THE AIR-SEA INTERFACE
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EXTRACTION OF WAVE DATA FROM ERS-1 SAR WAVE MODE IMAGE SPECTRA

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Abstract. Ocean wave spectra retrieved from ERS-1 SAR wave mode image spectra using a recently developed nonlinear SAR imaging spectral transform and inversion method show good overall agreement with complex ocean wave spectra computed with the ECMWF operational global wave model WAM. In order to present global distributions of spectral fields, the full spectral information is reduced to a smaller number of variables by partitioning the spectra into a finite number of wave systems, which are characterized by a few mean parameters.

1 Introduction

Although the ability of satellite-borne Synthetic Aperture Radars (SARs) to observe ocean waves was clearly demonstrated already in 1978 by SEASAT, there has been a continuing concern that quantitative measurements of ocean wave spectra by a SAR would never be possible because of the strong nonlinearities of the imaging mechanism induced by the orbital velocities of the waves (Hasselmann *et al.*, 1985). However, the recent derivation of a closed nonlinear integral transformation relation for the mapping of an ocean wave spectrum into a SAR spectrum, together with a numerical technique for inverting the mapping (Hasselmann and Hasselmann, 1991) has provided a feasible algorithm for retrieving quantitative wave spectra from SAR image spectra. The retrieved spectra can be calibrated by the background clutter noise level of the SAR image spectrum, independent of the SAR calibration (Alpers and Hasselmann, 1982). A first guess wave spectrum from a model is required as input to resolve the 180° ambiguity in wave propagation direction inherent in any frozen image spectrum and to augment the spectrum beyond the nonlinear azimuthal cut-off of the SAR spectrum. The retrieved spectrum is found to be fairly insensitive to the first guess spectrum.

Examples demonstrating the feasibility of the inversion algorithm were given in Hasselmann and Hasselmann (1991) for SEASAT data. Here we verify the method by comparing the wave spectra retrieved from the global ERS-1 SAR wave mode data with wave spectra computed with the operational wave model WAM of the European Centre for Medium Range Weather Forecasting (ECMWF) (WAMDI,1988). A more detailed presentation is given in Brüning *et al.* (1994) – see also Brüning *et al.* (1993, 1996).

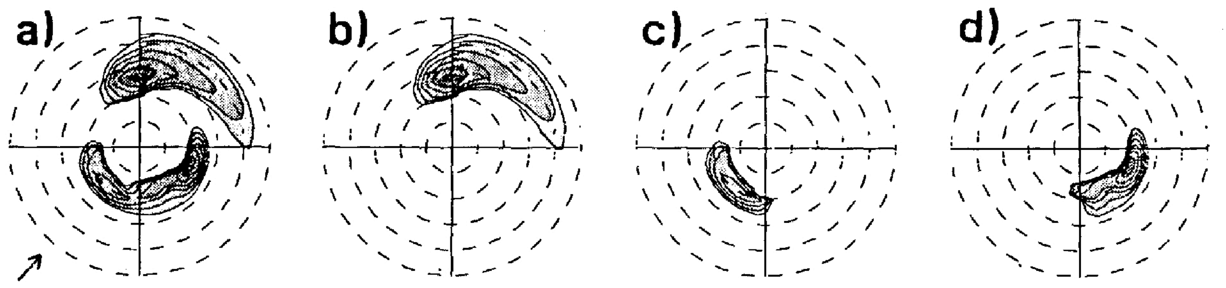

Fig. 1. Polar diagram of a modelled 2-dimensional frequency-direction wave spectrum at 13 W and 60 S on 30th January, 1993 at 10:00 (panel a) and its partitioned wave systems (panel b: mixed windsea-swell; panels c and d: swell systems). The wind direction is denoted by an arrow. Circles correspond to $\Delta f = 0.05$ Hz. Dashed isolines show energies on a logarithmic scale from $10^{-.8}$ m^2 / Hz to 1 m^2 / Hz, solid lines from $10^{.2}$ m^2 / Hz to $10^{1.4}$ m^2 / Hz.

2 Spectral partitioning scheme

Open ocean wave spectra are generally complex, containing several independent wave systems from different storms and local, often skewed, wind seas (Fig 1, panel a). To investigate fields of spectra, as required for a global intercomparison study, some method of compressing the spectral information to a manageable number of parameters is needed. For this purpose we applied a modified form of the spectral partitioning scheme originally proposed by Gerling (1992). The basic idea is to decompose the two-dimensional spectrum into a set of wave systems assigned to individual peaks of the spectrum, each of which can be characterized by a few standard integral parameters (significant wave height, mean wave direction, and mean wave length).

We use a partitioning algorithm based on the simple concept of an inverted 'catchment area' (*cf.* Brüning *et al.*, 1993, 1994, 1996). In hydrology, a topographical domain is decomposed into a set of catchment areas. Each catchment area is assigned to a *local minimum* of the topography and consists of the set of all points whose run-off drains into the local minimum. In the same spirit, we define a wave system associated with a given peak of the wave spectrum by inverting the spectral topography, so that the peaks are converted to minima, and then identifying the catchment area of the minimum of this inverted topography with the spectral domain of the wave system. Expressed directly, the wave system domain of a given spectral peak consists of all spectral points whose paths of steepest ascent lead to the peak. The path of steepest ascent is defined here, for a discretized spectrum, as the directed set of line segments connecting spectral grid points to the highest of the four nearest neighbour grid points. Mathematically (and numerically), the wave system domain of a spectral peak can be constructed by the simple induction rule that a grid point and its highest nearest neighbour grid point (if it is higher than the first grid point – otherwise the first grid point is a peak) belong to the same wave system (*cf.* Fig. 2).

The method coalesces wave systems if the peaks lie only two grid points apart and the minimum spectral value between two peaks is greater than 85 % of the

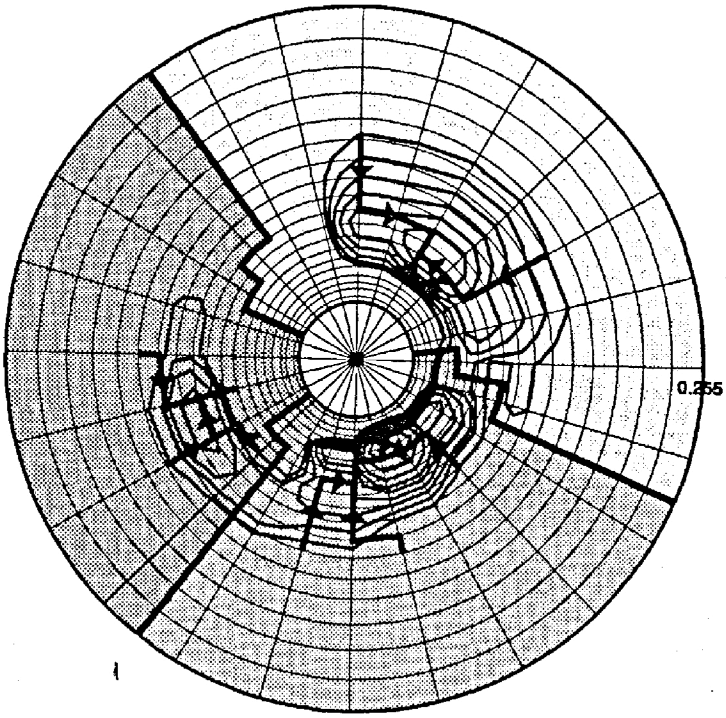

Fig. 2. Spectrum with overlayed frequency-directional grid and examples of paths of steepest ascent.

minimum spectral value of the two peaks.

The wave systems can be classed into windseas, swells and mixed windsea-swell systems. A wave system is regarded as a windsea if the phase velocity of the spectral peak is less than 1.3 times the component of the wind speed in the wave propagation direction. Mixed windsea-swell systems occur in turning wind situations. If the change in wind direction is not too abrupt and not too large, a new windsea peak does not immediately build up in the new wind direction, because the nonlinear transfer couples the components developing in the new wind direction with the former windsea still propagating in the old wind direction (*cf.* Young *et al.*, 1987). The resultant spectrum appears as a single-peaked skewed spectrum containing both new windsea components and old windsea (swell), the peak being given still by the old windsea. The identification of such a coupled windsea-swell system must therefore be based on a criterion involving, not simply the peak of the system, but also the new waves developing in the turned wind condition. We used the following definition: a mixed windsea-swell system is a system for which the peak fails to satisfy the pure windsea criterion, but one of the two spectral components $(f_p + \delta f, \theta_p \pm \delta\theta)$ does, where $\delta\theta^2 = \delta\bar{f}^2/(\bar{f}_p)^2$ and $\delta\bar{f}^2 = \overline{(f_x - \bar{f}_x)^2} + \overline{(f_y - \bar{f}_y)^2}$. The bar denotes the mean over the wave system domain and $\bar{f}_x = \overline{f\cos\theta}$ and $\bar{f}_y = \overline{f\sin\theta}$. Wave systems which satisfy neither the pure windsea criterion nor the windsea-swell criterion are defined as swell.

3 Comparison of mean wave system parameters for modelled and retrieved spectra

Wave spectra retrieved from global ERS-1 SAR wave mode data between June 1992 and July 1993 were partitioned and compared with the co-located partitioned spectra from the ECMWF operational wave model WAM (see also Brüning *et al.*, 1993, 1994, 1996). The global distributions of the mean parameters of the partitioned wave systems show good overall agreement (Figs. 3, 4). In most regions of the ocean, several different wave systems are superimposed in complex multi-system wave spectra, but both the WAM model and the SAR wave mode successfully identify the same principal wave systems, many of which can be tracked over large distances in the ocean.

Well known features such as the strong western wind belts and storm regions in the mid-latitudes, generating predominantly eastward travelling waves, and westward travelling waves created by the trade winds can be clearly recognized. The long swell systems travelling northward or southeast from the strong wind areas in the Southern or Northern Pacific, respectively, (*cf.* Snodgrass *et al.*, 1966) stand out most clearly in Fig. 4 showing the distributions of wave lengths, which change relatively slowly along a satellite track due to wave dispersion. For short lived storm systems, the wave length measured along a satellite track increases with distance from the storm.

A closer inspection of Figs. 3, 4, however, reveals some systematic differences between the WAM model and SAR derived wave systems, for example in the North Atlantic. This is illustrated in Fig. 5, which compares the model and SAR derived spectra and their partitionings for a point in this region. The wave system travelling southwest in the WAModel spectrum is seen to be travelling south in the SAR derived spectrum, where it has a longer peak wave length and less total energy. The eastward travelling systems show the same peak wave length and energy. However, differences arise through the different cut-offs of the WAM model and SAR spectra at high wavenumbers. The WAM model extends to wavelengths of 9 m, while the ERS-1 SAR wave mode fast delivery spectral product is limited to wavelengths longer than 100 m. For azimuthally travelling waves, the effective cut-off is normally at still longer wavelengths. The present retrieval algorithm returns the first guess spectrum in the high wavenumber (frequency) region where the SAR provides no information. This tends to create discontinuities in the retrieved spectra between the low wavenumber region, where the SAR data lead to a modification of the spectrum, and the unchanged high wavenumber region. This is the origin of the extra lobe at high wavenumbers seen in the eastward travelling system of the SAR retrieved spectrum. A method is currently being developed for removing the discontinuity in the retrieved spectrum in the neighbourhood of the cut-off by applying the wave partitioning technique already in the inversion algorithm.

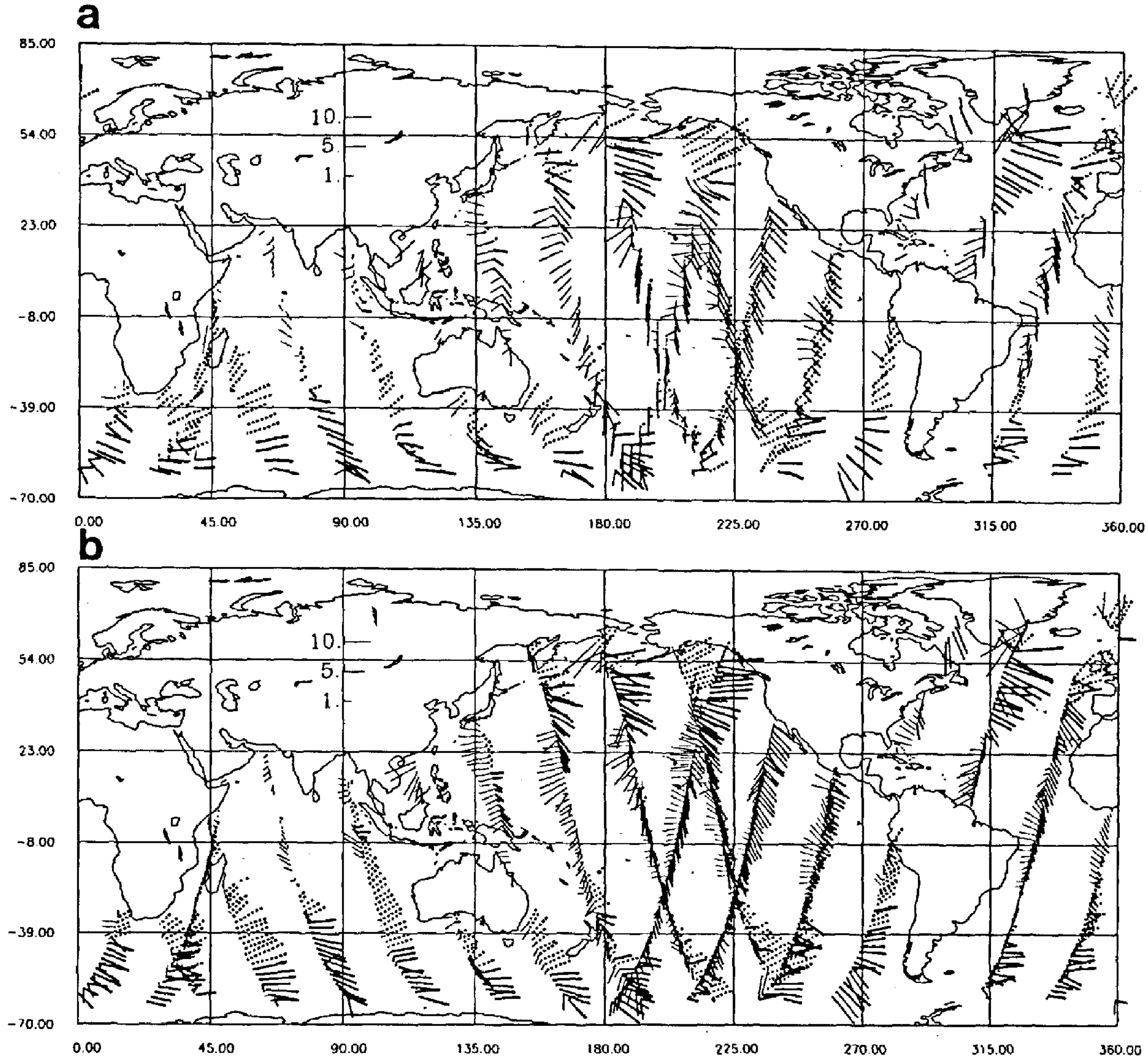

Fig. 3. Significant wave heights and directions (length and direction of bars) for partitioned co-located WAModel spectra (panel a) and SAR derived spectra (panel b), for all satellite tracks during the period 28th November at 12:00 to 29th November at 12:00, 1992.

4 Application of spectral partitioning to wave data assimilation

The availability through ERS-1 for the first time of global near-real-time wave data in the form of significant wave heights and, as demonstrated here, even calibrated two-dimensional wave spectra, has provided a strong motivation for the development of wave data assimilation methods. Several systems are currently being developed. Operational schemes for the assimilation of ERS-1 radar altimeter data in the third generation WAM model at ECMWF (Lionello and Janssen, 1990) and a second generation model at the UK Meteorological Office have already been implemented. These are essentially single-time-level optimal interpolation methods.

Although the schemes yielded a minor but statistically significant improvement in forecast skill (*cf.* Komen *et al.*, 1994), a basic problem with the as-

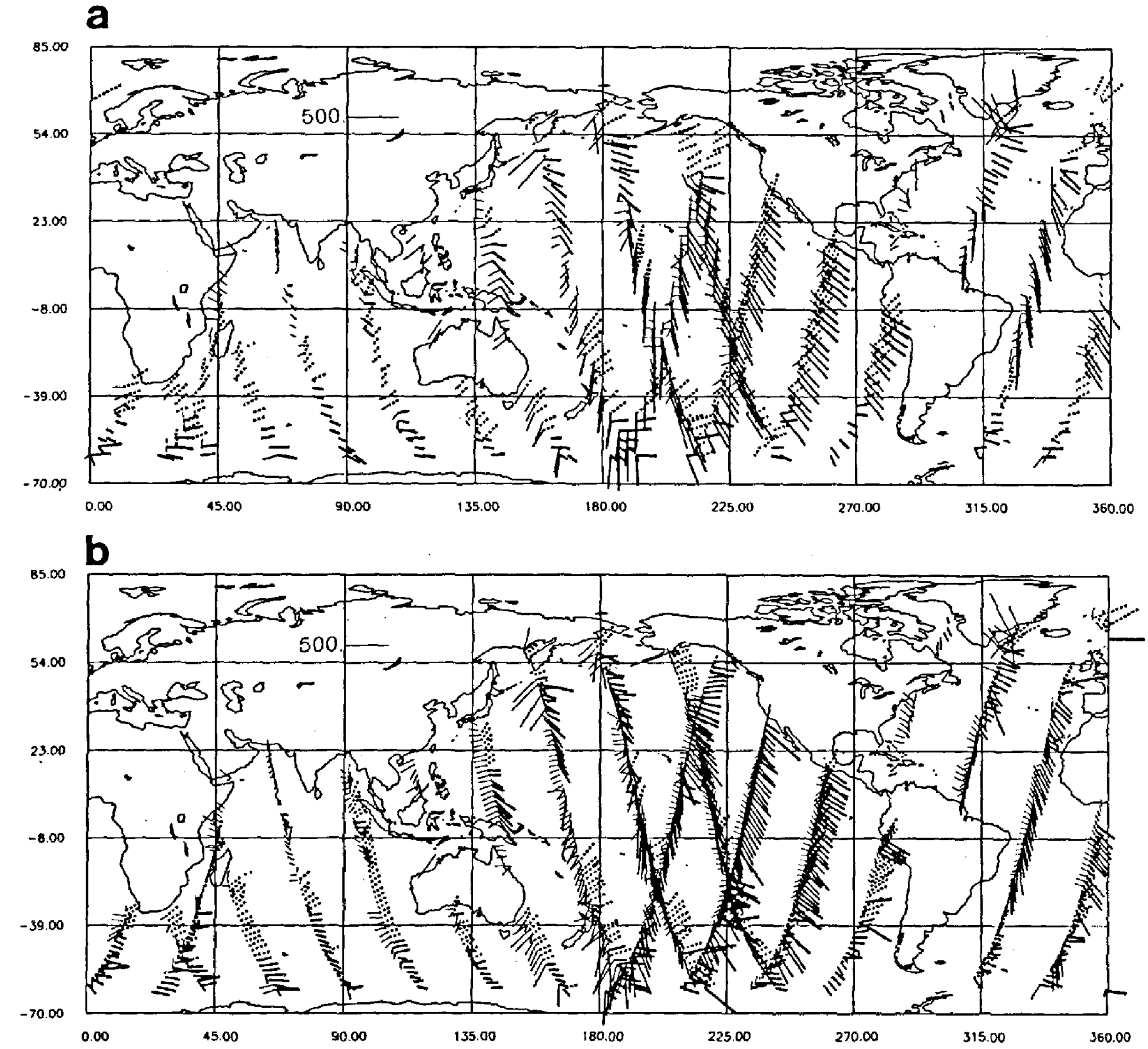

Fig. 4. Same as Fig. 3 for mean wave lengths and directions (length and direction of bars, respectively).

similation of altimeter data is that a number of – necessarily rather arbitrary – assumptions must be introduced to translate the information of a single wave height measurement into corrections for the entire two-dimensional wave spectrum. This difficulty can be resolved by using also the two-dimensional spectra retrieved from the SAR wave mode data. The present schemes can be readily generalized to these data by using the reduced set of spectral partitioning parameters. Optimally analyzed fields of the mean parameters of the partitioned wave systems are generated by the same optimal interpolation scheme used to create optimally analyzed fields of significant wave heights. These data are then used to reconstruct the corrected wave spectra. Since the wave spectrum can normally be well characterized by its wave-system parameters (which can be extended to a larger set if necessary), the extended scheme avoids the ambiguity problems of using only wave height data. The corrections of the local wind sea spectrum can be used to infer corrections of the local wind forcing. A further,

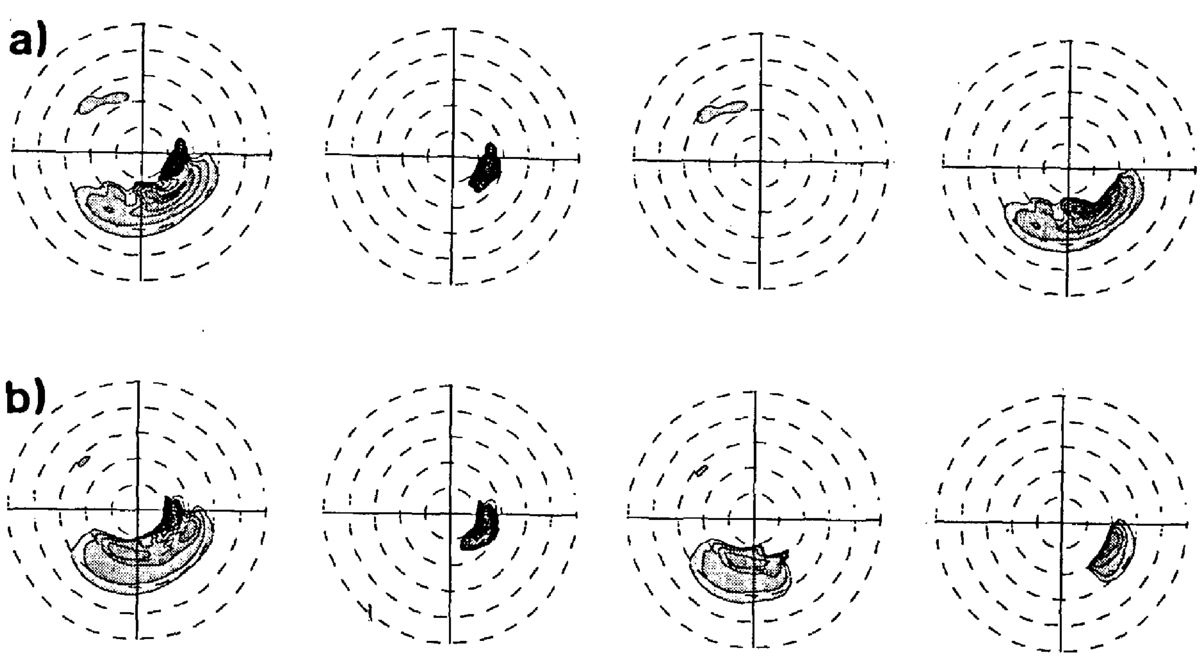

Fig. 5. Two-dimensional wave spectrum and its partitioned wave systems for WAModel (panel a) and SAR derived (panel b) at 33W, 35N, 30th January, 1993 at 12:43

but more difficult, step is then to follow the individual wave systems back to their origin and correct the wind fields in the past also (*cf.* Komen *et al.*, 1994).

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