Derivation and assimilation of ERS-1 wind and wave data

European Space Agency Project PP2.D1

Final Report

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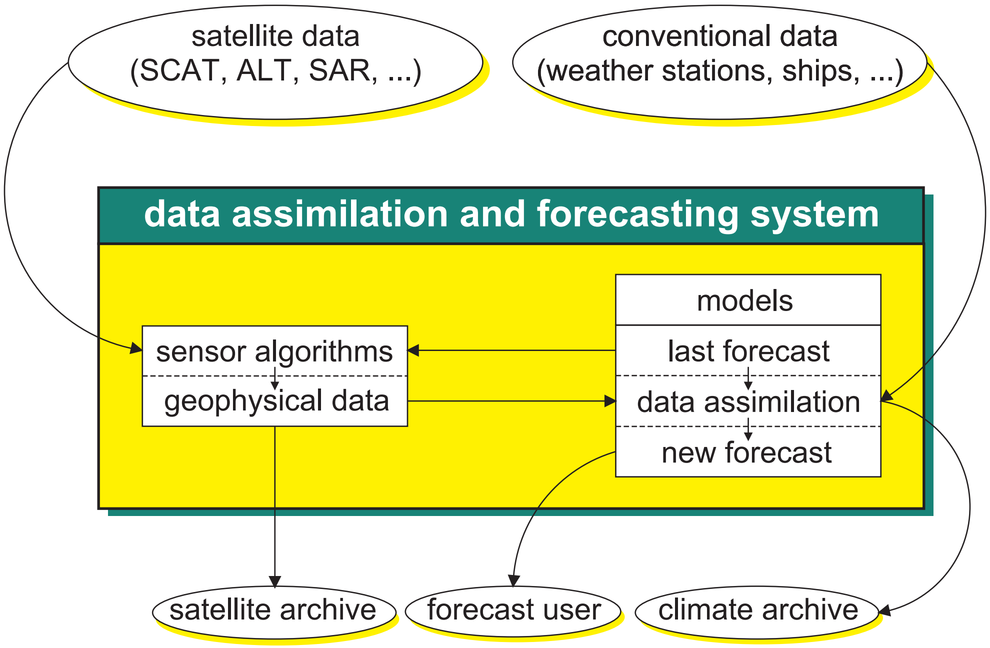
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1 Introduction

One of the major drivers of the first European Remote Sensing Satellite ERS-1, launched on 17 July 1991, was applications in wave research and wave forecasting. The Synthetic Aperture Radar (SAR) of ERS-1 provided for the first time detailed spectral information on the ocean surface waves. The SAR Wave Mode (SWM) data were available continuously and in quasi-real time from the global oceans. These spectral wave data opened up exciting new approaches to wave research and applications which reach far beyond the capabilities of the previous wave observation systems.

In general, three different investigations are pursued using the ERS-1 wave and wind data. First, the improvement of the ocean wave models, second the assimilation of the remotely sensed data into operational wave forecast models, and third the elaboration of long-term spectral wave climatologies. These investigations are of considerable economic benefit for numerous activities, such as ship routing *Lehner et al.* [1996], fisheries, off-shore operations and coastal and harbour protection. Beyond these practical applications, an understanding of the dynamics of waves is essential also for an improved understanding of the mechanisms that govern the transfer of momentum, sensible and latent heat and gases such as CO_2 across the air-sea interface – an area of research that is rapidly gaining significance through the development of sophisticated global coupled ocean-atmosphere-carbon cycle climate models.

2 Objectives of the investigation

The objectives of the ESA pilot project PP2.D1 focus on the derivation of wave and wind data from the SAR and the wind scatterometer of the ERS-1 satellite and the assimilation of the wave data into the third-generation wave model WAM. In recent years significant advances to develop wave models and methods to assimilate satellite data were gained (see *Komen et al.* [1994] for an extensive overview of the field). These developments were, in fact, strongly motivated by the prospect of ERS-1.

A significant contribution to further developments was achieved within the ESA pilot project PP2.D1 through the application of the ERS-1 wave and wind data. They fall into six main categories:

1. Development of an algorithm to retrieve ocean wave spectra from ERS-1

SWM data within the computational constraints of real time applications

2. Assessment of the SWM data quality and the retrieval performance; operational efficiency of the algorithm and the imbedding dissemination chain

3. Cross-validation of the ERS-1 SWM spectral retrievals using independent data of the ERS-1 and TOPEX altimeter

4. Global statistical analysis and intercomparison of the ERS-1 SWM spectral retrievals with WAM model data; hints for model deficiencies and test of adequacy of the SWM retrievals for scientific investigations

5. Statistical comparison of wind data from ERS-1 scatterometer, modelling and in situ data

6. Development of a hierarchy of schemes to assimilate ERS-1 SWM spectral retrievals into the wave prediction model WAM for model parameter tuning and for improving wave prediction

The main achievements of these topics are presented in the following sections. A list of reports, publications and documentations produced in the context of this project is given at the end.

3 Results of the investigation

3.1 Retrieval of ocean wave spectra from ERS-1 SAR wave mode data

The use of ERS data for global wave modelling focuses on the SAR wave mode fast delivery product (SWM.UWA). The operation of the ERS-1 Synthetic Aperture Radar (SAR) in the intermittent SAR Wave Mode (SWM) provides for the first time continuous global two-dimensional wave spectral data in near real time. The European Space Research Institute (ESRIN) at Frascati (I) distributes the ESA fast delivery product (FDP) in quasi real-time to the major operational forecasting centres. For the present project we received the FDP in Hamburg via the United Kingdom Meteorological Office (UKMO) at Bracknell (UK) and the Deutscher Wetterdienst (DWD) at Offenbach (FRG).

3.1.1 Outline of the retrieval algorithm

The retrieval of ocean wave spectra from the SWM imagette spectra is not straightforward, since the SAR imaging mechanism is strongly nonlinear due to the distortions induced by the long-wave orbital motions. Basic research to understand the imaging mechanism culminated in a comprehensive imaging theory presented in the MARSEN review (Hasselmann et al., 1985; J. Geophys. res.). Despite the first achievements of simulating the fully nonlinear velocity bunching mechanism using Monte Carlo methods it was not until the derivation of *Hasselmann, K. and Hasselmann, S.* [1991] of a closed nonlinear spectral integral transform that the inversion problem of deriving a wave spectrum from a measured SAR spectrum became tractable.

Furthermore, *Hasselmann, K. and Hasselmann, S.* [1991] proposed a method to invert this transform which forms the basis for the development of a retrieval algorithm of wave spectra from SWM data. Starting from a first guess spectrum a SAR spectrum is simulated via the full nonlinear transform and then compared to the measured SAR spectrum. The deviation is measured by means of a suitably defined spectral error cost function. Through the derivative of the cost function with respect to the spectral components an improved wave spectrum can be calculated which serves as new input for an improved simulation of the SAR spectrum. The iterative minimisation of the cost function finally leads to a best estimate wave spectrum whose simulated SAR spectrum closely matches the observed SAR spectrum.

3.1.2 Algorithm implementation and improvement

The inversion algorithm described above was developed at the MPI für Meteorologie and the Institut für Meereskunde, Hamburg. An important feature of the algorithm is that the SWM spectra can be calibrated internally, independent of the instrument calibration (*Brüning et al.* [1994a]). The modulation transfer functions incorporated in the nonlinear forward mapping were extensively investigated by *Brüning* [1994]. First tests were performed *Brüning et al.* [1993] and showed promising results. The iterative minimisation of the cost function is seen to decouple the retrieved spectrum effectively from the first guess. A set of three days of ERS-1 SWM data between January 22–24, 1992, in the Atlantic were inverted and subject to a first detailed evaluation (*Brüning et al.* [1994a]). Based upon this study recommendations were proposed for an improved algorithm (*Hasselmann, S. et al.* [1996a], *Hasselmann et al.* [1996b], *Heimbach et al.* [1996]). This so-called WASAR algorithm has been implemented and is available from the German Climate Computing Centre (DKRZ) along with a software documentation (*Hasselmann, S. et al.* [1998a]). The first (unimproved) version of *Hasselmann, K. and Hasselmann, S.* [1991] has also be implemented at the ECMWF.

3.2 Assessment of the SWM data quality, the retrieval performance, and the operational efficiency

In *Heimbach et al.* [1998] a comprehensive assessment was given for a three year set between January 1993 and December 1995 of ERS-1 SWM data and their spectral retrievals in terms of the SWM data quality and the retrieval performance or fidelity as well as the operational feasibility of the retrieval algorithm. 12 % of the SWM data were rejected before retrieval for data quality reasons; 85 % of the retrieved data achieved an acceptable retrieval fidelity. A single or second iteration of the input spectrum yielded an appreciable improvement of the retrievals. Sensitivity experiments were performed to demonstrate the independence of the SWM-retrieved wave spectrum upon its first guess spectrum.

3.3 Cross-validation of the ERS-1 SWM retrievals using different altimeter data sets

Complementary to the quality and performance analyses, a global validation of SWM–retrieved significant wave heights H_s^{swm} was performed for the period 1994, using independent, collocated data from the ERS-1 (H_s^{ers}) and the TOPEX/POSEIDON (H_s^{top}) altimeters (*Heimbach et al.* [1997b], *Heimbach et al.* [1997d], *Bauer and Heimbach* [1998]). The available altimeter data of H_s^{top} and H_s^{ers} were assured to be of high absolute accuracy. The data of H_s^{swm} showed a good overall agreement with these altimeter wave heights. However, the higher waves of H_s^{swm} appear to be slightly underestimated with respect to both H_s^{ers} and H_s^{top}. This deviation was analysed more closely by taking advantage of the spectral information provided by the SWM data to stratify the full H_s sample with respect to spectral characteristics. The slight underestimation of H_s^{swm} could be attributed to the underestimation of high windseas by the SWM. The altimeter and SWM–retrieved swell wave heights were in very good agreement. The windsea underestimation could not be unambiguously attributed to a single cause.

As a necessary prerequisite *Hansen et al.* [1994], *Bauer and Staabs* [1998] performed a comprehensive multisensor study of all available spaceborne altimeter wave heights from SEASAT, GEOSAT, TOPEX/POSEIDON and ERS-1 altimeter data together with WAM model data of the respective period to assess their individual value. One important result regarding the use of the ERS-1 altimeter data for operational assimilation into the WAM model at ECMWF (implemented since August 1993) was that although the altimeter data were apparently low-biassed their assimilation had a positive impact (*Staabs and Bauer* [1998]). The elaboration of a long-term wave climatology through combining the different data sets to study wave climate changes during the last decades is found to require further systematic reanalyses of the data sets.

3.4 Statistical comparison of spectral wave data of SWM and the WAM model

A statistical analysis of ERS-1 SWM-retrieved spectra was carried out for the three-year period January 1993 to December 1995 and the data compared with WAM model spectra (*Heimbach et al.* [1997a,c, 1998],*Heimbach* [1998]).

The time series of SWM-retrieved and WAM-derived monthly mean significant wave heights H_s in various ocean basins show good overall agreement, but with a small systematic underestimation of H_s by the WAM model. A decomposition of the wave spectra into windsea and swell reveals on average 10 % overprediction of the windsea by the WAM model, while swell is underpredicted by 20 to 30 %. The positive windsea bias exhibits no clear wave height dependence, while the negative swell bias decreases with swell wave height. This could be due to a too strong damping source term in the WAM model at low frequencies. The windsea overestimation is attributed to erroneous wind forcing by the ECMWF wind analyses. This is in accordance with wave assimilation studies (*Bauer et al.* [1997]), and with comparisons between ERS-1 scatterometer and ECMWF surface wind fields. Detailed spatial and temporal intercomparisons were presented for retrieved and modelled windsea and swell wave heights, wave lengths and propagation directions. By means of the ERS-1 SWM spectral retrievals evidence was found that the wave field carries a signature of a misalignment between the wind vector and the wind stress, the latter being rotated towards the direction of the swell part of the wave spectrum.

An intercomparison was made of the observed and modelled azimuthal cut-off length scales. The adjustment of the WASAR retrieval algorithm to reproduce the observed cut-off length scale is found to be very effective. Computed ratios of the observed azimuthal cut-off wavenumber to the mean azimuthal wavenumber component indicate that about 75 % of the swell can be directly resolved by the SAR, whereas about 70 % of the windsea spectra lie at least partially beyond the cut-off. A global map of seasonal mean cut-off length scales indicates that stronger cut-offs generally occur in regions of strong wind activity and, as expected from the fetch laws, in closed regional ocean basins. A linear relationship between the cut-off and the wind speed without consideration of the stage of development was unable to explain the observed relationship.

A further validation strategy of retrieved swell wavelengths was proposed and analyzed by *Heimbach et al.* [1998]. The ERS-1 SWM data were found to be suitable for tracking propagating swell over large distances across the ocean.

3.5 Statistical comparison of wind data from ERS-1 scatterometer, modelling and in situ data wind data

A comparison of the statistical properties of near surface winds from the ECMWF analysis, ERS-1 scatterometer and in situ measurements revealed significant differences. These differences could largely be attributed to shortcomings of the initial sensor algorithms of the scatterometer data (*Bauer* [1995, 1996]). Subsequent improvements of the scatterometer algorithm led to a better agreement between winds of the scatterometer, the atmospheric model and measurements. The influence of the atmospheric stability and of rain on the wind vector retrieval from the scatterometer data may be considered to be of minor importance (*Staabs* [1998]).

A spectral analysis of the kinetic energy of the atmospheric motions in the wavenumber domain is seen not to be affected by the shortcomings of the sensor algorithm described before. The spectral analysis revealed that the level of the spectral kinetic energy derived from the scatterometer winds is considerably larger than inferred from the atmospheric model winds for scales smaller than 1000km (*Bauer* [1997]). This result is in agreement with previous studies based on the scatterometer winds of the SEASAT satellite. As a consequence the variability of the modeled wave fields is seen to be considerably underestimated compared to the measurements from altimeters.

3.6 Assimilation of SAR wave mode data

Before wave data assimilation schemes for SAR wave mode data were developed experiences with the assimilation altimeter wave heights were gained. Although a single parameter is of limited value in updating the full 2d wave spectrum, its assimilation already yielded improved results, The initial assimilation experiments provided further support that the major cause for erroneously modelled wave data are errors in the wind fields driving the wave model.

3.6.1 The optimal interpolation scheme

At ECMWF an OI scheme was implemented operationally for ERS-1 altimeter data (*Lionello et al.* [1992, 1995]). This scheme can be readily generalized to wave spectral data derived from ERS-1 SWM spectra (*Hasselmann, S. et al.* [1994, 1997], *Voorrips et al.* [1997]). For this purpose, both the WAM model and SAR-retrieved wave spectra are partitioned into a small number of windsea and swell systems, each of which is characterized by a few mean wave parameters. After cross-assigning the observed and model wave systems, analysed fields of the wave system parameters can be constructed by standard optimal interpolation. The updated full wave spectra in the vicinity of the observation point are recovered by superimposing the corrected wave systems. From the corrected windsea, errors in the driving wind field can be inferred using empirical laws for growing windseas.

3.6.2 The Green's function assimilation method

Bauer et al. [1996a] take a step further towards a dynamical rather than interpolative assimilation scheme using a Green's function method. The basic idea is to correct the wind field, thereby obtaining dynamically mutually consistent corrected wind and wave fields. The Green's function assimilation method exploits two-dimensional wave spectra and determines wind corrections for each spectral wave system at its position of origin. The position of origin is derived from the spectral wave age associated with each wave system. For windsea the wind corrections are to applied locally and for swell at past times and at positions inferred from the wave propagation path. The method was calibrated using synthetic test cases.

Then the calibrated assimilation scheme was applied for realistic conditions of the Atlantic using the wave spectra retrieved from the SWM as described before (*Bauer et al.* [1995, 1996b]). The analysis for the entire Atlantic revealed substantial errors in the driving wind fields which occur occasionally. Using the spectral wave age erroneously modelled swell waves were traced back to their origin in space and time, i.e. to the original, erroneous windsea. The method was thus corroborated by the repeated identification of the same wind corrections at the same position from the assimilation of different SWM spectra measured at different times and places. A further support of the usefulness of the Green's function scheme is obtained from the comparison of the wind corrections of the Green's function scheme and of the optimal interpolation scheme. For windsea the wind corrections are in close agreement (*Bauer et al.* [1997]). The spreading of erroneous windsea and subsequently as erroneous swell is seen to be most appropriately corrected by the correction of the winds generating the windsea.

3.6.3 The adjoint technique

The adjoint technique is a general, dynamically consistent variational method for optimising free model parameters or assimilating observational data. For a large set of control variables it avoids the prohibitive computation costs incurred in the determination of the cost gradient by direct finite differences.

- *Application of the adjoint technique to model tuning.* In a first step, an adjoint model for a 1d version of the WAM model was developed and applied to inverse modelling studies (*Barzel et al.* [1993],*Barzel* [1994]). A total of five free parameters in the source terms of the energy balance equation were optimised by fitting the model to fetch-limited wave data. The latest WAM model cycle 4 was compared with the former WAM cycle 3 and with a boundary layer model. The comparison revealed that there is substantial ambiguity in the choice of the wind input term in combination with a suitably adjusted dissipation term, at least in fitting to fetch-limited wave data. The resolution of this ambiguity requires data involving inhomogeneous or non-stationary wind fields and the adjoint of the full 2d wave model, corroborating the need for 2-dimensional wave spectral observations such as provided by the SAR wave mode. The extension of the adjoint to the full spatial dimensions of WAM was pursued in joint work by MPI and KNMI (*Hersbach* [1997a,b]). The work makes use of an adjoint model compiler developed at the MPI für Meteorologie (*Giering and Kaminski* [1998]).

- *The use of SWADE data for adjoint wave modelling.* With the availability of more complex data from the Surface Wave Dynamics Experiment (SWADE) in the North Atlantic (*Cardone et al.* [1995]) an extensive set of observational data is available for studying the interplay of the different data sources. The observational instruments comprised bouys, and various microwave instruments (ROWS, RESSAC, SRA, airborne SAR). The SAR data were used to perform additional investigations on the WASAR retrieval algorithm used for the ERS-1

SWM data (*Hasselmann, S. et al.* [1998b]).

- *Towards an integrated wind and wave data assimilation.* As part of the efforts to construct an adjoint model for ECAWOM model (*Weisse and Alvarez* [1997]) for assimilation of wind and wave spectral data the application of the adjoint model technique for wave data assimilation is envisaged in the near future. Ultimately, a dynamically consistent assimilation scheme has to include both an atmospheric and a wave model, as wind and wave field corrections are intimately related to each other and to their respective dynamical history.

4 Conclusion

Within the ESA pilot project PP2.D1 reliable wave and wind data were derived from the SAR wave mode and the scatterometer of the ERS-1 satellite, and several wave data assimilation studies were performed revealing the positive impact on wave prediction. The benefit of ERS-1 SAR wave mode spectral data for improving global wave modelling has been clearly demonstrated.

The results were briefly summarized in this final report of the European Space Agency pilot project. A more complete overview of the results can be obtained from the reference list below. The potential of spectral wave data for monitoring global wave spectral climatology, and the benefit of combined use of different space borne remote sensing instruments for instrument and model validation is shown explicitly. More insights into the dynamics at the wavy air–sea interface can be expected with the data already provided by ERS-1/2 and anticipated from ENVISAT.

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