Calibration and Validation of HY-2 Altimeter Wave Height

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ABSTRACT

Hai Yang-2 (HY-2) satellite altimeter measurements of significant wave height ($H_s$) are analyzed over the period from 1 October 2011 to 6 December 2014. They are calibrated and validated against in situ buoys and other concurrently operating altimeters: Jason-2, CryoSat-2, and Satellite with Argos and ALtiKa (SARAL). In general, the HY-2 altimeter measurements agree well with buoy measurements, with a bias of 0.22 m and a root-mean-square error (RMSE) of 0.30 m. When the reduced major axis (RMA) regression procedure was applied to the entire period, the RMSE was reduced by 33% to 0.2 m. A further comparison with other satellite altimeters, however, revealed two additional features of HY-2 $H_s$ estimates over this period. First, a noticeable mismatch is present between HY-2 and the other satellite altimeters for high seas ($H_s > 6$ m). Second, a jump increase in HY-2 $H_s$ values was detected starting in April 2013, which was associated with the switch to backup status of the HY-2 sensors and the subsequent update of its data processing software. Although reported by previous studies, these two deficiencies had not been accounted for in calibrations. Therefore, the HY-2 wave height records are now subdivided into two phases (time periods pre- and post-April 2013) and a two-branched calibration is proposed for each phase. These revised calibrations, validated throughout the range of significant wave heights of 1–9 m, are expected to improve the practical applicability of HY-2 $H_s$ measurements significantly.

1. Introduction

Ocean surface winds and waves are of much interest to the oceanography and ocean engineering communities. They interact with each other in a very complicated manner. On the one hand, winds generate waves through the component of pressure in quadrature with the wavy surface (e.g., Young 1999). On the other hand, waves influence sea surface drag and consequently change the flux transferred by winds and the very winds that generated them (e.g., Janssen 2004; Babanin and Makin 2008). When waves propagate against local winds, wave decay is also expected (Donelan 1999). To investigate winds and waves, apart from building analytical theories and numerical models, in situ or remote sensing measurements of them is crucial. Among the diverse methods to observe winds and waves, satellite radar altimeters play a special role. Although having a limited time resolution when compared with buoys or other platforms, altimeters provide an excellent global coverage and by now satellite data have been available for three decades (e.g., Young et al. 2011, 2015). It is well known that the earliest global wave measurements by satellite altimetry can be dated back to 1985, when Geosat was launched (e.g., Zieger et al. 2009). So far, with the efforts of agencies from different countries, a total of 11 satellite altimeter missions have been operational, including the most recent ones by Jason-2 (Dumont et al. 2011), CryoSat-2 (ESRIN/MSSL 2012), Satellite with Argos and ALtiKa (SARAL; Bronner et al. 2013), and Hai Yang-2 (HY-2; NSOAS 2013). HY-2 (also termed HY-2A), launched on 16 August 2011, is China’s first dynamic environmental satellite. It is positioned in a sun-synchronous orbit at an altitude of 971 km and an inclination of 99.34°. Its nodal period is 104.46 min, which translates into an exact repeat ground-track cycle of 14 days (see also Table 1). In addition to a radar altimeter,
HY-2 is also equipped with three other microwave sensors: a scatterometer, a scanning radiometer, and a calibration radiometer. This enables it to simultaneously monitor multiple ocean surface dynamic parameters, such as wind speed and direction, wave height, sea surface height, and temperature. Similar to Jason-2, the HY-2 altimeter operates at dual-frequency bands: Ku band (13.58 GHz) and C band (5.25 GHz). Note that although HY-2 was initially planned for 3 years of operation, at present it is still fully operational. To provide an uninterrupted ocean monitoring service, the Chinese National Satellite Ocean Application Service (NSOAS) has started developing follow-on satellite missions, namely, HY-2B and HY-2C, which are scheduled to launch in 2017 and 2018, respectively.

Table 1. Summary of altimeter missions and data used in this paper including orbit parameters, data duration and source, and the percentage of flagged records, etc. Note that CryoSat-2 here denotes its low-resolution, nadir-looking altimeter mode, and except for the repeat period of 369 days, it also has a subcycle period of 30 days.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Inclination (°)</th>
<th>Repeat period (days)</th>
<th>Band</th>
<th>Data type</th>
<th>Duration</th>
<th>Source</th>
<th>Flagged records (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CryoSat-2</td>
<td>92.0</td>
<td>369</td>
<td>Ku</td>
<td>IGDR</td>
<td>29 Sep 2011–4 Dec 2014</td>
<td>NOAA/NESDIS</td>
<td>14.6</td>
</tr>
<tr>
<td>SARAL</td>
<td>98.6</td>
<td>35</td>
<td>Ka</td>
<td>GDR-T</td>
<td>14 Mar 2013–30 Oct 2014</td>
<td>AVISO</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Altimeter-derived 1-Hz $U_{10}$ and $H_s$ have been extensively used in the literature. As mentioned above, because of the excellent global coverage of altimeter-provided $H_s$ measurements, they can be applied to tune and validate source term components in numerical wave models (e.g., Tolman 2002; Ardhuin et al. 2010; Zieger et al. 2015) and also to verify wave hindcast data archived in operational centers or institutes (e.g., Chawla et al. 2013; Rasle and Ardhuin 2013). Unlike wind observations provided by a scatterometer, the altimeter-derived $U_{10}$ is not usually assimilated into atmospheric models. Therefore, as an independent database, it can be used to evaluate or intercompare different reanalyses (e.g., Caires et al. 2004; Stopa and Cheung 2014). Another advantage of altimeter wind and wave products is their continuity in time, which provides an extraordinary opportunity to study wind–wave climatologies and their trends (e.g., Young et al. 2011). Combined with $U_{10}$ measured by altimeters or other platforms, altimeter-estimated $H_s$ measurements can also find their way to generate global climatologies and seasonal patterns of wind seas and swell (Chen et al. 2002). In addition, Young et al. (2013) demonstrated that by considering certain altimeter transects in the Southern Ocean, a possibility of using altimeter-measured $H_s$ to investigate the decay rate of oceanic swell, upon which these authors then proposed a source term pertaining to swell dissipation for wave models. Other possibilities for the application of satellite altimeter measurements range from assimilating $H_s$ measurements into wave models (e.g., Lionello et al. 1992), monitoring the extreme sea states generated by extratropical and tropical storms (e.g., Tolman et al. 2005; Hanafin et al. 2012; Smith et al. 2013), and validating and optimizing parametric hurricane wave models (Young and Vinoth 2013). It is worth mentioning that additional parameters can also be inferred from a satellite altimeter, such as wave period (e.g., Gommenginger et al. 2003; Mackay et al. 2008; Badulin 2014), ice type (Tran et al. 2009; Rinne and Skourup...
2012), and size (freeboard and area) of small icebergs (Tournadre et al. 2008). The latter two ice-related parameters can be further utilized to study wave climates (Zieger et al. 2013; Babanin et al. 2014) and to interpret the error source in numerical wave models (Ardhuin et al. 2011) in marginal ice zones.

To sum up, by covering long periods of time and extended spatial scales, altimeter-estimated $U_{10}$ and $H_s$ are reliable, useful, and therefore valuable. The uncorrected altimeter measurements, however, tend to bias the true values. Hence, before the data can be analyzed, they should be carefully quality controlled, calibrated, and validated. A number of efforts have been conducted for this purpose. More recently, three consistent, long-term, and multiplatform altimeter datasets have been established and continuously updated—the global altimeter significant wave height (SWH) dataset (Queffeulou 2004 and Queffeulou and Croizé-Fillon 2016), the Global Wave Project (Ash 2010), and the joint calibrated multiplatform altimeter data (Zieger et al. 2009)—with the first two relating to each other (Queffeulou 2013b). The work presented in this paper is the initial attempt to incorporate the HY-2 altimeter data into the third dataset.

There have been several published works assessing HY-2 $H_s$ measurements; these have consistently demonstrated its good quality (Yang et al. 2014; Chen et al. 2013; Wang et al. 2013; Zhang et al. 2015; Ye et al. 2015). The first three works focused on the preliminary calibration of HY-2 wave observations shortly after its launch, while the latter two considered a rather long duration of measurements (>2 yr). A conclusion, however, can be drawn that HY-2 tends to overestimate low $H_s$ (<1 m) and underestimate wave heights throughout the remaining range of heights, especially for high seas, $H_s > 5$ m (e.g., Chen et al. 2013; Zhang et al. 2015). The overall negative bias is $\sim 0.2$ m and the root-mean-square error (RMSE) is $\sim 0.3$ m (see also Table 2). However, regardless of this nonlinear bias, all of these studies employed a linear regression method for calibration. Though significantly decreasing the overall RMSE, such linear correction could not remove the apparent mismatch between HY-2 and other satellite missions, like Jason-2 for high seas (e.g., see Fig. 5 of Zhang et al. (2015); our Fig. 3). This deficiency would severely constrain the application of the HY-2 altimeter data in monitoring high seas, for example, in tropical cyclones. Motivated by this, we reanalyzed the available HY-2 wave products against in situ buoys and other satellite altimeters with the objective of refining its existing calibration. Another motivation was the result reported by Ye et al. (2015) that the accuracy of HY-2 $H_s$ measurements varies with time. Based on measurement performance, they subdivided the whole data period studied into three phases. They, however, did not provide a separate calibration for each phase; thus leaving such an effort for further improvement to this study.


table 2

<table>
<thead>
<tr>
<th>Study</th>
<th>Period</th>
<th>No.</th>
<th>Bias (m)</th>
<th>RMSE (m)</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang et al. (2014)</td>
<td>1 Oct 2011–30 Jun 2012</td>
<td>412</td>
<td>-0.30</td>
<td>0.38</td>
<td>$H_s = 1.070 \times H_s + 0.140$</td>
</tr>
<tr>
<td>Chen et al. (2013)</td>
<td>1 Dec 2011–31 May 2012</td>
<td>617</td>
<td>-0.22</td>
<td>0.36</td>
<td>$H_s = 1.077 \times H_s + 0.067$</td>
</tr>
<tr>
<td>Wang et al. (2013)</td>
<td>1 Oct 2011–29 Aug 2012</td>
<td>902</td>
<td>-0.17</td>
<td>0.30</td>
<td>$H_s = 1.122 \times H_s - 0.025$</td>
</tr>
<tr>
<td>Zhang et al. (2015)</td>
<td>1 Oct 2011–31 Dec 2013</td>
<td>1775</td>
<td>-0.23</td>
<td>0.34</td>
<td>$H_s = 1.031 \times H_s + 0.173$</td>
</tr>
<tr>
<td>Ye et al. (2015)</td>
<td>1 Oct 2011–30 Sep 2014</td>
<td>3745</td>
<td>-0.13</td>
<td>0.38</td>
<td>$H_s = 1.176 \times H_s - 0.200$</td>
</tr>
</tbody>
</table>

This article is organized as follows. Section 2 presents the data and methods we used to evaluate HY-2 $H_s$ measurements. Section 3 shows the overall calibration of HY-2 $H_s$ data against buoys and the cross validation.
against other concurrently operated satellite altimeters. Section 4 proposes our revised calibration for HY-2 $H_s$ measurements, followed by a further discussion in section 5, in which we use data produced by a wave model to demonstrate the validity of our calibration. A brief conclusion in section 6 finalizes this paper.

2. Data and methods

a. Quality control

We analyzed geophysical records from four satellite altimeters: HY-2, CryoSat-2, Jason-2, and SARAL. Data from HY-2 and CryoSat-2 are denoted as the interim geophysical data records (IGDRs), while data for the other two missions are referred to as the geophysical data records (GDRs). Table 1 summarizes the information regarding these data, including their sources, data periods, and the orbit parameters of each mission. Except for SARAL, all the missions have provided records for more than 3 yr.

As far as the calibration of altimeter products is concerned, the first step is to quality control them—that is, to remove the erroneous or suspicious records normally through using a number of empirical criteria. These criteria should not be so rigorous or loose that the calibration and statistics we finally obtain are unrepresentative (Cotton et al. 2003). Basically, the methods of quality control can be roughly categorized into two groups. Both groups rely on the basic flags for altimeter records; for example, land, ice, rain flags, other 1-Hz quality flags, and the number of valid waveforms that make up the 1-Hz sample. The first group, furthermore, depends on additional auxiliary information, such as range $R$, off-nadir angle, peakiness, and the standard deviation (std) of $H_s$ measurements. One should make sure these parameters fall into reasonable ranges that usually can be obtained from handbooks and statistical analyses (e.g., see the appendix of Mackay et al. 2008; Ash 2010). Noteworthy, based on the fact that the logarithm of the std of $H_s$ can be approximately considered to be Gaussian distributed (e.g., Queffeulou 2004), an upper limit of the std of $H_s$ is usually set up to identify “bad” records. This characteristic is shared by many missions, such as Jason-1, the Environmental Satellite (Envisat; Queffeulou 2004), and SARAL (Sepulveda et al. 2015), and also holds true for HY-2. The methods from the first group, however, are somewhat laborious because the thresholds—criteria are normally platform dependent. Thus, we should analyze each mission separately to find reasonable criteria (e.g., Cotton et al. 2003).

The second group uses a more straightforward and also a very efficient method. Under the assumption that the sea state will not change dramatically within a limited geophysical scale say less than $\sim$200 km, altimeter records along the track are divided into blocks of $\sim$25 observations for a further statistical consistency check (Young and Holland 1996; Zieger et al. 2009; Queffeulou and Croizé-Fillon 2016). Spikes or outliers within each block—that is, values that deviate significantly from the mean value of the block—are flagged as bad. Not only intuitive, methods of this kind can also be directly applied to various missions with a slight modification of block size that depends only on the ground scanning speed of each satellite altimeter. A combination of these two groups is also feasible (Abdalla and Hersbach 2004). Following Young and Holland (1996), we chose the second method for the purpose of quality control. For further details of this three-pass procedure, please also refer to Zieger (2010). The proportion of the “flagged” records for the four altimeters used in our work is also shown in Table 1 (last column). Note that HY-2 has the highest percentage (21%).

b. Calibration against in situ measurements

Although not free of errors, the in situ measurements are always regarded as ground truth and were applied to calibrate satellite measurements and to validate wave models (e.g., Bidlot et al. 2002; Li and Sauter 2014). Of all globally operating buoy networks, data from the buoys maintained by the U.S. National Data Buoy Center (NDBC) are most widely used and referenced in the literature due to their excellent quality and long duration, dating back to the early 1970s. After being quality controlled by NDBC staff, the historical NDBC data are archived at the National Oceanographic Data Center (NODC). For this paper, we obtained data for the period from 1 October 2011 to 31 November 2014, which nearly covers the durations of all available altimeter records. Only buoys located more than 40 km offshore were considered in order to avoid the heavily seaward sampling problem when a buoy is too close to a coastline (Greenslade and Young 2004). This criterion finally yielded 63 stations, whose locations are shown in Fig. 1. Although the buoy data were checked by a number of quality-control procedures, a few erroneous values are still unflagged (not shown). Therefore, an additional quality control was carried out in a fashion similar to the method described in Caires and Sterl (2003). More precisely, wave measurements that (i) are too extreme—that is, $H_s < 0.15$ m or $H_s > 30$ m—and (ii) deviate more than 6 times the std of the monthly data from the monthly mean or more than 2 times the std of the monthly data from previous measurements are discarded.

Using the criteria of 50 km for spatial separation and 30 min for time difference (Monaldo 1988), we calculated
the average values along satellite altimeter transects (~15 observations) and linearly interpolated the value to the nearest hourly or half-hourly buoy records (e.g., Queffeulou 2004; Zieger et al. 2009; Durrant et al. 2009). Only transects with more than four valid 1-Hz records were used. Once all the possible altimeter–buoy collocations were located, the reduced major axis (RMA) regression procedure was used to calibrate the altimeter data, with major outliers being eliminated by robust regression (Zieger et al. 2009). Note that other techniques like orthogonal regression and ordinary least squares can also be used to establish the best fit between a buoy and an altimeter measurement (e.g., Queffeulou 2004; Durrant et al. 2009; Ray and Beckley 2012). Other calibration techniques, such as two-branch linear functions or high-order polynomials, were also investigated. The four following statistical parameters: bias $b$, RMSE $\varepsilon$, correlation coefficient $\rho$, and the scatter index $SI$, were utilized to evaluate the performance of the altimeter estimates:

$$b = \frac{1}{N} \sum_{i=1}^{N} (x_i - y_i),$$

$$\varepsilon = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - y_i)^2},$$

$$\rho = \frac{\sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N} (x_i - \bar{x})^2 \sum_{i=1}^{N} (y_i - \bar{y})^2}},$$

$$SI = \frac{1}{N\sum_{i=1}^{N}} [(x_i - \bar{x}) - (y_i - \bar{y})^2].$$

where $x$ and $y$ represent the estimates from two different platforms, for example, buoy, altimeter, or model; the bar over $x$ and $y$ denotes their mean value; and $N$ is the number of collocated measurements. When necessary, $\varepsilon^*$, which signifies the RMSE between the calibrated altimeter values and estimates from other platforms, together with the number of outliers $N_{out}$ among the collocated data, were also used to illustrate the effect of our calibrations.

c. Cross validation against other altimeters

The altimeter–buoy collocated data were basically limited to an area off the U.S. coastline; therefore, altimeter measurements needed to be further validated against other simultaneously operating altimeters on a global scale. For HY-2 validations, three other missions were available: Jason-2, CryoSat-2, and SARAL. Jason-2 and CryoSat-2 operate on the same Ku-band frequency as HY-2. SARAL operates in the high-frequency Ka band (35.75 GHz), which reduces the size of the altimetry footprint and provides better spatial and vertical resolutions. This Ka band–operated altimeter is expected to provide more accurate $H_s$ and an improved performance along coast lines (Hithin et al. 2015, see also our section 3). These advantages are, however, countered by the fact that Ka band is more sensitive to water vapor and cloud cover than Ku band, and therefore the transfer function needed to derive wind speed would need to be revisited (e.g., Lillibridge et al. 2014).

To confidently use $H_s$ measurements from these three altimeters, we first needed to calibrate them against buoys in the same way as previously mentioned and then undertake a cross-validating procedure by analyzing the altimeter to altimeter collocated data, that is, dual-satellite crossovers (Kim 1997) within a 30-min separation. A 100-km along-track average (50 km at each side
of crossovers) of altimeter transects, containing at least 10 valid 1-Hz records, was finally used. Altimeter–altimeter collocated measurements were processed in the same way as was done for the altimeter–buoy collocated measurements (section 2b). In order to detect any variation (jump or drift) of altimeter performance, time series of the differences between altimeter pairs were also investigated (Zieger et al. 2009).

d. Further verification against wave model

Although the period of the altimeter data we considered was relatively long (e.g., >3 yr for HY-2), the altimeter–buoy and altimeter–altimeter collocated measurements were still limited in total number, usually of the order of $O(10^3)$ (section 3). In addition, high sea states ($H_s > 6$ m) were less frequently sampled by these collocated measurements (Fig. 2). Because we wanted to increase the number of collocated points for the calibration of HY-2 $H_s$ measurements, in particular for high seas, we looked at matchups between HY-2 estimates and modeled significant wave height. With the extensive efforts of the wave modeling community over the past several decades and the increasing quality of the wind-driven forcing (e.g., wind fields), wave models nowadays are capable of providing a satisfactory estimate of the sea state, particularly of $H_s$. A very thorough review of this wide topic is given in Cavalieri et al. (2007). Moreover, most recently, the National Oceanographic Partnership...
Program (N OPP; Tolman et al. 2013) dedicated to transition the latest advances in wave science to operational wave models has made several new source term packages available (e.g., Ardhuin et al. 2010; Filipot and Ardhuin 2012; Donelan et al. 2006; Babanin et al. 2010; Rogers et al. 2012; Zieger et al. 2015) and the performance of wave models has been further enhanced.

Modeled wave heights were sourced from the Integrated Ocean Waves for Geophysical and Other Application (IOWAGA) database [Institut Francais de Recherche pour l’Exploitation de la Mer (Ifremer); http://www.ifremer.fr/iowaga], which is available at a resolution of 0.5° spatially and 3-hourly temporally. The database is based on WAVEWATCH III using the semiempirical parameterizations (ST4, TEST471). The reader is referred to Ardhuin et al. (2010), Filipot and Ardhuin (2012), Rascle and Ardhuin (2013), and Leckler et al. (2013) for details. Instead of calibrating the satellite data again, the main objective was to demonstrate the validity of our calibration. Thus, we used only 2 months of data (January 2013 and January 2014) for a very simple illustration. As mentioned in Rascle and Ardhuin (2013), when driven by ECMWF operational winds, the Ifremer wave model presents an obvious negative bias in the predictions for very high seas as a result of the bias existing in the ECMWF winds (see their Figs. 1 and 2). A simple linear correction is proposed by Ifremer for the years 2006–11, given by

\[
H_s^* = \begin{cases} 
H_s, & H_s \leq 8 \text{ m} \\
1.25 \times (H_s - 8) + 8, & H_s > 8 \text{ m}
\end{cases}
\]

(5)

where \(H_s\) and \(H_s^*\) are the raw and corrected wave heights, respectively. We assumed this correction was still applicable for 2013 and 2014, which proved to be reasonable in section 5. The altimeter-measured \(H_s\) was collocated with model products in a similar way as in Rascle et al. (2008). First, the modeled \(H_s\) was interpolated bilinearly in space and linearly in time to the altimeter-measured \(H_s\). And then these interpolated values, together with their 1-Hz altimeter counterparts, were averaged along the track into 1° bins.

3. Results

a. Calibration against buoys

An overall comparison of \(H_s\) measurements between the four altimeters and buoy measurements is presented in Fig. 2. In general, agreements between all the four altimeters and the buoys are very good with high correlation (\(\geq 0.98\)), low RMSE (\(\leq 0.30\)m), and a small scatter index (\(\leq 0.09\)).

1) HY-2

Performance of the HY-2 \(H_s\) measurements is illustrated in Fig. 2a. Based on 1814 collocations, HY-2 has a slightly high negative bias (\(-0.22\) m), a very high correlation coefficient (0.98), and a low RMSE (0.3 m) that is within the stated accuracy (0.5 m). These statistics agree well with the existing studies on HY-2 \(H_s\) measurements as summarized in Table 2. The slope and intercept of the RMA regression are 1.077 and 0.063, respectively, comparable with those of Chen et al. (2013). Seen in Fig. 2a, an underestimation tendency of HY-2 \(H_s\) measurements exists throughout the whole range (1–6 m) and becomes a little more marked for higher values. This is consistent with other studies (e.g., Zhang et al. 2015). The overestimation tendency for low sea states (\(H_s < 1\) m) as addressed in previous studies is, however, absent here due to a severe dearth of small values in our quality-controlled dataset. This lack of small wave height data may have two implications. First, the method we used for quality control (section 2a) may be somewhat too strict for HY-2, although it has been used for previous satellite altimeters (Zieger et al. 2009; Zieger 2010). Second, wave height estimates of less than 1 m tend to be suspicious or erroneous as previously reported by Zhang et al. (2015, see their Figs. 3 and 4). They indicated that at low sea states, HY-2 measurements are either invalid or severely overestimated, and they speculated that this strange behavior might be associated with the limitation of the data retrieval algorithm. The hooklike data cluster for HY-2 and Jason-2 collocated measurements shown in the lower-left corner of their Fig. 5a also shows the strong gradient of HY-2 wave height estimates within this narrow range. Therefore, the absence of low values in our data is probably not caused by our quality-control procedure. Another peculiarity of HY-2 is that the total number of its collocations with buoy measurements is far below those for Jason-2 and CryoSat-2 (Figs. 2b and 2c), although they span the same duration. As explained in Zhang et al. (2015), this is mainly caused by the high proportion of missing–invalid records in HY-2 IGDRs (see also Raynal 2014). The RMA regression reduces the RMSE to 0.2 m, which is a considerable 33%. However, as we can see in the section 3b, this needs to be further reduced.

2) OTHER THREE ALTIMETERS

There are many studies that address the quality of wave height measurements as estimated by the Jason-2, CryoSat-2, and SARAL altimeters (e.g., Queffeulou et al. 2011; Ray and Beckley 2012; Sepulveda et al. 2015; Zhang et al. 2015). The differences in the calibration
results from these studies are usually caused by inconsistent methods of data processing. Therefore, we applied the same calibration procedure to these three altimeters for consistency and show their performances in Figs. 2b–d.

A total of 3164 collocations between Jason-2 and buoys (Fig. 2b) show a significant correlation (0.99), an RMSE as low as 0.14 m, and a negligible bias (0.02 m). The RMA regression is very close to the 1:1 line. All the buoys (Fig. 2b) show a significant correlation (0.99), an correct same feature and proposed a two-branched function to estimate high values. Queffeulou (2013a) found the Fig. 2c, reduces the RMSE from 0.19 to 0.14 m and thereby improves the accuracy of measurements, agreeing well with other studies. It is worth mentioning that both Queffeulou et al. (2011) and Zhang et al. (2015) showed a positive bias, which is similar to our results. Since both the latter two studies and our work focus on the most recent Jason-2 data this might indicate that Jason-2 wave products may have had a marginal change in the past several years. Another factor possibly responsible for this slight difference might be the different version of Jason-2 GDRs [GDR, version T (GDR-T); or GDR, version D (GDR-D)] used by these authors.

For CryoSat-2, data from 2820 collocations are presented in Fig. 2c; these display a slightly higher bias (0.10 m) and RMSE (0.19 m) compared to those from Jason-2 measurements. Compared to Jason-2, CryoSat-2 measurements show a nonlinear bias. CryoSat-2 tends to underestimate $H_s$ for low values ($H_s < 1$ m) and overestimate high values. Queffeulou (2013a) found the same feature and proposed a two-branched function to correct CryoSat-2 $H_s$ measurements (see their Figs. 7 and 8) that consists of a third-order polynomial for low values and a linear adjustment for high values. We, following Greenslade and Young (2004), use a rather simple two-branched linear correction to eliminate this nonlinear bias, given by

$$
H_{s}^{*} = \begin{cases} 
0.836 \times H_s + 0.157 & H_s \leq 1.853 m \\
1.001 \times H_s - 0.149 & H_s > 1.853 m
\end{cases}
$$

This two-branched correction, shown as a gray line in Fig. 2c, reduces the RMSE from 0.19 to 0.14 m and thereby improves the accuracy of CryoSat-2 $H_s$ measurements to the same level as those from Jason-2.

Among the four altimeters considered in this article, measurements from the SARAL mission are of the highest quality. In Fig. 2d, SARAL measurements show the lowest RMSE (0.13 m) and scatter index (0.07). But they have a slightly higher bias (0.06 m) than that of Jason-2 measurements. Also, the RMA regression can further decrease the RMSE to 0.11 m. Sepúlveda et al. (2015) also pointed out that SARAL measurements has a slightly larger bias but lower RMSE than Jason-2 measurements. Since, as mentioned in section 2b, SARAL is capable of providing a high spatial and vertical resolution, it is not surprising that SARAL is superior to the Ku-band altimeters. Most importantly, its performance along coastlines is also fairly encouraging. Hithin et al. (2015) analyzed SARAL $H_s$ measurements in coastal ocean and inland waters, and concluded that SARAL gave a very good performance near the coast (6-cm bias and 19-cm RMSE). In the coastal zone (<2 km from coast), SARAL measurements have a high correlation (0.94) and a low RMSE (0.24 m), with which even the Jason-2 products optimized for coastal application cannot compete.

To summarize briefly, among the four altimeters, SARAL $H_s$ measurements are the best in performance, followed by wave height measurements from Jason-2, CryoSat-2, and HY-2. Nonetheless, the HY-2 $H_s$ measurements are still well within the NSOAS required accuracies and are highly correlated with buoy observations.

b. Cross validation against other altimeters

For HY-2 $H_s$ measurements, the deficiency in the RMA regression shown in Fig. 2a or any other corrections described in previous studies (see Table 2) are clearly shown in this subsection. The collocation data for the four altimeters are shown in Fig. 3, and the time variations of the differences between specific pairs of altimeters are presented in Fig. 4. Note that all the wave heights presented in these two figures were already corrected by the calibration procedures presented in section 3a.

Inspection of Fig. 3 shows that the agreement between Jason-2, CryoSat-2, and SARAL-calibrated $H_s$ measurements is very good (Figs. 3d–f). An almost perfect agreement can be found in SARAL–Jason-2 collocated measurements (Fig. 3d) with a correlation coefficient of 1 and a 0 bias. Since all satellite altimeters use the same principles to sense the ocean surface, the altimeter–altimeter collocated measurements are less scattered than those between altimeter and buoy measurements. For example, for SARAL, the RMSE relative to Jason-2 is 0.07 m, compared to 0.11 m relative to buoys [see also Zieger et al. (2009) for previous missions]. The excellent consistency between the three different satellite measurements reveals that (i) the calibration proposed in section 3a for each satellite is reasonable, especially the two-branched correction for CryoSat-2 [Eq. (6)], which effectively eliminates its nonlinear bias; and (ii) although all the calibrations are derived from a range of wave heights of 0–6 m, the calibrations also perform well for high sea states ($6 < H_s < 10$ m). These conclusions, however, do not hold for HY-2 measurements. An
FIG. 3. The cross-validation results for calibrated $H_a$ measurements (see section 3a) from the different altimeters: (a)–(f) HY-2–Jason-2, HY-2–CryoSat-2, HY-2–SARAL, SARAL–Jason-2, SARAL–CryoSat-2, and Jason2–CryoSat-2, respectively. Shaded contours and statistical parameters are as in Fig. 2, except that the RMA regression formulas are not shown.
examination of Figs. 3a–c shows that although calibrated HY-2 measurements agree well with the measurements from the other three satellites, several incompatibilities can be found. First, HY-2 measurements present a positive bias relative to the other three altimeters; that is, after being calibrated by the RMA regression, HY-2 Hs measurements are inclined to overestimate the sea state. This is most evident when compared with SARAL (Fig. 3c). Second, when $H_s > 6$ m, an apparent mismatch between HY-2 and Jason-2/CryoSat-2 measurements exists (Figs. 3a and 3b); this is represented by the upward bend of the shaded contours and the appearance of the small cluster of outliers. This mismatch is absent in collocation measurements between HY-2 and SARAL because their crossovers are constrained to low latitudes (30°S–30°N). As previously described, these other three altimeters have a very consistent behavior; therefore, we conclude that the RMA regression procedure for HY-2 should be further revised.

Another shortcoming of the HY-2 RMA calibration is displayed in Fig. 4, where the difference between altimeter–altimeter collocated measurements is shown.
as a function of time. For better visualization, block averages over 20 points have been used (Zieger et al. 2009). Similar to what has been seen above, differences between \textit{Jason}-2, \textit{CryoSat}-2, and SARAL (Figs. 4d–f) are relatively insignificant and remain so with time. Only a bias of a few centimeters is to be expected between \textit{CryoSat}-2 and \textit{Jason}-2/SARAL (see also Figs. 3e and 3f). A noticeable jump in \textit{HY-2} measured $H_s$ values occurred in April 2013 and is consistently captured in Figs. 4a–c (the shaded area). According to NSOAS, this jump is related to the switch of \textit{HY-2} to backup status and the subsequent update of data processing software. On the basis of monthly bias and the RMSE of \textit{HY-2} $H_s$, relative to NDBC buoys. Ye et al. (2015) subdivided their data period into three phases: the first phase for the period from October 2011 to September 2012, the second for the duration from October 2012 to March 2013, and the third for the period after April 2013. They reported that the RMSE of \textit{HY-2} $H_s$ measurements was around 0.4 m during the first phase, increased to $\sim 0.5$ m in the second phase, and then improved to 0.3 m after April 2013 in the third phase. The decline of \textit{HY-2} $H_s$ measurement accuracy in their second phase, however, is not obvious in our Fig. 4 (see also Fig. 7), which might be ascribed to the differences between our data processing methods. Nevertheless, the \textit{HY-2} $\sigma_0$ of this period indeed became more scattered (not shown), indicating that electronic drift and sensor degradations could have taken place. Since we only address wave measurements in this article, which are unrelated to the backscatter $\sigma_0$, we chose to divide the data period of \textit{HY-2} $H_s$ measurements shown in Fig. 4 into two phases: phase 1 for the period from 1 October 2011 to 1 April 2013 (cycle < 41) and phase 2 for the period from 15 April 2013 and after (cycle $\geq$ 41).

4. Revised calibration of \textit{HY-2} $H_s$ measurements

As explained in the previous section, \textit{HY-2} $H_s$ data behaved differently in the two separate phases and presented a significant underestimation for high sea states, making the linear RMA best fit formulated in Fig. 2a impractical. In this section, a revised two-branch calibration method for \textit{HY-2} $H_s$ measurements is proposed for both phase 1 and phase 2.

The best way to calibrate altimeter wave height is undoubtedly to use in situ buoy measurements as we did in section 3a. Nonetheless, for \textit{HY-2} measurements, there were only very few buoy collocations when sampling high seas (Fig. 2a) and thus this presented difficulties for our study. Considering the excellent consistency between \textit{Jason}-2, \textit{CryoSat}-2, and SARAL-calibrated $H_s$ measurements (Figs. 3 and 4) throughout the 0–10-m range, we resorted to adopting measurements from these three satellites for this recalibration objective. This method is appropriate and has been employed by Queffeulou (2013a) to calibrate \textit{CryoSat}-2 $H_s$ measurements in a global sense.

In Fig. 3, the negative bias in \textit{HY-2} $H_s$ measurements present at high $H_s$ values is clearly illustrated by its \textit{Jason}-2 and \textit{CryoSat}-2 collocated measurements (Figs. 3a and 3b). We opted to regard the corrected \textit{Jason}-2 $H_s$ measurements as reference, leaving \textit{CryoSat}-2 values as a uniquely independent source to verify the revised calibration, especially for high sea conditions. Following Queffeulou (2013a), the collocated \textit{HY-2} and \textit{Jason}-2 measurements shown in Fig. 3a were grouped into 0.25-m bins and averages and stds were calculated and are shown in Fig. 5. Afterward from these binned statistics, a two-branch correction was fitted that consists of a linear function for small waves and a second-order polynomial for large waves as given by Eqs. (7) and (8) for phase 1 and phase 2, respectively,

\begin{align}
H_s^{\text{phase 1}} &= \begin{cases} 
1.003 \times H_s + 0.287 & H_s \leq 3.504 \\
0.040 \times H_s^2 + 0.838 \times H_s + 0.376 & H_s > 3.504 
\end{cases}, \\
\text{phase 2 (cycle} \geq 41): \\
H_s^{\text{phase 2}} &= \begin{cases} 
0.977 \times H_s + 0.187 & H_s \leq 3.568 \\
0.013 \times H_s^2 + 1.083 \times H_s - 0.359 & H_s > 3.568 
\end{cases}. 
\end{align}

Once again, an examination of Fig. 5 shows that the negative and nonlinear bias in \textit{HY-2} $H_s$ measurements is present in each phase. The two-branched corrections (black solid lines) are capable of following the upward bends of shaded contours that are present in the 5–7-m wave height range. Moreover, the two-branched calibration in Fig. 5b is closer to unity than that in Fig. 5a, which in fact demonstrates the better quality of \textit{HY-2} wave products in the second phase. We note that for phase 1, the nonlinear bias of \textit{HY-2} $H_s$ measurements relative to \textit{Jason}-2 previously had been fitted by Chen et al. (2013) with a fifth-order polynomial; however, they finally applied a linear regression method to calibrate \textit{HY-2} wave estimates.

The \textit{HY-2} measured-wave heights calibrated using Eqs. (7) and (8), were again compared to collocated-buoy

\footnote{There were no \textit{HY-2} data from 2 to 13 April 2013 due to the instrument maintenance.}
measurements and the values from the other three satellite altimeters (calibrated values) in Fig. 6. When compared to buoys (Fig. 6a), HY-2 wave height estimates now are almost unbiased (0.01 m) and have a much lower RMSE of 0.17 m versus 0.30 m for the uncorrected data (Fig. 2a). The RMA best fit is nearly equal to 1, proving that using Jason-2-calibrated Hs measurements as the ground truth, does not trigger any incompatibility with in situ observations. Since Eqs. (7) and (8) are derived from Jason-2-corrected Hs values, it is not surprising that after the calibration, HY-2 and Jason-2 are in excellent agreement (Fig. 6b), represented by the zero bias and full linear correlation. The most encouraging result is displayed in Fig. 6c, where HY-2 and CryoSat-2 collocated data are illustrated. Here, the mismatch between HY-2 and CryoSat-2 shown in Fig. 3b is absent. The RMSE also decreased from 0.15 to 0.11 m. Improvements can also be seen in the collocated data differences between HY-2 and SARAL. In Fig. 3c, HY-2 is clearly overestimating sea states in the 3–5 m range; while in Fig. 6d, these two altimeters on different platforms agree much better, as indicated by the decrease of RMSE from 0.12 to 0.07 m. To check whether the revised calibration eliminates the time discontinuity displayed in Figs. 4a–c, the variation with time of the difference between HY-2 and buoy measurements is plotted in Fig. 7. Statistics for HY-2 measurements relative to the buoys can also be seen in Table 3. For phase 1 (the third row of Table 3) HY-2 raw wave data show a bias of −0.31 m and an RMSE of 0.37 m; while for phase 2 (the fourth row in Table 3) the bias and RMSE are considerably improved to −0.13 and 0.21 m, respectively, approaching the quality level of CryoSat-2. Our final calibration turned out to be effective, especially for phase 1 in which the RMSE decreased from 0.37 to 0.19 m. Furthermore, the marginal distinction between RMSEs of HY-2-calibrated Hs values from the two phases (0.19 and 0.16 m, respectively) indicates that the quality of each phase is now similar. Visually, the sign of this improvement can be seen in Fig. 7, where the bias between HY-2-calibrated Hs and buoy measurements are clustered around the horizontal zero line without any conspicuous jump.

5. Discussion

This section focuses on verifying the practical applicability of our revised calibration provided in the section above. One may argue that the dataset we used to fit the calibrations Eqs. (7) and (8) is limited and less representative for real high seas. Here, we attempt to indirectly prove the validity of the revised calibration. Numerical wave models can provide excellent resolution in both temporal and spatial scales. Comparing altimeter data to a model can definitely increase the sample size of the collocated dataset and, consequently, the probability of representing a wide variety of sea states. However, since wave models are inclined to be

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2 When more data are available in the future, a method that uses half of the reference data for calibration and the other half for validation is preferred.
less accurate than altimeters, we avoid using them for
the ground truth. Instead, we compared both HY-2- and
Jason-2-calibrated \( H_s \) values to wave model estimates. If
the two altimeters yield similar patterns and statistics,
then we could conclude that if adopting our calibration,
results in HY-2 \( H_s \) values are to some degree similar to
Jason-2 ones—then these calibrated HY-2 \( H_s \) values are
now more realistic.

Since we just wanted to demonstrate the validity of
our calibration, we used only two-months of model data,
consisting of January 2013 from phase 1 and January
2014 from phase 2 of HY-2 measurements. The com-
parison between Jason-2–HY-2 and the wave model is
shown in Fig. 8. For both Jason-2 and HY-2, more than
50,000 instances of collocated measurements were ob-
tained for each month. Focusing first on Jason-2 (Figs. 8a
and 8d), the agreement between Jason-2 results and the
wave model is quite good: for each month, the correla-
tion coefficient is 0.97 and the scatter index is 0.12. The
comparison of January 2013 shows a bias of 0.11 m and
an RMSE of 0.34 m; while January 2014 gives slightly
improved result (a bias of 0.07 m and an RMSE of
0.31 m). These statistics are very similar to the results of
Zieger et al. (2015, see the middle panel of their Fig. 13).
The difference between Figs. 8a and 8d is that in the
latter panel, Jason-2 \( H_s \) values tend obviously to be
higher than model estimates in the 6–10 m range,
whereas this is not evident in Fig. 8a. As the correction
of Ifremer waves given by Eq. (5) is only a simple ap-
proximation, this relative discrepancy is not unexpected.
Figures 8b and 8e show the comparison between HY-2
raw data and model estimates. As expected, the statistics
are more scattered than that for Jason-2. The shaded
contours show an underestimation of HY-2 \( H_s \) values in
high seas. The improvement in HY-2 \( H_s \) values in phase
2 can be seen through better error metrics and the more
compact contours in Fig. 8e. Finally, HY-2 \( H_s \) mea-
surements, calibrated by Eqs. (7) and (8), are compared

![Graphs showing data comparison](image-url)
with collocated model estimates in Figs. 8c and 8f. As seen in these two panels, our calibration significantly improves the performance of HY-2 $H_s$ values, particularly when bias is considered. Both the statistics and the patterns are much closer to those of Jason-2 (Figs. 8a and 8d), except that HY-2 $H_s$ values are slightly scattered. It is worth noting that the overestimation of HY-2 values in low sea states, which is not conspicuous in collocated measurements by HY-2 and buoys or other altimeters (Figs. 2 and 3), now becomes noticeable. These small waves, however, were not resolved sufficiently by our quality-controlled datasets (see also section 3a) and hence no attempt was made to correct them.

6. Conclusions

The $H_s$ values obtained by the HY-2 altimeter (IGDRs) and three other concurrently operated satellite altimeters were evaluated against NDBC buoys. A cross validation of these four altimeters was also undertaken. From our studies, the following conclusions are drawn.

1) Among the four altimeters, SARAL gives the lowest RMSE (0.13 m) and the lowest scatter index (0.07), followed by Jason-2, CryoSat-2, and HY-2. Despite this, HY-2 obtained $H_s$ values are still well within its stated accuracy (Fig. 2).

2) When compared with in situ buoy measurements, HY-2 $H_s$ values have a tendency to underestimate real sea states when $H_s > 1$ m (Fig. 2a) and overestimate small waves (Figs. 8c and 8f). However, this latter characteristic is not well resolved by our quality-controlled datasets, in which a severe dearth of small waves exists. The absence of the “good” small waves in HY-2 $H_s$ estimates probably resulted from the error in the data retrieval algorithm, as

Table 3. The final calibrations of $H_s$ from each altimeter used in our work. Statistical parameters are for the calibrated data, relative to buoys.

<table>
<thead>
<tr>
<th>Altimeter</th>
<th>Period</th>
<th>Calibration</th>
<th>$b$ (m)</th>
<th>$\rho$</th>
<th>$e$ (m)</th>
<th>$e^*$ (m)</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jason-2</td>
<td>25 Sep 2011–19 Oct 2014</td>
<td>$H_s = 1.019 \times H_s - 0.050$</td>
<td>0.02</td>
<td>0.99</td>
<td>0.14</td>
<td>0.14</td>
<td>3164</td>
</tr>
<tr>
<td>CryoSat-2</td>
<td>29 Sep 2011–4 Dec 2014</td>
<td>$H_s = \begin{cases} 0.836 \times H_s + 0.157 &amp; H_s \leq 1.853 m \ 1.001 \times H_s - 0.149 &amp; H_s &gt; 1.853 m \end{cases}$</td>
<td>0.10</td>
<td>0.99</td>
<td>0.19</td>
<td>0.14</td>
<td>2820</td>
</tr>
<tr>
<td>HY-2</td>
<td>1 Oct 2011–1 Apr 2013</td>
<td>$H_s = \begin{cases} 1.003 \times H_s + 0.287 &amp; H_s \leq 3.504 m \ 0.040 \times H_s^2 + 0.838 \times H_s + 0.376 &amp; H_s &gt; 3.504 m \end{cases}$</td>
<td>-0.31</td>
<td>0.98</td>
<td>0.37</td>
<td>0.19</td>
<td>932</td>
</tr>
<tr>
<td>HY-2</td>
<td>15 Apr 2013–6 Dec 2014</td>
<td>$H_s = \begin{cases} 0.977 \times H_s + 0.187 &amp; H_s \leq 3.568 m \ 0.013 \times H_s^2 + 1.083 \times H_s - 0.359 &amp; H_s &gt; 3.568 m \end{cases}$</td>
<td>-0.13</td>
<td>0.98</td>
<td>0.21</td>
<td>0.16</td>
<td>882</td>
</tr>
<tr>
<td>SARAL</td>
<td>14 Mar 2013–30 Oct 2014</td>
<td>$H_s = 0.997 \times H_s - 0.056$</td>
<td>0.06</td>
<td>0.99</td>
<td>0.13</td>
<td>0.11</td>
<td>1657</td>
</tr>
</tbody>
</table>
FIG. 8. Comparison between (top) Jason-2 $H_s$, HY-2 (middle) $H_s$, and (bottom) $H_s^*$ vs Ifremer wave hindcast products for January (a)–(c) 2013 and (d)–(f) 2014. The model $H_s$ values were corrected by Eq. (5). The $H_s$ values on the vertical axes represent raw data, while $H_s^*$ represents values calibrated by formulas summarized in Table 3.
pointed out in Zhang et al. (2015). The underestimation of HY-2 $H_s$ values becomes more marked for a high sea state ($H_s > 6$ m), contributing to the mismatch between the HY-2 and other altimeters (Fig. 3). Furthermore, influenced by the switch to backup status of HY-2 sensors and the subsequent update of data processing software, HY-2 altimeter-measured $H_s$ values moved to a better quality level in April 2013 and afterward (corresponding to cycle $\geq 41$), and approached the accuracy of CryoSat-2 wave products.

3) We finally proposed a two-branched calibration for HY-2- and CryoSat-2-estimated $H_s$ values. The whole duration of HY-2, considered in our study, was subdivided into two phases on the basis of their different performances during these two periods. A detailed summary of the calibrations of the four altimeters can be seen in Table 3. These calibrations behave in a significantly consistent way. The best agreement is found between Jason-2 and SARAL values (Figs. 3 and 4). Inspection of Table 3 (column $e^*$) shows that determining significant wave heights using HY-2 $H_s$ measurements is eventually enhanced and is comparable with the other three satellite missions.

4) Our calibration for HY-2 $H_s$ values was further verified in an indirect way by using outputs from a wave model. When compared to the model, HY-2 obtained $H_s$ values present similar patterns and statistics to those from Jason-2; thus indicating that HY-2 derived wave products, once calibrated, are as realistic as those from Jason-2.

As mentioned in section 1, NSOAS is now reprocessing HY-2 altimeter IGDRs by adopting a different retracking method with the objective to supply a much better sea surface height ($h$) and wind speed $U_{10}$. The reprocessed data, as demonstrated in Zhang et al. (2015), also have a marginal improvement in wave height values. Our results presented here summarize and complement the existing studies on the calibration of HY-2 $H_s$ values, confirm its good quality, enhance its practicability especially for extreme weather research, and point out the potential deficiencies to be further improved by new data. For completeness, the assessment of the HY-2 altimeter-derived $U_{10}$ values will be reported in the future.

The study focused on the ability of satellite-altimeters to derive $H_s$ in open water. Buoys less than 40 km offshore were not considered in order to eliminate land contamination. As shown in Zieger et al. (2009), with the development of satellite altimetry, wave products derived from data obtained by these altimeters in the last two to three decades are fairly reliable; however, the performance of measurements of this kind in coastal areas was limited until the recent advent of SARAL (Hithin et al. 2015). The use of the Ka band enables SARAL to yield more precise estimates of waves in coastal waters. This advancement might have many practical implications, and at the very least can be used to validate and improve the skills of numerical wave models near the coast. As stated in Sepúlveda et al. (2015), good coastal measurements can be used to study fetch-limited wind-wave growth in finite depth water. However, the difficulty in finding regions suitable for this objective might hinder its feasibility.

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