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VALIDATION OF JASON-2 AND ENVISAT WIND SPEED AND SIGNIFICANT WAVE HEIGHT DATA IN THE INTERTROPICAL ZONE

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ABSTRACT. The estimates of significant wave height (SWH) and wind speed at 10 meter height (u10) from the Jason-2 and ENVISAT satellites, over the intertropical region, are analysed. Some authors have tested the dependency of satellite radar wind/wave measurements on local environmental conditions, particularly on wave age, with no conclusive results. Our data show that Jason-2 overestimates high values of SWH and underestimates low values, while ENVISAT exhibits the opposite behaviour. The correlation coefficient between buoy measurements and altimeter data is around 0.95, with bias and root mean square error (RMSE) of, 3 and 15 cm respectively. On the other hand, Jason-2 underestimates u10 throughout the whole measured range, while ENVISAT overestimates throughout the whole range for speeds over 3 m/s. The correlation coefficient is around 0.90, with bias and RMSE around 0.20 cm and 1.5 m/s, respectively. The altimeter estimates in the intertropical region are similar to those obtained with global coverage, hence the sensitivity to sea state to extract wind speed and wave height is not so obvious in our data set. Therefore, the results indicate that the algorithms employed have a fair enough performance in the intertropical region.

Keywords: wind waves, wind speed, altimeter, Jason-2, ENVISAT.

RESUMO. As estimativas de altura significativa de onda (SWH) e de intensidade do vento a 10 metros de altura (u10) dos altímetros dos satélites Jason-2 e ENVISAT, obtidas na região intertropical, são analisadas. Alguns trabalhos apontam para uma possível dependência da esbeltez das ondas, e portanto do estado de mar, para extração de u10 e SWH, o que tornaria os algoritmos empregados dependentes da localidade. Os resultados aqui obtidos mostram que o Jason-2 em geral superestima altos valores de SWH e subestima baixos valores, enquanto que para o ENVISAT a tendência encontrada é a inversa. Foram obtidos coeficientes de correlação entre a SWH de boias e dos altímetros em torno de 0,95, e bias e erro médio quadrático (RMSE) de aproximadamente 3 e 15 cm, respectivamente. Em relação à u10, o Jason-2 subestima ligeiramente os valores, independente da faixa de intensidade do vento, enquanto que o ENVISAT os superestimam em quase todas as faixas de intensidade, exceto para ventos menores que 3 c/s. Os coeficientes de correlação se encontram em torno de 0,90, com bias e erro médio quadrático de, respectivamente, aproximadamente 0,20 cm e 1,5 c/s. Os resultados indicam que o desempenho na região intertropical é similar aos resultados obtidos empregando medições globais, que são altamente concentradas em altas latitudes no Hemisfério Norte. O efeito da condição do estado de mar para extração de SWH e u10, caso seja importante, não aparenta ser considerável no conjunto de dados aqui empregado. Portanto, os resultados apontam para um desempenho bastante aceitável de tais algoritmos quando empregados na região intertropical.

Palavras-chave: altura significativa de ondas, intensidade do vento, altimetria, Jason-2, ENVISAT.

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INTRODUCTION

The way we see and understand the oceans has changed significantly since the launch, in the early eighties, of the first satellites dedicated to environmental studies. Unquestionably, from the point of view of operational applications, the largest impact comes from measurements obtained by radar altimeters, which are routinely assimilated in the main meteo-oceanographic forecasting centers on Earth. For over two decades, altimeters continue to generate a huge database of sea surface height, significant wave height (SWH) and wind speed at a height of 10 m (u10) values, among others, with global distribution.

Radar altimeter is a nadir observation instrument that operates in the microwave band, emitting electromagnetic pulses and measuring it's return time, the magnitude and the shape of the signal after its backscatter from the sea surface. From these data, we obtain the distance between the satellite and the ocean, the surface roughness and the height of the waves in the illuminated region by the pulse, ranging from 2.8 km in a calm sea to 10 km in higher energy conditions (Robinson, 2004).

With spatial resolution of about 5 km along their trajectory, the limitation of the altimeters is the compromising relationship between satellite revisit time and the spatial resolution along the orbits. For illustration purposes, Jason-2 satellite shows a relatively short cycle of repetition (10 days), being able to observe the same point in the ocean frequently, though with groundtracks – the satellite orbit's projection on Earth's surface – relatively closely spaced, 315 km at the equator. ENVISAT, on the other hand, has a higher repetition cycle of 35 days, and comparatively smaller spacing at the equator, 80 km.

The first fundamental information obtained by the satellite is the sea level, given by the difference between the satellite height relative to the reference ellipsoid and the surface of the ocean, discounted the corrections along the signal path. As the pulse backscatter occurs first on the crest and then on the trough, the duration of the radar pulse that returns to the altimeter is a function of the wave height, allowing also a SWH estimate. Through this backscattering it is also possible to extract the wind field of the investigated area. Wentz et al. (1986) demonstrated that this is possible since the magnitude of the backscattered radiation is a function of the sea surface roughness, which, in turn, is highly correlated with the near surface wind.

Overall, there is a consensus that the values of SWH altimeters and the buoys are equally accurate (Gower, 1996). The SWH estimation by the altimeter is obtained directly from the shape of the pulse backscattering to the sensor, without using any algorithm. A number of recently published studies show that these estimates are very close to the measurements obtained through. Queffeulou (2004), for example, observed that the standard deviation of the differences between altimeter estimates and buoy measurements is around 0.30 m, with the altimeter having a tendency to slightly overestimate low SWH values and overestimate high SWH values. Additionally, some studies have sought evidence of dependence on SWH estimates with parameters such as the local sea and swell energy ratio, the water or air temperature, the wave peak and mean period, the wave age (which is the ratio between the wave velocity at peak frequency and u10, and can be used as an indicator of the stage of development of the sea), the wind speed and the stability of the boundary layer. Cotton (1998) pointed out anomalous SWH values in the vicinity of Hawaii, where swell is the dominant state of the sea, with most of the energy concentrated at the low frequencies. Although the author has not found in his data any explicit dependence on sea state, some differences between buoy-altimeter comparisons, conducted in various regions of the planet, remain and may be indicative of some kind of dependence on local conditions.

However, the question of how best to obtain u10 estimates is still subject to debate. Similar to SWH, there is a strong correlation between u10 and the feedback signal of the pulse emitted by the altimeter, called sigma-0 or NRCS, Normalized Radar Cross Section. In models such as the one proposed by Witter & Chelton (1991), for example, u10 is obtained only as a function of sigma-0. However, a number of studies questions whether there is a further dependence on the sea state parameters in the relationship between sigma-0 and u10.

In his work, Cotton (1998) also investigated whether estimates of u10 depended on local conditions. The author reported that the altimeter tends to underestimate u10 in the presence of waves of short length, small SWH and of small wave age, characteristics of sea states in development. Other works, such as Freilich & Challenor (1994) also confirm this dependence, with increasing errors in cases where the wave age is higher. Therefore, a number of researchers have proposed algorithms for obtaining u10 that take into account some kind of sea state indicator, usually SWH since this parameter is readily obtained from the altimeter. More recent works, like Gourrion et al. (2002), consider the value of SWH in their algorithms, based on observations showing that different values of sigma-0 can be obtained for the same value of u10, depending on the development stage of the sea. However, there is no clear evidence that algorithms based on sigma-0 and SWH result in better u10 estimates than the algorithms that employ only sigma-0, as discussed in Zieger et al. (2009).

The climatologies of wind speed, and therefore of SWH, differ significantly in different regions of the world (Young & Holland, 1996). In the Northern Hemisphere, seasonal variations of the mean wind velocity are more intense than those that occur in the Southern Hemisphere and tropical regions. The local sea swell energy ratio also presents differences due to geographical location. In intertropical regions, much of the spectral wave energy is contained in low frequency, in contrast to regions of higher latitudes that have a comparatively larger contribution of local sea.

Algorithms developed to estimate SWH and u10 stumble in the limited number of *in situ* measurement points available used to adjust the remote measurements. Furthermore, the vast majority of these measurements was obtained from buoys anchored on the coast of the United States, usually in excess of 40 degrees latitude, and located entirely in the Northern Hemisphere.

This study investigates the values of SWH and u10 obtained in the intertropical region by two satellites currently in operation. *In situ* measurements of wind speed and significant wave height are compared with the values estimated by the satellites. The regressions obtained for the intertropical region are compared with the ratios, usually global, presented in literature, and their accuracies discussed. To this purpose measurements obtained in the Tropical South Atlantic are employed, together with data from buoys located in Hawaii and the North Equatorial Atlantic.

METHODOLOGY

Data of various satellite missions of the past 20 years are combined to produce a set of almost uninterrupted altimeter data. The main data base of SWH and u10 values used for calibration of these data consists of buoys installed in the North Atlantic and North Pacific, especially along the coast of the United States and Western Europe. These buoys are maintained by different organizations, ranging from private institutions to federal agencies aiming at joint action.

Altimeter data validation studies seek to obtain a set of colocated *in situ* and remote sensing measurements. The great difficulty of this procedure is that measurements have different spatial and temporal characteristics (Monaldo 1988). Thus, data obtained by the two methods may differ even though both methods of data acquisition may work flawlessly. According to Monaldo (1988), these differences can be divided into three categories: temporal proximity, spatial proximity and sampling variability.

The differences related to the temporal proximity of the samples are due to the fact that measurements made by the altimeter and by the instrument *in situ* are rarely done simultaneously. Because of that, there is a need to establish a temporal window to make possible the comparison of measurements. In other words, altimeter and *in situ* measurements that are separated by a predefined maximum time interval are paired and considered comparable.

Similarly, differences associated to spatial proximity occur because measurements of both data acquisition methods usually do not coincide at the ocean surface. Thus, similar to the temporal window, a spatial window is established. In this case, however, the *in situ* measurement location is defined as the center of this spatial window. A maximum radius delimits an area in which all the altimeter measurements in this region are considered comparable and paired with the *in situ* data.

The differences related to sampling variability also occur in validation studies of wind and wave data obtained by altimetry because the altimeter measurements are instantaneous spatial averages in the area illuminated by the satellite, while the *in situ* measurements are, in general, temporal averages at a single point. In other words, since the sampling procedures are different, the correlation between values obtained by the different methods is also a function of the difference between the sampling methods (Monaldo, 1988).

The *in situ* measurements are commonly considered representative of the ground truth data for wave and wind. Therefore, for data validation, it usually fits altimeter data to buoy data sets, *i.e.*, data validation is done by treating the altimeter data as the independent variable and the *in situ* data as the dependent variable (Durrant et al., 2009). However, according to Caires & Stud (2003), both data acquisition methods have comparable errors, suggesting that fitting techniques should be applied for errors arising from both types of data sets.

In situ measurements

Overall, data from meteo-oceanographic buoys are the most used in validation studies. However, there are several other devices which are used for wave data acquisition, such as pressure sensors and radars. In this work, *in situ* measurements from three different equipment types were used for wave data measurements.

The buoy data are from the NDBC (National Data Buoy Center), a network maintained by the U.S. government. The accuracy of the buoy is of the same order of the altimeter. The other wave data were obtained by pressure sensors and radars installed on Petrobras oil platforms, namely the pressure sensor FSI-3D and radar MIROS. Figure 1 shows all *in situ* measurement sites. In all wave data measurement sites – both NDBC buoys and Petrobras platforms – wind speed data were aquired using YOUNG anemometers. A brief description of the basic features of these measuring devices follows.

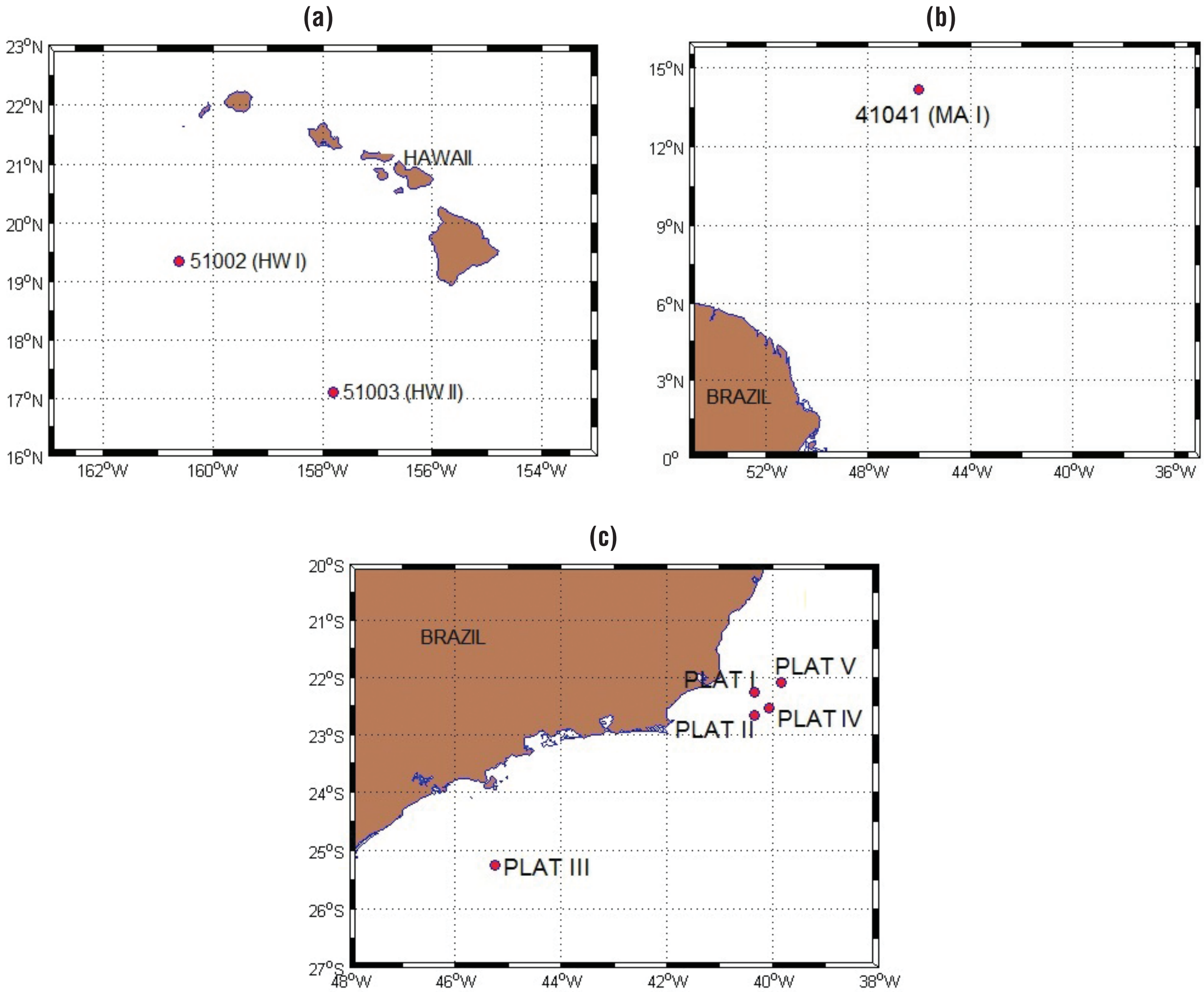

Figure 1 – Stations of SWH and u10 *in situ* measurements at (a) the coast of Hawaii, (b) Brazil southeast coast and (c) Equatorial Atlantic.

NDBC buoys: Accelerometers and/or inclinometers on the buoys measure the acceleration and/or the vertical displacement of the hull during data acquisition. Acquisition time is 20 minutes with accuracy for SWH measurement of ± 0.2 m. More detailed information can be found at:
<http://www.nlbc.noaa.gov/wave.shtml>.

3D-FSI: Made by Falmouth Scientific Inc, they measure pressure and velocity horizontal and vertical components. Usually located in the subsurface at a depth between 10 and 20 meters, they perform data acquisition every second, generating SWH data files for the last 20 minutes (1200 data) of each hour. The accuracy for measuring SWH is a function of the depth of the device, nominally equal to $\pm 0.01\%$ of full scale. More details at: <http://www.falmouth.com/sensors/currentmeters.html>.

MIROS: Radar developed by MIROS AS for measuring the directional wave spectrum in real time (more details at: <http://www.miros.no/>). Operates in the microwave band and takes measurements along a semicircle located at distances ranging 180-450 m from the sensor, which is installed at a height of 20 to 100 m from the sea surface. It has a resolution of 0.1 m and records every 3 seconds, with accuracy for SWH measurement of $\pm 5\%$. It should be noted that, although it is not an orbiting altimeter, this equipment is a remote sensor, however, in this work, MIROS radar data are classified as *in situ* data.

YOUNG: anemometers that measure the intensity and direction of the wind. When in platforms, they are usually installed between 50 and 100 m high. In buoys, they are generally located around 5 meters above sea level. Subsequently, their data are converted at elevation of 10 m, using the method described at <http://www.ndbc.noaa.gov/adjust_wind.shtml>. They have an acquisition rate of 1 Hz and compute an average every 10 minutes. They register winds up to 60 m/s with an accuracy of 1 m/s.

Details of the technical specifications can be found on the manufacturer's page (<http://www.youngusa.com/products/>).

In total, three years of data were used, with short gaps between sets that correspond to gaps in the *in situ* measurements. Table 1 shows the main information of the data collection stations that were used in the work, while Figure 1 illustrates their geographical position. Petrobras platforms are indicated as Plat I to V. NDBC buoys located in the vicinity of the Hawaiian Islands are identified as HW I and II, while the buoy located in the North Atlantic is identified as MA I.

Altimeter Data

The altimeter data from ENVISAT and Jason-2 satellites, were obtained from the data base RADS (Radar Altimeter Database System in http://rads.tudelft.nl/rads), which is a GDR (Geophysical Data Record) data repository. GDR data are stored, usually up to two months after acquisition date, and undergo validation testing and geophysical corrections. For the u10 data from the Jason-2 stored in the GDR, the two parameter algorithm by Gourrion et al. (2002) is used, which employs both SWH and sigma-0 values to compute u10. ENVISAT u10 data, on the other hand, were generated by a single parameter algorithm proposed by Abdalla (2007) which computes the wind speed using a linear interpolation between the values sigma-0 and u10.

Selection Criteria

Spatial and temporal windows of 50 km radius and $\pm$30 minutes were used in order to establish the limits of selection for comparison between *in situ* and altimeter measurements. These values were proposed by Monaldo (1988), obtained through analysis of the influence of spatial and temporal variations on wave fields. Since then, this criterion has been widely used and is considered a standard, and is repeated here for comparison with other works.

Data from altimeters suffer interference near the coast. This interference was eliminated by selecting platforms located at least 50 km from the coast and 100 m deep (Table 1). For the same reason, no satellite measurements taken at less than both 100 m depth and 30 km from the coast were used, even if they were within the spatiotemporal window established. Each altimeter yielded a set of 14 to 18 measurements per second along the spatiotemporal window. From this set, values greater than twice the standard deviation were discarded. An average of these values is taken, so that, in each *in situ* measurement, there is a single measurement of the altimeter referring to that point.

Regression and Statistical Parameters

Regression analysis using least squares was performed to obtain the relationship between the altimeter data and *in situ* measurements, considering the satellite and *in situ* data as the independent and dependent variables, respectively. Additionally, the following statistics were calculated: bias, root mean square error (RMSE), scatter index (SI) and correlation coefficient (R), defined as:

$$
\begin{aligned}
bias &= \frac{1}{N}\sum_{i-1}^{N} A_i - B_i \\
RMSE &= \sqrt{\frac{1}{N}\sum_{i-1}^{N}(A_i - B_i)^2} \\
SI &= \sqrt{\frac{1}{N}\sum_{i-1}^{N}\left[(A_i - \bar{A}) - (B_i - \bar{B})\right]^2} \\
R &= \frac{\sum_{i-1}^{N}(A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_{i-1}^{N}(A_i - \bar{A})^2(B_i - \bar{B})^2}}
\end{aligned}
\qquad (1)
$$

Table 1 – Information of wave height and wind speed data measurement stations: type of sensor for measuring SWH, type of sensor for measuring u10, distance of the device from the coast, its local depth and the measurement period. The geographical position of the sensors is shown in Figure 1.

	Sites	Sensor SWH	Sensor U10	Dist. Coast Depth	Period
Plat I	FSI-3D	YOUNG	72 km	101 m	09/2008 – 09/2010
Plat II	MIROS	YOUNG	105 km	1040 m	06/2009 – 07/2010
Plat III	MIROS	YOUNG	143 km	189 m	10/2008 – 09/2010
Plat IV	MIROS	YOUNG	110 km	1047 m	06/2008 – 02/2009
Plat V	MIROS	YOUNG	118 km	1355 m	01/2008 – 02/2009
51002 (HW I)	Disc 3M	YOUNG	270 km	4919 m	01/2008 – 12/2010
51003 (HW II)	Disc. 3M	YOUNG	292 km	5002 m	01/2008 – 12/2010
41041 (MA I)	Nomad. 6M	YOUNG	1220 km	3397 m	01/2008 – 12/2010

where A is altimeter data, B the *in situ* data, N the number of measurements and the bar above the variables represents their average.

RESULTS

Table 2 shows the obtained regression coefficients, the statistical parameters calculated using equations (1) for all sensor types, together with results obtained by other authors in similar studies comprising measurements obtained globally. Abdalla et al. (2010) performed global comparisons of SWH and u10 using Jason-2, for the entire Northern Hemisphere, from October 2008 to September 2009. Abdalla (2006) made a similar analysis using ENVISAT from July 2002 to October 2003. Durrant et al. (2009) analyzed SWH from ENVISAT between September 2004 and April 2006. These three works employed measurements of the NDBC buoys. In the work of Queffeulou (2004), from April 2003 to February 2004, SWH measurements from ENVISAT were compared not only with the ones from NDBC buoys, but also against the database of Canadian center (MEDS) and the European center (Meteo-France).

SWH measurements are displayed at the top part of Table 2, where the first six rows correspond to measurements in the intertropical region, listed in Table 1, for MIROS, FSI and NDBC buoys. It can be seen that data from MIROS and FSI sensors present higher bias, mean square error and dispersion index values, and lower correlation coefficient (R) values when compared to measurements from the NDBC buoys. It is noteworthy that the results using only the NDBC buoys are closer to those of other studies listed in Table 2, than to those presented here using the MIROS and FSI. According to the results presented here, FSI and MIROS perform worse than the NDBC buoys.

The u10 data from Petrobras (Young_Bra) and NDBC (Young_NDBC) anemometers are presented in the lower part of Table 2. *Young_total* refers to the anemometers in the intertropical region, from platforms and buoys (*Young_total* = *Young_Bra* + *Young_NDBC*), listed in Table 1. Bias values between sensors are not exactly correspondent, however mean square error and correlation coefficient values demonstrate close agreement. The same applies when comparing the results with those obtained by other authors. Thus, the performance of anemometers located in oil platforms appears to be similar to that of the NDBC buoys. This should not come as a surprise, since it is the same sensor.

Significant Wave Height

Performance of NDBC buoys was better than FSI and MIROS. Hence, only the measurement values from NDBC buoys were employed in the analysis. SWH data from FSI and MIROS, however, are used for altimeter performance analysis, in order to estimate u10 under different wave energy conditions.

Figure 2 shows the scatter plot of the SWH values from NDBC buoys and Jason-2 satellite. With a total of 242 matches (as noted in Table 2), least squares method yields the following regression equation:

$$SWH^{J2} = 1.0242 SWH^{NDBC} - 0.0334 \qquad (2)$$

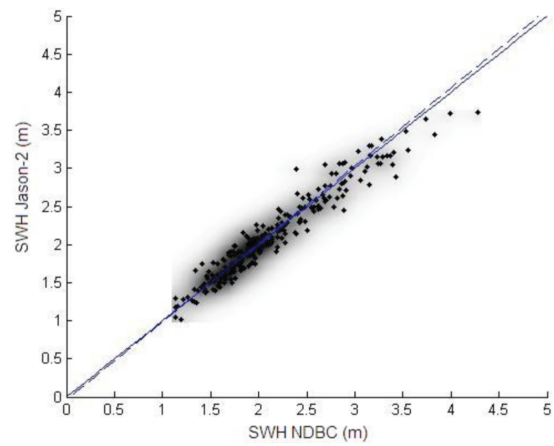

Figure 2 – Comparison between the SWH values of satellite Jason-2 and the NDBC buoys. The solid line represents perfect correlation while the dashed is the regression line.

Similarly, Figure 3 shows the scatter plot of the values obtained by the NDBC buoys and ENVISAT satellite. In all, 208 matches were obtained, resulting in the following regression equation:

$$SWH^{E1} = 0.9429 SWH^{NDBC} + 0.1029 \qquad (3)$$

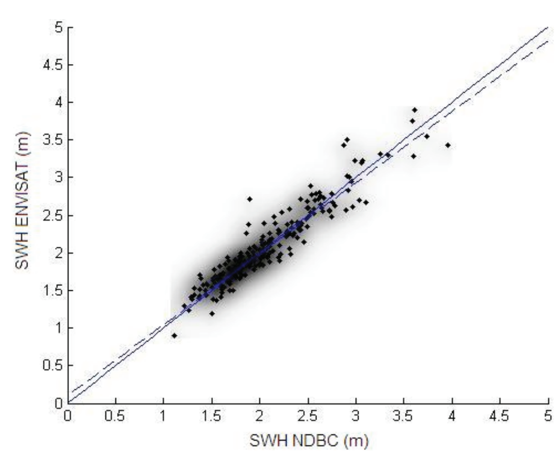

Figure 3 – Comparison between the SWH values of ENVISAT satellite and the NDBC buoys. The solid line represents perfect correlation and the dashed is the regression line.

Note that both satellites have measurements highly correlated with the *in situ* measurements and virtually no bias ($<$2 cm).

Table 2 – Comparison between Significant Wave Height (SWH) and wind intensity (U10) values for different sets of sensors (FSI, MIROS, NDBC buoys and YOUNG anemometers). The values in italics correspond to the results of this work and the rest correspond to the results of other authors. Slope, linear coefficient, bias, root mean square error, correlation coefficient, dispersion index and the number of points used in the analysis are shown for ENVISAT (E1) and Jason-2 (J2) satellites, respectively.

	Slope	Linear Coef	Bias	RMSE	R	SI	N
SWH							
SWH (MIROS) × SWH (J2)	0.9688	–0,2336	0.2979	0.4715	0.8793	0.2076	119
SWH (MIROS) × SWH (E1)	0.9530	–0.1029	0.2420	0.3915	0.8670	0.1742	125
SWH (FSI) × SWH (J2)	0.9112	–0.0570	0.2296	0.3714	0.8956	0.1703	67
SWH (FSI) × SWH (E1)	0.9696	–0.2449	0.3130	0.3796	0.9048	0.1331	34
SWH (NDBC) × SWH (J2)	1.0242	–0.0334	–0.0181	0.1533	0.9673	0.0700	242
SWH (NDBC) × SWH (E1)	0.9429	0.1029	0.0174	0.1783	0.9422	0.0849	208
Abdalla et al. 2010 SWH (NDBC) × SWH (J2)	0.9562	0.1233	0.0241	0.3936	0.9556	0.1739	30564
Abdalla, 2006 SWH (NDBC) × SWH (E1)	0.9292	0.2541	0.0911	0.3578	0.9640	0.1555	36806
Durrant et al. 2009 SWH (NDBC) × SWH (E1)	0.9090	–0.222	–0.010	0.227	0.983	0.110	3452
Queffeulou, 2004 SWH (NDBC) × SWH (E1)	1.0327	–0.1830	0.010	0.272	0.957	–	1280
U10							
U10 (Young_total) × U10 (J2)	0.9831	–0.2876	0.3204	1.3748	0.8756	0.1934	543
U10 (Young_total) × U10 (E1)	0.7577	1.6416	–0.1164	1.2714	0.8832	0.1744	489
U10 (Young_Bra) × U10 (J2)	0.9774	–0.3922	0.5478	1.6513	0.8472	0.2453	295
U10 (Young_Bra) × U10 (E1)	1.0299	–0.3710	0.1616	1.4051	0.8759	0.2037	276
U10 (Young_NDBC) × U10 (J2)	0.9831	0.0793	0.0498	0.9460	0.9191	0.1246	248
U10 (Young_NDBC) × U10 (E1)	1.0052	0.4388	–0.4765	1.0736	0.9100	0.1236	213
Abdalla et al. 2010 U10 (Young_NDBC) × U10 (J2)	0.9199	0.4685	–0.2016	1.5023	0.9077	0.1795	19216
Abdalla, 2006 U10 (Young_NDBC) × U10 (E1)	0.9815	–0.4919	–0.6447	1.5218	0.9083	0.1845	24416

The mean square error of the two satellites is also presented below. Jason-2 displayed a bias of −0.02 m and RMSE of 0.15 m. Abdalla et al. (2010) found a similar positive bias but a higher RMSE. Anyway, both results show that the differences between the SWH measurements from NDBC and Jason-2 are small.

ENVISAT data resulted in a bias of 0.02 m and RMSE of 0.18 m. Queffeulou (2004) reported a similar bias for SWH data measured by ENVISAT. Durrant et al. (2009) found a negative bias and larger RMSE for the same satellite. Abdalla (2006) found larger bias and RMSE values than those reported by both Durrant et al. (2009) and this study, showing a significant difference between results.

For Jason-2 there is a limiting value at about 2 m, where the perfect correlation line intercepts the best fit line. Below this value the sensor tends to slightly underestimate SWH values, while above it, SWH is slightly overestimated. This behavior differs from that reported by Queffeulou (2004) and Abdalla (2007), whose studies considered globally distributed measurements. The opposite is observed for ENVISAT, since satellites tend to underestimate SWH values greater than 2 m and slightly overestimate values below 2 m.

Abdalla (2006), considering only lower latitude regions, made an analysis of the SWH estimates of ENVISAT and observed that the bias and dispersion index decreased. This trend can also be observed in the present study, which similarly reports results that show a better performance of the estimates obtained only in the intertropical region compared with data covering several distinct regions of the planet.

Figures 4 and 5 demonstrate the differences between SWH measurements made by NDBC buoys and the two satellites (ENVISAT and Jason-2, respectively) for different wave heights observed by the buoys. In general, the bias appears evenly distributed across the SWH value range. However, for both satellites, in the data set presented here, the difference between the satellites and buoys measurements is greater for larger SWH values. This trend is somewhat clearer for Jason-2 data, but as the number of SWH values greater than 4 m is small, it becomes more difficult to make statistically significant statements.

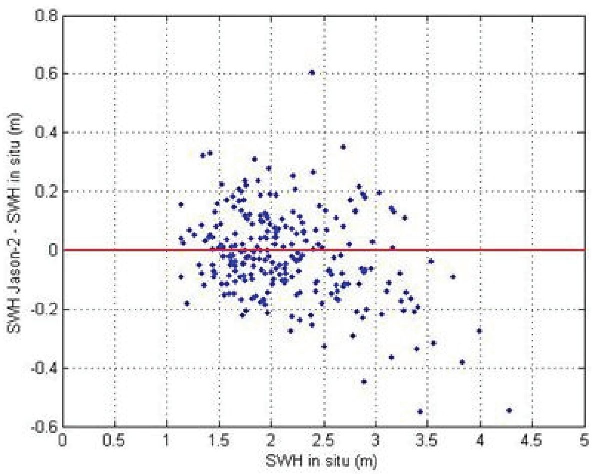

Figure 4 – Differences between the SWH measurements from Jason-2 satellite and the NDBC buoys for different SWH ranges from the buoys. The red line represents perfect symmetry.

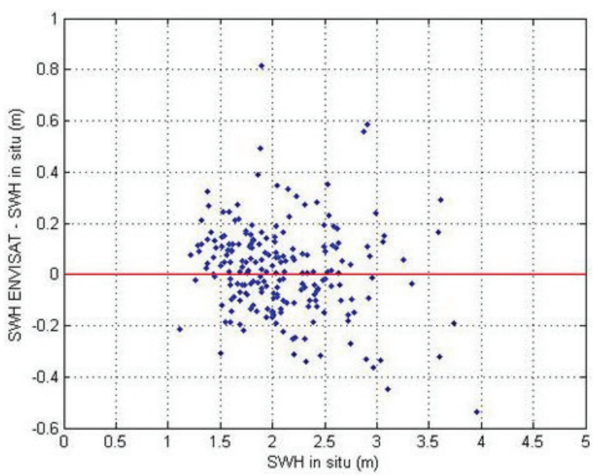

Figure 5 – Differences between the SWH measurements from ENVISAT satellite and the NDBC buoys for different SWH ranges from the buoys. The red line represents perfect symmetry.

Wind Intensity

Figures 6 and 7 present the scatter plots for u10 values from Jason-2 and ENVISAT, respectively. Regression equations, listed in Table 2 with 543 and 489 points are

$$u_{10}^{J2} = 0.9831 u_{10}^{YOUNG} - 0.2876 \quad (4)$$

$$u_{10}^{E1} = 0.7577 u_{10}^{YOUNG} + 1.6416 \quad (5)$$

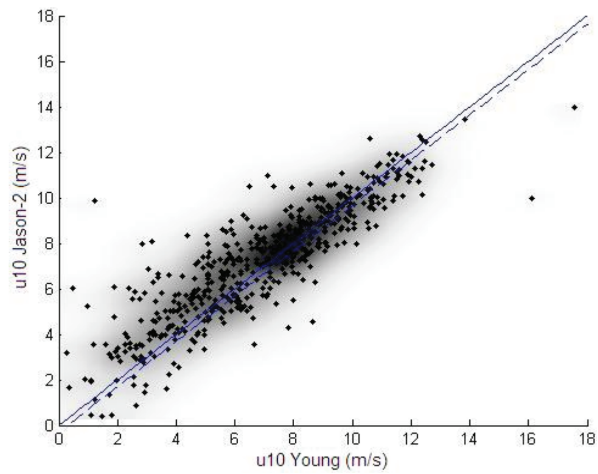

Figure 6 – Comparison between the u10 values from satellite Jason-2 and the anemometers. The solid line represents perfect correlation and the dashed line represents the data linear regression line.

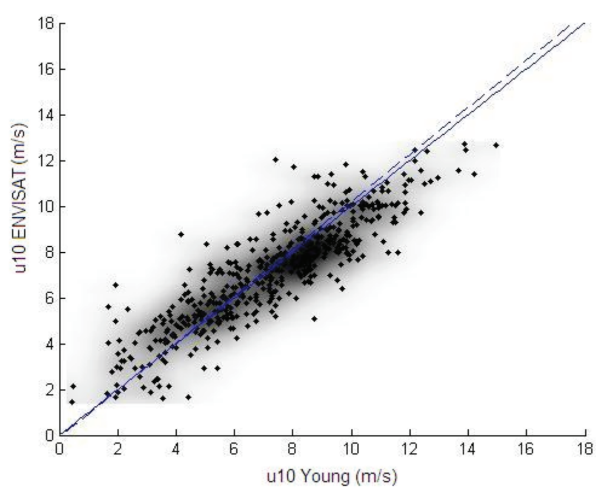

Figure 7 – Comparison between the u10 values from ENVISAT satellite and the anemometers. The solid line represents perfect correlation and the dashed line, the data regression line.

The correlation values obtained for u10 are lower than those for SWH. These values reinforce the perception that, despite the good quality of wind speed measurements taken by altimeters, they have relatively lower quality than SWH data (Fedor & Brown 1982).

Abdalla et al. (2010) found a smaller negative bias but higher RMSE for Jason-2 than presented here. As for ENVISAT, the negative value of the bias and of the mean square error obtained here is in agreement to that found by Abdalla (2006), albeit smaller. Jason-2 generally tends to underestimate u10 values, while ENVISAT overestimates them, except for wind intensity lower than 3 m/s.

Figures 8 and 9 show the differences between the wind speed measurements made by the altimeter and the anemometers for different wave heights. A clear trend of underestimating or overestimating u10 values measured by altimeters, in relation to SWH was not observed. The bias is regularly distributed along significant wave height for both satellites. Therefore, based on the data described here, there is no clear justification for the use of an algorithm to estimate u10 that takes into account the sea state.

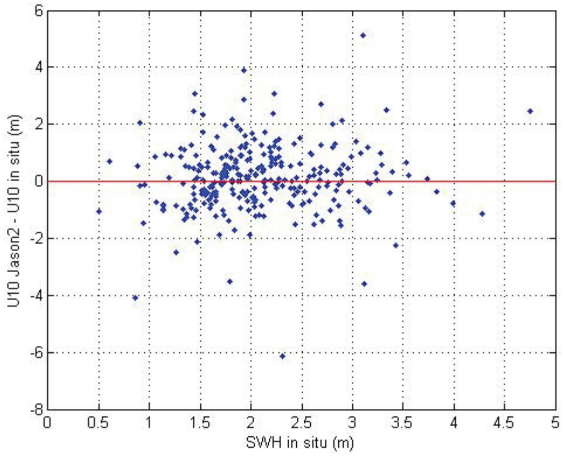

Figure 8 – Differences between the u10 measurements made by Jason-2 satellite and the anemometers for different SWH ranges from the buoys. The red line represents the perfect symmetry between the data.

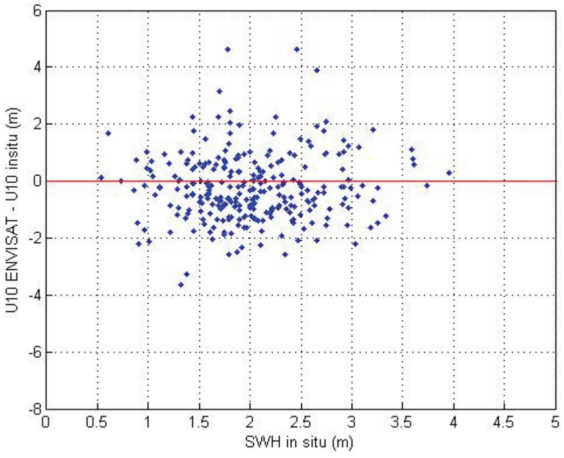

Figure 9 – Differences between the u10 measurements from ENVISAT satellite and the anemometers for different SWH ranges from the buoys. The red line represents the perfect symmetry between the data.

DISCUSSION AND FINAL CONSIDERATIONS

In this work measurements of significant wave height (SWH) and wind intensity (u10) made by altimeters Jason-2 and ENVISAT in the intertropical region were analyzed by comparison with *in situ* measurements. The results were analyzed in light of similar work, whose data, however, were almost entirely from high latitudes. The criteria for choosing spatial and temporal windows, distance from the shoreline and measurements in deep water used here are similar to these previous works for comparison purposes.

In the literature there is a discussion on the influence of the sea state on the performance of the algorithms employed to estimate SWH and u10, tending to make them dependent on location. These algorithms were developed using measurements, in latitudes above 40 degrees in the Northern Hemisphere. There is no further discussion about their performance in the intertropical region, which differs significantly from the areas located at higher latitudes, both in terms of seasonal variability and in terms of typical SWH and u10 values. Therefore, the work seeks to compare the performance of the altimeters of two currently operating satellites, focusing on measurements performed in the intertropical region.

To this purpose, measurements taken along three years in the North Pacific Tropical, North Atlantic Equatorial and South Atlantic Tropical, comprising the region between 25°S and 15°N, were used. Wind and wave data, available to the scientific community from the region approximately between 23°S and 23°N were used, thus seeking to characterize the intertropical region. In addition to the measurements from buoys of SWH and u10 made available by the U.S. Government (National Data Buoy Center, NDBC database), measurements performed on oil platforms along the Brazilian coast were also employed, using anemometers (u10) and pressure sensors and radars (SWH), MIROS and FSI systems, respectively.

In addition to comparing the results of *in situ* measurements with the values obtained from altimeters, data analysis allowed to compare the performance of different types of sensors employed in the study. The results demonstrate that the performance of MIROS and FSI systems is inferior to that of the NDBC buoys, with much higher bias and mean square error (Table 2). This fact prompted the exclusion of wave measurements in the Brazilian coast for the evaluation of SWH data obtained by the altimeter. However, data from FSI and MIROS were retained to evaluate the u10 measurements obtained from ENVISAT in different sea states, shown in Figure 8. For the u10 measurements made on oil platforms in the South Atlantic, on the other hand, we used the same type of anemometer used by NDBC. The bias and mean square error values found for the measurements taken by sensors installed on the platforms are similar to the buoys, and therefore retained for the analysis presented here.

SWH and u10 data from Jason-2 and ENVISAT satellites were found to have a fairly strong correlation to those obtained by buoys, as reported in previous studies. The difference in the altimeter performance in computing wave and wind data is evident, however, despite the existence of operating scatterometers, the significant amount of altimeter data still make them an interesting tool for assimilation in weather prediction numerical models.

Regarding SWH, Jason-2 tends to overestimate high values of SWH and underestimate lower values, while for the ENVISAT the pattern was reversed. For both satellites, however, the correlation coefficients are around 0.95 m with bias around 3 cm and mean squared error of approximately 15 cm. Overall, the results obtained in the intertropical region have lower bias, mean squared error and dispersion index than those obtained above 40°N, which shows that SWH estimates in the intertropical region are quite satisfactory. However, making such claims only with the results presented here requires caution, since the number of data analyzed, around 200 measurements, is small when compared to similar studies in other regions of the globe, specifically in the Northern Hemisphere. This is the type of problem usually found in similar studies, because the altimeter and *in situ* measurements coincidence determines that a small number of points is analyzed, unless one employs a very large number of buoys. This becomes a limiting factor in the intertropical region, due to the small number of quality wave measurements available.

The u10 results show performance similar to those described in other studies, with correlation coefficients around 0.90 and mean square error of approximately 15 m/s for the approximately 500 measurements used in the analysis. Jason-2 has a positive bias, while ENVISAT has higher and negative bias. It was also possible to compare the performance of two different algorithms for obtaining u10, although implemented in different satellites. The GDR data repository uses for Jason-2, a two parameter algorithm, *i.e.* both sigma-0 and SWH are used in the estimation of u10. For ENVISAT, on the other hand, only sigma-0 is used, in a single parameter algorithm. The results do not offer clear evidence of better performance of one method over another. Overall, the results obtained in the intertropical region have bias, mean square error and scatter index values similar to the other works mentioned here, covering mostly high latitudes.

Finally, it is important to highlight the shortage of quality measurements available to the scientific community, in the intertropical region and the Southern Hemisphere. Employing remote sensing satellites in general, and altimetry in particular, is a powerful tool to mitigate this problem. However, validation of the data is paramount for the evaluation and improvement of the performance over time, which requires a larger number of available local measurements.

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