# On the benefit of assimilation of wave spectra retrieved from ERS-1 SAR wave mode data

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**Abstract**

The results obtained with the optimal interpolation and the Green's function assimilation method using two-dimensional wave spectra from ERS-1 SAR wave mode imagette spectra are compared. The derived wind and wave corrections to the data of the wave model WAM are evaluated with independent observational data. Indications are found that, on one hand, the model winds and subsequently the model wind sea are occasionally overpredicted, and that, on the other hand, the modeled swell energy is underpredicted. The identification of these shortcomings will help to establish lasting improvements in the geophysical modelling of winds and waves for short-term forecasts as well as for climate predictions.

## 1 Introduction

Ocean wave predictions are now routinely taken into consideration for ship routing, offshore activities and coastal protection. Predictions of ocean wave data for both global and regional scales are world-wide obtained from a third-generation spectral wave model which is implemented at many operational weather and wave prediction centers.

Analogous to the weather prediction wave predictions need to be updated using real-time wave observations. The number and diversity of wave data has increased considerably since the operation of satellite-borne remote sensing instruments, namely the altimeter and the synthetic aperture radar (SAR).

The altimeter data provide measurements of significant wave height while the SAR data provide information of the two-dimensional ocean wave spectrum. Two-dimensional ocean wave spectra describe the spectral distribution of wave energy completely and therefore represent the most useful data for assimilation into a spectral wave model. Through wave data assimilation the model sea state is updated in close agreement with the observation which is needed to produce reliable forecasts of the spectral wave energy distribution.

The data assimilation scheme for spectral wave data consists of several modules which have been developed in concerted actions in the past years (Hasselmann, 1985; Komen et al., 1994). The three main modules are the third-generation wave model WAM (WAMDI Group, 1998), the algorithm to retrieve two-dimensional ocean wave spectra from imagette spectra of SAR wave mode (SWM) data (Hasselmann and Hasselmann, 1991; Hasselmann et al., 1996; Heimbach et al., 1998), and methods to assimilate observed wave spectra into WAM (Bauer et al., 1996; Hasselmann et al., 1997).

To obtain a long-lasting improvement of the forecast it is necessary to correct the model wave spectra as well as the winds driving the wave model. If the wave correction is not accompanied by a dynamic consistent wind correction the waves would lapse into the previous uncorrected state. Moreover, comparisons of modeled wind and wave data with observations have shown that, indeed, errors in the wind fields are the most often cause for incorrect wave predictions. Therefore, a reasonable starting-point of a wave data assimilation method is the determination of adequate wind corrections to adjust the incorrectly modeled wave systems. Wave systems are fractions of the two-dimensional wave spectrum which are known as wind sea and swell. The spectral properties of wind sea and swell require usually different corrections. This aspect has been addressed by the optimal interpolation and the Green's function assimilation method. These two different assimilation methods have been developed and validated independently. In the following, results from the assimilation of ERS-1 SAR-retrieved wave spectra are compared.

The purpose of this study is twofold. First, the results of the optimal interpolation and the Green's function method are evaluated by comparing the wind corrections obtained from assimilation of the same wave spectra. Second, the results from the wave spectra assimilation are evaluated more generally using independent wind and wave observations.

The structure of the study is as follows: Section 2 summarises the scheme to retrieve ocean wave spectra from the ERS-1 SWM data. The optimal interpolation and the Green's function assimilation method for the two-dimensional ocean wave spectra are described in section 3. Section 4 presents the results from comparing the two different assimilation schemes. The concluding section 5 discusses the results.

# 2 Ocean wave data from SWM data

The SAR instruments on board the ERS satellites receive in the so-called wave mode $5\times10$ km large imagettes of the ocean surface. The imagettes are composed of pixels of Bragg-backscatter intensities with a nominal resolution of 25 m. The ocean waves are imaged through the tilt and hydrodynamic modulation and the velocity bunching process. These three processes induce a modulation of the amplitudes of the Bragg waves, i.e. the small ripple waves. The SWM imagettes are transformed into spectra and transmitted to the ground when a ground receiving station is in sight. The SWM is continuously in operation and provides every 200 km along the satellite swath a snap shot of the surface waves on the global ocean.

Ocean wave spectra can be retrieved from the SWM imagette spectra using the WASAR algorithm (Hasselmann et al., 1998) which is developed for real-time applications. The WASAR algorithm contains an iterative inversion scheme of the closed nonlinear integral transform that describes the mapping of the ocean wave spectrum into a SWM imagette spectrum. In the initial step some information from a first-guess WAM spectrum is taken to compensate for the ambiguity of the spectral direction and for the loss of spectral energy beyond the azimuthal cut-off wavenumber. In the following steps of the WASAR algorithm a cost function is minimised which depends on the distance between the observed SAR imagette spectrum and the simulated SAR spectrum obtained from the forward transformation of the retrieved ocean spectrum. The impact of the first-guess information is seen to diminish with growing number of iterations.

The cost function puts a relatively large weight to adjust the simulated cut-off wavenumber to the observed cut-off wavenumber. The cut-off wavenumber is determined by the velocity bunching effect and appeared to be useful to retrieve the wave height from the observed spectra reasonably. The calibration of the observed spectra is done internally using the intensity of the background noise level. The SWM data quality and the retrieval performance of the WASAR algorithm have been assessed in detail (Heimbach et al., this issue, and Heimbach et al., 1998). The significant wave heights from SWM are in reasonably good agreement with significant waves heights measured by the ERS-1 and TOPEX altimeter (Bauer and Staabs, 1998; Bauer and Heimbach, 1998; Heimbach et al., this issue).

# 3 Wave data assimilation

## 3.1 Optimal interpolation method

The optimal interpolation method has been successfully applied for atmospheric modelling. It belongs to the class of kinematic methods as it ignores the model dynamics. An analysed ( = best-guess) model field at the analysis time results from a linear combination of the model first-guess at a grid point and the observed data within the analysis time window. The contributions are weighted depending on the data errors, the space-time distance between model and observed data and the typical correlation length scale.

The optimal interpolation method was transferred to assimilate significant wave heights from altimeter measurements into the wave model WAM (Lionello et al., 1992). The correction of the two-dimensional modeled wave spectrum using the integral wave energy from the altimeters takes into account the general form of the spectral shape, and the different contributions of wind sea and swell. The wind correction for the wind sea system is estimated from an approximation of the duration-limited growth law (Hasselmann et al., 1973).

The two-dimensional wave spectra from SWM data allow a more warrantable correction of the spectral properties of the modeled wind sea and swell. At the analysis time one wind correction can be derived, as before, which is consistent with the correction derived for the wind sea energy. The wind correction refers to the magnitude (not the direction) of the first-guess wind vector. A wind correction for the swell system would require estimates of the temporal evolution of the swell system.

## 3.2 Green's function method

The Green's function assimilation method belongs to the class of dynamic methods because the wave model dynamics is used as a constraint. The Green's function method provides dynamical consistent wind correction vectors for wind sea and swell. This is done, first, by computing the response function of the wave spectrum to a perturbation of the wind fields, and, second, by computing the spectral wave age. The impulse response function can be approximated, for reasons of plausibility, using a $\delta$-function. This wave response function represents a so-called impact function to filter out the most probable wind corrections among the possible solutions of wind corrections in the space-time domain. The approximation leads to a linear relationship between modifications of the spectral wave energy and changes of the first-guess wind fields. The wind correction vector is inferred for each spectral wave component from minimising the difference between the observed and the first-guess wave spectrum.

The spectral wave age follows from the time of wave generation. The wave generation time is the last instant of time when a wave component receives a forcing either from the wind or from the nonlinear energy transfer. After wave generation stops or after waves emanate from a storm region the wave age grows continuously from zero until the next forcing occurs. Incorrectly generated waves are most appropriately corrected at their generation region when the wave age is zero.

The spectral wind corrections and the wave ages are averaged for each wave system to increase the confidence of wind corrections statistically. The wind corrections for wind sea apply locally at the observation position. For swell, however, the wind corrections are applicable at a past instant of time and at a distant location. The space-time distance is to be traced back from the observation position along the great circle path of wave propagation, and is defined by the wave age and the wave group velocity. Thus the evolution of swell and its propagation enters the determination of dynamic consistent wind corrections.

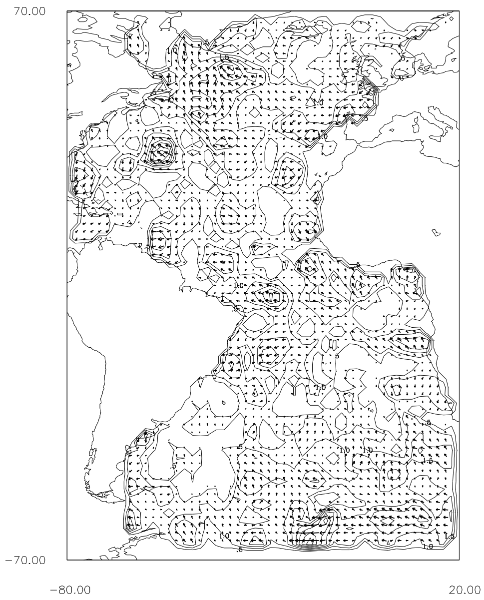


Figure 1: Mean wind corrections [m/s] averaged for November 1992 obtained with the optimal interpolation method assimilating ERS-1 SWM-retrieved wave spectra into WAM. Isolines of the wind corrections are given in steps of 0.5 m/s starting from 0.5 m/s.

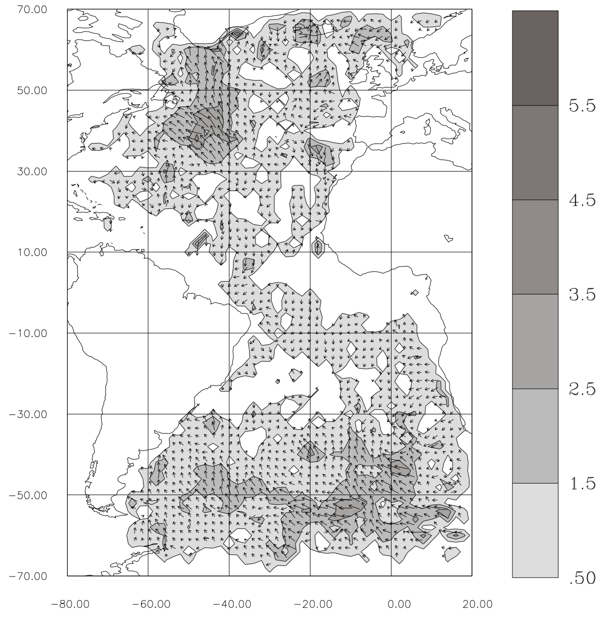


Figure 2: Mean wind corrections [m/s] averaged for November 1992 obtained with the Green's function method assimilating ERS-1 SWM-retrieved wave spectra into WAM. Isolines of the wind corrections are given in steps of 1 m/s starting from 0.5 m/s.

# 4 Results from assimilation of SWM spectra

Although the optimal interpolation and the Green's function method represent quite different approaches of wave data assimilation methods the (locally) determined wind corrections of both methods should be compatible. To test this, the methods have been applied using the same observed two-dimensional wave spectra. About 5000 ocean wave spectra were retrieved from ERS-1 SWM imagette spectra in November 1992 for the Atlantic Ocean which are exploited in this study.

The wave model WAM was run with the 6-hour analysed wind fields at 10m height from the European Centre for Medium-Range Weather Forecasts (ECMWF). The latitude-longitude grid was $1^\circ \times 1^\circ$ and the spectral resolution was 25 frequencies spaced logarithmically between 0.042 Hz and 0.41 Hz, and 24 directions in steps of $15^\circ$.

The one-month averages of the wind corrections from the optimal interpolation (Fig. 1) and from the Green's function method (Fig. 2) show a relatively large similarity. Some regions with relatively large and uniform wind corrections can be identified. These are visible in strong wind regions of the NW Atlantic, the NE Atlantic and the S Atlantic. From the comparison of the mean wind corrections with the monthly mean wind field for November 1992 follows that the first-guess winds in these regions tend to be too strong.

A different result is found for the tropical regions. The wind corrections in the tropical Atlantic indicates that the first-guess winds are underestimated. It has to be noted that the Green's function method yields less wind corrections in the tropical region than the optimal interpolation method. This results from the dominance of swell in the tropical region. The wind corrections for swell are determined at their generation regions which are the extratropical regions.

The tendencies of the wind corrections inferred for tropical and mid-latitude regions are in agreement with annual validations of ECMWF wind fields using ERS-1 scatterometer data (Bentamy et al., 1996).

For the overprediction of the modeled winds in the mid-latitude strong west wind regions some further evidence is found. The southeastward blowing winds of a cyclone in the NW Atlantic on the 3-4 November 1992 are seen to be overpredicted. In consequence the modeled waves are overpredicted by about 3 m. The optimal interpolation (Fig. 3) and the Green's function method (Fig. 4) yield a reduction of the first-guess winds by about 8 m/s. Swell waves emanating from the storm are seen by the SWM data to be too high during the following 10 days. The corresponding wind corrections in the storm region from the Green's function method are about constant for a period of more than 10 days (Fig. 5).

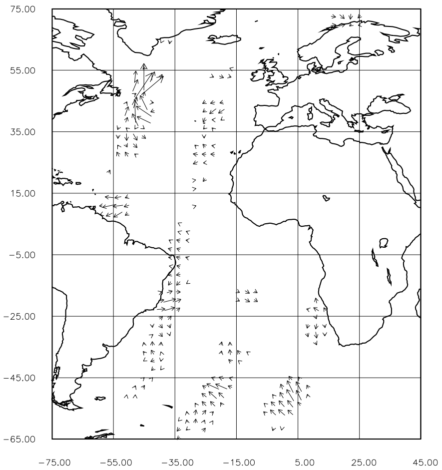


Figure 3: Wind correction vectors [m/s] computed from wind sea corrections with the optimal interpolation method using SAR-retrieved spectra from November 3, 1992 in the 6-hour interval centered at 12Z.

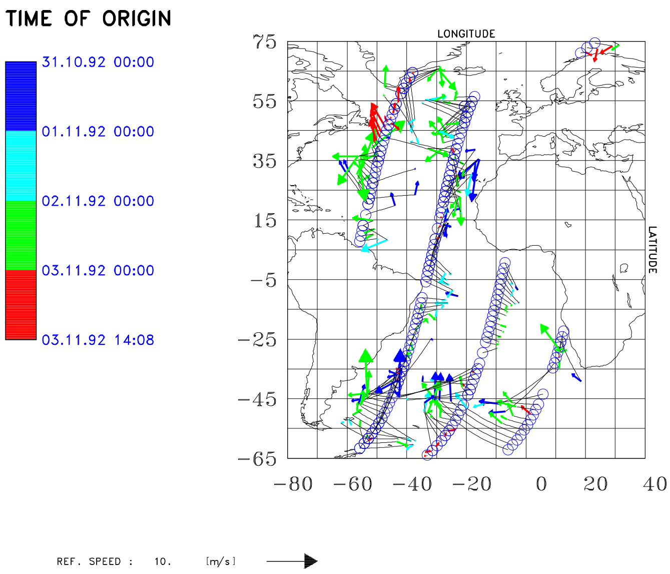


Figure 4: Wind correction vectors [m/s] computed with the Green's function method using the SAR-retrieved spectra as in Figure 2. For each wave system one wind correction vector is shown at the position of origin of the wave system which is determined from the corresponding wave age and the group velocity. Different shading refers to different time intervals in the past for the wind corrections.

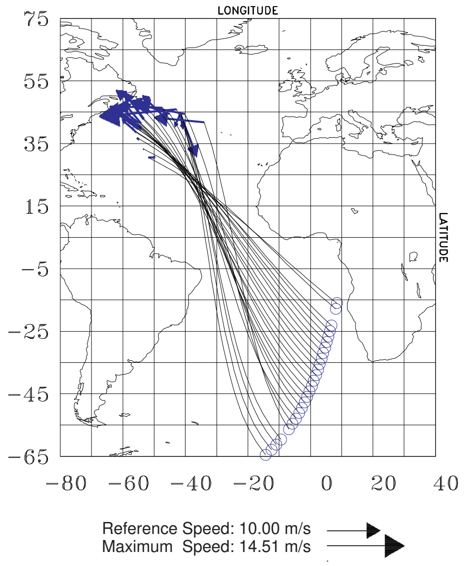


Figure 5: Wind correction vectors [m/s] computed with the Green's function method at times of origin between November 3 and 5, 1992 using the SAR-retrieved spectra from November 15, between 9.36Z and 9.50Z in the S-Atlantic. Observation positions and wind correction positions are connected by great circle lines.

# 5 Conclusions

The comparison study of the optimal interpolation and the Green's function assimilation method using two-dimensional wave spectra has demonstrated that all modules of the assimilation scheme produce useful results. The wave spectra retrieved from the ERS-1 SWM imagette spectra with the WASAR algorithm are reliable. The wind corrections to the first-guess model wind fields from the two assimilation methods agree reasonably well.

The agreement of both assimilation schemes to yield similar wind corrections is encouraging in view of the fact that the optimal interpolation scheme relies solely on the windsea part of the SWM-retrieved spectrum, whereas the Green's function method heavily exploits the availablity of swell spectra. This suggests, that some confidence can be put not only on the swell but also on the windsea retrieval of the WASAR algorithm.

The SWM-retrieved spectra indicate on average a slight underestimation of the wave energy by WAM. Separating the wave energy into wind sea and swell reveals an overestimation of the modeled wind sea and an underestimation of the modeled swell (Heimbach et al., 1998). These different deviations are clearly reflected in the wind corrections obtained from the assimilation. Model winds for strong wind sea are found to need a reduction and model winds for swell need an intensification.

The overestimation of model winds seems to occur occasionally. An example for a significant overestimation of the intensity of a deep pressure system in the N Atlantic was shown. Waves generated by this storm and which propagated as swell toward the S Atlantic involved repeatedly the same wind corrections from the assimilation of different SWM-retrieved spectra. In turn, the repeated finding of the same wind corrections puts confidence in the suitability of the modules of the assimilation scheme.

As the model wind sea is overestimated presumably due to overpredicted wind forcing another cause (than an incorrect wind forcing) appears to be likely for the underestimation of swell. Further evidence for the underestimation of the modeled swell energy is derived from the comparison of significant wave heights with the TOPEX altimeter data (Bauer and Heimbach, 1998). The underestimation of modeled swell is seen to grow with wave age (Heimbach et al., 1998) which suggest to re-examine the propagation and the dissipation of swell in the wave model.

Spectral wave data assimilation methods are an ideal tool for the combined analysis of modeled and observed wind and wave data. Such analyses need to be continued to find and to remedy eventually the real causes for shortcomings in the modelling of winds and waves. Further developed geophysical models will ultimately also contribute to improve climate predictions (WASA Group, 1998).

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