Validation and Intercomparison of SARAL/AltiKa and PISTACH-Derived Coastal Wave Heights Using *In-Situ* Measurements

N. K. Hithin, P. G. Remya, T. M. Balakrishnan Nair, R. Harikumar, Raj Kumar, and Shailesh Nayak

***Abstract*—SARAL/AltiKa, the first Ka-band altimeter, now provides an opportunity to study wave characteristics in the world's coastal ocean with improved accuracy. In the present work, AltiKa-derived significant wave heights (Hs) in the coastal ocean and inland water bodies have been analyzed using *in-situ* measurements. Analysis shows that AltiKa measured Hs agree well with the *in-situ* measurements with high correlation (0.98), low bias (6 cm), and low RMSE (19 cm) in the coastal ocean, and the performance is highly consistent across different coastal zones in the three tropical oceans. AltiKa performance is found to be very good (RMSE = 24 cm and correlation = 0.94) near to the coast (<2 km). In addition to the evaluation of AltiKa Hs, another coastal altimetry product, Innovative Processing System Prototype for Coastal and Hydrology Applications (PISTACH)-derived Hs using Jason-2 altimeter, has also been validated with *in-situ* measurements. The OCE3 retracking algorithm provided in PISTACH is able to improve the Jason-2 Hs in the 100–25 km coastal zone. None of the retracking algorithms showed significant improvement of Hs in the 0–10 km coastal zone.**

***Index Terms*—Buoys, coastal ocean, PISTACH, SARAL/AltiKa, significant wave height, validation.**

I. Introduction

OCEANIC surface waves are one of the most observable aspects of the air–sea coupling, resulting from the direct transfer of momentum from the surface winds. Wave measurements are necessary for a wide variety of applications ranging from studies on the wind wave evolution, validation and calibration of wave models, wave data assimilation as well as wave climate investigations. Proper monitoring of surface waves has significant commercial and economic implications. For example, high waves generated during tropical storms can pose significant threats to commercial shipping, coastal structures, and the coastal population. Moreover, accurate wave forecasting is necessary along the shipping lines for safe coastal navigation, for better supervising of off-shore engineering projects, and also for port and harbor maintenance. Hence, the measurements and analysis of waves are very important for ensuring sound coastal planning and public safety.

There are different platforms for measuring surface wave fields. Surface buoys provide the most accurate *in-situ* measurements of oceanic waves against which wave observations from other sources can be compared for validation purposes. The limitation of such data is the sparse availability of mooring observations in the world oceans. In most of the cases, buoy measurements would be much localized in response to particular demands associated with coastal engineering applications, beach processes, etc. Moreover, coastal wave monitoring is practically nonexistent in many countries around the globe. For routine monitoring of the coastal wave characteristics, a vast network of buoys at regular spatial intervals is required which is quite impractical due to its cost as well as its expensive maintenance.

In view of sparse and infrequent *in-situ* observations, best alternative can be the spaceborne altimeters having global coverage. Radar altimeters are continuously providing measurements of significant wave height (Hs) since 1985, apart from a small gap in 1991 [1], [2]. Hs is estimated directly by measuring the slope of the leading edge of the return pulse wave form [3]. There is a consensus that altimeter measures Hs with a similar accuracy to wave buoy [4]. Altimeter also provides wind-speed estimates through measurements of surface roughness. Few past studies have shown that it is possible to estimate wave period with a good accuracy from altimeters [5]–[7].

The era of altimetry started with the launch of Skylab in 1974 by the United States. Currently, there are many altimeters (Jason-2, CRYOSAT-2, etc) in the orbit for the continuous monitoring of the ocean. Most of the altimeters are using dual-frequency Ku- and C-band. Validation and calibration of satellite altimetry Hs have been carried out in many studies [8]–[10]. For example, the altimeter-derived Hs had been validated with buoy observations [11]–[14], including the systematic calibration and cross-validation of the Hs from different sensors. One noted drawback of satellite altimetry is its deterioration of accuracy toward the coast. Previous studies suggest that TOPEX/POSEIDON, one of the widely used altimeters which operated in Ku-band, had excellent accuracy in the open ocean; however, the agreement with *in-situ* observations is found to be deteriorated toward the coast [4]. There are few other studies that second the conclusion that satellite altimeter has limitations

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N. K. Hithin, P. G. Remya, T. M. Balakrishnan Nair, and R. Harikumar are with the ESSO-Indian National Centre for Ocean Information Services, Hyderabad 500090, India (e-mail: remya.pg@incois.gov.in).

R. Kumar is with the Space Applications Centre, ISRO, Ahmedabad 380015, India.

S. Nayak is with the Earth System Science Organisation (ESSO), New Delhi 110001, India.

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in coastal regions [15], [16]. Efforts have been made in recent years to improve satellite wave data in the coastal areas by using state-of-the-art retracking algorithms. Innovative Processing System Prototype for Coastal and Hydrology Applications (PISTACH) is one such product distributed by AVISO and dedicated to the monitoring of coastal areas and continental waters. Different PISTACH wave retracking algorithms are available and the performances of these algorithms vary regionally. The launch of SARAL/AltiKa, a joint mission of Indian Space Research Organization (ISRO) and Centre National d'Etudes Spatiales (CNES), on February 25, 2013, is now providing new opportunities for understanding ocean waves in the coastal region using the Ka-band (35.75 GHz). Unlike other altimeters operating in C-band or Ku-band, altimeters operating in the Ka-band frequency are able to provide higher spatial and vertical resolution over coastal regions [17].

An extensive validation of altimeter data (either derived directly or using any retracking algorithm) is very much required prior to its research or commercial applications. One of the focuses of this study is the extensive validation of AltiKa-derived Hs in the coastal regions using *in-situ* measurements for 1-year period (March 2013–March 2014). The temporal resolution of AltiKa is coarse as it has a repeat cycle of 35 days. As far as the coastal regions are concerned, frequent monitoring of the same point is very important. Jason-2 has a repeat cycle of 10 days which helps to observe the same point in the ocean frequently. PISTACH provides the corrected coastal data of Jason-2. So, another focus of this study is the validation of Jason-2 and PISTACH-derived Hs using different retracking algorithms with *in-situ* as well as SARAL/AltiKa-derived Hs in the 100-km area along the coast during the same period. In short, the main objective of this study is the performance analysis/validation of altimeter-derived Hs from SARAL/AltiKa, Jason-2, and PISTACH in the coastal regions so that wave information from altimetry can be used with confidence for the coastal applications.

The rest of this paper is organized as follows. Section II describes data and methodology. Section III presents the validation results and related discussions. Finally, conclusion is given in Section IV.

II. Data and Methodology

In this section, we first describe the various buoy data used in this study for the validation purpose, which is followed by a description on the SARAL/AltiKa and PISTACH-derived wave products. The last section describes the collocation method that has been used in this study.

A. Buoy Data

Since the focus of this study is to validate the altimeter-derived wave data on the coastal waters with *in-situ* observations, all the available buoy data within 100 km from the coastline are used without taking the depth of the mooring into account. There are 122 buoys within this coastal limit. Buoy locations are shown in Fig. 1(a)–(d). Data from these coastal buoys are obtained from U.S. National Data Buoy

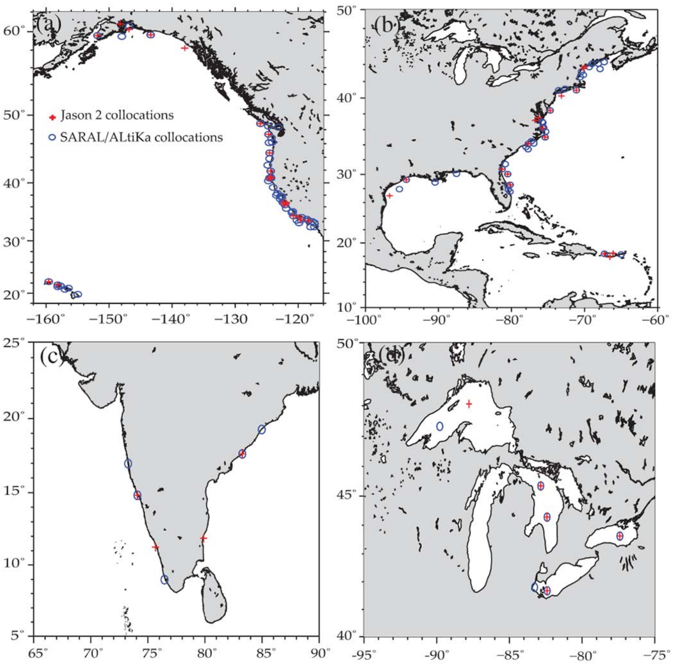

Fig. 1. Stations of *In-situ* measurements. (a) NE Pacific. (b) NW Atlantic. (c) North Indian Ocean. (d) Inland lakes of U.S.

Centre (NDBC) and the Earth System Sciences Organisation (ESSO)-Indian National Centre for Ocean Information Services (INCOIS). The buoys of North Atlantic and North Pacific are maintained by different organizations, and the data are available from NDBC (www.ndbc.gov.in). Out of 122 buoys, seven are from inland lakes, providing a unique opportunity to test the ability of altimeters to measure the inland lake Hs. The Indian coastal buoy network having seven buoys (with a minimum distance of 1 km from the coast to a maximum distance of 11 km) operated by the ESSO-INCOIS (www.incois.gov.in).

Rigorous quality control of the data has been undertaken, consisting of the flag or the complete removal of records containing default or null values [18]. The time series were processed further using a filtering process, all the observations for which $\mathrm{Hs} > 15$ m were discarded.

B. SARAL/AltiKa Data

AltiKa is an innovative Ka-band altimeter system, dedicated to accurately measure the ocean surface topography. It was launched on February 25, 2013, and continuous data are available from ISRO (www.mosdac.gov.in), AVISO (www.aviso.altimetry.fr), and TUDelft RADS database (http://rads.tudelft.nl/rads/rads.shtml) [19] with up-to-date corrections applied. SARAL/AltiKa data for the present study have been taken from TUDelft RADS database. SARAL/AltiKa is the first oceanographic altimeter using such a high frequency (35.5–36 GHz) to minimize the ionospheric attenuation and footprint size at the surface. SARAL/AltiKa is close to a beam-limited altimeter which has no "plateau" in the echo due to small antenna aperture, and this greatly reduces the pollution of "land gates" into "ocean gates" [20]. The use of Ka-band thus enables a better observation of ices, coastal areas, and continental water bodies as well as in the open ocean. However, the drawback of Ka-band frequency is its sensitivity to rain that can lead to signal attenuation. To ensure a continuity of altimetry observations in the long term, SARAL/AltiKa fly on the same orbit as ENVISAT with a repeat period of 35 days and it compliments Jason-2 [21]. SARAL/AltiKa provides significant wave height (Hs), sea level anomaly, and wind speed.

C. PISTACH Data

Jason-2 is a dual-frequency (Ku and C band) altimeter launched on June 20, 2008. Since Ku-band altimeters have some limitations over coastal regions, as part of the Jason-2 project, an experimental product, PISTACH, has been developed by Collecte Localisation Satellites (CLS) to improve the accuracy of satellite radar altimetry products over coastal areas and continental waters, which is available from AVISO (http://www.aviso.altimetry.fr). PISTACH products are derived from along-track Jason-2 measurements at 20 Hz. The PISTACH products include new retracking solutions, several state-of-the-art geophysical corrections in addition to the content of standard Jason-2 product [22]. The retracking algorithms used in the PISTACH products are dependent on different wave forms, which results from the heterogeneity of the backscattering surfaces in the coastal and continental waters. In this study, Jason-2 Hs processed using OCE3 and RED3 retracking methods, which are found suitable for the near-shore regions, is validated using buoy measured Hs. The OCE3 algorithm is a classical MLE3 (MLE3 fit from first-order Brown analytical model. MLE3 simultaneously retrieves the three parameters, range, amplitude, and sigma composite, which can be inverted from the altimeter waveforms) retracking algorithm performed on filtered wave forms. The filtering that has been applied is a singular-value decomposition filtering allowing to reduce the multiplicative speckle noise on the waveform and thus to reduce the estimation noise for each parameter. The RED3 algorithm works by selecting an analysis window centered on the main leading edge of the waveform and retracking parameters in this reduced window [-10; $+20$ samples] with a maximum likelihood estimator solving for three parameters, range, amplitude, and sigma composite. The details of the above algorithms are available in PISTACH handbook [22].

D. Collocated Data Sets

The altimeter and buoy measure different aspects of the temporally and spatially varying wave fields, and this causes differences such as temporal proximity, spatial proximity, and sampling variability [9], [23]. The comparison between buoy and altimeter is hence complicated by the fact that the data may differ even if both instruments collect accurate measurements [23]. Hence, a particular criterion for temporal and spatial separation of the data has to be used for a better comparison between the buoy and altimeter data. The widely applied criterion is to consider the data sets, which are within a spatial domain of 50 km and temporal domain of 30 min for collocation [2], [4], [8], [23]. As the present study focuses the validation in the coastal region, where the wave parameters are more dynamic, a smaller spatial (25 km) and temporal window (15 min) is adopted. The collocation points for a particular buoy location is then averaged [24] using the equation:

$$\mathrm{Hs}\,(x_0, y_0, z_0) = \frac{\sum_{n=1}^{N_p} \left(\mathrm{Hs}'_n W_n\right)}{\sum_{n=1}^{N_p} \left(W_n\right)}$$

where N_p is the total number of collocated buoy data points, Hs'_n is the wave height measured by satellite, and W_n is the Gaussian weight function given by

$$W_n = \exp\left\{-\left[\left(\frac{x_n - x_0}{X}\right)^2 + \left(\frac{y_n - y_0}{Y}\right)^2 + \left(\frac{t_n - t_0}{T}\right)^2\right]\right\}$$

The window size $X = 25$ km longitude, $Y = 25$ km latitude, and $T = 15$ min; x_0, y_0, t_0, respectively, are the spatial grid points in longitude, latitude, and time at the buoy location; x_n, y_n, t_n are the spatial grid points in longitude, latitude, and time of satellite data. In this way, two different collocated data sets, namely, buoy-AltiKa and buoy-PISTACH, have been prepared.

For cross-over comparisons, pairs of AltiKa-PISTACH data are selected when crossing point measurements are within a 30-min time window. The data are averaged in a spatial window of 10 km around the cross-over point. Spatial window is made smaller in this case as the time window is doubled to get more collocations, and also to nullify the effect of increased time window.

We have followed standard statistical techniques such as mean bias, root-mean-square error (RMSE), scatter index (SI $= \mathrm{RMSE}/\bar{X}$, $\bar{X}$ averaged observed value), and correlation coefficient (R) for comparison of altimeter data with the *in-situ* data.

III. Results and Discussions

In this section, first we discuss the comparison of SARAL/AltiKa Hs with buoy data, followed by similar comparison with PISTACH-derived products. This is then followed by a comparison of altimeter-derived Hs with data from Inland Lake buoys. This section concludes with an intercomparison of SARAL/AltiKa and PISTACH data.

A. Comparison of AltiKa Hs With Buoy Hs for the Coastal Waters

Primarily, AltiKa performance analysis has been carried out using coastal buoys under different networks covering the coastal areas of three oceans: the Pacific, Atlantic, and Indian Ocean. The collocation provided 1115 data points as shown in Fig. 2(a). The collocated points show the wave heights in the range 0–7 m [Fig. 2(a)]. AltiKa measurements of Hs are highly correlated ($R = 0.98$) with *in-situ* measurements and virtually there is no bias (<6 cm). AltiKa Hs are less scattered with an SI of 0.14. Analysis has been performed for different oceans separately to check the consistency of AltiKa performance [Fig. 2(b)–(d)]. In the Pacific Ocean, both low as well as high wave heights are observed. The highest Hs in the collocated data also occur in this Ocean. The comparison

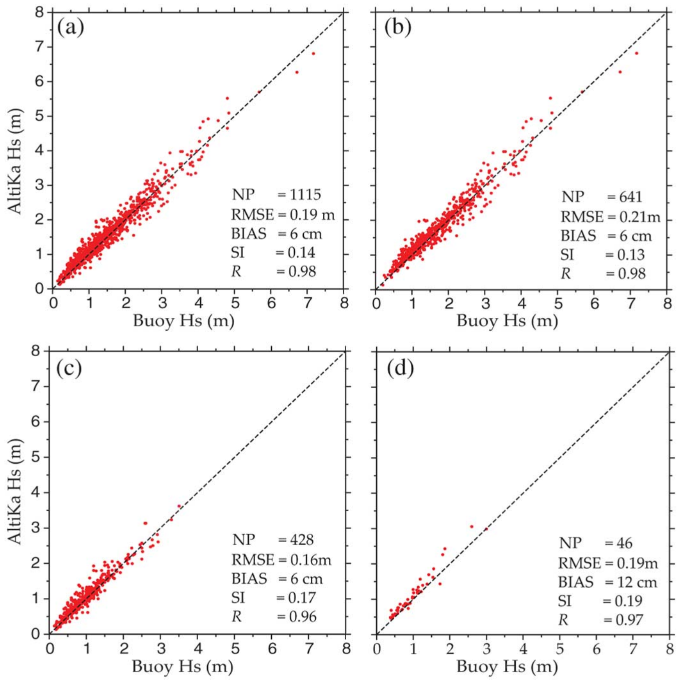

Fig. 2. Scatter plots of collocated Hs observations for AltiKa and buoy for different oceans.

shows very low SI (0.13), negligible bias (6 cm), and high correlation (0.98) in this ocean. The wave heights in the Atlantic Ocean are relatively low compared to Pacific. The statistics for the Atlantic basin are similar to Pacific Ocean with a negligible bias of 6 cm [Fig. 2(c)]. Very few collocated points are obtained for the Indian Ocean and all are very close to the coast. The observed bias is 12 cm with a low SI (0.19) and high correlation (0.97). In general, for all the locations, waves up to 4 m observed except for the Pacific Ocean, wherein high waves up to 8 m observed. The statistics exhibit the consistent performance of AltiKa in all the basins. There is a marginal overestimation of Hs in the low-wave heights and underestimation in the high-wave heights [Fig. 2(a) and (d)]. This is more clear from Fig. 3 which demonstrates the difference between Hs measurements made by the buoys and the AltiKa for different data bins. In the Indian Ocean, high bias is seen in the 2–3 m bin, however, since there is single data point for this bin, so it may not be important for the bias computation. Similarly, the underestimation in the high-wave heights does not seem to be significant as there are only few points greater than 4 m. The underestimation in the high wave heights does not seem to be significant as there were only few points greater than 4 m. Similar type of biases have been noted in past validation studies of altimeter Hs using buoy Hs [8].

The results explained above are based on the collocated points obtained from all the buoys within the 100 km area from the coast. Since AltiKa is a Ka-band altimeter, its performance is very near to the coast that has to be analyzed. For this purpose, the 100 km area has been divided into five zones: 100–50 km, 50–25 km, 25–10 km, <10 km, and <2 km according to the distance from the coast, and the performance of AltiKa is evaluated in these zones separately [Fig. 4(a)–(f)]. Most of the coastal buoys were within the 50 km area from the coast, and

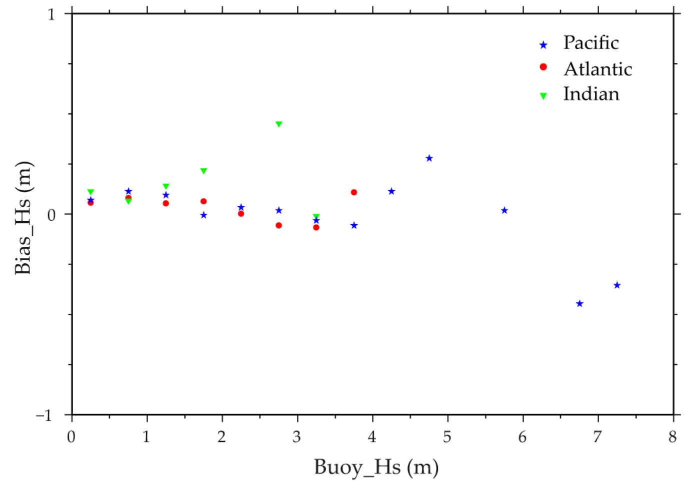

Fig. 3. Differences between the Hs measurements from AltiKa and the buoys for different Hs bins from the buoys.

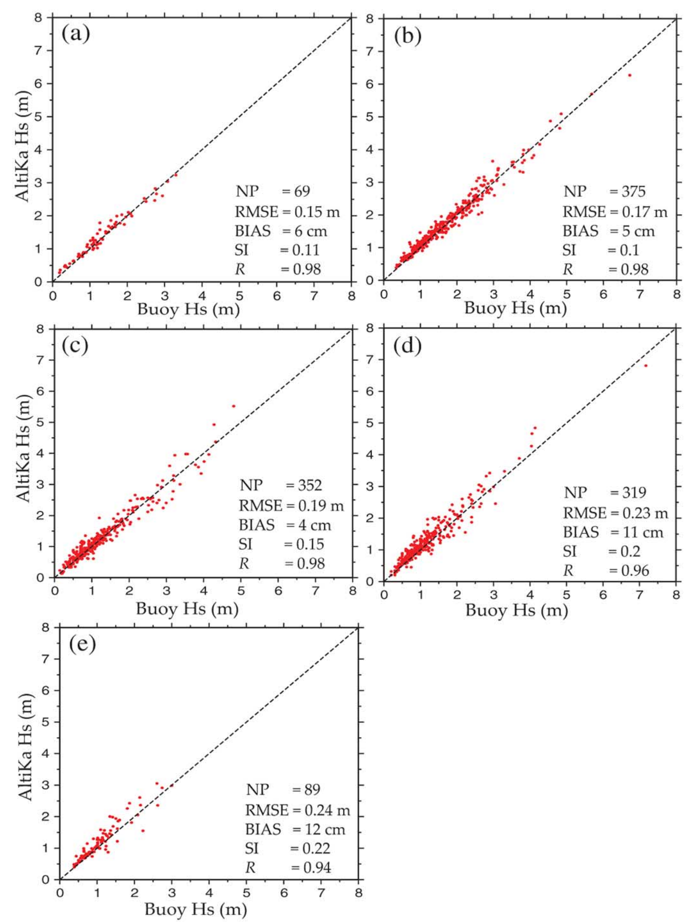

Fig. 4. Scatter plots of collocated Hs observations for AltiKa and buoy according to the distance from the coast: (a) 100–50 km. (b) 50–25 km. (c) 25–10 km. (d) <10 km. (e) <2 km.

there were only seven buoys in the 50–100 km zone. AltiKa Hs was in good agreement ($R = 0.98$, $\mathrm{RMSE} = 15$ cm) with buoy Hs [Fig. 4(a)]. The mean bias was only 6 cm and the SI was only 0.11. Past studies showed that Ku-band altimeters are also capable of giving good measurements of Hs in this area as this distance is sufficient to avoid coastal contamination [9].

Hence, the good agreement of high-resolution AltiKa Hs with buoy Hs is not surprising.

Fig. 4(b) shows the collocated points in the 50–25 km zone which resulted from 31 buoys. In this zone, most of the values are within the 0–6 m range. Similar to the earlier case, a marginal overestimation in the low-wave heights range ($\mathrm{Hs}<1$ m) and underestimation in the high-wave heights are seen here as well. Statistics shows the high accuracy of AltiKa Hs with weak bias (5 cm), high correlation ($R = 0.98$), and small SI (0.11) [Fig. 4(b)]. This shows the reliability of AltiKa data in this particular coastal zone.

In the 25–10 km area, the wave heights are within the range of 0–5 m, and the statistics once again proves the reliability of AltiKa Hs in the coastal waters. There are 32 buoys in this area which resulted 352 collocation points as shown in Fig. 4(c). There is only a slight over estimation in the low-wave height. The AltiKa shows a perfect agreement ($R = 0.98$) with a very low bias (only 4 cm) with the buoys measured Hs in this region. The statistics shows that there is not much difference in the performance of AltiKa in the 50–25 km and 25–10 km coastal zones. This reinforces on the stability of the AltiKa performance in the coastal zones.

Within the 10-km coastal zone, one usual behavior of altimeters is the deviation of the wave forms from the Brown model echo. This demands the use of retracking algorithm in the case of Ku-band altimeters. The high vertical resolution of the Ka-band altimeter in principle should provide accurate measurements in this region without any correction [20]. The performance of AltiKa is analyzed within 10 km coastal zone using data from 34 buoys. In this zone, most of the wave heights were seen in the 0–4 m range [Fig. 4(d)]. The collocated points (319 points) show good agreement with buoy with a marginal overestimation in the entire range of wave heights. The overall bias is 11 cm with an SI of 0.2. The correlation of 0.96 shows that AltiKa performs well within this area as expected. In the collocated data set of Hs, only once Hs was around 7 m. In a shallow water location, 7 m wave heights are quite high. This point resulted as a collocation point of the Scripp's station, 46243 (46.215N, 124.129W), Clatsop Spit, which was at a water depth of 24.7 m. This location receives high amount of wave energy all the times [25]. Fig. 4(b) also showed similar kind of wave height in the collocation data set for the same period. This was obtained in the collocation for the NDBC buoy 46041 (47.353N 124.731W, $\mathrm{Depth} = 114$ m), Cape Elizabeth, which was close and located north to the 46243 buoy. Further analysis of buoy data suggest that the high waves were observed during the period January 11–12, 2014 due to swells. The peak wave period observed was more than 16 s on January 12, 2014. The wave height went up to 7.17 m in the collocation dataset for Clatsop Spit buoy. The AltiKa wave height was 6.81 m. This clearly demonstrates the accuracy of AltiKa-derived Hs in a very high wave conditions in a shallow water location close to the land. The time series of Hs and wave period of Cape Elizabeth was very much similar to the Clatsop Spit buoy, and the peak wave period observed was around 16 s. The wave height in the collocation data set was 6.72 m, and the AltiKa gave a good measurement of Hs, 6.27 m.

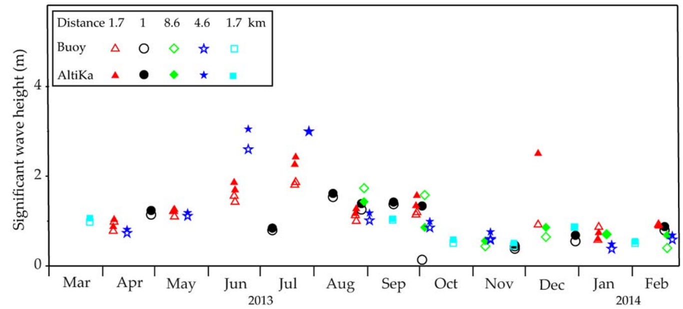

Fig. 5. Time series of collocated points in the Indian Ocean (Diamond, Star and Sqaure symbols: Arabian sea buoys; triangle and circle symbols: Bay of Bengal buoys).

There were eight buoys within the 2 km coastal zone which resulted in 89 collocated data points [Fig. 4(e)]. Most of the wave heights were in the 0–2 m range and show a marginal overestimation in the entire range ($\mathrm{bias} = 12$ cm). AltiKa-derived Hs agreement was quite encouraging with a high correlation ($R = 0.96$), low RMSE (24 cm), and low SI (0.22). The analysis clearly shows that there is no deterioration in the AltiKa Hs even very close to the land. Among the 122 collocated buoys, the Indian Ocean buoys were only seven in numbers. Since the Indian Ocean has only few *in-situ* observations available, a validation of AltiKa Hs is carried out for the Indian Ocean separately using ESSO-INCOIS coastal buoys. Fig. 5(a)–(e) shows the time series comparison of buoy-AltiKa collocated dataset for five buoys, three from Arabian Sea, and two from Bay of Bengal. These buoys are located very near to the coast (distance to the coast is 1–11 km). AltiKa Hs shows good agreement with all the buoys. The Indian Ocean experiences three different seasons (premonsoon, south-west monsoon, and north-east monsoon) in a year and hence different wave characteristics also. Moreover, the southern ocean swell greatly impact the north Indian Ocean wave characteristics, and as a result, most of the Indian coastal regions experiences a mixed sea state. The time series comparison shows AltiKa is capable of resolving dynamic coastal wave conditions (Fig. 5). It is quite encouraging to see that independent of the season and basin, AltiKa Hs shows a very good agreement with all the buoys. The error statistics have been computed for five buoys together. AltiKa Hs agrees well ($\mathrm{Correlation} = 0.97$, $\mathrm{SI} = 0.19$, and $\mathrm{RMSE} = 19$ cm) with the entire range of buoy Hs, with a marginal bias (<12 cm) [Fig. 2(d)]. Very good agreement of AltiKa Hs with the Visakhapatnam buoy Hs which is deployed at 20 m water depth and hardly 1 km from the coast is quite encouraging.

B. Comparison of PISTACH Hs With Buoy Hs for the Coastal Waters

AltiKa is the only one Ka-band altimeter available and it has a repeat cycle of 35 days. As far as the coastal applications are concerned, it is very much necessary to get frequent observation to monitor the coastal wave conditions. So, the wave measurements from a single altimeter having a 35-day repeat cycle may not be fulfilling the need of coastal applications in terms of temporal resolution. Hence, a validation of PISTACH

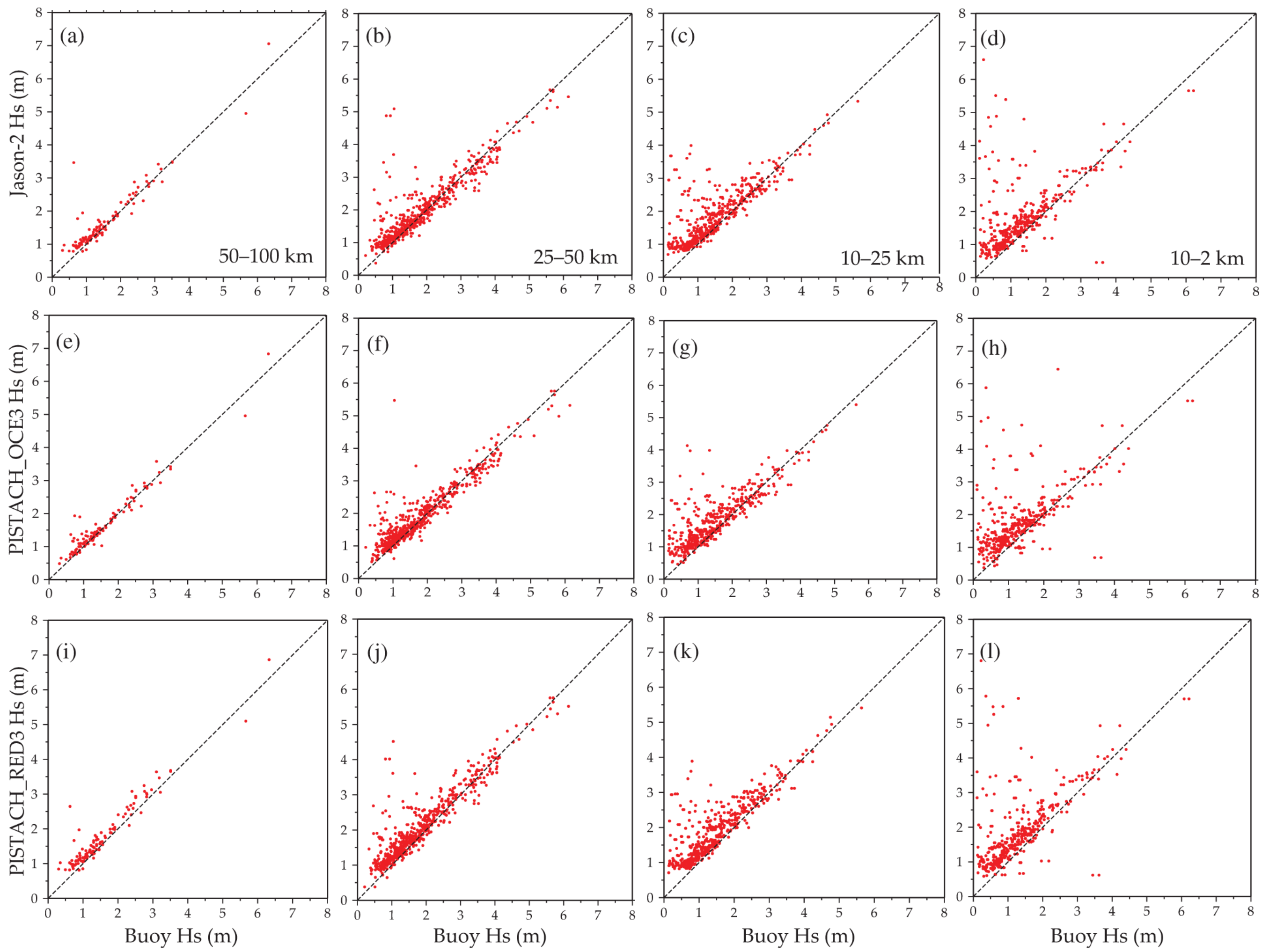

Fig. 6. Scatter plots of collocated Hs observations for Jason-2 with buoy according to the distance from the coast. (a) 50–100 km. (b) 50–25 km. (c) 25–10 km (d) <10 km. (e–h) similarly for PISTACH OCE3. (i–l) for PISTACH RED3.

Hs derived from Jason-2 Hs using retracking algorithms, OCE3 and RED3, has been carried out using buoy-measured Hs. Three different comparisons, Jason-2 Hs with buoy, Jason-2 corrected Hs using OCE3 algorithm with buoy, Jason-2 corrected Hs using RED3 algorithm with buoy (hereafter, PISTACH_OCE3 Hs and PISTACH_RED3 Hs) have been carried out in the different coastal zones according to the distance from the coast in a similar way as given in the earlier sections.

In the 100–50 km zone, the retracking algorithm OCE3 shows better results [Fig. 6(a), (e) and (i); Table I]. PISTACH_OCE3 Hs shows reduced bias and good agreement ($R = 0.97$) compared to the other two Hs (Table I). Similar results are also obtained for the 50–25 km coastal zone. Significant improvement of Hs could be achieved in the PISTACH_OCE3 Hs compared to the Jason-2 Hs. From Fig. 6(b) and (f), it can be seen that few highly overestimated points in the Jason-2 low-wave height measurements are brought close to the observation by the retracking algorithm OCE3. PISTACH_OCE3 Hs showed fairly good agreement ($R = 0.93$) with buoy and is having low bias (15 cm) and SI (0.24). Within the 25–10 km zone, there is a sharp decrease in

TABLE I
ERROR STATISTICS FOR THE JASON-2, PISTACH OCE3 AND RED3 COMPARISON WITH BUOY

Coastal zone	Type	BIAS (m)	RMSE (m)	SI	R	No.
2–100 km	JASON-2	0.3	0.7	0.45	0.78	1676
2–100 km	OCE3	0.28	0.63	0.41	0.82	1676
2–100 km	RED3	0.4	0.86	0.56	0.72	1676
50–100 km	JASON-2	0.15	0.37	0.24	0.93	111
50–100 km	OCE3	0.09	0.26	0.16	0.97	111
50–100 km	RED3	0.22	0.35	0.23	0.96	111
25–50 km	JASON-2	0.16	0.49	0.28	0.89	621
25–50 km	OCE3	0.14	0.41	0.23	0.93	621
25–50 km	RED3	0.26	0.48	0.27	0.92	621
10–25 km	JASON-2	0.36	0.67	0.46	0.79	522
10–25 km	OCE3	0.33	0.6	0.41	0.83	522
10–25 km	RED3	0.43	0.64	0.44	0.85	522
2–10 km	JASON-2	0.49	1	0.77	0.57	422
2–10 km	OCE3	0.48	0.94	0.73	0.6	422
2–10 km	RED3	0.63	1.44	1.11	0.42	422

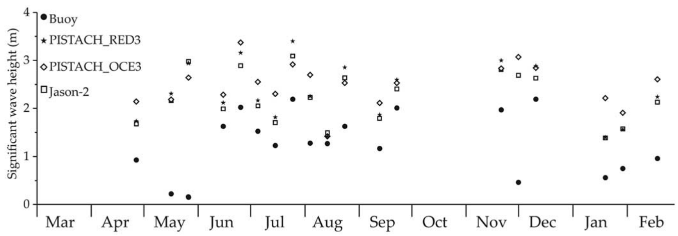

Fig. 7. Time series of wave height for the Visakhapatnam buoy.

the correlation and increase in the bias compared to the 50–25 km zone (Table I). In this range, AltiKa was agreeing well with buoy ($R = 0.98$ and $\text{bias} = 4\ \text{cm}$) [Fig. 4(b)], and this clearly shows the supremacy of AltiKa over Ku-band altimeters. PISTACH_OCE3 Hs shows better results compared to Jason-2 Hs in this zone. In the 2–10 km area, the statistics show a high positive bias. High overestimation of Hs is seen in the entire range of wave heights [Fig. 6(d), (h), (i)]. There is only a marginal improvement in the results of OCE3 which shows that in this area retracking algorithms are not able to improve the results. The performance of RED3 retracking algorithm was poor in the coastal zones. The validation results of the Visakhapatnam buoy, which is located on the east coast of India very close to the coast (<1 km), clearly show the problems in the PISTACH Hs data very close to the coast (Fig. 7). The results are similar for all the buoys within the 2 km area from the coast. This clearly shows that even retracking algorithms fail to correct the Hs data very close to the coast which in turn shows the superior performance of Ka-band altimeter for coastal applications. So, the buoys very close to the coast have been discarded from further analysis with the conclusion that the buoys very close to the coast PISTACH Hs are not accurate.

C. Comparison of AltiKa Hs and Buoy Hs for the Inland Lakes

Radar altimeters are mainly meant for studies of ocean and ice. The reflected echoes from the inland water bodies differ greatly from the ocean wave form in their characteristics [26]. In recent years, altimetry proved its potential to measure inland water surface as well. Even then, in land water bodies, the altimeter wave forms are highly perturbed by emerged lands within radar footprint, and this causes the measurement of Hs to be largely deviated from *in-situ* measurements [27]. AltiKa, like a beam-limited altimeter, is therefore supposed to give good agreement with *in-situ* data compared to Ku-band [20]. To analyze the performance of AltiKa over inland lakes and its advantage over Ku-band, collocation has been done for seven inland lake buoys of United States [Fig. 1(d)]. The collocated points for AltiKa Hs and Jason-2 Hs are shown in Fig. 8(a) and (b).

The statistics of the comparison are extremely encouraging with a very good correlation ($R = 0.94$) and low RMSE ($= 13$ cm). The Jason-2 Hs statistics show an RMSE of 62 cm which is around 5 times higher than the AltiKa RMSE. Jason-2 is having a bias of 41 cm, whereas AltiKa bias was only 1 cm which is negligible. This comparison proves the supremacy of Ka-band over Ku-band altimeters in accurately estimating Inland Lake Hs.

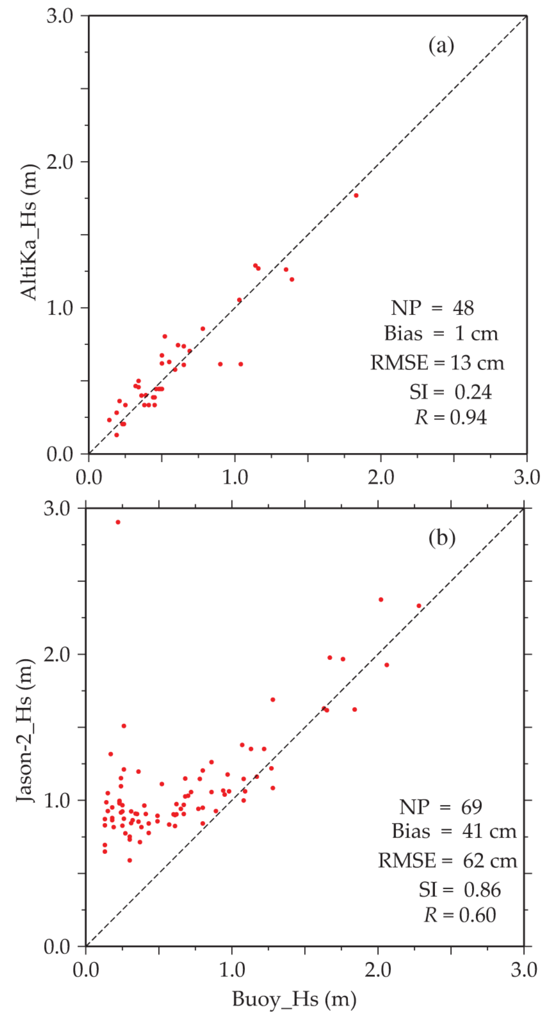

Fig. 8. Comparison between the Hs values of altimeter and inland lake NDBC buoys. (a) AltiKa Hs vs buoy Hs. (b) Jason-2 Hs vs buoy Hs.

D. Intercomparison Between AltiKa Hs, Jason-2 Hs, and PISTACH Hs

The validation of AltiKa Hs with buoy Hs clearly manifested the capability of AltiKa in estimating accurate Hs in the coastal waters. The change in bias (6–12 cm), RMSE (15–24 cm), SI (0.11–0.22), and correlation (0.98–0.94) was marginal from 100 km to near shore. This shows that there is no significant deterioration in the performance of AltiKa though it approaches the coast. The error statistics of Jason-2 Hs shows significant deterioration in the performance of Ku-band altimeter. This is very clear from the change in bias (15–49 cm), RMSE (37–100 cm), SI (0.24–0.77), and correlation (0.93–0.57) in the 100–2 km coastal zone (Section III-B and Table I). The retracking algorithms also failed to make any significant improvement in the Jason-2 Hs in the 25–2 km coastal zone.

In this section, an intercomparison of AltiKa Hs, Jason-2 Hs, and PISTACH Hs has been carried out as both are using same techniques for estimating the Hs. The comparisons have been

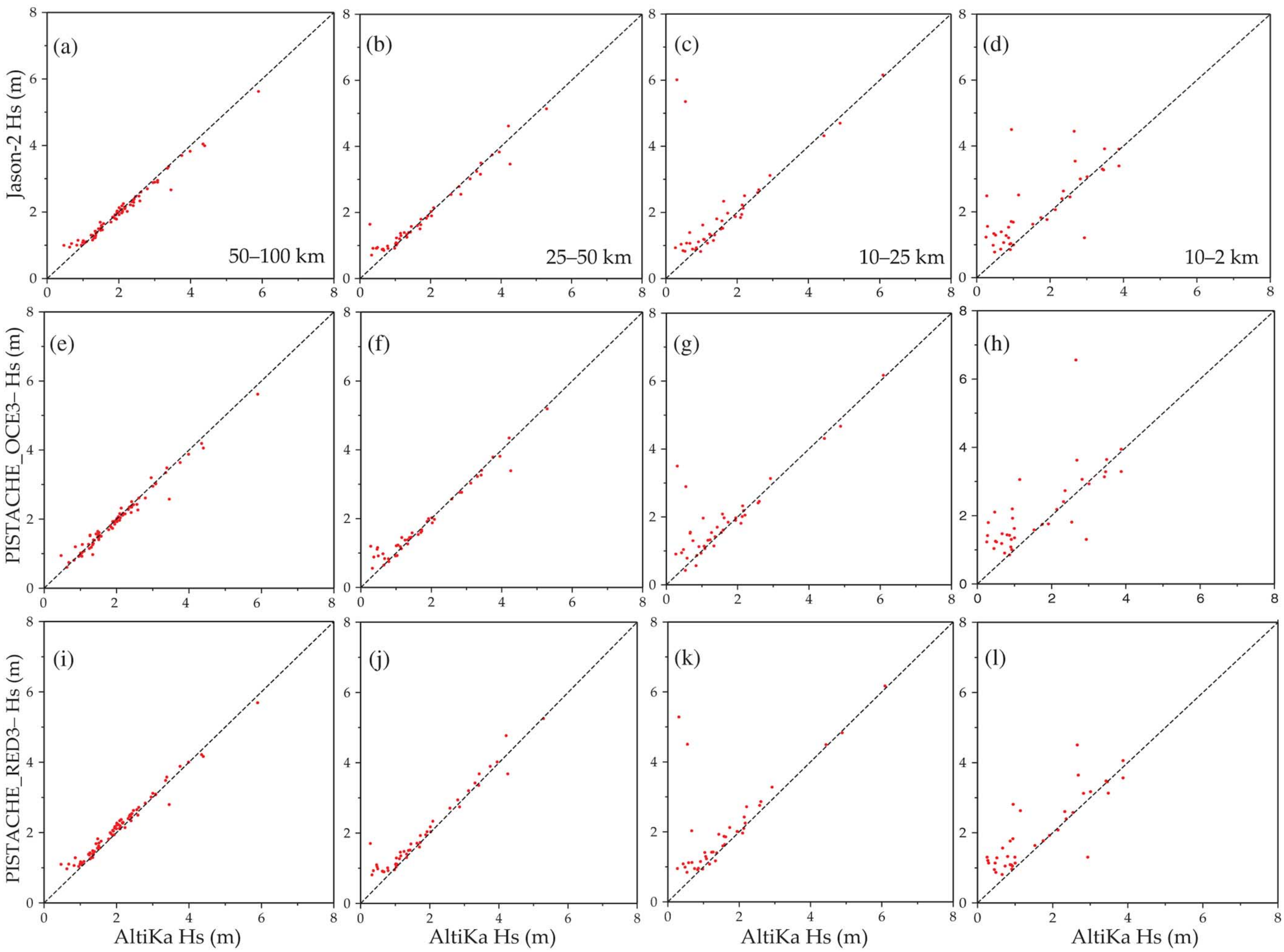

Fig. 9. Scatter plots of collocated Hs observations for Jason-2 and AltiKa according to the distance from the coast: (a) 50–100 km. (b) 50–25 km. (c) 25–10 km. (d) <10 km similarly for PISTACH OCE3. (i–l) for PISTACH RED3.

TABLE II
ERROR STATICS FOR THE JASON-2 HS, PISTACH HS COMPARISON WITH AltiKa HS

Coastal zone	Type	BIAS (m)	RMSE (m)	SI	R	No.
50–100 km	JASON-2	–0.02	0.16	0.08	0.99	81
50–100 km	OCE3	–0.03	0.17	0.08	0.99	81
50–100 km	RED3	0.10	0.18	0.09	0.99	81
25–50km	JASON-2	0.08	0.31	0.17	0.97	47
25–50 km	OCE3	0.07	0.28	0.16	0.98	47
25–50 km	RED3	0.19	0.33	0.19	0.98	47
10–25 km	JASON-2	0.40	1.20	0.75	0.62	41
10–25 km	OCE3	0.28	0.71	0.44	0. 85	41
10–25 km	RED3	0.45	1.06	0.66	0.71	41
2–10 km	JASON-2	0.46	0.94	0.58	0.72	38
2–10 km	OCE3	0.48	0.99	0.61	0.70	38
2–10km	RED3	0.39	0.73	0.45	0.84	38

carried out in different coastal zones as in the earlier cases. Very good agreement is found at collocated points which are within the 100–50 km zone (Fig. 9 and Table II). Jason-2, PISTACH_OCE3 Hs shows similar behavior in this region with a correlation of 0.99 and weak bias ($\sim$10 cm) (Table I). On the contrary, PISTACH_RED3 Hs has degraded the Hs in this area.

At the coastal distance of 25–50 km coastal region, Jason-2 Hs and PISTACH_OCE3 Hs algorithms agree well with AltiKa Hs. PISTACH_OCE3 Hs shows an improved statistics in this zone. In the 10–25 km zone and 2–10 km zone statistics show a degradation of the Hs estimates of Jason-2. OCE3 retracking algorithm found to produce reasonably good Hs in the 10–25 km area. At very near to the coast (distance less than 10 km), collocations are more scattered and the retracking algorithms do not show any improvement in the Hs estimates. Detailed statistics are shown in Table II. Both Jason 2 and retracking algorithms are overestimating the Hs.

IV. CONCLUSION

In this study, significant wave height measurements of AltiKa were analyzed by comparison with buoys in the coastal waters of the global ocean. The comparison is carried out for different basins as well as for different coastal zones according to the distance from the coast. Due to the coarse temporal resolution of AltiKa, another coastal data product PISTACH-derived Hs also has been validated using buoy Hs as well as AltiKa Hs.

Consistent performance of AltiKa is seen in all the basins. No significant deterioration in the performance of AltiKa is seen from the 100 km distance to near shore. The statistics of the comparison proved that the AltiKa meets the expectations of coastal applications in terms of preciseness of the measured Hs. AltiKa was expected to give useful data as close as 5 km from a majority of coastal areas [20]. The comparison of AltiKa with the Indian coastal buoys clearly shows the capability of AltiKa in providing useful data as close as 1 km which is beyond the expectation. The error statistics of the comparison suggest that AltiKa-derived Hs can be used for the coastal studies and validation of model results for the Indian coastal areas. AltiKa measurements over inland lakes showed very good agreements with the *in-situ* observations exhibiting a strong potentiality for monitoring inland water bodies. The overall performance of AltiKa within the 50 km area from the coast also increases confidence in utilization of AltiKa data for the study of coastal dynamic process. AltiKa-derived Hs accuracies in the coastal waters and the assimilation of AltiKa Hs in coastal wave model would significantly improve the coastal wave forecast. It will also contribute significantly to the operational oceanography, which seeks large amounts of *in-situ* and space observation data mainly in the coastal zones.

Validation of PISTACH Hs in the coastal region shows that a significant improvement of Hs could be achieved using OCE3 retracking algorithm in the 100–25 km coastal zone. In the 25–2 km coastal zone, retracking algorithm is failed to make significant improvement in the Hs. Very close to the coast (<2 km), also the quality of Jason-2 as well as PISTACH Hs are not good. This analysis shows the need of a Ka-band altimeter for coastal wave monitoring.

AltiKa is the only available Ka-band altimeter and would not be sufficient to meet all the need of the coastal applications. The study of Jacobs in 2009 has estimated that three altimeters are needed to directly observe the mesoscale variations without any support from the numerical models [28]. A minimum of two satellite altimeters will be required even if the assimilative models are available [20]. So, the launch of Ka-band SARAL/AltiKa altimeter follow-on missions would meet most of the requirement of coastal applications and would definitely help in the improvement of coastal wave forecasting.

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N. K. Hithin received the B.Sc. degree in physics from Kannur University, Kannur, India, and the M.Sc. degree in oceanography from Cochin University of Science and Technology, Kochi, India, in 2010 and 2012, respectively.

From 2013 to 2014, he worked as a Research Assistant with ESSO-INCOIS and completed the present work. Currently, he works as an Assistant Oceanographer with Fugro Survey (India) Pvt. Ltd., Navi Mumbai, India. He has authored an international journal.

P. G. Remya received the B.Sc. degree in physics from Kannur University, Kannur, India, and the M.Sc. degree in physics from M. G. University, Kottayam, India, in 2004 and 2006, respectively, and the Ph.D. degree in physics from Gujarat University, Ahmedabad, India, in 2013.

She was a Research Fellow with Space applications Centre, ISRO, Ahmedabad, from 2008 to 2012. Currently, she works as a Scientist with ESSO-INCOIS, Hyderabad, India. She has authored more than seven papers in the national/international journals. Her research interests include numerical modeling of ocean surface waves and remote sensing.

T. M. Balakrishnan Nair received the Master's degree from Cochin University of Science and Technology, Kochi, India, in 1994, and the Ph.D. degree in marine geology and oceanography from Mangalore University, Karnataka, India, in 2001.

Currently, he is the Head of Ocean Science and Information Services with ESSO-INCOIS, Hyderabad, India. He has authored 32 scientific papers in reputed national and international journals.

Dr. Nair has received the Certificate of Merit for Outstanding Performance in setting up of ocean forecast system from the Ministry of Earth Science, Government of India and Best Government Website Award for contributing in the development of INCOIS Ocean Portal. He is also the recipient of prestigious DAAD Fellowship from Government of Germany.

R. Harikumar received the Master's degree in physics from Kerala University, Thiruvananthapuram, India, in 2002, and the Ph.D. degree in physics, with atmospheric science as his specific research area, from Cochin University of Science and Technology, Kochi, India, in 2010.

He is a Scientist and In-Charge of the Ocean State Forecast Services with ESSO-Indian National Centre for Ocean Information Services (ESSO-INCOIS), Ministry of Earth Sciences, Government of India, Hyderabad, India. Currently, he works in the fields of operational oceanography and marine meteorology. He has research experience in Earth system science for more than 10 years. He has authored 13 papers in the national/international peer-reviewed journals and 35 in conference/symposium proceedings. He has written a book on tropical rain drop size distribution and integral rain parameters.

Raj Kumar received the Master's and Ph.D. degrees in physics from Lucknow University, Lucknow, India, in 1982 and 1984, respectively.

Since 1983, he has been pursuing the research in applications of satellite data for various studies at Space Applications Centre, ISRO. He is leading the research in India on ocean state forecast and satellite data assimilation. Currently, he is heading the Atmospheric & Oceanic Sciences Group, SAC, ISRO.

Dr. Kumar has been awarded the P. R. Pisharoty Memorial Award 2006 and Vikram Sarabhai Award 2008 for his contributions in remote sensing.

Shailesh Nayak received the Ph.D. degree in geology from the M.S. University of Baroda, Vadodara, India, in 1980.

He joined the Space Applications Centre, ISRO, India, in 1978, as a Scientist, and subsequently, elevated as the Director of Marine and Water Resources. He was mainly responsible for conceptualizing, formulating, and executing many national-level projects related to application of satellite data on ocean color, integrated coastal zone management, snow and glacier studies, and water resources.

Dr. Nayak was appointed as the Director, Indian National Centre for Ocean Information Services (INCOIS), Hyderabad, India, an autonomous institution under ESSO, in May 2006. At ESSO-INCOIS, he set up a state-of-the-art Early Warning System for Tsunami and Storm Surges in the Indian Ocean. Currently, he is the Chair, Earth System Science Organization (ESSO), and Secretary to the Government of India for the Ministry of Earth Sciences (MoES), since August 2008. He has authored about 100 papers in international and national journals and atlases.