

# **Augmenting Tide Gauge Data with Satellite Altimetry in the Observation of Sea Level Rise in the Caribbean**

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**Keywords:** Sea Level Rise; Satellite Altimetry; CORS; Tidal Monitoring; Caribbean

## **SUMMARY**

Traditional methods of Sea Level Rise (SLR) determination in the Caribbean have been plagued with problems of currency and availability of data to establish reliable regional models. Since most of the operational tide gauges used are in the northern Caribbean and the southern Florida coastline, the studies were focused on areas in the northern Caribbean, creating a gap in the data for the southern Caribbean island states. There also existed a potential problem of data reliability in that data from the tide gauges were not necessarily reduced to any level previously established from sea level observations.

This paper examines presents a review of the state of SLR determination in the Caribbean and outlines satellite altimetry as an alternative method of sea level observation, where sea level change based on satellite altimetry is measured with respect to the Earth's centre of mass, and thus is not distorted by land motions. This, along with a network of GPS monitor stations and tide gauges and incorporating the creation of localised geoidal models for the sites are proposed as a methods to bridge the current data gap to develop regional SLR models with respect to a geocentric reference frame.

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## 1.0 INTRODUCTION

From the cinematic portrayal of climate shifts and global flooding to the reality of the devastation of storm surges and tsunamis, sea level rise is an area that has universally captured public, political and scientific interest and imagination. Changes in the sea level relative to landmasses result from the combination of climatic effects as well as vertical land movements through subsidence or uplift. An examination of key climatic indicators, such as increases in global average air and ocean temperatures, the melting of snow and ice and rising global average sea levels suggest that warming of the climate is taking place. Increased sea levels, for example, due to the thermal expansion of upper layers of the ocean and subsequent melting of glaciers and ice sheets are consistent with global temperature increase. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report of 2007, for the period 1993 to 2003, the contributions from thermal expansion is  $1.6 \pm 0.5 \text{ mm yr}^{-1}$  and the loss of mass from glaciers, ice caps and the Greenland and Antarctic Ice Sheets together give  $2.8 \pm 0.7 \text{ mm yr}^{-1}$ .

For small island states, a sea level rise (SLR) worst case scenarios would result in significant loss of land space and utilization. For Caribbean territories, a substantial percentage of the population live and work within coastal regions, and almost without exception, international airports, roads and capital cities in the small islands of the Caribbean are sited along the coast. A recent study calculated that a 1 meter rise in the Caribbean would submerge 98 coastal communities in Cuba, threatening more than 50,000 persons (Taylor 2003). The importance of properly determining the existence and the extent of sea level rise in order to discern potential threats that may arise as a result cannot be overstated in the Caribbean context.

Traditional methods of SLR determination for the region have been plagued with problems of currency and availability and reliability of data to establish reliable regional models. This paper offers a brief review of the current state of SLR monitoring mechanisms in the Caribbean, and proposes alternative methods of sea level observations through the use of satellite altimetry, along with a network of continuous (CORS) GPS monitor stations and tide gauges. Incorporating localised geoidal models along with these techniques is suggests as a key strategy in bridging the current data gap to develop regional SLR models with respect to a geocentric reference frame.

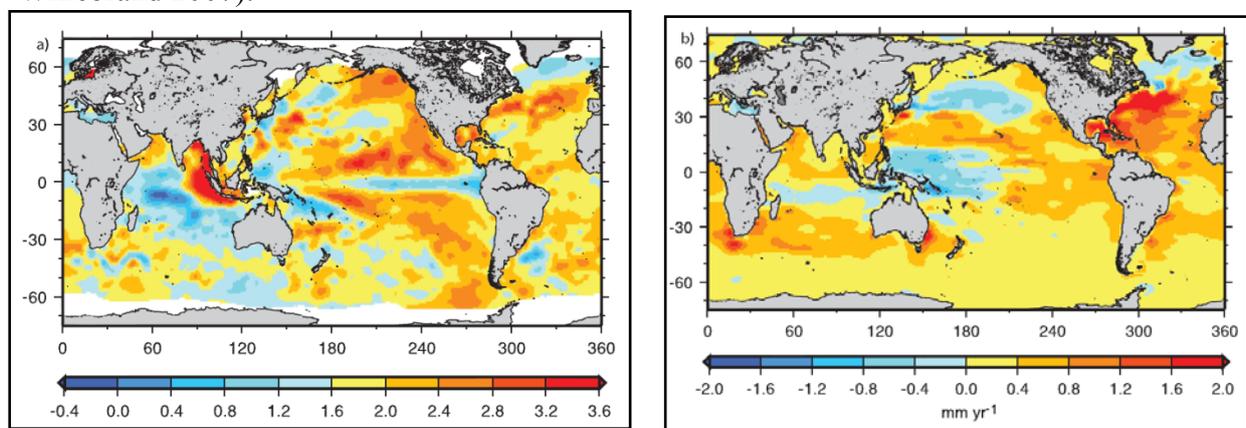
## 2.0 SEA LEVEL RISE – CURRENT GLOBAL TRENDS

In the twentieth century, global sea level rose by 10-20 centimetres, averaging  $1.7 \pm 0.3 \text{ mm yr}^{-1}$  with an acceleration of  $0.013 \pm 0.006 \text{ mm yr}^{-2}$ ; this rate is expected to accelerate over the next century (Church and White 2006). According to the IPCC, the sea level will rise

9-88 centimetres in the next 100 years, with a mid-estimate rise of 50 centimetres. This translates into 5 millimetres per year, which is two to four times faster than during the twentieth century (Taylor 2003).

The rise in global mean sea level is accompanied by considerable decadal variability. For the period 1993 to 2003, the rate of sea level rise is estimated from observations with satellite altimetry as  $3.1 \pm 0.7 \text{ mm yr}^{-1}$ , significantly higher than the average rate of 1.7mm. Tide gauge records indicate that similar large increases in rates have occurred in previous 10-year periods since 1950. There is therefore an uncertainty whether the higher rate in 1993 to 2003 is due to decadal variability or an increase in long term trend (IPCC 2007).

In agreement with the climate models, satellite data and hydrographic observations confirm that sea level is not rising uniformly around the world. In some regions, rates are up to several times the global mean rise, as shown in Figure 1. This creates the need to determine localised models to evaluate the existence and extent of sea level rise, hence negating the possible application of a global model for any particular region (Bindoff and Willebrand 2007).



**Figure 1 (a) The geographic distribution of sea level rise trends using tide gauges and satellite altimetry and (b). thermal expansion from 1955 to 2003 (from Bindoff and Willebrand 2007).**

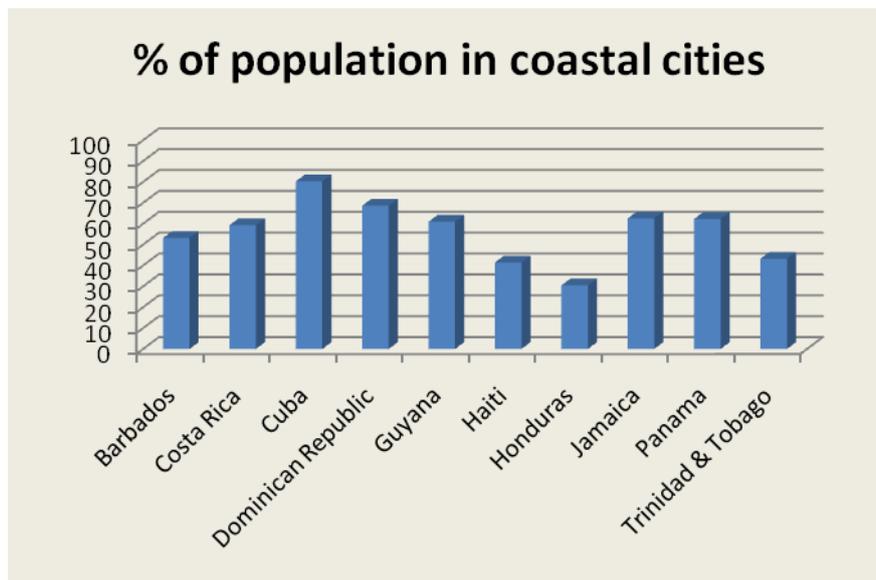
Global sea level rise is of major international interest, impacting on millions of lives within the coastal zone; however, small island states are amongst the regions that are most at risk from the impacts of climate change and sea level rise. While the long term threat is inundation, the more immediate hazards are those associated with storm surges, flooding, coastal erosion, saltwater intrusion into freshwater supplies and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of island communities (Taylor 2003).

### 3.0 SEA LEVEL RISE IN THE CARIBBEAN

The nations and territories of the Caribbean all share a common resource, their regional seas, which, together with the adjacent land areas, comprise the wider Caribbean region. On the region's eastern perimeter is the insular Caribbean, together with the Gulf Coast states of the United States, coastal Mexico, Central America and the northern tier states

of South America complete the terrestrial perimeter which encloses the region's two major basins, the Gulf of Mexico and the Caribbean Sea (UNEP 1996).

Miller (2008) places the population in the region living within 2 km of the coastal zone is more than 50% and is increasing, along with the size and densities of coastal cities. Almost without exception the capital cities of the Caribbean islands are situated on the coast, and throughout the entire region coastal areas are identified with principal industrial complexes, trade centres and tourist resorts (Miller et al. 2008). In addition to the socio-economic factors, the geography of many states, which may vary from heavy forest to volcanic and semi-mountainous regions, creates challenges for development inland. From UNEP census data for the year 2000, a random selection of ten territories consisting of Caribbean islands and Central and South American countries gives an average percentage of population living in coastal regions to be approximately 56% as shown in Figure 2.



**Figure 2. The percentage of population living in coastal cities for 10 randomly selected territories in the Caribbean**

A comparatively small sea level rise would greatly impact on the homes and livelihoods of many inhabitants as well as on the infrastructure. Most island and sea bordering states depend heavily on the tourist industry for income and the relevant developments that have taken place to facilitate this industry are built in close proximity to the coastal zone. Other major sources of income for a large fraction of the population such as fishing, agriculture, and much of the plant and machinery associated with installations to process minerals take place in coastal areas with the infrastructure that exists by way of habitats and factories being constructed just above sea level (Miller et al. 2008).

Sea level rise “worst case scenario” of 1 metre over the next 100 years has been compiled for Caribbean islands like Antigua and Nevis by Synthesis and Upscaling of Sea-Level Rise Vulnerability Assessment Studies (SURVAS), where such a rise would result in a loss of 940 hectares and 340 hectares, respectively, leading to a reduction in island size.

Another study calculated that a 1 meter rise in the Caribbean would submerge 98 coastal communities in Cuba, threatening the lives of more than 50,000 persons (Taylor 2003). The need for effective sea level monitoring is therefore critical.

Over the past 20 years, some 70 sea level gauge stations have been installed in the Caribbean and surrounding countries by Caribbean Planning for Adaptation to Global Climate Change (CPACC), RONMAC (Water Level Observation Network for Latin America), NOAA and other locally and internationally-funded programs. However, only 44 of these stations have been identified as functioning (Von Hillebrandt-Andrade 2009). Henson (2006) observes that most stations were in various states of disrepair, the majority of which no longer collected data, and in many cases, installations were missing equipment (Henson, 2006). Some equipment in Trinidad for example was vandalised within three months of installation and required repairs. In addition, there are currently tide gauges with just a few years of data, and results in estimates of sea level change with low precision, making some derived results statistically insignificant (Miller et al. 2008).

The distribution of monitoring stations in the region is also an issue since most of the operational gauges are present in the northern Caribbean and the southern Florida coastline, the studies were focused on areas in the northern Caribbean, creating a gap in the data for the southern Caribbean island states. Of the 44 identified operational tide gauges, 23 can be found in 4 northern territories, USVI, Puerto Rico, Cuba and Bahamas.

Data reliability was also a problem, where data from the tide gauges were rarely continuous and not necessarily reduced to any level previously established from sea level observations. Often it was established before sea level readings were taken, and was never subsequently amended. Completeness of sea level records is also flawed by faulty equipment, so data are rarely continuous and as a result changes in datum occur. Smith and Small (1999) concluded, during their work in determining the CARIB97 geoid that there are errors in the local tidal heights on the island of Grand Bahama as well as other inadequacies with respect to tidal heights in the Caribbean (Miller et al. 2008).

An analysis of these studies shows that the only location where records of suitable length for both sea level and GPS existed to provide a good estimate of absolute sea level change is St. Croix in the U.S. Virgin Islands. Many observations are poorly sampled in space and time, and regional distributions are often quite heterogeneous, with records extending over a small period of time. Also, the primary function of the instrumentation that was deployed was to measure sea level in ports for navigational and hydrographic surveying purposes; it was never designed for scientific use.

Due to data gaps stemming from insufficient and inconsistent data, faulty equipment and flawed data sets, a full analysis of the region's extent of sea level change could not have been made from these studies. Conclusions based on previous studies using tide gauges as the source of data for sea level rise, indicate that further studies using this method would require the implementation of a new network, which will serve to provide complete monitory coverage of the Caribbean. Ideally, this will include the installation of operational tide gauges, along with a Continuous Global Positioning System (CGPS) to monitor the earth's crustal movements for vertical land movement. There is a definite need for more rigorous, accurate and sustainable monitoring systems to be put in place in order to fully assess sea level rise in the Caribbean.

## 4.0 METHODS OF SEA LEVEL RISE DETERMINATION

Currently, there are two major methods that are used for the determination and monitoring of sea level rise – *tide gauge monitoring and satellite altimetry*. Coastal tide gauges have provided the main technique by which sea level variation has been measured in the past century. However, during the past decade, satellite altimetry has been utilised to monitor sea level changes worldwide, in particular TOPEX/Poseidon and Jason satellites, with global coverage, high spatio-temporal resolution, and direct tie to Earth's center of mass (Cabanes et al. 2001)

### 4.1 Tide Gauges

Tide gauges have historically been used to monitor sea level rise. This method involves the use of tide gauges placed at points along a coast and provides eustatic variations relative to the land on which they lie. In order to extract the signal of sea level change due to ocean water volume and other oceanographic change, land motions need to be removed from the tide gauge measurement (Vilibić 1997).

Vertical land movements such as those resulting from tectonics, subsidence and sedimentation influence local sea level measurements but do not alter ocean water volume; nevertheless, they affect global mean sea level through their alteration of the shape and hence the volume of the ocean basins containing the water (Bindoff and Willebrand 2007).

Published values for global mean sea level rise determined from tide gauge records reveal significant scatter, ranging from 1 mm to 3 mm/yr. However, this disparity is not attributable to instrument error since long-term trends computed at adjacent sites are often to within a few tenths of a millimetre per year. Instead, the differing estimates of global sea level rise appear to be due to data from gauges located at convergent tectonic plate boundaries, where changes of land elevation give fictitious sea level trends (Douglas 1991).

For a tide gauge record to be used to establish the climate related component of changes in sea level, it is therefore necessary to correct for the vertical land movement component of the observed change in sea level. However, there are many issues to be considered when trying to monitor vertical land movement at a degree of millimetres per year, in order to decouple these from the true sea level variations in tide gauge records. All of these issues effectively relate to the accuracy and precision of the vertical station velocity estimates (Teferle et al. 2006).

In some parts of the world, vertical land deformations can be corrected for the effects of Glacial Isostatic Adjustment, however, it is not the only geological process leading to vertical land movement. Global averages of tide gauge data, after the application of corrections for the effects of post glacial rebound on individual station records, reveal an increase in sea level over the last 80 years of between 1.1 and 1.9 mm yr<sup>-1</sup> at an average of 4 mm yr<sup>-1</sup> (Holgate and Woodworth 2004). Conclusively, the method of tide gauge measurements is considered to be a relatively direct, though spatially sparse, measurement of the sea surface height (Mitchum 1998).

### 4.2 Satellite Altimetry

Tide gauges measure sea level relative to the ocean floor whereas the reference for satellite altimetry is geocentric, that is to the earth's centre (Clark et al. 2002). Satellite

altimetry is an established technology for studying open oceans, and one of the existing challenges is to extend its use to near coastal applications (Vignudelli et al. 2005).

A satellite altimeter uses pulse-limited radar to measure the altitude of the satellite above the closest point of the sea surface. Global precise tracking coupled with orbit dynamic calculations provide an independent measurement of the height of the satellite above the ellipsoid. The difference between these two measurements is equal to the height of the sea surface minus any delays in the propagation of the radar echo due to the ionospheric and tropospheric interference (Yale et al. 1998).

At present, Jason the successor to the TOPEX/Poseidon satellite altimeter mission, has revolutionized the study of sea level, by making available near global coverage from 66° North to 66° South, almost all of the ice-free ocean, from 1992 to the present. The current accuracy of satellite altimetry data allows global average sea level to be estimated to a precision of  $1.67 \pm 0.08$  cm at a 10 day temporal resolution, with the absolute accuracy limited by systematic errors (Leuliette et al. 2004).

In contrast to the sparse network of coastal and mid-ocean island tide gauges, measurements of sea level from space by satellite radar altimetry provide near global and homogenous coverage of the world's oceans, thus allowing the determination of regional sea level change (Church and Gregory 2001). Though the results must be corrected for glacial isostatic adjustment, satellite altimetry avoids other vertical land movements that affect local determinations of sea level trends measured by tide gauges (Peltier 1998).

Attaining the required sub-millimetre accuracy for sea level rise monitoring, is exigent and requires satellite orbit information, geophysical and environmental corrections and altimeter range measurements of the highest accuracy. It also requires continuous satellite operations over many years and careful control of biases (Church and Gregory 2001). Accurate positions of the satellite are also necessary, to facilitate this, the satellite carries three tracking systems that enable its position in space to be determined with an accuracy of  $\pm 3.5$  cm (Tapley et al. 1994).

High precision satellite altimetry requires high quality gravity fields to estimate the perturbations in the satellite's orbits caused by the spatial changes in the gravity field. As a result, the changes in mass and hence, gravity caused by movement of the oceans by tides need to be included in the gravity models to obtain the best possible altimeter orbits. The TOPEX/Poseidon and Jason-1 satellites have an orbital height of approximately 1340 kilometres, since the high altitude assists with orbit determination because the gravity field is a bit smoother at this altitude as well as the presence less atmospheric drag on the satellite at this height (White 2008). Another critical element to altimetric measures of sea level variation is the accuracy and drift of atmospheric path delay due to water vapour as derived from on-board satellite microwave radiometers (Edwards et al. 2004).

Recent estimates of global average sea level rise established from the six years of TOPEX/Poseidon data incorporating corrections from tide gauge comparisons show  $2.1 \pm 1.2$  mm/yr (Nerem et al. 1997),  $1.4 \pm 0.2$  mm/yr (Cazenave et al. 1998) and  $2.8 \pm 0.2$  mm/yr (Leuliette et al. 2004).

Ultimately, satellite geodesy will aid in resolving the inherent ambiguity between the land and ocean level changes recorded by tide gauges (Gornitz 1995).

## 5.0 STRATEGIES FOR CARIBBEAN SEA LEVEL MONITORING

SLR monitoring activities in the regions need to go beyond the installation of equipment. The ideal system employed for effective and reliable sea level monitoring in the Caribbean should satisfy several key characteristics to appropriately address the data, technical, institutional and socio-economic deficiencies in the current monitoring techniques.

*The system should be truly regional* – allowing for an effective distribution of observed data points throughout the Caribbean to eliminate problems of and potential regional models being skewed towards an island or specific territory.

*The system should be current* – providing near real time data allowing for both up to date and historical data evaluation for trend analysis and to support forecasting.

*The system should be sustainable* – free from the socio-economic, institutional and political influences of specific territories. Monitoring activities should be independent from political bias and agendas, the economic and technical ability of the country to support data collection, analysis and dissemination. It should also be ‘tamper’ free i.e. free from vandalism or breaking down without the system operators being aware.

*The system should be continuous* – reliable long-term strategies need to be adopted to effectively show long-term trends. Tide gauge data for example needs to be collected for a minimum of 18.6 years to fully account for the influence of the moon’s orbit. The ability to capture and analyse data for any time period would offer significant advantages over single epoch based measurement.

*The system should provide the link to monitor land movement* – the system should have the ability to incorporate vertical land movement in the assessment of sea levels.

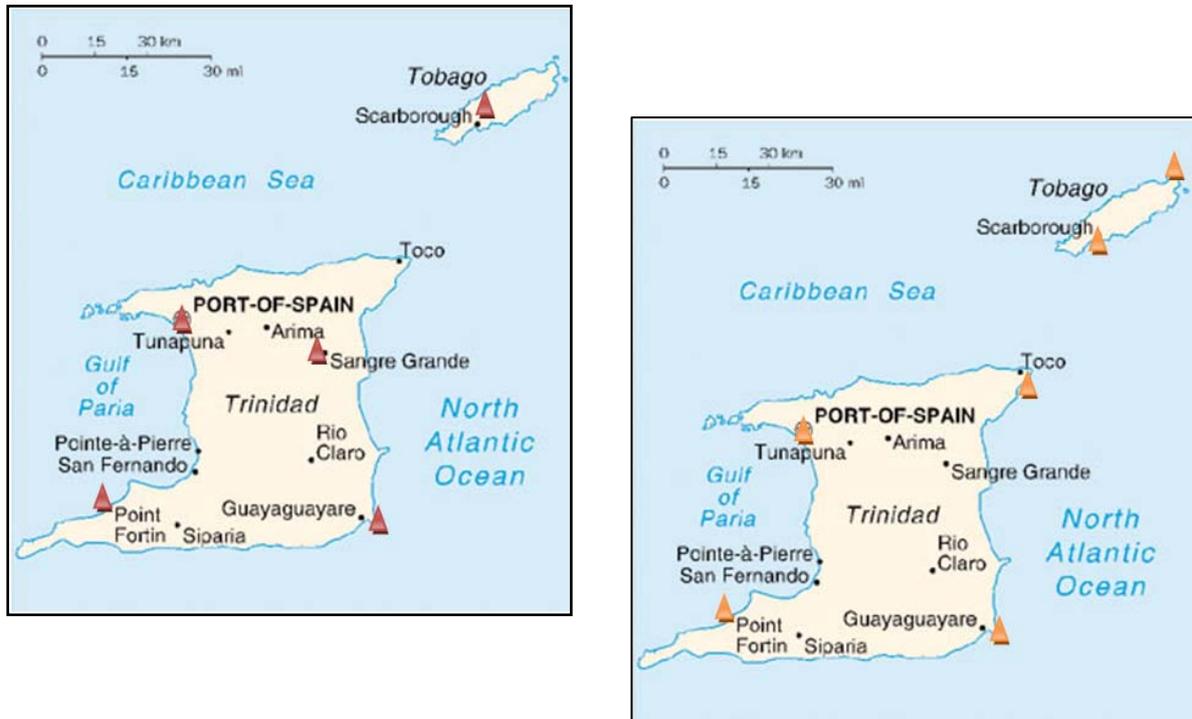
*The system should have added value* – the system should lean towards building capacity within the region, strengthening the technological base, intellectual and institutional capacity of the region. It should also have the ability to generate other data products and create opportunities for additional uses and applications, such as early warning systems.

*The system should be globally interoperable* – the system should have the ability to integrate into global monitoring systems

The current strategy proposed involves the integration of tide gauge and satellite altimetry data with continuous GPS measured CORS points, starting in the islands of Trinidad and Tobago as an initial test site.

Dong et al. (2002) outline a strategy for the calibration of TOPEX/Poseidon altimetry data using GPS and tide gauge stations and precise local geoid differences in the UK to determine altimeter biases. This technique required collocated tide gauge and GPS points to meet the fundamental data requirements to allow for the application of the altimetry data. Teferle et al (2006) make use of continuous GPS monitoring stations and tide gauge data to evaluate vertical land movement. A key element in these investigations is the proximity of the CORS GPS stations to the tide gauges to be easily accessible.

Adopting similar strategies for Caribbean application would meet many of the desired system characteristics. Satellite Altimetry data can provide regional coverage with current and historical data sets. The use of satellite data virtually eliminates the need for ongoing maintenance, minimising the institutional requirements as data can be obtained any time via



the internet. The incorporation of CORS measurements provides the avenue for vertical land monitoring

**Figure 3 The location of the CORS network stations (left) and tide gauges (right) in Trinidad & Tobago**

Trinidad & Tobago is being used because it currently provides many or the ideal measurement parameters. Figure 3 shows the active CORS network that consists of four stations in Trinidad and one in Tobago. The stations are located in Port of Spain (ALBION), Point Fortin (FORTIN), Sangre Grande (GRANDE), Point Galeota (GALEOTA), and CALDER in Tobago. The network has been in operation since 2006, providing continuous GPS data at these sites. There are also six operational tide gauges around the coastline of Trinidad and Tobago, each of which have integrated GPS antennas, barometric pressure, temperature, humidity, wind and rainfall sensors. The gauges located in Port of Spain, Point Fortin, Point Galeota, and Scarborough, Tobago are located within close proximity to the CORS network stations, creating an ideal geographic configuration for determining vertical land motion at the tide gauge sites, in order to discern mean sea level changes void of VLM. These points will be used to calibrate Jason-1 altimetry data and to evaluate any VLM components.

## 6.0 CONCLUSION

Concern over the global impacts of change in sea level is of topical interest internationally, however small island states, like those in the Caribbean are amongst the regions that are most at risk from the impacts of climate change and sea level rise, largely because of their environmental and economic dependence on coastal zones. As such studies have been conducted in an attempt to investigate and monitor sea level rise in the Caribbean.

Unfortunately, the studies were incomplete and deficient owing to limitations in the tide gauge data reliability and a lack of data coverage for the Caribbean region. For the region to be able to fully monitor and assess sea level trends, it will not be sufficient to deploy a CORS network and tide gauges.

The proposed method of the use of satellite altimetry data to determine sea surface heights will seek to fill the existing voids and resolve the sparse and unreliable network of existing island tide gauges. To accomplish this, Trinidad and Tobago will be used as a test area, where the existing tide gauges and CORS data will be used to determine the altimeter bias, in order to calibrate the satellite data for the determination of sea level rise. This test area will verify the viability of the methodology for the execution in the Caribbean region. Upon the success of the proposed methodology, it will provide for a full and adequate assessment of sea level change in the Caribbean region.

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