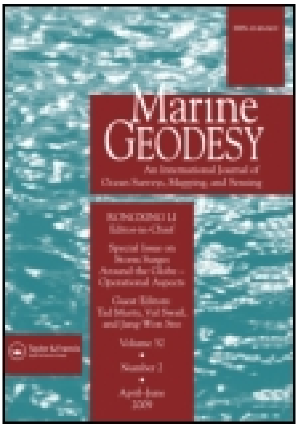

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Altimeter Near Real Time Wind and Wave Products: Random Error Estimation

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Triple collocation technique is used to estimate the errors in near-real time altimeter wind and wave products of Jason-2, Envisat and Jason-1. Significant wave height (SWH) error is estimated by collocating altimeter products with buoys and model hindcasts over the period August 1, 2009 to July 31, 2010. It is estimated that Jason-2 absolute SWH error is about 0.13 m, or about 5.4% relative to the mean SWH value. The SWH errors of Envisat, Jason-1, buoys and the stand-alone model hindcast are about 6.2%, 7.8%, 8.6% and 9.7%, respectively. The wind speed error is estimated by collocating altimeter products with buoys and ECMWF model 1-day forecast over the same period. Jason-2 wind speed absolute error is about 1.0 m.s^{-1} ($\sim$11.9% of the mean). For the collocation data sets used, it is found that wind speed errors of Envisat, Jason-1, the buoys and the model 1-day forecast are, respectively, 0.9 m.s^{-1}, 1.0 m.s^{-1}, 1.2 m.s^{-1} and 1.0 m.s^{-1}.

Keywords Atmospheric model, ECMWF, error estimation, Envisat, FDMAR, OGDR, OSDR radar altimeter, random error, significant wave height, triple collocation technique, WAM, wave buoy, wave model, wind speed

1. Introduction

Abdalla, Janssen and Bidlot (2010) described the validation and the use of wind and wave products from Jason-2 radar altimeter fast delivery OGDR-BUFR products. It was shown that compared to the European Centre for Medium-Range Weather Forecasts (ECMWF) model products and in situ (buoy) observations, Jason-2 products are of high quality. However, there was no precise statement about the errors of those products. This statement cannot be reached based on direct comparison against model results and/or buoy measurements. To this end, triple collocation technique has been used by several researchers. Stoffelen (1998) applied this technique to estimate the errors of wind measurements from ERS-1 scatterometer, buoys and model analysis. Caires and Sterl (2003) used the same method to estimate the errors in the 40-year ECMWF Re-Analysis (ERA-40) wind speed and significant wave height. Tokmakian and Challenor (1999) implemented the same technique to estimate the mean sea level anomalies from the model, ERS-2 and TOPEX/Poseidon altimeters. Freilich and Vanhoff (1999) and Quilfen, Chapron and Vandemark (2001) used

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a similar approach with an assumption that the true wind speed is Weibull distributed. Janssen et al. (2007) estimated significant wave height errors in ERS-2, buoy and ECMWF model analysis, first guess and hindcast. They extended the method to include two extra sources of information, that is, quintuple collocation, to estimate the covariances due to the existence of correlations between the errors in ERS-2, and Envisat observations. This was the way out to estimate the errors in Envisat RA-2 wave heights in a collocation data set that involves ERS-2 data and model first-guess data. Triple collocation technique was also used by Abdalla and Janssen (2007) in a different context to estimate the error of the total column water vapour from the micro-wave radiometers onboard Envisat and Jason-1 as well MERIS onboard Envisat and the ECMWF model analysis.

Janssen et al. (2007) also proposed a totally different approach that did not require three estimates for the truth. Instead, they made use of the change of the standard deviation of the difference between the ERS-2 altimeter wave height super-observations and the ECMWF model by varying the number of observations used for the super-observation.

Strictly speaking the "error," or the "instantaneous error," is the difference between the estimate and the (usually) "unknown" truth. The standard deviation of the instantaneous errors is used to describe the uncertainty in the measurement or the model output. It is a common practice to use the term "error" or "random error" to refer to this uncertainty. Therefore, this "inaccurate" usage of the term will be used here.

Given three independent estimates, with uncorrelated errors, of the truth, T, it is possible to show that error in each estimate can be found using the "known" variances and covariances of the three data sets in addition to the "unknown" covariances of the errors. Therefore, further assumptions are needed to estimate the error covariances. The assumption that the errors are not correlated is very useful because under such an assumption the error covariances vanish. If the assumption is not correct, the error estimates will not be correct. It is also important to note that although the errors in two data sets may not be correlated directly, it may possible to have a pseudo correlation due to the nonlinear nature of both errors. This is what Janssen et al. (2007) found when they tried to estimate the errors of ERS-2 and Envisat altimeters from a collocation that involves both altimeters and the buoys and another collocation that involved Envisat, which was not assimilated in ECMWF model at the time, and the model first guess. Contradictory results were obtained. With the help of two extra data sets, there was a strong correlation between the errors in both altimeters.

Section 2 provides an overview of the data used in the current work. The selection criteria will be discussed as well. An overview on the error estimation using the triple collocation technique is provided in section 3. The results of the error estimation of significant wave height are presented in section 4 and those for wind speed are given in section 5. Finally, conclusions are listed in section 6.

2. Data Used

Apart from the covered period, the data sets used for this study are mainly similar to those used by Abdalla et al. (2010). Therefore, only a short description is given here with emphasis on the different aspects.

The first data set used in this study consists of the Ku-band significant wave height (SWH) and surface wind speed within the BUFR (Binary Universal Form for the Representation of meteorological data) version of the Operational Geophysical Data Record (OGDR) of Jason-2 radar altimeter received in near real time (NRT) from EUMETSAT and NOAA. The OGDR product may be of slightly degraded quality compared to the final

Geophysical Data Record (GDR), which is not available for operational weather prediction. However, the quality of the SWH and the surface wind speed parameters does not differ between the OGDR and the GDR; only the retracker is of lower quality.

The second data set consists of SWH and wind speed collected by wave buoys or various wave gauges mounted on offshore platforms as disseminated to the weather centers via the Global Tele-Communication System (GTS). It is commonly believed that this type of data represents the ground truth. The total number of in situ stations is limited (slightly above 100), and most of them are located in the Northern Hemisphere (NH) around the North American and European coasts, including two buoys in the Western Mediterranean. The exceptions are a few buoys in the Tropics, mainly around Hawaii. Therefore, any assessment involving in situ data would not be of global coverage. The term “buoy” is usually used to refer to this type of data even if it is originated from a different in situ source. More information about in situ ocean wave data, including the preprocessing method used for the quality control and averaging, can be found in Bidlot et al. (2002).

The triple collocation technique with the assumption of uncorrelated errors does not work with the model analysis (AN) or the model first-guess (FG). Even short-term model forecasts (FC) may not be suitable. The SWH from Jason-2, Jason-1 and Envisat RA-2 are all assimilated into the ECMWF ocean wave model. Jason-1 SWH has been blacklisted since late March 2010 following the degradation of the product caused by the instability of the platform. Even if the SWH from one or more of the altimeters is not used, it cannot be considered that the errors in models AN and FG are independent from that altimeter (Janssen et al. 2007). All altimeters share the same principles of measurements and algorithms. The dependency becomes weaker further along the forecast range. Therefore, altimeter data and the model forecast (FC) can be assumed to have independent errors, especially for forecasts beyond 2–3 days except for any possible systematic errors in the observations. Therefore, it was decided to run a wave model stand-alone experiment without any data assimilation (model hindcast). The model (Janssen 2004) is configured similarly to the ECMWF wave model operational configuration that has been in place since late January 2010. The details are given in ECMWF (2010). In short, the wave model uses a horizontal resolution of about 28 km and a spectral resolution of 36 directional and 36 frequency bins. The wave spectra and the integrated parameters are saved every 6 hours. The experiment has used the 6-hour neutral wind vector analysis fields from the high resolution T1279 (16-km horizontal resolution) atmospheric model operational since late January 2010. The wind fields for the period prior to the operational implementation of the high resolution model were obtained from the preoperational experimental suite (e-suite).

The wind speed data from altimeters are not assimilated in the ECMWF atmospheric model. However, the buoy wind data are assimilated. This leads to a high correlation in error between the model analysis winds and the buoys and the model first-guess winds and the buoys preventing the use of those model fields in triple collocation. A coupled atmospheric-wave model experiment without assimilating the buoy winds for a long period of time, for example, a year, is very expensive. Fortunately, the impact of assimilating wind data is short-lived. It is commonly accepted that 24 hours in the forecast is enough for the model to lose the impact of assimilated wind information. Therefore, 1-day forecast fields will be used for wind speed.

The numerical procedures used in the atmospheric models introduce a kind of smoothing to ensure numerical stabilities. Such smoothing can affect 3–6 grid points (Nils Wedi 2011, personal communication). Therefore, the effective model scales can be in the order of 48–96 km (i.e., with an average value of about 72 km). On the other hand, the numerical procedures of the wave model involve linear interpolation that can increase the model scale. Furthermore, the scales of the wind fields from the atmospheric model play a role in dictating the wave model scales. Therefore, it is assumed that the effective wave model scale can be as high as 70–80 km.

The NRT altimeter data from Envisat and Jason-1 are used to form two independent triple collocated data sets. The former data stream is made available by European Space Agency (ESA). In particular, Level 2 of RA2 Fast Delivery Marine Abridged Records (FDMAR) product is used. For Jason-1, the NRT Operational Sensor Data Record (OSDR) product is used here. In fact, the two data sets are not needed here for the estimation of Jason-2 products. Instead, two other triple collocation data sets are constructed, each consisting of the altimeter (Jason or Envisat), the buoy and the model. The corresponding errors are estimated independently for each data set ending in three error estimate for the buoys (one from each triple collocation set), three error estimates for the model in addition to single error estimates for each altimeter. If the three error estimates for the buoy are almost equal and similarly for the three model errors, then one can be more confident about the robustness of the approach.

The altimeter data are preprocessed in a way similar to the approach outlined in Abdalla and Hersbach (2004) with slightly modified parameters. The data go through a quality control process to remove erroneous and inconsistent observations. The observations are then averaged along the track to form super-observations with scales compatible with the model scales of about 70–80 km. This corresponds to 13 individual (1 Hz) Jason-1 and Jason-2 observations and to 11 individual (1 Hz) Envisat observations.

The buoy super-observations are formed from the averaging of 5 hourly observations spanning over a 4-hour time window. This is selected to reflect the model scale of about 70–80 km. Since the buoy observations are done in time, another piece of information is needed to convert this into space. For SWH error estimation, the wave group velocity can be used to estimate the buoy spatial scale. The average value of the buoy mean wave period is about 6.5 s (other values can be found depending on the definition of the mean wave period). The group speed corresponds to this wave period in deep water can be estimated as 5 m.s^{-1}. Therefore, the spatial scale corresponding to 4 hours is about 73 km. For the wind speed error estimation, a mean buoy wind speed of 6 m.s^{-1} can be used. The spatial scale corresponding to this speed in 4 hours is about 85 km.

The data cover the period from August 1, 2009 to July 31, 2010. It should be noted that the model is changed a few times a year. Although this may impact results, it is not the case for this study as the model changes during this period are expected to be of limited impact on wind and waves. However, there was an important change of the Envisat RA-2 processing chain introduced on February 2, 2010. This change has a significant impact for SWH and wind speed. Furthermore, Jason-1 suffered a period of instability starting from late March 2010. This was reflected in a degradation of Jason-1 products especially the wind speed.

3. Triple Collocation

Comparisons of pairs of observation products are usually not enough to estimate the error in each product. If enough data products are available, a multiple collocation analysis can be used to give some absolute error estimates of each product. A simplified version of the approach proposed by Janssen et al. (2007) was used here. Three triple collocation exercises were performed. For the first exercise, Jason-2, buoys and model (hindcast for SWH and forecast for wind speed) were collocated. The second and the third data sets are similar to Jason-2 being replaced by Envisat RA-2 and Jason-1, respectively. The

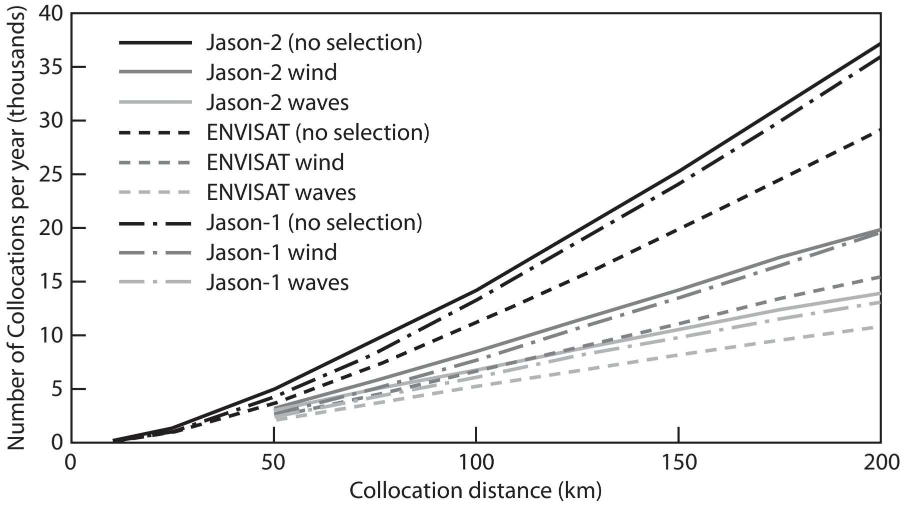

Figure 1. Number of collocations for various restriction conditions for the period from August 1, 2009, to July 31, 2010.

collocation is built up by collocating first the altimeter super-observations with the model using proper interpolation. Then the buoy observations are collocated with the model. Finally, the altimeter observations (and the model values at the altimeter locations) are collocated with the buoy observations (and the model values at buoy location) within 2 hours and 200 km (this will be adjusted for later). The model values at the altimeter and the buoy locations are used for the triplet selections as will be described later.

Ideally, it is desirable to collocate the altimeter and buoy observations at no spatial or temporal difference. Unfortunately, there would be very few collocations, if any. Figure 1 shows the number of Jason-2-buoy-model triplets in a year for various limitations on the collocation distance. It is clear that the more restricted the distance is the less the number of collocations there are and, therefore, the less statistically representative the results are. It will be shown later that the more relaxed this condition is, the larger the representativeness errors become. On the other hand, the temporal restriction was not tested as the buoy super-observations are constructed using 5 observations with 1-hour increments. The 2-hour restriction is within the 4-hour duration of the buoy super-observations.

It is essential that assumptions are made regarding the relation between model and observations on the one hand and the truth on the other. At the same time, this gives an implicit definition of the error. Because of an assumed relation between the observation and the truth, it follows that in case this relation is incorrect the error has both a systematic and random component. Therefore, the assumption of uncorrelated errors is by no means evident and should, if possible, be tested.

Suppose we have three estimates of the truth, denoted by X_p, $p = 1,2,3$, obtained from observations or from simulations by means of a forecasting system of the same truth, T. In the following, all these estimates of the truth will be referred to as measurements. Furthermore, it is assumed that the measurements depend on the truth T in a linear fashion for any triplet, i, as follows:

$$X_{pi} = ß_p T_i + e_{pi} \tag{1}$$

where e_{pi}, $p = 1,2,3$ denote the instantaneous (or individual) residual errors in the measurements X_p and β_p are the linear calibration constants.

The calibration constants are found by an iterative procedure utilizing a neutral regression (Marsden 1999) and the errors in the variable X_p using the method described by Janssen et al. (2007). For the simplicity of the formulation below, the variables X_p are divided by the calibration constants, that is, $X_p = X_p/\beta_p$. By taking mean-square of the differences between each pair in the triplets, it is possible to write for the variance of the unknown error of each product (Janssen et al. 2007) as:

$$\langle e_{pi}^2 \rangle = 0.5[\langle (X_p - X_{p1})^2 \rangle + \langle (X_p - X_{p2})^2 \rangle - \langle (X_{p1} - X_{p2})^2 \rangle] \tag{2}$$

Here, X_{p1} and X_{p2} are the other two products in the triplet. It is only possible to reach Eq. (2) by assuming that there is no correlation between the errors of the triplets. For example, Eq. (2) cannot be used to estimate the errors if the triplet includes a model analysis or first guess together with the observations that have been assimilated into that model. Furthermore, two altimeter products cannot be used in a triplet to estimate errors through Eq. (2) due to the intrinsic correlation arising from sharing the same algorithm and nature of error (Janssen et al. 2007). Detailed description of the technique can be found in Janssen et al. (2007).

4. Estimation of SWH Errors

One of the keys to the success of the triple collocation technique as presented above is to ensure the independence of the errors in all data sets used. This was done by selecting the altimeter, the buoy and the model hindcast data. The three data sources are totally independent estimation of the truth and, therefore, their errors are expected to be uncorrelated.

The second key of success is the proper selection of triplets. The collocated altimeter and buoy measurements should be very close to each other to represent the same truth and, at the same time, this restriction should be relaxed to have enough triplets to yield statistically representative error estimates. Figure 1 shows that the number of collocation triplets of Jason-2, buoy and model within a collocation distance between the altimeter and the buoy over a period of a year is about 37,000. With some quality control checks, this number reduces to about 14,000. The quality control checks are composed of a few basic tests to ensure that all measurements in the triplet are valid (e.g., SWH values between 0.5 and 20 m). Another selection criterion is to ensure that both the altimeter and the buoy, which can be in this case as far as 200 km apart, sense the same truth. The collocation procedure used here is simple in the sense that any altimeter super-observation within 200 km from a buoy location is collocated with super-observation of that buoy (within 2 hours). If there is a large gradient or discontinuity of the SWH between the locations of the two observations, the "natural" difference between them will be interpreted as an additional error that cannot be separated from the random error. For example, if the buoy is located at one side of an island or a peninsula while the altimeter track is at the other side, for sure both measurements will not be representing the same truth. To eliminate, as much as possible, this kind of added error, any triplet is rejecting when the model estimates at the altimeter location and at the buoy location differ by more than 5% as was recommended by Janssen et al. (2007). The assumption here, which is a fair one, is that the model is able to reproduce the true geophysical variability. Therefore, too different "model" SWH values are a strong indication that the altimeter and the buoy measurements do not represent the same geophysical truth. Furthermore, any triplet with the model mean wave direction at the altimeter and at the buoy locations that are different by more than 45 degrees is rejected.

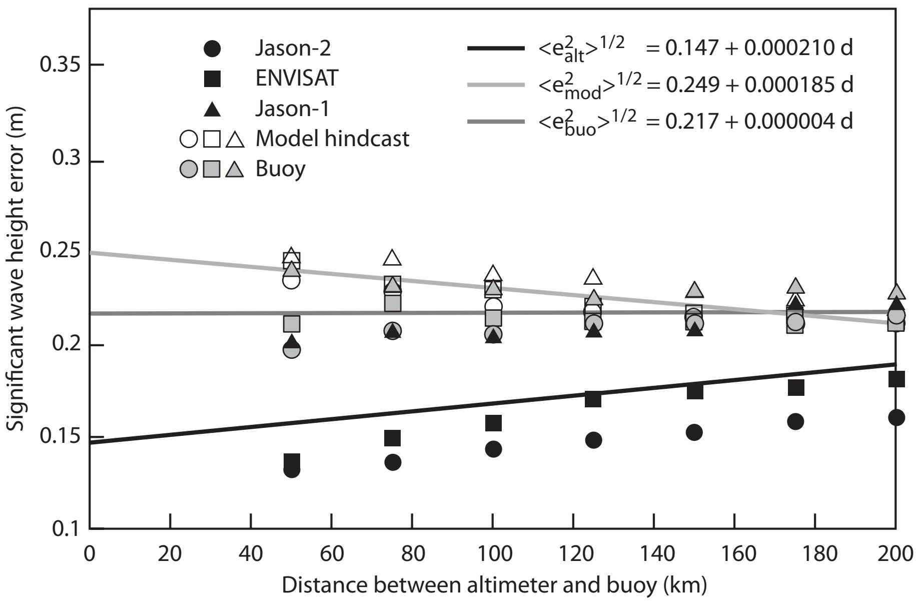

Figure 2. Change of SWH errors as functions of the maximum allowed collocation distance. The linear regression fits are given. The errors $\langle e_{alt}{}^2\rangle^{1/2}$, $\langle e_{mod}{}^2\rangle e^{1/2}$, $\langle e_{buo}{}^2\rangle^{1/2}$ of the altimeters, the model and the buoys are in m while the collocation distance, d, is in km.

This is another measure intended to filter out the field inhomogeneities due to, for example, atmospheric fronts. It should be noted that in the criteria mentioned above, the 5% and the 45 degrees are empirical values based on experience. Reducing the acceptable collocation distance to 100 km, for example, reduces the number of collocations to slightly above 7,000. At 50-km distance, the number of collocations over a year is only a few hundred.

Using Eq. (2) to estimate the SWH error for the three altimeter-buoy-model data sets with the dependence of the error on the collocation distance is shown in Figure 2. The change of error with respect to the collocation distance is linear. Altimeter (at different levels but have more or less same slope) and buoy SWH errors are found to increase by increasing the collocation distance at a rate of about 0.024 m and 0.004 m, respectively, per 100 km. The model error was found to reduce at a rate of about 0.023 m/100 km. More or less the same slopes were found for the other triple collocation data sets, namely, Envisat and Jason-1 buoy models.

When the collocation data set is binned based on the wave height values or the month in order to estimate the errors at each bin, the number of collocations may not be enough to draw firm conclusions. Therefore, the result above can be utilized to increase the number of collocations by adopting the 200 km restriction of the collocation distance. The error estimates are then adjusted by using the results in Figure 2. An argument can be raised if one needs to adjust for a zero collocation distance or for a collocation distance depending on the scale of the model and super-observations which is about 75 km in the current data sets. Using the 75 km distance instead of the 0 km distance, would add about 0.018 m and 0.003 m to the altimeter and the buoy errors, respectively, and will reduce the model error by about 0.017 m. It was decided that a collocation distance equals to the scale of the data would be a proper selection here.

Table 1

The absolute and relative (SI) significant wave height errors of Jason-2, Envisat RA-2, Jason-1, model hindcast and buoy as estimated using the triple collocation technique using three data sets each involving one of the altimeters in addition to the model hindcast and buoys for the period from August 1, 2009, to July 31, 1010 (mainly in the NH)

Number of collocations	Jason-2 Data Set 13,920		Envisat RA-2 Data Set 11,005		Jason-1 Data Set 13,281	
	Abs. (m)	SI (%)	Abs. (m)	SI (%)	Abs. (m)	SI (%)
Altimeter Error	0.130	5.4	0.152	6.2	0.192	7.8
Model Hindcast Error	0.234	9.7	0.235	9.7	0.241	9.8
Buoy Error	0.206	8.6	0.203	8.4	0.218	8.9

The estimated SWH errors, both the absolute values and the relative values with respect to the mean (also called scatter index, SI), in the three altimeters Jason-2, Envisat and Jason-1, the model hindcast and the buoys are listed in Table 1. The altimeter SWH relative errors (with respect to the SWH mean value) are about 5.4%, 6.2% and 7.8% for Jason-2, Envisat RA-2 and Jason-1, respectively. The model hindcast SWH error is slightly less that 10%, irrespective of the data set used for this estimation, while the buoy SWH error is slightly less than 9%. These values have been adjusted for a maximum collocation distance of 75 km as discussed earlier. It is clear that Jason-2 has the lowest error followed closely by Envisat RA-2. The Envisat processing changed on February 1, 2010, while Jason-1 has had a few periods of instability. Finally, although the model set-up was very close to the operational ECMWF wave model, it is not exactly the same. The hindcast experiment was forced by 6-hour wind fields compared to changing wind field at each time step in the operational set-up. Furthermore, the impact of gustiness and variable air density was not considered in the experiment. Finally, the operational model assimilates altimeter wave heights and this is not the case for the hindcast experiment used for the error estimation.

Although this work is devoted to the estimation of random errors, the values of the linear calibration constants in Eq. (1) are worth mentioning. The buoy SWH measurements are considered as the reference. The SWH calibration constants of Jason-2, Envisat and Jason-1 are 0.998, 1.011, and 1.041, respectively. This indicates that Jason-2 SWH is almost unbiased compared to the buoys. Envisat SWH is about 1% higher than the buoys. Keeping in mind the Envisat SWH algorithm change in February 2010, this 1% is the result of two SWH populations with different characteristics: with about 4% overestimation before the change and about 1% underestimation afterwards. Jason-1 SWH is about 4% higher than the buoys. Finally, the calibration constant for the model is 0.966 for the three data sets which implies that the model is lower than the buoys by about 3.4%.

To get a better idea about the SWH errors at various regimes of SWH values, the collocated data sets were binned and the triple collocation technique applied for each bin of wave heights. Figure 3 shows the SWH error at various SWH values. Note that there are only a few collocations at the bins with high SWH values, and these may not be representative of those bins. It is clear that the error of Jason-2 SWH is more or less the same at all SWH values while Envisat error is relatively large at low SWH values. The buoy error is lower

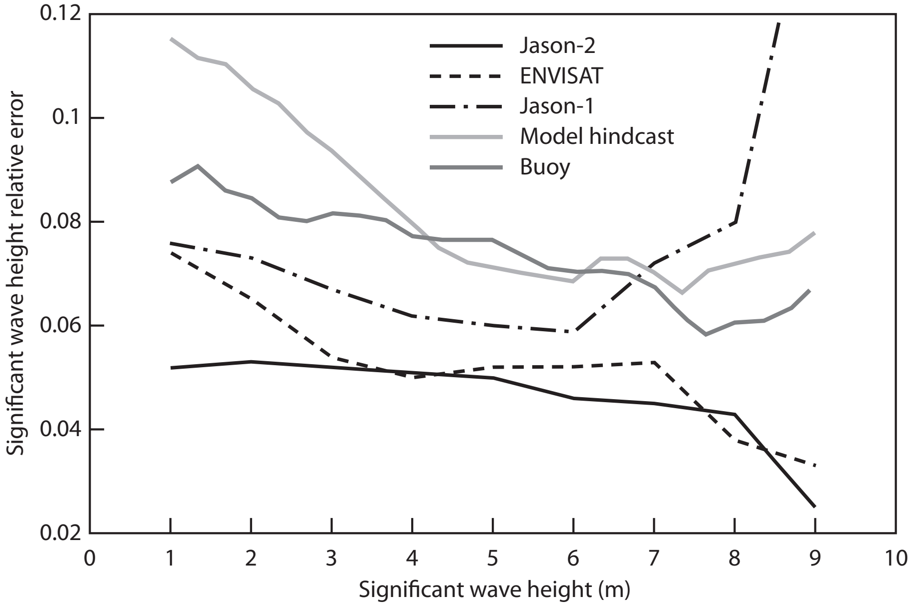

Figure 3. The SWH relative error as a function of the wave height value.

at higher waves. Finally the model error is high at lower waves and gets better for wave heights above 4 m.

To get an idea about the seasonal variability of the errors or the error variations due to the changes in the model or measurement quality, the triple collocation procedure was applied to the monthly data. The SWH error as a function of the month of the year is shown as 3-monthly running averages in Figure 4. Jason-2 monthly errors show very small variability over the whole year. Envisat RA-2 shows higher errors around October 2009 and during the summer months of 2010. The impact of the problems of Jason-1 can be clearly seen in a form of increased errors during the last 6 months of the considered period. During the early months (summer 2009), the buoy error was higher than the other months. This may be due to the presence of the hurricanes in the North Atlantic during that period. The model error is almost unchanged over the whole period.

5. Estimation of Wind Speed Errors

The wind speed from the buoys is assimilated into the ECMWF atmospheric model. Therefore, Eq. (2) cannot be used for any collocation data set involving the buoys and the models AN or FG. Therefore, model forecast, which is expected to be independent from the buoy measurements during the forecast range after about 24 hours, is used. The 5% criteria used to ensure that both the altimeter and the buoy sense the same SWH truth cannot be justified for the wind speed case. Compared to the SWH, the wind fields show much higher natural variability. Therefore, constraining the difference between model values at altimeter and at buoy location to 5% would be an artificial constraint. Therefore, this criterion was changed into another that restricts the difference between the SWH (not the wind speed) values to 50% ensuring a fair amount of homogeneity and allowing for local winds to have their impact without any constraints. This specific criterion is very effective to prevent the

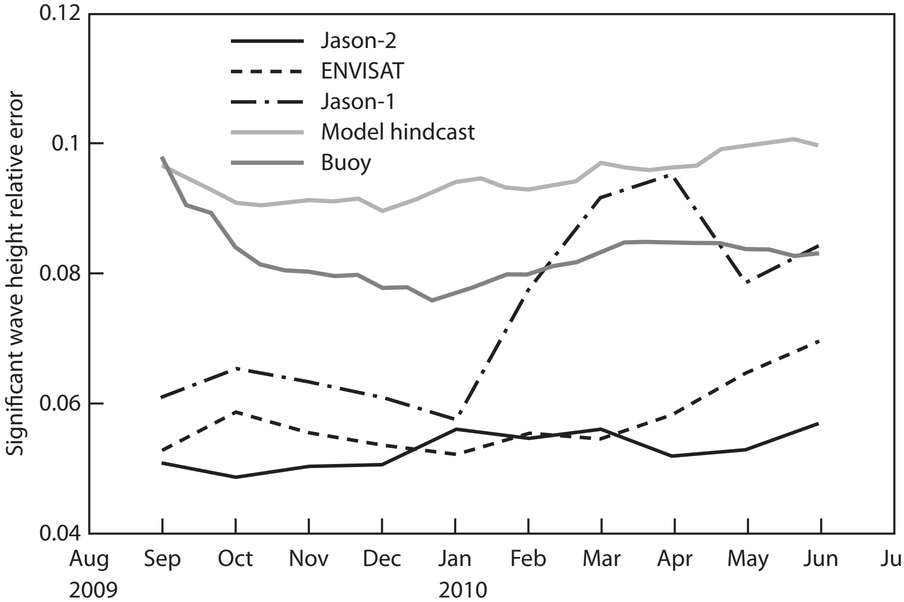

Figure 4. The time series of the monthly SWH errors (3-month running means).

acceptance of triplets when the locations of buoy and altimeter observations are separated by land and the wind is blowing along the axis connecting three (the location of the two observations and the land). The SWH will act as the appropriate filter here since the SWH value at the leeward will be much smaller than the one on the windward. On the other hand, the restriction on the model wind direction difference was tightened up. Any triplet with the "model wind direction" at the altimeter and at the buoy locations with a difference of more than 20 degrees is rejected. Again, the 50% and the 20 degrees above are empirical values based on experience. Therefore, within a collocation distance of 200 km and during a whole year, the number of the quality-controlled valid collocation triplets of Jason-2, buoy and model after this criteria is reduced to about 20,000 (out of the original 37,000) as can be seen in Figure 1. Reducing the acceptable collocation distance to 100 km reduces the number of collocations to about 9,000. At 50 km distance, the number of collocations over a year is only a few hundred.

Similar to what was done for the SWH, the wind speed errors for the triple collocation data set were estimated using Eq. (2) for different collocation distances between the altimeter and the buoy. Figure 5 shows those results. Similar to the SWH case, the relation between the error and the corresponding collocation distance is linear. However, the rates of the change of the error with respect to the distance are rather large compared to those from the SWH. The altimeter and the buoy wind speed errors increase by increasing the collocation distance at 0.13 m.s^{-1} and 0.17 m.s^{-1}, respectively, per 100 km. On the other hand, the model error decreases at a rate of about 0.24 m.s^{-1} per 100 km. Almost the same slopes can be found from the other triple collocation data sets, namely, Envisat and Jason-1 buoy models. This result is used to relax the collocation distance to 200 km for more triplets in the collocation data set. The estimated errors are then adjusted based on Figure 5.

The estimated errors for all data sources are tabulated in Table 2. The wind speed errors were estimated as 1.00 m.s^{-1} ($\sim$11.9%) for Jason-2, 0.93 m.s^{-1} ($\sim$11.1%) for

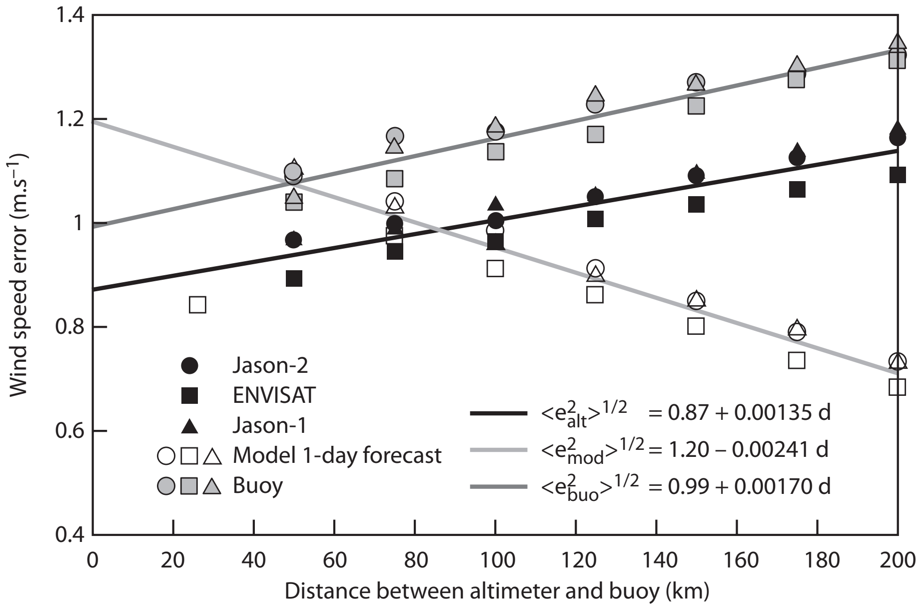

Figure 5. Change of wind speed errors as functions of the maximum allowed collocation distance. The linear regression fits are given. The errors $\langle {e_{alt}}^2\rangle^{1/2}$, $\langle {e_{mod}}^2\rangle^{1/2}$, $\langle {e_{buo}}^2\rangle^{1/2}$ of the altimeters, the model and the buoys are in m.s^{-1} while the collocation distance, *d*, is in km.

Envisat RA-2, 1.01 m.s^{-1} (∼12.0%) for Jason-1, 1.15 m.s^{-1} (∼13.7%) for the buoys and 0.97 m.s^{-1} (∼11.5%) for the 1-day model forecast. These figures were adjusted for a maximum collocation distance between the altimeter and the buoy of 75 km. This was selected to reflect the model scale and the scale used to form the altimeter and buoy super-observations. It may be useful to mention that the Envisat RA-2 wind speed estimate is based on the one-parameter (altimeter backscatter coefficient) algorithm of Abdalla (2007), and Jason-1 and Jason-2 wind speed estimates are based on the two parameter (altimeter backscatter coefficient and SWH) algorithm of Gourrion et al. (2002) with

Table 2
Similar to Table 1 for wind speed and the model hindcast is replaced by the ECMWF model 1-day forecast

Number of collocations	Jason-2 Data Set 19,856		Envisat RA-2 Data Set 15,552		Jason-1 Data Set 19,613	
	Absolute (m.s^{-1})	SI (%)	Absolute (m.s^{-1})	SI (%)	Absolute (m.s^{-1})	SI (%)
Altimeter Error	1.00	11.9	0.93	11.1	1.01	12.0
Model 1-Day FC Error	0.97	11.5	0.94	11.2	0.97	11.6
Buoy Error	1.15	13.6	1.14	13.7	1.17	13.8

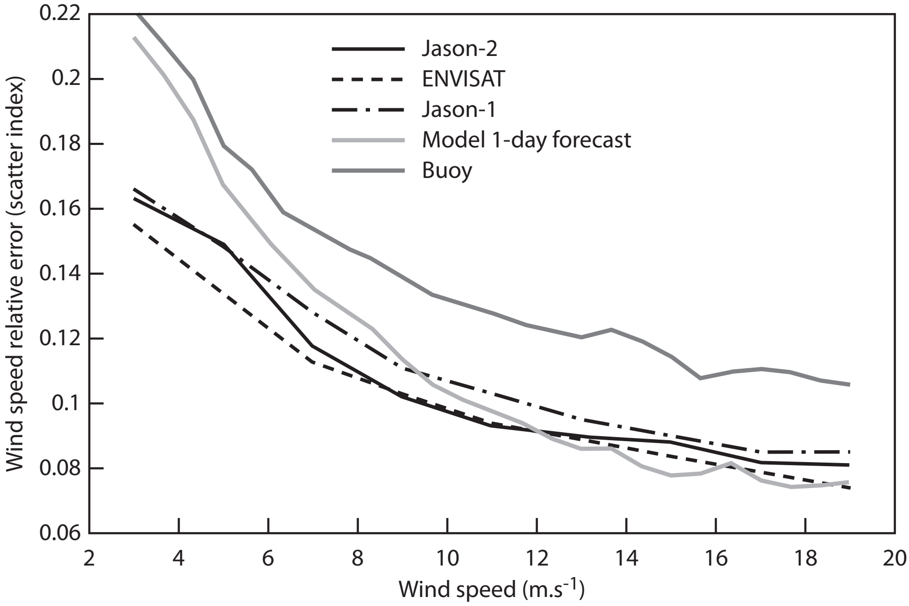

Figure 6. The wind speed relative error as a function of the wind speed value.

modified coefficients. It is important to stress that the model error here is the ECMWF 1-day forecast error which is quite higher than the analysis error.

To find out the values of the linear calibration constants in Eq. (1), the buoy wind speed measurements are considered to be the reference. The wind speed calibration constants of Jason-2, Envisat and Jason-1 are 0.998, 0.990, and 1.026, respectively. This indicates that Jason-2 wind speed is almost unbiased compared to the buoys. Envisat wind speed is about 1% lower than the buoys, and Jason-1 wind speed is about 2.6% higher. The wind speed calibration constant for the model 1-day forecast is about 0.990 for the three data sets which implies that the model is lower than the buoys by about 1.0%.

To find out what is the wind speed error at various wind speed values, the data sets were binned and the triple collocation technique was utilized to estimate the wind speed error for each subset. Figure 6 shows the wind speed relative error as a function of the wind speed itself. Although Figure 6 suggests that the errors are relatively high at lower wind speed values and decreases for higher values, it should be mentioned that the absolute wind speed errors, in fact, increase by increasing the wind speed value (not shown). However, the increase in the error is not fast enough and therefore the relative error appears to be decreasing with wind speed increase. Figure 6 indicates that Jason-2 wind speed is not good at the low wind speed regime. Furthermore, it is clear that the error of all instruments, especially the model and the buoys, is very high at low wind speeds with errors of about 16% of the mean for the altimeters and about 25% of the mean for the buoys and the model 1-day forecast. The high buoy error, especially at lower wind speed values, may be a reflection of the fact that the buoy wind speeds communicated through the GTS are reported to the closest 1 m.s^{-1}. An interesting observation in Figure 6 is the relative low wind speed error in the model 1-day forecasts for wind speeds higher that 12 m.s^{-1}.

The temporal variation of the 3-month running average of wind speed errors is shown in Figure 7. Jason-2 wind speed product seems to have suffered some degradation in February

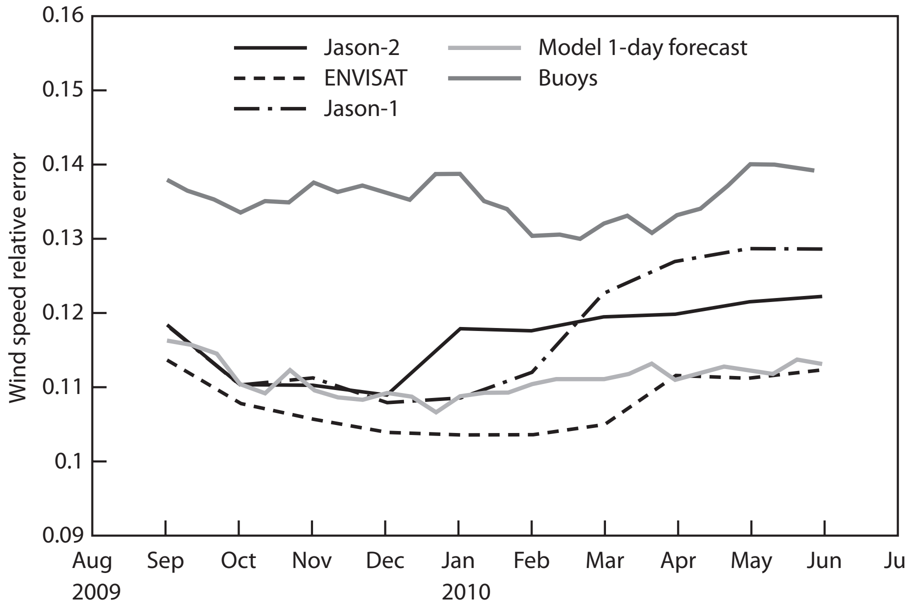

Figure 7. The time series of the monthly wind speed errors (3-month running means).

2010 and possibly in May 2010. The impact of Jason-1 degraded products can be clearly seen starting from March 2010.

6. Conclusions

Altimeter (Envisat, Jason-1 and Jason-2) near real time wind and wave products have been analysed to estimate their random errors. The triple collocation technique was utilized for this purpose. The model scale of 70–80 km dictates the scale at which errors were estimated. Eleven (Envisat) and 13 (Jason-1/2) 1-Hz observations were used for altimeters and 5 observations done once per hour for 5 hours were used for buoys. Jason-2 Ku-band significant wave height (SWH) product turned out to be of very high quality. The SWH error was estimated to be 0.13 m or about 5.4% of the mean. Its relative error is rather equal at most of the SWH range. Envisat RA-2 SWH, which has some degradation at wave height values lower than 3 m, has a slightly higher error of about 0.15 m. Jason-1, which suffered some stability problems between the end of March and end of summer 2010, showed relatively higher errors especially after March 2010.

On the other hand, Jason-2 wind speed error at a level of 1.00 m.s^{-1} ($\sim$11.9%) may not be the lowest compared to the other instruments. Envisat RA-2 wind speed error, which was estimated to be 0.93 m.s^{-1} ($\sim$11.1%), is the lowest. It seems that the error in the wind speed at low wind speed values is relatively high for all instruments especially the buoys and the model. The model 1-day forecast winds seem to be of relatively small error for wind speeds in excess of 12 m.s^{-1}.

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