Assimilation of SAR data into the ECMWF global wave model

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Abstract

A brief review of the wave data assimilation at ECMWF is given. In particular, the potential use of SAR data is explored.

1. Introduction

The operational wave models at ECMWF have been making use of altimeter wave height observations since August 1993, first with ERS-1 data and currently with ERS-2. In the current system configuration, altimeter data are the only data source in the wave model assimilation. In the near future, other satellites will also carry an altimeter radar (ENVISAT, Jason,...), resulting in a better coverage of the world oceans. Unfortunately, the altimeter only yields significant wave heights and wind speeds over a small footprint. A more accurate description of the sea state requires the full two-dimensional wave energy spectrum. Such observations, albeit not necessarily fully comprehensive nor independent, are already available with the ERS synthetic aperture radar (SAR). With the launch of ENVISAT, a more advanced SAR (ASAR) with a higher spectral resolution will soon operate at twice the current ERS data coverage by providing an observation every 100 km along the SAR swath over the oceans.

The improved quality and processing of the data should be thoroughly exploited to obtain better analyses of the ocean sea state. In a more distant future, other space borne instruments which are capable of also measuring the directional wave spectra might become available (e.g. SWIMSAT, Hauser et al. 2001). The advent of more global wave spectral observations will require the development of new data assimilation techniques and ultimately, the testing of their impact on operational wave forecasting. In this paper, we have revisited the problem of wave data assimilation in the context of the ECMWF operational system. In section 2, we review the ECMWF forecasting system with emphasis on its data assimilation system. The processing and impact of altimeter wave height data are discussed in section 3. SAR data and their assimilation are the subject of section 4 and 5. Conclusions, however preliminary, are presented in section 6.

2. The operational global wave model at ECMWF

ECMWF runs a global version of WAM cycle 4 coupled to its atmospheric model with feedback of the sea surface roughness change due to waves via an update to the Charnock parameter (Janssen et al. 2000a). Altimeter wave height data are used in the wave model assimilation. In general, data assimilation aims at obtaining the best estimate for the initial state used in the subsequent forecast by combining model first guess with observations. For the atmospheric model, a four dimensional variational approach (4dvar) is applied (Rabier et al. 2000) in which initial conditions obtained from a very short forecast (3 hours) are modified by successive minimizations and integrations so that a forward integration of the model at full resolution (trajectory evaluation) yields a better fit to the data both in space and time than what is obtained with the forecast. The integration period for which data are currently considered is 12 hours (12 hour 4dvar). The wave model assimilation is however based on a much simpler optimal interpolation (O.I.) scheme which combines at analysis time data and model estimates in a gross average sense provided observation and model error estimates are prescribed (Lionello et al. 1992). In the past, the WAM first guess was obtained by running the model with analyzed winds from the 6 hourly archive but in the coupled system, better wind estimates are available when computing the 4dvar trajectories. Therefore, in the current system, the wave model assimilation is carried out in the last trajectory by calling the O.I. scheme from within WAM at both synoptic times within the 12 hour integration.

One of the main limitations when using altimeter wave height data is the lack of spectral information. The wave model assimilation scheme must therefore make some assumptions on how to transform the wave height update as obtained from O.I. into an update to the spectrum. A relatively arbitrary decision is made on whether windsea or swell are the dominant part of the spectrum and a rescaling and redistribution of the different spectral components is determined based on some assumption on how a model spectrum should be modified when its total energy is changed (Lionello 1992 but with new non dimensional growth curves which are in better agreement with the latest model physics). When windsea is assumed to be dominant, an update to the surface stress is also derived which is returned to the atmospheric model via a corresponding update to the Charnock parameter. In this manner, wave observations have a very small impact on the atmospheric analysis since they will only influence the remaining trajectory calculation.

3. Altimeter data

Altimeter wave heights from ERS-2 are used in the ECMWF operational system. There is therefore a need to check the quality of the data. Daily, weekly and monthly statistics are produced and exchanged with the European Space Agency (ESA). For example, a time series of the daily scatter index (normalized standard deviation of the difference) for the comparison between altimeter wave height and model first guess is presented in figure 1. The improvement due to the introduction on the 21st of November 2000 of the new horizontal resolution (T511, 40km) in the atmospheric model combined with the increased spectral resolution in WAM (30 frequencies and 24 directions) is clearly visible. Similarly, the interruption in data coverage at the end of January 2001 and the disastrous statistics when the altimeter data were first redistributed (7th February) are also shown (the data were no longer used). ESA quickly corrected the problem with the instrument and the statistics returned to a level which could be expected when altimeter data are not assimilated. As a result, the altimeter wave height data were used again on March 6th. The impact of the assimilation is clearly displayed by the reduction of scatter index after March 6th.

The ECMWF spectral update scheme does not use the altimeter wind speeds. They are only applied to a rather loose check on the update to the surface stress derived from the assimilation of wave heights. However, they were quite useful for independent validation of the model wind fields (Janssen et al. 2000b) until their quality degraded in 2000.

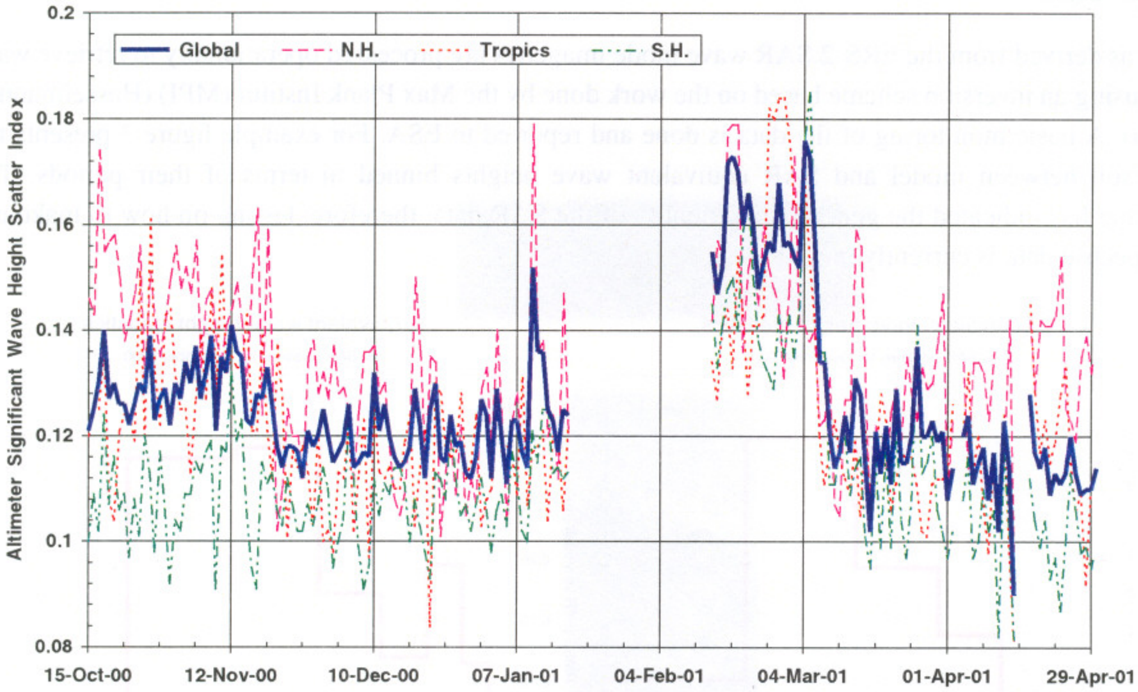

Fig 1: Time series of the daily scatter index (standard deviation of the difference normalized by the mean observation value) for the comparison between model first guess and altimeter wave height super observations (average of 30 consecutive observations). Results are given for the whole globe (Global), the northern hemisphere (N.H., north of 20°N), the tropics and the southern hemisphere (S.H., south of 20°S).

Following the temporary loss of ERS-2 data, the impact of altimeter data was quickly reassessed. As shown in figure 2, using altimeter data has a positive impact on the forecast for up to 3 days.

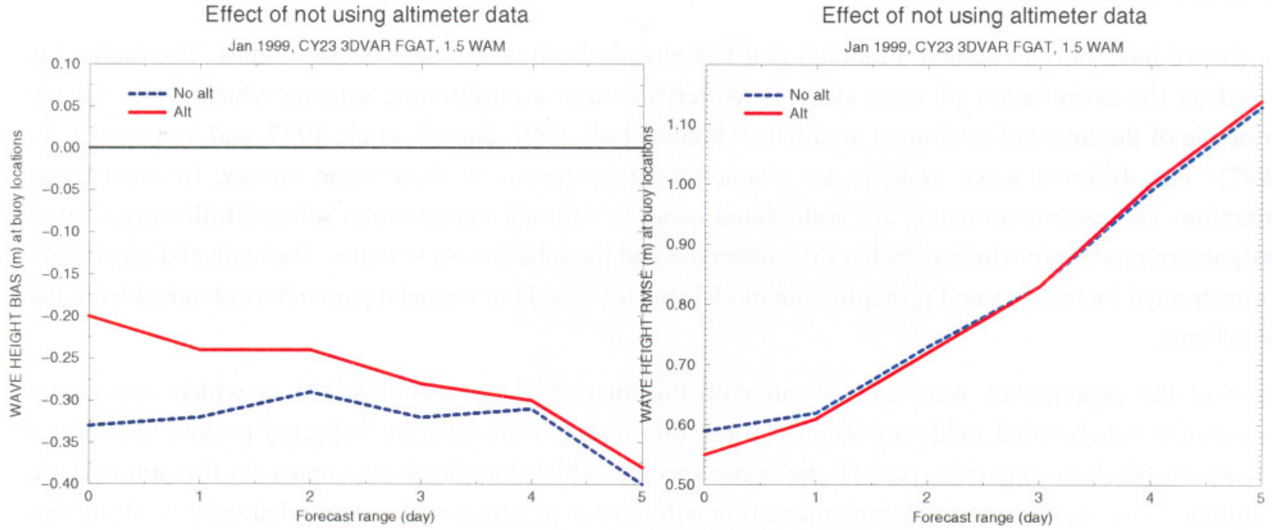

Fig 2: Bias and RMSE for the comparison between buoy wave heights and model analysis and forecasts (up to day 5). The model data were obtained by running the simple 3dvar FGAT system coupled to the 1.5° WAM (12 directions and 24 frequencies) for the month of January 1999.

4. SAR data

Spectra as derived from the ERS-2 SAR wave mode imagettes are processed operationally to retrieve wave spectra using an inversion scheme based on the work done by the Max Plank Institut (MPI) (Hasselmann et al. 1996). A basic monitoring of the data is done and reported to ESA. For example figure 3 presents the comparison between model and SAR equivalent wave heights binned in terms of their periods. The monitoring has indicated the general good quality of the SAR data, therefore, testing on how to make use of the spectral data is currently in progress.

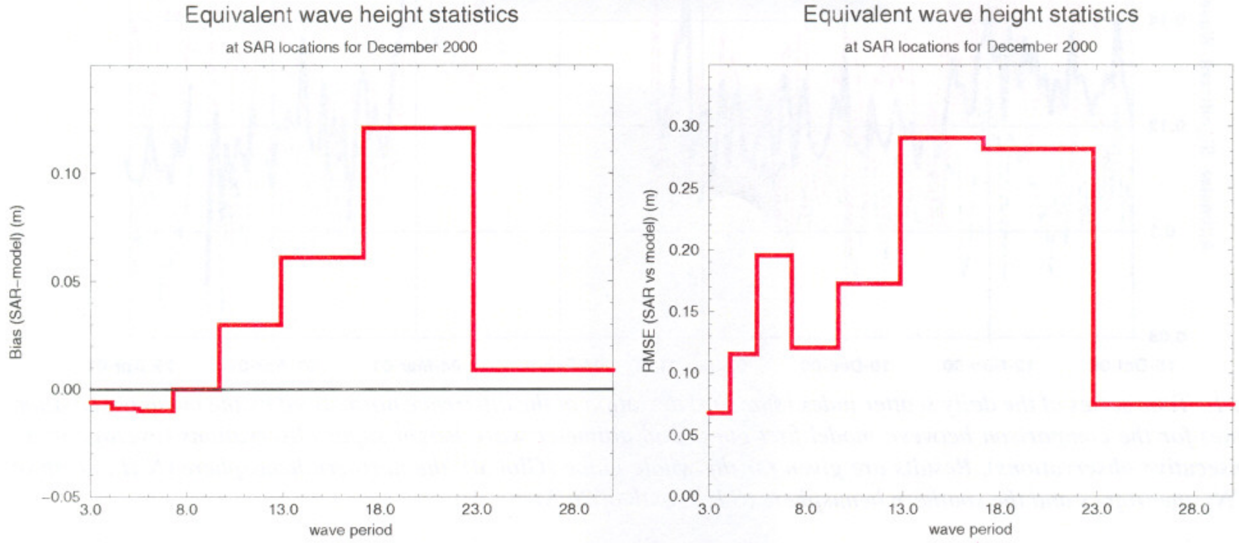

Fig 3: Comparison between model first guess and SAR inverted data in term of integrated binned frequency spectra converted to a wave height equivalent. The binning was done over 3 consecutive WAM frequency bins. The bias (SAR-model) and the RMSE are given as function of the binning periods.

5. SAR data assimilation

So far we have only evaluated a method that has already been tested in previous studies. The method is based on the assimilation of wave systems as derived from a partitioning scheme which works on the principle of the inverted catchment area (Hasselmann et al., 1997, Breivik et al., 1997, and Voorrips et al., 1997). The different wave systems are characterized by means of their mean energy, frequency and direction. The mean parameters are assimilated using an optimal interpolation scheme following a cross assignment procedure which correlates the observed and modelled wave systems. The analyzed spectra are reconstructed by resizing and reshaping the model spectra based on the mean parameters obtained from the OI scheme.

Most of the experiments were carried out with the uncoupled version of WAM in which operational analyzed 6 hourly wind fields are used to force the model. SAR data are expected to have the largest impact on the low frequency part of the wave spectra, which has the least impact on the atmospheric coupling. Nevertheless, the final implementation will have to be tested with the coupled system. Moreover, it will also have to work with altimeter data.

Table 1 summarizes the hindcast results obtained for February 1999. The different experiments are compared to buoy data (analyzed wave heights and peak periods) and the first guess wave height to altimeter data. For more information on buoy data refer to Bidlot et al. (2000) or Janssen et al. (1997). Winds are from the T213 (60km) analysis and 12 directions and 25 frequencies were used to discretise the model spectra as was the case before the operational change in November 2000. A reference run without any data assimilation was performed (NOAS). SAR data were assimilated in another experiment (SARAS) and a run with only altimeter data (ALTAS) was also done.

	NOAS e4cw	SARAS e4g2	ALTAS e4cu	ALTAS SARAS e4ga
BUOY wave height	mean = 1.8 m	7,621 collocations		
BIAS* (m)	-0.43	-0.38	-0.26	-0.26
RMSE (m)	0.70	0.67	0.55	0.56
S.I. (%)	0.19	0.19	0.17	0.17
Altimeter wave height	mean = 2.4 m	134,582 collocations		
BIAS* (m)	-0.10	-0.01	-0.04	-0.02
RMSE (m)	0.45	0.43	0.38	0.38
S.I. (%)	17.7	16.9	14.9	15.1
BUOY peak period	mean = 9.81 s	4,835 collocations		
BIAS* (s)	-0.26	-0.12	0.27	0.27
RMSE (s)	2.01	1.76	1.84	1.82
S.I. (%)	20.4	17.9	18.6	18.4

Table 1 Global wave height and peak period statistics for February 1999, uncoupled 0.5° WAM (12 directions and 25 frequencies) forced by operational archive winds

* Bias is defined as model values minus observations

Table 1 shows that using either set of data improves the global statistics. Altimeter data have the largest beneficial effect on the wave height statistics, whereas the impact of SAR data is mostly on the peak periods. A first attempt at combining altimeter and SAR data was done by calling the altimeter assimilation first followed by SAR assimilation (ALTAS+SARAS). Note that the current data assimilation set-up in WAM is not yet able to assimilate both data sets simultaneously. The results were not very encouraging. As it turns out, we were using SAR wave spectra as derived from the operational inversion. Some information from the operational first guess used in the retrieval might still be contained in the inverted products. The resulting analysis increments displayed many small irregularities (not shown) which might be attributed to differences between hindcast and operational spectra for the part not resolved by the SAR data. As we have mentioned above, the wave model assimilation when coupled to the atmospheric model will be performed during the trajectory calculation in order to get the best wind estimates to determine the first guess. It is therefore sensible to test whether the SAR inversion could be done within the wave model run such that the best available spectral estimate is used. Moreover, it is realized that some information from the first guess always get through the inverted spectra. It is thus preferable to invert the SAR data using the actual analysis first guess. WAM has therefore been modified to also include the SAR inversion software which is called just before the analysis calculation. The resulting analysis increments are smoother (not shown) and the global statistics are better.

A second period was studied with the increased wave spectral resolution and winds from the T511 analysis. Table 2 shows the same global statistics as in the previous case but for May 2001. Note that for this group of tests the SAR inversion is always performed within WAM with the analysis first guess (i.e. before any assimilation). We encountered difficulties with the partitioning scheme due to the increased spectral resolution. At the end, better results were obtained when both SAR retrieved and modelled spectra were smoothed out. Furthermore, it was found that the SAR data assimilation should only be performed for wave systems which are longer than the cut-off wave length as determined by the SAR inversion. The hindcast results confirm that using both data set has a positive impact, however small for wave heights when SAR data are added. Figure 4 displays the monthly mean wave height difference when SAR data are added. Some large pattern can be recognized, indicating that SAR data assimilation can have some impact.

	NOAS e7aw	**SARIN + SARAS e8bf**	**ALTAS e8c5**	**SARIN + SARAS + ALTAS e87h**
BUOY wave height	mean = 1.63 m	8,526 collocations		
BIAS* (m)	-0.03	-0.06	-0.03	-0.03
RMSE (m)	0.38	0.36	0.31	0.31
S.I. (%)	23.4	21.5	18.9	18.8
Altimeter wave height	mean=2.52 m	128,611 collocations		
BIAS* (m)	-0.05	-0.08	-0.01	-0.02
RMSE (m)	0.40	0.38	0.34	0.34
S.I. (%)	15.8	15.5	13.6	13.5
BUOY peak period	mean = 8.75 s	5,309 collocations		
BIAS* (s)	1.26	0.40	0.54	0.35
RMSE (s)	3.23	2.21	2.14	1.93
S.I. (%)	34.0	24.8	23.6	21.7

Table 2 Global wave height and peak period statistics for May 2001, 0.5° WAM uncoupled (24 directions and 30 frequencies) forced by operational archive winds. SAR data inverted in WAM

* Bias is defined as model values minus observation.

As a first attempt at differentiating the impact of SAR assimilation on the different spectral components, we have processed frequency spectra obtained from the National Oceanographic Data Center web pages (http://www.nodc.noaa.gov/). Hourly buoy spectra were averaged in 4 hour time windows around the main synoptic times for which WAM spectra were also produced. The information contained in the 1-D spectra was reduced by integrating over frequency intervals corresponding to 3 consecutive WAM frequency bins. The binned equivalent wave heights from the buoys and the model are compared in figure 5. The comparison indicates the SAR data have some beneficial effect around the 10 to 21 second swell.

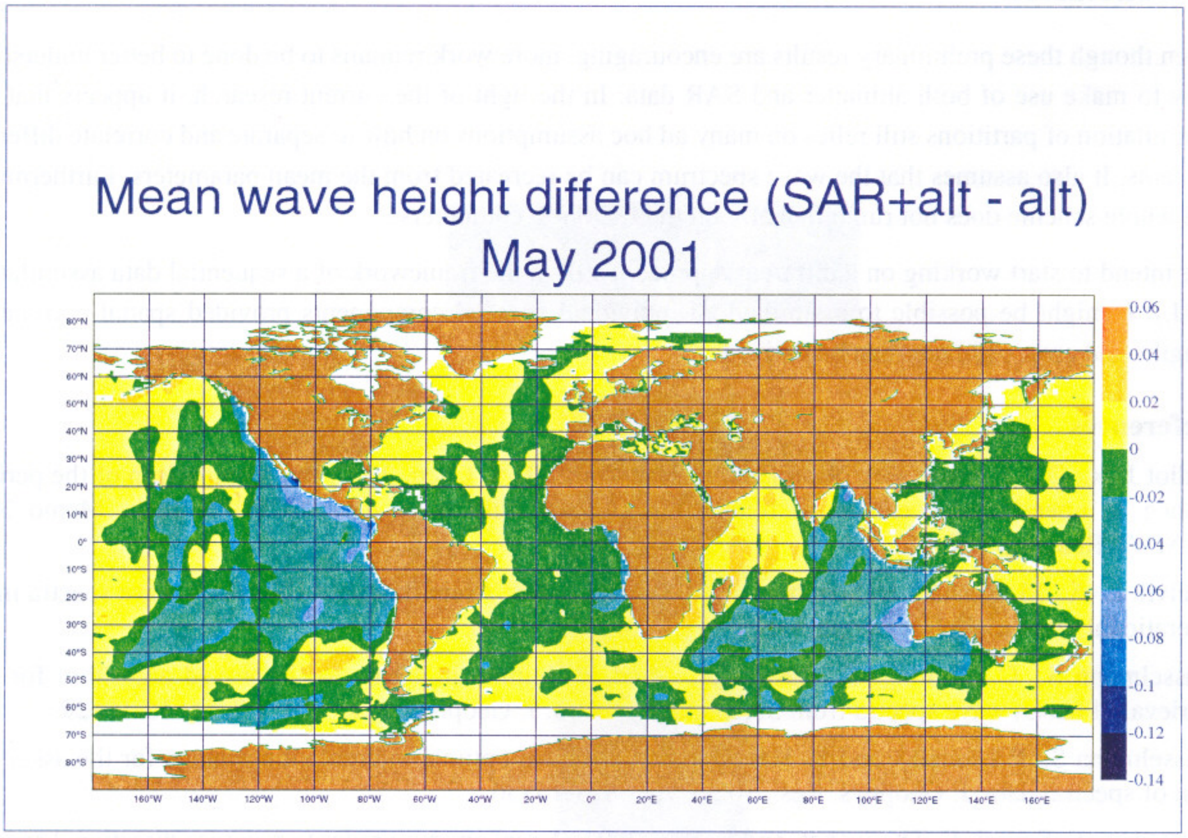

Fig 4: Mean wave height difference between a run which assimilate altimeter and SAR data and a run which only had altimeter data. Both hindcasts were made with the uncoupled WAM (0.5° 24x30).

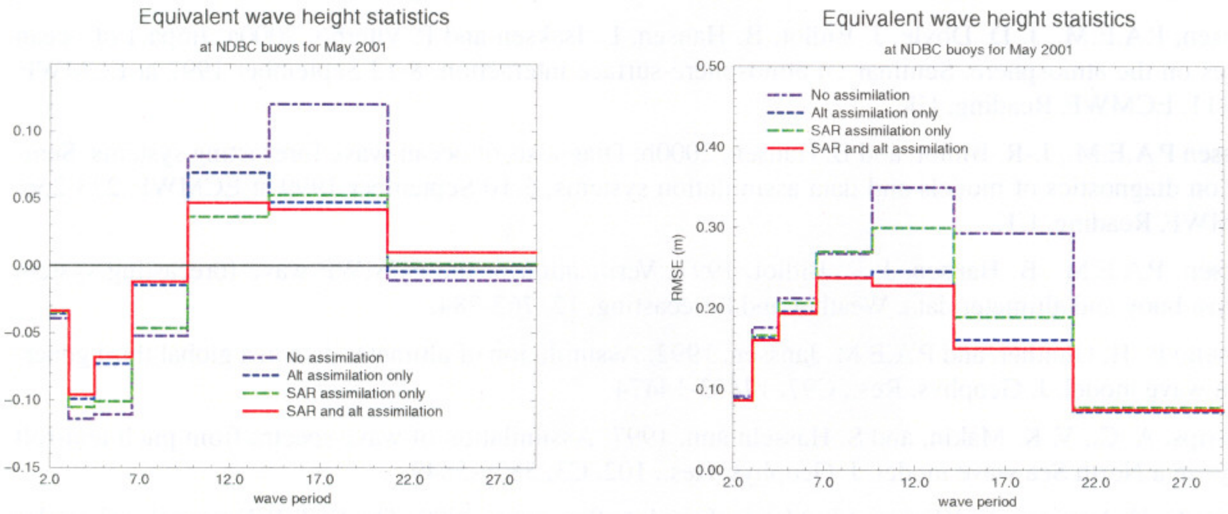

Fig 5: Comparison between model analysis and buoy data in term of integrated binned frequency spectra converted to a wave height equivalent. The binning was done over 4 consecutive WAM frequency bins. The bias (model-buoy) and the RMSE are given in function of the binning periods. Buoy spectral data were obtained from the American network only (refer to the National Data Buoy Center, http://seaboard.ndbc.noaa.gov/).

6. Conclusion

Even though these preliminary results are encouraging, more work remains to be done to better understand how to make use of both altimeter and SAR data. In the light of the current research, it appears that the assimilation of partitions still relies on many ad hoc assumptions on how to separate and correlate different systems. It also assumes that the wave spectrum can be recreated from the mean parameters. Furthermore, the whole scheme does not run efficiently on the ECMWF computers.

We intend to start working on a different approach, still in the framework of a sequential data assimilation (O.I.). It might be possible to assimilate all individual spectral components provided spatial correlation lengths and error estimates can be derived.

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