OCEAN WAVES ASSIMILATION

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1. INTRODUCTION

Research on, and the development of, assimilation schemes for wave data is at a relatively early stage of development, certainly when compared to atmospheric data assimilation. There are two reasons for this. In contrast to the atmospheric problem, ocean waves are more sensitive to boundary conditions such as the forcing by wind than to the initial conditions. Thus if one forces a wave model by means of analysed winds from an atmospheric model, already a reasonably reliable "analysed" wave field may be obtained. The second reason for the slow development of wave data assimilation schemes has been lack of global wave data. This situation has changed dramatically in recent years with the launch of satellites such as Geosat, ERS-1 and ERS-2. For example, ERS-2 now provides a wealth of data on the sea state (wave heights (altimeter) and wave spectra (SAR)) and the low level wind (scatterometer).

In this lecture we shall try to summarise recent developments in wave data assimilation where we start with simple OI schemes for wave height data. It should be realised, however, that one then faces a problem of indeterminacy because the basic quantity in a wave model is the wave spectrum which has typically 300 degrees of freedom while only one piece of information is supplied, namely the wave height which is related to an integral over the wave spectrum. Initially, the many degrees of freedom problem was solved by using some simple scaling laws which follow from our knowledge of wave evolution. This approach works well for wind sea (waves under the direct influence of wind) but may not be reliable for swell (because no simple scaling law exists). Nevertheless, both UKMO and ECMWF have been running the simple OI scheme operationally since the middle of 1993. Because of the strong coupling between wind and waves in case of wind sea, the ECMWF scheme also provides an estimate of the local wind speed which is consistent with the waves and which is used to drive the ocean waves. We shall briefly summarize the present operational performance of the ECMWF wave data assimilation scheme, where we emphasize the quality of the observations (ERS-1 and ERS-2 altimeter) used in the assimilation scheme. By a comparison with an independent wind speed data set it will be shown that the inferred wind speed, consistent with the waves, provides useful information. This confirms on the one hand the quality of the ERS altimeter data and on the other hand the quality of the wave model. Presently, the quality of the wave analysis is so high that it can be used for quality control of observations. An example illustrating this point is given.

Another way of circumventing the many degrees of freedom problem is by supplying more observed information, for example by using the two-dimensional SAR spectrum. This is a recent development at MPI, Hamburg and first results are already interesting enough to discuss. Recent improvements in the SAR retrieval algorithm suggest a promising future for SAR data assimilation.

Finally, perhaps the most elegant way to solve the many degrees of freedom problem is the use of a variational approach which takes the wave model dynamics into account (*de las Heras*, 1994). We will show that wave data may provide information on the surface wind speed and surface stress. Combined with the recent results of *Thépaut et al.* (1993) it follows that wave data may even give beneficial information on the atmospheric state throughout the troposphere. In order to enjoy this benefit, however, a coupled wind-wave model is required. In closing, we also discuss an alternative method (the Green's function technique), to obtain the minimum of a cost function in a more efficient way.

Many of the developments discussed here may be found in *Komen et al.* (1994).

2. OPTIMUM INTERPOLATION

The optimum interpolation method described in this Section was developed for the WAM model (*Komen et al.*, 1994) and is operational at ECMWF. Similar single-time level data assimilation techniques have been applied by *Esteva* (1988), *Thomas* (1988), *Janssen et al.* (1987, 1989), *Hasselmann et al.* (1988), and *Francis and Stratton* (1990).

The method, developed by *Lionello et al.* (1992), consists of two steps. First a best guess (analysed) field of significant wave height is determined by optimum interpolation (*Lorenc*, 1982) with appropriate assumptions regarding the error covariances. Then, this analysed field is used to retrieve the full two-dimensional wave spectrum from a first-guess spectrum, introducing additional assumptions to transform the information of a single wave height spectrum into separate corrections for the wind sea and swell components of the spectrum. For both the wind sea part and the swell part of the wave spectrum the analysed spectrum, $F_{an}(f, \theta)$ (where f is the frequency and θ the direction of the waves) is computed from the first-guess spectrum $F_{fg}(f, \theta)$ and the analysed wave heights $H_{s,an}$ by rescaling the spectrum with two-scale parameters A and B:

$$F_{an}(f, \theta) = A \; F_{fg}(Bf, \theta) \tag{1}$$

Different techniques are applied to compute the parameters A and B for the wind sea part and the swell part of the spectrum. For details we refer to *Komen et al* (1994). We shall only discuss the wind sea case to emphasize the strong coupling that exists between wind and waves. For wind sea it is known since *JONSWAP* (1973) that the wave spectrum has a universal shape which is determined by a single parameter, namely the wave age $\chi = c_p/u_*$ (where c_p is the phase speed of the peak of the spectrum). For the non-dimensional energy $\varepsilon_* = g^2\varepsilon/u_*^4$ (where ε is the wave variance $\int df d\theta \; F(f,\theta)$) the following empirical growth law for wind sea exists

$$\varepsilon_* = \text{const} \;\; \chi^3 \tag{2}$$

Since the first guess friction velocity was used to generate the waves and the first guess peak phase speed c_p is known, the first guess wave age χ_{fg} may be obtained. Assuming that the wave age is correctly estimated, the analysed height then yields a best estimate of the friction velocity $u_{*,an}$ and the peak frequency $f_{p,an}$. For example, with the significant wave height $H_s = 4\sqrt{\varepsilon}$,

$$u_{*,an} = u_{*,fg} \sqrt{\frac{H_{s,an}}{H_{s,fg}}} \tag{3}$$

The best estimate wave height and peak frequency then determine the two scaling parameters A and B from (1) as follows:

$$A = \left(\frac{H_{s,an}}{H_{s,fg}} \right)^2 B \text{ and } B = \frac{f_{p,an}}{f_{p,fg}}$$

The analysed winds $u_{*,an}$ are then used to drive the wave model. In a comprehensive wind and wave assimilation scheme, the corrected winds should also be inserted into the atmosphere assimilation scheme to provide an improved wind field in the forecast. This step has not been implemented yet as it required the development of a coupled wind-wave model.

This OI scheme has been operational at ECMWF since August 1993. Extensive pre-operational tests with the scheme revealed that the assimilation scheme works satisfactorily. Fig 1 shows the impact of data assimilation (using ERS-1 altimeter data) on model forecasts in the northern and southern hemispheres and in the tropics for March 1992. As can be seen, the impact of data assimilation on forecast wave heights decays most rapidly in the wind sea regions in the North. The reason for this rapid loss of measured information is most likely that the corrected winds are not used in the atmospheric assimilation. On the other hand, the impact on the forecast in the tropics (this area has mainly swell with longer memory) can still be clearly seen after five days.

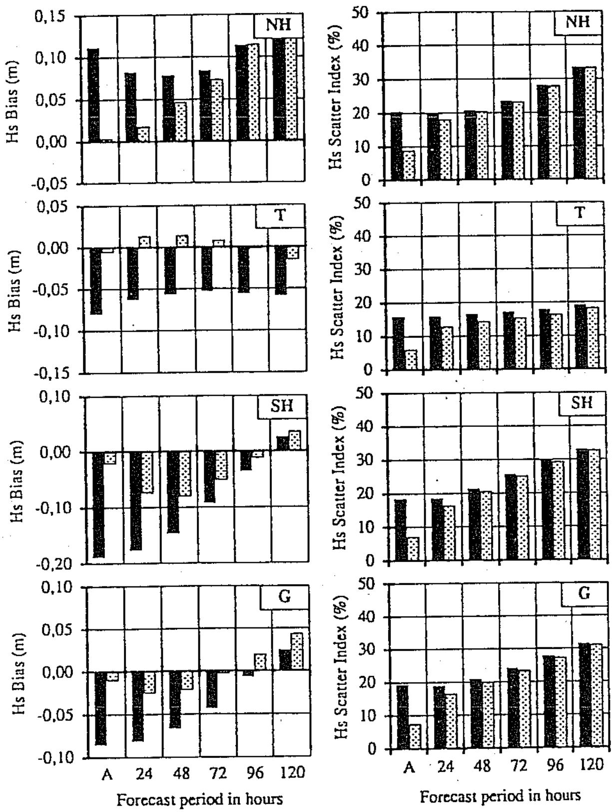


Fig 1 Comparison between model forecast and altimeter observations in March 1992. The panels show the bias (left) and scatter index (right) for the analysis (A) and five forecast ranges. Full bars denote the reference run, dotted bars the assimilation run. From top to bottom: Northern Hemisphere (NH), tropics (T), Southern Hemisphere (SH) and global (G).

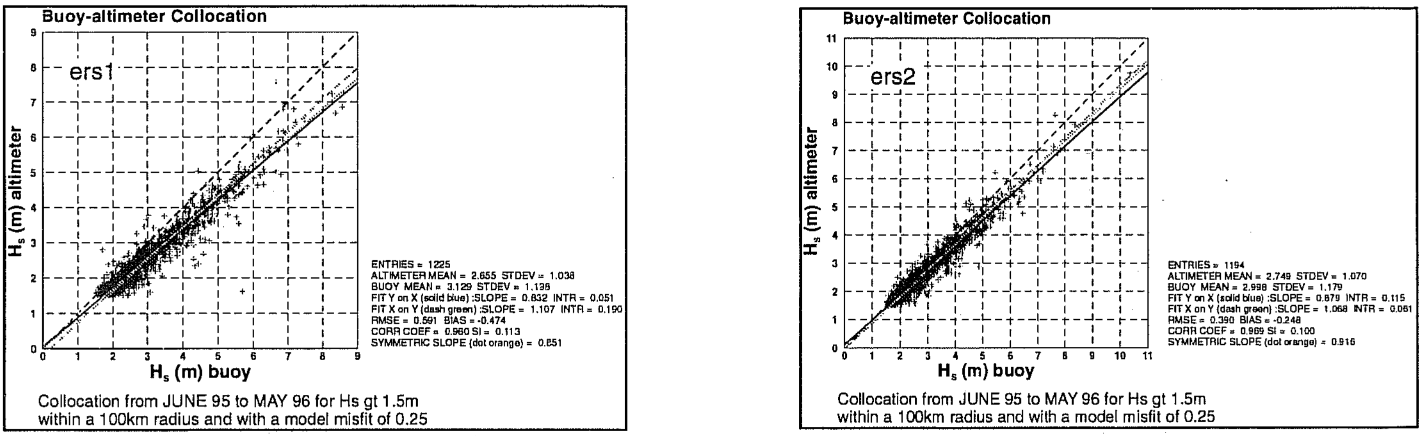


Fig 2 Comparison of ERS-1 (2a) and ERS-2 altimeter wave heights with buoy data over the period June 1995 until May 1996.

The ECMWF assimilation scheme uses only wave height data from the ERS-1 and ERS-2 altimeter, while buoy data are not being assimilated and may therefore be used for verification purposes. The success of an assimilation scheme depends, of course, to a certain extent on the quality of the observations being assimilated. By comparing ERS-1 and ERS-2 altimeter wave heights with collocated buoy data over a one year period in 1995-1996, ERS-1wave height data were shown to underestimate wave height by 15% (see Fig 2a), while verification of the wave height analysis, based on ERS-1 data, against buoy gave a negative bias of about 25 cm (see Fig 3). On the other hand, the ERS-2 wave height data showed less problems in this respect (see Fig 2b). As may be seen from Fig 3, the switch from ERS-1 to ERS-2 data in the ECMWF wave assimilation scheme at the end of April 1996 resulted in a beneficial impact as the bias is now reduced to a few centimetres while parameters such as symmetric slope have improved as well. Although the ERS-1 wave analysis showed a reasonable quality, it may be concluded that with the switch to ERS-2 data in the assimilation, the quality of the wave analysis has improved.

In passing, we remark that independent of the data used in the assimilation, the wave analysis may be used as quality control of buoy observations. This is illustrated in Fig 3 where we concentrate on the time series for the root mean square error of wave height for different areas. Inspection of these time series shows the north-east Atlantic area as an outlier in the period January-July 1995. Prompted by our concerns, the data producer replaced the communication software buoy by buoy and the consequences of that action are clearly visible in the second half of 1995, and the first half of 1996.

Finally, we discuss the quality of the analysed wind speed (consistent with the observed wave height) by means of the case of December 16, 1995, which occurred in the data void area of the Labrador Sea. Fig 4a shows the analysis increments in wave height for that area, while Fig 4b shows the increments in wind speed caused by the wave height observations. The winds, as updated by the combination of wave observations and wave model, verify well against the independent radar altimeter wind speeds. This is illustrated in Fig 4c which shows along the satellite track winds from the atmospheric analysis (NOASSIM), radar altimeter wind speeds (ERS-1 RA) and corrected winds by the wave data assimilation

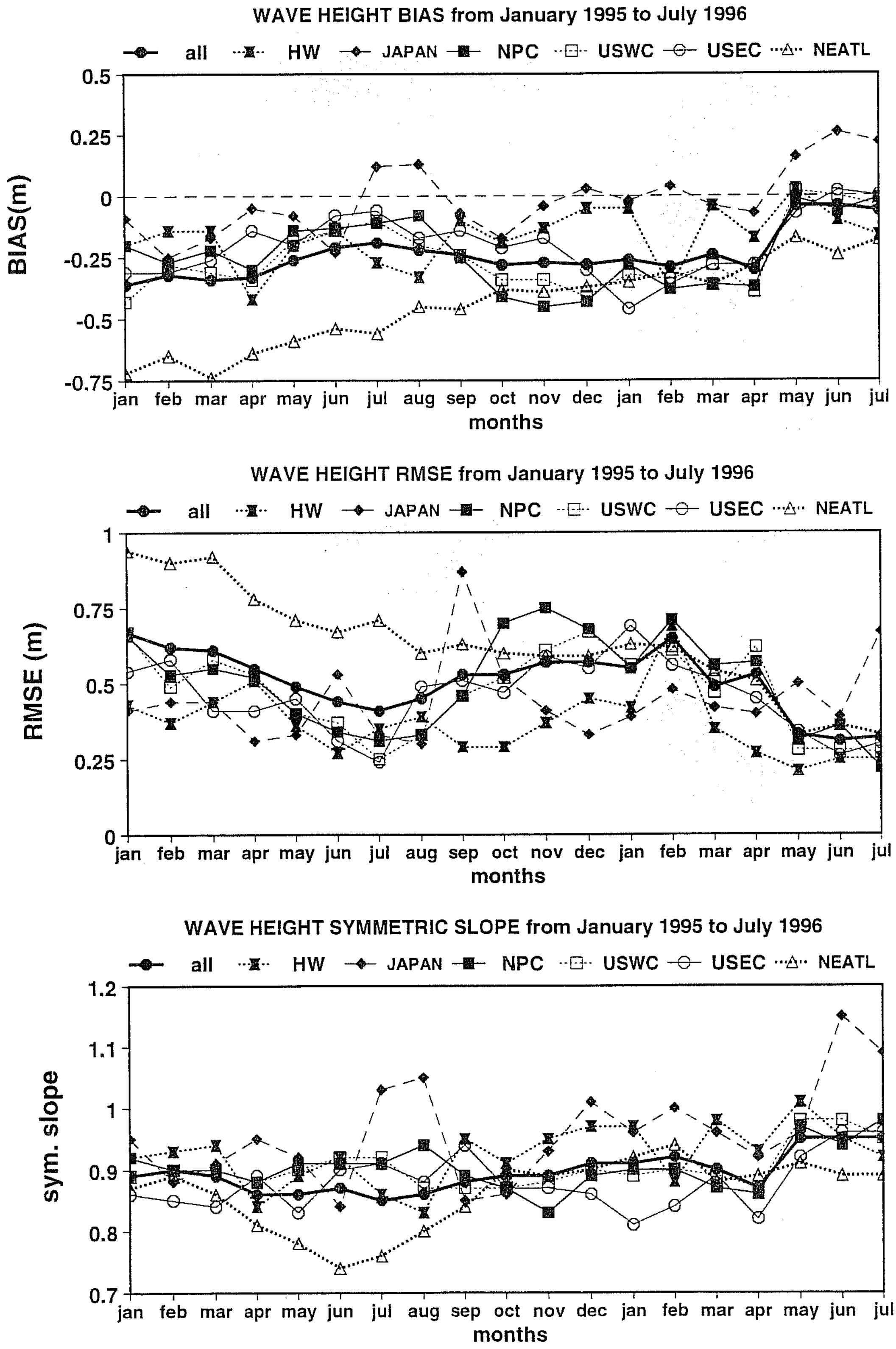


Fig 3 Time series of monthly statistics from the comparison of wave model analysis with observations at 30 ocean (deep water) buoys. The buoy data are obtained every hour via the GTS and a basic quality control procedure is used to remove outliers before averaging over 6 hour time windows which are centred around synoptic times. Bias, root mean square error (RMSE) and symmetric slope are plotted for all 30 buoys as well as for particular areas as Hawaii (HW, 4 buoys), Japan (2 buoys), the North Pacific (NPC, 4 buoys, off the West and East Coasts of the US (USWC, 5 buoys, USEC, 6 buoys) and the North East Atlantic (NEATL, 6 buoys). Negative bias denote lower model values with respect to the buoy observations

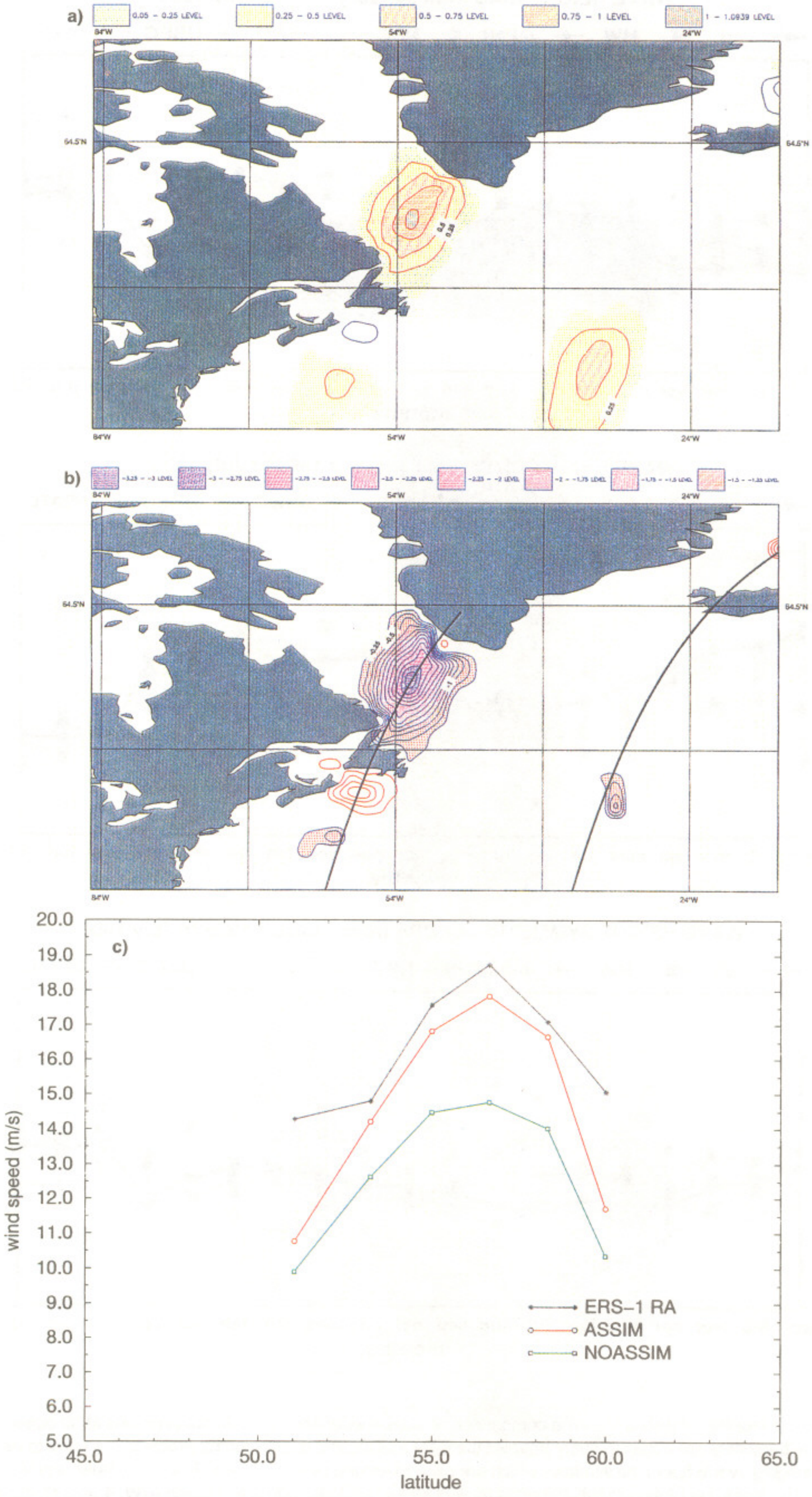


Fig 4 Increments in wave height (4a) and wind speed (4b) caused by the assimilation of ERS-1 data for December 16th, 12Z, 1995. Fig 4c shows the validation of winds according to wave analysis and atmospheric analysis against independent radar altimeter wind speeds.

scheme (ASSIM). The differences between ASSIM and NOASSIM winds amount to 3 m/s and ASSIM is closer to the truth as presented by the ERS-1 radar altimeter. This suggests that the winds from the wave data assimilation scheme contain useful information for the atmospheric model.

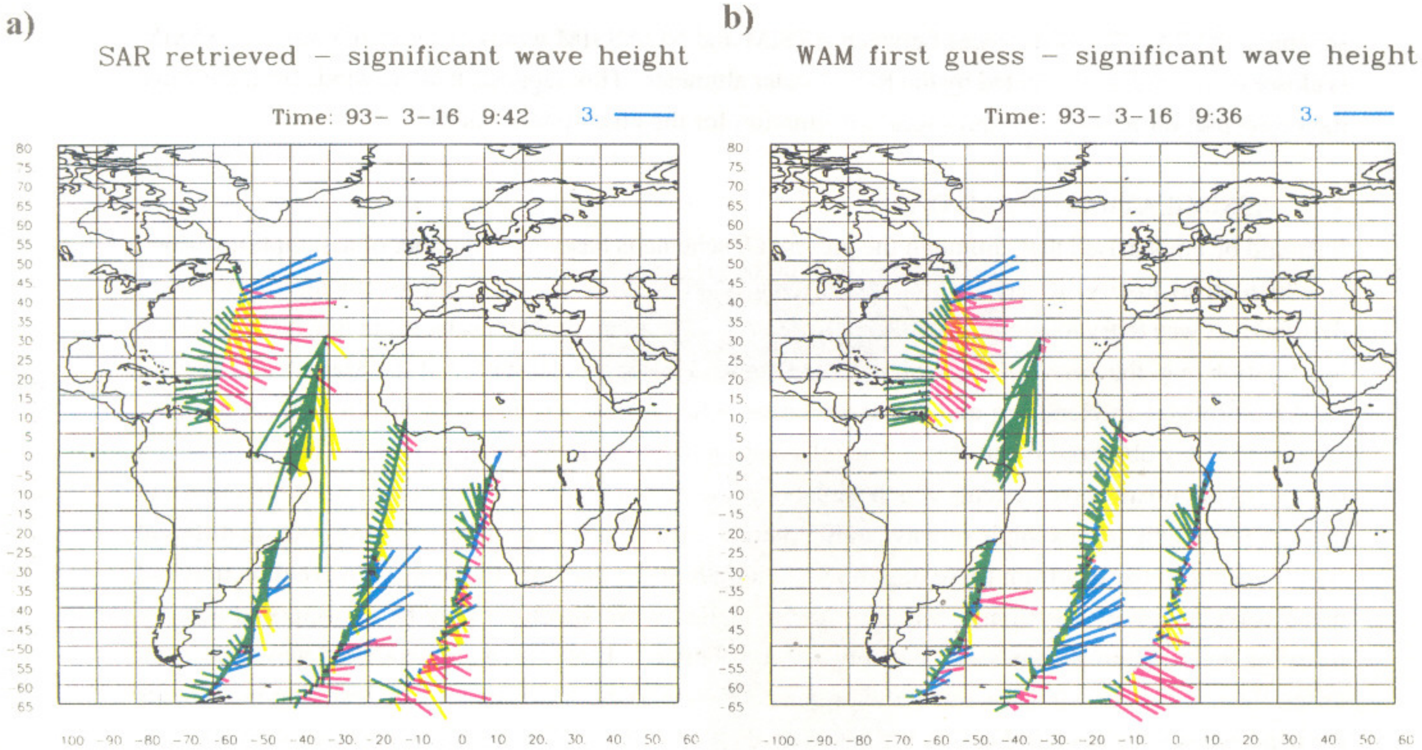
3. ASSIMILATION OF SAR DATA

It should be emphasised that, although the present OI scheme is based on a number of assumptions which are difficult to justify, it seems to work reasonably well. Nevertheless, improvements to this seem desirable. A way to try to circumvent the many degrees of freedom problem is by supplying more observed information, e.g. the two-dimensional SAR spectrum. This approach started at the Max-Planck Institut für Meteorologie in Hamburg and the assimilation scheme is an extension of the OI scheme but now applied to many observed parameters. The information in the SAR spectrum is reduced by identifying a number of dominant wave systems which are labelled by means of wave energy, mean wave direction and mean wave length. An example of wave train separation is given in Fig 5 where the bars refer to different wave systems in the spectrum (here direction and length of the bar refer to the mean wave direction and mean wave height of a system). Similarly the modelled wave spectrum may be decomposed and, by rescaling and rotation, an analysed spectrum may be obtained. If observed and modelled wave spectrum differ, then, in case of wind sea, this will imply a correction to the wind speed. The resulting increments for wind speed are shown in Fig 2 as well and may be up to 5 m/s. This result suggests the usefulness of wave data for the atmospheric state over the ocean.

Recent improvements in the SAR retrieval algorithm (*Hasselmann et al*, 1996) have increased confidence in the usefulness of SAR image data in a real time data assimilation system. This is illustrated in Fig 6 where results of the original retrieval algorithm and the improved one are compared with WAM model wave heights. While the use of the original algorithm (*Hasselmann and Hasselmann*, 1991) would have led to considerable inconsistencies with the radar altimeter data, the new algorithm has much improved in this respect.

4. ON VARIATIONAL WAVE DATA ASSIMILATION

The most promising way to avoid the problems of wind sea, swell separation and to avoid the many degrees of freedom problem seems to be a variational approach which takes the wave model dynamics into account. This approach was followed by *de las Heras* (1994), who studied wave data assimilation in the relatively simple case of the generation of ocean waves by wind. As the control variable, the wind speed at 10 m height was taken. The cost function was quadratic and penalized deviations between observed and analysed wind field under the constraints imposed by the WAM model (this, of course, required its adjoint). True and first guess wave spectra were obtained by running the single grid point version of the WAM model for one day with a wind speed of 18 and 12 m/s respectively. Wave heights of the "true" model run were regarded as observations which were assimilated every 3 hours. No wind data were assimilated. Fig 7 shows the resulting analysis and the comparison with the first guess and the truth for a number of parameters. The agreement is impressive for wind speed, friction velocity and the mean frequency. The approach was equally successful for turning wind sea cases (provided the mean wave direction was used in the assimilation) and for cases of simulated observed wave height not generated by the WAM model itself. The work of *de las Heras* (1994) (see also *de las Heras et al*, 1994) therefore shows that a variational approach seems promising. Clearly, wave data alone may provide information on



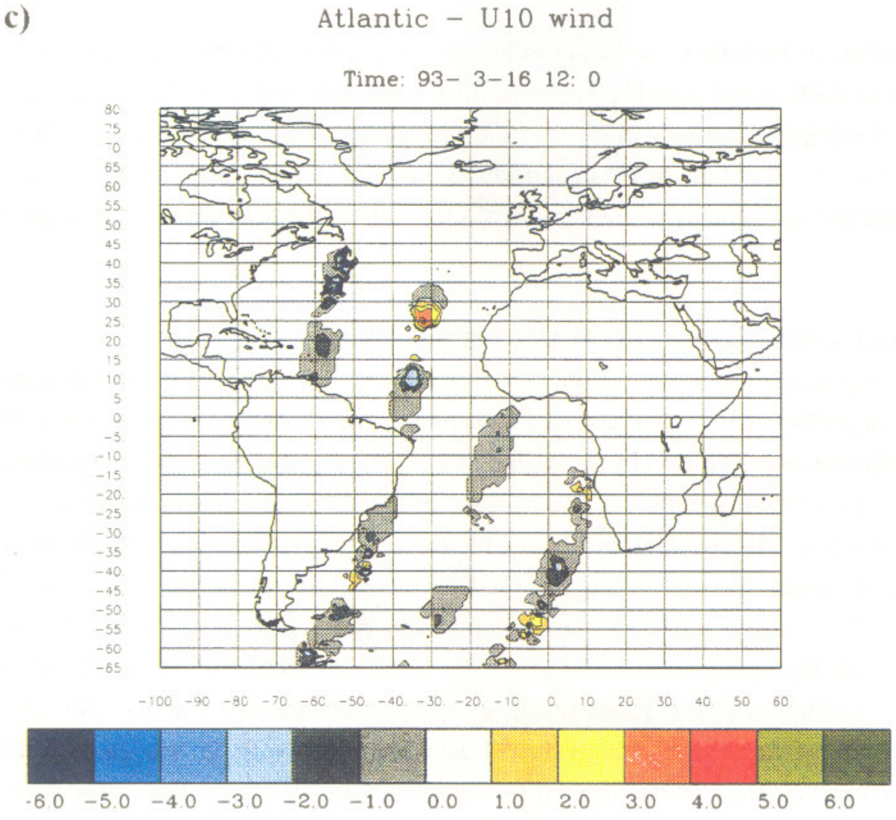


Fig 5 Mean wave heights (proportional to length of bars) and direction of major wave spectrums for 16/3/93 at 12Z. Panel a) ERS-1 SAR derived spectrum; panel b) first guess WAM spectrum. In panel c) the wind speed increment is shown as a result of the assimilation of SAR data (obtained from S. Hasselmann)

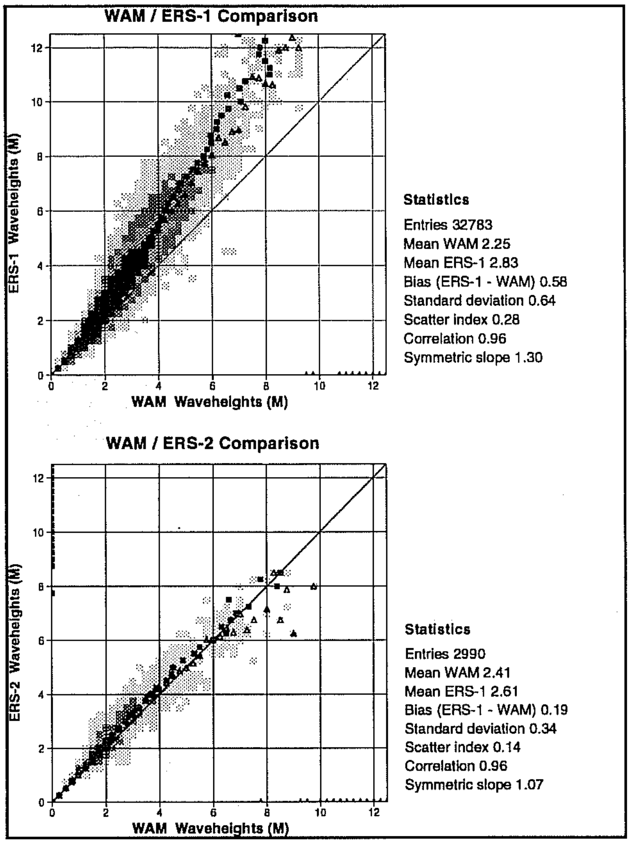


Fig 6 Comparison of retrieved SAR wave heights from old and improved SAR inversion algorithm against WAM modelled wave height.

the surface wind and surface stress. In the context of a coupled wind-wave model, wave data may therefore even give beneficial information on the atmospheric state throughout the troposphere.

The variational approach needs to compute the cost function gradient and to integrate the wave model equations a large number of times in an iterative search for the cost function minimum. This expensive approach is avoided by the Green's function approach advocated by *Bauer et al*, 1996 (see also *Komen et al*, 1994). Here, the perturbed wave model equations determining the response of the wave spectrum to small perturbations of the forcing wind field are inverted explicitly. The wave spectrum perturbations are thus expressed in terms of the wave-spectrum impulse response or Green's function as a space-time integral over the wind field perturbations. The cost function is thereby reduced to a function of the forcing wind field only, and its minimum can be readily computed. Unfortunately, the exact determination of the Green's function of the perturbed wave model is, in practice, an insoluble task, so that the approach can be carried through only after several approximations have been introduced. The advantage of the Green's function technique, however, is that the required computation time, in contrast to the adjoint approach, is of the same order as integration of the model itself, so that it can be readily implemented operationally. The success of this approach therefore critically depends on the above mentioned approximations of the Green's function. Results where the Green's function is assumed to be highly localised in space and time are discussed in *Komen et al* (1994) and in *Bauer et al* (1996).

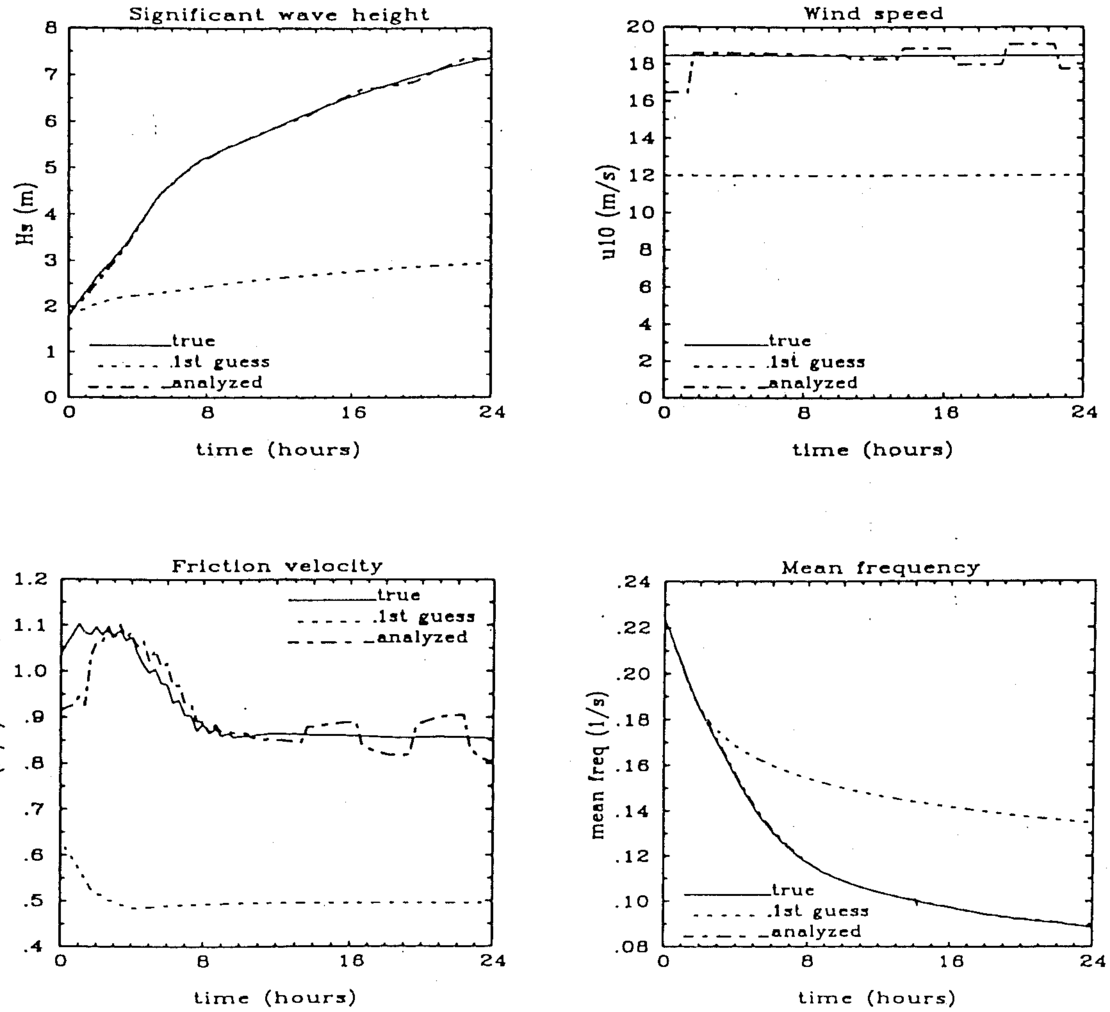


Fig 7 Comparison of true, first-guess and analyzed wave height, wind speed, friction velocity and mean frequency, respectively. The adjoint method is used to assimilate wave-height observations in case of a constant wind.

5. CONCLUSION

We have reviewed recent developments in wave data assimilation. Although this is a relatively young field, considerable progress may already be reported. Presently, OI schemes using altimeter data are operational at a number of weather centres. In the near future, it is expected to utilise the wealth of data from the SAR. These satellite data are beneficial for the quality of the ocean wave field. However, wave data also have the potential to provide useful information on the weather over the oceans because of the strong interaction between wind and waves. Optimal benefits for the atmosphere are expected in the context of a coupled wind-wave model.

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