Latest developments in wave data assimilation

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Abstract

With the growing availability of satellite wind/wave data, operational assimilation of wave data for wave prediction has been developed during the last two decades. While very sophisticated methods have been developed for data assimilation in weather numerical prediction model and tested for wave data assimilation, most of operational prediction systems using satellite information are based on the simple optimum interpolation method, for a few reasons presented here. A review of the past work related to wave data assimilation is presented before a description of the latest developments done for the new Meteo-France wave prediction system to assimilate current altimeter data and SAR data. The MFWAM wave model uses a new dissipation term for wave breaking and a modified term concerning the wind input. The assimilation scheme based on optimal interpolation is using wave partitioning to assimilate SAR data. The ASAR (Envisat) level 2 wave spectra are selected through a quality control procedure. A variable cut-off procedure depending on the azimuthal cut-off, the satellite direction track and the wave component direction from the model is also used. The impact of the assimilation has been evaluated using independent wave data form NDBC buoys and altimeters. Thanks to the assimilation of both altimeter and ASAR data, RMS errors of the significant wave height is reduced by 25% in the analyse and remains significant up to two days in the forecast period, when the impact is evaluated globally against independent altimeter data. The reduction is only 10% when evaluated against buoys data, mainly located in the Northern Hemisphere and relatively close to the coast. The impact on the wave period is also significant with about 20% reduction in the analysis, when using ASAR in addition to altimeter or ASAR alone, but is very weak when using only altimeter data.

1. Introduction

Assimilation of observations in operational numerical weather prediction models is essential unlike in operational wave forecasting. Weather prediction is an initial value problem whereas wave prediction is a forcing problem. Analysis errors are amplified in the forecast period for weather forecasting while errors in the wave analyses are reduced. As a consequence, huge efforts have been made in the last two decades to improve data assimilation techniques for weather forecasting. Moreover, before the availability of wave remote sensing data, only few wave data where available in real time with inappropriate location for data assimilation because most of buoys are close to the coast (Figure 1). The interest in the assimilation of wave observations in operational wave forecasting came with the potential availability of wave data in real time with a global coverage, after SEASAT and GEOSAT periods.

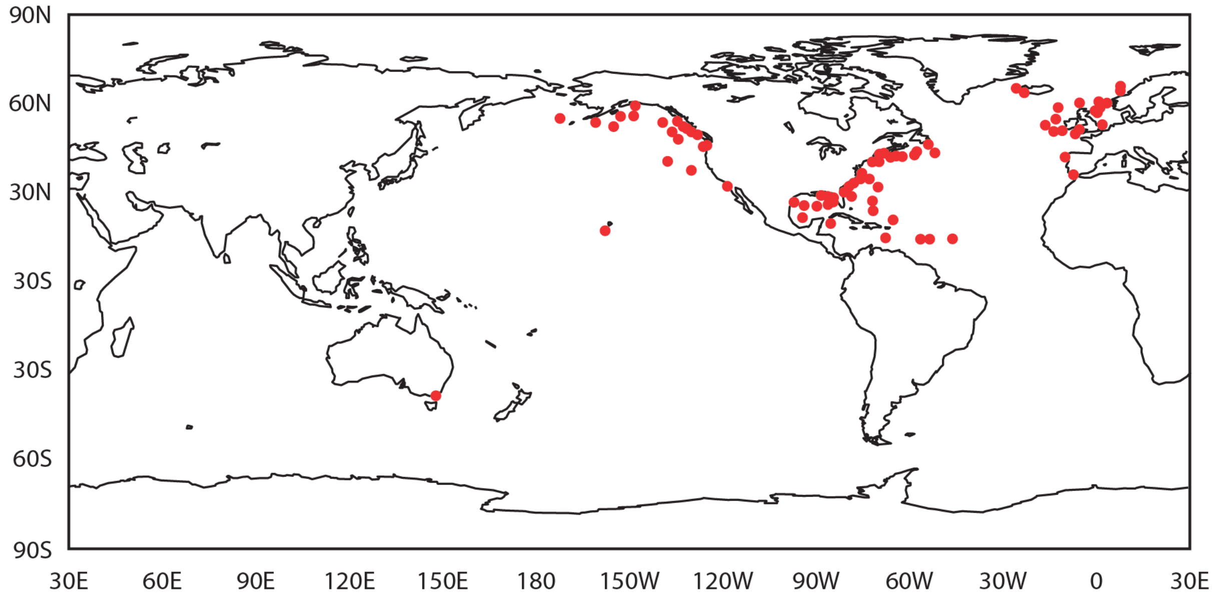

Figure 1: location of the 90 wind wave buoys used global comparison between MFWAM wave model SWH analysed values and in-situ values during the period of 1 April 2011 and 31 December 2012 (mainly in the NH).

2. Data assimilation in wave models

An interesting introduction to data assimilation can been found in Talagrand (1997). The aim of data assimilation in the field of weather prediction is to combine observations with a background field or first guess field to improve the initial conditions and consequently to improve forecasts. When considering a background value and one observation and assuming no bias and uncorrelated observation and first guess errors, an estimate value defined as a linear combination of the two can be unbiased with a minimum error provided that coefficients are adequately chosen. In addition, the inverse of the corresponding minimum of the estimation error variance is the sum of the inverse of the variance errors of the observation and of the first guess. This means that the error variance of the analysis is smaller than the error of the first guess, whatever the error variance of the observation is. This is true only if first guest errors and observation errors are well known. Most of assimilation methods used in wave forecasting are either sequential or dynamical type and a review can been found in Vilolante-Carvalho and Ramos (2006). Sequential methods are time independent while dynamical ones are time dependent allowing the take the model dynamic into account. For sequential methods, the estimate is obtained at a given time with observations at the same time (or almost) while for dynamical methods the estimate is obtained by combining the background and the observations in a time window: the optimum model trajectories have to minimize the estimation error variance within the whole time window. Due to its relative simplicity and low computational cost, the optimal interpolation method has been first introduced for operational application in meteorology and ocean wave prediction, at global scale in Thomas (1988), Janssen et al. (1989), Lionello et al. (1990, 1992), and at regional scale (Lefèvre 1992) for the assimilation of wind/wave altimeter data in wave models.

Some refinements of the Lionello et al. (1992) scheme have been introduced in Le Meur et al. (1995) and in Greenslade (2001), Greenslade et al. (2004,2005). Optimal interpolation and successive corrections methods have been also used to assimilate data from directional sensors such as provided by pitch and roll buoys (Voorips et al. 1997) or Synthetics Aperture Radar (Breivik et al., 1998; Aouf et al., 2006, 2008). Kalman filter based methods have been also developed and evaluated in the research context because they require much larger computer resources, not affordable yet at global scale in an operational context (Voorrips et al., 1999). Dynamical or variational methods are time dependent and take the model dynamics into account but have much higher computational cost compared to sequential methods because they require many iterations of the adjoin model. They also require maintaining three source codes: the direct model, the linear tangent model and the adjoin model. Such methods have been developed and tested for a single point model (De la Heras and Janssen 1992) and for synthetic observations in a limited area model (De Valk, 1994 in Komen, 1994) and for pitch rolls buoys (Voorrips and De Valk, 1997) also in a limited area model and compared with optimum interpolation based method. Finally, variational methods based on Green functions have been developed by Bauer et al. (1996). Up to now, the advantage of using advanced methods for wave data assimilation has not been established.

3. Data assimilation in MFWAM

3.1. The data

In level 2b products from the ASAR instrument on board ENVISAT, there is no use of any first guess wave spectrum from numerical wave models to derive them. Because of a quasi-linear assumption for the SAR image mechanisms for long wave systems, the level 2b products provided by ESA are issued from a simple method developed by Chapron et al. (2001). The 180° directional ambiguity in the wave propagation direction is removed by using the complex SAR data as developed by Engen et Johnsen (1995). Collard et al. (2005) have checked the level 2b products corresponding to large wavelengths and smaller steepness. They showed that the imaging mechanism is well described under the quasi-linear assumption. The ASAR wave data used in this study are such level 2b products provided by the European Space Agency, and retrieved with the new operational processor since November 2007 (Johnsen and Collard, 2007). This processor uses an improved filtering of non-wave signatures in the radar images, which are generally caused by ships, slicks and sea ice.

The level 2b products contain directional wave spectra with an angular resolution of 10° and an exponential increase in wave numbers from 30 to 800 meters, distributed in 24 intervals. These wave spectra are interpolated and adjusted to the MFWAM model resolution in frequency and directions used in this study. The level 2 products also provide some important parameters such the normalized variance of the imagettes, the ratio of signal to noise and the wind speed at the sea surface. A robust quality control procedure uses these parameters with thresholds values obtained in our previous work concerning the validation of ASAR wave data (Aouf et al, 2006). This validation has been investigated very carefully in order to avoid any including of corrupted data in the assimilation system. Otherwise, this could induce unrealistic wave forecasts. The directional wave spectra are considered relevant for being assimilated if the values of normalized variance of imagettes are between 1 to 1.6, the wind speed is between 3 and 17m/s and the ratio of signal to noise is between 2 and 20. The RA-2 altimeter data are provided by the European Space Agency (ESA). First, the ASAR level 2b wave products are presented by the directional wave spectra and the ASAR wind speed at ocean surface. The RA-2 altimeter provides the significant wave height and the wind speed at 10 m height. The ASAR and RA-2 wave data have a separate orbit tracks, which the average distance is of 200 km.

3.2. Data Quality and data preparation

Before being assimilated, data must be checked in order to eliminate spurious data. A first editing procedure has to be done based on some parameters associated with the values of interest. For instance, for each 1 hertz altimeter significant wave height which is computed by averaging 10 to 20 values, an rms value is given. A threshold value can be used to eliminate values with too high variability within 1 second. Also to reduce representativeness errors, data can be averaged in sequences of the size of the model mesh. Doing this, it is also possible to check the variability of the data in order to eliminate sequences with spurious data. For SAR data, signal to noise ratio and normalized variance of imagettes are used as quality control parameters. Typically 10 to 15% of the data can be rejected. As mentioned in the previous paragraph, observations and model data must be unbiased. Data must be corrected in order to remove such biases if any (see Queffeulou, P. et D. Croizé-Fillon, 2009). Different corrections must be applied according to instruments and data sources. Random errors for model first guess and observations must be estimated. The multiple collocation method (Janssen 2003, Abdalla 2005) can be used to estimate such errors of each source of data. To correct the model value at a given grid point using an observation at another place at the same time, or almost, one must know how model forecast errors are correlated in space. When several observations are considered, an Error Forecasting Correlation Matrix (EFCM) can been introduced and must be estimated or calculated, depending on the method. There are several methods to estimate the EFCM. One of these is the observational method of Hollingsworth and Lönnberg (1986) which uses differences between the observations and the background field over long periods. This method has been used in Lefevre (1992) for the assimilation of altimeter data in the Mediterranean Sea using differences between altimeter data and WAM model data. Another method may be used to estimate the structure of the background errors, based on forecast divergence (Parrish and Derber, 1992; Rabier et al. 1998). The EFCM can be directly computed within the Kalman Filter Method, while small ensemble assimilation can be used in dynamical methods.

3.3. The MFWAM wave model

Modern wave prediction is based on the balance energy equation for the directional wave spectrum or for the action density. In this equation, the temporal evolution of the directional wave spectrum is balanced by the advection term and the source terms. Those terms parameterize the wind input including the air friction, the wave breaking dissipation, the nonlinear wave-wave interactions, the bottom friction, the wave-current interaction. The operational wave model of Meteo-France is a third generation model called MFWAM, based on the ECWAM code (2007 version) modified with a new physics package from Ardhuin et al. (2010). The wind input source term, based on BAJ (2007) has been adjusted to fit the new dissipation term, and a new term to take into account air friction has been added. The input source term can be written as follow:

$$S_{in} = S_{baj} + S_{out}$$

Where S_{baj} is the wind input term based on BAJ (2007) and S_{out} is the negative input source term due to air friction with two possible formulations depending upon whether the boundary layer state is laminar or turbulent. This is indicated by the boundary Reynolds number given here below:

$$R_e = 4\mathrm{u}_{orb} a_{orb} / v_a$$

where U_{orb} and a_{orb} are respectively the orbital velocity and displacement amplitude at the sea surface, while v_a is the air viscosity.

The formulation used depends upon a threshold value of the boundary Reynolds number of 2.10^4 and are as follows:

$$S_{out}(f,\theta) = -1.2\varepsilon\{2k\sqrt{2v\omega}\}F(f,\theta)$$

$$S_{out}(f,\theta) = -\varepsilon\{16 f_e \omega^2 u_{orb} / g\}F(f,\theta)$$

where f_e is expressed by using adjustments from SAR wave data from Collard et al. (2009):

$$f_e = 0.7f_{e,GM} + [0.015 - 0.018\cos(\theta - \varphi \quad)]u / u_{orb}$$

where $u*$ is the friction velocity and, θ and φ are respectively the wave and wind directions.

The wave breaking dissipation term has been modified to introduce a thresholds mechanism instead of using mean wave steepness parameters. The dissipation term is related to the wave spectrum with a saturation rate. The term is a combination of an isotropic part with and a directional dependent part in order to control the directional spreading of the resulting spectra. A cumulative effect describing the smoothing of big breakers on small breakers is also parameterized. The term also uses a wave turbulence interactions part which is weak as indicated in the paper of Ardhuin et al. (2010). The quadruplet nonlinear interactions term is the same as the one of ECWAM which uses the discrete interactions approximation (DIA). In this study, the wave model MFWAM was implemented at a global scale covering 80°N to 80°S on an irregular latitude-longitude grid. The grid resolution is 0.5° longitude by 0.5° latitude at the equator and becomes coarser in degrees at the poles as the grid mesh remains constant in distance (about 55km). The directional wave spectrum is discretized in 24 directions (step of 15°), and 30 frequencies starting from 0.035 Hz with an increment factor of 1.1. The wave model is 6-hourly forced by analyzed winds from IFS/ECMWF model.

The global model MFWAM is compared to others wave models using buoys data as a reference. Figure 2 is from Bidlot J., ECMWF (see Bidlot et al., 2008 for details about the intercomparison exercise).

The improvement of the alternative physical package used in MFWAM (purple lines) is clear in Figure 2 for the peak period for all forecast range and less important for the significant wave height.

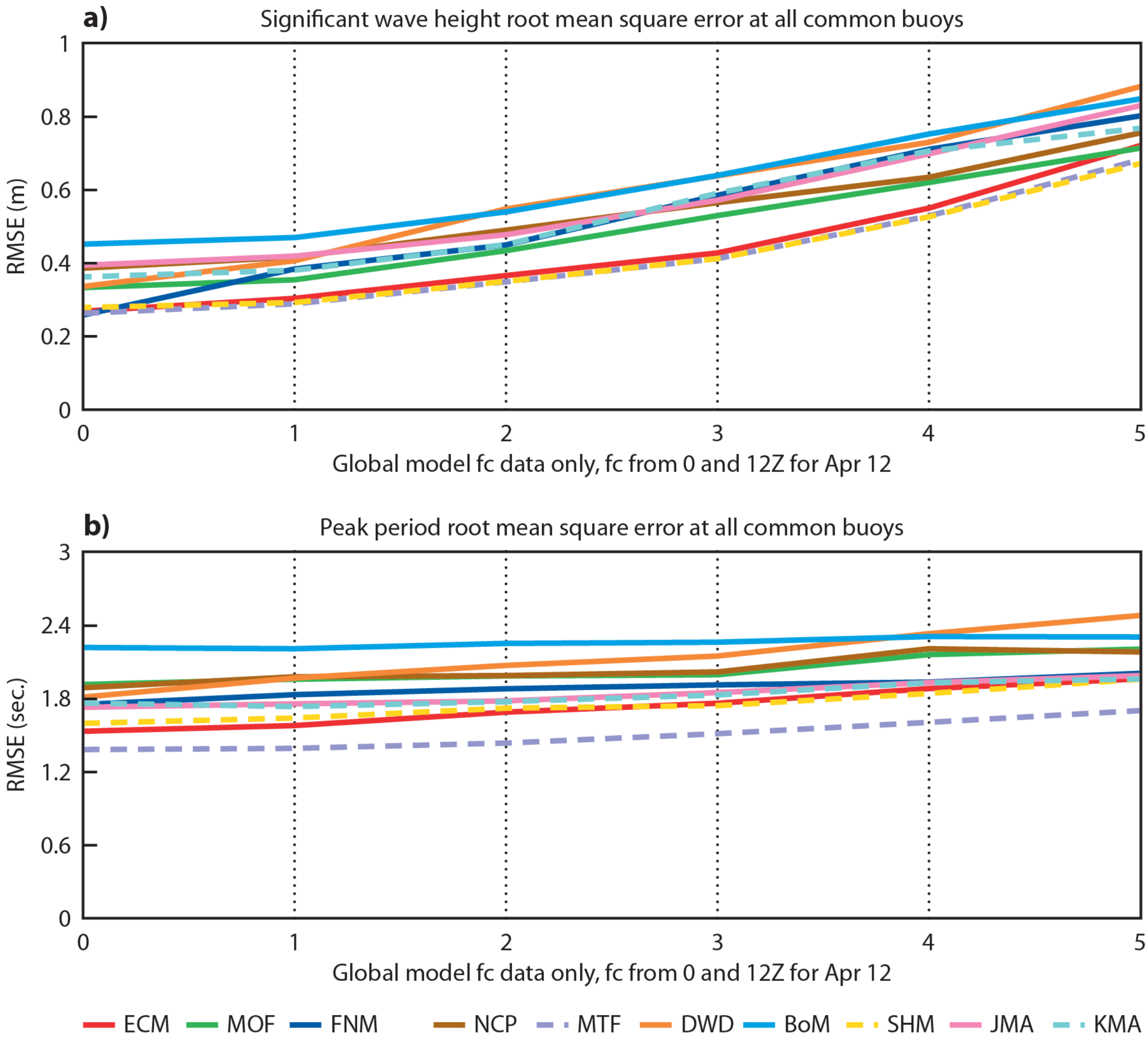

Figure 2: RMS error of analysed and forecast wave height (top panel) and peak period (bottom panel) from Meteo-France wave model MFWAM driven by IFS/ECMWF winds (purple dashed line) and some other centres against buoy wave height data for April 2012.

3.4. The assimilation system

3.4.1. The optimal interpolation procedure

Optimal interpolation consists in computing appropriate corrections for the first guess at the observation locations and then spread them over the model grid points. For this reason, a correlation function depending on observation errors and model errors, and a simple Gaussian distribution of the corrections over grid points (spatial scale), can be defined (Kalnay, 2002). The weights W assigned to the observations were chosen as follows:

$$W = PH^T\left[HPH^T + R\right]^{-1} \quad (1)$$

Where P and R are respectively the forecast or background and observation error covariance matrix, while H is the matrix which projects the model state onto the measurements. By considering the background error homogeneous and isotropic, we expressed P and R as follows:

$$P = \exp\left(-\left(\frac{d_{ij}}{\lambda_c}\right)\right) \tag{2}$$

$$R = \frac{\sigma_o^2}{\sigma_b^2} \tag{3}$$

Where i and j are respectively the model grid points, d is the distance from the observation location to the grid point, and λ_c is the correlation length.

Consequently, the optimal analyzed mean wave parameters can be written as follows:

$$X^a = X^b + \sum_i^N W_i (X_{i^o} - HX_{i^b}) \tag{4}$$

Where X^a and X^b represent the analyzed and background (first-guess) mean wave parameters (energy, wave number) at every model grid points, respectively. Upper index “o” stands for observations, while “N” is the number of observations selected for a given model grid point.

The assimilation step considered here is of 6 hours and the wave model MFWAM is driven by analyzed wind fields from the IFS/ECMWF atmospheric model.

The ratio between errors of observations and model (background) is chosen equal to one. The correlation length and the distance of influence of observations are of 300 km and 850 km, respectively.

3.4.2. Conversion to spectral information

The assimilation system, using conjointly altimeters wave height and ASAR directional wave spectra is implemented in two parts. The first one concerns the assimilation of data provided by altimeters. This consists in performing an optimal interpolation on the total significant wave height. The wind sea is searched in the wave spectrum and compared to the swell part. If the wind sea part of the analyzed wave spectrum is dominant, the spectrum is corrected according to empirical power laws between dimensionless significant wave height and mean wave period for growing wind waves (Lionello et al., 1992). If the swell is dominant, the spectrum is corrected such as the mean steepness is conserved (Lionello et al. 1992).

The second part is related to the assimilation of ASAR directional wave spectra. This procedure is based on a partitioning scheme, which consists in splitting the wave spectrum in wave trains (partitions) characterized by their mean parameters (wave energy, period and direction). The difficult part of the assimilation scheme is the cross-assignment between the observed partitions and the first guess ones. To this aim a criteria proposed by Hasselmann et al. (1997) is used. This consists in computing a normalized distance in wave numbers space between the mean wave numbers of partitions (see Aouf et al. 2006). If the distance is less than a threshold value (a value of 2 has been chosen), then the partitions are cross-assigned and are ready for the assimilation. Afterwards, an optimal interpolation is performed on mean wave energy and components of wave vectors of the selected partitions. Then, analyzed partitions are superimposed to derive an analyzed wave spectrum. Analyzed partitions are linked using a bi-parabolic interpolation.

4. Impact study

Since March 17, 2011, the new MFWAM model has been operationally assimilating RA2 and Jason-2 altimeters data and ASAR data from ENVISAT. Results from an impact study over a seven months period from April 1 to December 31, 2011 are presented here. A MFWAM free run (without assimilation) has been performed for the same period in order to estimate the impact of the assimilation. Again, the wave model is forced by 6 hourly analysed winds from the IFS/ECMWF atmospheric model.

From the operational run, the parameters used for the assessment are the significant wave height and the peak wave period of the 1-D wave spectra. Independent wave observations are used for the validation from buoys and Jason-1 altimeter that were not assimilated in the operational system in 2011. The buoys provide the significant wave height and the peak wave period parameters. They are mainly located off-shore North America and North-West of Europe. These data are obtained from the archive of the intercomparison of wave forecast systems supported by J. Bidlot from ECMWF as part of WMO/IOC wave forecast verification project for the Joint technical Commission for Oceanography and Marine Meteorology (JCOMM). Figure 3 shows the global comparison between MFWAM wave model SWH analysed values and in-situ values during the period of 1 April 2011 and 31 December 2012 (mainly in the NH). Left panel for operational MFWAM model, right panel for MFWAM hindcast without assimilation. Left panel shows less scatter in comparison with right panel. Table 1 indicates that the normalised scatter index is improved by 10% when assimilating data. The reduction of the scatter index is much higher when the reference data is from the Jason-1 altimeter. The scatter index decreases from 14.1% to 10.6%. Also, it is clearly showed that the slope of the orthogonal regression between the significant wave heights from the model analyses and the Jason-1 altimeter is reduced to a value close to one when assimilating the satellite data. The impact is less significant when comparing with buoys data, suggesting that most of the impact is located in the southern hemisphere where very few buoy data are available (see figure 3). However, the impact on the wave period is significant when comparing to buoys as shown by figure 4.

	Buoys		Jason-1	
	A	B	A	B
Bias (m)	-0.04	-0.01	-0.09	0.04
SI (%)	15.1	16.1	10.6	14.2
NRMSE (%)	15.3	16.4	11.0	14.2
slope	0.98	1.02	1.02	1.12
intercept	-0.01	-0.05	-0.14	-0.29
Collected data	79420		170942	

Table 1. Statistical analysis of significant wave height (Hs). A and B stand for significant wave heights obtained from the operational wave forecasting system and the run of MFWAM without assimilation, respectively. SI and NRMSE are scatter index and normalized root mean square errors.

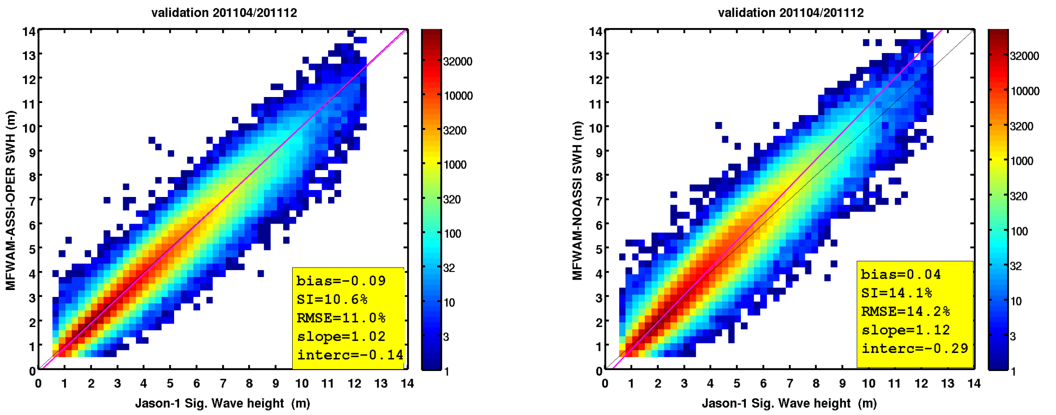

Figure 3: Global comparison between MFWAM wave model SWH analysed values and Jason-1 OSDR values during the period of 1 April 20011 and 31 December 2012 (mainly in the NH). Left panel for operational MFWAM model, right panel for MFWAM hindcast without assimilation.

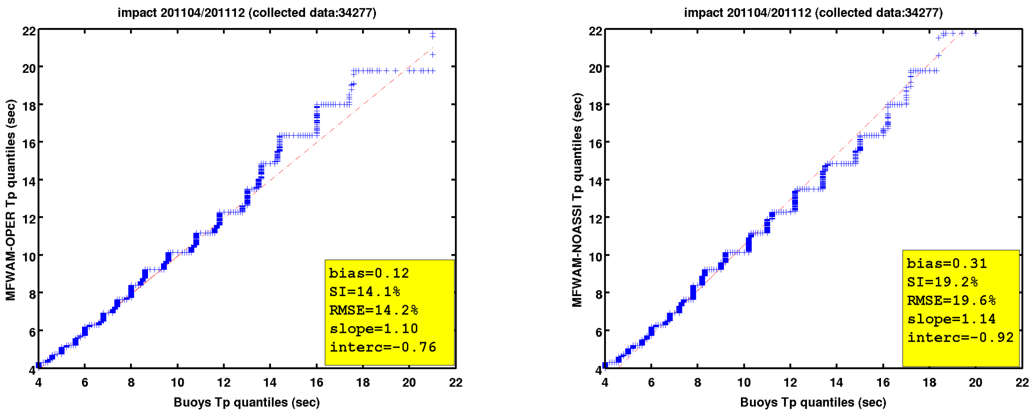

Figure 4: Global comparison between MFWAM wave model peak periods analysed values and in-situ values during the period of 1 April 20011 and 31 December 2012 (mainly in the NH). Left panel for operational MFWAM model, right panel for MFWAM hindcast without assimilation.

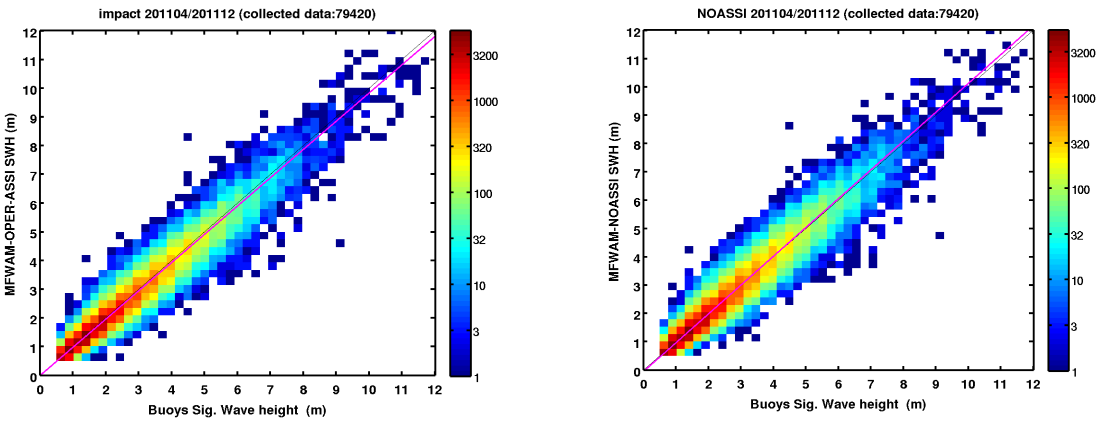

Figure 5: Global comparison between MFWAM wave model SWH analysed values and in-situ values during the period of 1 April 20011 and 31 December 2012 (mainly in the NH). Left panel for operational MFWAM model, right panel for MFWAM hindcast without assimilation.

Assimilation tests with the ASAR directional spectra only were also conducted to analyse the contribution of ASAR in the performance of operational wave forecasting system. The test period was from September 1, 2010 to April 1, 2011. Tables 2.1 and 2.2 show the statistical parameters of the significant wave height differences between model data and Jason 1-2 data.

Results are also given according to different areas. Three regions are defined: the high-latitude region above and below 50° north and south respectively, the low-latitude region between 20° north and south, and the mid-latitude region for the remaining area. The scatter index is reduced after the assimilation of ASAR wave spectra for high latitudes and intermediate ocean areas. The decrease is respectively about 8% and 7% in comparison with altimeters Jason 1 and 2. However, the assimilation of the ASAR wave spectra has no impact in the tropical region. This is probably mainly due to recent improvements concerning the wave dissipation term implemented in the wave model MFWAM. The slope between the significant wave heights of altimeters Jason 1 and 2, and those from the model MFWAM after assimilation has been slightly improved.

	Run with assimilation of ASAR		
	High	**Mid**	**Low**
Bias (m)	0,06	-0,08	-0,12
SI (%)	13,9	13,0	11,3
slope	1,04	1,04	1,00
intercept	-0,06	-0,21	-0,16
Collected data	958564	1238962	720063

Table 2.1. Statistical analysis of significant wave heights for the run with assimilation of ASAR directional wave spectra. SI is the normalized scatter index.

	Run without assimilation		
	High	**Mid**	**Low**
Bias (m)	0,23	0,04	-0,10
SI (%)	14,8	13,3	11,3
slope	1,08	1,08	1,03
intercept	-0,03	-0,20	-0,17
Collected data	958564	1238962	720063

Table 2.2. Statistical analysis of significant wave heights for the run without assimilation of ASAR directional wave spectra. Ocean areas A, B and C stand for high, intermediate and tropical latitudes, respectively. SI is the scatter index.

We have also compared the peak wave periods from the operational model with buoys located off shore North America. Both scatter index and bias are significantly reduced as shown in table 3. The normalised root mean square errors of the peak period are reduced by 27.5 %. The slope and intercept are also well improved after the assimilation. In order to analyse the contribution of each wave observation in the assimilation system we compared the assimilation of ASAR wave spectra and altimeters performed in the operational run with the assimilation of altimeters wave heights only. The most remarkable fact in the statistical analysis of the peak period for long waves (peak period Tp > 10 sec) is when adding the ASAR Level 2b wave spectra in the assimilation the scatter index is improved by 15%. Otherwise the scatter index approaches the case without assimilation. This clearly indicates the importance and usefulness of using ASAR-L2 wave spectra in the forecasting system.

	A	B
Bias (sec)	0,12	0,31
SI (%)	14,1	19,2
RMSE (%)	14,2	19,6
slope	1,10	1,14
intercept	-0,76	-0,92
Collected data	34277	

Table 3. Statistical analysis of peak wave period. A and B stand for MFWAM operational run with assimilation and run without assimilation, respectively.

5. Conclusions

ECMWF and more recently Meteo-France have been assimilating operationally ESA/ASAR data and Altimeter data. Meteo-France is using level 2b products from SAR while ECMWF is using level 1b products which are inverted using a first guess model wave spectrum. The impact of using altimeter data alone, SAR data alone, and both source of information have been evaluated. When using ASAR and altimeters data together, the reduction of the RMSE in the wave model analysis is about 10% for SWH and 25% for the peak period when statistics are against buoys data. The reduction for SWH is much more when estimated against independent altimeter data (25%), which are homogenously distributed whereas buoys are mainly located in the Northern Hemisphere. With MFWAM, a significant bias has been found in the Southern Hemisphere (Lefèvre et al. 2009), which could explain such different RMSE according to data sources. The contribution of ASAR data alone in the assimilation is clearly showed for the peak period parameter, when above 12 seconds. Only the use of ASAR data is reducing the RMSE for the peak period by more than 20%b (not shown). The assimilation of ASAR Level 2b products alone improves the estimate of the SWH by about 10% in comparison with altimeters (not shown). The impact in the forecast is decreasing quite rapidly depending on the area and parameter. When assimilating altimeters (Ra2 and Jason2) and SAR data or SAR alone, the global reduction in the RMSE for SWH when altimeters data (Jason-1) are used are reference data is typically less that 2% for the 2 days forecast.

However with the coming deployment of more altimeters and new instruments, it is expected more impact in the wave analysis and forecast. For instance the SWIM instrument (Hauser and al. 2010) on the CFOSAT satellite (Chinese-French program, launch scheduled end 2014) should provide shorter wave spectral component than the SAR but with lower spatial resolution. The new Ka band altimeter from the French Indian mission SARAL/Altika (Verron et al. 2006) should also provide (Launch scheduled end 2012) more accurate SWH and a smaller lower limit for SWH. The European Space Agency (ESA) missions of the Sentinel series (from 2013) will also provide new data in the next years. Impact studies based on synthetic wave spectra from SWIM instrument in combination with other instruments could be performed with the new MFWAM model. The assimilation scheme based on OI should be also improved by using a better description of the model prediction error covariance functions that should not be isotropic, following the work of Delpey et al. (2010). Then, revisiting more sophisticated techniques could a possibility to better combine all source of information.

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