Assimilation of directional wave spectra in the wave model WAM: an impact study from synthetic observations

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ABSTRACT

In the framework of proposed satellite mission SWIMSAT (Surface Waves Investigation and Monitoring from SATellite) to the European Space Agency, an assimilation scheme has been implemented in the WAve Model (WAM) in order to estimate the impact of the spectral information on the wave prediction. A sequential method based on the optimum interpolation and the "partitioning" concept, is used. The synthetic wave spectra are located along a SWIMSAT orbit track and they are assimilated in a 4 days period simulation. The results show at first that the impact on the wave height, which is significant during the assimilation period, continues in the forecast period for more than 5 days. Secondly, good corrections of the wave frequency and direction is also observed in both analysis and forecast period. The dependence of the scheme performance with the radius of influence and the correlation length is analysed by considering several combinations of these parameters. Statistical analysis on wave parameters is developed to clearly show the contribution of the assimilation of spectral information comparing to the assimilation of the significant wave height only (altimeter case) and its benefits on the impact.

KEY WORDS: Assimilation, wave model, spectral information, SWIMSAT, assimilation index, analysis, forecast, sea state

1- INTRODUCTION

One of the best approaches to extrapolate the information about the sea state from observations is the one, which consists in assimilating this information in numerical wave models. Until now, most of meteorological services, which are operating numerical wave models, are using satellite information restricted to the significant wave height (altimeter data). It has been established that this yields to an improvement in the wave height prediction (Lionello and Janssen, 1992, Le Meur et al. 1995). Recently main research orientation in wave modelling is focused on taking into account all the spectral information of the wave spectrum in the assimilation scheme. This permits on one hand a better description of the sea state especially in severe storms conditions, and on the other one a better understanding of the physics of wave models. Here, a simple assimilation scheme such as a sequential method based on Optimal Interpolation (OI) is preferred to more advanced one using the wave model dynamics (variational technique), because of less time consuming and because advanced developments have been already performed. Hasselmann et al. (1994, 1996) developed an assimilation scheme based on optimum interpolation and on the partitioning concept, which reduces the number of elements in the wave spectra. Voorrips et al. (1996) implemented this assimilation scheme to the North Sea and applied it for buoys data. They show that the main improvement in the correction of wave parameters is obtained for the swell cases and in particular for low frequency wave height. The use of other data source such as SAR wave spectra has been studied for local applications by Breivik et al. (1998) for the North Sea; and Dunlap et al. (1998) for the North Atlantic area, in severe storms where a wave height of 14 m was recorded. The fact that the products inverted from the SAR data in these studies depend on an external information (wave model first guess), associated with a relatively low sampling (one SAR spectra every 200 km along the satellite track), can explain the small assimilation impact found in the above studies. Considering an alternative or complementary data sources can reduce these kinds of limitations.

Surface Waves Investigation and Monitoring from SATellite, which is referred to as SWIMSAT, is innovative for measuring the directional spectra of waves from space using real-aperture radar with a low-incidence beam (0-10°) scanning in azimuth (0-360°) (Hauser et al. 2001). This will allow measuring the directional spectra of ocean waves along the track at scales ranging from 50x50 km to 90x90 km. Moreover the inverted wave product should provide a minimum detectable wavelength of about 70 m instead of 200 m for SAR, a resolution in direction of 15° after the averaging process is applied, whereas resolution in wavelength is about 10 to 20% of the wavelength.

The goal of this study is on one hand to develop an assimilation system able to use SWIMSAT spectral information in wave models, and on the other hand to evaluate its impact in analysis and forecast periods. Furthermore, the assimilation of spectral information is compared to the assimilation of significant wave height only, which is the case of altimeter data. In section 2, we present a brief description of the methodology of assimilation schemes and the corresponding simulation runs. The results are discussed for different case studies in section 3. Finally in section 4 conclusions and future works are presented.

2- METHODOLOGY

2.1- WAVE MODEL

In this study we used the wave model WAM cycle 4, which is a third generation wave model. Let us recall that the wave model integrates explicitly the wave action equation. The physics of the model consists in expressing the spatial and temporal variation of the wave energy spectrum with the external forces of the dynamic system. These forces can induce the generation and the dissipation of the waves through wind input, white capping dissipation, energy transfer induced by non-linear quadruplet interactions and bottom dissipation (for more details see Gunther et al. (1992), Komen et al. (1994)). The wave model WAM cycle 4 was implemented for the global scale with a resolution of 1x1 degrees in latitude and longitude. The wave spectrum was discretized in 24 directions and 25 frequencies ranging from 0.04 to 0.41 Hz.

2-2 ASSIMILATION SCHEME

The scheme is based on a sequential assimilation method. It uses the wave model forecast at a certain time at which observations are available and it combines the model state at that time (first guess or background field) with the observations to compute an analyzed model state.

This latter is used as an initial condition for a new model run until a new observation is processed. The observations, which are in our case the directional spectra, are assimilated simultaneously in multi-time level scheme, which means that all observations available over a certain period called "assimilation window" of typically 3 or 6 hours are used at the time of assimilation. The assimilation scheme, which is an adaptation of the scheme developed by Voorrips (1997), is based on Optimum Interpolation (OI) and on the partitioning concept. The optimum interpolation consists first in computing the model forecast, which is interpolated to the observation locations. If they are different, then the differences between the first guess and the observation are computed and called "innovations" or observational increments. The analysis parameter is therefore obtained by adding the innovation to the first guess with weights that are determined based on the estimated statistical error covariances of the forecast and the observation. Consequently, the optimal analysed mean wave parameters can be expressed as follows:

$$X^a = X^f + \sum_i^N W_i \, (X_i^{\,o} - HX_i^{\,f}) \qquad (1)$$

Where X^a and X^f represent the analysed and first-guess mean wave parameters (energy, wave number) at every model grid points, respectively. Upper index o (resp. f) stands for observations (resp. first-guess, while N is the number of observations affecting for a given model grid point. H is the observation operator that performs the necessary transformation from model space to observation space. The weights assigned to the observations are chosen as follows:

$$W = PH^T \left\lfloor HPH^T + R \right\rfloor \qquad (2)$$

Where P and R are respectively the forecast and the observation error covariance matrices. By assuming a correlation model of a simple gaussian form, P and R are expressed as follows:

$$P = s_i^{\,f} s_j^{\,f} \exp\left(-\left(\frac{d_{ij}}{l_c} \right)^{1.5} \right) \qquad (3)$$

$$R = s_o^{\,2} \qquad (4)$$

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. To express the standard deviation σ

indicated in the Eqs (3-4), Voorrips et al. (1996) assumed that the observations errors and the corresponding model forecast errors are unbiased and uncorrelated. After analysing a two-year data set in the North Sea, they obtained the following empirical relation, which depends on the mean wave energy E (mean over the total spectrum):

$$s_f = s_o = 0.02 + 0.35E \quad (5)$$

In practice, in order to avoid errors induced by a bad conditioning of covariance matrix, we computed this latter for every boxes, where each one contains a limited number of observation and affected grid points.

To reduce the complexity of the problem, while considering 2D spectral information, Hasselmann et al. (1994), proposed to assimilate particular mean parameters (energy, frequency, direction) of all separate wave systems, which are classified and can be identified in observed and modelled wave spectra. For this, the concept of "spectral partitioning" was developed. It consists in decomposing the wave spectrum in a few distinct wave trains, which correspond to the various peaks in the spectrum. They represent independent wave systems associated to a certain meteorological event (for example swell generated by storms or wind waves generated by local strong wind). Each partition is characterized by its mean parameters (energy, direction, frequency). The most difficult part of the assimilation scheme is the cross assignment of each partition of observed wave spectrum to the equivalent partition of first guess wave spectrum. To this aim, a criterion given by Hasselmann et al. (1997) is used. It consists in computing a “normalized” distance in the spectral space (k_x, k_y) between the mean wave numbers of partitions, we write:

$$d = \frac{\left(\overline{k}_x^1 - \overline{k}_x^2\right)^2 + \left(\overline{k}_y^1 - \overline{k}_y^2\right)^2}{\left(\overline{k}_x^{1\,2} + \overline{k}_x^{2\,2}\right) + \left(\overline{k}_y^{1\,2} + \overline{k}_y^{2\,2}\right)} \qquad (6)$$

Where subscripts 1 and 2 refer to model and observation partitions, respectively, while the over line means the mean value over the wave system (partition). If the estimated distance is less than an assumed threshold value then the partitions are cross-assigned and they are ready for the optimal interpolation (OI) procedure, otherwise the first guess wave train remains unchanged. The smallest is this threshold value, the largest is the selection of partitions, and then more partitions are rejected.

In order to reconstruct the analysed wave spectrum, the first guess partitions are rotated and stretched to match the mean energy, mean direction and mean frequency of the analysed partitions. Then, the partitions are superimposed to derive a combined wave spectrum. To eliminate gaps between the partitions a bi-parabolic interpolation is applied. For wind sea partitions the driving wind velocity is corrected by using empirical relations obtained from growth curve relations (Lionello and Janssen (1992), Voorrips et al. (1996)).

2-3 ASSIMILATION OF WAVE HEIGHT ONLY

To estimate the effect of using spectral information, it is necessary to make a comparison with the assimilation of wave height only, as for altimeter data. In this case we don't need a partitioning concept and the assimilation scheme, which is developed by Lionnello et al.(1991), consists in applying an optimal interpolation on the significant wave heights and the stress at the sea surface (from wind speed at 10 m). After separation between Wind Sea and swell, the analysed field for the wave height and the friction velocity is used to produce an analysed wind sea spectrum. Then an analysed spectrum can be written as follows:

$$F^a(f,q) = AF^b(Bf,q) \qquad (7)$$

Where a and b stand for analysed and first guess, while f and θ stand for frequency and direction of waves. The parameters A and B are obtained by using empirical power laws for a growing wind sea spectrum, which takes into account analysed and first guess wave energy and mean wave frequency (Hasselmann et al (1997)).

2-4 CASE STUDIES

The algorithms presented here above have been tested with synthetic wave spectra. First, the simulation consisted in running the wave model without assimilation driven by analysed wind fields from the ECMWF atmospheric model. The obtained directional wave spectra at the observation locations were stored and considered as synthetic SWIMSAT wave spectra. The corresponding wave parameters are called the "truth" and are taken as observed parameters. Secondly the wind fields have been disturbed to generate a new wave field. This was achieved by using wind fields corresponding to the forecast of several days before (4 days), instead of the last analysis and a random error was added in order to get uncorrelated observation errors. Assimilation of the synthetic SWIMSAT data was then applied to the wave field from wave model driven by disturbed wind fields.

By comparing disturbed and analysed wind fields, we can estimate how strong is the perturbation of wind fields over the global domain. Figure 1 shows the variation of the root mean square (RMS) of wind speeds with time. It is easy to remark that RMS values for disturbed wind fields with random error are of about 3 m/s, while they are of about 2.5 m/s for the case without random error. In general, the RMS error in ECMWF winds is typically 1.5 m/s, so then the error introduced in the waves by disturbed winds is totally realistic.

The assimilation run is performed in several steps. At first, we run the wave model WAM for three days to get a well-developed sea state. Thereafter, the assimilation is started for a period of 4 days, from October 22, 2000 until October 26, 2000 at 0:00. After this date a forecast period is considered to evaluate the effect of assimilation with time. The assimilation time step is of 3 hours and the observation locations follow an orbit track for SWIMSAT chosen here with a repeat cycle of approximately 17 days. Here below, table 1 indicates the performed runs, which will be discussed in the following sections. The radius of influence and the correlation length used in runs 3 and 4 are respectively 600 and 250 km. The threshold cross-assignment parameter considered in run 3 is taken equal to 8. Tests were also performed with a different correlation length (Run 5) or a different cross-assignement threshold (Run 6).

3- RESULTS

To assess the impact of synthetic SWIMSAT data on wave parameters in analysis and forecast periods, we compared model outputs from different runs mentioned in table 1. Two impacts are indicated in order to have relevant description of the assimilation results. The first one consists in comparing model outputs from runs 2, 3 and 4 to observed parameters obtained from run 1 (truth). This impact evaluates the efficiency of the assimilation schemes and shows whether the use of spectral information gives better performance than the assimilation of wave height only. The second impact is based on a comparison between model outputs with and without assimilation (runs 3 and 4 compared to run 2). This gives information about the improvement induced by the assimilation.

In the following sections, we first analyse the results during the analysis period and then, discussions are developed for results obtained after stopping the assimilation. Also statistical analysis presented at the end of this section for both periods provides a way to estimate the effect of assimilation in various conditions.

3-1 ANALYSIS PERIOD

During the period of assimilation (4 days), the impact illustrated in figure 2a (difference between runs 3 and 2) is significant and in some cases exceeds 2 meters. Figure 2a also shows that the analysed wave field "keeps memory" of the previous assimilations and most of the largest impacts are located in the southern hemisphere for the latitude bands 40^o to 60^oS, where high winds are dominant. The efficiency of the assimilation scheme is well observed in figure 3a, where the runs with and without assimilation (Runs 2 and 3) are compared to the observations in the analysis period (Run 1). This shows that the correlation between analysed and observed significant wave heights (calculated for the model grid points affected by the observations) is well improved after the assimilation, and it is close to 1. However we point out that first guess wave height is of already good quality (mean correlation is of about 0.8).

In addition, the strong impact of the assimilation is observed on the mean wave period of the total spectrum where it reaches more than 5 seconds in the latitude bands 40^o to 60^{o}S and 20^o to 50^{o}N in the pacific ocean, as shown in figure 4a.

The benefit of assimilating spectral information instead of significant wave height only is shown by comparing figure 2a and 2 b: an higher impact on significant wave height is obtained with the assimilation of synthetic wave spectra compared to the assimilation of wave height only. Furthermore, in the case of spectral information (run 3), there is a more important spread of the correction on wave parameters over the whole domain.

3-2 FORECAST PERIOD

During the forecast period, the impact of the assimilation on the significant wave height remains quite significant (Figure 5a, 5c, and 4b: 2 days after the assimilation period it reaches more than 0.8 m in the mid-east pacific at latitude bands 20^{o}N to 20^{o}S, while in northern hemisphere it is less than 0.3 m (Fig. 5a). This impact decreases progressively in the forecast period until it reaches about 0.5 m at latitude bands 20^{o}N to 60^{o}S in east pacific, 5 days after the end of assimilation (Fig. 5c).

This trend is also observed for the wave period: 2 days after the assimilation period the impact reaches more than 2 seconds, as illustrated in figure 4b. For the chosen period of analysis, the largest impact of assimilation is found in the inter-tropical region.

The comparison between figure 5a and fig. 5b shows that the spectral information increases the impact on wave heights and consequently corrects much better the sea state. The decay of the impact with time is faster for the assimilation of the significant wave height only than the assimilation using spectral information.

3-3 STASTICAL ANALYSES

To analyse more qualitatively the assimilation results, statistical parameters over all grid points have been computed during the analysis and the forecast periods. As wave parameters describing the sea state, we considered significant wave height, mean wave frequency and mean wave direction. Also, we added another parameter, which is the low frequency swell wave height. This latter is defined as the wave height of wave spectrum limited in frequency and can be obtained by the following relation:

$$H_{10} = 4\sqrt{\int_{f_1}^{f_{10}} E(f)df} \qquad (8)$$

Where E(f) is the density of wave energy, while f_1 and f_{10} are respectively the first value in the frequency interval of the wave spectrum (f_1=0.044 Hz) and the cut-off frequency (f_{10}=0.1 Hz).

This parameter was defined to focus on the impact on swell wave height, which has a correlation time larger than wind-sea wave height and which is the effective parameter that can be deduced from most of remote sensing measurements systems.

The following index, given by Equation (9) was defined to quantify the skill of the assimilation process:

$$IA = \frac{RMSN - RMSA}{RMSN} * 100(\%) \qquad (9)$$

Where RMSN is the root mean square of the difference between the synthetic observed wave parameters and the wave parameters obtained without assimilation. While RMSA is the root mean square of the difference between the synthetic observed wave parameters and the wave parameters obtained with assimilation. More the assimilation index is close to 100 %; more the analyzed parameters are close to the observations, and then better the assimilation skill is. On the contrary a negative index means that the assimilation deteriorates the first guess.

Figure 6 shows the variation of the assimilation index for all wave parameters mentioned above, in analysis (0 to 4) and forecast (4 to 9) periods. We can easily see that the assimilation index increases in the analysis period and then decreases progressively in the forecast period. Assimilation using spectral information gives better index values for all wave parameters than assimilation of wave height only. The maximum index value for significant wave height, low frequency swell wave height, mean wave frequency and direction are respectively 25, 34, 18 and 8 %, and are located during the analysis period. The highest index value is obtained for low frequency swell (H_{10}); this indicates the relevant use of spectral information for swell characterization. For all plots we compared the assimilation index of runs 3 (assimilation of spectral information) and 4 (assimilation of wave height only). For the significant wave height, there is small difference between index values of Runs 3 and 4 in the forecast period. For low frequency swell wave height and mean wave frequency, the difference between the assimilation indexes is more significant and shows that the assimilation using spectral information stays more efficient than the assimilation of wave height only in the forecast period, as illustrated in figures 6b and 6c.

Figure 6d shows that the assimilation index of mean wave direction for run 4 are negative during both analysis and forecast periods; this indicates that the assimilation of wave height only (altimeter case) deteriorates the first guess estimation of the wave direction. In the contrary, the index values for run 3 are positive and this shows that the use of spectral information improves the estimate of mean wave direction.

The radius of influence and the correlation length used in the computations of error covariances play an important role in the assimilation scheme. For this reason, we performed a run similar to run 3 but with a smaller correlation length of 125 km, and we kept the same radius of influence, which is of 600 km (Run 5). The assimilation index of significant wave height shown in figure 7 indicates that the assimilation efficiency decreases when a smaller correlation length is chosen, with the maximum value of the assimilation index, decreasing from to 25 % for run 3,to 15 % for Run 5. In addition, this significant decrease induced by the use of a smaller correlation length, is also observed in the forecast period.

The impact of the choice of the cross-assignement threshold δ was also tested. As pointed out in section 2.2, a small value of the threshold cross-assignment (δ) parameter induces more rejection of observed partitions. This also reduces the performance of the assimilation scheme, as illustrated in figure 7 (line with circles), where we can see the assimilation index of significant wave height obtained in simulation run same as run 3 but with a threshold value of 1.

In figure 8, we plot the root mean square of significant wave height obtained from runs 2, 3 and 4. We can clearly see that run 3 gives the best reduction of root mean square, in particular during the analysis period. The RMS value is of about 0.9 m for run 2 and it decreases to almost 0.6 m for run 3 in the analysis period. After the end of assimilation RMS values for runs 3 and 4 are close to each other and they increase and tend to RMS values obtained for run 2.

To further assess the impact of assimilation, we computed the standard deviations (STD) for the differences of significant wave heights of runs 3 and 2, and those of runs 4 and 2. This impact on significant wave heights is significantly larger for run 3 than run 4, as illustrated in figure 9. The maximum value of STD is of 0.32 m for run 3, while for run 4 it is of 0.21 m. Moreover, after the end of assimilation the STD values for run 4 decrease more rapidly than those of run 3, and both tend to 0, which indicate the end of assimilation effect.

4- CONCLUDING REMARKS

Algorithms for the assimilation of spectral data in the WAM model have been tested successfully and have shown the benefits of using spectral synthetic data promising for SWIMSAT. A strong impact on the mean wave parameters after the assimilation was observed; moreover it was found that the contribution of spectral information induces a better correction of the sea state than the altimeter data assimilation in the analysis and forecast periods. These improvements have been clearly shown by the statistical analysis and give a considerable benefit to get a better description of the swell characteristics. An optimised combination between parameters influencing the optimal interpolation was obtained after testing several cases.

Future works will be focused on the improvement of the performance of the assimilation scheme. In particular, the correlation functions associated with the model will be evaluated, and the dependence between the correlation length and the wave frequency will be taken into account; indeed low frequency waves (swell) must be correlated over a larger area than high frequency waves (wind-sea). The correlation length can be taken of 1000 km for the swell case as used in the work of Francis and Stratton (1990). Moreover separate statistical analysis for swell and wind-sea is required in order to get more valuable interpretations.

Furthermore the use of more realistic data like those given by the new products of ENVISAT ASAR wave mode is under development and will prepare the operational assimilation system to combine several spectral data source. Also, this will contribute to a better understanding of the physics of numerical wave models.

Finally longer periods of assimilation with real data are needed to study the wave climatology and consequently to improve empirical relations used in the assimilation scheme and in particular the correction of the wind field after finding the analysed sea-state.

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FIGURE CAPTIONS

Figure 1: Root mean square of wind speed (at 10 m above sea surface) time series. Triangles: 4 days forecasted wind fields with added random error; circles: 4 days forecasted wind fields without random error.

Figure 2: Difference in meters of significant wave heights between runs with and without assimilation on October 23 at 0:00 (after 1 day in the analysis period); radius of influence, correlation length and threshold distance are respectively 600 km, 250 km and 8; the (+) black line is the synthetic observation locations with an assimilation time window of 3 hours; (a): assimilation of synthetic wave spectra; (b) assimilation of wave height only (altimeter case).

Figure 3: Correlation between analysed and observed significant wave heights in the assimilation period; the radius of influence, the correlation length and the threshold distance

are respectively 600 km, 250 km and 8; (circles) without assimilation; (triangles) with assimilation of wave spectra.

Figure 4: Difference in seconds of the mean wave period between runs with and without assimilation of synthetic SWIMSAT data; the (+) black line is the SWIMSAT orbit track for an assimilation window of 3 hours; radius of influence, correlation length and threshold distance are respectively 600 km, 250 km and 8; (a): on October 23 at 0:00 (after 1 day in the analysis period); (b): on October 28 at 0:00 (after 2 days in the forecast period).

Figure 5: Difference in meters of the significant wave heights for the runs with and without assimilation in the forecast period; the radius of influence, the correlation length and the threshold distance are respectively of 600 km, 250 km and 8 (a): on October 28 at 0:00, i.e. 2 days after the end of assimilation; (b): same as (a) but assimilation with wave height only information (altimeter; run 4); (c) same as (a) but for October 31, at 0:00, i.e. 5 days after the end of assimilation.

Figure 6: Variation of the assimilation index in analysis (0 to 4) and forecast (4 to 9) periods. (a) For significant wave height; (b) for low frequency swell; (c) for mean wave frequency; (d) for mean wave direction; triangles: assimilation with spectral information (run 3); circles: assimilation with wave height only (altimeter, run 4); squares: same as in run 3 but with small correlation length of 125 km (run 5).

Figure 7: Variation of the assimilation index of significant wave heights in analysis (0 to 4)

and forecast (4 to 9) periods. Triangles: assimilation with spectral information (run 3); circles: same as in run 3 but with threshold value δ equal to 1 (run 6); squares: same as in run 3 but with small correlation length of 125 km (run 5).

Figure 8: Variation of the root mean square of significant wave height in analysis (0 to 4) and forecast (4 to 9) periods. Triangles: assimilation with spectral information (run 3); circles: assimilation with wave height only (run 4); squares: without assimilation (run 2). The end of assimilation is on day 4, which corresponds to October 26, 2000 at 0:00.

Figure 9: variation of the standard deviation of significant wave heights with and without assimilation, in analysis (0 to 4) and forecast (4 to 9) periods. Triangles: assimilation with spectral information (run 3); circles: assimilation of wave height only (run 4).

TABLE CAPTIONS

Table 1: description of the performed runs

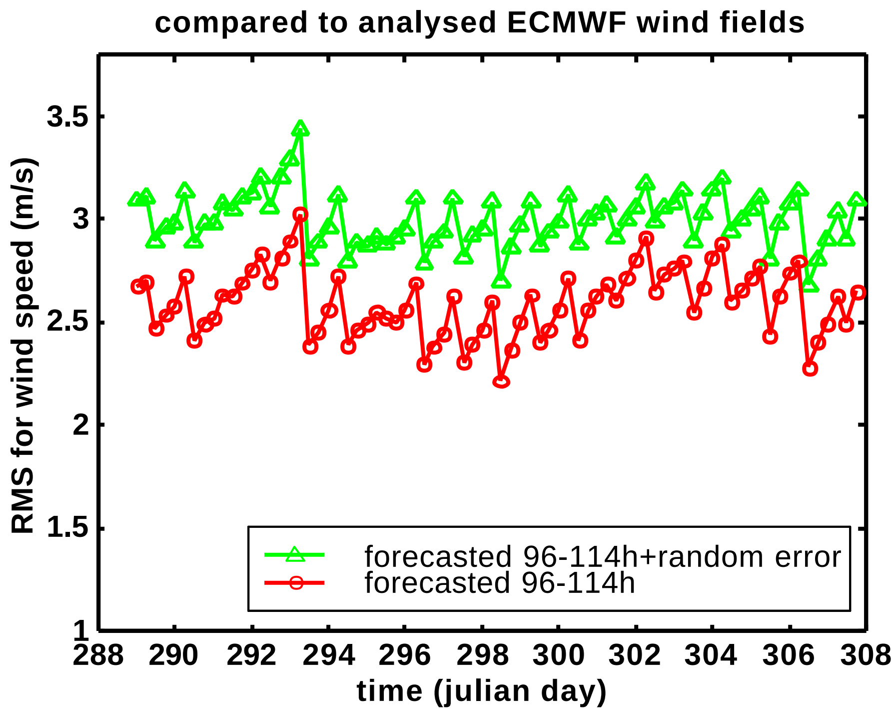
compared to analysed ECMWF wind fields
RMS for wind speed (m/s)
3.5
3
2.5
2
1.5
1
288
290
292
294
296
298
300
302
304
306
308
time (julian day)
forecasted 96-114h+random error
forecasted 96-114h

FIG. 1

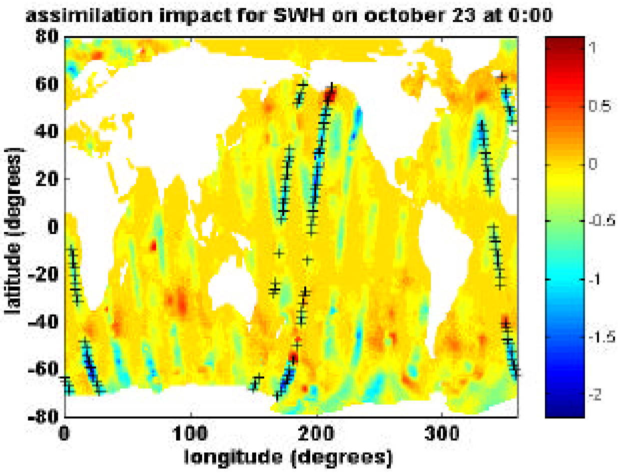
assimilation impact for SWH on october 23 at 0:00
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
1
0.5
0
-0.5
-1
-1.5
-2

FIG. 2a

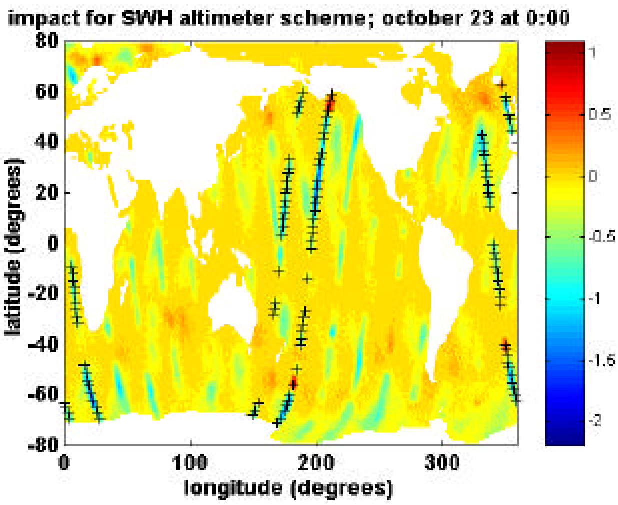
impact for SWH altimeter scheme; october 23 at 0:00
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
1
0.5
0
-0.5
-1
-1.5
-2

FIG. 2b

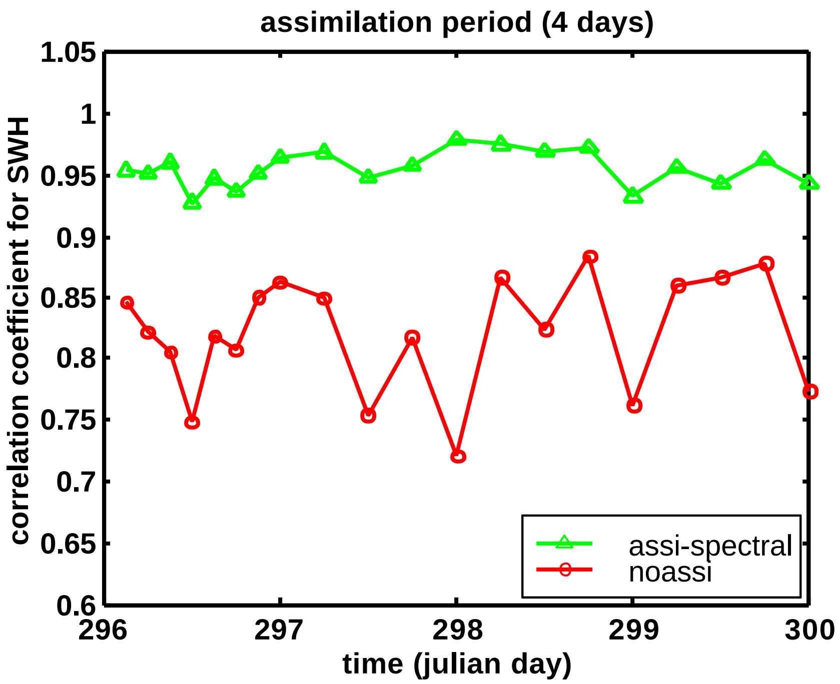
assimilation period (4 days)
correlation coefficient for SWH
time (julian day)
assi-spectral
noassi
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
296
297
298
299
300

FIG. 3

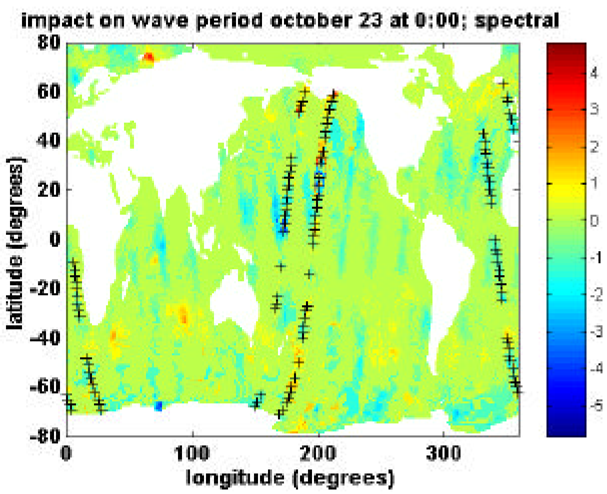
impact on wave period october 23 at 0:00; spectral
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
4
3
2
1
0
-1
-2
-3
-4
-5

FIG. 4a

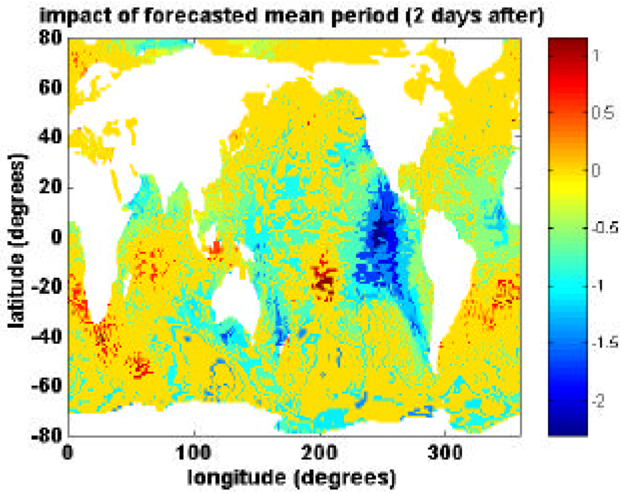
impact of forecasted mean period (2 days after)
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
1
0.5
0
-0.5
-1
-1.5
-2

FIG. 4b

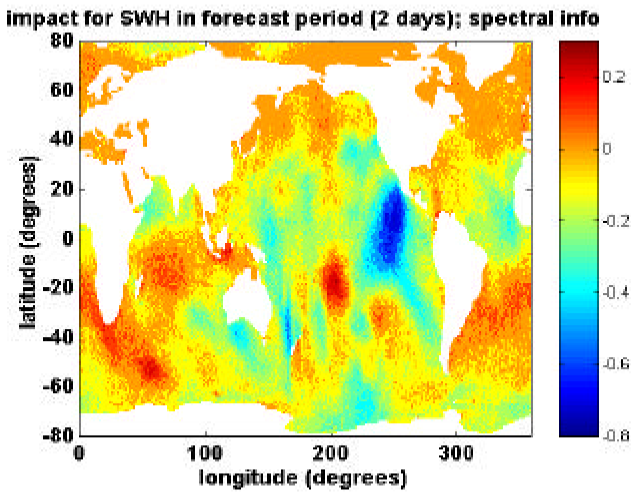
impact for SWH in forecast period (2 days); spectral info
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
0.2
0
-0.2
-0.4
-0.6
-0.8

FIG. 5a

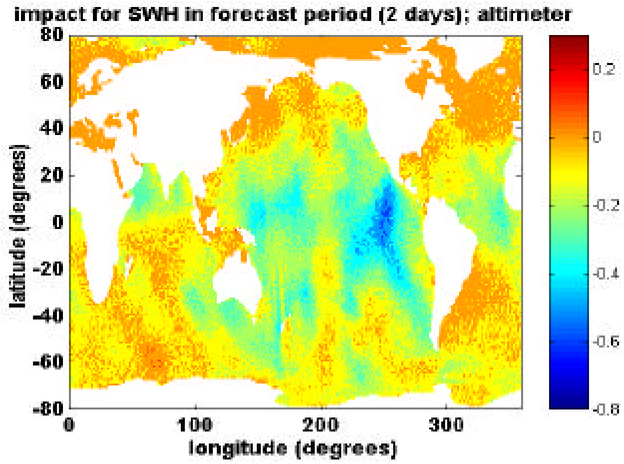
impact for SWH in forecast period (2 days); altimeter
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
0.2
0
-0.2
-0.4
-0.6
-0.8

FIG. 5b

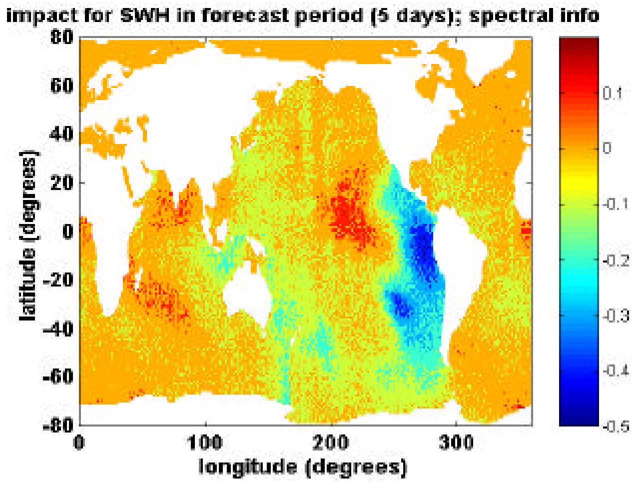
impact for SWH in forecast period (5 days); spectral info
latitude (degrees)
longitude (degrees)
80
60
40
20
0
-20
-40
-60
-80
0
100
200
300
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5

FIG. 5c

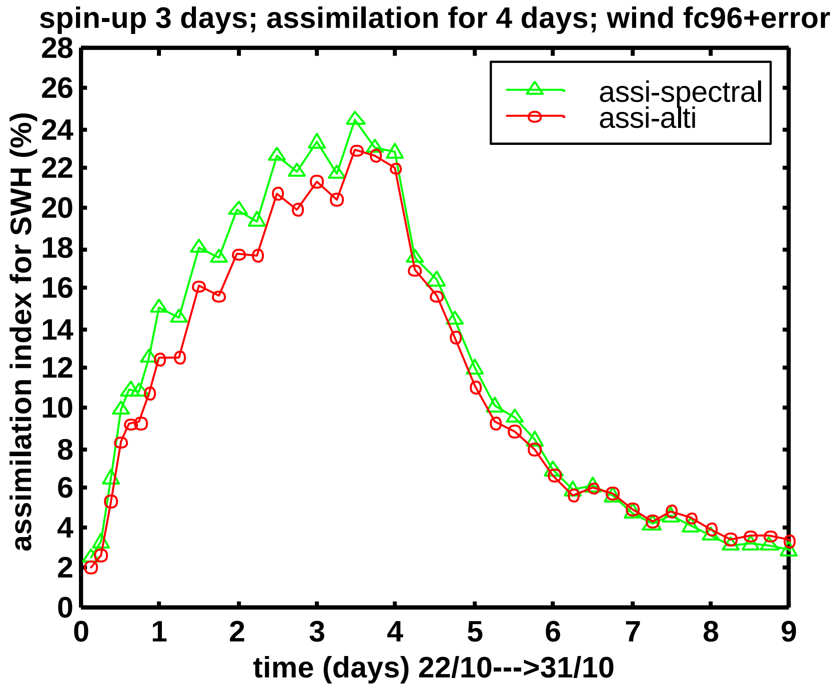
spin-up 3 days; assimilation for 4 days; wind fc96+error
assi-spectral
assi-alti
assimilation index for SWH (%)
time (days) 22/10--->31/10

FIG. 6a

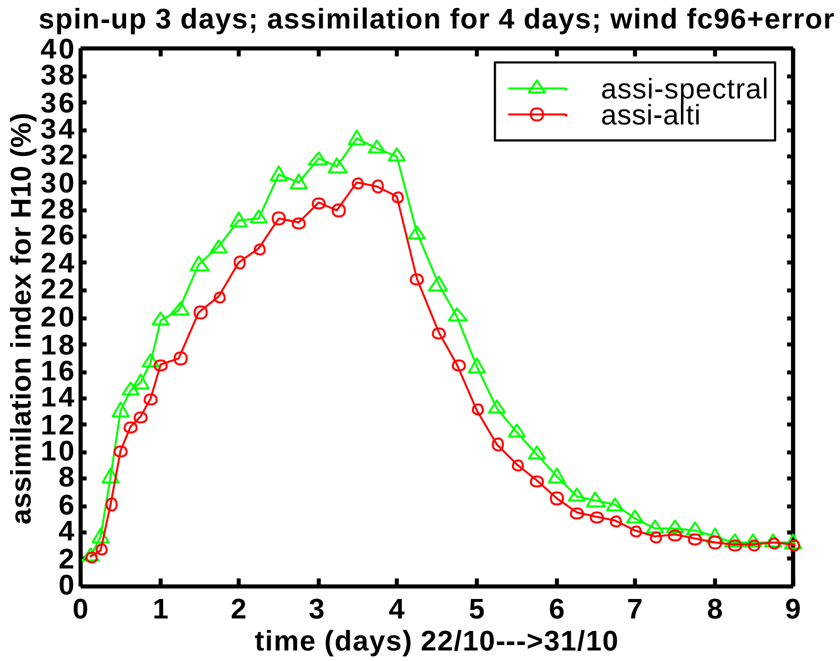
spin-up 3 days; assimilation for 4 days; wind fc96+error
assi-spectral
assi-alti
assimilation index for H10 (%)
time (days) 22/10--->31/10

FIG. 6b

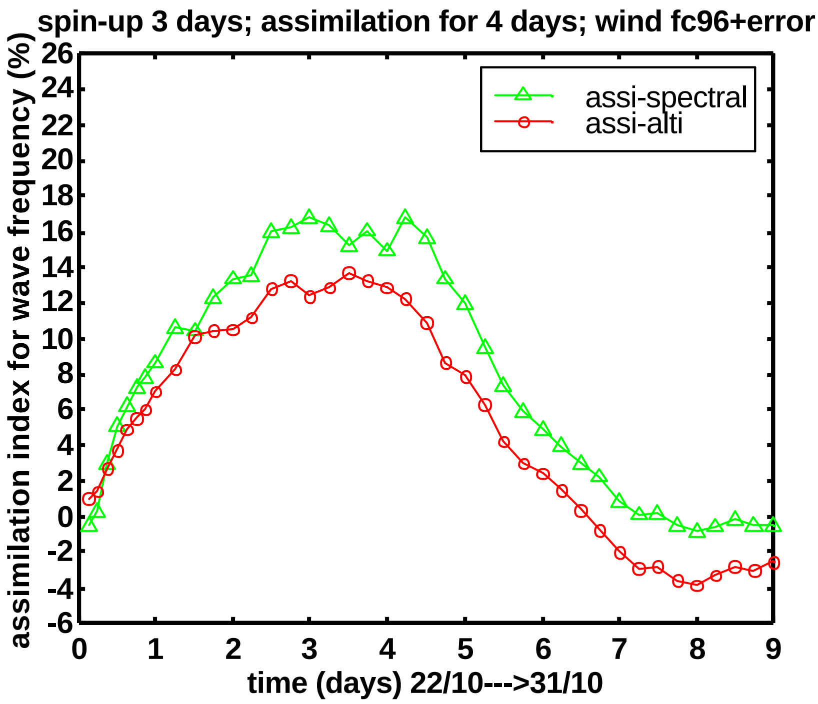
spin-up 3 days; assimilation for 4 days; wind fc96+error
assimilation index for wave frequency (%)
time (days) 22/10--->31/10
assi-spectral
assi-alti

FIG. 6c

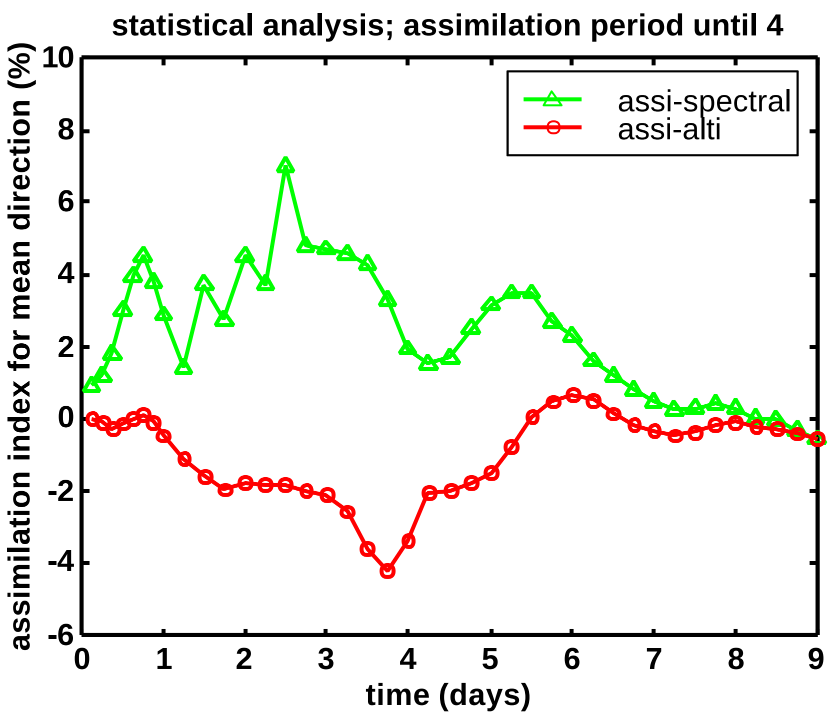
statistical analysis; assimilation period until 4
assimilation index for mean direction (%)
time (days)
assi-spectral
assi-alti

FIG. 6d

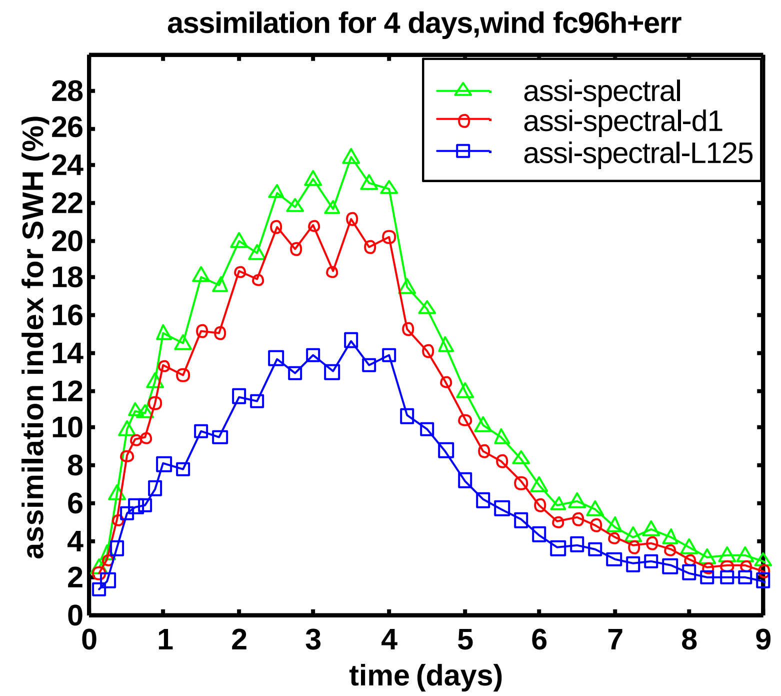
assimilation for 4 days,wind fc96h+err
assi-spectral
assi-spectral-d1
assi-spectral-L125
assimilation index for SWH (%)
time (days)

FIG. 7

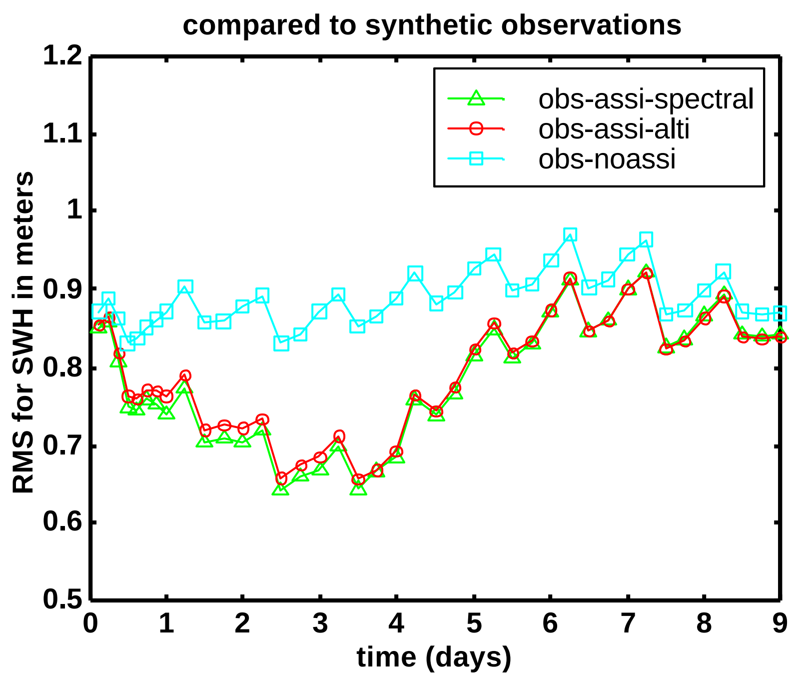
compared to synthetic observations
obs-assi-spectral
obs-assi-alti
obs-noassi
RMS for SWH in meters
time (days)

FIG. 8

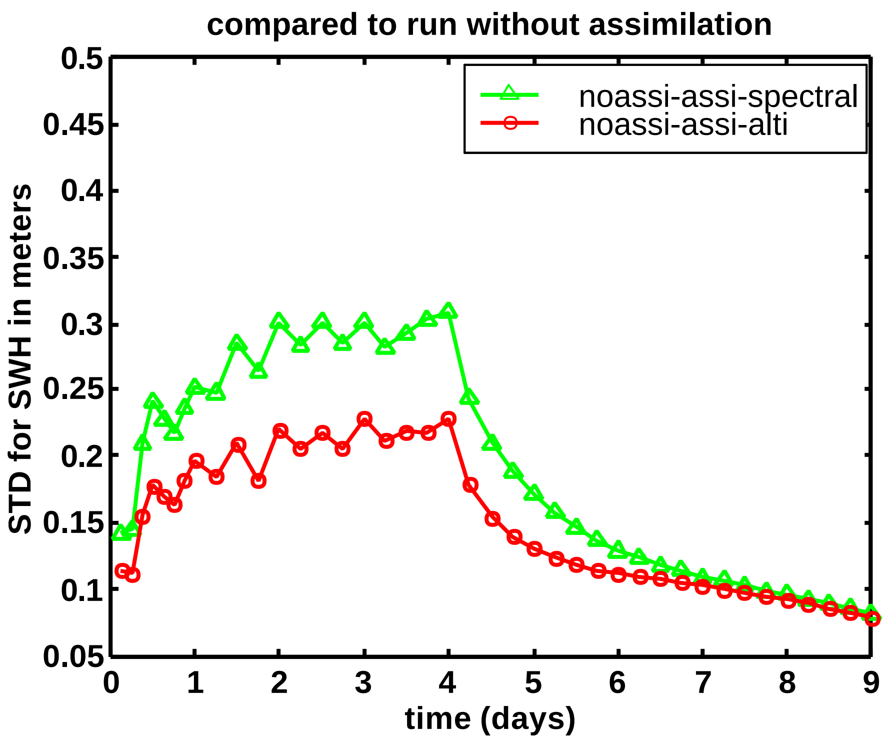
compared to run without assimilation
noassi-assi-spectral
noassi-assi-alti
STD for SWH in meters
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
9
time (days)

FIG. 9

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
	WAM with analysed wind fields (synthetic observations)	WAM with disturbed wind fields (without assimilation)	WAM with assimilation of synthetic wave spectra	WAM with assimilation of wave height only (altimeter case)	Similar to Run 3, but with a different λ parameter	Similar to Run 3, but with a different δ parameter
Correlation length λ			250 km	250 km	125 km	250 km
Threshold value δ for cross-assignement			8		8	1

Table 1