Extreme waves in the ECMWF operational wave forecasting system

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1. Introduction

The European Centre for Medium range Weather Forecasts (ECMWF) produces twice daily analysis and forecasts of the sea state over the world oceans. For wave modelling it relies on the development and maintenance of its version of WAM cycle 4 (ECWAM). In its current global configuration ECWAM is two-way coupled to the atmospheric model; it assimilates altimeter and ASAR data to produce its analysis. It is run in all forecasting systems in use at ECMWF, from deterministic and probabilistic 10 day forecasts, to monthly and seasonal time scales. Constant progress has been made in forecasting wave parameters such as wave height, wave periods and wave directions. This continued improvement has been fuelled by the frequent improvements to the forcing wind fields due to model changes as well as increases in model resolutions. Changes to the wave model have also been quite beneficial. With a current atmospheric model horizontal resolution of 25 km, the deterministic forecast model is able to represent the characteristics of the winds over the world oceans with some details. In turns, the wave parameters associated with stormy conditions are also well represented. The latest developments have been summarised in Janssen et al. (2005) and Janssen (2004).

2. Performance of the ECMWF deterministic model

Verification against wave observations is routinely performed to assess the quality of the wave model analysis and forecasts. Wave data from moored buoys and platforms that are broadcasted to the meteorological community via the Global Telecommunication System (GTS) are used. These data are not assimilated by the model and hence constitute an ideal independent data set. The necessary buoy data quality control and scale matching procedures were described in Bidlot et al. (2002). The method was extended to include data from platforms as described in Sætra and Bidlot (2004). Note that in this paper we will refer to these data as buoy data since the bulk of the data is from moored buoys, except if stated otherwise.

Fig. 1 shows how the quality of the wave height analysis has steadily improved with respect to buoy data both in terms of scatter index (standard deviation of the error normalised by the buoy mean) and bias (model – observation) since the beginning of operational production in 1992. In recent years, the wave height analysis has been found to be in very good agreement with buoys, with a small underestimation in winter (negative bias) and virtually no bias in summer. In relative term, the standard deviation of the error is larger in summer than in winter.

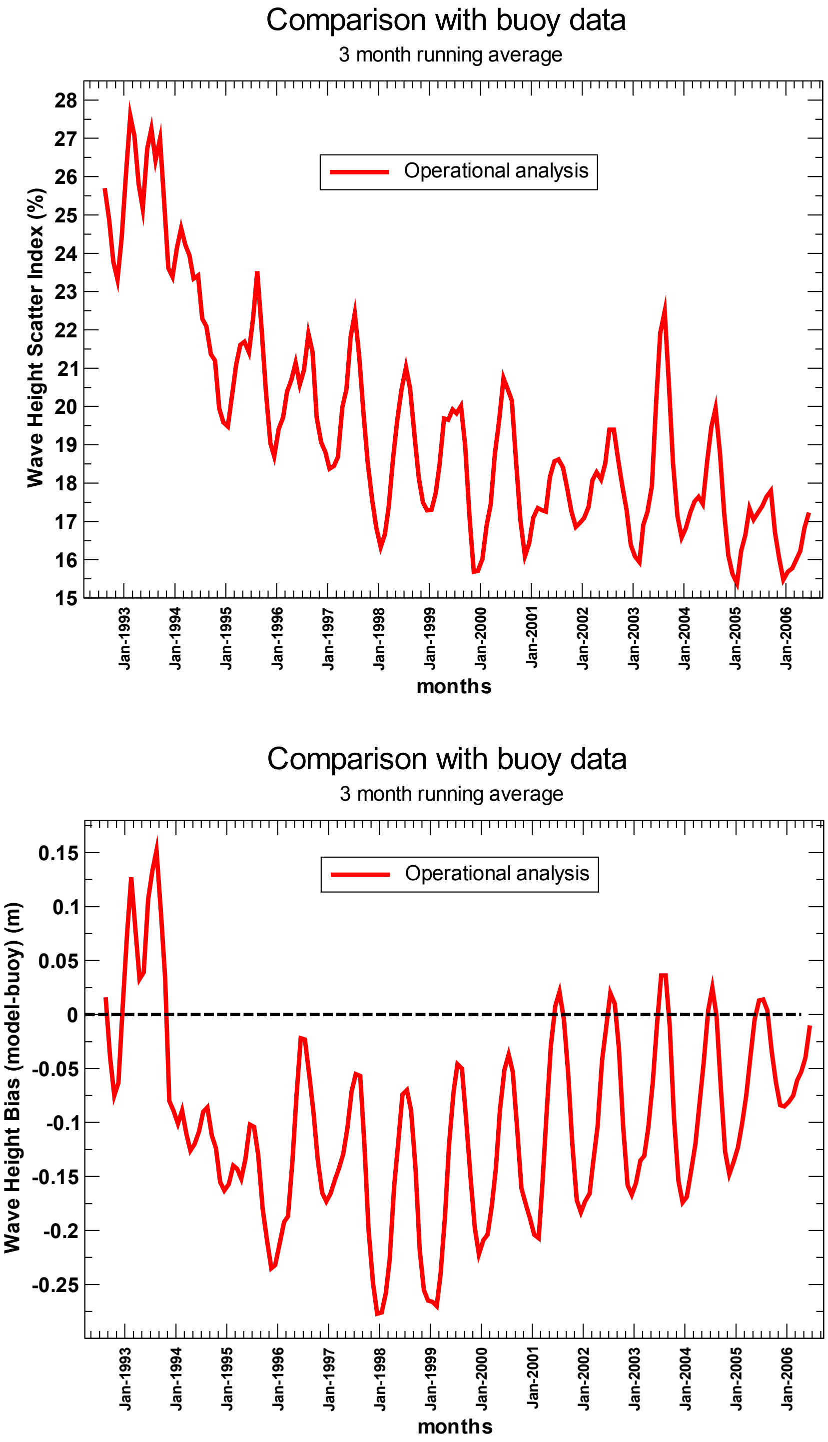

Figure 1: Comparison of ECMWF operational wave height analysis with buoy data in terms of scatter index (standard deviation of the difference normalised by the mean of the observations) (top panel) and bias (model – buoy) (bottom panel). Statistics were computed by combining 3 month of data centred on each monthly abscissa. The comparison is presented for all available buoy locations, primarily located along the US (including Hawaii) and Canadian coasts, the Euro-Atlantic area and the North Sea.

A more informative look at the wave model performance is obtained by comparing the model with 1-D spectra. The details of the method were explained in Bidlot et al. (2005), but essentially, the information contained in the 1-D spectra is smoothed by integrating over frequency intervals and by converting the average energy density to 'equivalent' wave height (EWH). The binned EWH for the model and the buoys are compared for different frequencies or wave periods.

Long term comparison of operational analysis data with 1-D wave spectra from US and Canadian buoys is shown in Fig. 2. The summer overestimation of swell energy around 12 seconds has been substantially reduced since April 2005, following the implementation of a revised dissipation source term in ECWAM (Janssen et al. 2005 and Bidlot et al. 2006). Similarly the high frequency (low period around 6 s) part of the spectrum is in better agreement with the observations.

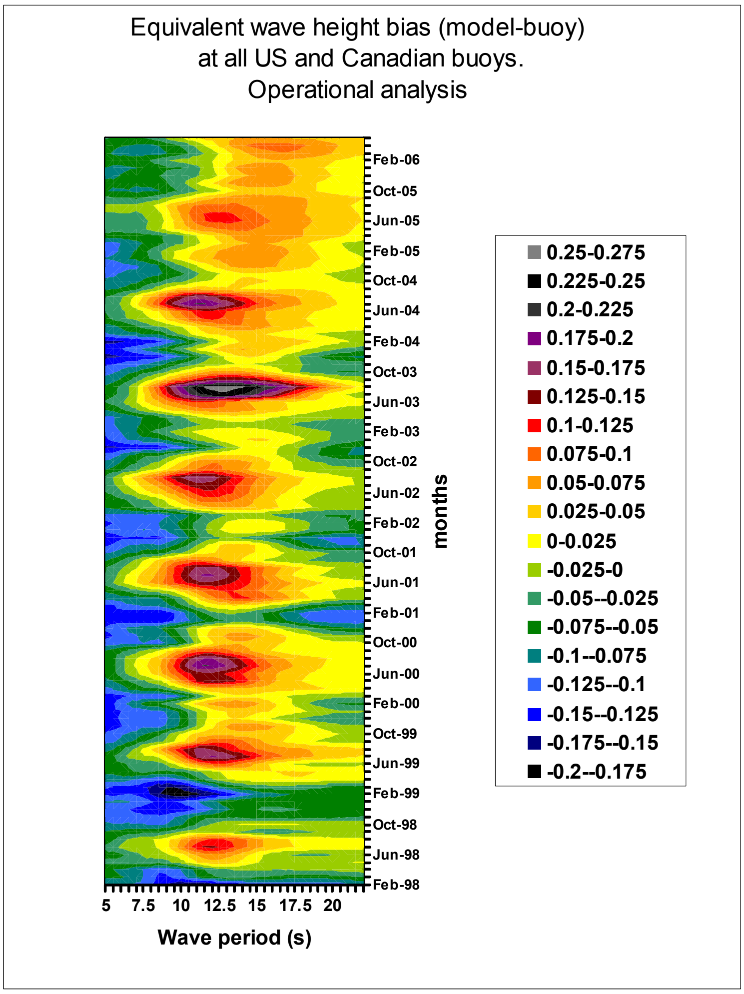

Figure 2: Comparison between operational wave model analysis and buoy 1D-spectra for locations along the American and Canadian coasts. The spectral data were smoothed by averaging over 3 consecutive wave model frequency bins and by converting to equivalent wave heights. The different monthly biases (model – buoy) are plotted in terms of the corresponding wave period of each model frequency bin at mid point (horizontal axis) and time (vertical axis).

Benefits of successive improvements to the ECMWF forecasting system were not only confined to the analysis. Better forecasts are also produced. This is nicely illustrated by looking at yearly forecast scores as shown in Fig. 3 for the wave height root mean square error (RMSE). The latest scores are generally the best in the medium range (similar conclusions can be drawn for mean error and correlation).

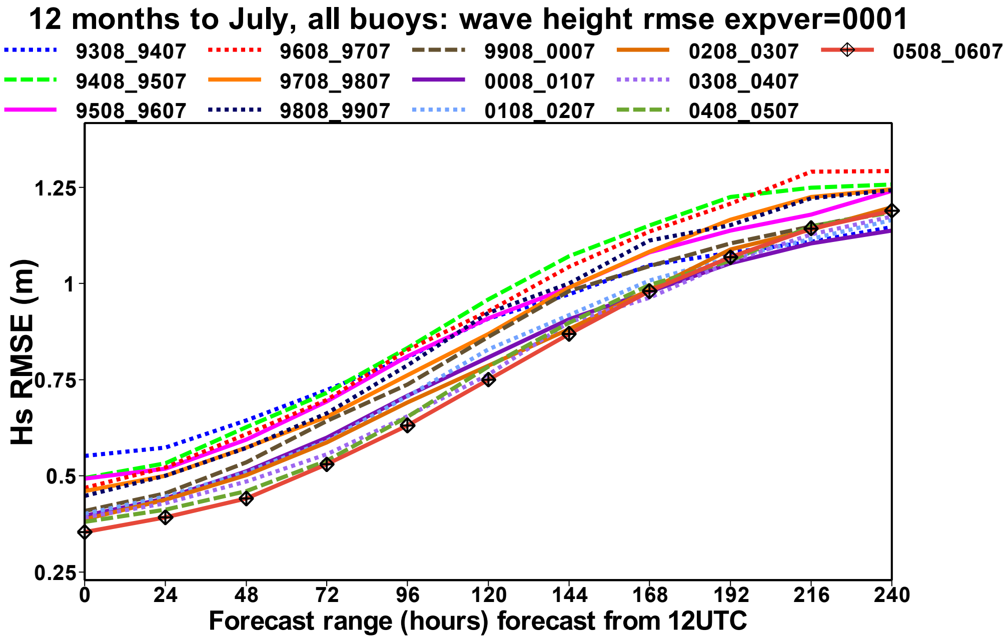

Figure 3: Forecast RMSE compared to buoy data for a full year (August to July) since 1993. The most recent scores are displayed with the curve with diamond symbols. All forecasts from 12 UTC are used.

3. Probabilistic wave forecasts

The Ensemble Prediction System (EPS) has been part of the ECMWF operational suite since December 1992. EPS wave forecasts became available following the introduction of the coupled atmosphere-wave model in the forecast model in June 1998. The EPS is essentially built from a set of forecasts (currently 50, twice daily) started from perturbed initial conditions and run with stochastic perturbations to the atmospheric model representation of some physical processes. The aim is to model the impact on the forecast evolution of both errors in the initial conditions (analysis) and the model uncertainty in representing physical processes. A control forecast is also run with unperturbed initial condition and no stochastic physics, albeit with a coarser resolution than the deterministic forecast. Because of limited computer resources, EPS forecasts are run at lower resolutions than the corresponding deterministic forecasts. By construct the EPS is supposed to sample the forecast probability distribution, therefore probability of certain events can be derived, such as the likelihood of wave heights exceeding a certain threshold in a given forecast range.

As such, probabilistic forecasts of wave parameters are potentially very useful. For the offshore and shipping industry, such a forecasting tool can have numerous applications, such as the planning of high risk operations. In many maritime activities, the most critical environmental parameter is ocean waves. When hazardous or delicate operations are to be performed, ensemble forecasts can be used to estimate probabilities of weather events that are considered dangerous. Particularly if such activities need to be planned days ahead, probabilistic forecasts of dangerous sea state can provide important information. Similarly, on a routine basis, EPS forecasts can be used as a warning system for possible extreme conditions to come, not necessarily captured at an early stage by deterministic forecasts. It can also be quite useful in supporting the deterministic forecast if interesting conditions are expected. A comprehensive validation of the EPS wave forecast was carried out by Sætra and Bidlot (2004). Two examples of extreme cases are presented here.

On the night of 10-11 November 2001, severe wave conditions were experienced in the Norwegian Sea. At two oil platforms (Heidrun and Draugen) and on board the weather ship Polarfront (MIKE), significant wave heights in excess of 15 m were observed. These observed wave heights were among the largest ever recorded.

Post processing products from the EPS runs are the probability fields of significant wave height above thresholds of 2, 4, 6, and 8 m. When looking at the probability forecast 5 day ahead, as shown in Fig. 4, it is ominous that some large waves could be expected. With probability of 40% or more that significant wave heights will be greater than 8m at the platform locations, it is clear that the EPS provided an early warning five days ahead of this extreme situation.

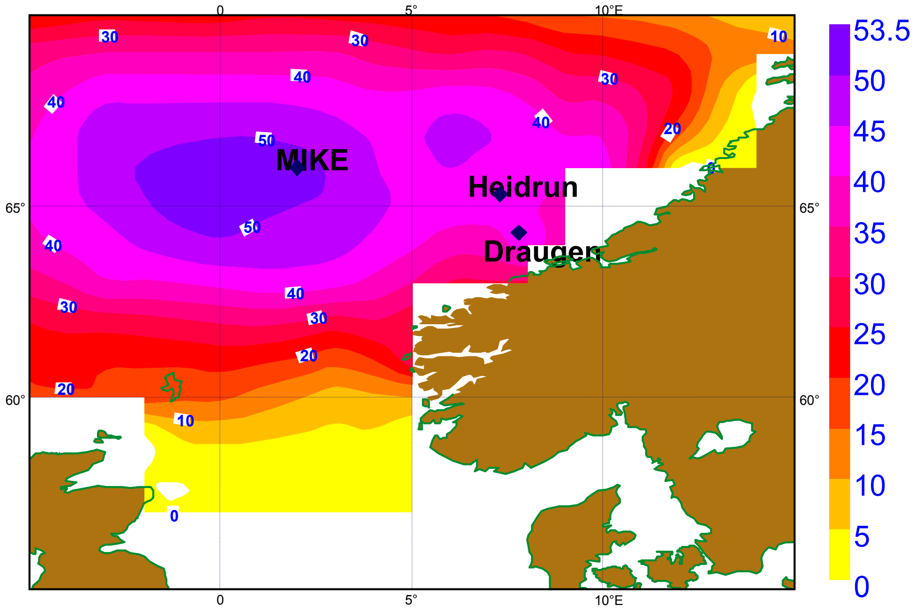

Figure 4: Probability (in %) that wave heights will exceed 8m on November 11, 2001, 12 UTC based on EPS forecasts from 5 days earlier. Heidrun and Draugen are two oil platforms and MIKE is the weather ship Polarfront.

A closer look at the actual ensemble forecasts in this case as illustrated by a plume diagram (Fig. 5) for the forecasts from November 6, 2001, 12 UTC reveals that although none of the ensemble members predicted waves above 15 m, five of them were above 12 m, and one was above 14 m. It is important to note that at the time only model outputs at 00 and 12 UTC were available. Wave observations at Heidrun indicated that the largest waves were measured between 05 and 08 UTC, though at 00 and 12 UTC the measured wave heights were still about 12 m.

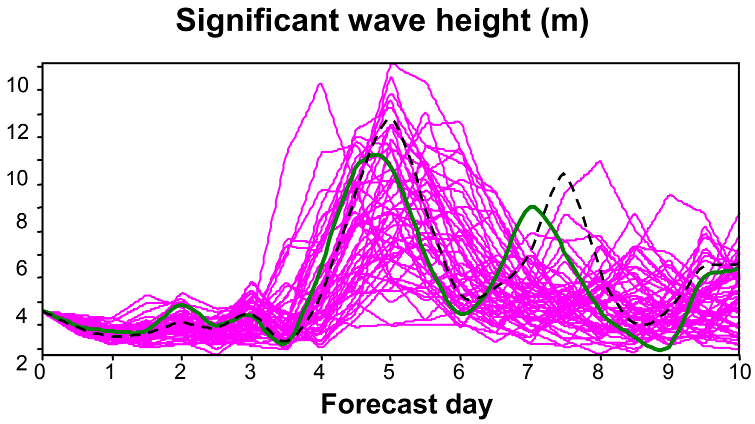

Figure 5: Plumes showing the deterministic high-resolution (black dash) and the ensemble wave height forecasts (solid green for the control and magenta lines for the perturbed forecasts) at platform Heidrun (see Fig. 4 for the location). Forecasts were based on the analysis for November 6, 2001, 12 UTC.

The other example is provided by Hurricane Katrina. This hurricane was one of the strongest storms in the last 100 years. Katrina started to develop as a tropical depression on August 23, 2005 south-east of the Bahamas, reached category 5 on 28th and category 4 when it landed on the 29th. At land fall, close to New Orleans, sustained winds of more than 220 km/h were detected. At the time of Katrina, ECMWF was testing its latest upgrade to its model resolutions (which became operational in February 2006, Untch et al. 2006). It is well known that in order to properly model such intense storms, sufficient model horizontal resolution is necessary. Fig. 6 shows that both operational analysis at T511 horizontal resolution (~40 km) and pre-operational analysis at T799 (~25 km) captured well the extreme waves associated with Katrina. However, the operational EPS forecasts at T255 (~80km) failed to given adequate warning of the incoming huge waves. On the other hand, the pre-operational EPS at an increased T399 resolution (~50 km) was able to give some indications of the oncoming onslaught.

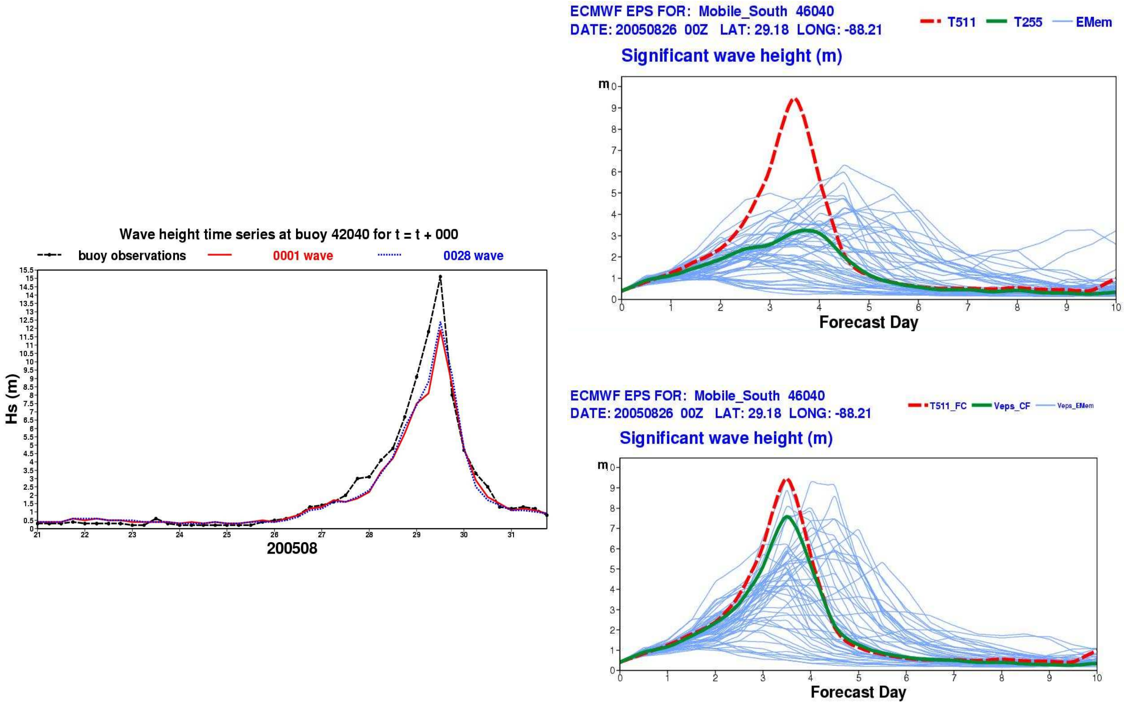

Figure 6: Left panel: wave height observations at buoy 42040 (Mobile south) around August 29, 2005. Also shown are the operational analysis (red solid curve) at T511 resolution and the pre-operational analysis (blue dash curve) at T799 resolution. Top right panel: plumes showing the operational deterministic forecast (red dash) at T511 resolution and the operational ensemble forecasts (solid green for the control and blue lines for the perturbed forecasts) at T255 resolution at buoy 42040. Forecasts were based on the analysis for August 26, 2005, 00 UTC. Bottom right panel: same as top right panel except that the EPS forecasts are at the pre-operational T399 resolution.

As a consequence of the more accurate development and intensification of the hurricane in each ensemble member, wave height probabilistic forecasts for the Gulf of Mexico are more accurate in the new system. This can be seen by comparing the 3 ½ day probability forecast of significant wave heights exceeding 6, 8 or 10 m (Fig. 7). The T255 system does not give any probability (not shown), while the new T399 system gives a 10-20% probability of waves larger than 8 m correctly located in the area where the operational analysis is in excess of 8 m. Indication of even larger waves (above 10m) is also visible. Similar differences were also noticed by comparing probabilistic forecasts for earlier forecast ranges.

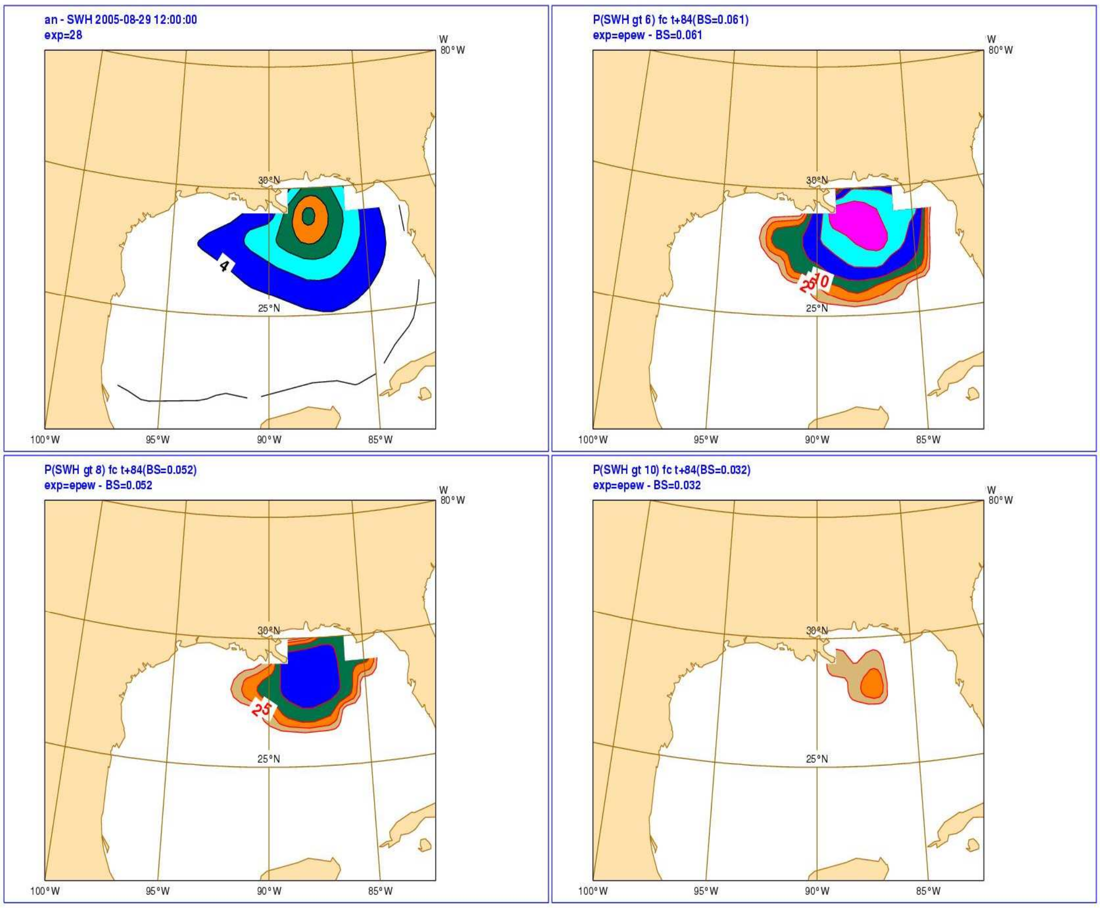

Figure 7: The top-left panel shows the significant wave height (SWH) in the T799 analysis on August 29, 2005, 12 UTC (contour interval is 2m). The other panels show the probabilities derived from the EPS forecasts from 3 ½ days earlier that SWH > 6m (top-right), SWH > 8m (bottom-left) and SWH > 10m (bottom right). Probability contour isolines are 2/5/10/20/40/60%.

4. Freak waves prediction

So far, we have only described systems that predict extreme sea state in the mean, in terms of wave energy spectrum, or more commonly in terms of integrated wave parameters. However, extreme conditions can also arise on a much smaller time scales in the form of waves much larger than the mean, known as freak waves. Renewed interest in the subject of freak waves in the past few years has led to the development of a theory for the prediction of sea states that are more likely to produce freak waves (Janssen 2003). The key factor in the understanding of freak waves is the fact that finite amplitude waves are able to interact with each others. For deep-water gravity waves this interaction is efficient when at least four waves are involved (four-wave interaction). As a consequence, nonlinear focusing can occur, which may counteract the linear dispersion of waves. The result of this balance between nonlinearity and dispersion is that stable wave groups are formed which may last for some time.

It appears that freak waves can only arise when the waves are sufficiently coherent. In these circumstances, when the waves are sufficiently steep, nonlinear focusing can act resulting in extreme sea states. These favourable conditions for the formation of freak waves can be quantified by means of a dimensionless parameter called the Benjamin-Feir Index (BFI). Noting that the coherency of a wave system can be measured by the width of the corresponding wave spectrum, the BFI is basically the ratio of the steepness of the waves and the width of the spectrum. Large values of the BFI correspond to favourable conditions for freak waves to occur.

The prediction of individual extreme sea states seems to be impossible, because their generation depends on the initial phases. This is by itself already quite an intractable problem on a global scale with current computer capabilities. Furthermore, it turns out that the nonlinear evolution of the phase becomes chaotic after just a few hundred wave periods. Therefore, one has to resort instead to a prediction of the statistical properties of the sea surface elevation.

Janssen (2003) has shown that when four-wave interactions are important, there is a direct correspondence between the wave spectrum (through the BFI) and the kurtosis of the probability distribution of the surface elevation. Small BFI corresponds to the kurtosis of about 3, or a normal distribution. For increasing BFI values, the kurtosis increases rapidly to values of order 4, suggesting a sharp increase in the probability of the occurrence of extreme events.

Based on these theoretical considerations, BFI and kurtosis have been produced operationally since October 2003. From the kurtosis one may obtain the enhanced probability of extreme events (Janssen and Bidlot 2003). As an example, in Fig. 8 the one-day forecast enhancement is shown for February 8, 2004. As expected, in most locations, the probability distribution of the surface elevation is close to the normal distribution, as is reflected by an enhancement close to one. In only a few locations, extreme sea states are found, for example east of Newfoundland where the enhancement is nearly a factor of five. In those circumstances, one expects an extreme event every eight hours, rather than every forty hours as obtained from linear theory.

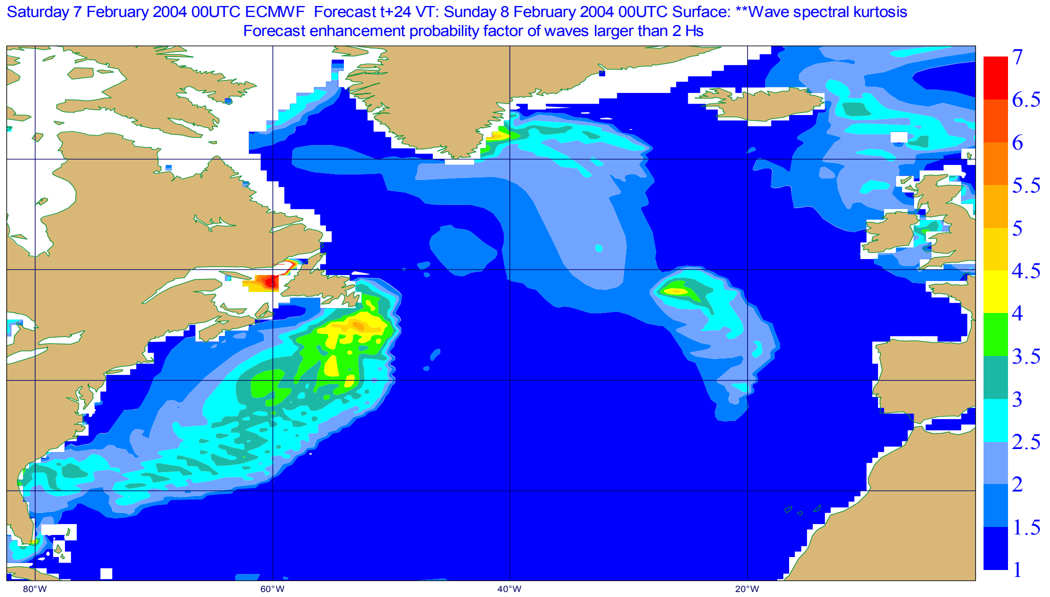
Saturday 7 February 2004 00UTC ECMWF Forecast t+24 VT: Sunday 8 February 2004 00UTC Surface: **Wave spectral kurtosis
Forecast enhancement probability factor of waves larger than 2 Hs

Figure 8: One day forecast of enhanced probability of extreme events on February 8, 2004, 00 UTC. The extreme event is defined as waves larger than twice the significant wave height.

5. Conclusions

In the last 10 years or so, ECMWF has been at the forefront of quite some significant improvements to the quality of wave (and wind) analysis and forecasts over the world oceans. Deterministic prediction of extreme sea state is however still a difficult issue. Nevertheless, marine forecasters can now gain extra insights on the likelihood of incoming severe weather (or not) from information derived from ensemble forecasts. Finally, new research in the understanding of non-linear wave-wave interaction has led to the development of a theory for the prediction of sea states that are more likely to produce freak waves. From this work, wave parameters that quantify the deviation from the mean sea state are now produced operationally.

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