Validation of HY-2A Remotely Sensed Wave Heights against Buoy Data and Jason-2 Altimeter Measurements*

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ABSTRACT

The Haiyang-2A (HY-2A; HaiYang means ocean in Chinese) satellite was successfully launched in China on 16 August 2011, carrying the nation’s first operational radar altimeter along with three other microwave sensors. In this study, HY-2A altimeter significant wave height (SWH) data have been validated against National Data Buoy Center (NDBC) buoy and Jason-2 altimeter SWH data over a period of 27 months (from 1 October 2011 to 31 December 2013). During the collocation, the effects of different thresholds of several flags are carefully studied. These flags prove to be useful for the SWH selection and different thresholds are observed to change the results remarkably. The final results show that HY-2A SWHs, with a 0.339-m root-mean-square (RMS) difference and a negative bias of 0.231 m in buoy comparison, have reached the mission target (0.5-m RMS). Nonetheless, the Jason-2 altimeter performs better with a lower RMS difference of 0.292 m and a positive bias of only 0.016 m. In addition, by analyzing the residuals (altimeter minus buoy), the bias for the HY-2A altimeter is found to decline monotonically over the whole range with an overestimation at low sea state (SWH < 1 m), a minor underestimation at middle sea state (1 m < SWH < 5 m), and a severe underestimation at high sea state (SWH > 5 m). However, only an underestimation at high sea state is found for the Jason-2 altimeter. A linear regression is also proposed. The 20 days of the newly processed HY-2A SWHs are investigated and discussed as well, and a slight quality improvement has been observed using these data.

1. Introduction

Measurements of waves over the oceans are of great significance in areas such as modeling and forecasting of weather, ocean surface conditions, and ocean circulation. These measurements can be used to validate and calibrate models for waves and other ocean processes; to improve the understanding of the physical processes responsible for wind-wave evolution; and to investigate the wave climate, which has the potential to help shipping and offshore engineering projects.

Widely recognized as they are, these measurements were not obtained from space until around three decades ago. For wave height, since 1985 when the Geodetic Satellite (Geosat) was successfully launched by the U.S. Navy, several major altimeter missions have been operational, typically including the European Remote Sensing Satellites-1/2 (ERS-1/2), the Ocean Topography Experiment (TOPEX), and Jason-1/2 as its successors; the Environmental Satellite (Envisat); Cyrosphere Satellite-2 (CryoSat-2); etc. Although the products derived from these satellites are of different qualities, they have

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provided a unique database spanning nearly three decades of continuous global coverage, which makes these observations ideal for assimilation into global wave models, model evaluation, and the construction of wave climatologies.

The Haiyang-2A (HY-2A) satellite was successfully launched on 16 August 2011 (please refer to Table 1 for more HY-2A technical parameters). This is the third ocean satellite launched by China after the successful HY-1A, launched in 2002, and HY-1B in 2007. Both the HY-1 series satellites are designed for the observation of marine ecological environment with the Chinese Ocean Color and Temperature Scanner (COCTS) on board. Different from HY-1, the HY-2 series satellites focus on ocean dynamic environment observations, with the main tasks of measuring the sea winds, the sea waves, and also the sea surface temperature (SST). As for the HY-3 series satellites, which are still under development, they will carry synthetic aperture radar (SAR) to monitor coastal conditions, islands, mobile targets, and so on under all weather conditions. All these ocean satellites will eventually form a comprehensive ocean observation network and boost the development of satellite oceanography in China. As the first satellite of the HY-2 series, HY-2A flies in a polar sun-synchronous orbit with an inclination of 99.34°. It is equipped with four scientific instruments: 1) a radar altimeter, 2) a microwave scatterometer, 3) a scanning microwave radiometer, and 4) a three-frequency microwave radiometer. The radar altimeter is an active microwave remote sensor with the main objectives of measuring sea surface height (SSH), significant wave height (SWH), and wind speed along its nadir track with high accuracy (please refer to Table 2 for technical parameters of the HY-2A altimeter). The microwave scatterometer is dedicated to determine the wind vector field, including both wind speed and direction, of the ocean surface. The scanning microwave radiometer is a multichannel radiometer to obtain ocean circulation parameters, such as SST, sea surface winds, total water vapor (WV), and cloud liquid water (CLW) content under all weather conditions. With similar data processing to the scanning radiometer, the three-frequency microwave radiometer functions only to provide the path delay for the altimeter’s atmosphere attenuation correction. In this study, the performance of the SWH radar altimeter measurement is investigated.

It is commonly agreed that data obtained from a newly launched satellite should be thoroughly validated and carefully calibrated before they can be utilized with confidence. For those altimeter missions before HY-2A, numerous investigations have been conducted to assess the data qualities and to propose calibration algorithms (e.g., Queffeulou 2003, 2004; Zieger et al. 2009; Ray and Beckley 2012). However, since HY-2A was recently launched and data availability only started in October 2011, the validation work is still urgently called for. Jiang et al. (2012) first gave a comprehensive overview of all four instruments and concluded that almost all parameters, including SWHs, conform to the designed technical specifications. This preliminary conclusion, however, could be considered as only a qualitative reference because it was drawn from no more than a visual comparison of two figures showing the SWH measurements of around a dozen passes of HY-2A and Jason-2, respectively. Yang et al. (2012) tried to realize the data fusion of SWH from HY-2A and other satellite altimeters by first correcting HY-2A SWH data using collocated NDBC buoy data. They believed that the comparison results were good and that the HY-2A altimetry data could work well with other altimeter data. However, there was no direct comparison between HY-2A SWHs and buoy data. Only a linear correction was proposed. Chen et al. (2013) validated HY-2A SWH measurements against the data from the South China Sea (SCS) field experiment, NDBC buoys, and Jason-1/2 altimeters, and managed to calibrate the data using a linear regression with in situ measurements. In their work, a root-mean-square (RMS) difference of 0.36 m (0.31/0.34 m) was found when comparing HY-2A (Jason-1/2) SWHs with NDBC buoy data using a short database (6 months, from 1 December 2011 to 31 May 2012). Chen et al. (2013) also outlined the nonlinear behavior of HY-2A SWH relative to Jason-2, which was then considered in their proposed correction. Wang

### Table 1. Main parameters of the HY-2A satellite (source: http://www.nsoas.gov.cn/).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit type</td>
<td>Sun synchronous</td>
</tr>
<tr>
<td>Equator crossing (LST)</td>
<td>0600</td>
</tr>
<tr>
<td>Altitude (km)</td>
<td>970</td>
</tr>
<tr>
<td>Inclination (°)</td>
<td>99.3</td>
</tr>
<tr>
<td>Period (min)</td>
<td>104.50</td>
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<tr>
<td>Life span (yr)</td>
<td>3</td>
</tr>
<tr>
<td>Output power (W)</td>
<td>1550</td>
</tr>
<tr>
<td>Downlink frequency</td>
<td>X band</td>
</tr>
</tbody>
</table>

### Table 2. Main parameters of the HY-2A radar altimeter (source: http://www.nsoas.gov.cn/).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>13.58, 5.25</td>
</tr>
<tr>
<td>Pulse-limited footprint (km)</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Frequency bandwidth (MHz)</td>
<td>320</td>
</tr>
<tr>
<td>Pulse repetition frequency (kHz)</td>
<td>2</td>
</tr>
<tr>
<td>SWH measurement accuracy (m)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
et al. (2013), using 11-month data (from 1 October 2011 to 29 August 2012), validated HY-2A SWHs against NDBC buoy data and an RMS of 0.297 m (0.243 m) was found between HY-2A (Jason-2) SWHs and buoy data. This result was much better than Chen et al. (2013). However, according to Wang et al. (2013, p. 88), the SWH data of altimeters and buoys that were larger than 7 m were discarded in order to “verify the altimeter data against the buoy data better.” Although the collocations discarded were probably small (not shown in their study), this method indeed improved the result to a certain level as discovered in this study. This method thus should not be recommended because it is also important to validate altimeter SWHs in very high sea state conditions. For instance, Jason-2 SWH values up to 20 m have been shown to be of good quality and consistent with other observations (Hanafin et al. 2012). The ordinary least squares (OLS) regression method was performed for correction. All these previous studies combined are able to give a general idea of the performance of the HY-2A altimeter SWHs. However, during the collocation step, although general processes like the spatial–temporal windows and no ice or rain were mentioned, none of them brought up and analyzed the influence of different quality control (QC) flags criteria on the data quality, which can be significant as discovered in this study. Hence, before the assessment of the HY-2A altimeter SWH products, this study first focuses on the effects of different restrictions of QC flags. A much longer database is also adopted.

The organization of this paper is as follows: section 2 briefly describes the data sources and processing methods used; section 3 illustrates the effects of several QC flags with different thresholds; section 4 displays the validation, intercomparison results, and calibration; followed by section 5, which provides the discussion; and conclusions are provided in section 6.

2. Data and methods

a. Data

Datasets used in this study consist of two level 2 satellite datasets, HY-2A and Jason-2, and NDBC buoy measurements as reference data.

The altimeter on board HY-2A performs SWH measurements at both Ku and C bands. Only Ku-band level 2 data are considered in this study due to the fact, which is clearly outlined in OSDPD (2009, p. 39), that the accuracy of Ku-band range measurement is much higher than that of the C-band measurement. These data were developed from level 1 data after differentiating the ocean from land and some basic QC steps and then distributed by the National Satellite Ocean Application Service (NSOAS), State Oceanic Administration of China (http://www.nsoas.gov.cn). These are the interim geophysical data records [IGDRs from ftp://114.255.97.103 (authorization needed to access data)], indicating that they have not been fully validated yet compared with GDRs. The period is 27 months from 1 October 2011 (cycle 1, pass 1) to 31 December 2013 (cycle 59, pass 302). Plus, 20 days (1–20 June 2014) of newly processed IGDRs with refined algorithms are also investigated (details are seen in the discussion section).

To make the validation results more easily related to, Jason-2 data (ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason2/gdr/gdr) are utilized in this study and have gone through all the same processes. As a successor to the two very successful altimeter missions (TOPEX/Poseidon and Jason-1), Jason-2 was launched in 2008 to continue recording the ocean surface topography measurements. As a mission of great reputation, Jason-2 is globally recognized and appropriate to serve as a reference to HY-2A. Different from HY-2A, it flies in a 1336-km circular, nonsun-synchronous orbit at an inclination of 66°. This inclination prevents it from getting as close to the poles as HY-2A does (see Fig. 1). The same time period is adopted for Jason-2 data. Instead of IGDRs, Jason-2 GDRs are used in this study.

Buoy data are considered to be of very high quality, or even as “ground truth.” In most validation works of remotely sensed data, they serve as standard data. For this study, buoy data used are obtained from NDBC operated by the United States (http://www.nodc.noaa.gov). NDBC buoy data are assumed to be of very high quality and have extensively been used for altimeter SWH validation work. A range of ocean environmental parameters are reported at constant time intervals in buoy data, including air temperature, sea temperature, and wave height. For wave height, one measurement is recorded each hour. Despite the poor spatial coverage, as most buoys are located along the coastal lines of the North American continent, this archive features a quite excellent temporal coverage that dates back to the early 1970s. Conventionally in altimeter validation studies, buoys within 50 km offshore are always not taken into the dataset because if the buoy is too close to the coast, altimeter overpasses will normally occur seaward of the buoy location, and then higher wave conditions are sampled. Thus, to eliminate the effect of the land, it is usually required that buoys are at least 50 km offshore. Durrant et al. (2009) proved 50 km to be sufficient, since further distance, like 150 km, exerts a negligible influence on the results. Based on this criterion, a total number of 56 buoys are selected. Note that not all of them (only 38 out of 56) cover the whole period from 1 October 2011 to 31 December 2013 (see Fig. 2).
b. Method

1) IN SITU VALIDATION

The general idea to validate the SWH ground-track measurements is to get a set of collocations of satellite and buoy data and then assess the performance of the altimeter by a number of indexes, such as bias and RMS difference. To accomplish the collocation step, several selection criteria have to be followed, since the altimeter and buoy are measuring actually different aspects of the temporally and spatially varying wave field. The general selection process, for both HY-2A and Jason-2 data, is described as follows.

First, spatial and temporal windows are discussed. As proposed in Monaldo (1988) and widely adopted thereafter in most altimeter validation work, altimeter data are selected when they are less than 50 km away from the buoy location and within a 30-min temporal window. The spatial criterion is often replaced by a latitude–longitude proximity to ease the calculation. This method might damage the conclusions because it is obvious that zonal proximity will not be consistent with changing latitudes. However, this should not make much difference to the results due to its widespread use (e.g., Chen et al. 2013; Wang et al. 2013; Greenslade and Young 2004). Therefore, in this work, 0.5° for both latitude and longitude proximity is adopted.

The next criterion is QC flags. Level 2 (I)GDR data provide a series of QC flags also known as geophysical processing flags. They are determined from various statistical checks on the residuals after smoothing or fitting through the data themselves (OSDPD 2009). Data of different quality can be filtered based on different QC flags. This part has been largely missing in most of the previous studies of HY-2A SWH validation. The flags they have overlooked are in fact able to provide useful information in regard to the corresponding SWH measurements. As discovered in this study, different selection criteria could result in quite a significant shift in the conclusions. Specific flags and the impact of different criteria investigated in this study are illustrated in section 3.

Generally, after setting and following certain selection criteria, within the temporal and spatial windows, there are normally between 12 and 20 altimeter observations that can be considered as simultaneous. Again, before averaging, these values are quality controlled by removing those lying outside two standard deviations. Finally, the averaged altimeter measurement and the corresponding hourly buoy observation form a single collocation.

2) ALTIMETER INTERCOMPARISON

For the whole period under consideration, altimeter missions such as HY-2A and Jason-2 are in orbit simultaneously, making it possible to cross validate the performance of different altimeters by comparing observations at crossover points. So, an intercomparison between HY-2A and Jason-2 SWHs is also conducted. Temporally, ground-track crossovers between the two altimeters are considered when both pass the ground point within a 30-min separation. Spatially, the 100-km (50 km each side) along-track measurements are averaged for either satellite at each crossover point, as in Zieger et al. (2009). Then, two averages compose one collocation at one crossover point. Expectedly, many more collocations are obtained and they are basically evenly distributed throughout the global oceans.

Bias, RMS of differences, scatter index (SI), and correlation coefficient ($R$) are the statistical parameters used in this work for both in situ comparison and intercomparison.
3. Impact of different criteria of QC flags

QC flags investigated in this study include 1) ice_flag and rain_flag, 2) swh_ku, 3) swh_rms_ku, and 4) swh_numval_ku. While studying one flag, all other flags are left out. Please also note that these are the only flags closely related to the SWH.

a. ice_flag and rain_flag

These are basic flags that should be taken into consideration. Only no ice and no rain measurements are selected.

b. swh_ku flag

Strictly, this is not a QC flag but the Ku-band SWH value itself. Although it is recommended in NSOAS (2011) that only SWHs smaller than 11 m [7 m was adopted in Wang et al. (2013)] should be filtered to retain only the most valid data, it would be interesting to investigate the altimeter accuracy in high sea state larger than 11 m if there exists any valid collocations. However, as shown in Table 3, among 21,890 (35,664) HY-2A (Jason-2) SWH measurements falling within the temporal and spatial windows, only 5 (2) of them are over 11 m. A comparison with buoy data that are all around 1 m indicates these are actually false values. Deleting these records will change neither the number of the final collocations for both satellites nor any indexes in the Jason-2 case. While in the HY-2A case, the RMS has a remarkable reduction by 0.022 from 0.392 to 0.370 m. If we set the threshold to be 7 m, then the number increases to 38 (106) for HY-2A (Jason-2) SWHs. Under this condition it cannot be determined if all of these records are flawed. Although the final number change of collocations is small (one pair fewer for HY-2A and four pairs fewer for Jason-2), both RMSs have seen a decline by 0.012 and 0.025 m, respectively. This shows that discarding SWHs larger than 11 or 7 m indeed improves the data quality to different degrees.

In this study, as it is meaningless to keep the satellite SWHs larger than 11 m, the threshold for this flag is set to be 11 m (swh_ku ≥ 11m), which is also to be consistent with the suggestion in NSOAS (2011). Maybe in the future when using longer datasets the performance of the HY-2A altimeter in an extremely high sea state can be investigated with enough valid collocations.

c. swh_rms_ku flag

This flag indicates the RMS of the Ku-band SWH. Compression of Ku-band high-rate elements is preceded by a detection of outliers. Only valid high-rate (20 Hz) values are used to compute this element. This flag offers reference to the quality of the corresponding SWHs with high values flagging low-quality SWHs (Queffeulou 2013).

In Queffeulou (2004), the criterion of this flag is set to be 1 m; that is, SWHs with this flag larger than 1 m are discarded. In this study different thresholds are
investigated for both satellites. Although the highest swh_rms_ku value is larger than 12 m (8 m) of all 21 890 (35 664) HY-2A (Jason-2) SWHs falling within the windows, the majority of the values are between 0 and 1 m. However, even though the number of extremely high values is not large, they prove to greatly impact the whole data quality.

The swh_rms_ku flag has been set to be a series of different values. Note that only several representative thresholds are shown in Table 3. Let us first focus on the HY-2A altimeter. As shown in Table 3, as the threshold gets smaller, all indexes but the bias get better as expected, indicating the improvement of the data quality. When the threshold is 3 m, even though only 35 satellite SWHs are discarded and one final collocation is reduced, the RMS significantly decreases to 0.347 m. The absolute value of the negative bias, however, goes up by 0.012 m. Investigation into the discarded 35 SWHs shows that altimeter wave measurements are severely overestimated (most SWH_{HY-2A} > 5 m) at low–middle sea state (most SWH_{Buoy} < 3 m). This also shows the relatively poor performance of the HY-2A altimeter at low and low–middle sea state condition. The abandonment of these possible flawed measurements resultantly causes the abnormal increase of the absolute value of the negative bias. As the threshold keeps decreasing, RMS (R/Sl) also is getting smaller (larger/smaller) and at last leveling off at around 0.340 m (0.947/0.161) for thresholds under 2 m. The absolute value of the negative bias, however, steadily gets larger because of the same reason. When the threshold falls below 0.8 m, the number of discarded SWHs begins to surge; therefore, the threshold is not suggested to be set under this value. The trend for Jason-2 is almost the same but with different values. Also different from HY-2A, the positive bias is decreasing as expected, showing the more consistent performance of the Jason-2 altimeter.

Overall, the threshold between 2 and 0.8 m for this flag is proven to be fine for both altimeters and can effectively discard questionable values and improve the data quality. For the rest of this study, the 1-m threshold is adopted.

d. swh_numval_ku flag

This flag presents the number of valid waveforms used to compute Ku-band SWHs. IGDRs typically provide one measurement every second. Each 1-s (or 1 Hz) measurement is the average of all the valid 20-Hz waveforms. The maximum number of the 20-Hz measurements being averaged is 20 in both the HY-2A and Jason-2 cases. Waveforms that fail to meet the predefined requirement are discarded. If the final number
of waveforms that are averaged to get a 1-s measurement falls significantly under 20, it indicates that this 1-s observation should be considered to be of questionable quality. In this study, influences of different number criteria are investigated.

For both altimeters, different thresholds for this flag are investigated and only three representative values are illustrated here: 1) 18 as for Jason-1 in Queffeulou (2004), 2) 15 as for Jason-1 in Zieger et al. (2009), and 3) 10. As shown in Table 3, if 1-s SWHs averaged from more than 18 waveforms are selected, then there are 77.3% (98.8%) HY-2A (Jason-2) SWH records filtered within the windows and resulting 1570 (2839) final collocations. As the thresholds get lower to 15 and 10, as expected, more satellite SWHs and final collocations are obtained.

The results are a bit confusing. According to the authors’ understanding, the lower the threshold is (from 18 to 15 to 10), the more possible low-quality data are included; therefore, the data quality should, if not level off, gradually get poorer with larger bias and RMS. However, this is not the case. For HY-2A, except that the bias values are getting larger, all other indexes, including RMS, \( R \), and SI, are all decreasing, indicating that the data quality is getting better rather than worse. For Jason-2, even the bias is also declining. Moreover, all filtered results with any specific threshold (18, 15, or 10) are supposed to be better than with no flag filter at all, which means the threshold is zero. In reality, still except for the abnormal bias in HY-2A, all other indexes show that the filtered results are actually less satisfactory. The almost “opposite” results are not explained at this moment and call for further study. In the following work, no threshold is applied to this flag.

4. Results

a. In situ validation

Following the above-mentioned flags criteria and the subsequent processes, the comparisons yield 1775 collocations for HY-2A and 2840 collocations for Jason-2. The difference between the two numbers is quite significant and has been also shown but left unanalyzed in previous HY-2A SWH validation works described in the introduction of this paper. The no-flag numbers of HY-2A (21890) and Jason-2 (35664) SWHs falling within the temporal and spatial windows are also showing this large difference (see Table 3). Thus, excluding the flags’ filtering factor, the primary reason for this is that there are too many invalid (not including false or flawed) measurements in HY-2A data. This should also in part be attributed to the different repeat cycle orbits. Scatterplots and statistical parameters are presented in Figs. 3a and 3c. To have a better understanding of the distribution of the collocations, density plots are shown in Figs. 3b and 3d.

For HY-2A, as shown in Fig. 3a, the RMS difference is 0.339 m with a negative bias of 0.231 m. This is within the mission requirement, as the accuracy specified in the mission goal of HY-2A altimeter is a 0.5-m RMS. However, the result may not be satisfying enough. The overall negative 0.231-m bias indicates serious underestimation as a whole. The RMS difference for Jason-2 is 0.292 m, with a small positive bias of 0.016 m. With the correlation coefficient of 0.962, Jason-2 has a better agreement with the buoy measurements than HY-2A with a 0.947 correlation coefficient. Shown in Figs. 3b and Fig. 3d are the density plots of the collocations for HY-2A and Jason-2, respectively. The size of each bin is 0.25 m \( \times \) 0.25 m. For HY-2A, good agreement is observed for SWHs less than 2 m, with most of the data lying basically evenly on both sides of the reference line. There is a strange feature in that there are fewer measurements of SWHs less than 1 m in the HY-2A case. This has also been clearly revealed in Chen et al. (2013, see their Fig. 4), in Wang et al. (2013, see their Figs. 2 and 3), and in Xu et al. (2014, see their Fig. 6). The reasons are discussed later. For SWHs larger than 2 m, however, the densest bins are practically all lying under the line and the higher the sea waves are, the worse it is. The distribution relative to Jason-2 (Fig. 3d) is much better with no deviation from the reference line over most of the range, although a slight underestimation is seen for SWHs larger than 5 m. These features will be shown again in the later analysis. The general results of both altimeters are similar to prior studies (see the introduction) with a minor difference that should be caused by different data periods and collocation criteria.

To examine the dependency of the bias (altimeter minus buoy) between altimeters and in situ measurements, the number of collocations, bias, and standard deviations is calculated within each 1-m buoy SWH bin from 0 to 12 m. The results for HY-2A and Jason-2 are presented in Figs. 4a and 4b, respectively. The histogram shows the number of collocations. One can see that the collocation number of SWHs less than 1 m in the HY-2A case is much less than that in the Jason-2 case, consistent with the difference revealed in Figs. 3a and 3c. The dotted line represents the trend of the bias and the error bar indicates the standard deviation in each bin. As shown in Fig. 4a, the bias for the HY-2A altimeter declines monotonically over the whole range with an overestimation at low sea state (SWH < 1 m), moderate underestimation at middle sea state (1 m < SWH < 5 m), and severe underestimation at high sea state (SWH > 5 m). The quite flat slope in the middle sea state
shows that the measurements are relatively stable. However, at high sea state, the absolute values of the negative bias are even larger than 1 m with unstable standard deviations (STDs). A high sea state situation in Jason-2 is much better. This is consistent with Chen et al. (2013), even though they use Jason-2 SWH data rather than NDBC buoy data as reference. Considering the Jason-2 SWH data agree much better with the buoy data (see Fig. 4b), this may not cause much difference.

b. Intercomparison with Jason-2

The intercomparison between HY-2A and Jason-2 SWHs yields 4378 collocations, which is expectedly much larger than the buoy comparisons. The collocations and some statistical parameters are presented in Fig. 5.

As shown in Fig. 5a, HY-2A altimeter SWH data agree well with Jason-2 altimeter, as $R$ is as high as 0.988. A negative 0.272-m bias between HY-2A and Jason-2 is obtained, reproofing HY-2A’s overall underestimation. Consistent with Fig. 4, the overestimation (underestimation) of HY-2A for SWHs less than 2 m (larger than 5 m) is clearly observed. Besides, an exceptionally small quantity of SWHs less than 1 m is again shown in addition to Fig. 3a and Fig. 4a. Investigation indicates that most HY-2A altimeter measurements for buoy SWHs less than 1 m are either invalid or severely overestimated. This is not due to the flag selection because only four final collocations are missing compared with the no-flag restrictions condition (see Table 3). If, as told by the NSOAS, the HY-2A sensor has almost equal capacity with Jason-2 to measure SWHs less than 1 m, then the reason may lie in the data retrieval. The very detailed algorithm is not further studied here, but a general description of the level 2 data algorithm in the discussion.

Fig. 3. Scatterplots of collocated SWH observations for (a),(b) HY-2A and (c),(d) Jason-2 altimeters against NDBC buoys. Number of collocations and statistical parameters, including the bias, RMS, SI, and $R$, are presented. Density plots for (b) HY-2A and (d) Jason-2. Size of each bin is 0.25 m × 0.25 m.
c. Calibration

The OLS regression method is applied to correct the HY-2 and Jason-2 altimeter SWH data. The linear equation is expressed as

$$\text{SWH}_{\text{corrected}} = \alpha \times \text{SWH}_{\text{raw}} + \beta.$$  (1)

The regression coefficients ($\alpha$ and $\beta$) are listed in Table 4. Statistical parameters (altimeter against buoy data) are compared before and after correction. After correction, while the RMSs only slightly drop, both biases are all reduced to almost zero. Cross validation for corrected HY-2A altimeter SWHs against raw Jason-2 SWHs are displayed in Fig. 5b, showing data quality improvement with a much smaller bias and a bit smaller RMS.

5. Discussion

According to the results stated above, it is reasonable to conclude that Jason-2 altimeter SWHs do perform better than HY-2A, especially in low and high sea states. Through communication with NSOAS, we have learned that the difference between the sensors is negligible. The primary reasons accounting for the different performance of the datasets lie in the processing, that is, retrieval algorithms. According to Brown (1977), the average return power for a rough scattering surface could be expressed as a convolution of three terms: 1) the probability density function for the sea surface height; 2) the radar point target response; and 3) the flat surface impulse response (Hayne 1980; Amarouche et al. 2004). It is known that for altimeter missions, it is the so-called retracking algorithm that fits an analytical model to the measured waveforms that makes the precise estimates of the geophysical parameters possible. The Brown model, which is usually developed at the first order, is believed to be suited for antenna mispointing angles only up to 0.3°. Based on this model, a maximum likelihood estimator (MLE) 3 algorithm is commonly used. The MLE3 algorithm estimates three parameters (range, significant wave height, and power; Thibaut et al.}
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The MLE3 algorithm was adopted in HY-2A SWH processing because HY-2A retracking specifications assumed an antenna mispointing angle smaller than 0.3°. However, some occasional abnormal behaviors of the star trackers system were observed, leading to mispointing angles higher than the specification limits. In this context waveforms do not conform to the Brown model. In Amarouche et al. (2004), a second-order analytical model of the altimeter echo was derived to take into account attitude angles up to 0.8°. Consequently, the retracking algorithm was adapted to MLE4. The MLE4 estimates four parameters (the three previous ones and the slope of the waveform trailing edge). The MLE4 algorithm was adopted for the Jason-2 nominal waveform retracking despite the good pointing performance of the Jason-2 satellite (Thibaut et al. 2010). This could be the major reason accounting for the observed difference between the satellite datasets.

Again, through personal communication (Y. Jia 2015), we were lucky to first get the newly processed HY-2A SWHs from NSOAS. This dataset is not publicly accessible yet and only about 20 days (1–20 June 2014) of data are obtained. Both the MLE3 and MLE4 algorithms are utilized in the new data, which offers a great opportunity to make a comparison with buoy and Jason-2 data over the same time span. All collocation steps are the same as those mentioned above. Statistical parameters are shown in Table 5. Expectedly, the collocations with buoys are very limited. A comparison between MLE3 and MLE4 processed HY-2A SWHs has shown slight improvement in the latter case, yet Jason-2 still outperforms both. Several reasons are possibly responsible for the not very evident improvement in the HY-2A MLE4 case. The remarkably short time period yields only very limited collocations and all of them are within SWH smaller than 4 m (not shown). HY-2A SWHs perform relatively stable for this sea state. Another reason might lie in the very small quantity of points with an antenna mispointing angle larger than 0.3°. MLE4 are supposed to lead to better results for such cases, the lack of which also limits the improvement. Nonetheless, better quality data are shown with the MLE4 algorithm with quite evidently reduced bias. Although collocations are very small in quantity, this fact should not be regarded as random, as all parameters are indicating quality enhancement, making these newly processed data worth expecting.

6. Conclusions

After HY-2A was launched in 2011, several validation and calibration works have been conducted sporadically so far. In this paper, using data from a period of 27 months (from 1 October 2011 to 31 December 2013), the HY-2A altimeter SWH performance is validated against NDBC buoy and Jason-2 altimeter SWH data. Then, the linear OLS calibration against buoy data is proposed.

Instead of a conventional data selection and then jumping to the results as for many previous HY-2A validation works, the collocation process was first carefully investigated by studying the impact of different QC flags constraints, including 1) swh_ku, 2) swh_rms_ku, and 3) swh_numval_ku. Research into the swh_ku flag indicates that SWHs larger than 11 m are very rarely recorded in altimeters and all turn out to be false values in this study. Nonetheless, deleting those measurements can enhance the data quality to some extent; therefore, this threshold is adopted for this study. The 7-m threshold is not used here or recommended in further studies, as it is also meaningful and necessary to assess the altimeter performance in very high sea state condition. The swh_rms_ku flag proves to be indicative of the quality of the corresponding SWHs. Different thresholds can cause quite different data quality results. Thresholds between 0.8 to 2 m prove to be all acceptable for HY-2A SWHs and the 1-m threshold (swh_rms_ku ≤ 1 m) is adopted in this study. The effects of different swh_numval_ku thresholds are not as expected. The higher threshold value leads to poorer rather than better data performance, which is not explained in this paper and calls for deep research in the future. No threshold for this flag is set for the following work. The analysis of these flags should be useful in further selection and application of the data.

In the final results, an RMS of 0.339 m (0.292 m) is found between HY-2A (Jason-2) and NDBC buoy data. The bias between the HY-2A altimeter and in situ measurements is found to be positive at low sea states, indicating an overestimation; and negative at middle sea states and high sea states, indicating an underestimation. In contrast, only an underestimation at high sea states is found for the Jason-2 altimeter. A consistent linear calibration is proposed at last.

Although generally HY-2A SWHs behave well with quite stable measurements for the middle sea state, the
performance of the HY-2A altimeter still can be improved. Through personal communication (Y. Jia 2015), we are aware that a new HY-2A SWH product using refined algorithms will soon be publicly available from NSOAS. Gratefully, we managed to obtain a very short period of data to first examine its performance. Slight improvement is indeed observed. The much better performance in points with antenna mispointing angles larger than 0.3° is not revealed because of the absence of such cases. Hopefully, the new HY-2A SWH data can be as competitive as other high-reputation altimeter missions.

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