Ocean waves at ECMWF

ECMWF and marine forecasting

ECMWF is an intergovernmental organisation supported by more than 30 member states. Its principal objectives are the production of operational medium-range weather and ocean wave forecasts (up to 10–15 days ahead), and carrying out research directed at improving the quality of these forecasts.

Traditionally, many weather centres have applied their weather forecasts to activities associated with the marine environment. Shipping, fisheries, offshore operations, coastal protection and recreation are all strongly dependent on weather and require marine weather forecasts extending to the limit of the medium-range forecasting period. An important component of the marine weather forecast is the sea state and, therefore, wave forecasting using high quality forecasts of low-level winds or stresses from an atmospheric model is of prime importance. Surface winds should be of high quality as the wind speed error is an important component of the accuracy of the forecast for wave height.

One specific example of the benefits of ocean wave prediction is that since Iceland started using the ECMWF wave products there has been a considerable drop in the number of fishermen that have died at sea, as our wave forecasting system provides valuable and timely information on where serious sea state conditions occur. Another example is the role of swell forecasting during the installation of a storm surge barrier at the entrance of the Eastern Scheldt. During the works, which were completed in 1986, very heavy barriers (up to 38 m high) were prefabricated on land and transported by the pier-carrier Ostrea to the right location. This transport was sensitive to even tiny amounts of energy in the long waves. The task of predicting these small amounts of wave energy was daunting. In fact, in those days wave prediction systems were not reliable enough to give accurate estimates of the low-frequency energy, and the actual marine forecast advice was based on a mixture of knowledge of dedicated forecasters and a numerical wave prediction system.

Not satisfied with the quality of wave forecasting, as exemplified by the Eastern Scheldt wave forecasting project, a number of mainly European wave modellers decided to combine their efforts by forming what became known as the WAM (Wave Model) group. Their main task was to develop a wave prediction system based on existing basic knowledge of ocean waves, including the physics of wind-wave generation, nonlinear interactions and dissipation by wave breaking. Combined with the promise of global satellite data on the sea state and the availability of sufficient computing power (notably provided by ECMWF), there was rapid progress in the development of a third-generation wave prediction system. The global version of this model, called the WAM model, was introduced into operations at ECMWF on 21 June 1992. Over the past two decades there has been a systematic effort to improve the original WAM forecasting system. Key enhancements include the introduction of the assimilation of altimeter wave height data in August 1993, the two-way interaction of wind and waves introduced in June 1998, the effects of unresolved bathymetry introduced in March 2004 and the introduction of a new formulation of the dissipation source function in April 2005. In addition, spatial resolution of the wave model was increased from 330 km to 25 km. Over the same period we have seen massive improvements in our ability to forecast the driving surface wind fields (thanks to advances in atmospheric modelling, the introduction of a new analysis system and the use of satellite observations, notably the scatterometer). Progress in wave forecasting over the past 15 years is shown in Figure 1. The good performance of the ECMWF wave model is also evident from Figure 2.

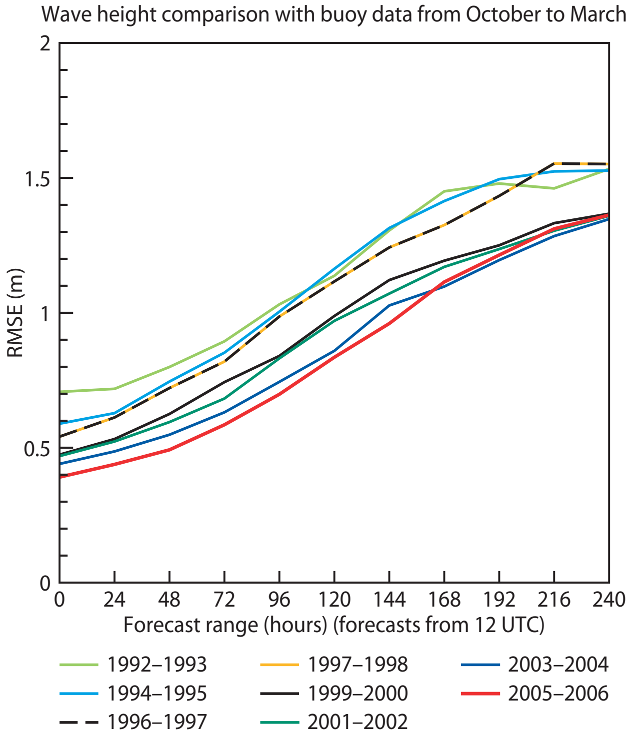

Figure 1 The figure shows winter root mean square error (RMSE) in forecast wave height verified against independent observations from buoys. The plot suggests an improvement in forecast skill of more than two days.

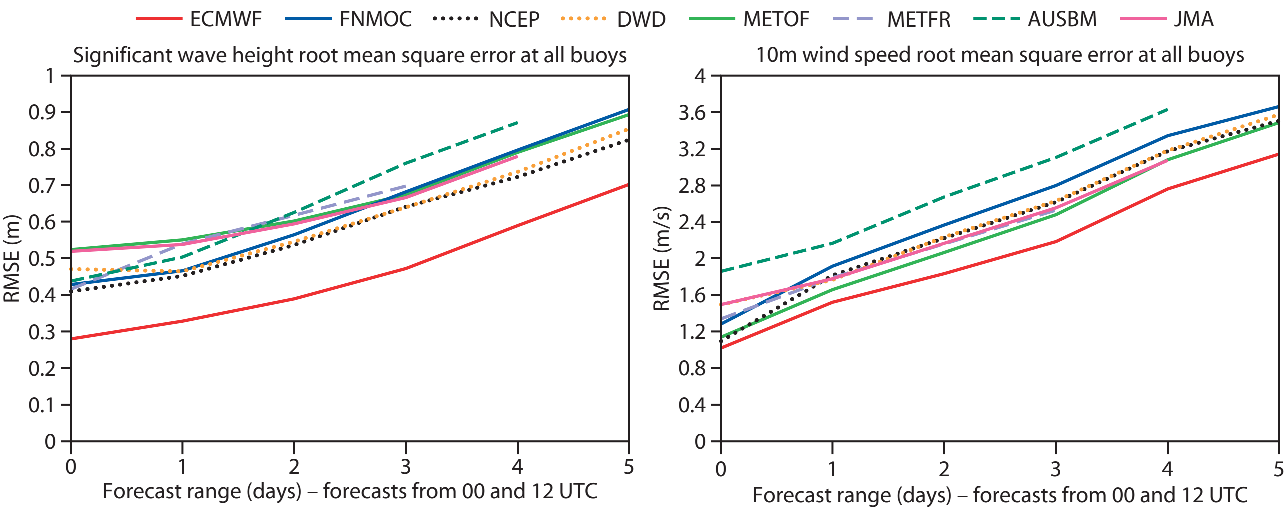

Figure 2 Intercomparison of root mean square error in forecast wave height and wind speed, as obtained by comparing forecasts with buoy observations. The period is from October 2007 to September 2008. Forecast centres involved in the intercomparison are indicated by the different line styles.

Ensemble prediction of ocean waves

It is well known that the accuracy of the weather and wave forecasts worsens with increasing forecast period. It is therefore important to provide the forecaster with guidance regarding the forecast skill. Typically, forecast skill depends on the meteorological situation and therefore ECMWF runs a lower resolution ensemble prediction suite with the coupled ocean-wave, atmosphere model to assess forecast accuracy. The ensemble prediction results for ocean wave height give useful information on forecasting the uncertainty in a predicted ship route, for example. This is illustrated in Figure 3, which shows a crossing over the Atlantic from Brest to New York, a journey which typically takes six days. The blue line shows the optimal ship route according to the deterministic forecast, while the error bars show the uncertainty in the route as derived from the 50-member ensemble.

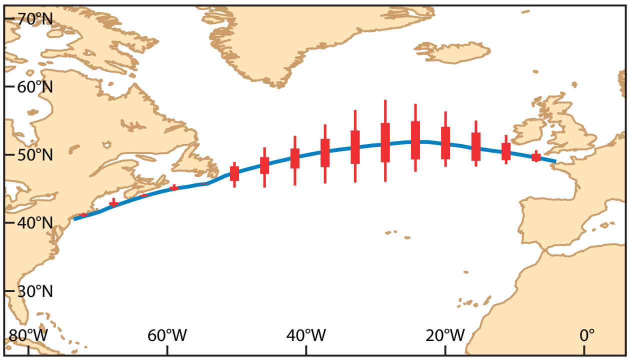

Figure 3 Optimal ship route for a crossing over the North Atlantic and the forecast uncertainty in the accuracy of the forecast ship route.

Extreme wave forecasting

One of the remits of ECMWF is to provide forecast guidance for extreme events. In the context of marine weather this means that we have to be able to give an accurate prediction of wind speed and wave height when there is a big storm over the oceans. A considerable amount of effort in the past 15 years has been devoted to achieving high accuracy for such events.

However, for ocean waves there is another type of extreme event which is termed freak waves. The term describes the phenomenon whereby during a fairly modest sea all of a sudden large waves seem to come out of the blue and these waves may cause considerable damage to a ship. An example of a freak wave is given in Figure 4. This case was exceptional because the ship's captain usually steers the vessel against the big waves but this freak wave came from behind the ship.

Until a few years ago our wave forecasting system predicted only the average sea state at a certain time and location. Freak waves and thus occasional large deviations from the mean state do occur from time to time and it is of great interest to have an indication why and when such extreme events happen. Recent advances in the theory of nonlinear extreme events now allow the estimation of the expected maximum wave height during a chosen time window of, say, three hours. Figure 5 shows an example of an extreme event during Storm 'Klaus'. The mean wave height forecast for the storm was 12 m, with a maximum wave height of just over 24 m predicted in the Bay of Biscay, while anecdotal evidence suggested a maximum wave height of 27 m.

Figure 4 A large freak wave (15–20 m high) hits an ocean vessel from behind during moderate sea state conditions of about 4–5 m. © Philippe Lijour

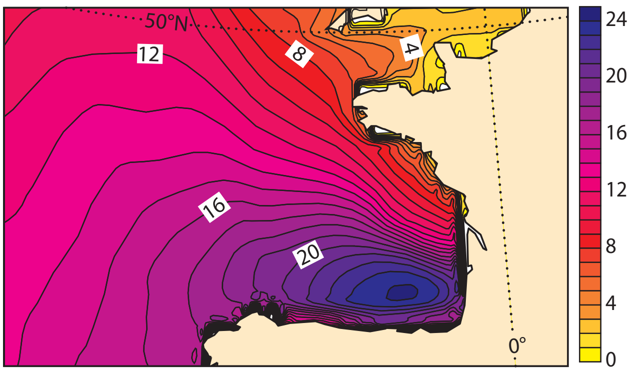

Figure 5 The maximum wave height field (in metres) in the Bay of Biscay during Storm Klaus on 24 January, 2009 at 6 UTC.

Wave forecasting and satellite observations

Since the start of the European Remote Sensing (ERS) satellite series in 1991 there has been close collaboration between the wave model community and the European Space Agency. These satellites were the first to give in near real time wave height and wind field information on a global scale. ESA had a keen interest in assuring the quality of the satellite data, while the wave modellers were keen to improve their wave models. In the early 1990s the root mean square difference between the ERS-1 altimeter wave height and model wave height was typically more than 0.5 m. Nowadays this difference has reduced to about 0.25 m, reflecting improvements in the altimeter wave height algorithm, the accuracy of the instrument and the wind-wave modelling. As an example, the reduction in wave height differences between ENVISAT and the model is shown in Figure 6. Apart from helping to improve wave modelling, altimeter data have been used since 1993 to provide a more accurate estimation of the initial condition for the wave forecast.

The ERS satellites also carry a scatterometer on board, which measures the surface wind vector. Assimilation of scatterometer data commenced in 1996 and resulted in considerable improvements in wave forecasting skill.

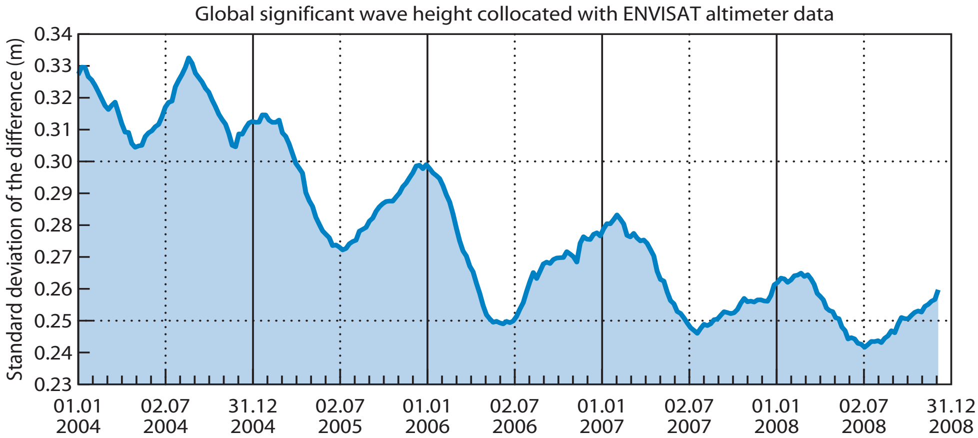

Figure 6 Verification of first-guess significant wave height against altimeter observations over the five year period from January 2004 until December 2008.

Outlook

A considerable amount of progress in wave modelling has been achieved in the past 20 years or so and there are definite reasons for further development. They derive, as they should, from a number of applications in which the wave spectrum plays an important role. Just recently we have seen rapid progress in the understanding of the mechanisms behind the generation of extreme sea states such as freak waves. Prediction of the maximum wave height of extreme events is of tremendous benefit to the marine world, but clearly an accurate prediction of the detailed low frequency part of the wave spectrum is of utmost importance. Although there is already evidence of this capability of wind-wave forecasting systems it is nevertheless expected that further improvements may be required.

On the other hand, knowledge of the high-frequency part of the wave spectrum is important in all remote sensing applications that depend to some extent on properties of the sea surface. These include instruments such as the altimeter, the scatterometer, SSM/I, and ATOVS, in short, any instrument that involves aspects of specular reflection. In fact, the ocean surface albedo depends in a straightforward manner on properties of the slope spectrum. Also, knowledge of the high-frequency spectrum is important in order to determine the air-sea momentum exchange, and as a consequence it is also important for the exchange of passive scalars such as carbon dioxide. Progress in this area, and the prospects of modelling the impact of ocean waves on ocean circulation promise very exciting times ahead in the field of ocean waves.

ECMWF is an intergovernmental organisation supported by more than 30 States. It provides weather services with medium-range forecasts of global weather to 15 days ahead as well as with monthly and seasonal forecasts. ECMWF's computer system at its headquarters in Reading, United Kingdom, is one of the largest for meteorology worldwide and contains the world's largest archive of numerical weather prediction data. It runs a sophisticated medium-range prediction model of the global atmosphere and oceans. The National Meteorological Services of Member States and Co-operating States use ECMWF's products for their own national duties, in particular to give early warning of potentially damaging severe weather.

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