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Comparison of gridded multi-mission and along-track mono-mission satellite altimetry wave heights with in-situ near-shore buoy data

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Abstract

The applicability of altimeter data for the coastal region is examined by comparing the gridded multi-mission and along-track mono-mission significant wave height (SWH) data with the in-situ buoy measurements at four stations off the east and west coasts of India. Among all of the satellites, a greater number of collocated points and better correlation were found for Jason-2. A comparison of the SWH data from multi-mission products (Jason-1, Jason-2, Envisat, and ERS-2) obtained from AVISO with the measured buoy data shows that all of the satellites overestimated the SWH. Applying a correction factor of 0.75, 0.70 and 0.69 to the altimeter data for stations 1, 2 and 4, respectively, resulted in close agreement with the buoy data (correlation coefficient ~ 0.9-0.96). Monthly averaged buoy and altimeter SWH values show convincing correlation ranging from 0.97 to 0.98 for three stations. The smallest correlation coefficient (0.6) was found at station 3, where the selected grid points are located close to the coast and are influenced by land contamination and wave decay effects. For waves with a SWH < 0.5 m, the correlation coefficient is sparingly low for all stations, which underlines the fact that the altimeter observations for SWH < 0.5 m are unreliable.

Keywords: Satellite altimetry, significant wave height, coastal area, Arabian Sea, Bay of Bengal

1. Introduction

Wave data over periods of many years are necessary for estimating the wave climate at a location. Because the measured data are scarce and measurements are expensive, the wave data are generally derived either from numerical hind-cast models or from satellite-derived observations. During the 1970s, global monitoring of significant wave height (SWH), defined as the average of the highest one third of the waves over time, became a reality and resulted in the first global atlas of SWH data derived from satellite observation (McMillan, 1981), and satellite altimetry brought a global perspective to ocean wave climate assessment (Chelton et al., 1981). Since then, the SWH data from several different satellites have become available, including SEASAT (1978), GEOSAT (1985-1990), TOPEX/POSEIDON (1992-2006), ERS-1 (1991-2000), ERS-2 (1995-2011), ENVISAT (2002-2012), Jason-1 (2002-2013), Jason-2 (2008-present) and Cryosat-2 (2010-present), SARAL/AltiKa (2013-present).

Satellite altimetry has proven its ability to measure a wide variety of oceanographic phenomena, particularly over the data-sparse Indian Ocean region. In the Indian Ocean region, studies have been designed to: i) examine the applicability of altimeter data in the circulation and large-scale model (Eigenheer and Quadfasel, 2000; Basu et al., 2003; Shenoi, 2010), ii) explore the coastal dynamics (Birol et al., 2006), iii) compare the model results (Sarkar et al., 1996) and iv) investigate the variation in sea surface height (Prasannakumar et al., 1993). Sarkar et al. (1990) synthesised the SWH data off the Indian coastline, derived charts showing the monthly mean values over $2.5^\circ \times 2.5^\circ$ grids and studied the validity of these observations against ship-reported and buoy data. Many studies have been undertaken on how best to use the data available from satellite observation systems in wave models (Mastenbroek, 1994; Young and Glowacki, 1996; Voorrips et al., 1997; Greenslade, 2001; Rajkumar et al., 2009). Kshatriya et al. (2001) compared the TOPEX/POSEIDON altimeter-derived wind speed and wave parameters with buoy data in the north Indian Ocean. Validation and calibration of satellite altimetry wave heights have been carried out in many studies (Queffeulou, 2004; Durrant et al., 2009; Abdalla et al., 2010; Ablain et al., 2010; Quartly, 2010; Ray and Beckley, 2003, 2012). The overall accuracy of altimeter measurements of the SWH are compared with buoy observations (Young, 1994; Janssen et al., 2007; Li and Holt, 2007; Zieger, 2009), including the systematic calibration and cross-validation of the SWH data from different sensors. Buoy data are generally assumed to be of high quality and have been used in numerous studies for validation of model data (Janssen et al., 1997; Caires and Sterl, 2003;

Caires et al., 2004) and altimeter data (Tolman et al., 2002; Queffeuilou, 2004; Faugere et al., 2006). Similar efforts have been carried out with Jason-1 data by Desai and Vincent (2003) and Durrant et al. (2009). Calibrations and validation of the TOPEX/POSEIDON, Jason-1 mission have been performed by Ray and Beckley (2003) and Queffeuilou and Bentamy (2007).

Most of the above studies were performed for locations away from the coast, and the altimeter observations collected over the coastal region remain largely unexploited in the data archives (Cipollini et al., 2008). The coastal domain represents a challenging target for exploiting satellite information in which the accuracy is degraded due to a number of factors, including issues of land contamination in the altimeter and radiometer footprints, and these corrections require special attention (Andersen and Scharroo, 2011; Bouffard et al. 2011; Cipollini et al. 2010). Recent developments and processing techniques have increased the level of accuracy of the altimetry data. Even though the altimeter data is contaminated near the coast (<10 km), the long-term measurements in the coastal region is a challenge and the measured data are scarce especially for the North Indian Ocean, we have done a study to know what will be the error in the altimeter data for the coastal locations in North Indian Ocean. Because the waves off the Indian coastlines are influenced by the monsoons, understanding the quality of altimeter data over different seasons or different ranges of wave height is important. Recently, the near-shore wave data collection program off the Indian coastline was launched; therefore, the work described in this paper is designed to compare these data with the nearest available altimeter data. The main objectives of the study are to examine the performance of satellite altimetry SWH data along the coastal region via comparison with the measured buoy data during the years 2010 to 2012 and to understand the variation in the altimeter data for different wave height ranges at four locations off the east and west coasts of India.

2. Data sources

2.1 Satellite altimeter data

A satellite altimeter measures the wave height using the shape of the radar return pulse. Each altimeter mission (GEOSAT, ERS-1, ERS-2, TOPEX, Jason-1, Jason-2, ENVISAT, GFO, and Cryosat-2) has collected global SWH data at various spatial and temporal resolutions. The repeat period (the time required for the satellite to return to the same location) for each altimeter mission varies, and the minimum period is 10 days (Table 1). The altimeter SWH data were obtained from two sources: i) the

along-track mono-mission products of Jason-1, Jason-2, Envisat, ERS-2 and Cryosat-2 from the TUDelft RADS database (Schrama et al., 2000) (<http://rads.tudelft.nl/rads/rads.shtml>) enabling records to be retrieved with the most up-to-date corrections already applied and ii) the near-real-time merged gridded data with a resolution of $1^\circ \times 1^\circ$ from the multi-mission product of AVISO (<http://www.aviso.oceanobs.com/>); these data are used in the study.

Mono-mission processing: The mono-mission product arrays are averaged using $1^\circ \times 1^\circ$ boxes, which are subsequently smoothed and extrapolated using a low-order equivalent system filter algorithm of $16^\circ \times 8^\circ$. Gaps or missing data are filled accordingly. The extrapolation is limited to $8^\circ \times 4^\circ$ to avoid artificial filling of areas without data. Next, a reduced bathymetry mask is applied in which points greater than 2° from the sea are forced to a default value. If more than 30% of the points have default values, no map will be generated (<http://www.aviso.oceanobs.com/>).

Multi-mission processing: High precision altimetry data can be retrieved by multi-mission processing. It allows more along-track data for model assimilation, higher resolution of multi-mission mesoscale maps and better resilience of the multi-mission observation system if an old altimeter becomes unavailable. Topex/Poseidon-ERS and Jason-Envisat are fine examples of how altimetry satellites can operate together. Topex/Poseidon and Jason-1 follow a repeat cycle of ten days designed to monitor ocean variations, so they pass over the same points fairly frequently but their ground tracks are some 315 kilometers apart at the equator-more than the average span of an ocean eddy. On the other hand, ERS-2 and Envisat only revisit the same point on the globe every 35 days but the maximum distance between two tracks at the equator is just 80 kilometers. If one location is the focus of the study, a balance must be ensured between the spatial and temporal resolution. In fact, a satellite that revisits the same location frequently covers fewer points than a satellite with a longer orbital cycle. A better solution for the problem is to combine several operating satellites. At least two altimetry satellites are required to map the ocean and monitor its movements precisely, particularly at scales of 100 to 300 km. With four altimetry satellites available, the resolution of the sea surface height measurements is greatly enhanced in the mesoscale variability (Pascual et al., 2006). A merged map is generated if a minimum of 2 missions are available and the data are cross calibrated using OSTM/Jason-2 as reference mission. The mapping method is similar to that of the mono-mission products (<http://www.aviso.oceanobs.com/>).

Data quality check: All flagged data are rejected, and if a data point is identically zero or exceeds 25 m, then that point is excluded. Data records are also rejected if the orientation of the satellite altimeter drifts

significantly from the nadir. Finally, if the along-track samples are highly variable, then the data are also rejected. The Ku-band SWH data are used for all altimeters because this band is available from all missions. The data rejection has been carried out with default editing criteria on the 20 Hz standard deviation has been applied. The SWH data are generated at a rate of 1 Hz from more rapidly sampled (10 or 20 Hz) data. The details of the RADS altimetry data used in the present study are given in Table 1.

2.2 Buoy data

As we are comparing spatially varying data of satellite with temporally varying significant wave height data from buoys, it is important that the buoy data are measured in areas where the gradients in significant wave height are rather small. The wave conditions often vary rather strongly near to coasts both due to geographical sheltering effects, fetch limited wave growth in winds blowing offshore and shallow water effects. Accordingly two locations (Ratnagiri and Honnavar) located off the west coast of India, and two additional locations (Puducherry and Visakhapatnam) positioned off the east coast of India are selected for the study. The measured wave data used in this study were obtained using directional wave rider buoys (Barstow and Kollstad, 1991) at four locations (Fig. 1). The water depth at the measurement locations, the period of the measurements and the geographic position are listed in Table 2. The wave rider buoys measure the heave in the range of -20 to +20 m and the periods between 1.6 and 30 s with a resolution of 1 cm for the heave. The cross sensitivity of the heave is less than 3%. Data are recorded continuously at 1.28 Hz, and the data for every 30 min are processed as one record. The collected time series is subjected to standard error verification for spikes, steepness and constant signals (Haver, 1980). The wave spectrum is obtained via the Fast Fourier transform (FFT). In the FFT, eight series of 256 measured vertical elevations of the buoy data are added to obtain the spectra. The high frequency cut-off occurs at 0.58 Hz, and the resolution is 0.005 Hz. The SWH, which equals $4\sqrt{m_0}$, is obtained from the spectral moment, where m_0 is the zero-th order spectral moment given

by $m_0 = \int_0^{\infty} S(f)df$, and $S(f)$ is the spectral energy density at frequency f .

2.3 Collocation method

For multi-mission products, the merged gridded data are interpolated (bi-linear interpolation) to the exact buoy location, and a comparison is carried out by taking the nearest grid from the altimeter

multi-mission gridded data. The daily average data set of the gridded products is calculated for comparison. The comparison between the satellite and field data is complicated by the fact that each measures different aspects of the temporally and spatially varying field, and hence, the data may differ even if both instruments collect accurate estimates (Monaldo, 1988). For a better comparison between the buoy and altimeter data, we should use a particular criterion for temporal and spatial separation. Commonly, a temporal window and a spatial separation of acceptability are established between the altimeter track and the buoy location. In the space domain, the size of the window ranges from 0 to 150 km, whereas in the time domain, it varies from 0 to 1.5 h (Caballero et al., 2011). The criteria of 50 km and 30 min are also widely applied (Dobson et al., 1987; Monaldo, 1988; Gower, 1996; Queffeuilou, 2003, 2004; Queffeuilou et al., 2004). Because of the buoy locations considered in the present study are close to the coast (< 5 km), and the time period of study is short (2010-2012), the collocation points obtained are smaller for a 50-km window. Hence, holding the time domain as constant (30 min) and applying a spatial window of 100 km resulted in a larger number of collocation points, an improvement that would make the comparison statistically stable. The Gaussian weight function is applied for averaging the along-track altimeter data to the exact buoy location. The collocated value of the SWH is averaged using Eqn .1 (Kessler and McCreary, 1992).

$$SWH(x_0, y_0, t_0) = \frac{\sum_{n=1}^{N_p} (SWH'_n W_n)}{\sum_{n=1}^{N_p} (W_n)} \quad (1)$$

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

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

where x_0, y_0, t_0 , respectively denote the spatial grid points in x (longitude), y (latitude) and time at the buoy location, and x_n, y_n, t_n are the respective spatial grid points in x, y and time of the satellite data. Additionally, $X = 100$ km, $Y = 100$ km, and $T = 30$ min.

The statistical parameters used for comparison of the altimeter data with the measured data are the bias, root-mean-square error (RMSE), scattering index (SI) : (SI is defined (see Eqn 5) as the

standard deviation of error divided by the mean observed SWH) and correlation coefficient (r) defined as follows.

$$BIAS = \frac{1}{N} \sum_{I=1}^N (Ai - Bi) \quad (3)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{I=1}^N (Ai - Bi)^2} \quad (4)$$

$$SI = \frac{\sqrt{\frac{1}{N} \sum_{I=1}^N [(Ai - \bar{A}) - (Bi - \bar{B})]^2}}{\bar{B}} \quad (5)$$

$$r = \frac{\sum_{I=1}^N [(Ai - \bar{A})(Bi - \bar{B})]}{\sqrt{\sum_{I=1}^N [(Ai - \bar{A})^2 (Bi - \bar{B})^2]}} \quad (6)$$

where Ai represents the SWH from the altimeter, Bi represents the SWH obtained from the buoy measurements, N is the number of data points (collocation points for mono-mission) and the over bar represents the mean value.

3. Results and discussions

3.1 Mono-mission

Calibration of the altimeter SWH data is carried out by comparing the buoy measurements with the collocated along-track quasi-simultaneous radar observations for the SWH taken from different satellites (Fig. 2). Among the satellite altimeters used, a larger number of collocated points were found for Jason-2 and Envisat (815 and 592, respectively, for all stations). The ERS-2 satellite track is missing off the west coast of India during the study period, and hence no collocated points are found for stations 1 and 2. For Jason-1, the along-track data are collected in such a way that the data point does not fall in the window size determined by the collocation criteria. Because the Cryosat is a recently launched mission, the collocated points are few compared with those of other satellites. Dobson et al. (1987) and Monaldo (1988) analysed the typical errors associated with altimeter-buoy comparisons with

consideration of spatial and temporal separation, buoy record duration, and altimeter footprint averaging size as well as platform-specific instrumental error. Monaldo (1988) concluded that differences for an SWH of approximately 0.4 m can be expected when comparing altimeter and buoy estimates, whereas Dobson et al. (1987) found that an overall RMSE of 0.5 m could be expected in collocated measurements within a 50-km range.

At station 1, a high r is obtained with all satellites ranging from 0.93 to 0.97 (Table 3). The RMSE obtained between the buoy and altimeter data varies from 0.32 m to 0.45 m. Jason-2 shows the smallest RMSE of 0.32 m at station 1. The SI values are almost similar and relatively high (0.37 m and 0.36 m) for Cryosat-2 and Envisat, whereas the values are 0.31 m and 0.28 m for Jason-1 and Jason-2. The biases calculated are 0.28, 0.23, 0.17, and 0.25 m. All mono-mission satellites shows over estimation of SWH for higher wave heights similar to the results obtained for multi-mission product. Validation of the wave height data from Jason-2 has been reported in several studies (e.g., Abdalla et al., 2010; Ablain et al., 2010; Quartly, 2010). Ray and Beckley (2012) compared the Jason-1 and Jason-2 wave height measurements with those of the 29 NDBC buoy network and found an RMSE of 0.24 m and 0.23 m with a r of 0.98 each. Using the collocation criteria of 50 km and 30 min, Durrant et al. (2009) found an overall RMS error of 0.227 m for the Jason-1 and Envisat satellites with 3452 and 2157 collocation points, respectively. The Jason-1 data are not collocated at station 2, and the ERS-2 data are not available during the study period. The comparison statistics produced an RMSE of 0.34, 0.38 and 0.37 m for the Cryosat-2, Envisat and Jason-2, respectively, with a r of 0.94-0.96. The SI values are observed as similar (0.31 to 0.35).

Off the east coast of India at stations 3 and 4, comparatively less correlation is observed with all satellites. Among all satellites, station 3 was the least correlated with a r of 0.78, 0.82, 0.88, and 0.83, respectively, for Cryosat-2, Envisat, Jason-1 and Jason-2, whereas for station 4, the values obtained are 0.92, 0.84, 0.92 and 0.77 for Cryosat-2, Envisat, Jason-2 and ERS-2, respectively. The SI values are similar (0.31) for the Cryosat-2 and Envisat at station 3, whereas at station 4, these values are 0.33 and 0.29. The most collocated points (635) are obtained for station 1. Only a few collocated points are obtained for ERS-2 satellite at station 3 (14 points) and station 4 (52 points), where the observed RMSE, bias and SI are 0.20 m, 0.23 m, and 0.23 and 0.31 m, 0.20 m, and 0.27, respectively. A similar study with ERS-2 is reported by Greenslade (2001) using 15 months of ERS-2 data and comparison with data from buoys situated around the coast of Australia. The collocations are limited to altimeter overpasses

occurring within 0.75° of the buoy location. With a limited number of buoys, there were only 83 collocations in this study. The RMSE between the two data sets was 0.38 m, and overall, the altimeter is observed to overestimate the SWH by 0.21 m. In a study of 1194 collocations of buoy and altimeter ERS-2 data with SWH > 1.5 m over 1-year period, Janssen et al. (1997) found an RMSE of 0.39 m and a negative bias of 0.25 m.

The results from station 3 showed a reduced correlation due to the low wave energy condition (SWH varied from 0.2 to 2.4 m with a mean value of 0.7 m) that persists off the east coast of India due to the shadowing effect of Sri Lankan land mass compared with the SW-monsoon-dominated high wave energy condition at stations 1 and 2 (SWH varied from 0.2 to 3.8 m with a mean value of 1.1 m) in the Arabian Sea.

3.2 Multi-mission

Comparisons of the SWH for the altimeter and buoy data show good agreement (respective r of 0.96 and 0.95 during 2010 and 0.97 and 0.94 during 2011) off the west coast of India at stations 1 and 2 (Figs. 3 and 4). The observed exception occurs at station 3, which shows an overestimation of the SWH by the altimeter data during the SW monsoon (June to September). Off the east coast of India, station 4 also shows good agreement (r of 0.9), but slightly less than that observed at stations 1 and 2 (Table 4). The r obtained for stations 1 and 2 is similar to the value (0.96) obtained by Kshatriya et al. (2001) for the data from the North Indian Ocean. At station 3, the correlation reaches its minimum values with a r of 0.59 and 0.68 due to the relatively low SWH at this station compared with that of stations 1 and 2, respectively. The grid point chosen at station 3 is also located close to the coast, and hence errors due to land contamination resulted in error in the SWH. The SWH ranged up to 4 m at stations 1 and 2, whereas the SWH values were low (< 2.5 m) at station 3. The p -value obtained for all stations for the multi-mission products shows that the values are statistically significant for both years (Table 4). The altimeter data shows that the bias obtained indicates that the altimeter overestimates the SWH compared with the buoy measurements. The bias values obtained are 0.39, 0.40, 0.57 and 0.39 m for the four stations during the year 2010, and biases of 0.36, 0.42 and 0.58 m are found at stations 1, 2 and 3 during 2011. A positive bias indicates overestimation of the SWH by the altimeter with respect to the buoy. High values of the estimated slope ranging from 1.19 to 1.38 also indicate the overestimation by the altimeter data. The RMSE between the altimeter and buoy data was similar for both years at station 2

(0.54 m), station 3 (0.72 m), and station 4 (0.51 m). For station 1, the RMSE observed is 0.53 and 0.47 m, for altimeter and buoy, respectively. The SI values obtained are 0.33 at stations 1 and 4, 0.36 at station 2, whereas at station 3, a high value (0.65) of SI is observed during 2010. The present study also indicates the fact that because the grid point is located away from the coastal buoy, the land influence will have a significant effect on the grid averaging. A high RMSE is observed for the coastal location (station 3). Indeed, the closer the satellite tracks to the buoy, the smaller the estimate of the bias between the altimeter and the in-situ data. For collection the gridded data, the reverse situation occurs because the point comes under the influence of the land, and it is also noted that a point that is located too far away (>100 km) will generate error. Less correlation is observed at station 4 compared with the other stations because the selected grid point is 100 km away from the buoy location. The comparison is also carried out after interpolating (bi-linear interpolation) the gridded observation of the AVISO to the exact buoy location rather than taking the nearest grid point (Table 5). Only a slight variation of RMSE on the order < 0.05 m was noted in comparison with the nearest grid and the interpolated grid altimeter data. Although the correlation shows high values at stations 1, 2 and 4, a suitable correction factor is applied to reduce the RMSE between the altimeter and buoy SWH and for use of the value in practical applications. In general, the buoy observational errors are small (< 2%) and include both instrument error and the error caused by misrepresentation of the signal at all scales smaller than the sampling interval. An additional source of error arises from the fact that the buoy observation is a temporal average at a point, whereas the altimeter yields a spatial average over a short period of time. The error arising from these different sampling methods is approximately 8% of the mean observed SWH (Monaldo, 1988).

The over estimation of altimeter data over buoy data observed at all stations (Figs. 3 and 4) is due to the fact that the data available for comparison is not exactly the point of observation, but at the nearest available grid, which is away from the buoy location. The earlier studies done in other parts of the globe also reported over estimation of altimeter data over buoy data. Abdalla (2006) carried out a investigation on Envisat FD wind-wave performance based on data from July 2002 to October 2003 and found that the altimeter overestimates Hs about 9 cm relative to buoy data. Greenslade (2001) studied 15 months analysis with fast delivered ERS-2 situated around Australia and observed that the RMS difference for altimeter and buoy as 0.38 m and the altimeter was found to overestimate SWH by 0.21 m.

The possible approach to get good correlation between altimeter and buoy data is by applying suitable correction factor for the particular region. Correction factor is applied for various regions in the past (Desai and Vincent, 2003; Ray and Beckley, 2003; Queffeuilou, 2004; Abdalla, 2006). All these studies proposed a correction factor using linear regression analysis between buoy and altimeter data by considering either the altimeter or buoy data as dependent and other as independent variable. In present study, the buoy data are taken as the independent variable and altimeter data as dependent variable. Then Altimeter SWH can be written as the linear function of Buoy measured SWH as;

$$SWH_{\text{altimeter}} = SWH_{\text{buoy}} * \text{correction factor} \quad (7)$$

The correction factor represents the slope of scatter plot when the intercept is forced to zero so as to get the proportionality factor (regression coefficient) between altimeter and buoy data. The correction factors estimated for stations 1, 2, 3 and 4 are 0.75, 0.70, 0.51 and 0.69 respectively. Figure 5 presents the scattered plots of the SWH based on the altimeter and buoy data from 2010 and 2011 after correction is applied. When applying the correction factor, the slope is reduced to less than unity, but it is closer to unity than before the correction is applied. The RMSE is reduced from 0.47 m to 0.21 m, 0.54 m to 0.22 m, 0.72 m to 0.29 m and 0.51 m to 0.20 m, respectively, for stations 1, 2, 3 and 4 (Table 6). These results are consistent with those found for the North Indian Ocean (Kshatriya, 2001). The monthly average estimates of the SWH from the altimeter and buoy measurements show that the relationship between the monthly averaged buoy and altimeter measurements of SWH are well described by the straight-line least squares fit (Fig. 6). The y-axis intercepts and slopes differ for each station, and the RMSE varies from 0.42-0.64 m during 2010 and 0.41-0.65 m during 2011, which can be considered an estimate of the uncertainty in the measurement of monthly averages after calibration against buoy measurements (Fu and Cazenave, 2001). It should be noted that a slope less than one in the scatter plots is expected between two measurements of a non-negative quantity (such as the SWH) if random errors occur in both measurements, and it is therefore not indicative of systematic errors in the Jason-1 data (Chelton, 2001). After the correction, the slope of the straight line is close to one at stations 1 and 4.

The SWH in the study region generally ranges from 0 to 3.8 m with SWH more than 1.5 m during the monsoon (Glejin et al., 2013; Kumar et al., 2013). Hence more detailed statistical analysis is carried out by classifying the SWH into four classes for a better understanding of the sensitivity of the altimetry data to low and high wave conditions. The classifications of SWH are: a) SWH > 2.5 m (typical wave height during the peak SW monsoon season), b) SWH between 1.5 and 2.5 m (waves

generally observed during the SW monsoon season off the west coast of India and during the NE monsoon of November-January off the east coast of India), c) SWH between 0.5 and 1.5 m (waves of this range are normally observed more than 50% of the time) and d) SWH < 0.5 m (waves of this class are observed less than 20% of time). At stations 1 and 2 (Table 7), the waves with SWH > 2.5 m show lower correlation (0.46 and 0.54) and a higher RMSE (0.84 m and 0.90 m) with a positive bias of 0.73 m and 0.82 m, whereas the waves in class 'b' and 'c' at stations 1 and 2 show a relatively high correlation (0.71, 0.72 and 0.87, and 0.84). Waves of class 'c' are observed to be more reliable because the RMSE observed is low compared with all other wave classes. The study indicates that the altimeter data show good correlation with the buoy data for SWH values between 0.5 m and 1.5 m. It is also observed that for waves with SWH < 0.5 m, the r is notably low for all stations, which underlines the fact that altimeter observations of SWH less than 0.5 m are unreliable. Reason for this low magnitude of correlation for low values of SWH is directly related to the filtering process and data process. According to the high variability of the natural behaviour of low SWH reaching the coast, the reliability of this low range SWH is directly related to the filtering control and possible bias of the data processing. Hence it can generate inaccurate results.

3.3 Sensitivity with spatial window

A statistical comparison was also performed by reducing the spatial window size from 100 to 75 to 50 km while holding the time domain constant (30 min). It is clear that the reduction in the spatial window size can collocate only a few points, and for certain stations, specific satellites could not collocate even a single point (Fig. 7 and Table 8). For most of the satellites, if the spatial window size is 50-km, the number of points collocated with the buoy locations is reduced to less than half of the value obtained using the 100-km window size. At stations 1 and 3, the Jason-1 satellite pass could not match up < 100 km from the buoy locations. At stations 2, 3 and 4 for Jason-2 and Envisat, most of the collocated points fall within the 75-km range window.

From most of the studies, a more precise comparison can be observed when the buoy and altimeter tracks are closer, and result are more precise. In the present study, similar results are found for Cryosat-2 at station 2; for Envisat at stations 2, 3 and 4; and for Jason-2 at stations 2 and 3. As the window size approaches the buoy location, the RMSE, bias and SI are reduced with a slight increase in the r. The Cryosat-2 shows a similar bias for the SI, with a slight increase in the RMSE and r for the

reduction in window size. Only a few collocated points for Jason-1 resulted in a significant error in the bias and RMSE with much less correlation, similar to the case of ERS-2 in which the r is found to be much smaller (0.75-0.85) compared with that of other satellites. Compared with station 1 and 2, a larger number of collocated points are observed for the 75-km window at station 3 and station 4, which results in a slightly reduced r .

Spatial and temporal phenomena play a vital role in the relationship between Satellite and in-situ data. We have found minimum correlation at station 3 even though the fact that the satellite tracks are closer to the buoy location at the same time station which is far (100 km) away from the grid point has less bias. This contradiction is a result of the fact that even the tracks and buoy location are closer; the tracks are closer to the coast. This will mask the performance of the satellite. Similarly, the error associated with the buoy altimeter comparison greatly reduced if the tracks are closer at some locations for some satellites (Envisat and Jason-2). Also as the spatial window reduces results are more precise. This can be clearly seen from the comparison of Envisat with in-situ buoy for different spatial window. It is clearly seen that, for station 2, 3 and 4 the RMSE, bias and SI greatly reduced as the spatial window approaches the buoy with an increase in correlation coefficient. But all the satellites, not giving same results with Envisat itself fails at station 1. Similar results for Jason-2 at station 2 and 3 is observed, where the RMSE, bias greatly reduced with approaching window size with a small increase in r .

4. Conclusion

The comparison between the significant wave height (SWH) data from the multi-mission product of AVISO) and the measured buoy data at four stations off the east and west coast of India shows that the altimeter data showed good correlation at three out of four stations studied. The monthly average analysis of the buoy and altimeter data also showed good correlations at three stations with a correlation coefficient of 0.97 and linear correlation slopes ranging from 0.64 to 0.77. However, at station 3, the smallest correlations of 0.59 to 0.68 were observed because the grid points are located close to the coast, where the altimeter measurements are known to be unreliable. A suitable correction factor applied for the three stations resulted in a reduction of the RMSE between the altimeter and buoy SWH data. The sensitivity analysis carried out by classifying waves into different classes shows that waves with a SWH between 0.5 and 1.5 m have good correlation with the least RMSE. The sensitivity analysis also reveals the fact that the least correlation occurs when the SWH is less than 0.5 m, and hence the altimeter observations are unreliable when the SWH is less than 0.5 m. Least correlation of SWH for low values

of SWH is directly related to the data processing and filtering control. The complexity near the coast for low values after filtering and data process can generate inaccurate result and hence, the results are unreliable for low wave condition.

From the comparison of mono-mission data, the positive bias for all satellite SWH data with respect to the buoy data shows an overestimation of the altimeter data near the coast, which is similar to the results reported earlier. The results from stations 3 and 4 showed a slightly reduced correlation due to the low wave energy condition that persists off the east coast of India compared with the SW-monsoon-dominated high wave energy condition in the Arabian Sea. Notably good correlation was found for all satellites at stations 1 and 2. Among all satellites, Jason-2 showed better prediction and a larger number of collocated points. Although a slightly reduced correlation is found at stations 3 and 4, the observed statistical parameters of the RMSE, bias and SI values are small, which, in turn, give confidence for the applicability of satellite altimetry for locations within 5 km of the coast. The sensitivity analysis of changes in the collocation criteria by reducing the spatial window size to 75 km and 50 km resulted in only a few collocation points, which may not be sufficient to draw a firm conclusion.

Even when the high variability data are rejected, the performance shows good correlation with small bias. Thus, altimeter measurements represent a good data source to enhance our understanding the variability even near the coast. As the advancement and filtering control progresses even these small error caused due to the land contamination and other complicated processes can be masked in future.

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Figure captions

1. Study area showing the buoy measurement locations (Ratnagiri and Honnavar along the west coast of India and Puducherry and Visakhapatnam along the east coast of India). The depth contours are in meters.
2. Scatter plot of the comparison of data from mono-mission satellites with that from an in-situ buoy for the 100-km and 30-min collocation criteria. Enough collocated points are not available for ERS-2 at Ratnagiri, Honnavar and Puducherry and for Jason-1 at Honnavar and Visakhapatnam.
3. Time series plot showing the comparison between the significant wave heights obtained from an altimeter (AVISO) and from buoy measurements during 2010
4. Time series plot showing the comparison between the significant wave heights obtained from an altimeter (AVISO) and from buoy measurements during 2011
5. Scatter plot of the altimeter- and buoy-measured significant wave height values after applying correction factor during 2010-2011.
6. Scatter plot of the monthly average estimates of significant wave height from buoy and altimeter data for different stations during 2010 and 2011
7. Sensitivity analysis for different spatial windows at four locations for each mono-mission satellite

Table 1. Description of the RADS altimetry data used in the study

Altimeter	Phase	Period	Cycle numbers	Satellite Inclination (deg)	Cycle (days)	Spacing at Equator (km)	Launch date and end date
ERS-2	A	01 Jan 2010-04 Jul 2011	153 - 169	98.54	35	80	21 Apr 95-6 Jul2011
Jason-1	B	01 Jan 2010-03 Mar 2012	294 - 368	66	10	315	07 Dec 2001-01 Jul 2013
	C	07 May 2012-31 Dec 2012	382 - 407				
Jason-2	A	01 Jan 2010-31 Dec 2012	055 - 165	66	10	315	20 Jun 2008-present
ENVISAT	B	01 Jan 2010-22 Oct 2010	006 - 094	98.55	35	80	01 Mar 2002-01 May 2012
	C	26 Oct 2010-08 Apr 2012	095 - 113				
Cryosat-2	A	28 Jan 2011-31 Dec 2012	011- 036	92	30	250	08 Apr 2010-Present

Table 2. Features of the data sets used in the study for multi-mission and the measurement locations

Station number	Location name	Measurement location			Distance of buoy to the nearest selected grid point (km)	Distance of selected grid point from the coast (km)	Distance of buoy from the coast (km)	Temporal coverage
		Latitude (deg)	Longitude (deg)	Water depth (m)				
1	Ratnagiri	16.980	73.258	13	32.0	28	4	1 Jan 2010-31 Dec 2011
2	Honnavar	14.304	74.391	10	53.2	50	3.0	1 Jan 2010-31 Dec 2011
3	Puducherry	11.925	79.851	13	16.8	15	1.9	1 Jan 2010-31 Dec 2011
4	Visakhapatnam	17.632	83.265	15	101.4	100	1.4	1 Jan 2010-31 Dec 2010

Table 3. Statistics of mono-mission satellites comparison with buoy for collocation criteria: 100 km and 30 min

Mission	Station No.	Collocated points	RMSE (m)	Bias (m)	SI	r	Mean x (m)	Mean Y (m)
Cryosat-2	1	139	0.45	0.28	0.37	0.96	1.23	1.52
	2	62	0.34	0.23	0.31	0.96	1.12	1.35
	3	42	0.25	0.06	0.31	0.78	0.81	0.87
	4	85	0.40	0.16	0.33	0.92	1.20	1.37
Envisat	1	157	0.42	0.23	0.36	0.96	1.16	1.40
	2	168	0.38	0.20	0.3	0.94	1.06	1.26
	3	148	0.24	0.15	0.31	0.82	0.78	0.93
	4	119	0.29	0.10	0.29	0.84	0.99	1.09
Jason-1	1	136	0.37	0.18	0.31	0.93	1.20	1.38
	2	-	-	-	-	-	-	-
	3	142	0.24	0.17	0.35	0.88	0.67	0.84
	4	-	-	-	-	-	-	-
Jason-2	1	203	0.32	0.26	0.28	0.97	1.15	1.41
	2	164	0.37	0.24	0.35	0.94	1.04	1.29
	3	159	0.26	0.17	0.35	0.83	0.74	0.91
	4	289	0.39	0.29	0.36	0.92	1.08	1.37
ERS-2	1	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-
	3	14	0.20	0.23	0.23	0.86	0.86	0.92
	4	52	0.31	0.20	0.27	0.77	1.14	1.30

Table 4. Statistics of nearest grid altimeter and buoy SWH data during 2010 and 2011

Station no.	Year	Bias (m)	RMSE (m)	SI	r	p-value	Slope	Intercept (m)
1	2010	0.39	0.53	0.29	0.96	<0.0005	1.24	0.10
	2011	0.36	0.47	0.27	0.97	<0.0005	1.24	0.09
2	2010	0.40	0.54	0.36	0.95	<0.0005	1.31	0.09
	2011	0.42	0.54	0.34	0.94	<0.0005	1.23	0.19
3	2010	0.57	0.72	0.65	0.59	<0.0005	1.19	0.43
	2011	0.58	0.72	0.58	0.68	<0.0005	1.30	0.35
4	2010	0.39	0.51	0.33	0.90	<0.0005	1.38	0.01

Table 5. Statistics for the interpolated gridded altimeter data and buoy data during 2010 and 2011

Station no.	Year	Bias (m)	RMSE (m)	SI	r	p-value	Slope	Intercept (m)
1	2010	0.38	0.51	0.28	0.96	<0.0005	1.24	0.10
	2011	0.34	0.45	0.26	0.97	<0.0005	1.22	0.09
2	2010	0.37	0.48	0.32	0.95	<0.0005	1.23	0.15
	2011	0.39	0.49	0.30	0.94	<0.0005	1.14	0.24
3	2010	0.56	0.71	0.64	0.58	<0.0005	1.17	0.44
	2011	0.57	0.71	0.57	0.68	<0.0005	1.29	0.36
4	2010	0.38	0.50	0.33	0.90	<0.0005	1.38	0.01

Table 6. Comparison statistics of altimeter data and buoy data for the year 2010 and 2011 after correction factor applied

Station no.	Bias (m)	RMSE (m)	SI	r	p-value	Slope	Intercept (m)
1	-0.009	0.21	0.18	0.96	<0.0005	0.93	0.07
2	-0.013	0.22	0.22	0.94	<0.0005	0.89	0.10
3	0.084	0.29	0.38	0.64	<0.0005	0.78	0.24
4	-0.037	0.20	0.20	0.90	<0.0005	0.95	0.01

Table 7. Statistical analysis of altimeter and buoy data for different wave classes

Station no.	class	Bias (m)	RMSE (m)	SI	r
1	a	0.73	0.84	0.14	0.46
	b	0.68	0.76	0.17	0.71
	c	0.23	0.33	0.28	0.87
	d	0.32	0.39	0.55	0.32
2	a	0.82	0.90	0.12	0.54
	b	0.76	0.83	0.17	0.72
	c	0.32	0.46	0.38	0.84
	d	0.26	0.34	0.55	0.07
3	a	-	-	-	-
	b	0.63	0.81	0.28	0.02
	c	0.62	0.76	0.59	0.40
	d	0.41	0.56	0.96	0.38
4	a	-	-	-	-
	b	0.70	0.78	0.21	0.44
	c	0.38	0.48	0.31	0.84
	d	0.12	0.22	0.48	0.70

a) SWH > 2.5 m b) 1.5 < SWH < 2.5 m c) 1.5 < SWH < 0.5 m d) SWH < 0.5 m

Table 8. Number of collocated points for all stations for each satellite at different spatial window criteria

Satellite	Station 1			Station 2			Station 3			Station 4		
	Spatial window (km)											
	100	75	50	100	75	50	100	75	50	100	75	50
Number of collocated points												
Cryosat-2	139	96	64	162	45	30	42	24	14	85	54	40
Envisat	157	101	70	168	110	70	148	114	65	119	95	56
Jason-1	136	12	2	2	2	-	142	142	0	-	-	-
Jason-2	203	-	-	164	147	145	159	140	132	289	287	144
ERS-2	-	-	-	-	-	0	14	14	0	52	46	22

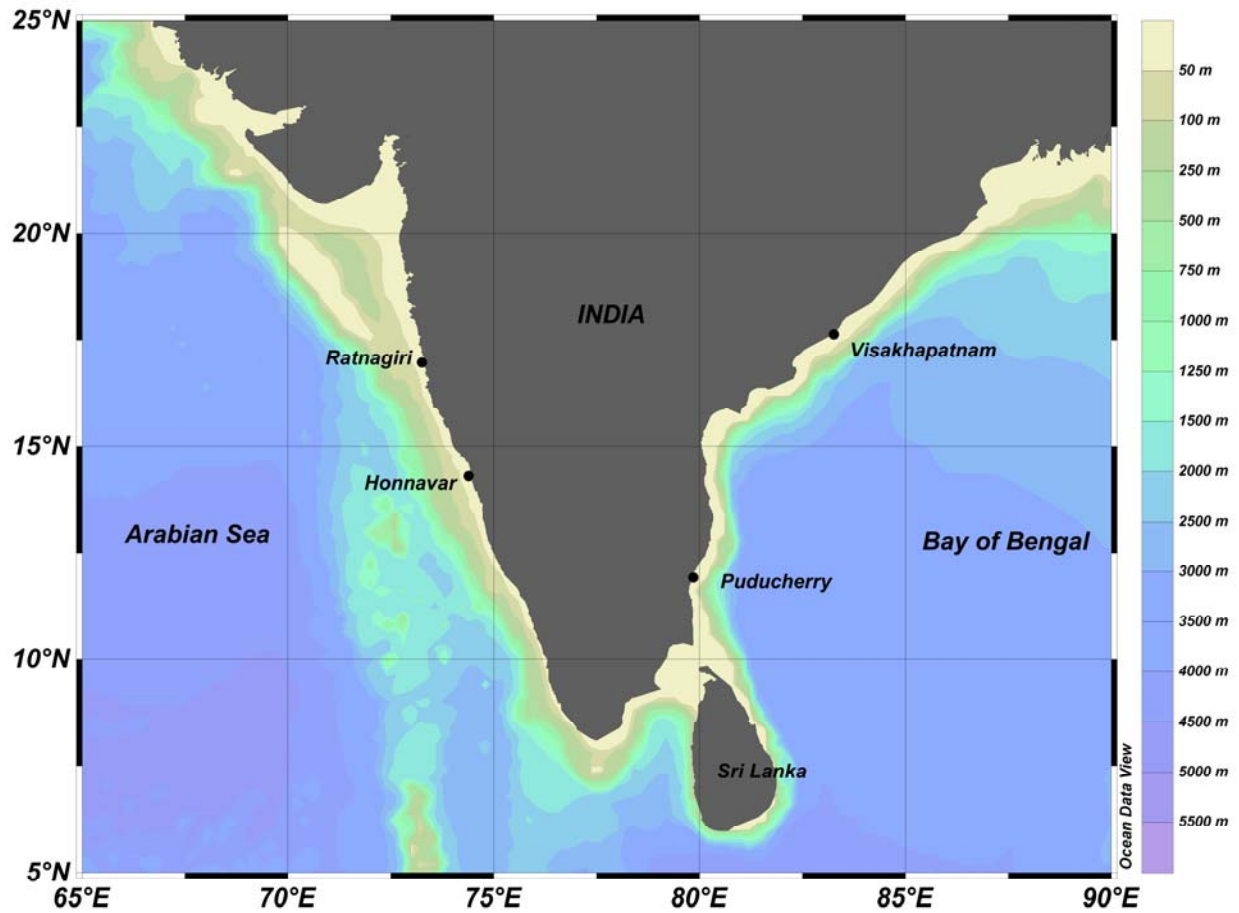


Figure 1. Study area showing the buoy measurement locations (Ratnagiri and Honnavar along the west coast of India and Puducherry and Visakhapatnam along the east coast of India). The depth contours are in meters.

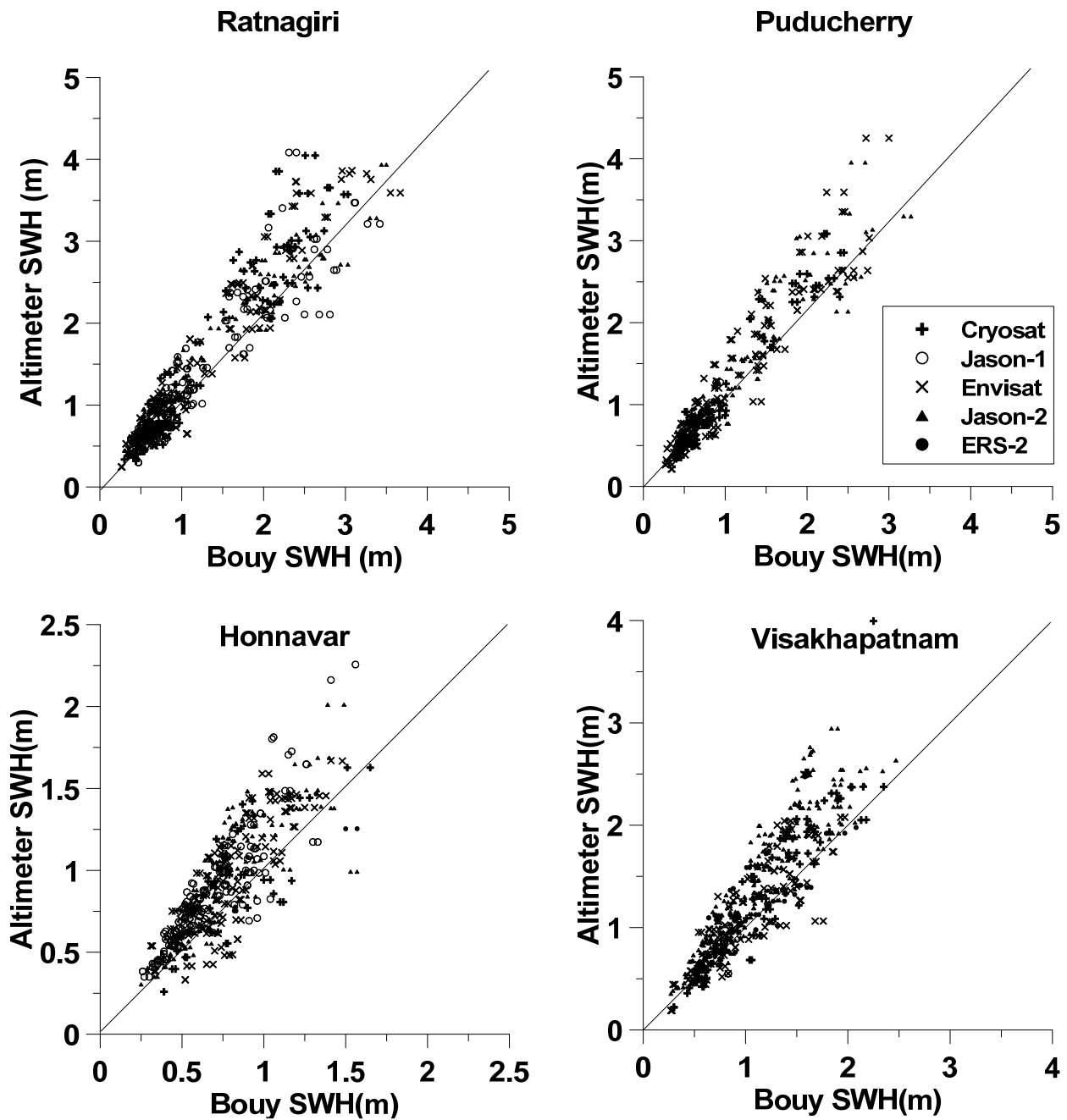


Figure 2. Scatter plot of the comparison of data from mono-mission satellites with that from an in-situ buoy for the 100-km and 30-min collocation criteria. Enough collocated points are not available for ERS-2 at Rantnagiri, Honnavar and Puducherry, for Jason-1 at Honnavar and Visakhapatnam.

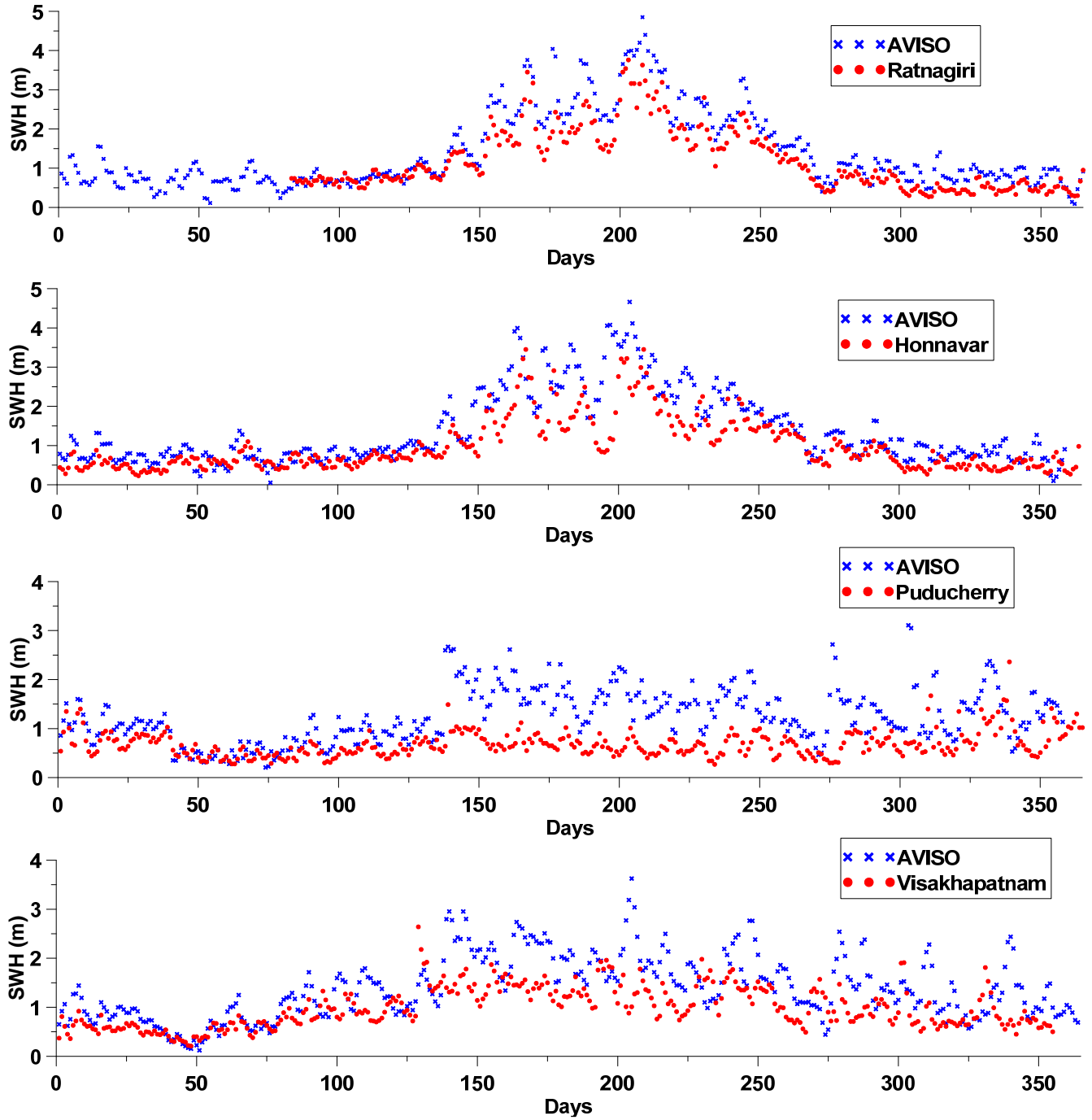


Figure 3. Time series plot showing the comparison between the significant wave heights obtained from an altimeter (AVISO) and from buoy measurements during 2010.

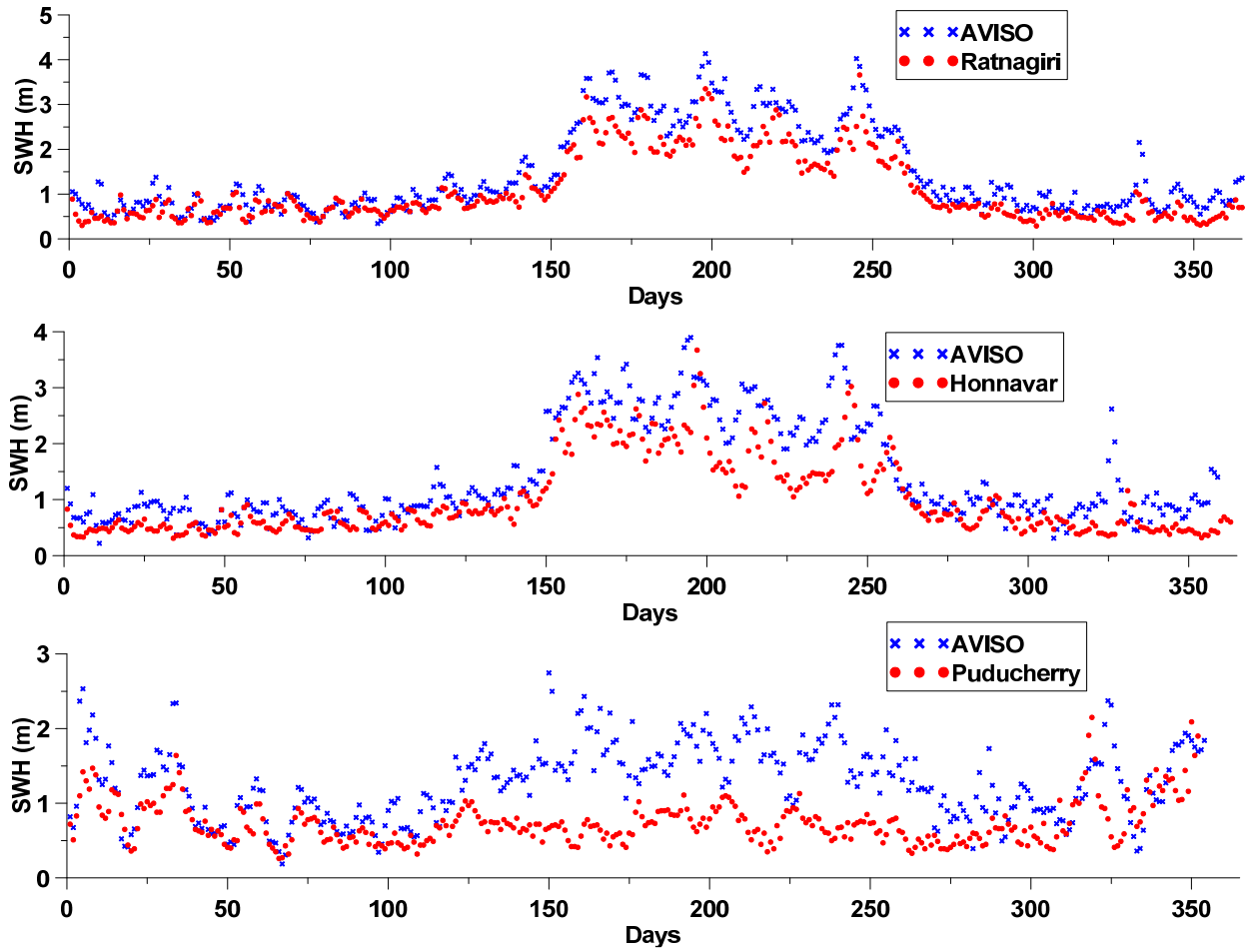


Figure 4. Time series plot showing the comparison between the significant wave heights obtained from an altimeter (AVISO) and from buoy measurements during 2011.

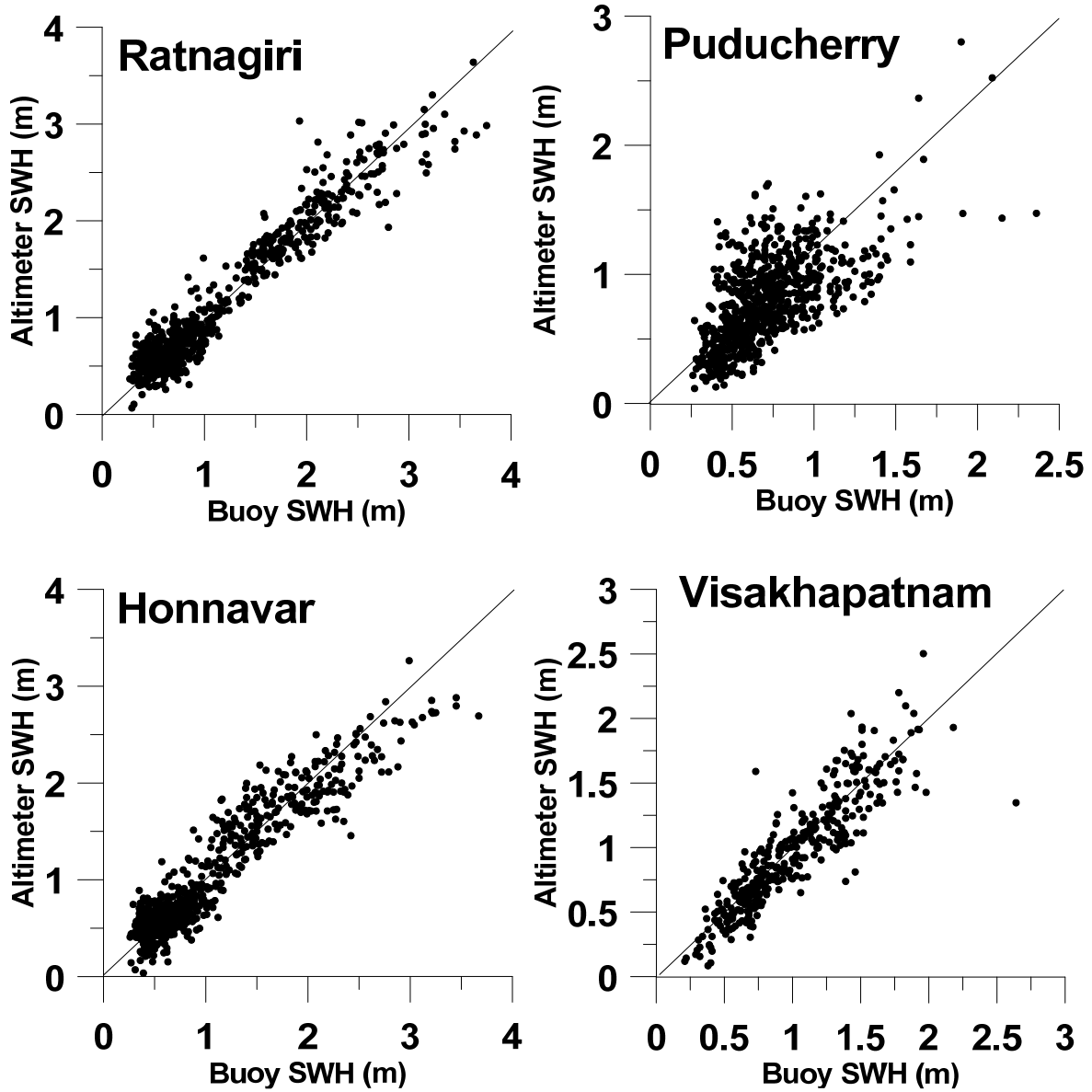


Figure 5. Scatter plot of the altimeter- and buoy-measured significant wave height values after applying correction factor during 2010-2011.

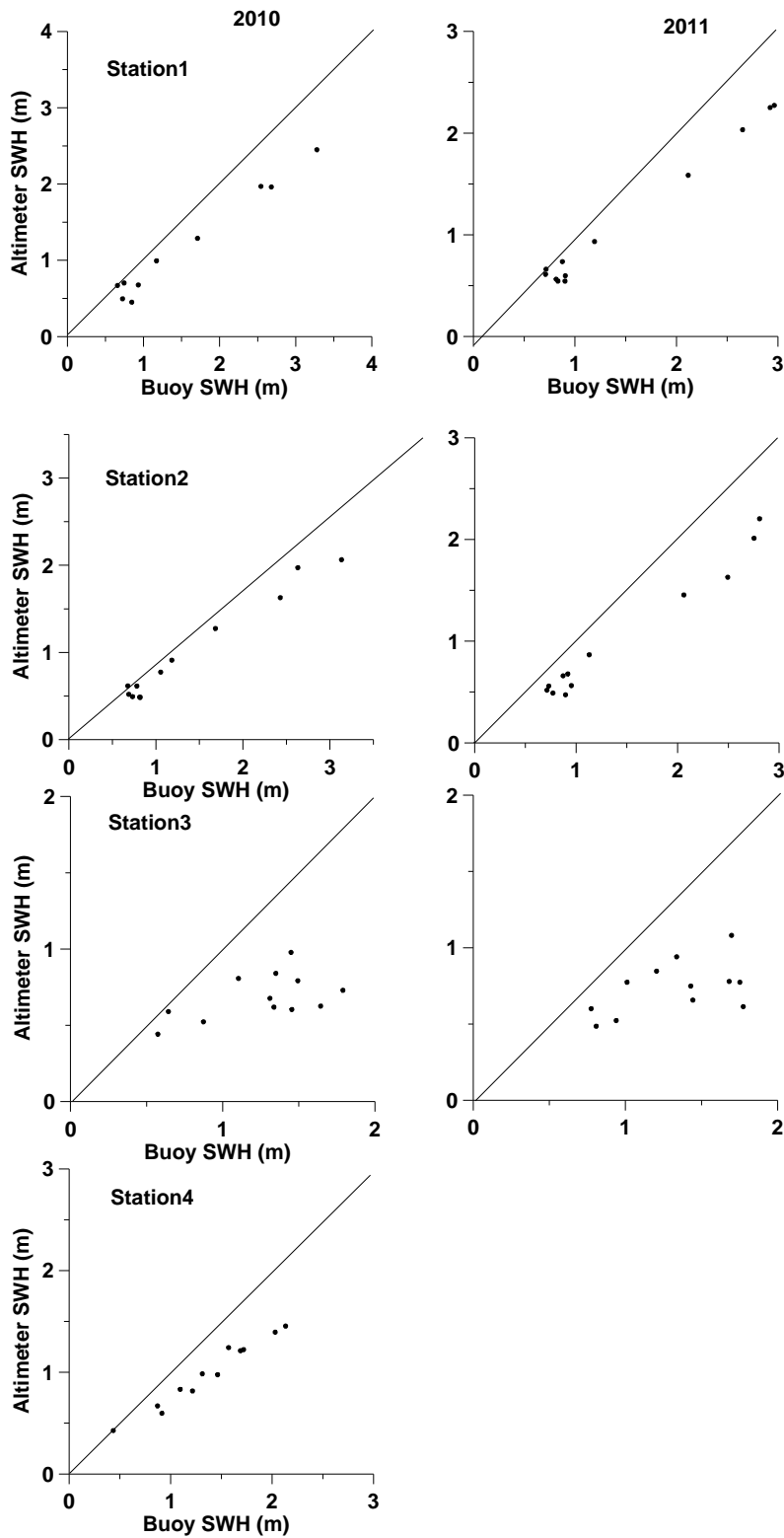


Figure 6. Scatter plot of the monthly average estimates of significant wave height from buoy and altimeter data for different stations during 2010 and 2011.

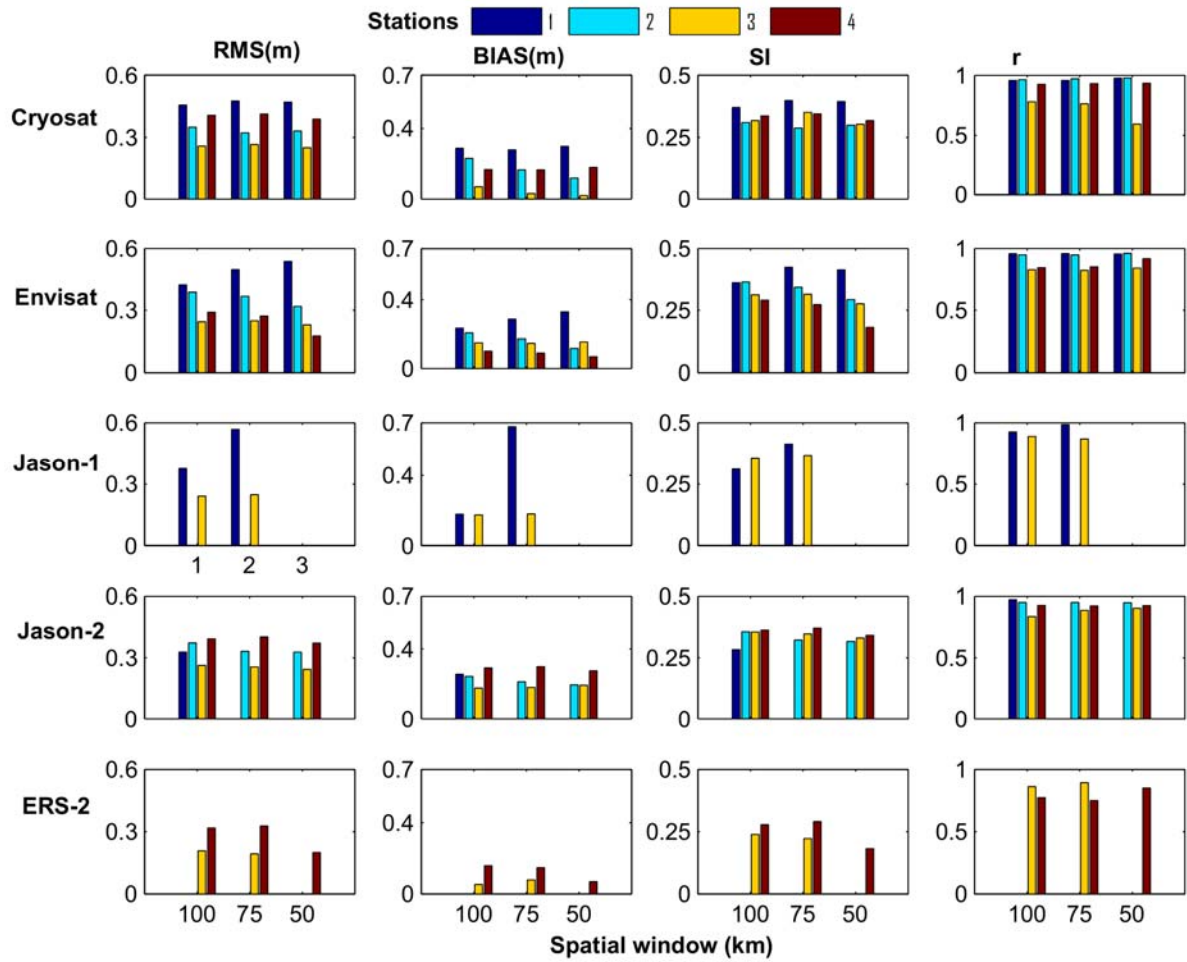


Figure 7. Sensitivity analysis for different spatial windows at four locations for each mono-mission satellite.