Assimilation of remotely sensed wave data at the Met Office

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1. The Met Office suite of wave models

The Met Office runs a suite of wave models, from global to regional European and finally UK waters. The models are used to provide real-time forecasts out to five days ahead, for a range of users. A particular application of output from the global wave model is in prediction of long period swell, particularly to help predict vessel response, for example for heavy lift operations, or for pipe-laying vessels, or for semi-submersible rigs engaged in offshore exploration drilling. Examples of this application are given in the next section.

The global wave model (Figure 1) runs on a regular latitude-longitude grid with resolution of 5/9° by 5/6°, approximately 60km in mid latitudes. This is the same resolution as the NWP model which provides the

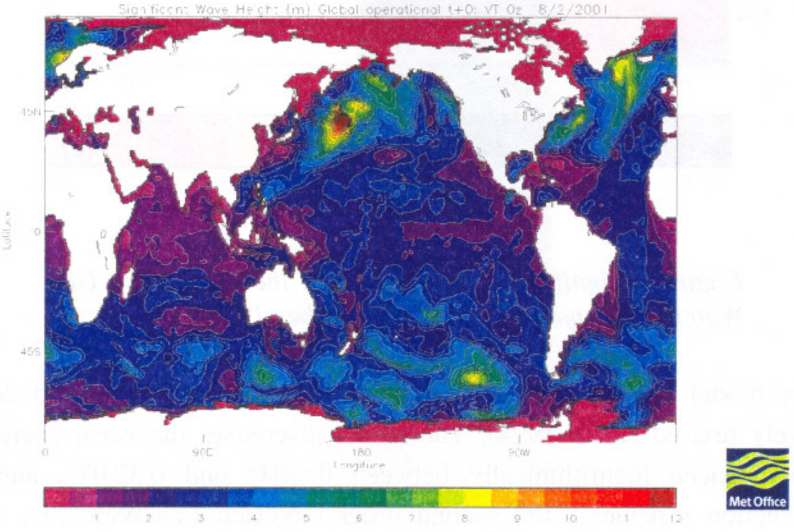

Figure 1 Significant wave height in the global wave model, including assimilation of altimeter data from ERS-2

surface winds, and the wave model data points coincide with the NWP model wind data points. The wave model runs twice daily, taking hourly winds from the global NWP model run, and provides a forecast to 5 days ahead. The ice edge analysis is updated daily, taken from the analysis used by the NWP model. "Fast delivery" wave and wind data from the ERS-2 altimeter are assimilated into the global model - more detail of this is given below. For all areas, the wave model formulation includes shallow water physics - depth dependent group velocity, bottom friction and depth refraction.

For the European area a nested model is run covering the NW European shelf and Bay of Biscay, the Mediterranean, Baltic and Black Sea. Resolution of this model is 0.4° by 0.25°, approximately 35km. The model is driven by hourly winds from the preliminary run of the global NWP model, which completes around 0230 and 1430 UTC each day. There is no data assimilation in this wave model.

For UK waters and the NW European shelf, the wave model is run on the same grid as the operational storm surge model (1/9° by 1/6°, approximately 12km), nested into the global model (Figure 2). In this implementation the wave model additionally calculates the effect on the waves of time-varying wave current interactions, using hourly currents taken from the operational storm surge model. The UK waters wave model provides a 48 hour forecast, updated four times daily, using forcing winds from the Mesoscale NWP model. An additional 5-day forecast using global NWP winds, but without wave-current interactions, is run twice daily.

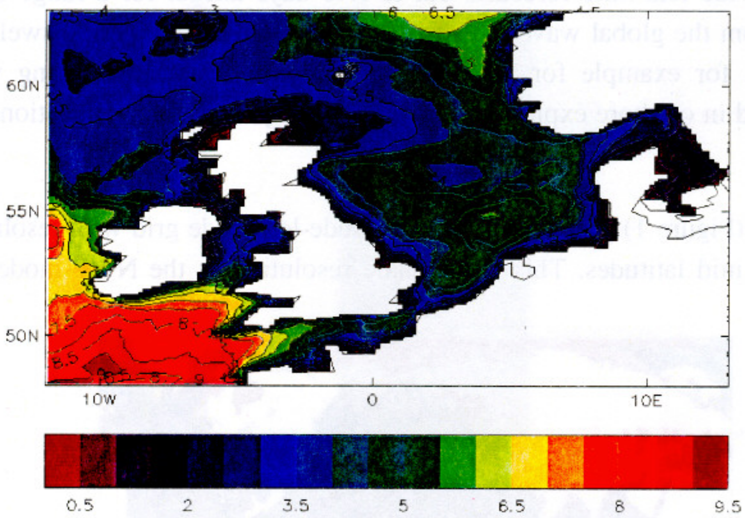

Figure 2 Significant wave height in the Met Office UK Waters wave model, 12z 25th December 1999

The Met Office wave model is the second generation model first developed and described by Golding (1983), later extensively revised (Holt, 1994). The model discretises the wave energy spectrum with 13 frequency components spaced logarithmically between 0.04Hz and 0.324Hz, and uses 16 direction components. The advection scheme is the second order modified Lax-Wendroff, which gives a good representation for long travelled long period swell.

2. Key applications

A traditional use for wave model output has been the prediction of wave height, for ship routing, offshore operations and coastal flood defence. However in recent years the use of the forecast wave energy spectrum for prediction of vessel response has become a key specialist application. Here the large semi submersible rigs, or heavy lift barges, or pipe laying vessels are particularly sensitive to the presence of long period wave energy. A heavy lift semi-submersible crane vessel is shown in Figure 3. Here the module being lifted will weigh around 10,000 tonnes. For a semi submersible rig the typical resonant period is at around 19 seconds or longer. Because of this, development of the Met Office wave model is concentrating on improving the predicted wave energy spectrum representation of long period swell. Key to this is the evaluation and use of the wave energy spectrum observed from satellite borne synthetic aperture radar, which is described in more detail later. Figure 4 shows a typical distribution of 18 seconds wave energy in the global wave model.

Figure 3 A heavy lift semi submersible crane vessel in operation

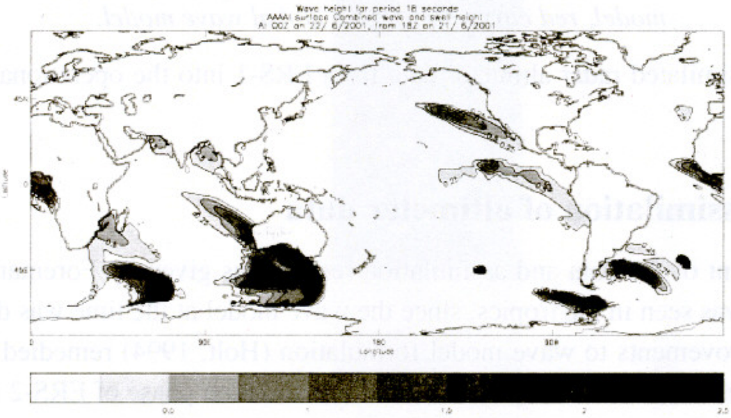

Figure 4 The distribution of waves of 18 seconds period in the Met Office global wave model, 22nd June 2001 (significant wave height, m)

3. Assimilation of Altimeter data

The radar altimeter on ERS-2 takes an observation of significant wave height and 10m windspeed every second, giving a spacing of 7km between observations along the satellite track. Prior to assimilation, the altimeter data are binned into 20-second consecutive observations, and quality checked. Those passing the buddy check are averaged to give a "super observation" representative of approximately 140 km. These averaged observations of wave height and windspeed are used in assimilation into the global wave model, using an analysis-correction scheme based on that previously used by NWP (Lorenc et al 1991). Three iterations are applied, with correlation length reducing to 300 km for the third iteration. Each super-observation is used once only, at the nearest hour to the time of validity.

The increments to wave height are partitioned to the wave energy spectrum following the scheme of Thomas, 1988. After assimilation the modelled windsea distribution is consistent with the observed windspeed, and fits a member of the JONSWAP family. This scheme assumes that the time evolution of modelled winds has been correct, though the value of windspeed may have been offset from that observed. The model swell energy is scaled up or down so that the modelled total significant wave height matches the observed, and care is taken to ensure that the pattern of the wave energy spectrum is maintained.

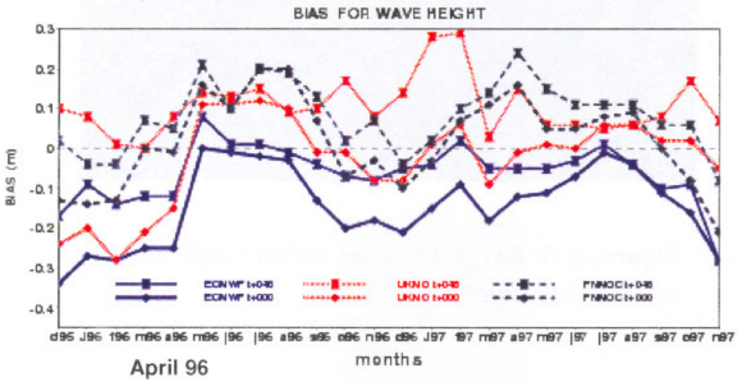

Figure 5 Monthly mean bias of significant wave height, compared to moored buoys, from December 1995 to November 1997. Blue curve, ECMWF global model, red curve Met Office global wave model.

The Met Office first assimilated radar altimeter data from ERS-1 into the operational global wave model in June 1993.

4. Impact of assimilation of altimeter data

A preliminary assessment of the data and assimilation results was given by Foreman et al, 1994. Initially a strong positive impact was seen in the tropics, since the wave model at the time was deficient in its treatment of swell. However improvements to wave model formulation (Holt, 1994) remedied this, and the impact of altimeter data became less marked. During the calibration-validation phase of ERS-2 in early 1996 it became clear that the characteristics of the fast delivery altimeter data differed between ERS-1 and ERS-2. A reduction in the overall slightly negative mean bias in those global wave models (ECMWF, Met Office) assimilating ERS data was noticed on the switch to ERS-2. Figure 5, taken from Bidlot et al, 1997, clearly shows the change in April 1996, in bias of global wave model significant wave height compared to moored buoy observations.

Normally it is not possible to detect with any certainty the direct impact of altimeter assimilation on a global wave model field of significant wave height (see for example Figure 1). Figure 6 shows the modelled significant wave height in the North Atlantic for ex-hurricane Irene in October 1999, along with the coverage of altimeter wave data for the 12 hour period, available for assimilation into the model.

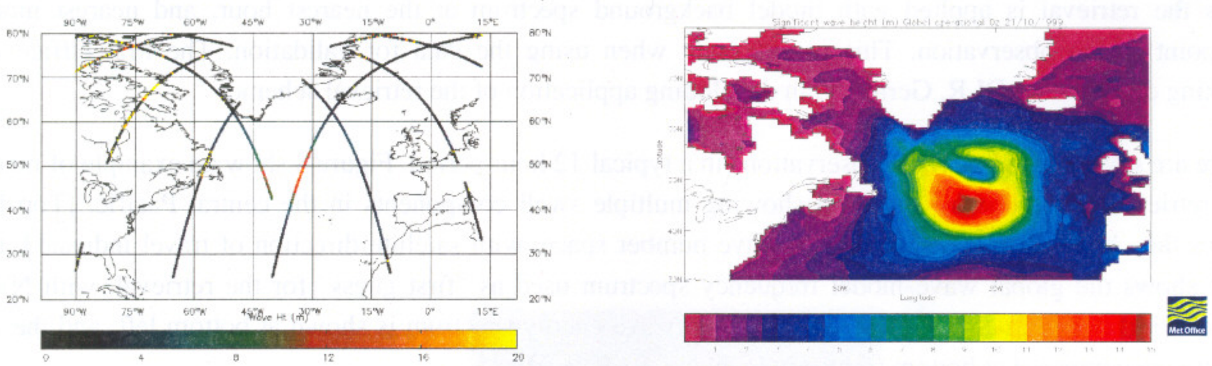

Figure 6 Significant wave height in the north Atlantic under ex-Hurricane Irene, October 1999. (Left) 12 hours of radar altimeter coverage from ERS-2 ending 00z 21st October (right) Met Office global wave model, 00z 21st October 1999

However during early 2001 it became clear that data quality from ERS-2 could become poor following satellite manoeuvres. In particular following the avoidance of the Leonid meteor shower the wind data quality was degraded for several weeks, since the altimeter was not quite pointing vertically. Following a period without supply of fast delivery altimeter data, in February 2001, the quality of data was poor when supply resumed. The impact of this is shown in Figure 7. For the present, ERS-2 altimeter data are not assimilated, pending the setting up of improved monitoring and tighter background checks prior to use.

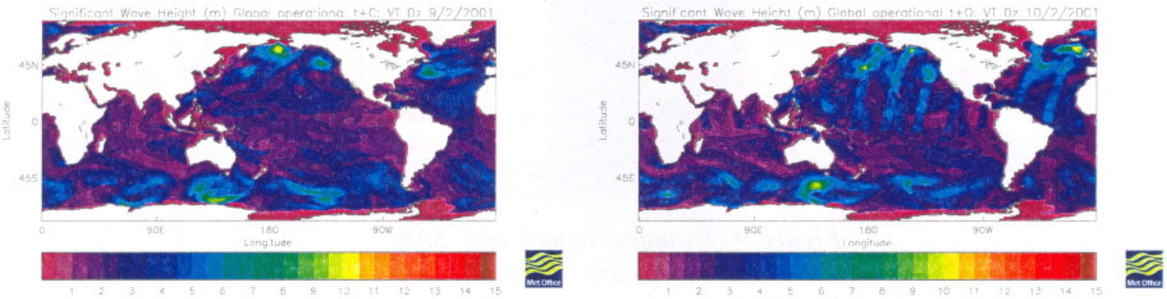

Figure 7 The impact of assimilating altimeter data on resumption of data flow in February 2001 (left) 00z 9th February, (right) 00z 10th February. Significant wave height (m) in the global wave model

5. Synthetic Aperture Radar observations of wave energy spectrum

The synthetic aperture radar on ERS-2 gives a wave observation every 200km along the satellite track. Because of the instrument geometry, the observation is some 250km to the right of the satellite track, and thus is at a different location to the altimeter observations. Each SAR observation consists of an imagette covering some 5 km by 10 km of the sea surface, which is then processed to give the power spectrum. A retrieval scheme is necessary in order to obtain the wave energy spectrum from this. The SAR provides information on waves longer than a given cut-off wavelength, which is typically around 100m.

From late 1997 the MPI retrieval scheme (Hasselmann et al, 1996) has been applied at the Met Office to the ERS-2 fast delivery SAR wave data. Initially co-located only in the north Atlantic, the global wave model has been extended to provide hourly spectra at the position of each observation in a given 12 hour period.

Thus the retrieval is applied with model background spectrum at the nearest hour, and nearest model gridpoint to the observation. This is important when using the data for validation. The Met Office are working closely with DLR, Germany, in developing application of the retrieval scheme.

There are several hundred SAR observations in a typical 12 hour period. Figure 8 show an example of model and retrieved wave energy spectrum showing multiple swell components in the central Pacific. [Top left shows the observed image spectrum in wave number space, with satellite direction of travel indicated, top right shows the global wave model frequency spectrum used as "first guess" for the retrieval, with NWP model wind direction also shown. The retrieved wave energy spectrum is shown at bottom left, and the 1D spectra are compared at bottom right.(model black, SAR red)].

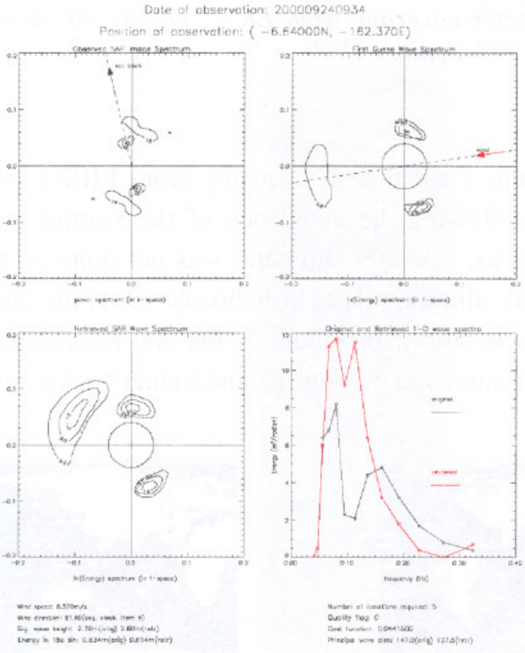

Figure 8 Example model and SAR wave energy spectra in the central Pacific

A comparison of 12 hours data with global wave model significant wave height is shown in the scatterplot in Figure 9a. There is generally good agreement between modelled and retrieved (observed) significant wave height. However when the comparison is extended to individual frequency components, some differences become apparent. Figure 9b shows the comparison for wave energy (significant wave height is plotted) at 8.8 seconds period. At these periods, agreement between model and observed is still good, as may be expected. Similar results apply for waves of up to some 12 seconds period. However comparison of longer period waves shows that the retrieval scheme significantly overestimates the wave energy present, when compared to the global wave model, Figure 9c. Alternatively it could be that the wave model underestimates the long period swell. Independent "ground truth" however suggests, at least for one site and time, that the wave model slightly overestimates the long period swell energy. Further work is required to compare SAR spectra derived from different retrieval techniques. This will be an important application of the ENVISAT ASAR wave observations.

Examination of individual cases also shows that the retrieval scheme has difficulties in light winds, where the scaling calculation can grossly overestimate the wave energy in the SAR retrieved spectrum. An example from a North Atlantic storm is shown at Figure 10. In these plots, the top left shows the observed power spectrum in wave number space, with satellite direction of travel indicated, top right shows the global wave

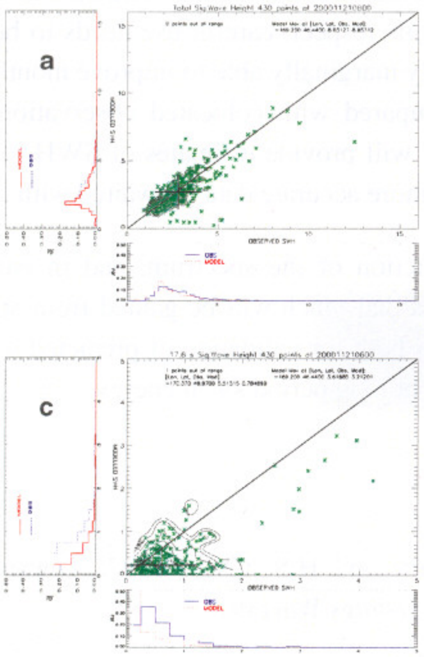

Figure 9 Comparison of global wave model with SAR retrieved significant wave height, 12 hours data on 21/11/2000 (a) total spectrum (b) waves at 8.8 seconds period (c) waves at 17.6 seconds period

model frequency spectrum used as "first guess" for the retrieval, with NWP model wind direction also shown. The retrieved wave energy spectrum is shown at bottom left, and the 1D spectra are compared at bottom right.(model black, SAR red). In Figure 10, the modelled NWP wind speed is 3.8 m/s, with modelled SWH of 6.15 m and SAR SWH of 18.9 m, in figure 10, 200 km along the satellite track, modelled NWP windspeed is 13.8 m/s with modelled SWH of 7.31m and SAR SWH of 8.08m

6. Future plans

Strategy for application of remotely sensed wave data is to use assimilation for added value, not for

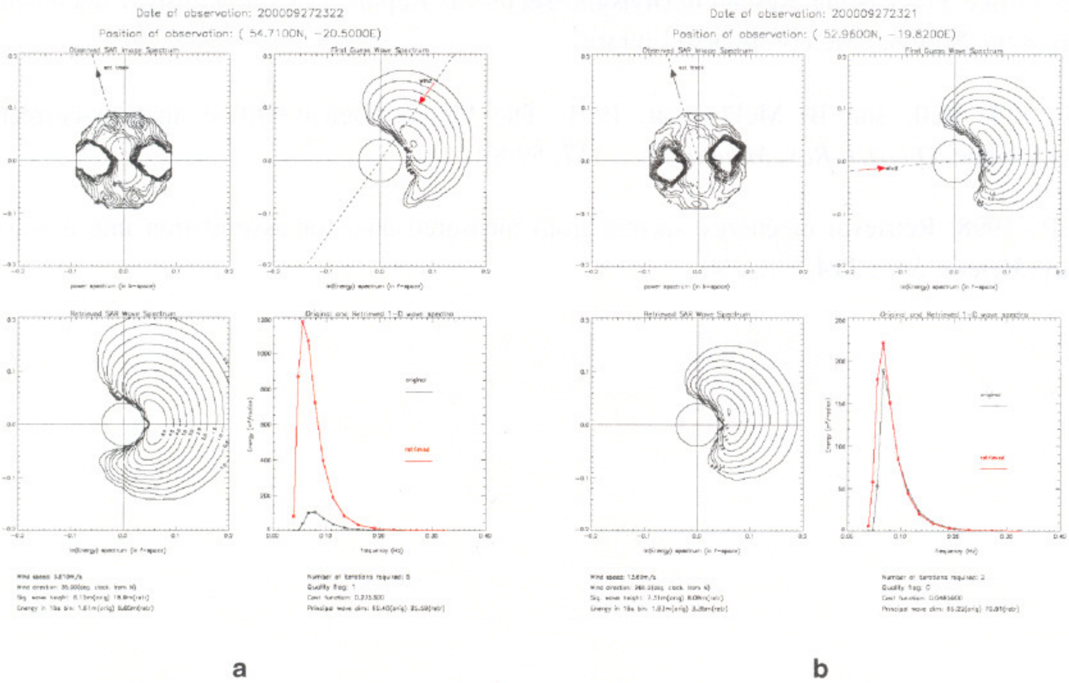

Figure 10 Comparison of two adjacent observed SAR spectra in a North Atlantic storm. September 27th 2000

correcting gross errors. With the improvement of wave models since the first attempts at assimilation, the impact of radar altimeter data is now much smaller. In this respect, careful use needs to be made of radar altimeter data. Assimilation of ERS-2 altimeter data is only marginally able to improve monthly mean bias of significant wave height in the global wave model, compared with colocated observations from moored buoys. The RA-2 instrument to be carried on ENVISAT will provide estimates of SWH to within 5% (for SWH>5m). or 0.25m for SWH < 5m. Application of this more accurate data is awaited with interest.

With model development focussing on improving prediction of the spectrum, and in particular on long period, low amplitude, long travelled swell, it is expected that much will be gained from application of the SAR observed wave energy spectrum. This will be useful both for validation of predicted wave spectra in a global wave model, and eventually for direct assimilation of long period swell energy.

References

Bidlot, J-R., M.W. Holt, , P.A. Wittman, R. Lalbeharry and H.S. Chen, 1997: Towards a systematic verification of operational wave models. *Conference Proceedings Waves97*

Foreman, S.J., M.W. Holt and S. Kelsall, 1994: Preliminary assessment and use of ERS-1 altimeter data. *J. Atmos. Oceanic Technol.*, **13**, 1370-1380

Golding, B.W., 1983: A wave prediction system for real time sea state forecasting. *Quart.J. Roy. Meteor. Soc.,* **109**, 393-416

Hasselmann, S, C. Bruning, K. Hasselmann and P. Heimbach, 1996: An improved algorithm for the retrieval of ocean wave spectra from synthetic aperture radar image spectra. *J Geophys Res* **101** 15823-15836

Holt, M.W., 1994: Improvement to the UKMO wave model swell dissipation and performance in light winds. Met Office Forecasting Research Division Technical Report 119 (unpublished document, copies available from the National Meteorological Library)

Lorenc, A., R.S. Bell, and B. McPherson, 1991: The Meteorological Office analysis-correction data assimilation scheme. *Quart.J. Roy. Meteor. Soc.*, **117**, 59-89

Thomas, J.P., 1998: Retrieval of energy spectra from measured data for assimilation into a wave model. *Quart.J. Roy. Meteor. Soc.*, **114**, 781-800