Global operational remote sensing and modelling of ocean waves

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Abstract

An overview is given of current operational methods for retrieving two-dimensional ocean wave spectra from near real-time ERS-1 SAR wave mode (SWM) imagette spectra. The SWM data quality and performance of the WASAR algorithm are assessed. Sensitivity analyses and validation studies are performed using two-dimensional NOAA buoy data as well as TOPEX and ERS-1 altimeter-derived significant wave heights. An inter-comparison between SWM-retrieved and WAM model spectral parameters shows a good overall agreement, however with a small but systematic over-prediction of windseas and underprediction of swell by the WAM. While the former can be explained by to too strong forcing by the ECMWF wind fields, the latter is attributed to too strong damping of swell by the WAM. Some evidence is found of a misalignment between the wind speed vector and the wind stress in the presence of swell.

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. Through the wave mode of the synthetic aperture radar (SAR) ERS-1 provided for the first time detailed spectral information on the sea state globally, continuously and in quasi-real time, far beyond the capabilities of other wave observation systems. These unprecedented data together with the third generation global wave model WAM, implemented operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF), enable for the first time a variety of ocean wave studies to be performed operationally and on global scale, some of which are outlined in the following.

1.1 Current and potential applications

- The development of improved ocean wave models for operational wave forecasts and the computation of wave climatologies is of considerable economic benefit for numerous activities, such as ship routing [*Lehner et al.* 1996], fisheries, off-shore operations and coastal protection. Such improvements have to rely on increasingly detailed wave measurements which, on a global scale, can only be provided through satellite remote sensing.

- The prospect of global continuous wave spectral data led to the development of spectral data assimilation schemes of various complexity with respect to dynamical consistency (see the overview in [*Bauer and Heimbach, this issue*]), which are able to assimilate individual spectral components of the wave field on the basis of SWM spectral retrievals. Although spectral assimilation schemes have not yet been implemented operationally at ECMWF, their benefit was clearly revealed in the above mentioned studies.

- Owing to the sensitivity of the surface wave field to the wind, assimilation of spectral wave data not only leads to improved wave fields but also to wind field corrections. In this way, accurate wave models combined with spectral wave measurements enable the validation of surface wind output of atmospheric general circulation models (GCMs).

- Beyond practical applications, monitoring and modelling 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 wavy 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 (e.g. *Weisse and Alvarez* [1997]). As an example, numerical simulations of the wind-driven ocean circulation have to rely on an accurate representation of the relationship between the wind stress, wind profile and sea state. The dependence of wind stress on sea-state is still an open question (*Rieder and Smith* [1998]; *Rufenach* [1998]). Spectral wave data are valuable to resolve this question.

- Various groups have recently begun to investigate long-term wave climatologies with the aim to assess possible changes of wave climate due to long-term natural variability such as the North Atlantic Oscillation (NAO), anthropogenic greenhouse warming, or other climate changes (see e.g. *Bouws et al.* [1996]; *Kushnir et al.* [1997]; *WASA Group* [1998]). Continuous global wave field observations would be valuable for such studies as the integration of wind effects by the waves cannot be recovered from impacts on wave height alone but translates into more complex spectral properties.

1.2 Outline of the performed analyses

The potential of forthcoming ERS-1 wave data has been a strong motivation for significant advances in wave modelling itself and the development of the third generation wave model WAM. In the spirit of data assimilation which may be viewed as an optimal methodology of fitting dynamics to data, and as a means to constrain the solutions to inverse problems related to the retrieval of geophysical parameters from remotely sensed measurements, the WAM model was developed to enhance the retrieval of wave spectral information from the nonlinearly distorted ERS-1 SWM data. A brief account of the history of spectral wave modelling is given in Section 2. The ERS-1 SAR wave mode data are described in Section 3. A brief outline of the inversion problem and of the wave spectral retrieval algorithm WASAR is given. A three year set of global ERS-1 SWM wave spectral retrievals between 1993 and 1995 and the WASAR algorithm were subject to various quality and performance analyses which are presented in Section 4. Sensitivity analyses and validation exercises of the ERS-1 SWM spectral retrievals using operational buoy data from NOAA, as well as altimeter-derived significant wave heights from TOPEX/POSEIDON are presented in Section 5 and 6, respectively. Finally, an intercomparison of SWM-retrieved wave spectral parameters with WAM model spectra is performed (Section 7).

2 Global ocean wave modelling

2.1 Historical aspects

First important developments in the modelling of ocean surface waves were made through the statistical approach of the wave spectrum, the evolution of which is described by an energy balance equation [*Gelci et al.* 1957]. A significant step was the derivation of a general expression for the source function for this equation, consisting of three terms which incorporate the basic physical processes of wave generation by the wind, nonlinear conservative spectral energy transfer, and white capping dissipation, governing the dynamics of surface waves [*Hasselmann* 1960]. By the mid-sixties explicit representations were available for the wind input [*Phillips* 1957]; [*Miles* 1957], as well as for conservative nonlinear interactions among different wave components [*Hasselmann* 1967], forming the basis of first generation wave models. However, in first generation models nonlinear effects were largely simplified or neglected altogether, thus avoiding an explicit modelling of the complete energy balance and resulting in a decoupled representation of the wave dynamics. Although of some success, these wave models were not able to account for some essential observed properties of growing windsea spectra. Gradually it was recognized that the nonlinear interactions played a central role for wave growth (see e.g. the Joint North Sea Wave Project [*JONSWAP* 1973]).

A significantly revised view of the spectral energy balance emerged, which found its way into wave modelling through the development of more sophisticated, second generation models [*SWAMP Group* 1985]. The representation of the nonlinear source term in second generation models is still based on a parametrization which is gauged on a family of spectral distributions. This effectively leads to a parametrical description of the windsea in terms of a few spectral parameters. This, and the limitation of the interactions to a set of idealized reference distributions, prevent an accurate description of the variety of wave conditions encountered in different regions of the world oceans.

2.2 The operational wave model WAM

Therefore, today's global third generation wave models like the WAM [*WAMDI Group* 1988]; [*Günther et al.* 1992] integrate the basic energy balance equation on the sphere from first principles without introducing prior assumptions on the spectral shape. The physical processes are fully incorporated into the three source terms for the wind input, the resonant nonlinear wave-wave interactions and the dissipation due to wave breaking.

The WAM model now runs routinely at most operational forecasting centres and has been implemented at more than 100 research institutions. It has been extensively validated locally through case studies and field data, including fetch-limited wave growth conditions and extreme storm conditions, and on a statistical basis against buoy data (for an overview see *Komen et al.* [1994]).

Besides its central role played in operational wave forecasting, the WAM model also plays an important role at interpreting image spectra measured with the ERS-1 SAR. It is used to provide the first guess for the wave spectral retrievals. Although this might cause doubts as to the applicability of the retrievals for model validations, it has been demonstrated in *Hasselmann, S. et al.* [1996a], (referred to in the following as [HBHH]) and *Heimbach et al.* [1998] that the approach is not as circular as this may appear, since the improved retrieval algorithm used here is insensitive to the initial input spectrum. The first guess information is used essentially only to remove the 180° ambiguity and augment the retrieved spectrum beyond the azimuthal cut-off.

2.3 WAM model data used here

Two sets of model data are at our disposal:

• The main set consists of three years of WAM spectra which were produced operationally at the ECMWF. The runs were performed every six hours, corresponding to one assimilation time step of ERS-1 altimeter data. The model spectra were collocated to the ERS-1 SWM spectra available in near real–time.

• In addition to the above data set a global run of the WAM model was conducted at MPI for austral winter JJA 1995. The model set-up and wind forcing was identical to the ECMWF set-up, but without the assimilation of altimeter data. The model was furthermore extended by a module to compute detailed wave age spectra at all model grid points [*Bauer and Heimbach, this issue*]. The reason for re-running the wave model was twofold:

1. The impact of the assimilation of ERS-1 altimeter wave heights on the ECMWF wave products needed to be assessed.

2. The spectral wave age is a useful quantity for dynamical investigations related to wave propagation. In the context of ocean swell propagation, spectral wave age enables one to trace back swell to its origin in space and time.

3 The ERS SAR wave mode

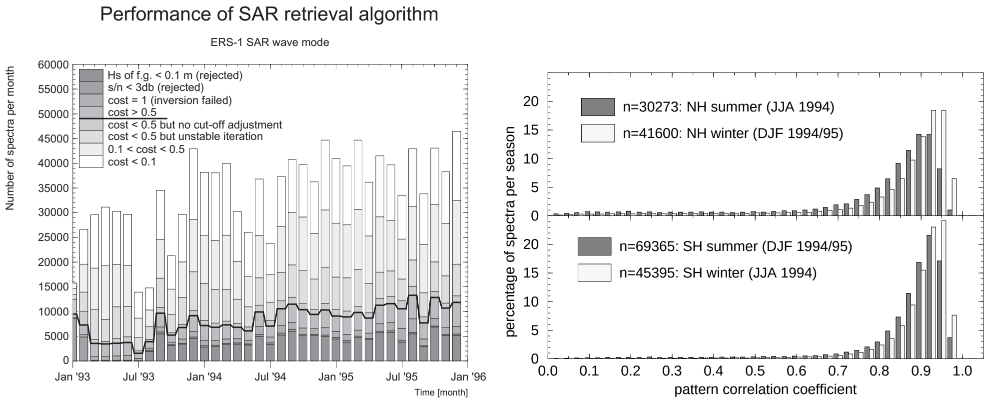
In the low bit rate intermittent sampling mode (so-called "wave mode") the ERS-1 SAR collects 5×10 km snap shot imagettes every 200 km along the satellite orbit. The data are transformed into low bit rate wavenumber spectra and disseminated in near real–time by the European Space Agency (ESA) as part of the fast delivery product (FDP) to the major forecasting services.

A necessary prerequisite for the use of the SWM spectra is the development of an algorithm to retrieve ocean wave spectra from SAR image spectra. This is not straightforward. The SAR imaging mechanism is strongly nonlinear through the distortions induced by the wave orbital motions (the "velocity bunching mechanism", cf. the MARSEN review in *Hasselmann et al.* [1985]). This results, among other effects, in image smearing and a loss of information beyond the so-called azimuthal cut-off wavenumber, corresponding typically to wavelengths shorter than about 100 – 200 m in the satellite flight direction. In addition, SAR images suffer from a 180° frozen-image ambiguity. Nevertheless, even with these limitations, *Hasselmann, K. and Hasselmann, S.* [1991], (referred to in the following as [HH]) were able to develop an efficient algorithm based on the inversion of the full nonlinear wave–to–SAR transform, enabling a reliable retrieval of wave spectra from SAR spectra within the computational constraints of operational applications. A first evaluation of the ERS-1 SAR wave mode was carried out for a three–day data set in the Atlantic [*Brüning et al.* 1994]. Based upon this evaluation, an improved algorithm has recently been proposed by [HBHH] and implemented [*Hasselmann, S. et al.* 1998]. This so-called WASAR algorithm was used for the retrieval ocean wave spectra from the three year global set of ERS-1 SWM data between 1993 and 1995.

4 Retrieval assessment

The SWM data comprises a total of some 1.2 million wave spectra with an average daily output of 1100 successfully retrieved spectra. The retrieval process incorporated a data quality test for the input SWM data, and a reliability test for the retrieval. The input SWM data was rejected if the signal-to-noise ratio of the SAR spectrum (defined as the ratio of the spectral peak to the clutter noise background) was less than 3 db or if the first guess wave height was below 0.1 m. The retrieved spectra were discarded as unreliable if the cost function was not reduced to less than half of its initial value. Fig. 1a shows that with the beginning of the quasi real-time distribution of the FDP about 75 percent of the SWM data could be successfully retrieved.

The retrieval fidelity is represented in Fig. 1b in terms of the distributions of the pattern correlation coefficients for the simulated and observed SAR spectra for the summer 1994 and winter 1994/95 seasons in the Northern and Southern Hemisphere. All distributions show a rather narrow peak around 0.9, indicating that for the major part of the data retrievals of high fidelity were achieved.



(a) Data and retrieval quality

(b) Retrieval algorithm fidelity

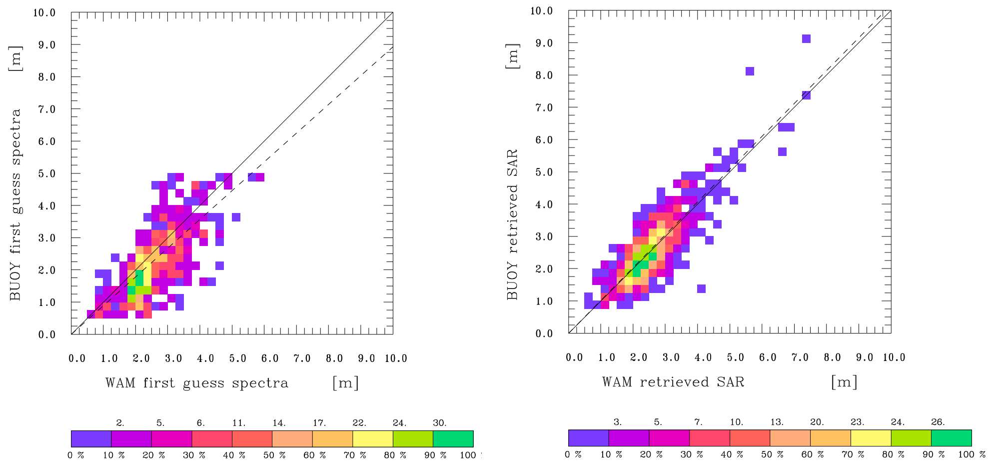
Figure 1: (a): Data quality and retrieval performance measured in terms of the cost function reduction factor. (b): retrieval algorithm fidelity measured in terms of the correlation between observed and simulated SAR spectrum.

5 Retrieval sensitivity and validation – buoy spectra

In a first step we present an intercomparison between ERS-1 SWM spectral retrievals and collocated two-dimensional buoy spectra during 1993. The buoy data were obtained from heave, pitch and roll buoys operated by the National Oceanographic and Atmospheric Administration (NOAA). Except one buoy off Hawaii, all buoys are located near the American continent, sufficiently off the shore to exclude orographic or coastal effects. Four buoys are situated in the North Pacific, four buoys in the North Atlantic. In view of the limited amount of collocated buoy spectra available we focus here on the use of buoy spectra for a sensitivity analysis of the WASAR algorithm rather than on a direct intercomparison. A validation of SWM-retrieved wave heights using a 1 year global set of TOPEX/POSEIDON and ERS-1 altimeter data will be presented in the next section. A further indirect validation based upon consistent wind field corrections inferred from the assimilation of ERS-1 SWM retrievals is given in [*Bauer and Heimbach, this issue*].

We allowed a very broad spatial collocation window of 600 km, yielding a total 1652 buoy spectra collocated to ERS-1 SWM data. While this broad window is sufficient for the present sensitivity study, a rigorous validation would have to restrict the distance to about 100 km, thus severely reducing the number of buoy data. An alternative sensitivity study based on a synthetic perturbation of first guess input spectra may be found in *Heimbach et al.* [1998].

Complementary to the retrieval of ocean wave spectra from SWM data using WAM spectra as first guess, a second retrieval exercise was carried out using buoy data as input. A symmetric regression between both retrievals was



(a) WAM vs. buoy f.g.

(b) Retrieval with WAM vs. buoy as f.g.

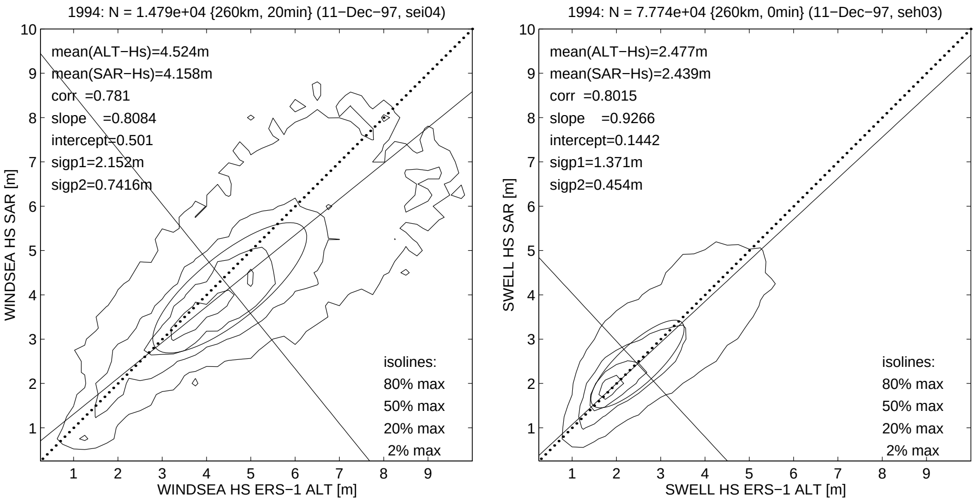
Figure 2: Sensitivity of retrieval with respect to first guess (f.g.) input.

performed, taking into account those retrieval pairs only which jointly fulfill the retrieval quality criteria described in the preceding Section. (notation: $y = b_{sym} \cdot x$, with mean $< \, . \, >$, bias $\Delta = < x > - < y >$, symmetric slope b_{sym} and correlation coefficient r). This yielded a subsample of roughly 1000 spectra. The statistical regression parameters for the significant wave heights are presented in Tab. 1.

	WAM vs. W-ret.	Buoy vs. B-ret.	WAM vs. Buoy	W-ret. vs. B-ret.
$< x >$ / m	2.53	2.16	2.53	2.57
$< y >$ / m	2.57	2.57	2.16	2.57
Δ / m	-0.04	-0.41	0.37	0.00
b_{sym}	1.02	1.16	0.89	1.02
r	0.73	0.71	0.72	0.82

Table 1: Statistical regression parameters of significant wave heights.

Fig. 2 shows that while buoy and WAM first guess differ considerably (a), a good agreement between buoy and WAM retrieval (b) is found (cf. Tab. 1), confirming the weak dependence of the the retrieval on the first guess. A direct comparison between buoy and WAM data reveals differences in terms of the mean spectral parameters. This can partly be explained by the large allowed collocation distance. The same applies for the comparison between buoy and buoy-input retrieved data. It should be noted that high sea states are extremely rare in the data sample. Therefore, no conclusions can be drawn yet with respect to direct validation of SWM retrievals using buoy spectra.



(a) windsea ERS-1 SWM vs. altimeter

(b) swell ERS-1 SWM vs. altimeter

Figure 3: Scatter plots of ERS-1 SWM and collocated ERS-1 altimeter windsea (a) and swell (b) wave heights.

6 Retrieval validation – altimeter data

Complementary to the quality, performance, and sensitivity 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 (H_s^{top}) altimeters (see also *Bauer and Heimbach* [1998]). The ERS-1 altimeter data were also part of the ESA FDP, and obtained via ECMWF. The TOPEX data were provided as offline product by AVISO, Toulouse (France).

Although limited in scope to one single parameter of the full spectrum, such an assessment is essential to increase confidence in the SWM retrievals, or to detect remaining deficiencies. Furthermore, it offers some advantages to buoy comparisons, since it yields a global coverage, comprising data of various wind and wave regimes.

Whereas the TOPEX data are of high accuracy (e.g. *Gower* [1996]), the ERS-1 altimeter FDP data are known to be low-biased. To compensate for this effect we applied a linear correction proposed by *Queffeulou* [1996]: $H_s^{ers} = 1.11\, H_s^{FDP\ ERS} + 0.09$

The spatial and temporal limits for SWM-to-altimeter collcations were set to
• 260 km and 1 min. for SWM-to-ERS-1 altimeter collcations
• 100 km and 90 min. for SWM-to-TOPEX altimeter collcations

A good overall agreement between SWM-retrieved and TOPEX and ERS-1 altimeter-derived H_s was found, with a slight low bias of H_s^{swm} with respect to both H_s^{ers} and H_s^{top} (not shown). Taking advantage of the spectral information provided by one partner of the collocated pairs, stratification of the full H_s

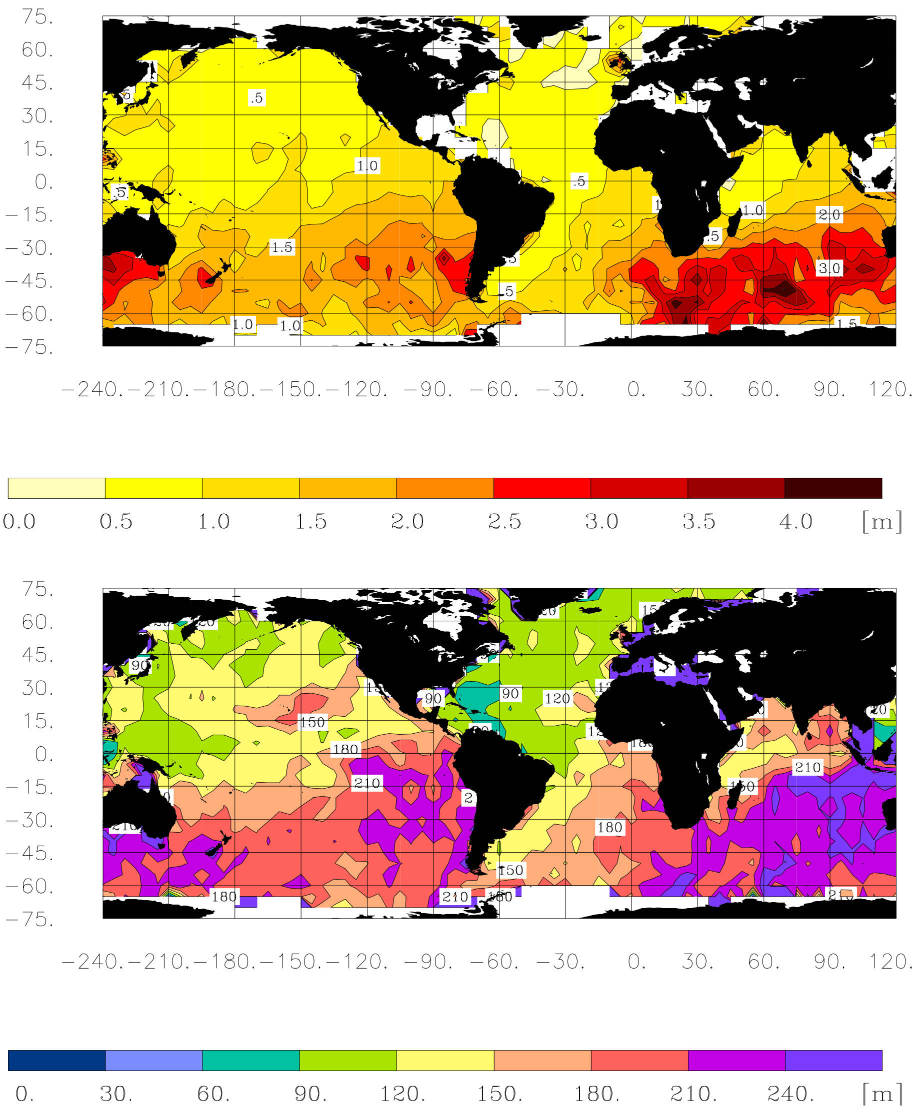


Figure 4: Seasonal mean wave height of individual largest wavelength swell systems > 250 m (top); sasonal mean swell wavelength (bottom); JJA 1994.

sample with respect to spectral properties could be made. Results of the regression SWM vs. ERS-1 altimeter regressions of pure windsea and swell cases are depicted in Fig. 3 together with mean regression parameters. 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. It should, nevertheless, be mentioned that the underestimation of SWM-retrieved H_s with respect to altimeter data is in conflict with the preliminary assessment of the SWM-retrievals with respect to buoy data, the latter suggesting H_s^{swm} to be overpredicted. Further validation should, therefore, aim at multisensor collocations to resolve this issue.

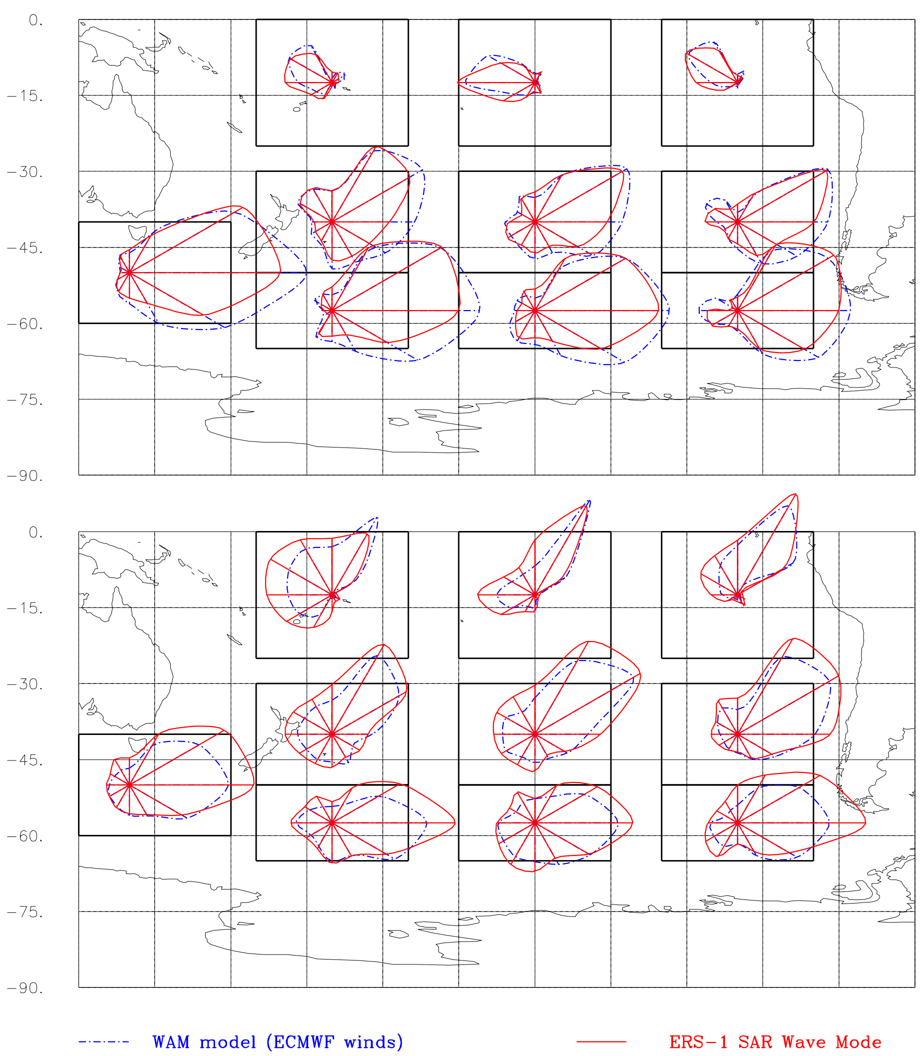


Figure 5: Seasonal directional wave height distributions for JJA 1994 in the South Pacific for windsea (top) and swell (bottom).

7 Model validation

Global validation of the WAM using spaceborne data has until recently been limited to H_s derived from altimeters. Because of their limitation to H_s, altimeter data, although providing continuous global coverage, are of limited value when trying to detect detailed deficiencies in the spectral properties of a wave model. The three year WAM vs. ERS-1 SWM intercomparison [*Heimbach et al.* 1998] has for the first time addressed spectral details of the wave field in various regions of the world oceans. In the following we focus on some aspects of the spectral characteristics.

Fig. 4 (upper panel) depicts the global distribution of seasonal mean swell wavelength for JJA 1994. The corresponding distribution of swell wave heights for the longest wavelength swell system in each spectrum is depicted in Fig. 4

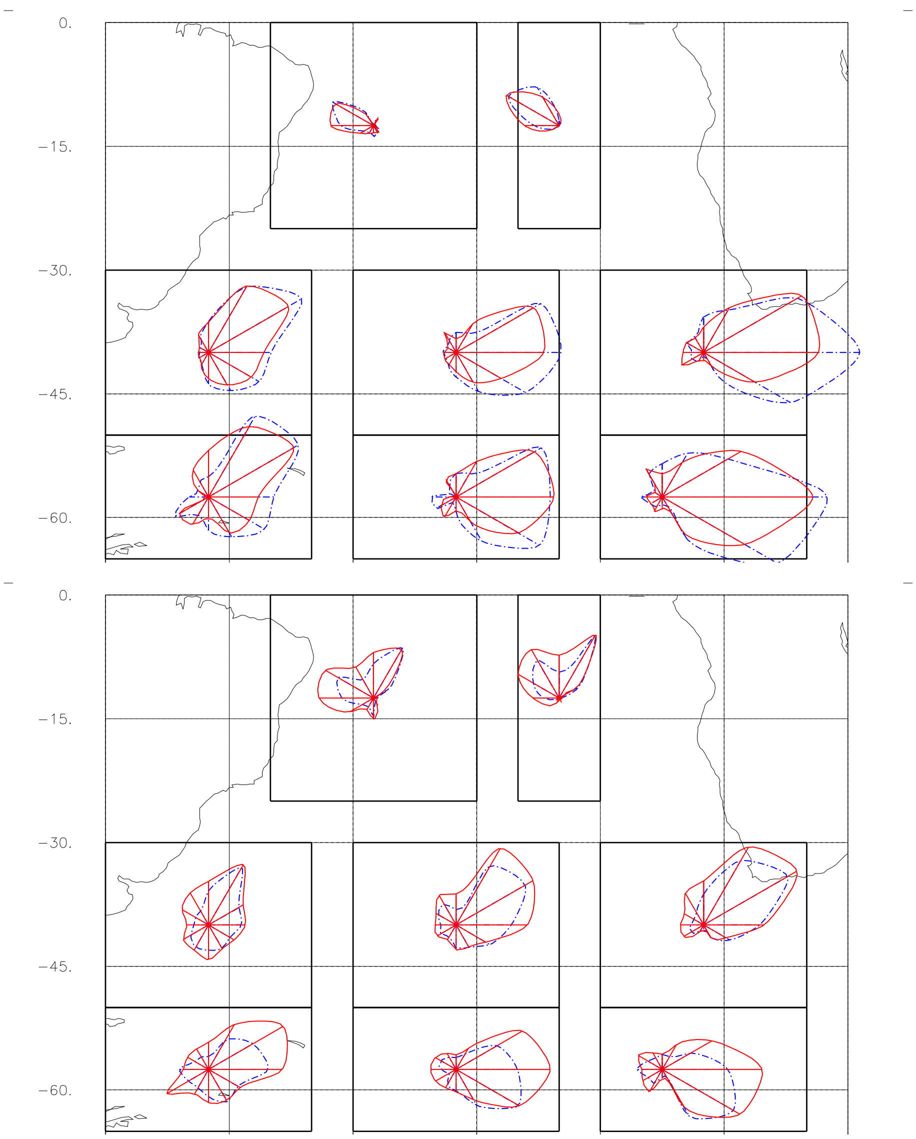


Figure 6: Same as Fig. 5 for the South Atlantic.

(lower panel). For the latter plot swell wavelengths were required to exceed a lower threshold of 250 m, the purpose being to focus on long wavelength swell. One can thereby more easily identify the regions into which the long wavelength swell is radiated.

The effect of fetch can be clearly seen in all Figures. The shortest wavelengths are found in the lee of the continents, in mid-latitudes off the east coasts, the longest wavelengths in the eastern parts of the ocean basins and in the open Southern Ocean. An interesting feature is the occurrence of long wavelength swell in the eastern equatorial oceans originating in the high-wind mid-latitude regions: the swell wavelength isolines exhibit a distinct eastward-equatorward slant, corresponding to the main direction of propagation from the extra-tropics.

Seasonal mean directional distributions for WAM (dashed-dotted) and ERS-1 SWM (solid) windsea and swell wave heights for JJA 1994 are shown in Fig. 5 and 6 for the South Pacific and the South Atlantic, respectively. The plots reveal an overprediced windsea wave height in contrast to an underpredicted swell wave height by the WAM model. The former was attributed by *Heimbach et al.* [1998] to too strong wind forcing by the ECMWF analysed u_{10} wind vector fields, consistent with an ECMWF wind field validation using ERS-1 scatterometer data by *Bentamy et al.* [1996]. The qualitative underprediction of swell was attributed to too strong damping of low frequency wave components by the WAM model. The magnitude of underprediction was found to be artificially increased though the assimilation of low-biased (uncorrected) ERS-1 altimeter data. The relative bias reported to be of the order of 20 percent could be reduced by half in the absence of assimilation [*Heimbach* 1998].

An interesting feature is revealed from the directional distrbutions of windsea wave heights. The two latitudinal bands between 30° and 50° as well as between 50° and 65° in the top panels of Fig. 5 and 6 reflect the mid-latitude westerly strong wind regime. Except for the sampling area between 30° and 50° in the South Atlantic off the South American coast all SWM-derived wave roses seem to be rotated compared to the model wave roses. The direction of rotation corresponds to the main propagation direction of the underlying swell (bottom panels of Fig. 5 and 6). As can be inferred from Fig. 4 the sampling area off the South American coast corresponds to the only region of the entire Southern Hemisphere ocean which does not carry important swell contributions of long wavelengths. This is due to the large scale shadowing of propagating swell by the South American continent. The results suggest that the observed wave field carries a signature of the misalignment of the wind stress with respect to the wind speed vector in the presence of swell, previously reported by *Rieder and Smith* [1998] in the context of three-component anemometer data, and *Rufenach* [1998] in the context of ERS-1 scatterometer and buoy data.

8 Conclusion

The ERS-1 SAR wave mode (SWM) data represent the first data set to provide detailed spectral information of ocean surface waves with continuous global coverage over several years. The present work has demonstrated the applicability of the SWM ocean wave spectral retrievals for global wave modelling through various quality and performance analyses of the WASAR retrieval algorithm, validation exercises as well as statistical and dynamical intercomparisons with WAM model data. The statistical and dynamical analyses presented here enabled the identification of a number of discrepancies between the ERS-1 SWM and the WAM model data, pointing to possible shortcomings of the WAM model or the forcing wind fields. More detailed investigations are needed of a larger ensemble of individual wave events to resolve the complex interplay between the basic dynamical processes of wave generation, dissipation and nonlinear energy transfer.

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