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Research Article

Comparison and Validation of Coastal Sea Level Measurements in the Indian Ocean Regions Using Coastal Altimetry

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Abstract

Satellite altimetry provides an important measurement source for coastal studies. The main aim of this study was to make an effort to check the availability of valid altimeter data and to compare and validate altimeter data in the coastal region of India. The study shows that by adopting specific coastal processing, it is possible to retrieve valid altimeter measurements in the coastal regions. The combined use of improved coastal multi-altimeter data would allow us to efficiently observe the temporal and spatial scales of coastal dynamics [16]. Thus, in the present study, two different altimetry missions were considered. The coastal sea-level data was computed from two different altimeter missions the Jason-2 PISTACH coastal data and SARAL Altika data separately and for sea level validation only the RED3 re-tracker and for SARAL 40 Hz high-frequency data was analysed and validated with *In-situ* tide gauge and PSMSL data. The RED3 re-tracker from Jason-2 PISTACH coastal product with *In-situ* measurements show that the valid altimeter data can be retrieved around 10 km close to the coast also. Also, the 41 point filtered data was able to reduce the noise in the data set and be able to capture all the oceanographic signals in the raw RED3 re-tracker. The comparison of RED3 re-tracker and filtered data show good matching with the *In-situ* data. This data helps us to obtain valid altimetry measurements more close to the coast. Similarly, for the SARAL Altika, SSHA measurements show very promising results in the coastal regions of India. This SARAL also enables us to reach as close as 3 km close to the coast because it is the first of its kind to provide sea level measurements in the proximity of the coastal regions due to its narrow footprint size. The validation of altimeter data from multiple missions with tide gauge data shows encouraging results. Along-track comparison shows that valid altimeter measurements were available close to the coast. Improvement of both qualitative and quantitative measurements in the coastal zone was observed from the coastal altimetry.

Keywords: Satellite Altimetry; Coastal Zone; Coastal Processes; Sea Level; Seasons; Tide Gauge

Introduction

Satellite radar altimeter was mainly intended to study the variation in sea level (or) height [1]. Satellite remote sensing especially radar altimeter provides a unique and simultaneous view over large expanses of the ocean and provide repeated observations with extensive geographic coverage unlike *In-situ* observations, which are point measurements of a particular location with respect to time. The spatial and temporal sampling of satellite altimetry is in general appropriate for measuring sea level variations over the open ocean, where the signals and corrections to be applied are well understood [2]. The usual validity checks for altimeter data editing have been designed for deep ocean regions [3]. However, the main advantages of altimeters include all day (day/night), all-weather operation without significant loss of data. Study of altimetry is well established over Open Ocean but its difficulty lies in extending its application to coastal regions [4]. So far altimeter measurements were ignored in coastal regions at least 50 km, where sea state conditions can be very different from the coastal region because of the land contamination in the altimeter footprint [5]. Both tide and atmospheric models currently used to correct the altimetry data are global and are focused on the open ocean. But, tides and meteorological conditions close to the coast and over continental shelves are often quite different from those found in the open ocean. With special processing and careful screening, valid data can be obtained from altimeter in the coastal region of 0 - 50 km [6].

Numerous efforts were made over the last decade (or two) to improve the quality of the altimetry data close to the coasts. Several approaches are available to address the problems described above. Therefore, a significant bias is introduced when applying these corrections to the altimeter data near shore [7,8]. Other efforts to correct the altimeter signal near the coast include re-computing the wet tropospheric correction (Manzella., *et al*. 1997; Vignudelli., *et al*. 2005 [9,10], the use of customized tidal modelling [11,12]), higher-rate data (e.g. [13], and/or re-tracking [14]). Algorithms to correct these and other effects of contamination of the atmosphere and land in coastal regions. Several international initiatives for developing new re-tracking algorithms, improvements in corrections and coastal dedicated projects such as ALTICORE [15,16]; www.alticore.eu), COASTALT [17]; (www. coastalt.eu), eSURGE (http://www.storm-surge.info/), PISTACH [18], among others. PEACHI [19] etc., and also a series of COASTALT workshops made a significant improvement in extending altimeter data from open ocean to the coastal zone [20]. The above-mentioned efforts to improve the quality of the altimetry data in coastal regions have encouraged studies at regional and global scale.

The Bay of Bengal is one of the most dynamic seas in the world. It undergoes dynamic seasonal behavior during South West (SW) and North East (NE) monsoons and having a transition period of the calm sea along with violent cyclones in between them. Variability of coastal sea level from seasonal to inter-annual time scales is caused by several processes, such as changes in ocean heat content and circulation, changes in sea level pressure, and changes in river runoff regimes (e.g. [21]), among others. The influence of the tide is negligible compared with those processes [22]. The main contributions to the seasonal cycle on sea level at global and regional scales have been addressed by several studies (e.g. [23-26]. The inter-decadal variability of sea level at Bombay represented the variability in rainfall over the Indian subcontinent [27]. They hypothesized that the seasonal river outflow of the monsoon rainfall into the seas around India and the dynamic currents along the Indian coast provide links between the rainfall over the Indian subcontinent and the sea level along the Indian coasts with coastal salinity playing an intermediate role. The heavy inflow of freshwater into the seas around India bring large changes in salinity, and therefore, in coastal sea level [28]. The annual variation of pressure-adjusted sea level is mainly explained by the expansion and contraction of the water column due to density changes (steric-effect) (e.g. [29,30]. This effect also contributes significantly to the observed sea level trends. Mean sea level along the coast of India is higher in the Bay of Bengal than in the Arabian Sea, the difference in sea level between Vishakhapatnam and Mumbai (Bombay) being about 30 cm [31]. The former (latter) is a consequence of the distribution of wind stress (rainfall) because of the monsoon [32]. [33] estimates that the mean sea level rise from past tide gauges at several coastal stations along the coast of India show a rise of slightly less than 1 mm/year without landslide corrections. In particular, the main contributor of the sea level rise is the thermal component of the steric effect in the upper 750m of the ocean, which is related to the global warning [34,35]. Mean-sea-level data from coastal tide gauges in the north Indian Ocean were used to show that low-frequency variability is consistent within the basin [36]. In coastal areas, the spatial and temporal variability of the sea level at seasonal scales is used to characterize the circulation, monitor shorelines, detect extremes and trends in sea level, and better understand dynamics of estuaries.

In this paper, comparison is made between the monthly mean variability of SSHA (SLA) computed from two different altimeter missions the Jason-2 PISTACH coastal data and SARAL Altika data separately and from tide gauges. Because the use of satellite altimetry is particularly useful in regions that lack long-term, high-quality records. As a case study, we focus only on three of those regions, where PSMSL tide gauge data available.

Data and Methods

Study area

The study region with bathymetry contours and Jason-2 and SARAL tracks with tide gauge locations were shown in figure 1.

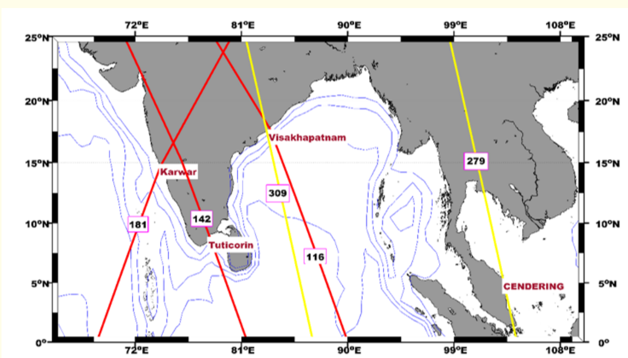

Figure 1: Study area showing selected Jason-2 tracks (RED) and SARAL Altika tracks (yellow) with tide gauge locations and bathymetry contours.

The study area comprises of a) three stations along the coastal India for Jason -2 track passes close to available tide gauge stations and b) two stations for SARAL tracks along Malaysia and India, where tide gauge observations available for comparison. The abutting east coast of India has a complex coastline with almost parallel bathymetry contours offshore plotted using GEBCO data and the adjoining sea, the Bay of Bengal is the largest bay in the world is as shown in the figure 1. The study region was influenced by three different conditions during a year. They are Southwest monsoon SW (June to September), Northeast monsoon NE (December to February) and a transition period in between these two seasons. Low-pressure systems and often severe cyclones also develop during the transition period also influence the study area.

In-situ data

The sea surface continuously changes with time. Its level, measured relative to an arbitrary datum, is called sea level, which, and is the most obvious indicator of change in oceans. Changes in sea level are greater in shallow waters in the vicinity of a coast than in the open sea, and since a large fraction of the human population resides in coastal areas, variations in sea level have aroused interest for a long time. A reasonably accurate prediction of sea level was necessary for safe navigation of boats and ships in harbors. This, and the relative ease of measuring sea level using tide gauge installed at a coastal station compared to measuring, say, temperature or currents, has led to it being one of the best-documented oceanic variables. Hourly measurements of sea level are available at several places around the globe, some of the records stretching back to the last century. Tide gauge measurements have some limitations due to their density of distribution, local impacts and are particularly affected by vertical land movements such as land subsidence [37].

The monthly and annual sea-level data are supplied by the Survey of India to the Permanent Service for Mean Sea Level (PSMSL) along with the datum to which the measurement is referred. Since the datum history is known for the tide gauges of India, a homogeneous series of levels can be prepared. These levels are adjusted by the PSMSL to a Revised [Roy, 1994]. As a result, many of the records are short, and only 12 [Emery and Aubrey, 1989] are acceptable for estimating sea-level variability on seasonal and higher time scales [38].

The tide gauges are located at Karwar, on the Indian west coast, at Vishakhapatnam on the Indian east coast and at Tuticorin was considered for the present because of availability of tide gauge data and altimeter tracks. Also for comparison of SARAL data at two tide gauge locations at Cendering (Malaysia) and Visakhapatnam (India) coast were selected for the study due to lack of sufficient *In-situ* and SARAL observations. The details of the tide gauge locations were presented in table 1.

Tide gauge station name/ ID	Latitude/ longitude (degrees)	Data period
Visakhapatnam	17.683/83.283	Aug-2008 to Dec-2012 and Oct-2014 to May 2016
Tuticorin	8.75/78.2	Aug-2008 to Dec-2012
Karwar	14.8/74.11667	Aug-2008 to Dec-2012
Cendering	5.26/103.18667	Sep-2014 to Nov-2015

Table 1: Provides the details of the tide gauge locations used in this study.

Altimeter data

Satellite Altimeter along track data are obtained from the AVISO (Archiving, Validating and Interpretation of satellite oceanographic data) website (www.aviso.oceanobs.com) through FTP service. In order to develop satellite radar altimeter products over coastal areas and continental waters in the Jason-2 Project (CNES) funded the PISTACH project to CLS and SARAL ALTIKA along track IGDR products were used for the present study.

Jason-2 PISTACH products

It consists of two products namely Coastal, covering the whole ocean plus a 25-km fringe over land and Hydrology, with all emerged lands plus a 25-km fringe over oceans (Mercier., *et al*. 2010). Coastal products were used for the present study.

The PISTACH products include new re-tracking solutions, several state-of-the-art geophysical corrections as well as higher resolution global/local models, in addition to the content of standard Jason-2 IGDRs with high resolution along track products (20 Hz sampling rate, with fields, either interpolated or copied) and about 80 extra fields [39]. Each algorithm has its own re-tracking strategy and so their outputs are different for each re-tracker. During the experimental PISTACH project, PISTACH is provided with three additional re-trackers RED3, OCE3and ICE3 in addition to standard MLE4 re-tracker. ICE3 re-tracker was to study the ICE studies. So the three re-trackers from PISTACH L2 products were MLE4 = standard re-tracking in the GDR products. OCE3 = MLE4 re-tracking applied on filtered waveform [40]. RED3 = MLE3 re-tracking on the reduced waveform to reduce the land contamination [41].

But for coastal studies, only RED3 (bumps in the waveforms are often observed in the trailing edge when approaching the shorelines. This algorithm works as ice3 does selecting an analysis window centered on the main leading edge of the waveform and re-tracking parameters in this reduced window [-10;+20 samples] with a Maximum Likelihood Estimator (solving for 3 parameters : range, amplitude and Sigma composite) and OCE3 (This algorithm is a classical MLE3 re-tracking algorithm but it is performed on filtered waveforms. The filtering that has been applied is an SVD filtering (Singular Value Decomposition Filtering) allowing to reduce the multiplicative speckle noise on the waveform and thus to reduce the estimation noise for each parameter) [41] in addition with the standard product were available. For more details regarding waveform re-tracking strategies please refer JASON-2 PISTACH handbook [39].

The data selected for the study were the Interim Geophysical Date records (IGDR) of the Jason-2 PISTACH coastal products. The Jason-2 ground tracks (or passes) selected for the study region are track number 116,142 and 181 with 10-day repeat cycle. The study period covers Jason-2 repeat cycles from 1 to 166 (August 2008 to December 2012).

SARAL ALTIKA products

SARAL along-track Intermediate Geophysical Data Records (IGDR) and Geophysical Data Records (GDR) data were obtained. SARAL data covers from cycle 16 to 29 (September 2014 to December 2015) with a repeat cycle of 35 days. As discussed in chapter 2 and 3, Instead of collocation, closest point analysis and along-track analysis methods were chosen for the comparison and validation.

In these methods, the comparisons or validations were carried out at the closest (or) the shortest point was carried out. This method is very useful especially in coastal regions to understand the extent of altimeter data validity proximity to the coast and also to study coastal sea level variability.

Altimeter corrections for Jason-2 PISTACH data for coastal sea level measurements

Prior to proper use of altimeter data in the coastal region involves a number of corrections of certain coastal issues especially related to tides, atmospheric forcing, dry and wet tropospheric corrections. The present study examines only the RED3 re-tracking algorithm, which in earlier chapter show optimal performance in the coastal region. Range and geophysical corrections (especially wet tropospheric, mean sea surface, geoid and the tides) applied were discussed.

Tidal corrections

The ocean tide correction is by far the correction that reduces the temporal sea surface height variance the most. Besides the dominating ocean tide signal, the tidal correction includes correction for several smaller tidal signals: the loading tide, the solid earth tide, and the pole tide. Only the ocean tide has been analyzed in coastal regions. The solid earth and pole tide correction are independent of coastal regions and are normally derived using closed mathematical formulas. [7]. As there is no regional tide model was used and which were already provided in the along track data were utilized for the study. There are two Ocean tide model solutions are available. They are The global ocean tide model called GOT4.7 model is from 2006 of empirical ocean tide models derived from satellite altimetry [42]. The model corrects for the major eight diurnal and semidiurnal constituents (K1, O1, P1, Q1, M2, S2, K2, and N2) along with a number of smaller constituents. Furthermore, a number of local tide models have been patched into GOT4.7 for several coastal regions. [7]. The 2D Finite Element Solution FES2004 [43] is another widely used global ocean tide model based on the assimilation of satellite altimetry into a time-stepping finite element hydrodynamic model. The FES models were pioneered by Christian Le Provost in the early 1990s (Le Provost., *et al*. 1994) and have been developed since to include 15 tidal constituents distributed on 1/8° grids. Both the GOT4.7 and FES2004 include corrections for long period tides and also the largest quarter diurnal shallow water constituent M4 [7].

The tidal range is larger in coastal regions than in the open ocean, and coastal tidal waves are much more complex. The pattern of the tidal waves is scaled down as the speed of the tidal wave reduces, because bottom friction modifies the progressions of the tidal waves. Similarly, resonance and near-resonance responses add to the complexity of the tidal pattern and produce some of the world's largest tidal amplitudes [7]. In the deep ocean, there is virtually no difference between the two models. But in the coastal region, there is a significant difference in the models. GOT4.7 model, which is most widely used ocean tidal solution was used for the present study.

Atmospheric corrections

There are two atmospheric corrections. Dry and wet tropospheric corrections.

Dry tropospheric correction

A modeled dry tropospheric correction was used for the present study.

Wet tropospheric corrections

The wet troposphere refraction is related to water vapor in the troposphere, and cloud liquid water droplets. The water vapor dominates the wet tropospheric correction by several factors, and the liquid water droplet from small to moderate clouds is generally smaller than one centimeter [44]. Although smaller than the dry tropospheric range correction in magnitude, the wet troposphere correction is more complex with higher temporal variations, with rapid variations in both time and space and therefore also needs careful attention in the coastal region. The correction can vary from just a few millimeters in dry, cold air to more than 30 cm in hot, wet air [7]. Two different wet tropospheric corrections are implemented in the PISTACH prototype for coastal oceans:

- A composite correction, whereby the model correction (European Centre for Medium-Range Weather Forecasts - ECMWF) replaces the radiometer near the coasts (<50 km), or the ECMWF correction is shifted to the nearest valid radiometer value in the transition case. Interpolation and detrending are also applied in complex cases.
- A decontamination correction, probably more suitable than the composite correction for areas where large and rapid fluctuations of air masses are observed, the composite correction being too smooth. On the contrary, decontamination may be less precise over areas with complex shorelines.

A decontaminated wet tropospheric correction was used for the present study.

Sea state bias

The Sea state bias was originally modeled as a simple percentage of the SWH e.g., Δh = -0.04 SWH explaining that with increasing SWH, altimeter ranges longer or more below the mean sea surface within the altimeter footprint. There is no Sea state Bias (SSB) was provided for RED3 re-tracker. So SSB was computed using a simple relation -0.04*SWH.

Mean sea surface

For oceanographic applications of satellite altimetry, an MSS is used along with the sea surface height observations to create sea level anomalies (h_{sla}) as the MSS can be given with higher accuracy than the geoid along the track. For ocean circulation studies, the Mean Dynamic Topography (MDT) is the fundamental parameter. The MSS is determined by averaging satellite-derived sea surface height observations over time. In many cases, the MDT model is determined from the mean sea surface and the geoid (e.g., [45]). In some Level-3 products from, e.g., AVISO, the MDT computed from an MSS minus a geoid model is even added back to the altimeter anomalies (Level-3 products) to compute absolute altimeter heights. It is therefore important that the suite of standard corrections applied to determine the MSS is the same as those used to compute the altimeter anomalies. There is otherwise a possibility that the differences in the corrections will show up the altimeter signal. The issue is equally important for the use of satellite altimetry in both open oceans and in shelf and shallow water regions. The sea level anomalies (h_{sla}) have been calculated using the same set of corrections that were used for the MSS. If not, the user might get erroneous results, caused by the difference in corrections rather than real ocean dynamic topography.

The presently two most widely used global MSS models are the DNSC08MSS [45] and the [46]. The CLS01 MSS model is based on 7 years of satellite altimetry data covering the period 1993-2000 whereas the DNSC08MSS is based on 12 years of data based on the 1993-2004 period. An updated version of DNSC08MSS using state of the art range and geophysical corrections was introduced in order to further explore the impact of using an updated set of corrections [7].

The difference between the two mean sea surfaces has a standard deviation of 2.3 cm and shows much variation towards the coastal regions. The differences can be related to three factors: different range corrections applied; Different orbital solutions; or a different averaging period for the mean sea surface determination [7]. The first important contributor to the difference between the two MSS models is the fact that CLS01 and DNSC08MSS have adopted a different mean reference pressure for the inverse barometer correction (it is otherwise identical). The CLS01 model uses the mean average pressure over the ocean of 1,011 millibars, whereas the DNSC08MSS uses the global mean of 1,013 millibars. This generates a 2 cm global offset or bias between the two mean sea surfaces. Interannual ocean variability that has been averaged out differently for the two MSS. DNSC08MSS is averaged over 12 years (1993 - 2004) whereas the CLS01 MSS is referenced to the 7-year (1993 - 1999) period. This can be seen by computing the differences between identically processed datasets averaged effect of inter-annual ocean variability to 7 years (1993 - 1999) or 12 years (1993 - 2004).

Results and Discussion

Data validity proximity to the coast using Jason-2 PISTACH data

An attempt to check the data validity within the 0 - 50 km coastal strip for the selected tracks by applying the PISTACH processing flag for re-trackers and by restricting the data between 0 - 50 km and to retain the valid ssha (KU band only) data close to the coast for different re-trackers.

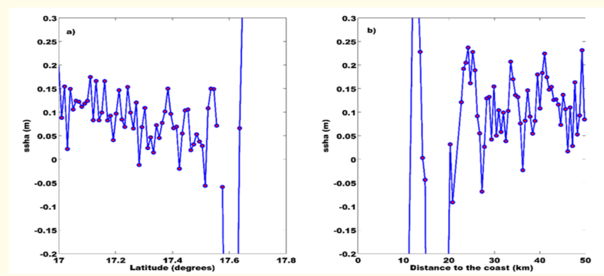

Figure 2: Shows the availability of valid SSHA data computed from Jason-2 PISTACH for the track 116 a) along the latitude and b) distance to the coast.

Figure 2 shows the availability of valid SSHA data from the track 116 along the latitude and distance to the coast in the coastal strip of 0 - 50 km and shows that valid data can be retrieved around 10 km close to the coast also. It is clear from the figure 2 that the raw PISTACH 20Hz data was too noisy and need to filter with a low pass along with the spatial filter. Here, as discussed in earlier in chapter 2, that Lanczos 41 filter was used to remove the noise as shown in figure 3 for both along the latitude and distance to the coast. It is obvious from the figure 3 that the Lanczos 41 point filter was able to capture all the oceanographic signals and show optimum results.

Comparison and validation of Jason-2 PISTACH coastal sea level measurements in the coastal regions

In this section, the validation of Jason-2 data with coastal buoys was presented for the coastal regions of India. In order to make a comparison, the data during low-pressure systems and cyclones were removed from all the three altimeter buoy pairs and comparison were carried out. The correlation coefficient (r), RMSE and bias parameters were used to check the data quality and for validating the Jason-2 PISTACH data at the closest altimeter- buoy pair for

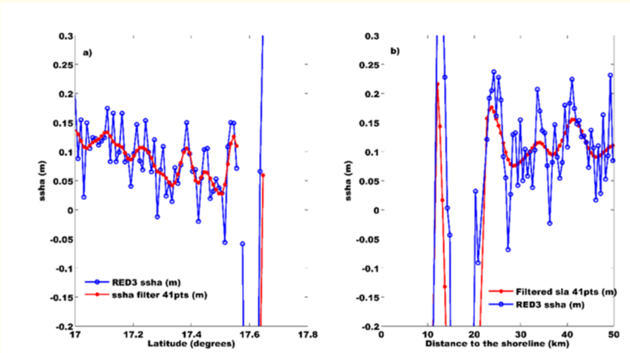

Figure 3: Shows the SSHA variability a) along the latitude and b) along the distance to the coast for the track 116 (cycle56) in the proximity to the coast.

closest point analysis and along all the track points close to buoy in the vicinity of the coast for along-track analysis. Also in order to make comparison with tide gauge data inverted barometer effect was not applied to the altimeter data [9]. Validation is carried out using two different analyses, the closest point analysis and along-track analysis for the four coastal stations using data availability. The coastal topography has a significant impact on coastal measurements especially proximity to the coast. The time series comparison of the three Jason -2 altimeter buoy pairs along the Indian coastal regions were shown in figure 4.

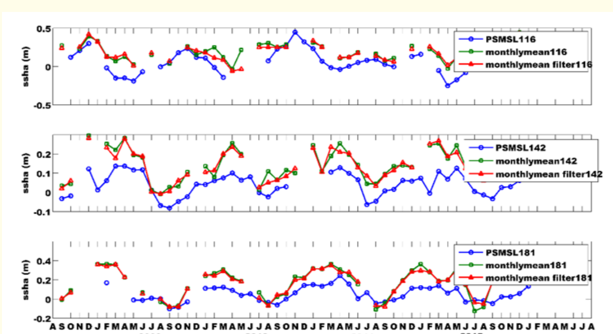

Figure 4: Shows the time series comparison of Jason-2 altimeter with monthly values of Tide gauges along the Indian coastal regions.

The time series comparison plots clearly show the dominance of seasonal signals in all the tracks. It also shows the influence of monsoon over the SSHA. The three tracks were chosen were one along the east coast of India, one along the southern tip of the India and the one along the west coast of India. The track 116 represents east coast, track 142 represents southern tip and the track 181 represents west coast of India. In the track 116, there are two peaks over a year and maximum during the November and minimum during the April. For the track 142, which is at the southern tip which shows a peak during April and minimum during August. Similarly, for the track 181, which is on the west coast of India, the peak was observed during December except during 2010 and minimum was observed during September. Also, there seems to be a minor peak during the south-west monsoon (June to September). The SSHA shows a symmetric behavior for the track 181, which is on the west coast.

The scatter plot for the three altimeter buoy pairs was presented in figure 5. It clearly shows that the Jason-2 altimeter is in good agreement with buoy data in all the three altimeter buoy pairs. Also, the filtered data seems to be less scattered than the raw data.

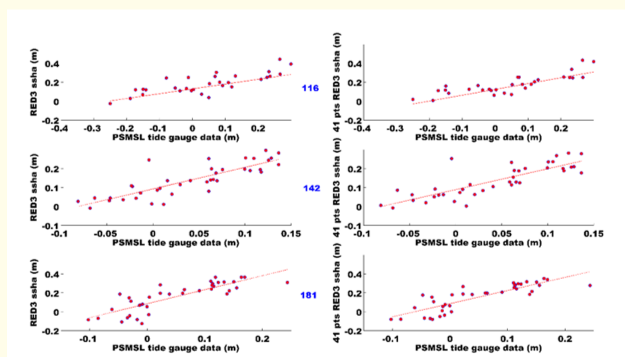

Figure 5: Shows the scatter plots of Jason-2 altimeter tracks with monthly values of Tide gauges along the Indian coastal regions.

The table for comparison statistics was presented in table 2. The statistics suggest that the altimeter data is in good agreement with the buoy data.

The correlation coefficient r was less (0.78 for raw) for the track 116 than for the other tracks because of the distance to the buoy

Jason-2 track	Correlation coefficient (r)	Bias (m)	RMSE (m)
116 RED3	0.78	0.13	0.06
RED3_41pts	0.83	0.14	0.05
142 RED3	0.84	0.09	0.04
RED3_41pts	0.83	0.09	0.04
181 RED3	0.83	0.10	0.08
RED3_41pts	0.84	0.10	0.07

Table 2: Comparison and validation statistics for the Jason-2 PISTACH coastal sea level measurements.

was a bit far than for the other tracks but in the filtered data the correlation(r=0.83) was much improved. This shows that apart from the distance other noises may be due to land contamination and low-pressure effects, Open Ocean and coastal effects. Also, the bias values (0.13m, 0.14m for raw and filtered data respectively) were also high because of altimeter-buoy separation distance was high. The RMSE values show only 6 cm and 5cm for raw and filtered data, which is quite acceptable.

The correlation coefficient (r) for the track 142 was 0.84 for raw and 0.83 for filtered data were in good correlation with buoy data. The bias values were about the same value 0.09m. The lowest of the three altimeter tracks used in this study. This shows that the better correlation values were obtained close to the coast also. The RMSE values were also about the same value about 4cm, which shows the best results as they closely match the mission objectives goals. Similarly for the track 181, the correlation coefficient (r) 0.83, 0.84 for the raw and filtered data, which also show the good matching with buoy data. The bias values were 0.1m for both raw and filtered data. The reason for this little higher bias is that the buoy is located inside the Karwar port as shown in the study area. The RMSE values were 8 cm and 7 cm respectively for the raw and filtered data. The reason for higher RMSE values may be due to the location of the buoy is the more inner side of the Karwar port and another important reason is it is located on the Kali river outlet/bank.

Along-track comparison

First, the validation test was performed on tracks 116, 142 and 181 passing off Visakhapatnam Tuticorin and Karwar coasts. The validation of these tracks was particularly important because of their strategic locations in the Indian coastal regions. Also the availability of the sufficient *in-situ* data for comparison purpose. The test was performed in an iterative way, for each location, the correlation, RMSE and bias of the tide gauge time series with the corresponding set of altimetry retrievals was checked. For each location, in order to produce an unbiased comparison, correlation, RMSE and bias were considered only when both tide gauge and PISTACH estimates are available.

Correlation coefficient

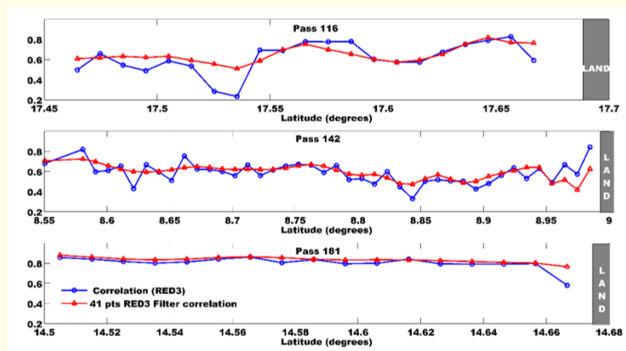

Figure 6: Shows the along-track spatial variation of correlation for the tracks near Visakhapatnam Tuticorin and Karwar coasts.

Along-track spatial variation of the correlation coefficient for the tracks near Visakhapatnam Tuticorin and Karwar coasts were presented in figure 6. Land shown is in grey. The x-axis represents the along-track progression of each track in latitude. The blue line with circle represents correlation coefficient of RED3 SSHA while the red line with triangle represent RED3 41pts filtered SSHA data. For each location, in order to produce unbiased comparison data were considered if both tide gauge and altimeter measurements available. Here Jason-2 PISTACH data shows good correlation proximity to the coast. The correlation (r) value for the track 116 was around 0.6 to 0.8 with a significant drop in between 17.5 and 17.55 may be the due presence of noise and outliers. But the 41pts filtered data constantly maintains 0.6 with two peaks. Both data show good matching between the latitudes 17.59 to 17.64. Similarly, for the track 142, the r-value from the raw RED3 SSHA data fluctuates between 0.6 to 0.8 with few drops to 0.4 but the 41pts filtered data shows a constantly maintains above 0.6 with two drops close to the coast may be due to the presence of outliers. For the track 181, the r value constantly maintains over 0.8 for both raw and filtered data up close to the coast. This particular track shows very good matching of the altimeter data with tide gauge data. The r value shows that the raw RED3 SSHA data more variable and contain erroneous data i.e. presence of outliers and the filtered data show some improvement and maintains uniform and gradual variation. The low values of r suggest that even though some processing was performed on altimeter data but suggest that a more careful quality control of the estimations will be necessary for a post-processing phase [47].

Root mean square error (RMSE)

The validation of altimeter sea level data with coastal tide gauges helps us to assess the comparability between *in-situ* data and altimetry in the proximity to the coast. Figure 7 shows the along track RMSE for the tracks near the Visakhapatnam, Tuticorin and Karwar coasts. Minimum RMSE values were observed at locations close to tide gauge locations.

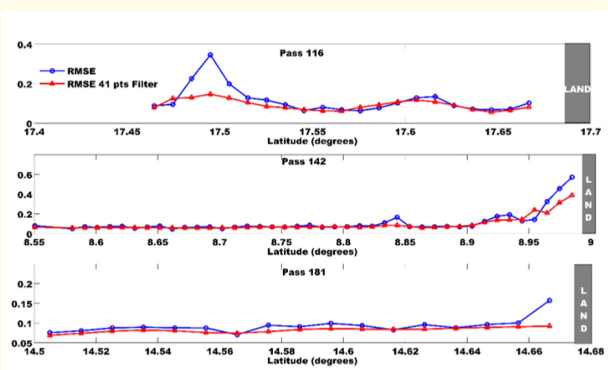

Figure 7: Shows the along-track spatial variation of RMSE for the tracks near Visakhapatnam, Tuticorin and Karwar coasts.

Sea surface heights observed from altimeter and tide gauges may not be the same as tide gauge is a point measurement measure inside or close to a port or harbor (in this case) while altimeters measure somewhere close to the coast with a footprint over an area. For the track 116, the RMSE value shows a peak at 17.5 latitudes for the raw data and reaches close to 0.4m. Bu the 41 pts filtered data shows a constantly maintains under 0.2m up to close to the coast also. For the track 142, the raw data shows two peaks with high variability in the proximity to the coast and maintains under 0.2m up to close to the coast and gradually increases up to 0.6m in the proximity to the coast. But the filtered data constantly maintains under 0.2m and increases gradually close to the coast. This shows that still, the outliers are present in the data which needs to be removed. Similarly, for the track 181, the raw data shows more variation in RMSE. But both raw data and filtered data were under 0.1m which shows that the quality of the data was good and the presence of outliers was minimum. In all the tracks the raw data shows high variability in RMSE and an increase of RMSE very close to the coast.

Bias

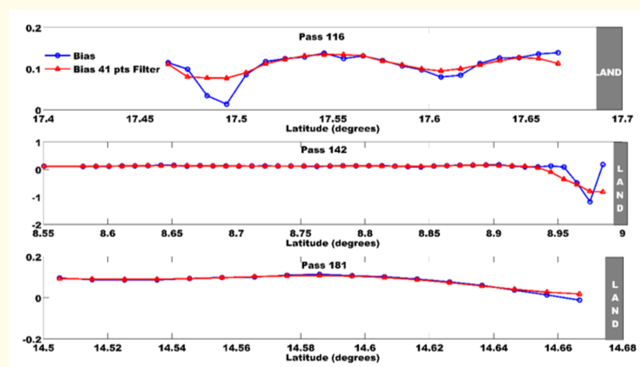

Figure 8: Shows the along-track spatial variation of bias for the tracks near Visakhapatnam, Tuticorin and Karwar coasts.

Figure 8 shows the along track variation of Bias for the tracks near Visakhapatnam, Tuticorin and Karwar coasts. As expected the track 116 shows the highest variation in bias as the distance between the tide gauge and altimeter were a bit too far than the other tracks. But still, the bias was under 0.2m. The filtered data show less variability.

The results discussed in the study were matching more or less with the results observed by [28] using tide gauge, model data and ship data on the Indian coastal regions. The statistics suggest that the Jason -2 PISTACH RED3 re-tracker was able to pick up all the coastal oceanographic signals that were captured in coastal tide gauges. The 41 point filtered RED3 data shows optimum results by removing noise. Thus, the Jason-2 PISTACH RED3 re-tracker along with 41 point filter data can provide valuable SSHA data in the proximity to the coast (Shown in figure 9).

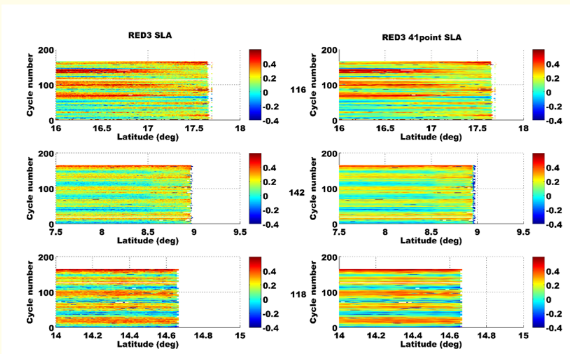

Figure 9: Showing the Jason-2 PISTACH RED3 SSHA (SLA) (m) (left) and 41 points low pass filtered RED3 SLA data (right) for the three altimeter buoy tracks selected for the study.

The SSHA exhibits a dynamic behavior and there is an influence of monsoon system on SSHA was clear especially in the bay of Bengal [48]. The reasons for this dynamic behavior was not clearly understood because of complex processes involved. The North Indian Ocean is a complex system consists of both Arabian Sea and Bay of Bengal. It has connected to the equator on the southern side but not connected to poles on the other side. So during the summer sea receives heat and stores it. This causes the changes in the SSHA. Moreover, the seasonal winds like South West (SW) and North East (NE) monsoon bring strong winds and heavy rainfall. Here also due to large freshwater inflow into sea cause SSHA changes. Also, strong winds cause high evaporation rates and this will also effect SSHA. In addition to this SW, monsoon will completely alter the circulation system so strong that even the equatorial current system also transforms into Somali current. This current system also causes changes in the SSHA. Later when the monsoon recedes that is during transition periods low-pressure systems develop over the sea and apart of the heat stored during in the summer was transferred to these low pressures and these low-pressure systems becomes violent cyclones and super cyclones. Again these fierce cyclones would eventually bring changes in the SSHA. Earlier studies by [38] indicate that there is a connection between variation in SSHA and the rainfall. This means rainfall, in turn, have an effect on river runoff and that river runoff may have an effect on SSHA. They also observed an important connection that there is a strong link between coastal currents and SSHA and also they inferred that there is a strong connection between North Indian Ocean circulation and low-frequency variation in SSHA. Finally, they concluded that the variation in SSHA was primarily due to coastal currents and rainfall (in turn on river runoff) that is thermohaline variations.

SLA data validity proximity to the coast using SARAL Altika data

SARAL Altika is a Ka-band altimeter is first of its kind in using such a high frequency (35.75 GHz, 500MHz) and is much less affected by the ionosphere than the Ku band, which are in operation now. It has less inter-track distance but has a repeativity of 35 days as ENVISAT. Therefore, SARAL data was only used for the comparison and validation purpose only because of only a limited availability of data. But it provides data as close as 3km close to the coast. In this Section of the chapter, an attempt to observe retrieve and validate SARAL along track SSHA data at Visakhapatnam (discussed in chapter 3) and other coastal regions (Cendering coast of Malaysia).

SARAL data editing criteria

In order to make a comparison with SARAL data Ocean tide correction was not applied for the track 309 of Visakhapatnam, India and applied for the track 279 of Cendering, Malaysia. Surface type flag was applied to select only data corresponds to the ocean were selected. Besides that, no specific filtering or editing was applied. Inverted barometer effect was not applied to both tracks. As the SARAL has a 35-day repeativity, very limited number of points were available for comparison. The SSHA was computed from IGDR data using a simple equation.

Comparison and validation of SARAL data

The time series comparison of SARAL tracks 309 and 279 respectively were compared with Visakhapatnam buoy and PSMSL data as shown in figure 10.

Although the SARAL repeat cycle is 35 days, the time series comparison plot shows very good matching of the SARAL 309 track data with coastal tide gauge data. All the oceanographic signal along with seasonal signal were captured by the SARAL with those reflected in the Tide gauge data. In the SARAL track, it is clearly evident that although there is a good matching in the data there seems to a large bias in the data sets. Also, the SARAL track

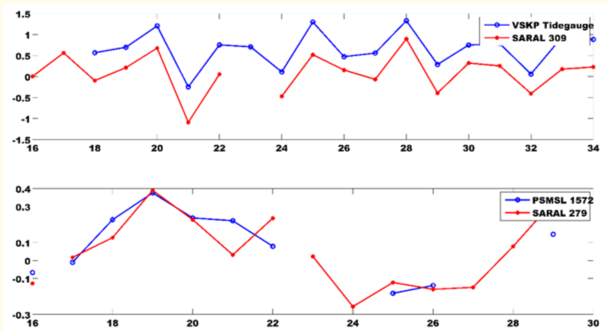

Figure 10: Showing the time series comparison of SARAL tracks 309 with tide gauge data and track 279 with PSMSL data.

279 shows good matching with the PSMSL Monthly mean data. The scatter plots of the SARAL tracks were shown in figure 11.

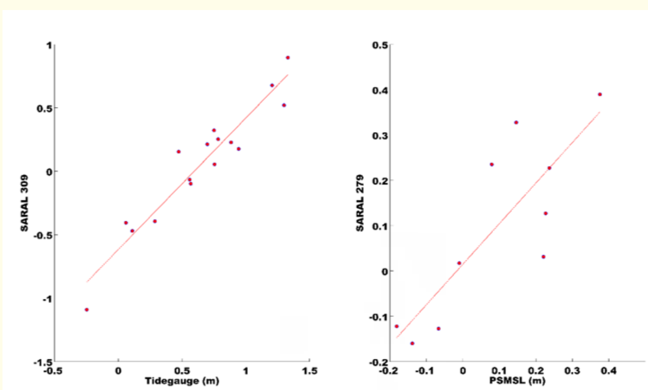

Figure 11: Showing the scatter plots of SARAL tracks 309 and 279 against *In-situ* observations.

The SARAL track 309 shows less scattered with the tide gauge data in the proximity to the coast and track 279 seems more scattered than track 309 as the comparison of SARAL track 279 is with the monthly mean values of tide gauge and sometimes SARAL Altika completely misses a month as its repeat cycle is 35 days. The basic statistics for the comparison and validation of SARAL data were presented in table 3.

The statistics suggest that the excellent behavior SARAL Altika in the close proximity to the coast. The correlation scales were good

SARAL track	Correlation coefficient (R)	Bias (Alt-buoy) (m)	RMSE (m)
309	0.95	-0.596	0.15
279	0.83	0.006	0.12

Table 3: Comparison and validation statistics for SARAL tracks 309 and 279

(>0.8) but there is a large bias (0.596) for the SARAL track 309 as expected due to the separation distance between the buoy and altimeter track. The tide gauge is coastally located and the SARAL track is around 3km close to the coast. Also, the difference in bias is only due to a tidal amplitude which is maximum near the coast. The RMSE is in the acceptable range of 0.15m. The Altika altimeter is able to resolve SLA signals of more than 2 cm, and gradients in those signals over several tens of kilometers [49].

Conclusion

Satellite altimeter measurements are amenable to provide multiple ocean parameters such as wave height and sea levels with global and temporal coverage. Therefore they often serve as an alternative for traditional *In-situ* observations. Satellite altimetry is a mature technology for studying open oceans, and one of the challenges now is to extend its use to near-coastal applications, even though the sampling strategy was not targeted for these purposes [4]. Satellite altimetry data are widely available in a ready-to-use form for the open ocean, but near-coastal applications require more specialized data treatment [9] this is especially true for Indian coasts, which experiences quite opposite northeast and southwest monsoons and a calm period in between them. In this present study, the satellite altimeter data was observed, retrieved and validated along the Indian coastal regions. The coastal sea-level data was computed from two different altimeter missions the Jason-2 PISTACH coastal data and SARAL Altika data separately and validated with tide gauge data. As discussed earlier, for sea level validation only the RED3 re-tracker and for SARAL 40 Hz high-frequency data was analyzed and validated with *In-situ* and PSMSL data for the Jason-2 PISTACH coastal products for different regions. Due to lack of sufficient *In-situ* data, SARAL data was validated for short time period but still show promising and encouraging results. This data is very much useful to address several coastal ocean dynamics and to understand several oceanographic processes. In addition to this, new altimeter processing strategy also allows us to approach closer to the coastline and to better highlight coastal dynamics with small spatial extents, such as coastal jets and fronts. Also, the combined use of coastal altimetry and *in-situ* data is also necessary for understanding coastal processes.

The scope for future research could usefully extend the present analysis are:

- Enhance the spatial resolution to a 0.125 X 0.125 grid and analyze the coastal areas where a finer resolution may be an advantage.
- Even though the methodologies and processing presented in this work are applied for sea level retrieval from Jason-2 and SARAL observations, these methods and processing can be applied to other altimeter sensors having similar characteristics such as the one on board Sentinel 3, Jason-3 and future altimeters from NASA and ESA respectively.
- This study presented a set of corrections applied to obtain sea level data and most of them were used which are provided by data agency. but a recent study [37] had discussed the state of the art corrections to correct the sea level data and showed their application for Indonesian seas using three different missions. A similar state of the art corrections can be applied or fine-tuned to Jason-2 and SARAL data for improving the Coastal ocean parameters.
- Also, many new and advanced processing strategies and different re-trackers like COASTALT, PEACHI, ALES and many pre and post-processing editing strategies, each of them were to be iteratively tested in order to improve the altimeter data in the limited areas of the coastal region.

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Volume 4 Issue 7 July 2021