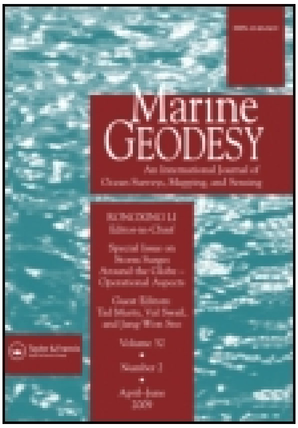

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Long-Term Validation of Wave Height Measurements from Altimeters

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Long-Term Validation of Wave Height Measurements from Altimeters

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Since July 1991, six altimeter missions have been launched successfully, and they have provided almost continuous wave height measurements for more than 12 years. Long-term series of wave height measurements are of major interest for climatology and oceanic wave modeling. Before using such data, the measurements have to be validated, and the homogeneity of the data from various satellites has to be checked. Significant wave height measurements from ERS, TOPEX/Poseidon, GEOSAT Follow-on, Jason-1 and ENVISAT altimeters are validated using cross-altimeter and buoy comparisons. Emphasis is put on the two recent missions Jason-1 and ENVISAT. Corrections for biases and trends are proposed for the six altimeters, allowing the generation of consistent and homogeneous data. Tests of these corrections are performed over global ocean simple statistics.

Keywords altimeters, validation, wave height

Since July 1991 six altimeter missions have been launched successfully. Altimeters on board ERS-1, ERS-2, TOPEX/Poseidon, GEOSAT Follow-on (GFO), Jason-1, and ENVISAT provided almost continuous wave height measurements for more than 12 years. From March 2002 until time of writing (June 2004) five altimeters were flying together, providing global and improved short scale sampling of significant wave height (SWH). Long time series of altimeter wave height measurements are of major interest for various domains of research, such as climatology (Carter et al. 1991; Gulev et al. 1997) and oceanic wave modeling (Lionello et al. 1992; Lefevre et al. 2003). Before using such data, the measurements have to be validated, and the homogeneity of the data from various satellites has to be ensured. Though altimeter SWH are calibrated and validated during dedicated commissioning phase operations, just after launch (Cotton and Challenor 1997, 2002; Lefevre and Le Berre 2002; Queffeulou 2003b and c), long-term monitoring of the quality of estimated geophysical parameters is needed. Moreover the validation requires, in general, a longer time period than the commissioning phase. Electronics drift and sensor damage affect the quality of measurements, inducing discrepancies between the various satellite data.

Within the aim of satellite validation and monitoring, the Laboratoire d'Océanographie Spatiale and the CERSAT (Centre ERS d'Archivage et de Traitement), in Institut Français de Recherche Exploitation de la mer (IFREMER), developed tools and data bases, using buoy data and cross-satellite comparisons. From past experiences in participating in satellite commissioning and long-term satellite monitoring activities (Queffeulou 2000, 2003a),

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significant differences have been identified between the wave height estimates from various altimeters, including a drift in instrument electronics, as in the case of TOPEX.

One objective of this study is to estimate the quality of the SWH measurements from the various altimeters, using the same analysis method, with particular emphasis on the recent Jason-1 and ENVISAT altimeter missions. A second objective is to provide the potential users of altimeter wave height data with validation informations and corrections to achieve homogeneity, if needed, to be applied to the specific products delivered by the space agencies.

In the first section, the validation methods are given. Then, the altimeter and buoy data are described. In the third part, the previous validation results are updated for ERS-2, TOPEX, and GFO. Previous ERS-1 validation results, recalled in the here in, are not updated because the reprocessing of the data, using the same software as for ERS-2, is still going on, due to some ESA delay in providing CERSAT with the ERS-1 level 1 data in compatible format.

The next two sections are dedicated to the validation of the significant wave height measured by the recently launched altimeters onboard Jason-1 and ENVISAT. In the last section, the proposed corrections are applied to the available altimeter data and tested on long-term simple statistics at the global ocean scale.

Validation Methods

Altimeter SWH validation is achieved using both buoy measurement comparisons and cross-satellite comparisons. Only the Ku-band SWH measurements are validated, though C-band measurements are available on TOPEX and Jason-1, and S-band on ENVISAT. For buoy comparisons, colocated data are selected when the closest approach of the altimeter ground track to the buoy location is less than 50 km, within a 30-minute time window. Altimeter colocated data is estimated as the closest along-track, 1-second, individual altimeter measurement, and/or as the 50 km along-track average. For along-track averaging, one specific requirement is that all the individual 1-second measurements, within the 50 km long arc, are valid, which increases the confidence in the altimeter measurement quality (no proximity of ice or land, or local spike in the signal). Furthermore the along-track averaging allows filtering the effect of time and space variability of SWH, though the energy level is low at the 50 km (Monaldo 1988) and half-hour scales.

For altimeter cross comparisons, ground-track crossing points are selected when the time difference between the two altimeter measurements is less than one hour. At the crossing point the locations of the two satellite measurements are separated by a distance less than the 1-second ground-track arc length, about 7 km for ERS and ENVISAT, and 6 km for TOPEX and Jason-1. Comparisons are performed over 1-second individual altimeter measurements, and (or) over 100 km along-track averages, 50 km each side of the crossing point, in order to filter time and space variability effects. For 100 km averaging, data are selected when the number of along-track individual 1-second valid measurements, to be averaged, is larger than or equal to 12 for ENVISAT (13 maximum), 14 for GFO (15 maximum), 16 for Jason-1 (17 maximum) and 15 for ERS-2 (15 maximum). A one-hour time window is selected as a compromise to get significant data sets, and then 100-km average is chosen by similarity with the 50-km and half-hour criteria used for buoy colocations.

Results are presented as scatter plots and tables of these following statistical parameters: number of analysed data points; mean value and standard deviation of differences between measurements from altimeter and buoys, or from different altimeters; slope and intercept of the orthogonal regression line; and root mean square of the fit. A confidence percentage is also given, corresponding to the percentage of data for which the difference is within the mean value (of differences) plus or minus twice standard deviation. In tables and graphs, SWH is expressed in meters.

In the following analysis, slope and intercept coefficients are obtained from various comparisons between buoys and altimeters and some are recommended for the correction of altimeter SWH. The question of the accuracy of these corrections is raised. In the present simple orthogonal regression scheme between altimeters or between altimeter and buoys, the data are assumed to have the same errors. In this case, the error on the coefficients depends only on the statistical distributions of the data. Ray and Beckley (2003) discussed this case, for TOPEX and Jason-1 SWH regressions, and, using Monte Carlo simulations, obtained very low standard deviation of the estimated slope (0.0016). In their comparisons between buoy measurements and Jason-1 and TOPEX data, they get standard deviation about 0.0014 on the slopes and 2 cm on the intercept.

The impact of buoy and altimeter SWH variances is discussed in Queffeulou (2003a). The analysis is based on the separation of the error variance into, on one hand, an instrumental variance (electronics and signal processing for buoy and altimeter measurements) and, on the other hand, a geophysical variance, associated with the SWH variability in time (1 hour) and in space (50 km to 100 km). The buoy instrumental error was, a priori, set to 10% of SWH, with a minimum value of 0.20 m. Of course, this parameter depends on the buoy technology and can change significantly from one buoy to another one. The geophysical variance was estimated in comparing SWH measurements separated by 1 hour on the same buoy. A linear regression was fitted to the standard deviation of differences as a function of SWH (1 m wide SWH classes), over the 0 m–6 m available SWH range, and extrapolated to higher values. The relation obtained (std $= 0.0238$ SWH $+ 0.0618$) is used to estimate the geophysical variance. The altimeter SWH rms accuracy specification is 10% or 0.5 m for ERS, TOPEX and GFO (a better accuracy has been specified for Jason-1 and ENVISAT); these values are used to estimate the instrumental variance. The altimeter measurement geophysical error is estimated as the standard deviation of the altimeter measurements over 50 km (for buoy comparison) or over 100 km for cross altimeter comparisons.

These combined variances are used to weight the individual distances between the data point and the orthogonal regression line. The uncertainties on slope and intercept are then estimated using , for two variables, the error propagation scheme described in Press et al. (1986). This method is applied to the present buoy altimeter colocated data, analysed in the following sections (see for instance Figure 1), and gives an order of magnitude of the error on the estimated coefficients. For TOPEX side-B (over 7826 colocated data points), two standard deviation errors are 0.010 for the slope and 1.6 cm for the intercept. For ERS-2 (12070 data points), almost the same results are obtained: 0.009 and 1.5 cm. The errors are larger for Jason-1 (2853 data points): 0.018 and 3.1 cm, and for ENVISAT (1280 data points): 0.024 and 4.2 cm.

Data

Altimeter Data

ERS altimeter data are the ESA Ocean Product level 2 (OPR-2) processed and distributed by the French Processing and Archiving Facility (CERSAT 1996), from the beginning of the mission, April 1995, to July 2003. Note that the ERS-2 data coverage was seriously degraded after 22 June 2003, due to the failure of the onboard storage device.

TOPEX/Poseidon data are the Merged Geophysical Data Record (MGDR) distributed by CNES AVISO (Aviso 1996), cycles 1–410, September 1992 to November 2003. The GFO data are the Intermediate Geophysical Data Record (IGDR) distributed by John Lillibridge

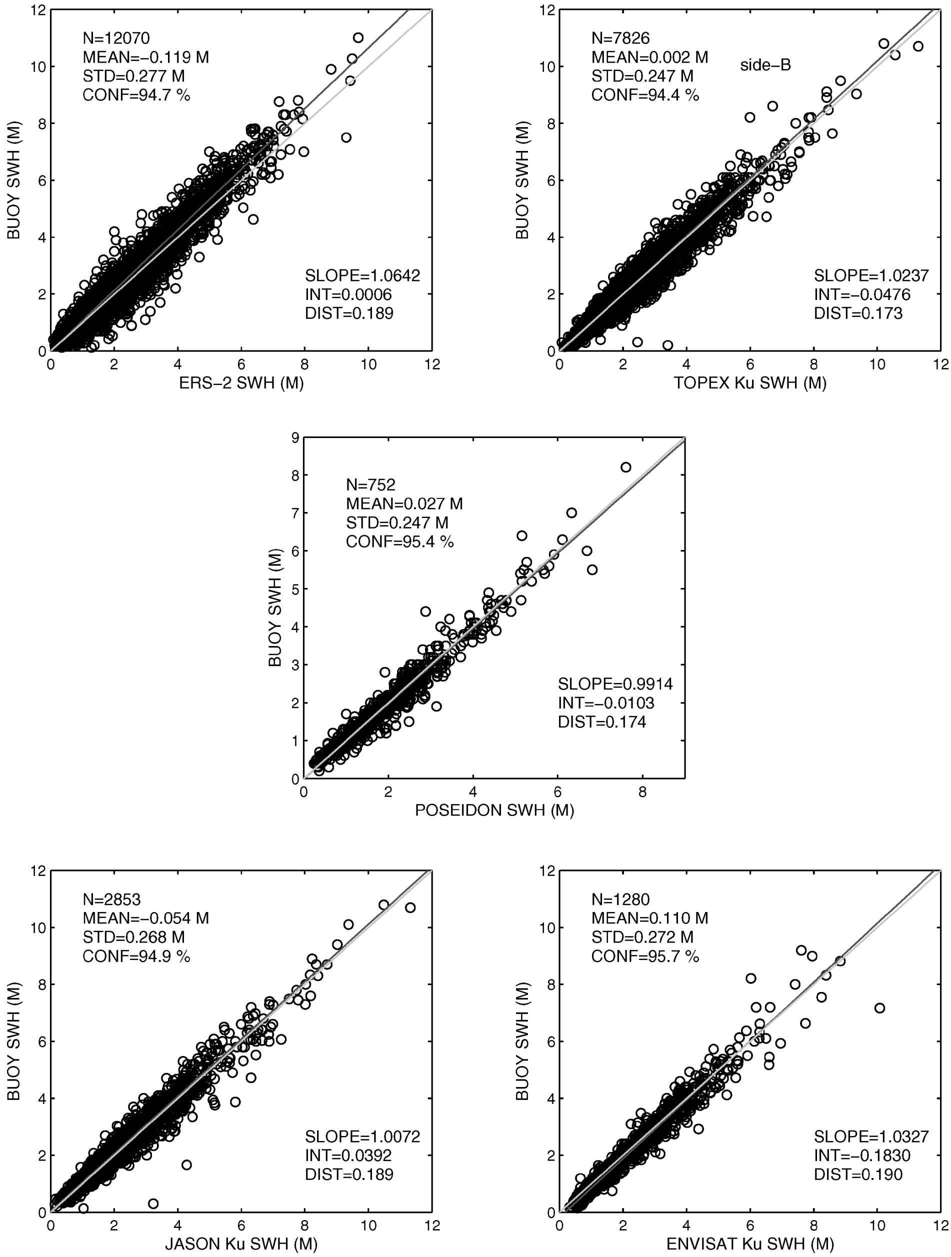

FIGURE 1 Comparison of buoy and altimeter colocated swh measurements. 30 minute maximum time separation and 50 km along-track averages. From left to right, and top to bottom: ERS-2, TOPEX side-B, Poseidon, Jason and ENVISAT.

(NOAA/NESDIS/ORA) through the GFO calibration validation dedicated web site, for the time period from 12 December, 1999 to the end of 2003, over which the GFO SWH time series is almost continuous.

ENVISAT RA-2 data (ENVISAT 2002) are the Intermediate Marine Abridged Record (IMAR) products available for the ESA Cross Calibration and Validation Team (CCVT), cycles 15–24, from April 2003 to February 2004.

Jason data are the CNES-AVISO GDR (Picot et al. 2003), cycles 1–60, from January 2002 to September 2003.

Altimeter Flags

For validation, the altimeter data are first selected according to the value of quality flags described in the specific user's handbooks. The following flags and conditions are tested, according to the altimeter.

For ERS: SWH zero and default values; number of averaged 20 Hz measurements larger than 16; measurement confidence data (mcd) flag bits 0, 7 and 8.

For TOPEX: SWH zero and default values; swh_Pts_Avg equal to 8; AGC_Pts_Avg equal to 16; Geo_Bad_1 bits 1 and 3; Geo_Bad_2 bit 0.

For Poseidon: above TOPEX flags and Alt_Bad_1 bits 2-5; Alt_Bad_2 bits 2–5.

For GFO: 1 Hz quality flag bits 0, 4, 6, 7, 9, 10, 19–21.

For Jason-1: qual_1Hz_alt_data flag; alt_echo_type; swh_numval_ku larger than 18; surface_type 0 or 1.

For ENVISAT: product quality flag; SWH zero and default values; mcd bits 0–6 and 16; alt_surface_type 0 or 1; num_18Hz_ku_ocean_swh larger than 18; ku ocean retracking quality flag.

Buoy Data

Buoy data are from three dedicated wave buoy measurement networks: the European, the U.S. National Data Buoy Center, and the Canadian Marine Environmental Data Service (MEDS) networks. The European network data are collected via the French met office Météo-France. The U.S. and Canadian network data are collected via ftp links to NDBC or NODC, and MEDS web sites, respectively. All the available buoy data are used, without taking into account the depth or the distance to the coastline. In general, for wind and wave validation purpose, buoys located close to land or in shallow water are discarded from the analysis (Monaldo 1988; Gommenginger et al. 2002). Though sea state is modified in locations near the coast (due to refraction, breaking of waves, fetch limited conditions etc.) and can corrupt the altimeter signal, the present study keep all the available wave measurements, to get a data set as large as possible and to estimate a global validation. Note that, because of the 50 km along-track averaging, the locations very close to the coast are nevertheless discarded. In a future work, particular data sets could be extracted from the present ones in order to investigate specific effects on the altimeter measurement, such as shallow water and short fetch.

Status of ERS, TOPEX and GFO SWH Validation

Corrections to SWH were previously proposed and tested, from buoy and cross altimeter comparisons (Queffeulou 2003a). These results are recalled below and in Table 1. In the present study, the comparison data sets are updated for ERS-2, TOPEX side-B, Poseidon and GFO, and new corrections are estimated.

ERS-1 and ERS-2

As indicated in the introduction the ERS-1 SWH is not reevaluated. For ERS-1 the previous proposed correction was linear for SWH larger than 2.87 m ($a = 1.2510$; $b = -0.2458$) and

TABLE 1 Corrections to Altimeter Significant Wave Height Measurements, Proposed Previously in Queffeulou (2003a)

Satellite	Reference	n	a	b
ERS-1 (1)	Buoys			
ERS-2	Buoys	8691	1.0740	−0.0079
TOPEX side-A (2)	Buoys	2562	1.0539	−0.0766
TOPEX side-B (3)	Buoys	4024	1.0461	−0.0541
GFO	ERS-2 & TP	21228	1.0802	0.0392
Poseidon	Buoys	719	0.9925	−0.0108

For ERS-1: for swh ≤ 2.87: $\mathrm{swh_{cor}} = \mathrm{poly3(swh)}$ with $a_0 = 0.3815$; $a_1 = 0.8692$; $a_2 = 0.0746$; $a_3 = -0.0062$.
for swh > 2.87: $\mathrm{swh_{cor}} = 1.2510\times$ swh - 0.2458

For TOPEX side-A, for cycle 98 to 235: $\mathrm{swh_{cor}} = \mathrm{swh}+\mathrm{poly3}(98)-\mathrm{poly3(cycle)}$ with $\mathrm{poly3(x)} = \sum \mathrm{a_i} \times \mathrm{x^i}$ and $\mathrm{a_0} = 0.0294$; $\mathrm{a_1} = 8.5621 \times 10^{-5}$; $a_2 = -1.1875 \times 10^{-5}$; $a_3 = 7.7294 \times 10^{-8}$.

For TOPEX side-B: $\mathrm{swh_{cor}} = \mathrm{swh} - \mathrm{poly1(cycle)}$ with $a_0 = 0.1182, a_1 = -2.6366 \times 10^{-4}$.

estimated by a third order polynomial for SWH under 2.87 m. The coefficients are given in Table 1.

The ERS-2 buoy colocated updated data set (from 12/2/1999 to 9/11/2003) is shown in Figure 1 (top, left) and statistics are given in Table 2. The large number of colocated data shows that high SWH are underestimated by the ERS-2 altimeter. Nevertheless, there are relatively few data over 7 m, and the scatter is large at high SWH. The intercept of the orthogonal regression line is almost zero, indicating that low SWH are in rather good agreement with buoy data. There are 2240 colocated data under 1 m SWH, with mean value and standard deviation (std) of differences about −1 cm and 20 cm, respectively. For the 2608 data of the 1 m to 2 m SWH class, mean and std are −2 cm and 20 cm, respectively. The global std is about 0.28 m. For the five altimeter buoy comparisons presented in Figure 1, the standard deviations of differences are between 0.24 m and 0.28 m. The difference with the previously proposed correction (Table 1) is less than 1% for the slope coefficient, and less than 1 cm on the intercept.

TOPEX/Poseidon

The TOPEX side-B SWH (Figure 1, top, right and Table 2) is also underestimated at high SWH, but the slope of the regression line is less than for ERS-2. At low SWH the few

TABLE 2 Statistical Characteristics Comparing Buoy and Altimeter SWH (50 km Averages): Number of Data Points (n), Mean Value (Mean) and Standard Deviation (std) of Differences (Satellite Minus Buoy Measurements), Slope Coefficient (a), Intercept (b) and rms of the Fit (Distance)

Satellite	n	Mean	std	a	b	Distance
ERS-2	12070	−0.1194	0.2776	1.0642	0.0006	0.1894
TOPEX-B	7826	0.0025	0.2470	1.0237	−0.0476	0.1736
Poseidon	752	0.0274	0.2478	0.9914	−0.0103	0.1750
Jason-1	2853	−0.0542	0.2680	1.0072	0.0392	0.1894
ENVISAT	1280	0.1105	0.2729	1.0327	−0.1830	0.1906

centimeter intercept indicates some overestimation of TOPEX: for buoy SWH between 0.1 m and 0.8 m, the mean value of differences is 8 cm (17 cm std, 968 data); for the 0.8 m to 1.5 m SWH range, the mean reduces to 2 cm (19 cm std, 2044 data). The change of the coefficient relative to the previous proposed corrections (Table 1) is a decrease of 0.022 for the slope, and an increase of 0.6 cm for the intercept.

For Poseidon, the plot in Figure 1 (middle) and statistics in Table 2 show that Poseidon is, on average, in good agreement with buoy data, with no need for correction, though there are few data, in the colocated data set, with SWH greater than 5 m.

The usual practice is to separate the TOPEX mission into two different time periods, determined by the switch on of the spare-B altimeter electronics on February 1999, due to significant drift of the side-A electronics (Hayne and Hancock 1998; Hancock et al. 1999). The impact of the drift on SWH is an increase of about 40 cm in SWH estimate from 1996 to end of 1998 (Queffeulou 2000, 2003a). Correction of the drift is achieved, using comparison with ERS-2 measurements at ground track crossing points. Figure 2 shows the mean values over each 10-day TOPEX cycle, of differences between TOPEX and ERS-2, and between Poseidon and ERS-2. The upper graph is relative to noncorrected altimeter data. The lower graph is relative to corrected data: the global updated relations of Table 2 (slope and intercept) are used to correct ERS-2 and TOPEX side-B SWH; TOPEX side-A (before cycle number 236) is corrected according to Table 1. These corrections reduce the levels of differences between the three altimeters, but, of course, do not suppress the drift between TOPEX and ERS-2. The difference between TOPEX and ERS-2 SWH increased by approximately 40 cm between 1996 and 1998, while no trend is observed in the Poseidon ERS-2 difference. The large differences observed for cycle 310 to 313 correspond to ERS-2 attitude perturbation during the particular Extra backup Mode phase in February and March 2001. The drift of TOPEX is evaluated as in Queffeulou (2003a), but with the upgraded available corrections, in fitting a third order polynomial to the data, as a function of cycle number. The correction of TOPEX SWH drift is done independently of the SWH level.

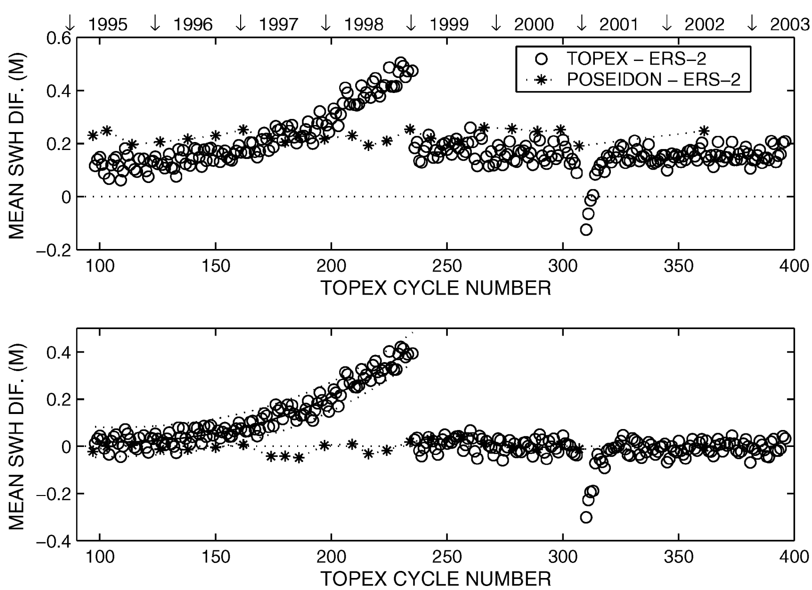

FIGURE 2 Mean values of altimeter swh differences at ground track crossing points (1 hour, 100 km along track averages) over successive TOPEX cycles. Raw data (upper graph) and corrected data (lower graph).

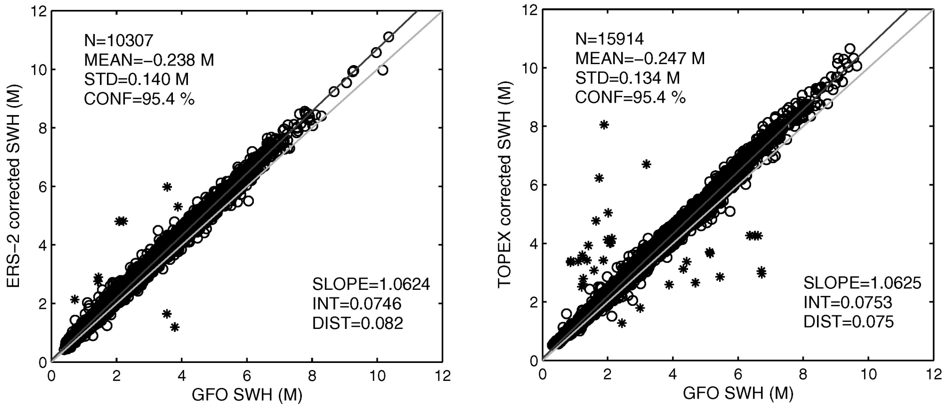

FIGURE 3 Comparison of colocated swh measurements at ground track crossing points (1 hour, 100 km along track averages): GFO ERS-2 (left) and GFO TOPEX (right).

This is justified because investigation of the trend for various SWH classes does not show significant dependence on SWH. The fitted curve is shown in the lower graph of Figure 2, with the 50% confidence limits. Coefficients of the polynomial are given in the summary Table 6. Note that a very slight negative trend is present on the TOPEX side-B minus ERS-2 differences, resulting in a decrease of 1.8 cm from cycle number 236 to 396, when a straight line is fitted.

GFO

We have not colocated GFO measurements with buoy data and so the GFO SWH validation is achieved using comparison with ERS-2 and TOPEX, at ground-track crossing points, for December 1999 to December 2003. The ERS-2 and TOPEX side-B data were first corrected according to the updated formulae of Table 2. Plots comparing 100 km along-track averages are shown in Figure 3 and statistics are given in Table 3. Some outliers (star symbols in the figure) are present, though all the flag tests were applied: these data were selected (and discarded) as being outside a threshold defined by the mean value of differences plus or minus 7 times (respectively 6) the standard deviation for ERS-2 and TOPEX, respectively. The number of discarded data is only 0.09% for ERS-2, and 0.22% for TOPEX. The standard deviations of differences for these altimeter to altimeter comparisons are smaller (about half) than for buoy to altimeter comparisons: the along track averaging distance is larger and the two data are of same nature. If TOPEX and ERS-2 corrected SWH are assumed to represent some truth, then the behavior of GFO is the same as other altimeters (with, maybe, the exception of Poseidon), that is to underestimate high SWH. Statistical parameters reported in Table 3, are very close for the two data sets. Results obtained with TOPEX, the largest data set, are used below, to correct the GFO SWH measurement. Note on the TOPEX GFO

TABLE 3 Statistical Characteristics Comparing GFO to ERS-2 and TOPEX Colocated SWH, for 100 km Along-Track Averages

Satellite	n	Mean	std	a	b	Distance
ERS-2	10307	−0.2381	0.1406	1.0624	0.0746	0.0824
TOPEX	15974	−0.2477	0.1350	1.0625	0.0754	0.0753

comparison plot that some change seems to occur in the data cloud feature, at about 6.5 m SWH.

Jason-1 SWH Validation

Comparing previous Jason IGDR data with buoy measurements has shown that using the SWH dedicated quality flags does not suppress some outliers (Queffeulou 2003c). Firstly, a particular problem was identified in relation to the SWH instrumental correction which is set to 0.008 m for all SWH less than 0.51 m. An accumulation of IGDR SWH values at 0.008 m was observed, corresponding indeed to zero noncorrected SWH; these data were discarded from the validation data set. The accumulation at 0.008 m is also observed on the GDR SWH: the percentage of such cases is about 0.4% over the 59 cycles analyzed here. Secondly, outliers were characterized by large values of the off nadir angle, estimated from the waveform, and (or) by large values of the 1-second rms of the SWH estimate. For the present GDR such outliers exist but in a lower ratio than for the IGDR. In practice, large values of SWH rms, of the order of 1 m to 5 m, are observed for instance over the medium SWH range of 1 m to 4 m. Some of these outliers are associated to large values of the off nadir angle, but a threshold on this parameter (0.1° squared for instance) or on the SWH rms (1 m) does not allow excluding all the outliers, and also discards some a priori noncontaminated data (in agreement with buoy measurements, particularly at high SWH). To select these outliers the method suggested by Cotton et al. (2003), for ENVISAT validation, was extended and applied to Jason.

The method is based on the fact that the distribution of the logarithm of the SWH rms is more nearly normally distributed than the SWH rms itself, which allows taking an upper limit value for the logarithm defined as the mean plus three times the standard deviation, corresponding to the maximum value rms_max = exp (mean +3std) for the SWH rms. As suggested by Cotton et al. (2003) the behavior of this upper limit was investigated as a function of SWH level: mean values of rms_max were estimated for SWH classes, 1 m wide, over successive 10-day time periods. Mean values and standard deviation of rms_max, over the 59 cycles, as a function of SWH, are shown in Figure 4 (left). The scatter is large at high SWH, nevertheless a second order polynomial fits rather well the data for SWH less than 10 m, and this excludes most of the outliers, representing 0.7% of the data, on average over the 59 Jason cycles. The coefficients of the fit are 0.9961, −0.0398, and 0.0132 for a0, a1 and a2, respectively. In the following, this relation is used to remove the SWH outliers.

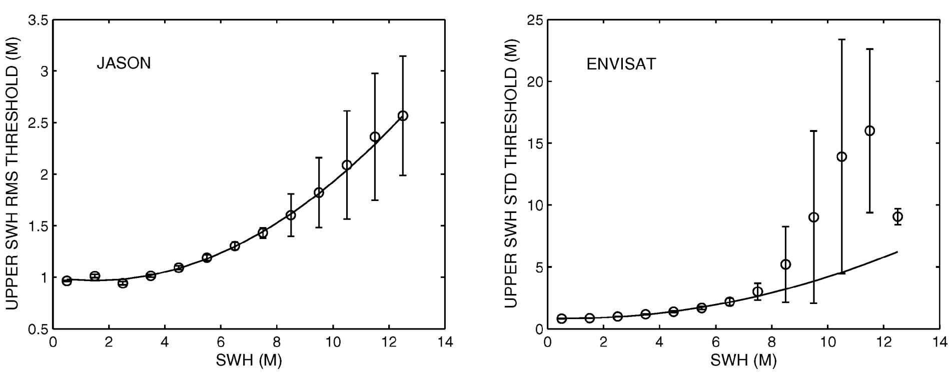

FIGURE 4 Estimation of the upper threshold value for swh rms, as a function of swh, for Jason GDR (left) and ENVISAT IMAR (right).

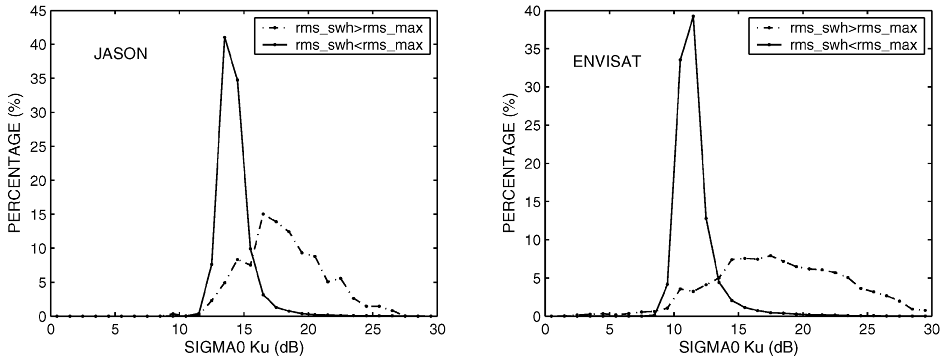

FIGURE 5 Comparison of Ku sigma0 distributions for swh measurements with a rms lower than (full line) or larger than (dotted line) the swh rms threshold, for a global 10-day data set and for medium 1 m–3 m swh conditions, for Jason (left) and ENVISAT (right).

As observed previously and reported in Ray and Beckley (2003), many of the outliers correspond to relatively high sigma0 values, in so-called "sigma0 blooms." Figure 5 (left) shows the difference between the sigma0 (Ku) distributions obtained for the data with a SWH rms larger than or lower than the upper SWH rms threshold defined above, over a 10-day Jason-1 global GDR data set, for a moderate range of SWH (1 m to 3 m). The sigma0 values are very high for the data with a SWH rms above the threshold. This suggests that in the future a more efficient filter will have to include the sigma0 value. This problem has been also recently addressed by the Jason-1 project and a mean quadratic error coefficient is now computed (within the ocean-2 retracking mode), characterizing the deviation of the sampled waveform from the theoretical one. This parameter is available in the SGDR (Sensor Geophysical Data Record) and not in the GDR, and for this reason, it has not been tested in the present study, but will be in the near future.

Results of buoy and Jason-1 GDR SWH comparisons, with outliers removed, are shown in Figure 1 (bottom, left) and in Table 2. The intercept is only about 4 cm, and the slope of 1.0072 is close to unity. This is different from the results obtained by Ray and Beckley (2003) for IGDR cycles 3–20 (1.100 slope and −10.4 cm intercept). The new GDR version 6 software improves the accuracy of the SWH estimate. The number of colocated data over 6 m SWH is poor and, in order to investigate the high SWH values, Jason-1 is also compared to GFO and ERS-2, at the ground-track crossing points. For the comparison GFO and ERS-2, SWH are corrected using the updated corrections. Scatter plots comparing the 1-second measurements in Figure 6 and statistical results in Table 4 show that the standard deviation of differences is larger with ERS-2 (0.35 m) than with GFO (0.24 m), and that the slope coefficients (1.0673 and 1.0533) are consistently larger than the 1.0072 slope obtained from the buoy comparisons (Table 2). This difference could result, partly, from the number of data at high SWH, which is larger for cross altimeter comparisons than for buoy comparisons. Results for 100 km along track averages are also given in Table 4. Mean values of differences are the same as for 1-second data (−0.12 m) and the standard deviation are reduced to about 0.15 m. The differences relative to ERS-2 and GFO are less than for 1-second data. For the 100 km along track averages, the regression lines from GFO and ERS-2 are very close; the difference between the two lines decreases from only 1.4 cm for 1 m SWH to −1.1 cm for 10 m SWH.

ENVISAT RA-2 SWH Validation

The same approach as for Jason-1 is adopted to validate the ENVISAT IMAR SWH. As found for the Jason-1 data, the application of the usual flags is not sufficient

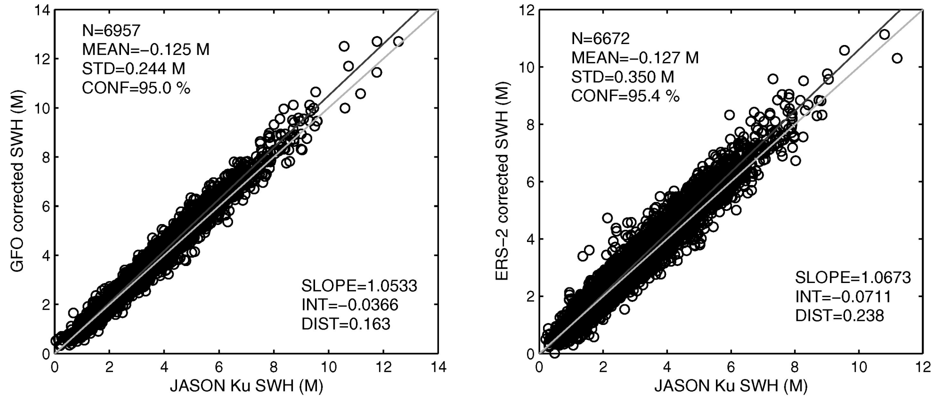

FIGURE 6 Comparison of Jason swh measurements with GFO (left) and ERS-2 (right) colocated data at ground track crossing points (1 hour, 1 Hz along track data).

(Cotton et al. 2003; Queffeulou 2003b). Visual inspection on plots of the SWH standard deviation as a function of SWH reveals, in general, two distinct data clouds: a first one with a realistic increase of SWH std with SWH; a second one corresponding obviously to erroneous data, with large SWH std at medium SWH range. A possible threshold for the SWH std is estimated with the same method as for Jason-1. Note that for ENVISAT the 1 second SWH standard deviation is available, instead of the SWH rms in Jason-1 case. Mean values and standard deviations of the upper SWH std threshold over the 34 10-day time periods analyzed are shown, as a function of SWH, in Figure 4 (right). A second order polynomial is fitted over SWH data less than 7 m to estimate the upper limit for the SWH std. Above 8 m SWH the scatter is very large, with some unrealistic values, as high as 25 m, of the SWH rms. Nevertheless the threshold was applied for all SWH ranges. The coefficients of the fit are 0.8457, −0.050 and 0.0384 for a0, a1, and a2, respectively. On average, over the whole IMAR data set, about 3% of the data are discarded in this way.

As for Jason-1, many of the outliers correspond to abnormally high values of Ku sigma0 (Figure 5, right), for open ocean. Some other outliers correspond to measurements located very close to the coastline and to the ice limit. Some of the outliers are clearly located over land!

Buoy ENVISAT comparison results, using the above upper SWH std limit, are shown in Figure 1 (bottom, right) and Table 2. ENVISAT underestimates high SWH, and overestimate low SWH, with a slope coefficient of 1.0327 and an intercept about −18 cm, the mean value of differences being 11 cm (underestimation). Slope and intercept are larger than for Jason-1. The scatter for SWH above 6 m is also larger, but the number of colocated data is less than for Jason-1. Results are confirmed by the comparison with GFO (corrected value), for 1 second colocated data (Figure 7), and 100 km average data (Table 5). The slope is about 1% larger than for the buoy comparisons, due to the higher weight of high SWH.

TABLE 4 Statistical Characteristics Comparing Jason to GFO and ERS-2 Colocated SWH, for 1-Second Data and 100 km Along-Track Averages

Satellite	n	Mean	std	a	b	Distance
GFO 1-s	6957	−0.1253	0.2442	1.0533	−0.0366	0.1635
ERS-2 1-s	6672	−0.1271	0.3502	1.0673	−0.0712	0.2387
GFO 100 km	6332	−0.1226	0.1456	1.0587	−0.0571	0.0852
ERS-2 100 km	6283	−0.1270	0.1549	1.0559	−0.0405	0.0965

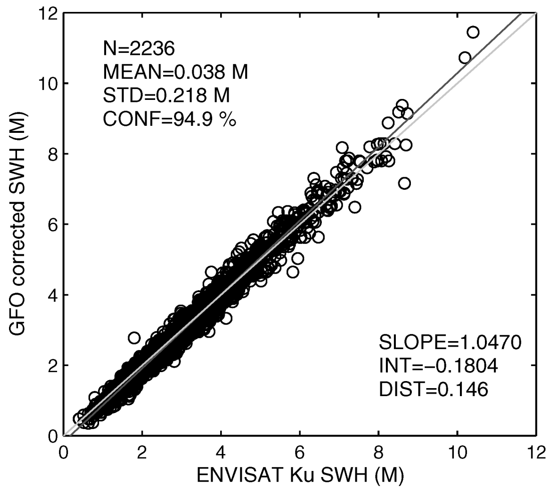

FIGURE 7 Comparison of ENVISAT swh measurements with GFO colocated data at ground track crossing points (1 hour, 1 Hz along track data).

Jason-1 and ENVISAT SWH Corrections

Though the criteria for the selection of the data are not well established, corrections are proposed for Jason-1 and ENVISAT SWH. For a better homogeneity among altimeters, the coefficients of the orthogonal regressions obtained with GFO (corrected measurement and 100 km averages) comparisons are suggested as corrections. A summary of the proposed corrections is given in Table 6. Applying these corrections to the ENVISAT Jason-1 ground-track crossing point measurements gives the results in Figure 8. Mean value of differences is almost zero, with a standard deviation of 0.27 m. The intercept is 2 cm and slope (0.9938) is almost unity. This can be seen as some check of the proposed corrections, which, nevertheless, will have to be tested with more high SWH wave buoy data.

Long-Term Statistics

Simple statistics, at global ocean scale, have shown significant differences between the SWH measurements of ERS-1, ERS-2, TOPEX, and GFO (Queffeulou 2003a). The same method is applied here to the updated data set for these altimeters and is extended to Jason-1 and ENVISAT. For each altimeter, averaged values of SWH are computed over the global ocean, limited by the TOPEX and Jason-1 extreme ground-track latitudes of about 66.15° North and 66.15° South, and over successive 10-day time periods. Though the sampling coverage is not the same for all the satellites due to different orbit inclination, phasing, and

TABLE 5 Statistical Characteristics Comparing ENVISAT to GFO and Jason-1 Colocated SWH, for 1 s Data and 100 km Along-Track Averages

Satellite	n	Mean	std	a	b	Distance
GFO 1-s	2236	0.0383	0.2186	1.0470	−0.1805	0.1468
Jason 1-s	1268	0.1502	0.2542	0.988	−0.1112	0.1791
GFO 100 km	1428	0.0417	0.1079	1.0526	−0.1991	0.0569
Jason 100 km	853	0.1450	0.1147	0.9979	−0.1380	0.0810

TABLE 6 Summary of the Proposed Corrections to Altimeter SWH Measurements. swh_cor = a swh + b

Satellite	Reference	n	a	b
ERS-2	Buoys	12070	1.0642	0.0006
TOPEX-A (1)	Buoys	2562	1.0539	−0.0766
TOPEX-B	Buoys	7826	1.0237	−0.0476
Poseidon	Buoys	752	0.9914	−0.0103
GFO	TOPEX	15974	1.0625	0.0754
Jason-1	GFO	6332	1.0587	−0.0571
ENVISAT	GFO	1428	1.0526	−0.1991

(1) TOPEX side-A has to be further corrected as a function of cycle number, for cycle 98 to 235: $swh_{cor} = swh + poly3(98) - poly3(cycle)$ with $poly3(x) = \sum a_i \times x^i$ and $a_0 = 0.0864$; $a_1 = -6.0426 \times 10^{-4}$; $a_2 = -7.7894 \times 10^{-6}$; $a_3 = 6.9624 \times 10^{-8}$

time repeat cycle, one can expect to detect any long term trend or anomaly when comparing the informations issued from the various satellites.

The upper graph in Figure 9 shows global 10-day SWH averages from uncorrected TOPEX and ERS-2, over almost 11 years; there is a significant difference between the two altimeter measurements. The 20 cm bias between the two altimeters is clearly shown on differences (middle graph), as is the known TOPEX SWH drift between 1996 and 1999. A bias of 20 cm is also observed between TOPEX and GFO. The lower graph in Figure 9 shows the results obtained, once the data are corrected with the relations proposed above (Table 6): linear correction for ERS-2, GFO, TOPEX side-A and side-B, and correction of the side-A drift, using the third order polynomial. The amplitude of differences is reduced to less than about 10 cm, over the three altimeters. There are still some biases and fluctuations with time, which cannot be solved by this simple method. The mean bias between TOPEX and ERS-2 is 5.8 cm (3.5 cm standard deviation), but this bias is not observed on the TOPEX ERS-2

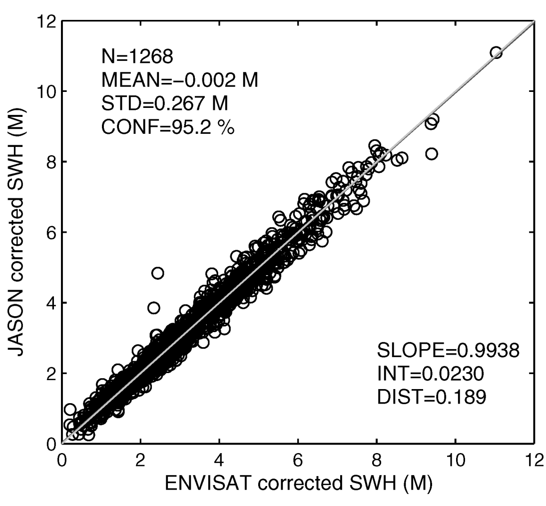

FIGURE 8 Comparison of ENVISAT swh measurements with Jason colocated data at ground track crossing points (1 hour, 1 Hz along track data). Both altimeter data sets are corrected using values given in Table 6.

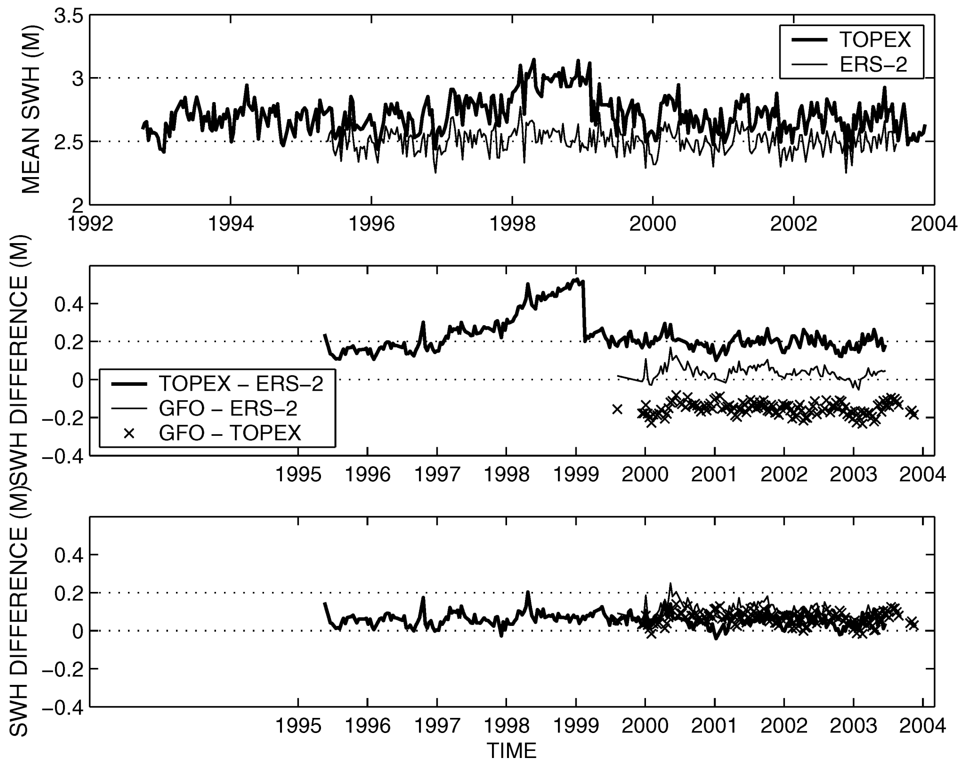

FIGURE 9 10-day averages of global ocean swh measurements from TOPEX and ERS-2 (top), and differences for raw data (middle) and corrected data (bottom), between TOPEX, ERS-2 and GFO.

crossing point comparisons of lower graph in Figure 2 before the beginning of the TOPEX drift. The origin might be in the different geographical samples of the two satellites. Due to the relative phasing of the orbits, particularly relatively to the land, combined with the length of the time repeat cycle, the sampling differs according to the latitude. For instance the total along-track length of valid ocean measurements was estimated over four consecutive months, for ERS-2 and TOPEX, and over two different latitude bands, characterized by different SWH distributions. For the latitudes between the equator and 30° South, the ERS-2 along-track sampling length is about 9.9% larger than the TOPEX sampling. At the opposite, for the 30°S–60°S latitude band (with statistically larger SWH) the TOPEX sampling is 2.8% larger than the ERS-2 one. Such sampling differences can induce biases on averaged SWH.

An equivalent global analysis (60°N–60°S, 10-day averages) was carried out for each of the five altimeters, over the time period of the Jason-1 and ENVISAT missions (Figure 10). The values for the upper graphs are calculated from the uncorrected measurements produced by the specific space agencies, and the lower graphs show the results obtained with altimeter SWH data corrected according to Table 6. Correcting the measurements greatly reduces the differences between the different satellite data sets. There are still some differences in SWH but these are reduced to less than about 10 cm. Of course above results do not validate entirely the proposed corrections, particularly for high SWH, but they do demonstrate an improved consistency between the SWH measurements of the different altimeters.

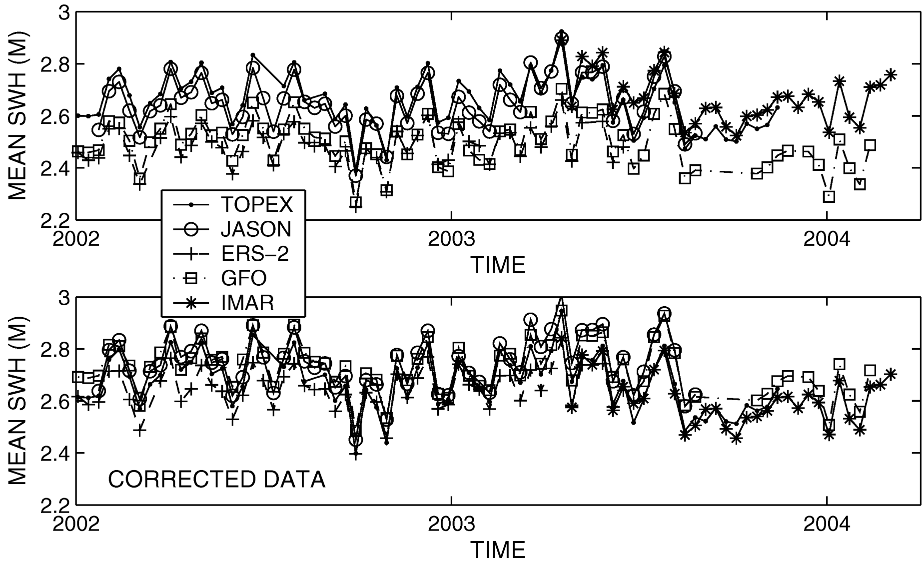

FIGURE 10 10-day averages of global ocean swh measurements from TOPEX, Jason, ERS-2, GFO and ENVISAT IMAR, for raw data (top) and corrected data (bottom).

Conclusion

Using buoy and cross altimeter comparisons, the previously proposed corrections to SWH measurements from ERS-2, TOPEX side-A and side-B, Poseidon and GFO were updated. When uncorrected, the altimeter SWH measurements can be in error, by as much as 40 cm for the TOPEX drift for instance. The consistency of the proposed corrections has been demonstrated, through multiple cross comparisons and long-term statistics. The corrections are still to be improved at high SWH.

SWH estimates from the recent Jason-1 and ENVISAT altimeter missions have been tested using buoy and cross altimeter comparisons. The agreement with buoy data is good, but, at high SWH, cross altimeter comparisons show that Jason-1 and ENVISAT SWH are underestimated, as is usual for the other altimeters. Due to the high sensitivity of the new sensors, it was also confirmed that the waveform sampling does not allow estimating correctly the SWH in particular cases of "sigma0 blooms," representing a very few percent of the data. In this case, the quality flags are not efficient, and empirical relationships were established to discard such data. More work is needed to investigate these occurrences in a more theoretical way. The corrections to SWH measurements have been established using similar methods for the whole set of altimeters and can help the users in getting homogeneous and consistent altimeter SWH data.

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