ISSN 0511-5728
The West Indian Journal of Engineering
Vol.35, No.1, July 2012, pp.66-72

Evaluating Satellite Altimetry for Monitoring Caribbean Sea Level Rise

Sandesh Jaggan[a] and Dexter Davis[bΨ]

Department of Geomatics Engineering and Land Management, Faculty of Engineering, The University of the West Indies, St. Augustine Campus, Trinidad and Tobago, West Indies
[a]E-mail: sand_jagg@hotmail.com
[b]E-mail: Dexter.Davis@sta.uwi.edu

Ψ *Corresponding Author*

(Received 30 June 2011; Revised 28 December 2011; Accepted 25 January 2012)

Abstract: *The global impacts of sea level change is of major interest internationally, especially for small island states, like those in the Caribbean which are amongst the regions that are most at risk from the effects of climate change and sea level rise. This is largely due to their environmental and economic dependence on coastal zones. Previous studies have been conducted in an attempt to investigate and monitor sea level rise in the Caribbean. Unfortunately, these studies were incomplete and deficient owing to limitations in the tide gauge data reliability and a lack of data coverage for the Caribbean region. This paper evaluates the method of satellite altimetry data to determine sea level change in the Caribbean region through a comparative analysis to eight tide gauge stations over a ten-year period. The sea level anomalies derived from the satellite altimetry technique agree with the tide gauge data with a mean RMS (Root Mean Square) of 0.058 m. The sea level change rates are on average ± 0.45 mm/yr within the tide gauge results, confirming the viability of satellite altimetry as a technique to determine sea level variations for the Caribbean region.*

Keywords: *Satellite Altimetry; Sea Level Rise; Caribbean Tide Gauges*

1. Introduction

The investigation of variations in sea levels spans many fields of research including oceanography, geology, climatology, geodesy, coastal engineering and the socio-economics of coastal zones. Sea level data find many practical applications such as in flood and storm surge warning and navigation, thus capturing public, political and scientific interest internationally. An examination of key climatic indicators, including increases in global average air and ocean temperatures, the melting of snow and ice and rising global average sea levels suggests that warming of the climate is taking place. In the twentieth century, global sea level rose by an estimated 10-20 centimetres, averaging 1.7 ± 0.3 mm yr^{-1} at an acceleration of 0.013 ± 0.006 mm yr^{-2}; this rate is expected to accelerate over the next century (Church and White, 2006).

The rise in global mean sea level can vary both regionally and with regard to time. There can be 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 ± 0.7 mm yr^{-1}, significantly higher than the average rate of 1.7mm for the previous century. Tide gauge records indicate that similar large increases in rates have occurred in previous 10-year periods since 1950. Therefore, there exists an uncertainty whether the higher rate in 1993 to 2003 is due to decadal variability or an increase in long term trend (Parry et al., 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. This creates the need for the ongoing determination of 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 et al., 2007).

This article reviews the current technique for monitoring sea level changes in the Caribbean using tide gauges, highlighting deficiencies of this system. An examination of the technique of satellite altimetry to determine sea level anomalies is presented. An analytical comparison between altimetric and tide gauge derived sea level anomalies and sea level change rates is provided, to assess the applicability of satellite altimetry to monitor sea level variation in the Caribbean region.

2. 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).

A 2008 study placed the population in the Caribbean region living within 2 km of the coastal zone as 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 inland development. 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 1.

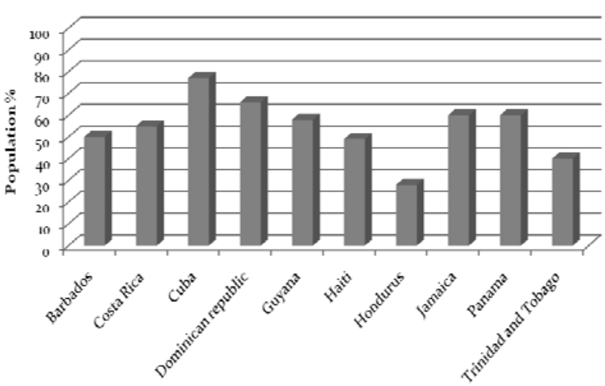

Figure 1. Percentage of population living in coastal cities for 10 randomly selected territories in the Caribbean
Source: Based on Davis et al. (2010)

A relatively small rise in the sea level would greatly impact the homes and livelihoods of many inhabitants as well as 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. Large sections of the Caribbean also depend on other major economic activities as sources of income such as fishing, agriculture, and much of the plant and machinery associated with installations to process minerals which 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).

A sea level rise "worst case scenario" of 1 metre over the next 100 years has been compiled for Caribbean islands by Synthesis and Upscaling of Sea-Level Rise Vulnerability Assessment Studies (SURVAS), where such a rise would result in a loss of 940 hectares in Antigua and 340 hectares in Nevis, 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.

3. Tide Gauge Observations of Sea Level in the Caribbean

Tide gauges have historically been used to monitor sea level rise. This method involves placing tide gauges at points along a coast to provide 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).

Tectonic land movement is defined as that part of the vertical displacement of the crust that is of non-glacio-hydro-isostatic origin (Church et al., 2001). 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 et al., 2007).

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). Figure 2 depicts the results of a 2005 study that showed 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, 2005). Some equipment in Trinidad for example were 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 spatial 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 therefore 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 (Davis et al., 2010).

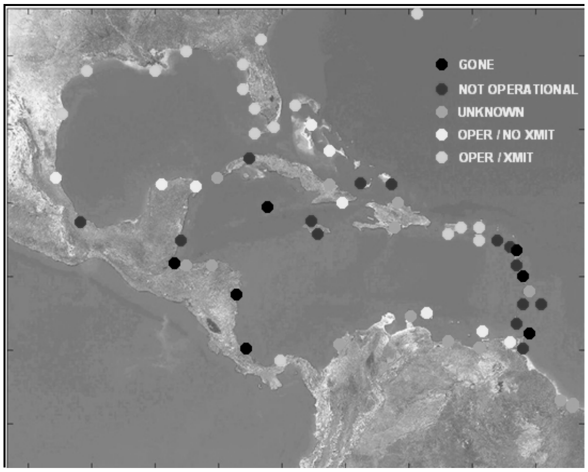

Figure 2. Distribution of Tide Gauges in the Caribbean region
Source: Based on Henson (2005)

Data reliability is also a concern, where data from the tide gauges are 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 (Miller et al., 2008). It was concluded that during the determination of 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 (Smith and Small, 1999).

An analysis of previous studies for the Caribbean 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 were 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 instrumentations that were deployed was to measure sea level in ports for navigational and hydrographic surveying purposes; it was never intended for scientific investigations.

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 sole source of data for sea level rise, indicate that further investigations 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 necessitate 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 (Davis et al., 2010).

4. Sea Level Rise Using Satellite Altimetry

Satellite altimetry has become an established technology in measuring sea level, and in contrast to the sparse network of coastal tide gauges, measurements of sea level from space by satellite altimetry provide near global and homogenous coverage of the world's oceans. Altimetry, as shown in Figure 3, uses pulse-limited radar to measure the altitude of the satellite above the closest point of the sea surface, H and global precise tracking coupled with orbit dynamic calculations to determine the height of the satellite above the ellipsoid, R. The difference between these two measurements results in the height of the sea surface, h given as

$$h = H - R \qquad \text{....Eq.(1)}$$

However, accurate estimates of R and H are not sufficient for oceanographic applications of altimeter range measurements. The sea surface height, h relative to the reference ellipsoid is the superposition of a number of geophysical effects. In addition to the dynamic effects of geostrophic ocean currents that are of primary interest for oceanographic applications, h is affected by undulations of the geoid, h_g about the ellipsoidal approximation, tidal height variations, h_r and the ocean surface response to atmospheric pressure loading, h_a. These effects on the sea-surface height must be modelled and removed from h in order to investigate the effects of geostrophic currents on the sea surface height field (Chelton et al., 2001). The dynamic sea-surface height is thus estimated as

$$h_d = h - h_g - h_r - h_a \qquad \text{....Eq.(2)}$$

Hence, the sea level is given as

$$h = H - \acute{R} + \Sigma \Delta R_j - h_g - h_r - h_a \qquad \text{....Eq.(3)}$$

Attaining the required sub-millimetre accuracy for sea level rise monitoring is challenging 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 (Chelton et al., 2001).

Since its launch in 1992, the TOPEX/Poseidon satellite altimeter mission has revolutionized the study of sea level, by making available near global coverage from latitudes 66° North to 66° South, almost all of the ice-free ocean. The current accuracy of satellite altimetry data allows global average sea level to be estimated to a precision of 1.67 ± 0.08 cm at a 10 day temporal resolution, with the absolute accuracy limited by systematic errors (Leuliette et al., 2004). Each 10 day estimate of global mean sea level has an accuracy of approximately 5 mm. Numerous papers on the TOPEX/Poseidon altimeter results show the current rate of sea level rise at 3.1 ± 0.7 mm yr^{-1} over 1993 to 2003 (Cazenave and Nerem, 2004).

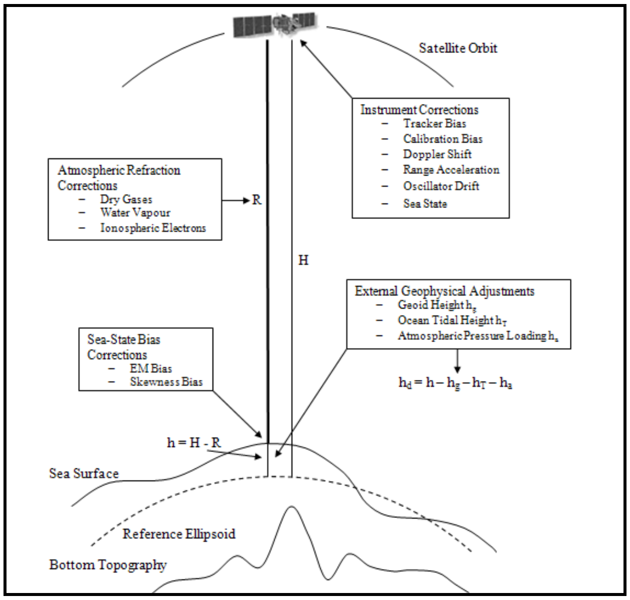

Figure 3. Relationship between the range, satellite orbit and sea surface

The altimetry data used in this study are the JASON-1/2 GDR (Geophysical Data Records) delayed time along-track altimetric measurements averaged over 1 second distributed by AVISO (2011) for the period spanning 2001 to 2010. The details concerning the pre-processing of the data are outlined in the JASON Handbook (OSTM/Jason-2, 2009). The procedure makes use of the following corrections:

Corrected Range
= Range + Wet Troposphere Correction
+ Dry Troposphere Correction
+ Ionosphere Correction
+ Sea State Bias Correction ....*Eq(4)*

Sea Surface Height
= Altitude – Corrected Range ....*Eq(5)*

Sea Level Anomaly
= Sea Surface Height – Mean Sea Surface
– Solid Earth Tide Height
– Geocentric Ocean Tide Height
– Pole Tide Height
– Inverted barometer Height Correction
– HF Fluctuations of the Sea Surface Topography
....*Eq(6)*

Through the application of the corrections identified in Equations (4), (5) and (6), sea level anomalies for the time series were determined.

5. Altimetric Bias Correction

In order to fully exploit the altimetric sea surface heights for the purpose of evaluating possible acceleration in the rate of sea level change, it was necessary to address the issue of the stability of the altimetric series. Though possible error sources are evident, inclusive of the troposphere delay correction, the electromagnetic bias correction and instrument corrections, an analysis of the altimeter data by itself is insufficient to allow an unambiguous determination of the drift error. Only by employing independent data can the long-term reliability of the measurements be established.

Estimating the altimetric drift errors involved an approach that combines altimetric sea surface heights with sea levels measured by tide gauges. Establishing the altimeter bias is ultimately based on monitoring time series of differences between sea levels at one or more tide gauges and the corresponding sea surface heights (SSH) observations from the altimeter (Mitchum, 1998). Studies by Bonnefond et al. (2003) and Dong et al. (2002) in the United Kingdom were successful in using an indirect method to determine altimeter bias and that approach was adopted in this study. In this case, SSH is estimated at a coastal tide gauge site which is subsequently transferred or extrapolated offshore using precise regional geoid models. This method utilises the following relationship to determine the altimeter bias.

$$Bias_{ALT.} = [SSH_{T.G.} - SSH_{ALT.}] - [Geoid_{T.G.} - Geoid_{ALT.}] \quad \text{..... Eq(7)}$$

where $SSH_{T.G.}$ is the sea level determined from coastal tide gauges, $SSH_{ALT.}$ is the altimeter derived sea level estimate in the same geocentric reference frame and $Geoid_{T.G}$ and $Geoid_{ALT.}$ are the geoidal heights at the tide gauge and the satellite altimeter observation point respectively.

This study used six in-situ independent tide gauges, along with collocated G.P.S. data in the Caribbean and the EGM2008 geoidal model to determine the altimeter bias for both the JASON-1 and JASON-2 altimeters. Using an extrapolation procedure on the derived biases, matching grids were created for the EGM2008 geoidal model and the altimetry data. The variations in sea level observed by altimetry were then combined with the altimeter drift biases to resolve the sea levels in the Caribbean.

By applying a linear regression model to the time series at each observation point, sea level rise rates were determined. This resulted in a gridded dataset of SLR values for the Caribbean region.

6. Comparison of Sea Levels

Eight tide gauges from the region were selected and compared to altimetric data based on the availability of data for the period 2001 to 2010 (see Figure 4). Data reliability was also a criterion in the selection process. The tide gauge anomalies are monthly mean values referenced to Mean Sea Level, obtained from NOAA Tides and Currents archive for the period 2001 to 2010 (NOAA, 2011).

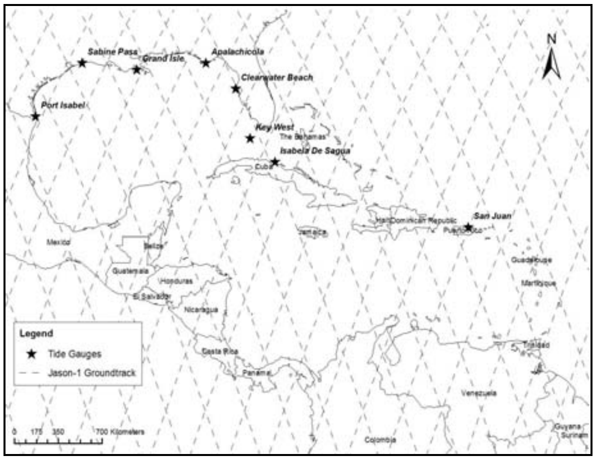

Figure 4. Jason satellite groundtrack in relation to the selected tide gauges

The altimetric data gives on the spot sea level anomaly values at a temporal resolution of 10 days. In order to match the time series of the tide gauge data, the observed sea level anomalies were averaged for each month during the period 2001 to 2010. The satellite data neighbouring each tide gauge station were interpolated using the Kriging interpolation method to obtain an anomaly closest to that tide gauge observation station. The resulting anomalies were plotted against the tide gauge sea levels and 3 of the 8 stations are shown in Figures 5, 6 and 7. These 3 sites were selected since they represent the maximum (Port Isabel), minimum (San Juan) and mean (Apalachicola) variations between the tide gauge and altimetry data.

A close agreement can be observed in the curves of each of these figures both the satellite altimetry and the tide gauge sea level anomalies trends. A quantitative comparison of the anomalies gives differences between the techniques ranging from 0.0001m to a maximum of 0.3210 m, as shown in Table 1. The highest variations were observed at the Port Isabel station with a mean difference of 0.0737 m (see Figure 4). The San Juan station in Puerto Rico showed the smallest differences, with a maximum of 0.0667m and an average of 0.0206m.

The plots show that the highest differences mainly occur at spikes in the amplitude of the sea level trend. The variations in the amplitudes may be due to the adjustment of the altimetric data to match the time series of the tide gauge. Satellite altimetry measures the sea level instantaneously every 10 days. Consequently only 4 to 5 observations of sea level anomalies were used to determine the average sea level for each month. In contrast, the tide gauges record continuous sea level anomalies at a period of six minutes, resulting in a much denser dataset for the determination of each monthly average.

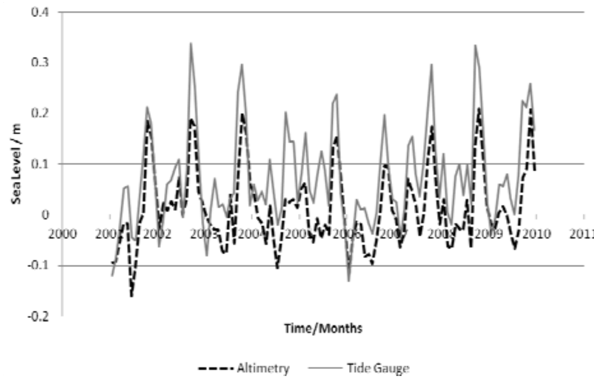

Figure 5. Sea level anomalies averaged over a month for Port Isabel, 2001-2010

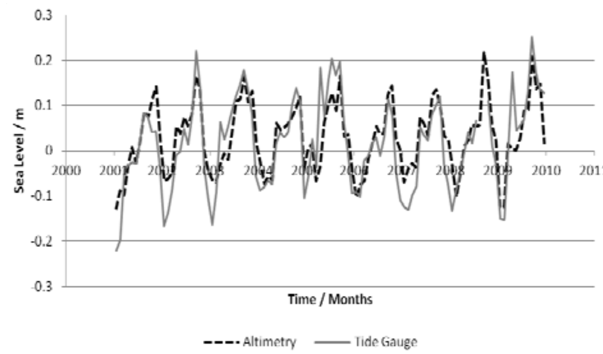

Figure 6. Sea level anomalies averaged over a month for Apalachicola, 2001-2010

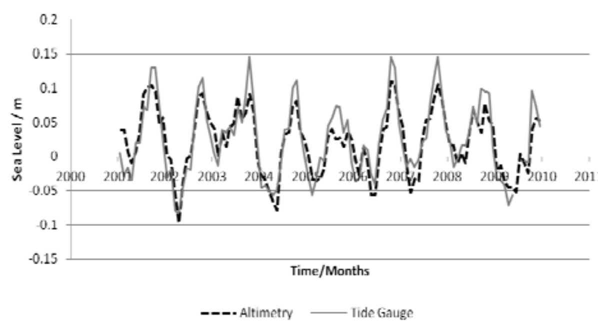

Figure 7. Sea level anomalies averaged over a month for San Juan, 2001-2010

The results of the linear regression done on the sea level anomalies resulting in sea level change rates at each station are shown in Table 2. The difference between the tide gauge and satellite altimetry determined rates ranges from 0.02 mm/yr to 0.90 mm/yr, indicating a close agreement between the altimetry and tide gauge data based on the ten year data period. A comparative analysis of 1 year of tide gauge and altimetry data for 2010 at a station in the southern Caribbean at Port of

Spain, Trinidad reveals a difference of only 0.52 mm between the techniques.

Table 1. Variations between altimetry and tide gauge sea level anomalies

Station Location	Max (m)	Min (m)	Mean (m)	RMS (m)
Sabine Pass, Texas	0.3210	0.0011	0.0203	0.0718
Port Isabel, Texas	0.2020	0.0017	0.0737	0.0782
Apalachicola, Florida	0.2188	0.0004	0.0160	0.0567
Clearwater Beach, Florida	0.1711	0.0010	0.0280	0.0568
Key West, Florida	0.1492	0.0008	0.0243	0.0548
Grand Isle, Louisiana	0.1497	0.0001	0.0088	0.0542
Isabela De Sagua, Cuba	0.1701	0.0002	0.0731	0.0724
San Juan, Puerto Rico	0.0667	0.0003	0.0206	0.0249

Table 2. Comparison of sea level change rates for tide gauge and altimetry

Station Location	Sea Level Change Rates (mm yr^{-1})		Differences (mm yr^{-1})
	Tide Gauge	Satellite Altimetry	
Sabine Pass, Texas	4.58	3.87	0.71
Port Isabel, Texas	7.14	7.80	0.66
Apalachicola, Florida	3.55	4.45	0.90
Clearwater Beach, Florida	7.88	7.86	0.02
Key West, Florida	6.09	6.34	0.25
Grand Isle, Louisiana	3.27	3.18	0.09
Isabela De Sagua, Cuba	0.97	0.85	0.12
San Juan, Puerto Rico	-1.92	-1.07	0.85

One of the reasons for the variations between the techniques is due to the disparity in location between the altimetric and tide gauge observations. Some tide gauges were spatially distant from the satellite ground track. Thus, an interpolation procedure was used to determine an altimetric based sea level anomaly value nearest to the tide gauge station in order to compare the techniques. This resulted in degraded altimetric derived sea level anomaly values.

The tide gauges are situated at sheltered coastal locations and influenced by localised conditions. Satellite altimetry however, makes measurements in the open sea and as such requires the application of various different corrections. Hence, atmospheric pressure, winds, currents and tidal effects influence the coastal and offshore environments differently, resulting in variations in sea level observations between the techniques.

7. Conclusion

Results show that variations between the method of satellite altimetry and tide gauges do exist, however satellite altimetry sea level anomalies are shown to agree with a mean of 3.31 cm at the eight comparison points. The sea level change rates presented are on average ± 0.45 mm/yr within the tide gauge derived rates. The tide gauge data used in this study were not corrected for vertical land motions, and could have had an impacting factor on the resulting discrepancies between the two techniques. These results presented support satellite altimetry as a technique to determine sea level change in the Caribbean, and will serve to fill the existing voids and resolve the sparse and unreliable network of existing island tide gauges.

While the results quantify sea level change in the Caribbean, there is scope for improvement in the accuracy of the method and areas of further research. The altimetric sea level change presented was determined solely based on Jason-1 and Jason-2 data for a 10-year period; however such a small time scale is insufficient to understand the complexities of sea level change. Future studies will be needed to improve and strengthen the methodology by integrating multiple simultaneous satellite altimetric data as well as investigations into the temporal and spatial variability accompanied by sea level change.

References:

AVISO (2011), *Distributes satellite altimetry data*, available at: http://www.aviso.oceanobs.com/ [Accessed: 24 March 2011]

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and Unnikrishnan, A. (2007), "Observations: Oceanic climate change and sea level", in Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.385-479

Bonnefond, P., Exertier, P., Laurain, O., Ménard, Y., Orsoni, A., Jan, G. and Jeansou, E. (2003), "Absolute calibration of Jason-1 and TOPEX/Poseidon Altimeters in Corsica", *Marine Geodesy* (Special Issue: Jason-1 Calibration/Validation), Vol.26, Nos.3/4, pp.261-284

Cazenave, A., and Nerem, R.S. (2004), "Present-day sea level change: Observations and causes", *Reviews of Geophysics*, Vol. 42, RG3001.

Chelton, D.B., Ries, J.C., Haines, B.J., Fu, L.L. and Callahan, P.S. (2001)(ed), "Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications", *International Geophysics*, Vol.69, pp.1-131

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D. and Woodworth, P.L. (2001), "Changes in sea level", in Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P., Dai, X., Maskell, K. and Johnson, C.I. (eds.), *Climate Change 2001: The Scientific Basis, Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp.639–694

Church, J.A., and White, N.J. (2006), "A 20th Century acceleration in global sea-level rise", *Geophysical Research Letters*, Vol. 33, L01602

Davis, D., Sutherland, M. and Jaggan, S. (2010), "Augmenting tide gauge data with satellite altimetry in the observation of sea level rise in the Caribbean", *Proceedings of the FIG Congress 2010, Facing the Challenges – Building the Capacity*, Sydney, Australia, April http://www/fig.net/pub/fig2010/papers/fs04i/fs04i_sutherland_davis_et_al_4614.pdf [Accessed: 10 June 2011]

Dong, X., Woodworth, P., Moore, P. and Bingley, R. (2002), "Absolute calibration of the TOPEX/POSEIDON altimeters using UK tide gauges, GPS, and precise, local geoid differences", *Marine Geodesy*, Vol., 25, No.3, pp.189-204

Henson, J. (2005), "Status report on tide gauges and observing stations in the Caribbean and adjacent waters", Presented to *The GLOSS IX Meeting*, Paris, France, February 24-25

Leuliette, E.W., Nerem, R.S. and Mitchum, G.T. (2004), "Calibration of TOPEX/Poseidon and Jason Altimeter Data to construct a continuous record of mean sea level change", *Marine Geodesy*, Vol. 27, Nos.1/2, pp.79-94

Miller, K., Sutherland, M. and Dare, P. (2008), "Monitoring sea level change in the Caribbean", *Geomatica*, Vol.62, No.4, pp.428-436

Mitchum, G.T. (1998), "Monitoring the stability of satellite altimeters with tide gauges", *Journal of Atmospheric and Oceanic Technology*, Vol.15, pp.721-730

NOAA (2011), *National Oceanic and Atmospheric Administration Tides and Currents*, available at: http://tidesandcurrents.noaa.gov/ [Accessed: 3 February 2011]

OSTM/Jason-2 (2009), *The Ocean Surface Topography Mission/Jason-2 Products Handbook*, in Reference, CNES: SALP-MU-M-OP-15815-CN.

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (2007)(Eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC/Cambridge University Press, Cambridge, UK, 976 pp.

Smith, A and Small, H. J. (1999), "The CARIB97 high resolution geoid height model for the Caribbean Sea", *Journal of Geodesy*, Vol.73, No.1, pp.1-9

Taylor, D. (2003), "Small islands threatened by sea level rise", *Vital Signs*, Vol. 84 pp.40-102

UNEP (1996), *Guidelines Integrated Planning and Management of Coastal and Marine Areas in the Wider Caribbean Region*, United Nations Environment Programme/Caribbean Environment Programme, Kingston, Jamaica, pp. iii-145

Vilibić, I. (1997), "Global sea level rise? New techniques of measuring the absolute sea level", *Geofizika*, Vol. 14, pp. 119-131

von Hillebrandt-Andrade, C. (2009), "Update on sea level network developments of the intergovernmental coordination group for the tsunami and other coastal hazards for the Caribbean and adjacent regions", available at: http://www.gloss-sealevel.org/publications/regional_reports.html [Accessed: 10 June 2011]

Authors' Biographical Notes:

Sandesh Jaggan *is a researcher in the fields of geodesy and geodetic surveying within the Department of Geomatics Engineering and Land Management. He is currently investigating the applications of Satellite Altimetry for Sea Level Rise monitoring in the Caribbean region.*

Dexter Davis *is a Lecturer in Geodesy and GNSS within the Department of Geomatics Engineering and Land Management. Some of his current areas of research include the applications of Satellite Altimetry for Sea Level Rise monitoring, the use of GNSS continuously operating reference stations (CORS) for seismic investigations and developing seamless vertical separation models for coastal zones within the Caribbean.*

■