Global wave model validation using ENVISAT ASAR wave mode data

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Abstract

Spaceborne active radar remote sensing, e.g., radar altimeter (RA) and synthetic aperture radar (SAR) have been playing an important role in the validation of numerical wave models, particularly in open ocean. Most forecast centres also use altimeter data in the wave data assimilation process. In this paper we present validation results based on the newly developed CWAVE_ENV algorithm.

SAR wave mode data have been available since 1991 when ERS-1 was launched. Operational availability, however, began with the ENVISAT Advanced SAR (ASAR) wave mode data. The CWAVE_ENV algorithm yields independent Significant Wave Height (SWH) measurements from the ASAR wave mode data without the need of a priori information. Using the CWAVE algorithm, ASAR data can significantly contribute to global wave monitoring and assimilation.

ASAR wave mode data have been processed covering the period from December 2006 to February 2007 using the CWAVE_ENV algorithm. Using both wave height measurements derived from the ASAR wave mode and RA data, we evaluated the performance of the operational DWD ocean wave model, particularly in stormy weather situations.

1. Introduction

Numerical wave models, e.g., WAM (WAMDI, 1988; Günther et al., 1992) or Wave Watch model (Tolman, 1989), are widely adopted at various weather centers and research institutes to predict dangerous sea state for early warning, e.g., providing daily optimizing shipping routes over the North Pacific and North Atlantic in short term (Chen et al., 1998).

The capability of numerical waves model to predict extraordinary wave height is examined by Behrens and Günther (2008) using the German Weather Service (Deutscher WetterDienst, DWD) forecast Local Sea wave Model (LSM) for two Northsea storm cases, namely Britta in 2006 and Kyrill in 2007. By comparison to in situ buoy measurements, it is claimed that the LSM model is able to provide good short-term forecast (1 up to 5 days) of high wind waves during extreme storm events.

However, with respect to long-term seasonal and annual assessment of numerical wave models, there are some deficiencies found. Sterl and Caires (2005) as well as (Caires and Sterl, 2003) reported that the reanalysis ERA-40 (Uppla et al., 2005) wave data severely underestimate high wave heights by more than 20% compared to buoy measurements. Cox and Swail (2001) also found that storm peak wave heights in extra-tropical storms were systematically underestimated in comparison to buoy and Radar Altimeter (RA) measurements over the North Atlantic. Although the proportion of storm sea states (significant wave height, SWH> 6 m) is quite small, this underestimation should not be neglected, even if the overall agreement between model and data seems to be satisfactory.

The SAR wave mode data are dedicated for investigating open sea surveillance. SAR data have been available since the beginning of the ERS-1 mission in 1991 and will be continuously provided for the upcoming Sentinel -1 mission. The SAR wave mode (image) spectra (Brooker, 1995) have been used as standard products for numerical wave model assimilation (Hasselmann et al., 1997) at various weather centers or institutes (Breivik et al., 1998; Bidlot et al., 2002). The newly developed CWAVE_ENV empirical algorithm by Li et al. (2011) is particularly applied to the operational ENVISAT ASAR wave mode data, namely the Wave Mode Imagettes (WVI). The CWAVE approach, provides an independent active satellite measurement in addition to the RA data. This algorithm does not need any priori information since only the ASAR image being used as input for deriving integral wave parameters, e.g., SWH. The accuracy of the retrieved SWH is close to in situ buoy measurement with a bias of 0.06 m in deep water (Li et al., 2011).

In the present study, CWAVE_ENV (Li et al., 2011) is applied to derive integral wave parameters from the ENVISAT ASAR for validating the DWD Global Ocean Wave Model. ASAR and Radar Altimeter 2 (RA-2) are both mounted onboard the ENVISAT. While RA-2 is gathering the nadir sea surface measurements ASAR is looking to the right with a spatial distance of around 300 km from the RA-2 track. The successful development of CWAVE_ENV algorithm makes the ASAR sensor be another independent observation for sea surface wave with addition to RA-2. Using the both sensors for measuring sea surface wave brings a twofold advantage, especially under high sea state. On one hand it can increase spatial sampling over open ocean and the simultaneous observations can reduce uncertainties of measurement. On the other hand, the spatial variations of SWH, e.g., wave height gradient, under wind storms situations are able to be investigated as the parallel ground tracks have a spatial distance of 300 km.

In Section 2, we briefly introduce the dataset used for the present study. Several cases are presented in Section 3 for demonstrating the potential of using ASAR and RA-2 jointly to validate the DWD wave model under extreme weather situations. Overall assessment of the storm wave height over the North Atlantic during winter seasons using ASAR and RA is given in Section 4. Conclusions and remarks are summarized in Section 5.

2. Dataset Description

ASAR Wave Mode Data

As the successor of ERS/SAR, ASAR onboard ENVISAT also collects wave mode data to form small images (imagettes) of 5 km x 10 km size every 100 km along the satellite's orbit. Unlike in ERS, where only the SAR image spectra of wave mode data are provided, ESA generates different ENVISAT ASAR wave mode high level products from the respective raw data, namely the level-1b products of WVI and WaVe mode cross Spectrum (WVS) and level-2 products of WaVe mode ocean Wave spectrum (WVW), i.e. the so called retrieved ocean wave spectra. Comparisons conducted by Janssen et al. (2007), Abdalla et al.(2008) and Li and Holt (2009) have shown that SWH integrated from the WVW spectrum is an insufficient measure for the true sea state. Particularly high sea state is severely underestimated (Li et al., 2011). This was our motivation to use the CWAVE_ENV algorithm to derive SWH from ASAR wave mode WVI product.

Based on December 2006, the CWAVE_ENV algorithm was firstly tuned (Li et al., 2011) using the ECMWF reanalysis wave model, in which the RA and SAR information had been assimilated. A total of 23,464 collocated data pairs were available for the tuning approach.

Further, we calculated the CWAVE_ENV sea state parameters for the full year of 2006 for collocation with *in situ* buoy measurements. The collocation distance between ASAR wave mode data and buoy is always less than 100 km and only buoys located in deep water were selected for comparison. Most of the buoy data are received from the NOAA National Data Buoy Center (NDBC) and the Marine Environmental Data Service (MEDS). The corresponding scatter plot is shown in Figure 1.

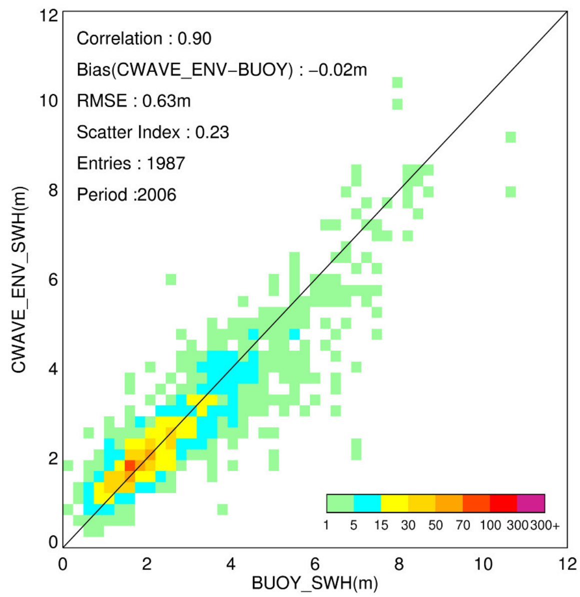


Figure 1*: Comparison of SWH derived from ASAR wave mode acquired from January to December 2006 using CWAVE_ENV algorithm to in situ buoy measurement in deep water and collocation distance is less than 100 km*

The retrieved SWH from ASAR wave mode data agrees well with *in situ* buoy measurement with a bias of -0.02 m and a RMSE of 0.63 m. Buoy measurements are often used for a linear calibration of remote sensing products, e.g., Radar Altimeter (Queffeulou, 2004). Following this concept we have also performed a calibration of the following form

$$SWH_{cal} = a_0 + a_1 * SWH_{CWAVE} \quad (1)$$

obtaining slope and intercept coefficients a_1=1.04, a_0= -0.07 m. Later in this paper, the calibrated wave height SWH_{cal} is used for comparison to results of the DWD wave model.

Besides the comparison of retrieved SWH from ASAR wave mode data with *in situ* buoy measurements, comparisons to the cross-over measurements of RA of GFO and JASON were also conducted (Li et al., 2011). The respective bias is -0.11 m and -0.13 m, scatter index is 17% and 13% in comparison to GFO and JASON.

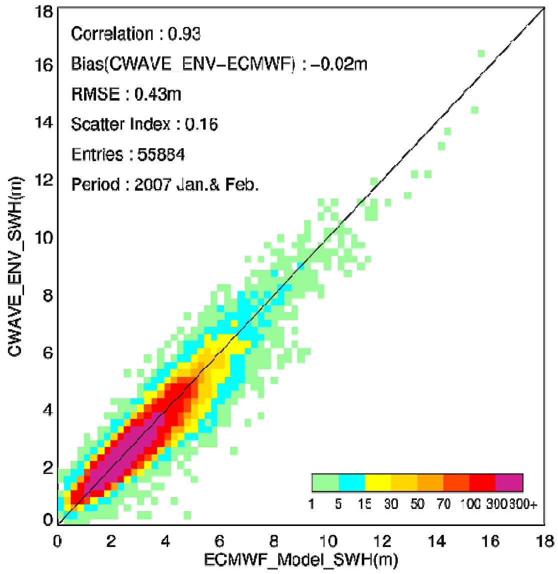
Radar Altimeter Data

SWH derived from RA-2 is accessed from the Centre ERS d'Archivage et de Traitement (CERSAT, Ifremer). These data were also calibrated linearly using *in situ* buoy measurements (Queffeulou, 2004), with $a_1 = 1.04$ and $a_0 = -0.17$. Therefore, bothe sensors, ASAR and RA-2, provide SWH being consistent with *in situ* buoy measurements and can be employed for measuring sea surface height over open sea. RA-2 nadir wave measurements are available every 7 km (1-second ground-track arc length) along track, whereas ASAR provides one wave mode imagette every 100 km along its orbit

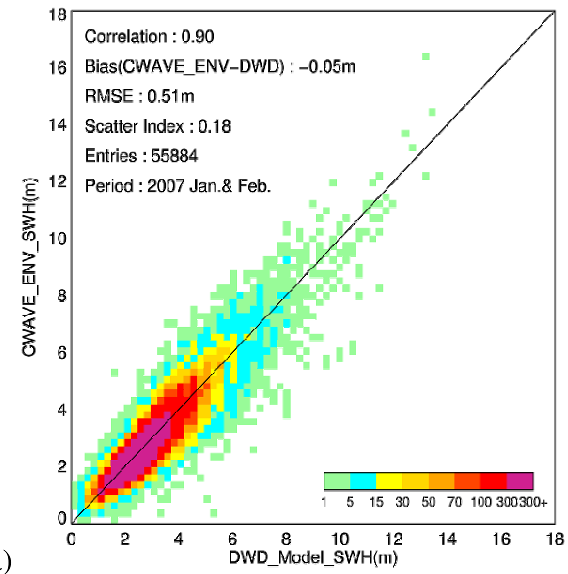
DWD Wave Model Data

The DWD global wave model is run operationally twice daily with a horizontal resolution of 0.75 degree. In the present study we use model data from December 2006 to February 2007. At that time, remote sensing data were not assimilated into the model. Therefore, the model data set consists of 3-hourly short term forecasts from T+3h to T+12h. Temporal difference between radar measurements and model output is thus less than 1.5 hour and spatial distance is around 50 km. As the parallel tracks of ASAR and RA-2 have a spatial distance of around 300 km, the DWD wave model results are respectively collocated to the ASAR and RA-2 measurements.

Scatter plots in fig.2 show that SWH retrieved by CWAVE_ENV algorithm shows good agreement with the ECMWF re-analyses and the DWD short term forecasts. In both cases, bias is near zero, with a root mean square error around a half meter and scatter indices well below 20%.



(a)

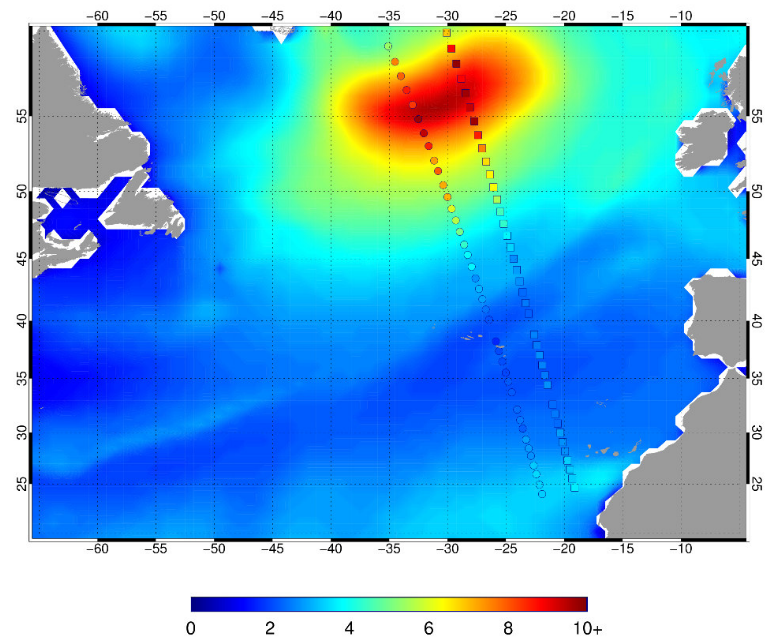


(b)

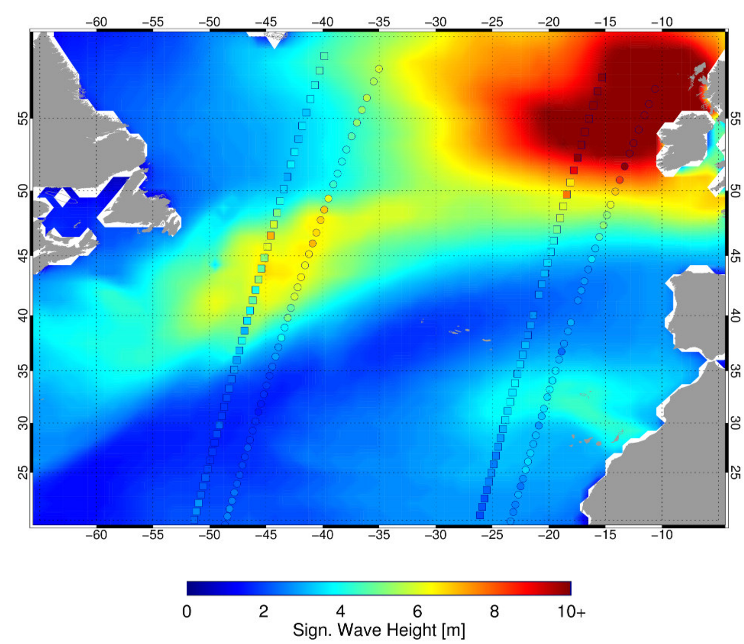
Figure 2: *Comparisons of (a) ECMWF and (b) DWD wave models vs. (uncalibrated) ASAR measurements on a global scale (January/ February 2007)*

3. Assessment of the DWD wave model in the North Atlantic

In this section, performance of the DWD wave model is assessed using the ASAR wave measurements derived by using the CWAVE_ENV algorithm on the global scale. As storms over the North Atlantic have gained increasing attentions, we focus the on storm wave height in the North Atlantic. Figure 3 shows four cases collected in January 2007 to demonstrate the double comparison between the DWD wave model and the spaceborne radar measurements under storm weather situations. There seems to be an general agreement between measurement and model, but looking into the detail in the storm regions, we find cases of significant underprediction and cases of overprediction, as well.



(a)

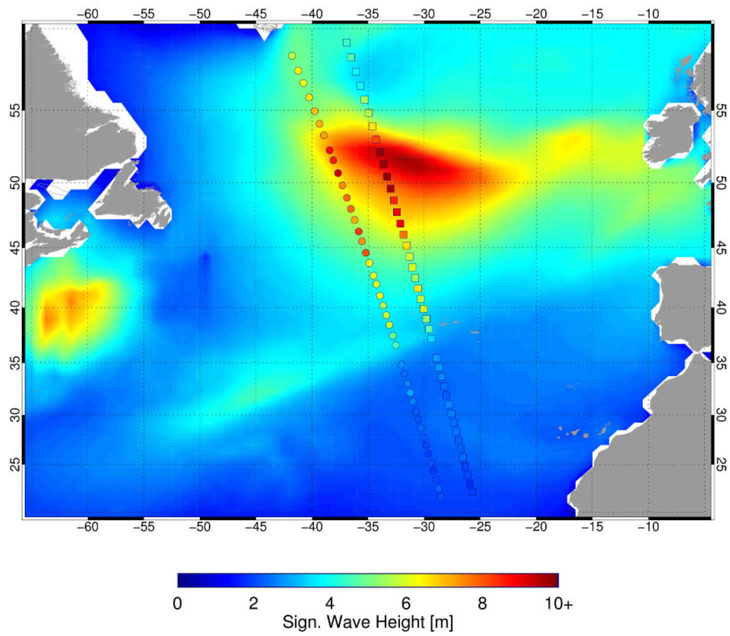


(b)

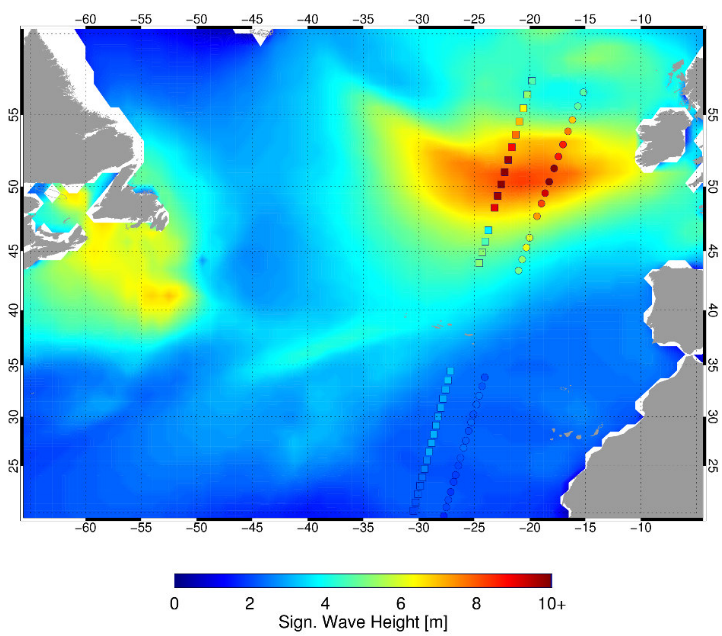
Figure 3: *Examples of using ASAR wave mode and RA-2 jointly for validating the DWD numerical wave model. The color-code squares and circles indicate SWH derived from ASAR and RA-2 respectively. The background is wave field predicted by the DWD wave model.*

(a) presents the case of ASAR wave mode and RA-2 data acquired during 23:11 ~ 23:22 UTC on Jan.4, 2007 and the DWD wave model is at 0:00 UTC on January 5th, 2007.

(b) The ASAR wave mode and RA-2 data (presented by the right two tracks on the plot) acquired during 11:34 ~ 11:45 UTC on Jan.11, 2007 and the DWD wave model is at 12:00 UTC on Jan.11, 2007.



(c)



(d)

Figure 3 cont.:

(c) The ASAR wave mode and RA-2 data acquired during 23:39 ~ 23:51 UTC on Jan.19, 2007 and the DWD wave model is at 0:00 UTC on Jan.20, 2007.

(d) The ASAR wave mode and RA-2 data (above 40°N) acquired during 11:52 ~ 11:56 UTC on Jan.20, 2007 and the DWD wave model is at 12:00 UTC on Jan.20, 2007.

We assessed the overall performance of the DWD wave model in the North Atlantic during December 2006 to February 2007. Figure 4 (a) and (b) shows comparisons of SWH predicted by the DWD wave model with measurements of the ASAR and the collocated RA-2 data, respectively. Since the ASAR track is 300 km away from the RA-2 track, two independent collocations had to be carried out.

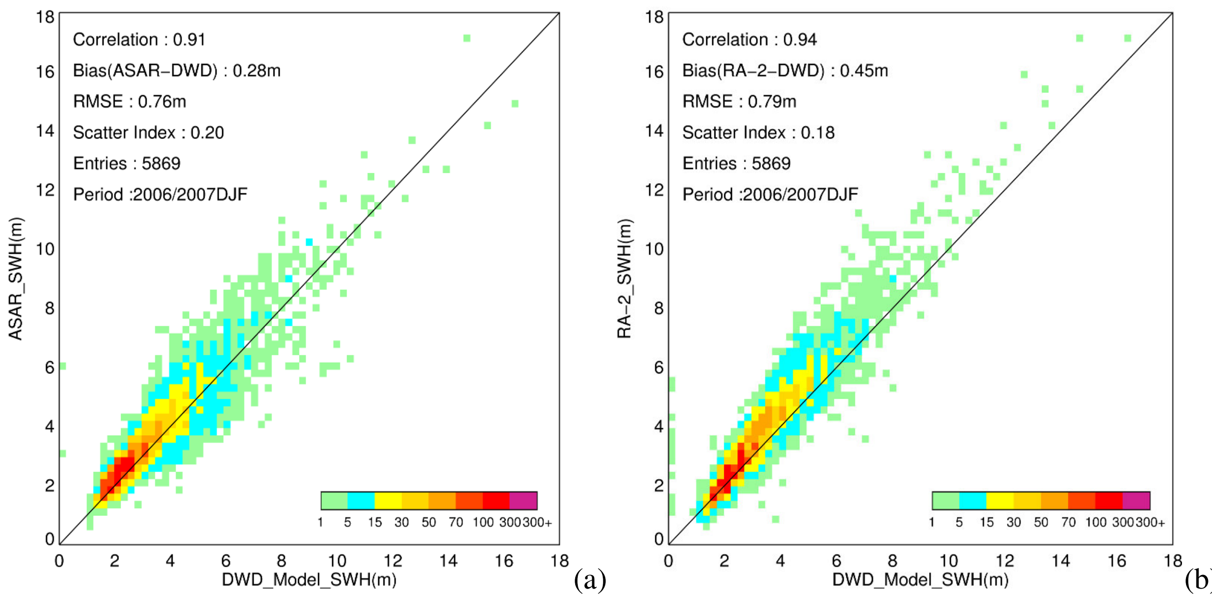
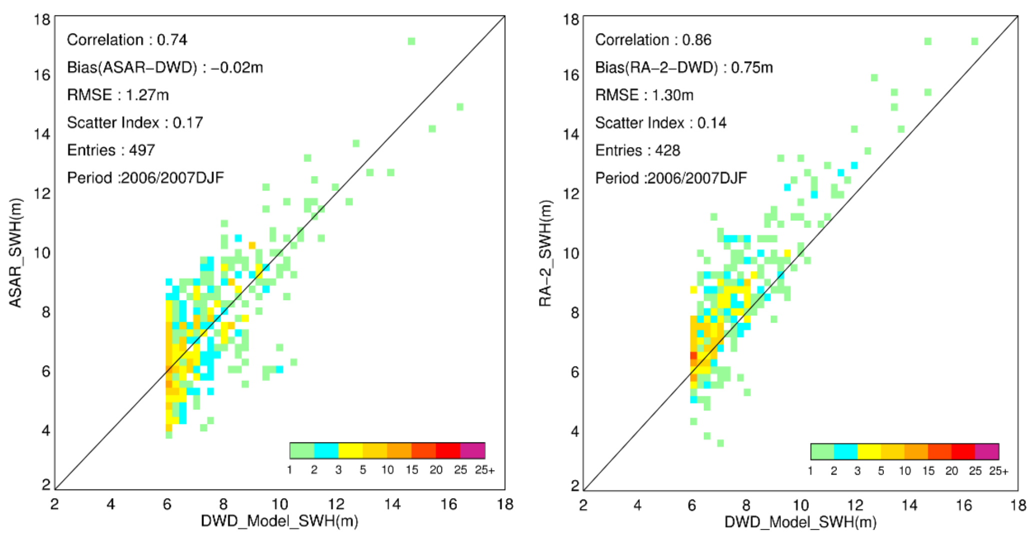


Figure 4: *Comparisons of DWD wave model SWH to (a) ASAR and (b) RA-2 measurements over the North Atlantic during winter months (December 2006 - February 2007)*

Predicted and measured SWH are highly correlated for both sensors. However, the other statistical parameters (bias, RMSE and scatter index) exhibit larger values compared to the global scale statistics for (uncalibrated) CWAVE_ENV (fig.2). In particular, the slope of the regression is obviously greater than 1, indicating a tendency of the DWD model to underpredict high sea states. For uncalibrated CWAVE_ENV and RA-2, however, the slope would reduce only slightly (not shown). Therefore, the underprediction of extreme SWH seems to be characteristical for the North Atlantic.

In order to investigate the model performance under storm conditions in more detail, datasets are reduced to situations with SWH above 6 m. The criterion whether this threshold is exceeded depends, however, on the referenced data set. As the *in situ* buoy measurements are not very often situated in places of high sea states, we use three alternate definitions of a storm event:

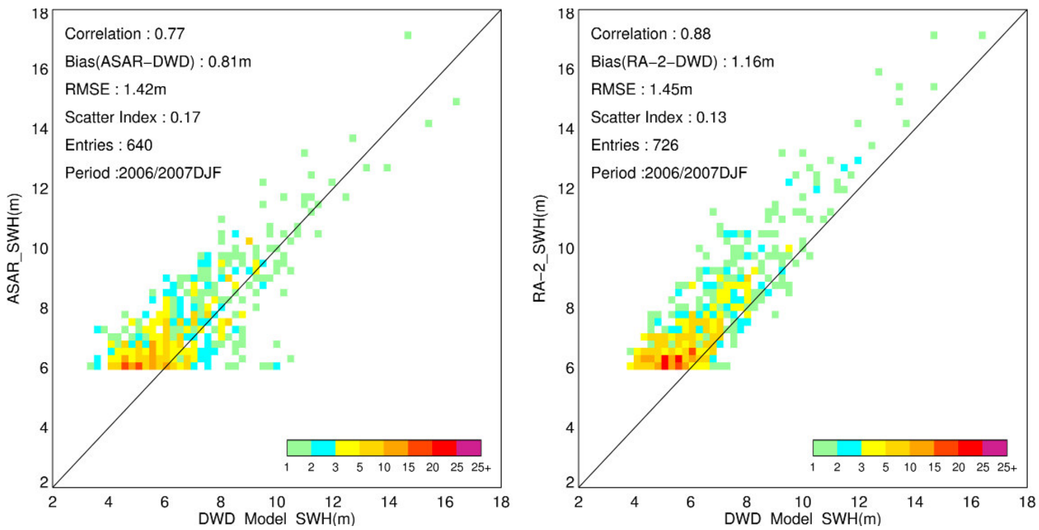
(i) The DWD wave model SWH_{DWD} above 6 m is used as reference for collocating radar measurements. The comparison results are shown in Figure 5. The predicted SWH is nearly unbiased as compared to ASAR measurements, though the correlation is low by 0.74, as shown in Figure 5 (a). But it seems to be underestimated when compared to RA-2 measurements with a high bias of 0.75 m. It is interesting to find that both comparisons show that the radar observations have significant spatial variations for SWH in range of 6 ~ 8 m.



(a) (b)

Figure 5: *Comparisons of predicted storm wave height of the DWD wave model to ASAR (a) and RA-2 (b) measurements.* ***The model results*** *are used as the reference for choosing sea state with SWH above 6 m.*

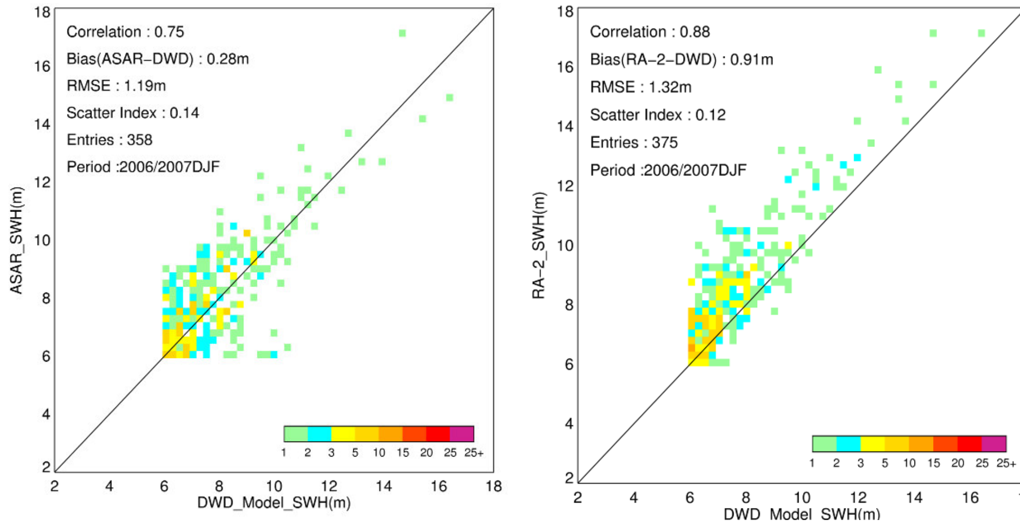
(ii) The radar observations, i.e. SWH_{ASAR} and SWH_{RA-2} above 6 m are used as the threshold for collocating the DWD wave model results. The comparisons shown in Figure 6 suggest that with this definition, the collocated model results are overall lower than the ASAR and RA-2 measurements, with the respective bias of 0.81 m and 1.16 m.



(a) (b)

Figure 6: *Comparisons of predicted storm wave height of the DWD wave model to ASAR (a) and RA-2 (b) measurements. The respective* ***radar observations*** *are used as the reference for choosing sea state with SWH above 6 m*

(iii) Both the radar observations and the collocated DWD wave model results are used jointly, i.e. only when SWH_{ASAR} and SWH_{DWD} (or SWH_{RA-2} and SWH_{DWD}) are both higher 6 m, the data pairs are chosen for comparisons. This may reduce the uncertainties for determining the wind storm weather situations. Regards to the comparison to ASAR wave mode data, the bias is 0.28 m and RMSE is 1.19 m, as shown in Figure 7 (a), which is reduced to 0.53 m compared to results if only the ASAR observations are used for determining the dataset for comparisons. The same situation is also found in comparison to RA-2 shown in Figure 7 (b). The bias is reduced from 1.16 to 0.91 m, while it is much higher than the comparison of DWD model to ASAR measurements.



(a) (b)

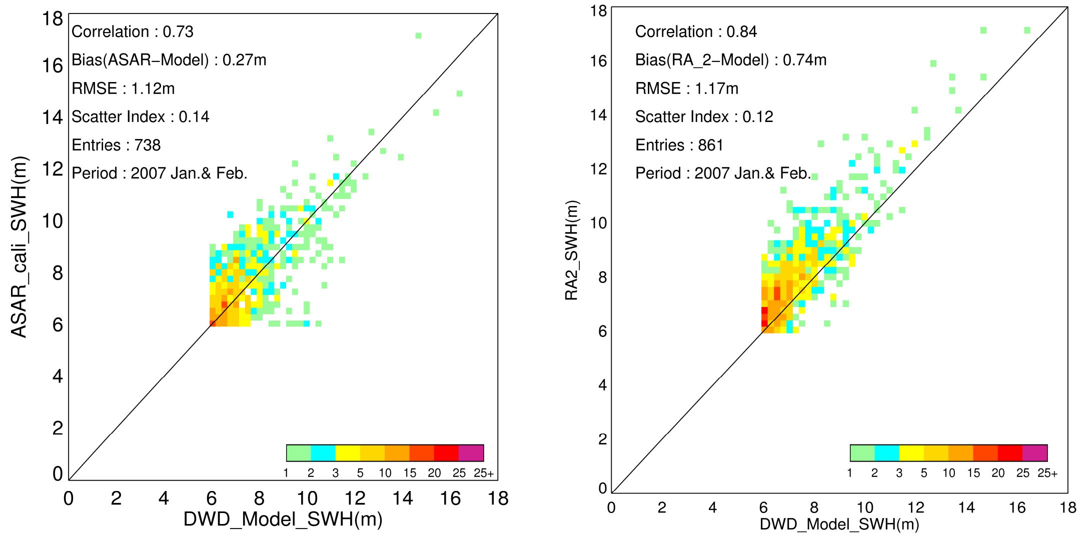
Figure 7: *Comparisons of predicted storm wave height of the DWD wave model to ASAR (a) and RA-2 (b) measurements. Both* ***radar observations and DWD model results*** *are used as the reference for choosing sea state with SWH above 6 m*

The statistical parameters for these comparisons based on three different methods are summarized in Tab. 1. Although the biases for different comparisons are considerably variable, the RMSE and Scatter Index (SI) are quite stable. By comparing DWD model wave height to the ASAR measurement, the averaged RMSE among the three types of comparisons is 1.30 m while the averaged RMSE among the comparisons to RA-2 is 1.35 m. This indicates that the DWD wave model systematically underestimates storm wave height over the North Atlantic based on the joint using of ASAR and RA-2 measurements.

Table 1 Statistical parameters of DWD wave height comparison to ASAR and RA-2 measurements for SWH above 6 m over the North Atlantic. Detailed explanation for (i), (ii) and (iii) is in Section 3

	(i)		(ii)		(iii)	
	vs. ASAR	vs. RA-2	vs. ASAR	vs. RA-2	vs. ASAR	vs. RA-2
Correlation	0.74	0.86	0.77	0.88	0.75	0.88
Bias (m) (Radar-Model)	-0.02	0.75	0.81	1.16	0.28	1.32
RMSE (m)	1.27	1.30	1.42	1.45	1.19	1.32
Scatter Index	0.17	0.14	0.17	0.13	0.14	0.12

Results on a global scale



(a) (b)

Figure 8: *Comparisons of predicted storm wave height of the DWD wave model to ASAR (a) and RA-2 (b) measurements. Both* ***radar observations and DWD model results*** *are used as the reference for choosing sea state with SWH above 6 m*

4. Conclusions and Discussions

In the present study, short term forecast results of the DWD wave model were assessed using ASAR and RA-2 onboard the ENVISAT platform. The CWAVE_ENV algorithm had been validated by comparison with *in situ* buoy measurements, two numerical wave models and cross-over measurements as presented by Li et al. (2011). The validation revealed that ASAR wave mode data is capable of deriving low, moderate and high sea states, as well. The quality of ASAR SWH compares well with SWH measured by radar altimeter mounted on the same platform. We therefore used both types of radar observation for evaluating the DWD wave model.

DWD wave model forecasts between December 2006 and February 2007 were collocated to ASAR and RA-2. Both comparisons indicate that the predicated wave heights are in good agreement with ASAR and RA-2 measurements. However, for high sea states (SWH > 6 m), we found significant differences between predicated and measured wave height. A detailed analysis has shown that the DWD wave model systematically underpredicts significant wave height in storm situations, at least in the North Atlantic. In storms RMSE ranges between 1.20 m and 1.45 m compared to ASAR and RA-2.

In future works, the following aspects need to be addressed.

In the present study, only model data acquired in three months were analyzed and therefore the selected collocations for high sea state have a very small proportion, which limits us to draw a final conclusion. More DWD wave model data especially covering the phase when RA measurements are assimilated are being collected.

The ASAR sensor has the so-called “frog-leg” configuration for acquiring wave mode data, i.e. incidence angle has a difference of around 0.5° between two consecutive imagettes, which can induce a change of normalized radar cross section (σ_0) particularly under extreme storm weather situations. Since the CWAVE_ENV algorithm is using calibrated ASAR image information directly, the change of σ_0 can cause different retrieved SWH between two consecutive ASAR imagettes even if both are acquired in a homogenous sea state. Taking this into account, a retune of the CWAVE_ENV algorithm is being implemented.

RA data has two main streams. The Fast Delivery (FD) products are used for operational services whereas off-line produces are better suited for scientific studies. Abadalla (2005) reported that the ENVISAT RA-2 FD products tend to overestimate SWH by about 9 cm relative to buoy data. In the presented study, the accessed RA-2 data are linearly corrected by comparison to *in situ* buoy measurements (Queffeulou, 2004) based on the off-line products. Desai and Vincent (2003) presented the difference between off-line and FD products for Jason-1. However, this relationship between these two products for ENVISAT remains unknown. This needs to be further investigated in the further works.

Acknowledgement

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