satellite. To circumnavigate these issues, it is recommended to use radar data, as the radar altimeters can penetrate cloud cover, and offer more temporal coverage. Radar data from the Physical Oceanography Distributed Active Archiving Center (PO.DAAC), using compiled data from ten satellite sources, provides Sea Surface Height (SSH) data which is extremely useful and accessible for altimetry. While easiest to interpret and analyze, the resolution of the data being on a 0.5-degree grid, does pose limitations in what the data is able to show. The timescale of the data from PO.DAAC is also more conducive to comprehensively showing change, as the data is collected every seven days. Software programs such as Panoply make viewing preliminary data files more user-friendly but are limited in aggregating data from more than one file. Once the data is in Python, the coordinate systems need to be adjusted to reflect a full 360-degree coordinate system, which makes the data plottable, and easier to navigate. This adjustment makes it so that the files can be concatenated, and the timeseries data becomes plottable. One key limitation to the progress and workflow of the PO.DAAC data and all associated outputs is time. Altimetry was not defined to be a key goal of this project, but after further consideration and observation of gaps in tide gauge data, we determined that it is possible to generate basic outputs and simple analysis, even in the two weeks we had available to complete this task.

Vulnerability assessments were limited by the scope and time of this project. Representations of potential flooding were limited to downscaled contour lines to capture potential zones of impact. These potential flood zones do not account for hydrodynamic flood models from pluvial deposits or storm surge during extreme weather events. Due to the impacts of coastal erosion and flooding on coastal settlements and ecological zones, future studies may consider integrating vulnerability assessment tools estimating potential loss or economic damages based on measured rates of change to the study area. These vulnerability assessments can consider lost carbon sequestration from sea level rise as well as potential building loss.

3.3 Feasibility & Partner Implementation

Overall, we determined that it is possible to use a mix of public and commercial satellites to analyze and measure different indicators of sea level rise. Both tidal gauge data and altimetry data remain important, albeit partial representation of sea surface changes despite being processed separately. Combined estimations using tidal gauge and altimetry data remain a crucial next step for regular estimations of short-to-medium term rates of sea surface change. Continued comparison against predicted scenarios derived from more complex general climate models should remain a critical resource for policy and a validation baseline for simpler, regression-based models of increased sea surface height. For shoreline delineation, more data products exist that provide integrated imagery from Sentinel and Landsat satellites used in and beyond this study (Appendix 9). The use of these harmonized datasets was found to be unfeasible given the timeframe of the study and remain a viable next step to begin addressing seasonal and tidal variation within the study epochs. Time constraints also lead to concerns of feasibility concerning processing and using altimetry data and commercial datasets. These datasets were investigated as possible sources of additional data but ultimately were found to be unfeasible within the allotted time to complete this study.

Creating replicable methodologies which utilize publicly accessible Earth observation data are important resources for public organizations such as the Institute of Marine Affairs because of existing barriers to private data access and the need for continued monitoring of coastal changes. Advancing methodologies to assess the applicability of publicly accessible Earth observation data for shoreline delineation as well as changes in sea surface height, support critical analyses of sea level rise and its impacts for small island states and territories in the Caribbean. Through the proposed methodology, officials from the IMA will be able to extend their existing Earth observation knowledge to consider future feasibility for public and commercial satellite data use as well as altimetry data for their ongoing research to measure sea level rise and coastal change. This feasibility study can facilitate opportunities for IMA officials to gain more precise and systematic data in the long term to gain more accurate visualizations of Trinidad and Tobago’s shoreline change over time as sea levels rise. Earth observation data, when publicly accessible, remains an important avenue for small island states and territories to have the information necessary to make informed decisions as climate dysregulation continues to impact critically important coastal zones’ ecological stability and human habitation.

4. Conclusions

Through this feasibility study, we found it was practical to use a combined Earth-observation and in-situ observation-based data approach to capture the preliminary effects of sea level rise through tidal gauge observation extrapolation, shoreline delineation, and altimetry-derived mapping, respectively. Tidal gauge data was used to estimate preliminary trends in future sea surface height between 2020 and 2050. Altimetry emerged as an adequate complement to and supplement for gaps in tidal gauge data and reflected the same trends as the tide gauge data – an increase to sea level over the study period. Shoreline delineation is feasible but depends upon sufficient imagery with limited cloud cover and availability of data within the spatial and temporal extent. We are confident that IMA officials can implement and expand upon this methodology in their current and future monitoring efforts.

Opportunities exist within the project methodology to refine the shoreline delineation process by developing automation procedures through publicly accessible neural networks for image classification to capture both regular landscape change and overall area change. Additionally, work to combine tidal gauge and altimetry data to evaluate and predict sea surface height remains a possible avenue to improve upon the current limitations within this project.

Sea level rise remains a complex, non-linear phenomenon impacted by factors which extend beyond the scope of this feasibility study. Therefore, we emphasize the role that publicly accessible Earth observation data can help capture the impacts of sea level rise for decision-makers in Trinidad and Tobago as they address the ongoing impacts of a changing climate. This feasibility study highlights a set of methodologies that can support policy and conservation efforts led by organizations like the Institute of Marine Affairs in Trinidad and Tobago. The proposed method can also be adopted by other marine policy institutes across the Caribbean facing similar data and capacity constraints. Future research should continue to emphasize the purpose of publicly accessible Earth observation data and methodologies to analyze and estimate the impacts of sea level rise for small island communities and coastal communities more broadly.

5. Acknowledgements

The Trinidad and Tobago Climate Team would like to thank Dr. Africa Flores-Anderson (Alabama – Marshall), Dr. Xia Cai (Virginia – Langley), Dr. Brett Buzzanga (California – JPL) and Dr. Robert Griffin (University of Alabama in Huntsville) for their science advising, Diego L. Gil Agudelo (NASA-University of Alabama in Huntsville) and Natalia Bermudez (NASA-University of Alabama Huntsville) for their regional expertise and research recommendations, Project Coordination Fellow Isabel Tate (Alabama – Marshall) and our Center Lead Cristina Vilalobos-Heredia (Alabama – Marshall) for project coordination support, and the Institute of Marine Affairs Geospatial Team including Nikia Gooding, Hamish Asmath, Rayna Sookdeo, Vishal Mohan, Malissa Moses, Julie McVorran, and Anastacia Auguste for their advice, support, and enthusiasm throughout the project term.

This material contains modified Copernicus Sentinel data (2020, 2024), processed by ESA.

This work utilized data made available through the NASA Commercial Smallsat Data Acquisition (CSDA) program.

This material is based upon work supported by NASA through contract 80LARC23FA024.

6. Glossary

ArcGIS Pro 3.4.0 – a desktop geographic information system (GIS) application developed and owned by Esri to analyze and share spatial data.
Cloud masks – an intermediate data product used on satellite images to reduce the impact clouds have on the final product created from satellite data.
Earth observations – a process of gathering information, via satellite or airborne remote sensing platforms, to track, measure, and analyze Earth's surface, water bodies, and atmospheric changes.
Deseasonalization – a statistical technique applied to time series data to remove seasonal effects and provide clearer view of data trends and cyclical patterns
IOC/UNESCO – Intergovernmental Oceanographic Commission of UNESCO provides open-access tidal gauge data through the online Sea Level Station Monitoring Facility platform.
Landsat 8 – satellite launched February 11, 2013, through a collaboration between NASA and the U.S. Geological Survey (USGS) with two science instruments, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS).
Landsat 7 – satellite launched between April 15, 1999, and May 5, 2022, with Enhanced Thematic Mapper Plus (ETM+) to capture global change such as land cover shifts and mapping large areas of land using optical imagery.
Nadir/Off-Nadir – "nadir" refers to a point directly below a satellite, affecting the accuracy and quality of the images or data retrieved by the satellite. Lower Off Nadir angles are preferred for higher resolution satellite data. A higher off nadir angle can introduce greater noise to data and complicated analysis.
Perigean spring tide – the highest tide of the year generated by the gravitational forces
PO.DAAC – NASA's Physical Oceanography Distributed Active Archive Center that provides, creates and maintains data and data products for Earth observation.
QGIS 3.34 LTR – a desktop geographic information system (GIS) application developed and managed as a free, crowd-sourced software to analyze and share spatial data.
Sentinel-2 –Earth observation mission from the ESA's Copernicus Program consisting of three satellites – Sentinel 2-A (launched June 23, 2015), Sentinel 2-B (launched March 7, 2017), and Sentinel 2-C (launched September 5, 2024). All three satellites are equipped with the Multi-Spectral Instrument (MSI).
USGS – The United States Geologic Survey provides access to Earth observation data.
Vertical land motion – a measure of the average long-term rate of change (decades, years) of land surface. This is often the combined effects of subsidence and uplift within a region, often measured in areas with close proximity to subduction zones and other fault lines.

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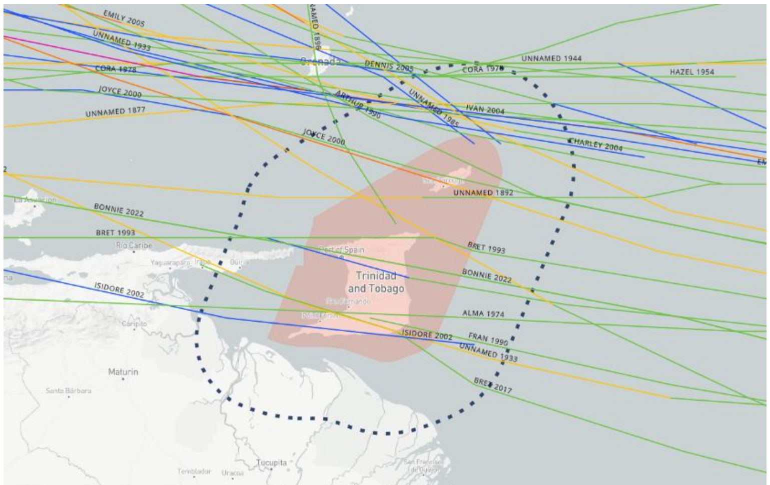
8. Appendix

Appendix 1

Historic Hurricane Paths crossing or near Trinidad and Tobago between 1856-2023. Source: [NOAA Historical Hurricane Tracks.]()



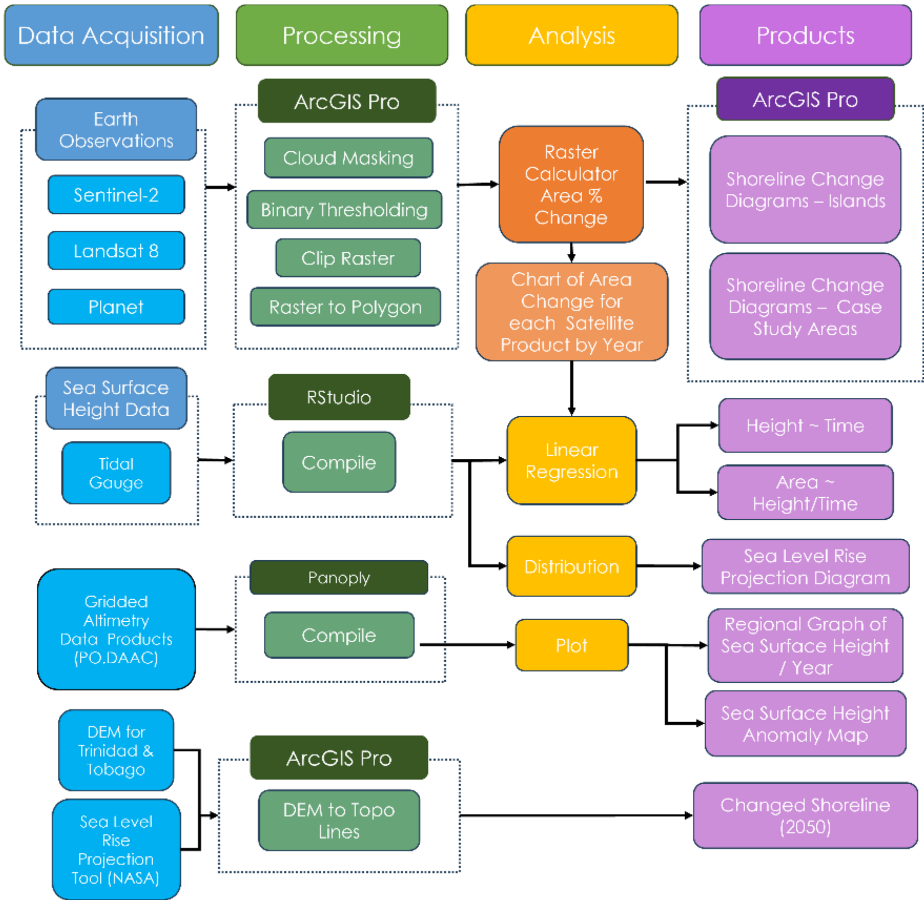
Appendix 2

Catalog of satellite instrument data products assimilated into composite dataset distributed by PO.DAAC

PO.DAAC Satellites	Composite altimetry data set using multiple data products from five satellites (TOPEX/Poseidon - SSLT, NRA, & TMR sensors; JASON-1/Poseidon-2 – Microwave Radiometer; OSTM/Jason-2 – Poseiden-3 and AMR sensors; JASON-3 – Poseidon-3B and AMR-2 sensors; Sentinel-6A – Poseidon-4 Radar Altimeter and AMR-C sensors)

Appendix 3

Methodology Diagram for Shoreline Delineation, Tidal Gauge Extrapolation, Sea Surface Height Anomalies from Satellite Altimetry, and Potential Shoreline Impact Zone Analysis



Appendix 4

Linear Regression Results for Sea Level Rise

Port of Spain – Avg. Maximum Height	Regression: Max Tidal Height	
Data Version	**Monthly Avg./ Year**	**Deseasonalized Avg./Year**
R2	0.7501	0.3658
P-Value	< 2.2e-16	1.497E-10
RSE	0.1634	0.2585
Coef 2020	0.859605766	0.06458

Scarborough – Avg. Maximum Height	**Regression: Max Tidal Height**	
Data Version	**Monthly Avg./ Year**	**Deseasonalized Avg./Year**
R2	0.9903	0.6648
P-Value	< 2.2e-16	5.09E-13
RSE	0.08871	0.522
Coef 2020	-0.27497756	0.06457936

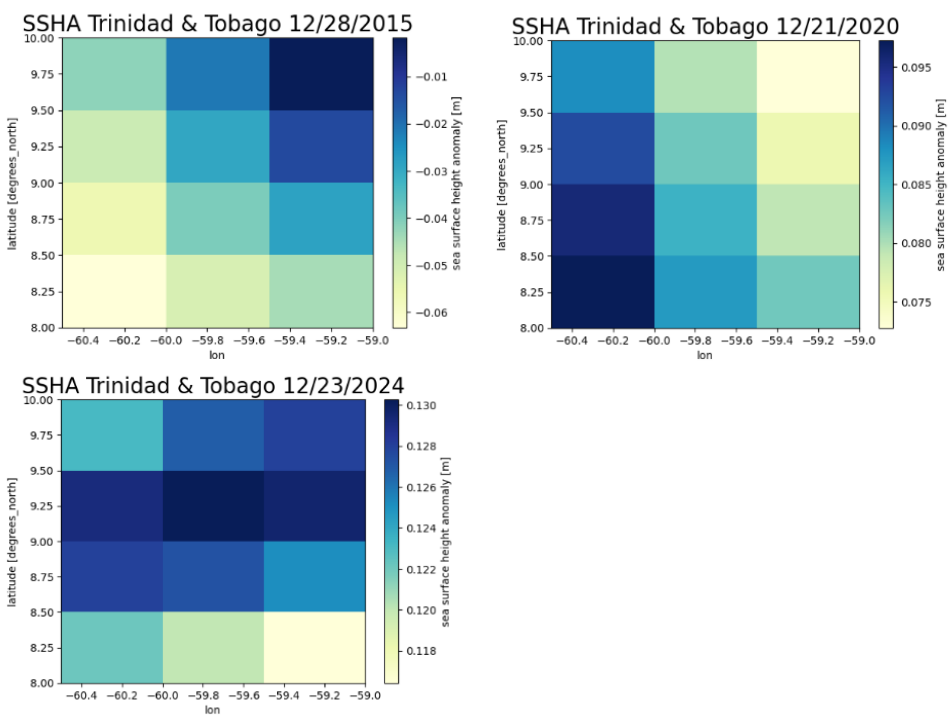
Port of Spain – Avg. Mean Height	**Regression: Mean Tidal Height**

Data Version	Monthly Avg./ Year	Deseasonalized Avg./Year
R2	0.8096	0.83
P-Value	< 2.2e-17	< 2.2e-16
RSE	0.1645	0.1549
Coef 2024	1.02217	1.02217
Coef 2020	0.967015	0.95949

Scarborough – Avg. Mean Height	Regression: Mean Tidal Height	
Data Version	Monthly Avg./ Year	Deseasonalized Avg./Year
R2	0.9961	0.9808
P-Value	< 2.2e-17	< 2.2e-16
RSE	0.05463	0.1205
Coef 2024	n/a	n/a
Coef 2020	-0.0630919	-0.16734

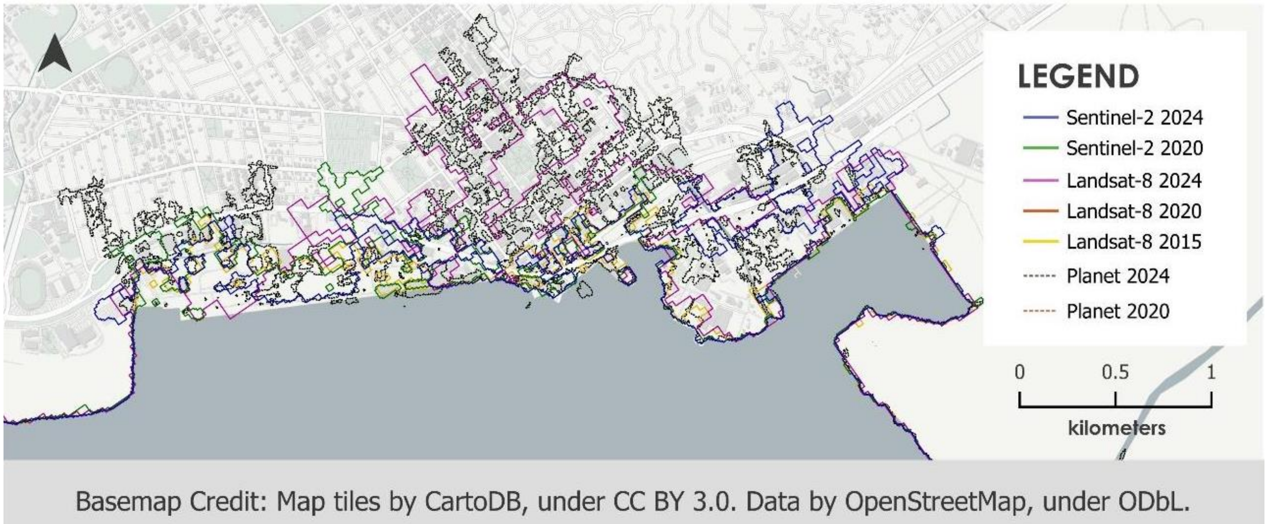
Appendix 5

Simple gridded plots of sea surface height anomaly (SSHA) data for similar dates over three of the study years (2015, 2020, 2024), across the latitude and longitude of Trinidad and Tobago.



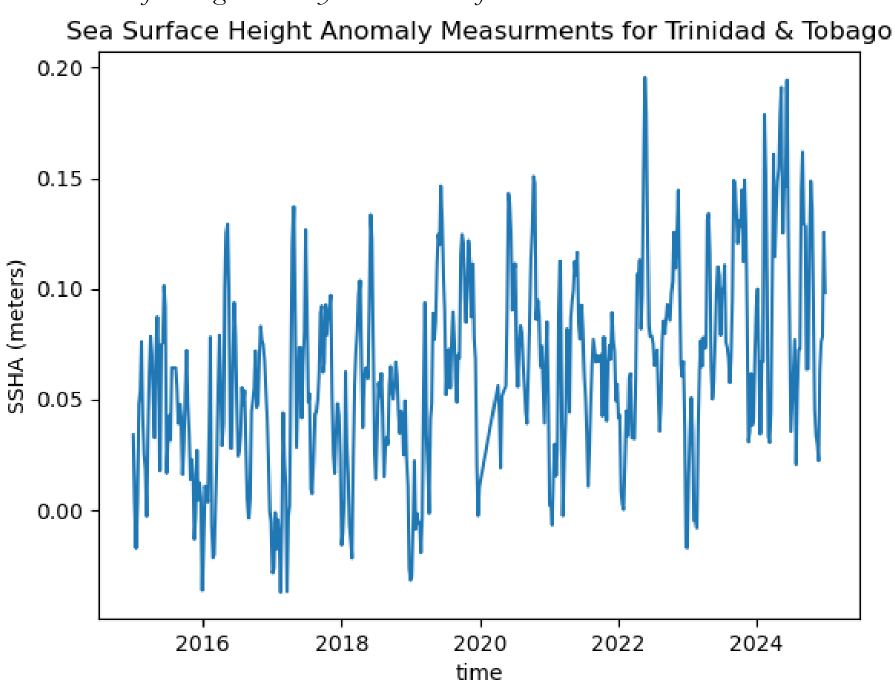
Appendix 6

Map depicting anomalies which emerged within shoreline delineation process, contributing to discrepancies in land area calculations and clear shoreline detection. Includes copyrighted material of Planet Labs PBC. All rights reserved.



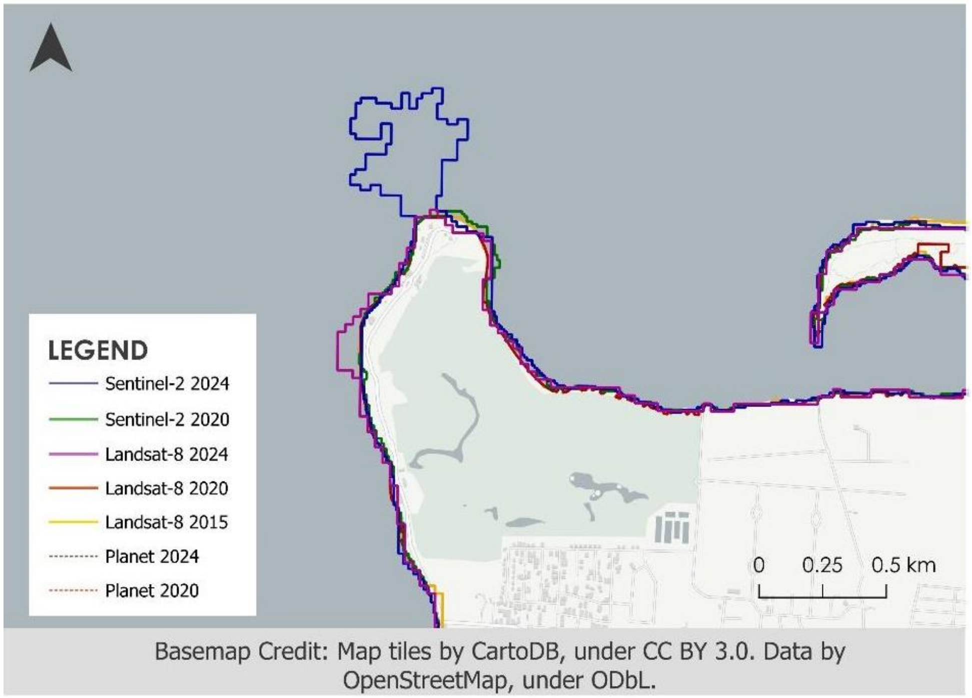
Appendix 7

PO.DAAC radar-based sea surface height anomaly measurements from 2015 to 2024.



Appendix 8

Map shows overlay of different satellite outputs from shoreline delineation. Anomalies appear due to cloud-contamination during image processing steps, which limits the accuracy of shoreline detection. Includes copyrighted material of Planet Labs PBC. All rights reserved.



Appendix 9

Harmonized Landsat and Sentinel-2 can provide more complete shorelines at monthly intervals when combined into a single output.