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An Investigation into Sea Level Rise in Sri Lankan Waters with Satellite Altimetry

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ABSTRACT

Most of the socio-economic activities of Sri Lanka are centred in the coastal regions, which can be described according to its unique geographical and geophysical backgrounds. It is estimated that Sri Lanka has a shore line about 1,700 km in length. Therefore, better knowledge and understanding of the characteristics of sea level is very essential. The sea level has traditionally been measured mainly at tide gauges set up along the coast line. However, the number of tide gauge stations is few and sparse in most countries. But, with the advancements of satellite altimetry technology, it is now accepted as an alternative technique to study regional and global sea level changes. The basic concept in altimetry is the range measurements to the water surface measured from the altimeter antenna. The surface of the sea, or sea level, is continuously changing for many reasons. Here, some changes are fast whereas others occur gradually. Among them, some factors are natural causes, while others occur due to man-made activities such as the greenhouse effect. These changes can be regional or extend at a global scale. The main aim of this research was to examine the trends in sea level rise around the Sri Lankan coastline using two decades of satellite altimetry data from 1993 to 2012. The computed sea level rise trends around Sri Lanka is around 2.5 to 3 mm per year, with a variance of ± 0.6 mm accuracy. The obtained trend of sea level rise from the altimetry data was validated with tide gauge data in Colombo, and found to be highly correlated, with a correlation coefficient (R^2) of 0.93 for annual mean sea level. This study confirms that satellite altimetry can be successfully used to investigate the long term sea level trend studies, particularly in the absence of long term tide data.

1 Background

Sea level monitoring is important for various environmental and socio-economic reasons, especially due to the fact that a larger portion of the world's population is living in the coastal regions. The sea level has conventionally been measured at tidal stations. Yet, these stations are few and sparse in most parts of the region. However, with the increased accuracy of altimetry measurements, this data provides an alternative technique to study the global and regional sea level changes (Cipollini and Snaith, 2015; eSurge, 2014).

Basically, satellite altimeter provides satellite altitude where the principal objective is to measure the range from the satellite to the sea surface. These measurements can be used to derive the sea surface heights with respect to the

referenced altimeter ellipsoid, which is usually the World Geodetic System 1984 (WGS84). Satellite altimeter is a space observing technique for monitoring the oceans. For example, in TOPEX/Poseidon system, it measured sea level along the same path every 10 days using a dual frequency altimeter and single frequency solid-state altimeter. This information collected along the tracks is used to derive changes in ocean surface as well as atmospheric and climate patterns. Observations from the satellite altimeters during the past four decades have provided dramatic results of sea level variability with a higher spatial resolution than tide gauges. Deformation of the ocean basins or land uplift/subsidence also contributes to relative sea level variations. Another important parameter is the melting of glaciers and the thermal expansion/contraction of oceans due to global warming. During the past five decades, a number of satellite altimeter missions were launched, and the list of some of the recent altimeter missions are given in Fig. 1. Further, Fig. 2 shows the TOPEX altimetric tracks around Sri Lanka.

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Fig. 1: List of Satellite Altimeter Missions. Source: (Vignudelli et al., 2019)

Fig. 2: TOPEX/Poseidon Sampling tracks around Sri Lanka (Source: Google Earth)

Since Sri Lanka is an island, a good knowledge and understanding of sea level behaviour in the region is very important. There are several aspects that causes the sea level to vary from time to time, i.e. local processes, ocean circulation changes, global and regional climate changes, and geological processes, and so on (Hettiarachchi and Samarawickrama, 2012). Long term sea level variation is also considered as one of the critical indicator of global climate changes (Chelton et al., 2001; Solomon et al., 2007). However, what is more significant is whether the sea level is rising around Sri Lanka, and if so, will it rise fast enough to pose a risk to the Sri Lankan coastal community?

Previous studies conducted in various regions have confirmed that the sea level has risen during the 20th century, and is still rising at a global scale of about 3.2 mm/year (Unnikrishnan et al., 2015). According to these researchers, the main driving factor here is the phenomenon of global warming. There will be numerous impacts to coastal environment in the future due to the sea level rise, such as beach erosion, inundation of coastal land, increase of flood and storm damage, increase of salinity in the coastal aquifers, and losses to the coastal ecosystem (Weerakkody, 1997; Wijeratne, 2007). Therefore, a correct

measure of changes in the sea level is important in coastal zone management (Titus and Anderson, 2009).

Conventionally, tide gauges are used to measure and study the sea level variations. However, in Sri Lanka, there is only one tidal station (Colombo) having significantly long and continuous data. As a substitute to overcome this problem, it is proposed to use the Sea Surface Height measurements (SSH) derived from the satellite altimetry. This has been successfully used as a complementary tool to the tide gauges in various regions, and has yielded good results in monitoring the sea level changes (Church and White, 2006; Fu and Cazenave, 2001; Naeije et al., 2008). However, altimetry data also has some considerable uncertainties due to undulation of geoid, tidal height variation and ocean surface response to atmospheric pressure loading, and so on. These geophysical effects must be modelled and omitted from the measured sea level height to derive the actual sea level. In addition to that, range estimation errors such as instrumental errors, refraction due to atmosphere, and the interaction between the radar pulse and the air-sea interlace, must be removed to obtain a better value of range measurements (Benveniste and Picot, 2011; Cipollini and Snaith, 2015; eSurge, 2014).

Nidheesh et al. (2013) have analysed sea level variations from 1966 to 2007 in the Indo-Pacific region using an ocean general circulation model forced by wind. There, they compared tide gauge data with satellite altimetric data, and their results confirmed an approximate of 5 cm long-term variation in the sea level in the region. In 2015, Unnikrishnan et al., studied the trends in sea level rise from 1993 to 2012 in the North Indian Ocean, based on satellite altimetry and tide gauge data. Their results over most of the North Indian Ocean stations reached a value closer to the global mean sea-level-rise trend of 3.2 mm/year. However, in some parts of the northern and eastern coasts of the Bay of Bengal, larger trends up to 5 mm/year were reported.

Luu, et al. (2014) have also used both long term tide gauge data and satellite altimetry from 1984 to 2011 to quantify the sea level trend and variability around the Malaysian Peninsular. Their results showed that the relative rate of sea level rise in the Malacca Strait was about 2.4 mm/year. Additionally, they have also noticed a significant vertical land movement in the region. Finally, an absolute sea level rise was computed as 3.6 mm/year from the altimetry, and it was a slightly higher value than the global tendency.

The aim of this research was to analyse the long term sea level changes around the Sri Lankan waters, and to quantify the trend statistically, using the observed tidal gauge data and altimetry sea surface heights from 1993 to 2013.

2 Sea Level Measurements around Srilankan Coastline

Processed altimetric SSH data was extracted between 20°N, 60°E and 10°S, 100°E from the AVISO website (<https://www.aviso.altimetry.fr/en/data/products/sea-surface-heightproducts/global/ssalto/duacs-experimental-products.html>) as monthly mean sea level anomalies from

Fig. 3: Study Area.

January 1993 to December 2012 (Fig. 3). These data were from Topex, ERS and Jason altimetric missions, and these SSH were merged and gridded at 0.3° resolutions in the NetCDF format. Network Common Data Form (NetCDF) is a common file format that can store multidimensional data and here, the time series SSH data is stored. These data are already corrected for standard altimetric errors such as orbital, atmospheric, sea state bias, tide loading, pole tide, solid earth tide, inverse barometric. As a result, these SSH are of 2-3 cm-level accuracy (Benveniste and Picot, 2011). Long

term tidal data (1993-2012) from Colombo tidal station were used to validate the altimetry data. These data were obtained from the Sri Lanka Ports Authority. The altimetric time series data was analysed using the Ferret software (V6.9), and the results were validated using the observed tidal data. Ferret is a computer visualization and analysis environment designed to analyse large gridded time series data (<http://ferret.pmel.noaa.gov/Ferret/>). Ferret runs on Linux platform and it enables in retrieving, visualising, and saving data according to the operators' coding as required.

3 Observed Long Term Sea-Level Variation around Sri Lankan Coastline.

Obtained monthly Mean Sea-Level Anomaly (MSLA) data from January 1993 to December 2012 were in NetCDF format, and required data queries such as monthly mean and climatology filters were generated in the Ferret software by developing various programming codes. The monthly MSLA data for the year 1993 are shown in the Fig. 4. According to these results, it is clear that the monthly MSLA around the Sri Lankan coastline varied over time throughout the year. The interaction of the water with the coastline was clearly visible in these results, and the continuous existence of a significantly high water column towards the Northeast of Sri Lanka was also clearly observed.

Fig. 4: Monthly Mean Sea Level Anomaly (in cm) from, left to right and top to bottom, January to December 1993.

This data is sensitive to the variations in the climate, especially during the South-East and North-West monsoon period. These biases must be eliminated in order to see the real Sea Level Anomaly (SLA) (NIO, 2004).

As a second step, the MSLA for the month of January for 20 years from 1993 to 2012 was studied. Even though these data corresponded to the month of January of every year, the anomalies were significantly different (Fig. 5) as these data are effected by various other non-seasonal influences such as El-Nino/La-Nina

Fig. 5: Mean Sea Level Anomaly (cm) in January 1993(top) and January 1994(bottom).

The annual MSLA for the corresponding 20 years were then computed using Ferret. This result also did not reveal a clear annual pattern due to both the short and long term climatic effects. However, there was a slight indication of the Indian Ocean Dipole (IOD) characteristic between the Bay of Bengal and the Arabian Sea (NIO, 2004). The existence of the high anomaly at the Northeast coast of Sri Lanka was more prominent in these results (Fig. 6). This is clearly visible in the 20 years of MSLA as given in the Fig. 7.

Fig. 6: Annual Mean Sea level Anomaly (cm) in 1993 (top) and 1994 (bottom).

Fig. 7: Long term Mean Sea Level Anomaly (cm) from 1993-2012

The long-term MSLA map revealed that the sea level anomaly in the East coast was around 2 cm, while in the West coast, it was about 1 cm. However, these data must be corrected for seasonal, annual and some long term climatic variations (Nerem et al., 2010; Omar et al., 2006). Hence, these affects were normalised by developing codes for

annual and semi-annual climatology using the Ferret software in order to determine a more realistic estimate. Finally, the climatology was modelled based on the 20 years' seasonal cycle from January 1993 to December 2012, and it was applied to the long-term MSLA data (Fig. 8). Nevertheless, these results were still having the inter-seasonal and long term influences such as El-Nino/La-Nina, which were out of context of this study (NOAA, 2015; Warrick et al., 1996).

Fig. 8: Long term Mean Sea Level Anomaly (MSLA) after climatology removed (in cm)

This can be considered as the Mean Sea Level Topography over the region for the period from 1993 to 2012. Overall, it does not exhibit a larger long term sea level anomaly around the Sri Lankan coastline. On the zero cm contour line going around Sri Lanka and towards the Bay of Bengal, there are two distinct high spots, which are also prominent in the annual MSLA, and this could be the resultant signal due to the dipole effect driven Kelvin waves trapped in the Bay of Bengal (Nidheesh et al., 2013).

4 Altimetric MSLA vs. Tidal Levels

A comparison between the altimetry and Colombo tide gauge station were done from 2007 to 2012. This data was used to validate the altimetry data results. Subsequently, sea level trends at three locations around the Sri Lankan coastline was computed (Fig. 9). Colombo was chosen as the west coast, Kirinda as the south coast, and Trincomalee was chosen to represent the east coast trend. Here, the daily mean tidal values were first averaged to obtain the monthly mean tidal levels, which are analogues to the MSLA. The MSLA were then extracted from the altimetry time series grid using the Ferret software for locations at close proximity to the selected tidal stations. Fig. 10 shows the extracted MSLA data for Colombo (79.7° E, 6.9° N), Kirinda (81.3° E, 6.2° N) and Trincomalee (81.3° E, 8.5° N). These MSLA data also needed to be filtered for the seasonal climatology (Fig. 11) so as to remove the seasonal climate biases in the data (Nidheesh et al., 2013). The monthly MSLA values near each tidal station are shown using the black line, and the climatology filtered data sets are shown

in red colour. After applying the climatology, the noise in the raw MSLA data due to various climatological reasons was also filtered, and the correlation was increased by 0.05. Then, the long term sea level fluctuations were clearly visible from the data.

Fig. 9: Location of the sites selected for SLR analysis.

5 Statistical Analysis of the Altimetry vs. Tide Gauge

The monthly MSLA data extracted from the altimetry data, and located near the Colombo tide gauge station, and the observed monthly mean tidal data at the Colombo gauge from 2007-2012 were compared statistically in this validation (Fig. 12). The Altimetry (X axis) and Tide Gauge data (Y axis) at Colombo are highly correlated, giving over 0.87 as the linear correlation coefficient value for monthly MSLA's, and it is over 0.93 for the annual averaged MSLA values.

The sea level rise trend lines were then computed for both data sets near Colombo (Fig. 13), and it was observed that the trend lines were nearly parallel during the period 2007-2012. This also confirms that the monthly mean and annual mean tidal data at the tide gauge is highly correlated with the satellite altimetric monthly MSLA and annual MSLA trends. Therefore, satellite altimetric MSLA data can be successfully used in analysing and forecasting the long-term sea level variations.

The estimation of the long term sea-level variations around the Sri Lankan coastline was then computed at the above mentioned three locations. From these, it was expected to identify and determine any variations to the sea level trend around the coastline. For this, climatology corrected annual MSLA values derived from the satellite altimetry was used. Fig. 14 shows the results of the computed sea level rise trend (X axis in years and Y axis in Sea Level Rise in mm).

According to Fig. 14, the sea level rise was 2.51 mm/year at Colombo with ± 0.53 mm accuracy, 2.64 mm/year ± 0.69 mm at Kirinda, and 2.61 mm/year ± 0.65 mm at Trincomalee, respectively, during the twenty year span from 1993 to 2013.

Fig. 10: Monthly Mean Tidal Levels (Y axis in cm) derived from the altimetry MSLA near the three selected sites from 1993 to 2012

Fig. 11: Monthly Mean Tidal Levels (in Y axis in cm) from the altimetry MSLA near the three selected sites - filtered for the Climatology from 1993 to 2012

Fig. 12: Statistical Testing of the Tide Gauge data vs. Altimetry in mm at Colombo: Top-monthly mean correlation, Bottom-annual mean correlation.

Fig. 13: Sea level trend from the altimetry and tide data at the Colombo tidal station (Y axis: sea level in mm and X axis: no of months from January 1993 to December 2012).

This indicates that the general tendency of the sea level rise around Sri Lanka is about 2.5 - 2.6 mm/year, with a variance of ± 0.6 mm accuracy, which was an almost similar result obtained for the North Indian Ocean region by various other authors over the years (Nidheesh et al., 2013; Unnikrishnan et al., 2015). In addition to that, the sea level rise trend is slightly higher in the Southern, Eastern and Northern coastline than the West coast around Sri Lanka.

Finally, a sea level rise trend map was produced for the entire region based only on the 20 years of altimetry data (Fig. 15). This confirmed the previous results of 2.5 - 3 mm/year sea level rise around the Sri Lankan coast.

Fig. 14: Sea level rise trends around Sri Lankan coastline (Y axis: sea level in mm and X axis: no of months from January 1993 to December 2012).

Fig. 15: Map of the sea level rise trends around Sri Lankan coastline (trend in mm/year).

6 Conclusions

Sea levels are changing, for many reasons. Some changes are rapid while others take place quite slowly. These changes can be local or can extend globally. The changes in

the sea level have conventionally been measured at a number of fixed tide gauge stations around the Earth, but the increased accuracy of satellite altimetry data now offers the best opportunity for improving knowledge about the global and regional sea level changes.

The estimated sea level rise trend around Sri Lanka is around 2.5-3 mm/year from 1993 to 2012. This is slightly less than the global mean sea level rise value of 3.2 mm/year over the same time frame. The observed annual mean sea level rise trend from the altimetry and tide gauge data are highly correlated ($R^2 \sim 0.93$), and as a consequence, altimetry data can be used to analyse the sea level rise successfully, especially where there are no tidal stations available, or no long-term tidal observations exist. Furthermore, it was noted that the sea level rise in the Western coast is slightly less than the sea level rise of the Southern and Northern coasts of the country.

These results can be used to project the trend in sea level rise for the future, and this information can be used to study environmental issues related to flood, coastal erosion and coastal habitat losses around Sri Lanka. Furthermore, along with various other coastal information such as elevation, the most susceptible areas can be identified, and advanced measures and precautions can be planned to minimise the effects associated with the sea level rise.

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Author Contributions

Conceptualization, methodology, analysis, writing original draft preparation, by M.D.E.K.G. and W.S.K., and writing, reviewing and editing, M.D.E.K.G. and W.S.K. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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