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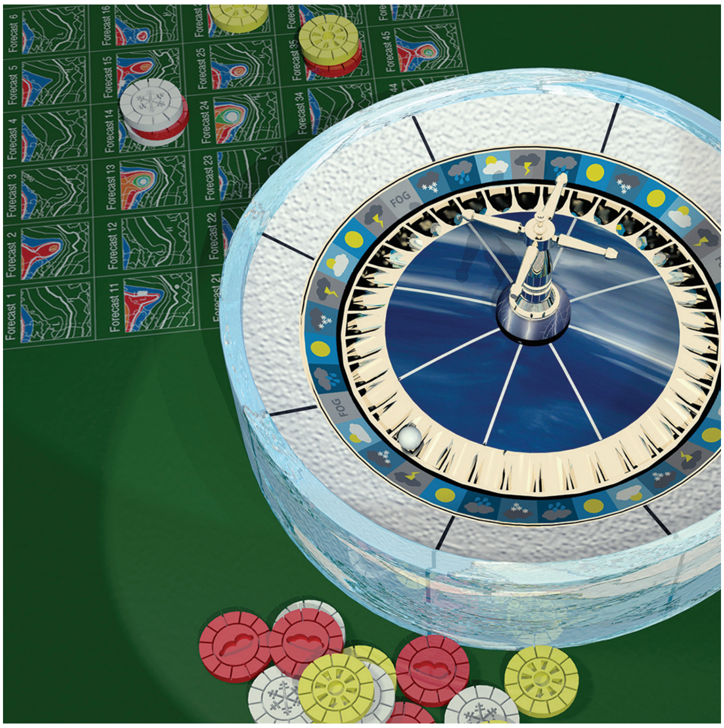
Progress in ocean wave forecasting at ECMWF



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Progress in ocean wave forecasting at ECMWF

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In the 1980s the introduction of the first supercomputers and the promise of the wealth of data on the ocean surface from remote-sensing instruments on board of new satellites such as ERS-1 and Topex-Poseidon provided a significant stimulus to the development of a new generation of ocean wave prediction models. The WAve Model (WAM) Group emerged and the main goal was to develop a spectral ocean wave model based on solving the energy balance equation which included explicitly the physics of wind-wave generation, dissipation due to white capping and nonlinear interactions. Development of this new wave prediction system was rapid and ECMWF helped by providing resources (in terms of computing facilities, advice by staff and office space). In June 1992 the WAM model became operational at ECMWF.

It soon became clear that the quality of wave forecasts was to a large extent determined by errors in the forcing wind field. Since the winds gave such a large contribution to the error budget of, for example, the significant wave height, it was expected that it would be difficult to show the effect of improvements from the wave model.

In this article, which is based on *ECMWF Technical Memo. No. 478* (where more details are given), we discuss progress in ocean wave forecasting during the past ten years. It will be shown that during this period there have been substantial improvements in the quality of the forecast wind and wave height fields. This follows from comparisons with the verifying analysis, in-situ buoy data and altimeter data. The main reasons for these large improvements are the introduction of 4D-Var, increases in atmospheric resolution, improvements of the physics of the atmospheric model and the two-way interaction of wind and waves.

Because of the large error reduction in the forcing winds, it is nowadays easier to see the consequences of wave model improvements. Two examples of recent wave model improvements after WAM CY4 are discussed: the introduction of the effects of unresolved bathymetry and the revised formulation of wave dissipation. There is then a discussion of the improvement in the quality of the forecasts of wave height over the last decade. Finally, we discuss the following two new developments.

- An important element of severe weather forecasting over the oceans is the prediction of freak waves. We will describe the steps that led to the introduction of the first operational freak wave prediction system.
- The sea state is affected by ocean currents, tides and storm surges. We will discuss preliminary results regarding the impact of ocean currents on the significant wave height field on a global scale. Also discussed is the forecasting of the sea state in the coastal zone, an area of important economic significance.

CY4 version of the WAM model

The present version of the ECMWF wave forecasting system is based on WAM CY4 (see *Komen et al.,* 1994). The WAM model is the first model that explicitly solves the energy balance equation. See Box A for more details.

The WAM model became operational at ECMWF in June 1992. Since that date there has been a continuous programming effort to keep the software up to date. For example, in order to improve efficiency, options for macrotasking (later replaced by open MP directives) and massive parallel processing were introduced. In addition, the software now fully complies with Fortran 90 standards. The advantage of this is that only one executable is needed for all the relevant applications, such as the deterministic forecast with resolution of 55 km, the ensemble forecast with resolution of 1 degree and the limited area forecasts with a resolution of 28 km. The same executable can also be run as a one grid point model, which is convenient when testing changes in physics, for example. Finally, over the past ten years a number of model changes were introduced which will be discussed in some detail in the next section.

Documentation of the present version of the ECMWF wave model may be found on the web (www.ecmwf.int/; click research, click on “Full Scientific and technical documentation of the IFS” and finally choose Chapter VII).

Presently the wave model is run for the global domain and as a limited area model for the waters surrounding Europe. The wave model software is furthermore run for the boundary conditions suite, monthly forecasting, seasonal forecasting and for the reanalysis. This note will concentrate on the global domain. The global model covers an area of 81°S to 81°N.

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Since the 29 June 1998 the wave model is part of the Integrated Forecasting System (IFS) enabling a two-way interaction between wind and waves, hence, the sea surface roughness, as seen by the atmosphere, is sea state dependent. An additional consequence of the coupling is that, just as for the atmosphere, there are for the globe two medium-range applications, namely, ten-day deterministic forecasts and probabilistic forecasts.

Basic formulation of CY4 version of the WAM model **A**

The usual wave number spectrum is denoted by $F(\boldsymbol{k}; \boldsymbol{x}, t)$, where $\boldsymbol{k}$ denotes wave number vector, $\boldsymbol{x}$ the position and t the time. In wave dynamics the fundamental quantity to predict is, however, the action density spectrum $N(\boldsymbol{k}; \boldsymbol{x}, t)$. It is defined as:

$$N = \frac{gF}{\sigma} \quad \text{with} \quad \sigma = \sqrt{gk \tanh(kD)}$$

where g is acceleration of gravity and D is the water depth. The action density plays the role of a number density of waves, hence (apart from the constant water density) the energy E of the waves is given by $E = \sigma N$, while the wave momentum $\boldsymbol{P}$ is given by $\boldsymbol{P} = \boldsymbol{k}N$.

The energy balance equation follows from Whitham's variational approach in a straightforward manner (*Janssen,* 2004) and the result for waves on a slowly varying current $\boldsymbol{U}$ is:

$$\frac{\partial N}{\partial t} + \nabla_{\boldsymbol{x}} \cdot \left(\nabla_{\boldsymbol{k}} \Omega N\right) - \nabla_{\boldsymbol{k}} \cdot \left(\nabla_{\boldsymbol{x}} \Omega N\right) = S$$

Here, Ω represents the dispersion relation:

$$\Omega = \boldsymbol{k}.\boldsymbol{U} + \sigma$$

The source function S represents the physics of wind-wave generation (S_{in}), dissipation by wave breaking and other causes (S_{dissip}) and four-wave interactions (S_{nonlin}). In other words:

$$S = S_{in} + S_{dissip} + S_{nonlin}$$

In the 1980s there was a major effort to develop realistic parametrizations of all the source functions. The present version of the WAM model has:

- S_{in} based on *Miles* (1957) critical layer mechanism (including the feedback of the wave stress on the wind profile – see *Janssen,* 1989).
- S_{dissip} based on the work of *Hasselmann* (1974).
- S_{nonlin} represented by means of the direct-interaction approximation of *Hasselmann et al.* (1985).

An account of this version of the WAM model is given by *Komen et al.* (1994), while a more up to date account of the status of wave modelling, including most of the new developments discussed in this article, can be found in *Janssen* (2004).

Developments after WAM CY4

Apart from the extensive code developments in order to be able to run the WAM model software on multi-processor machines, changes to the software have been introduced as well. In the first instance these have been mainly of a numerical nature; there were no changes to the formulation of the physical processes, only to its numerical representation. Recently, warranted by the considerable improvements in the model surface winds, a number of changes to the physics of the model have been implemented as well:

- Introduction of the effects of unresolved bathymetry
- Revised formulation of wave dissipation.

These changes will be described after consideration of the impact of the two-way interaction of wind and waves.

Two-way interaction of wind and waves

A two-way interaction of wind and waves was introduced in operations in June 1998. At the same time this made the operational running of ensemble wave forecasts easier.

The impact of two-way interaction on the atmosphere has been reviewed (*Janssen et al.,* 2002). At the time of operational introduction of the coupling there was an evident reduction of the systematic error in forecast wave height (verified against analysis) and the standard deviation of error was reduced by about 5%. Also, as illustrated in Figure 1, the RMS error in first-guess wind speed verified against scatterometer winds was reduced by 10%. There was also some impact on the accuracy of forecast atmospheric parameters (e.g. the 1000 and 500 hPa geopotential in the southern hemisphere).

It has been found that the impact of sea-state dependent drag on the atmospheric flow has increased over the years simply because the resolution of the atmospheric model has increased. This increase in resolution has resulted in a more realistic representation of the sub-synoptic scales, which are the ones that are relevant for the interaction of wind and waves. The point is perhaps best illustrated by the operational introduction of the T_L511 atmospheric system. At the same time it was decided to increase directional resolution of the wave spectrum by a factor of two from 12 to 24 directions while also a more accurate determination of the energy fluxes in the advection scheme was introduced. In the context of the lower resolution T_L319 atmospheric model it was possible to show that the proposed wave model changes had a small but positive impact on atmospheric and wave scores. However, with T_L511, impact was much more pronounced (for a more detailed discussion see *Janssen et al.* (2002)). The main reason for this is probably that in T_L511 the sub-synoptic scales are better represented.

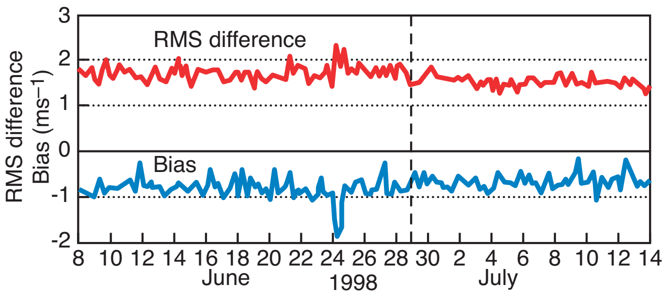

Figure 1 Bias and RMS difference between the background ECMWF surface winds and the ERS-2 scatterometer wind measurements. The vertical dashed line shows the date when two-way interaction was introduced operationally.

Unresolved bathymetry

Inspecting maps of monthly mean analysis wave height increments, especially during the Northern Hemisphere summer (Figure 2), it appears that there are areas where the wave model first guess is systematically too high or too low. The underestimation in wave heights tends to be located in the active storm track areas or in areas affected by the Indian sub-continent monsoon. The likely reason is that the model winds are too weak. On the other hand, the overestimation for most of the tropical and northern Pacific cannot be explained in terms of local winds. After further scrutiny, it appears that these systematic overestimations are often present in areas where small island chains exist (French Polynesia and Micronesia in the Pacific Ocean, Maldives Islands and Andaman Islands in the Indian Ocean and Azores and Cape Verde Islands in the Atlantic Ocean).

These small scale features are not well-resolved by the present operational grid which has a resolution of 55 km, and it would be far too expensive to resolve these features explicitly. Nevertheless, small islands can block considerable amounts of wave energy. In order to represent these unresolved features we have introduced in the wave model's advection scheme a wave number dependent blocking factor. Here the blocking factor was determined by estimating from the high resolution ETOPO2 topographic data set how much energy the unresolved features will block. This change resulted in a large positive impact on the wave height scores in the tropics, in particular the anomaly correlation (Figure 3). The scheme for the treatment of unresolved bathymetry became operational in March 2004.

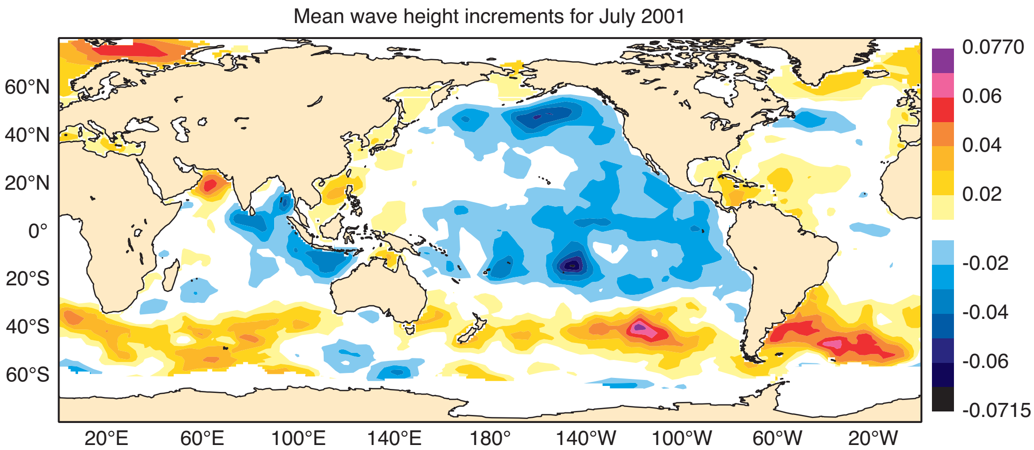

Figure 2 Mean wave height analysis increments for July 2001 (in metres). ERS-2 altimeter data were the only data used in the data assimilation. The stand alone WAM model on a 55 km grid was used.

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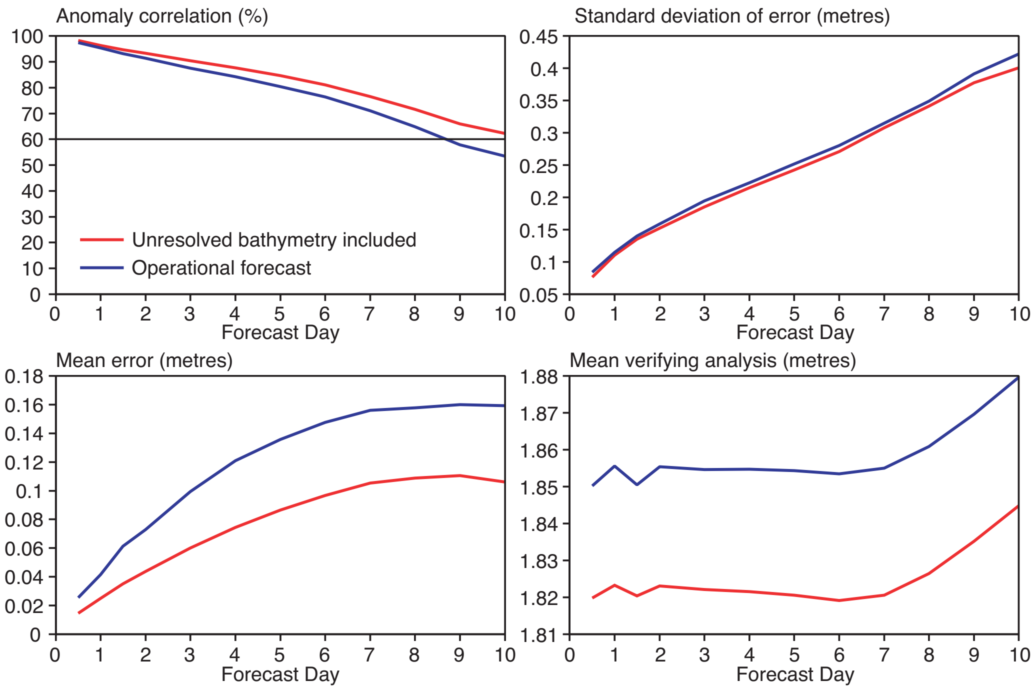

Figure 3 Wave height scores against own analysis for the tropical area for the operational forecast (blue) and the forecast with the treatment for unresolved bathymetry included (red) for the period 1 to 27 April 2003.

Dissipation

The dissipation source function is probably the least known source function in ocean wave modelling. In the past it has been determined starting from the assumption that wind input and nonlinear transfer are well-established and the dissipation term is then determined in such a way that in the steady state the observed Pierson-Moskowitz spectrum is reproduced (*Komen et al.,* 1984).

In this tuning exercise the dissipation source function is given by the general form $S_{dissip} = -\gamma_d N$ where γ_d depends upon the mean frequency and mean wavenumber defined in some suitable manner. Since 1985 the mean wavenumber has been calculated in such a way that emphasis was put on the slowly-varying low-frequency part of the spectrum as this produced less noisy fields than using an earlier formulation (see *ECMWF Technical Memo. No. 478* for more details). Recently, however, a drawback of the use of this approach has been realized. In the presence of low-frequency swell the dissipation of windsea turns out to be largely determined by the swell part of the spectrum. In fact, because the steepness of swell is usually small, the dissipation of windsea in the presence of swell is much smaller than in its absence. As a consequence, windseas have more energy in the presence of swell, which contrasts common knowledge and belief.

It was decided to define the mean wave number in terms of the so-called first moment which puts more emphasis on the high frequency part of the wave spectrum. This “new” definition does not suffer from the drawback mentioned above. In addition, as now the dissipation of windsea is much larger in the presence of swell, we could also relax dynamic range of the integration of the source functions in the energy balance equation so that windseas are properly generated, also in the presence of low-frequency swells.

The combination of these two changes gave a considerably positive impact on the analysis of parameters such as the mean frequency as shown in Figure 4, which gives a comparison of scores of the operational and experimental suites against buoy observations over a three-month period. A reduction in random error of 40% is an example of a large improvement. Note that this is not even the most extreme example of improvement. From around the Indian continent we recently started receiving buoy data. Against these data the experimental suite showed a reduction in the error of the mean frequency by a factor of two.

It is emphasized that these considerable improvements in spectral shape are caused by the introduction of a much wider dynamical range, made possible by the revised formulation of the dissipation source function. This allows the proper treatment of windsea in the presence of low-frequency swell. The consequence is, however, that variability in wave height has increased, in particular in the tropics. Also, since the dissipation source function is now determined in terms of the first moment of the spectrum, wave model results have become more sensitive to details in the high-frequency part of the spectrum. As the short waves are

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determined to a large extent by the wind, wave model results have become more sensitive to changes in the wind, in particular more sensitive to errors in the wind forcing. Therefore, when comparing wave forecasts against the own analysis, wave height scores of the experimental suite were in the medium range slightly worse compared to the operational suite. However, scoring the forecast results against ENVISAT altimeter data showed a small improvement in wave height scores, in particular in the Southern Hemisphere. The change was introduced in operations in April 2005.

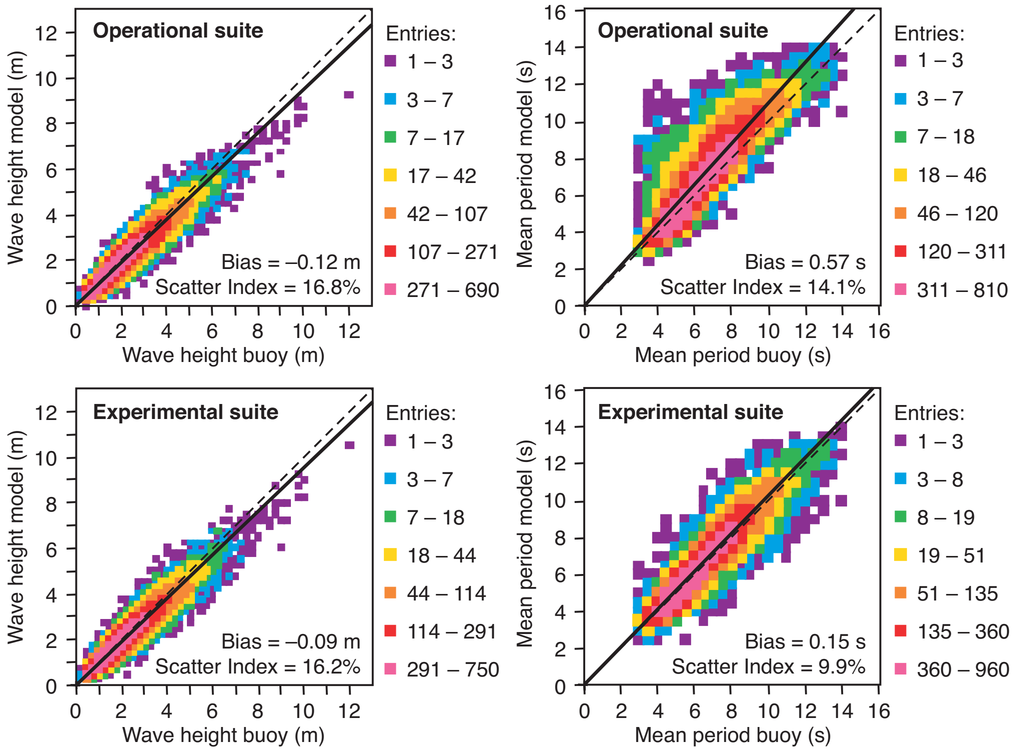

Figure 4 Comparison of wave height and mean period scores against United States and Canadian buoy observations from the operational suite and experimental suites for the three-month period of January to March 2005.

Verification and sensitive dependence on wind speed error

At ECMWF there is an extensive effort to validate analysis against available, independent buoy data, while the forecast is compared with buoy data, altimeter wave height data and the verifying analysis. For an overview of the quality of the ECMWF wave forecasting system in 1995 see *Janssen et al.* (1997), while the period between 1995 and 2003 is discussed in *Janssen* (2004). From the comparison of forecast surface winds and wave heights with the verifying analysis it turns out that over the last ten years the standard deviation of error in wind speed and wave height has been reduced by 40% in the northern hemisphere, while improvements in the southern hemisphere are similar. Also, when comparing first-guess wave height and analyzed wind speed with their counterparts measured by the ERS-2 altimeter, considerable reductions in the standard deviation of error are found (*Janssen* 2004). For example, first-guess wave height error is reduced from about 50–60 cm in 1994 to around 30 cm presently, while the analyzed wind speed error reduced from about 2 ms^{-1} to about 1.3 ms^{-1}.

This picture of improved wave forecast skill over the last decade is confirmed by means of a validation of wave height forecast and analysis against independent buoy data. This is illustrated in Figure 5 by plotting the RMS error of wave height as function of forecast time for the past nine winter periods. We infer from the figure an improvement in forecast skill of two days over a ten year period.

It is of considerable interest to try to understand some of the reasons for this massive improvement. Based on the verification results of forecast wind and waves against the analysis, *Janssen* (1998) found a close relation between wave height error and wind speed error. Therefore, one would expect that improvements in wind speed forecast could explain a considerable part of the improved skill in wave height forecast. In order to illustrate this, we study Figure 6 which shows a plot of the RMS error in wind speed as function of forecast time. Indeed, similar improvements in accuracy in forecast wind are seen as are found for the wave height forecasts (see Figure 5). From 1996 and onwards these improvements in the accuracy of the surface winds have been caused by:

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- Formulation of the new J_b in May 1997 and the introduction of 4D-Var in November 1997 (which allowed a better treatment of satellite data from, for example, (A)TOVS).
- Introduction of the T_L319 version of the IFS in March 1998.
- Two-way interaction of wind and waves in June 1998.
- Introduction of the T_L511 version of the IFS and doubling of the angular resolution in the wave model in October 2000.
- Operational assimilation of ERS-2 scatterometer winds in January 1996 and of QuikScat winds in January 2002.

In addition in 2003 we have seen a large increase in the amount of satellite data used in the analysis scheme. Despite the impressive improvements seen in the quality of the wind speed it should be pointed out that analyzed winds, for example, are still biased low with respect to the buoy observations. Presently, the bias is about -25 cms^{-1} in the Northern Hemisphere wintertime but ten years ago the bias was close to -50 cms^{-1}. Accordingly, wave heights are biased low in wintertime by about 15 cm.

The consequence of improved quality in surface winds is that the contribution of the wind speed error to the wave height error has reduced, so that wave model errors now play a much more prominent role in wave forecasting than ten years ago. As mentioned earlier we have therefore started improving some aspects of the model physics.

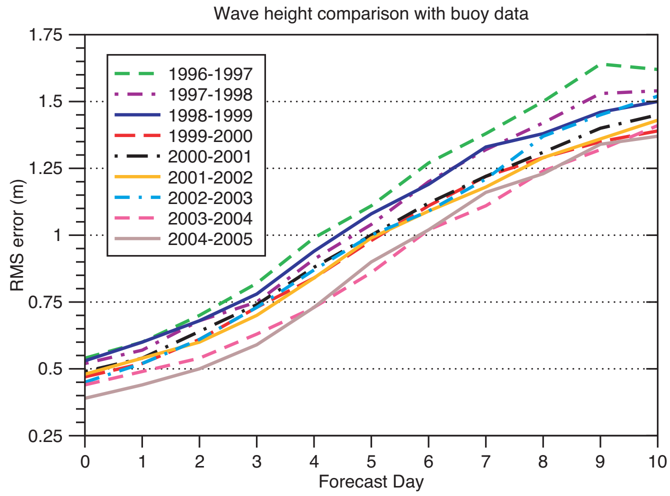

Figure 5 RMS error of analyzed and forecast wave height against buoy wave height data for all winters (October to March) from 1996 onwards. Forecasts are from 12 UTC.

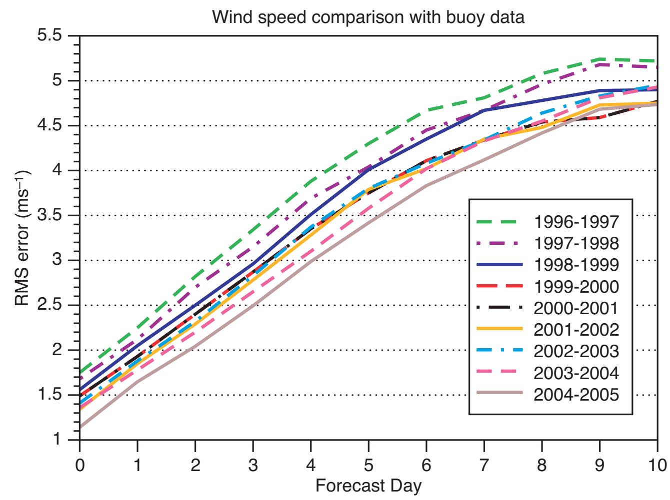

Figure 6 RMS error of analyzed and forecast surface wind speed against buoy wind speed observations for all winters (October to March) from 1996 onwards.

Extreme sea state forecasting

In the early 1960s there was a rapid development of the statistical theory of ocean waves, culminating in the basic evolution equation for the ocean wave spectrum (see the energy balance equation in Box A). In lowest order, the probability distribution function (pdf) for the surface elevation was found to be a Gaussian, corresponding to the case of linear waves. It was not realized at that time, however, that dynamical effects of finite amplitude on the pdf can be calculated and result in valuable information on extreme sea states.

The starting point for deriving the energy balance equation for the wave spectrum are a set of deterministic, nonlinear evolution equations for the amplitude and phase of the surface gravity waves. Because of nonlinearity, the equation for the second moment (i.e. the wave spectrum) is coupled to the third and fourth moment, and so on. An infinite hierarchy of equations follows and usually this hierarchy is closed by making the statistical assumption that the system remains close to Gaussian. However, finite deviations from the normal distribution are required in order to get a meaningful evolution of the spectrum (due to nonlinear three and four wave interactions). These deviations from normality can be obtained using the Chapman-Enskog Method to calculate the transport properties (such as the molecular viscosity) of fluids. Applied to the appropriate evolution equations for water waves, the result is the well-known Hasselmann equation for four-wave interactions. The deviations from normality contain, however, useful statistical information in itself, for example one may determine interesting parameters such as the skewness and the kurtosis of the pdf of the surface elevation.

Explanation of the formation of freak waves

An intuitively appealing explanation of the formation of freak waves is the following. If waves have a small amplitude then they behave in a linear manner, hence the superposition principle applies. This means that when two wave trains with nearly the same amplitude and wavenumber meet then, depending on the phases of the wave trains, one finds as extreme twice the amplitude at best (constructive interference). The corresponding pdf of the surface elevation is the normal distribution and this pdf is regarded as the norm against which to measure extreme events. Finite amplitude waves are different because due to nonlinearity there are four-wave interactions, hence it is possible to borrow energy and momentum from the neighbouring waves. This is called *nonlinear focussing* and may result in amplification rates of a factor of five (rather than the factor of two in linear theory). Therefore, when nonlinear focussing is present extreme events are more likely to occur.

Under what circumstances do we have an efficient formation of freak waves? Clearly, the waves need to be sufficiently nonlinear. This is measured by an integral measure of wave steepness which depends upon the product of a typical wave amplitude and peak wave number. In addition, the interaction between the waves should exist and should be efficient. For surface gravity waves it can be shown that resonant four-wave interactions do exist and they are the most efficient when the interacting waves have more or less the same phase (i.e. they enjoy a coherent interaction). Coherency is measured in terms of the relative width of the (frequency) spectrum; hence the smaller the relative width of the spectrum, the more coherent the corresponding wave trains.

An analysis of the relevant evolution equations for surface gravity waves reveals that for narrow-band spectra the nonlinear focussing is controlled by a single parameter, namely the ratio of integral steepness to relative width. This parameter is called the Benjamin-Feir Index (BFI). Large values of the BFI (in practice of the order 1) indicate that nonlinear focussing is important, resulting in large deviations from the normal distribution and therefore increased probability for the occurrence of freak waves.

The theoretical approach regarding spectral evolution and the corresponding statistical properties of the sea surface have been validated by means of Monte Carlo simulations of the deterministic evolution equations (*Janssen*, 2003).

In addition, the theoretical approach compares favourably with wave tank observations (*Onorato et al.,* 2005). This is shown in Figure 7 which gives the probability $P(h)$ that instantaneous wave height exceeds h times the significant wave height H_s, according to observations, theory (*Mori & Janssen,* 2005) and according to linear theory (Rayleigh distribution). As can be seen from the Figure 7, for positive kurtosis there are considerable increases in the probability of extreme sea states, and, indeed, from the observed time series a number of freak waves were visible.

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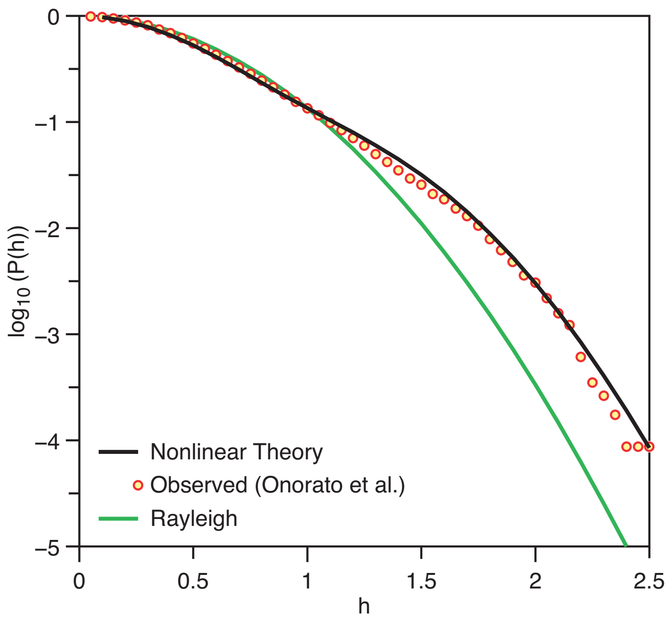

Figure 7 Comparison of theoretical and observed (Onorato et al., 2005) wave height distribution. For reference, the linear Rayleigh result is shown as well. Here h is the ratio of the instantaneous wave height (H) to the significant wave height (H_S) and P(h) is the probability of h occurring.

Operational Implementation

The first consequences of this approach have already been implemented in operations. An essential step in this implementation is a procedure to forecast the kurtosis parameter (defined in such a way that it vanishes for a normal distribution). Theoretically, the kurtosis is a very complicated expression in terms of the (action) wave spectrum. However, for Gaussian-shaped spectra in the narrow-band approximation the kurtosis shows a particularly simple dependence on the Benjamin-Feir Index (for a detailed derivation see *Mori & Janssen,* 2005). Here, this Index is obtained from the predicted wave spectrum; the kurtosis and other relevant statistical parameters of the sea surface then follow immediately.

It is emphasized that this approach is really an important step forwards. For the past fifty years we have concentrated on the description of the mean sea state. Now, there is perspective to start predicting deviations from the mean sea state, but it is clear that over the oceans a lot of validation of the skill of the new aspects of the wave forecasting system is still required. Validation of the skill of the probabilistic aspects of the wave forecasting system will be pursued in two directions.

- Using results from the new interim reanalysis we will collocate ship accidents with modelled sea state and kurtosis estimates. This work will be done together with the University of Leuven, Météo-France and the Met Office.
- We will attempt to validate modelled kurtosis with estimates from the radar altimeter. Namely, the radar return signal depends on the surface elevation probability distribution at zero slope and using the known, theoretical shape of the probability distribution function we might be able to estimate parameters such as the kurtosis directly from the observed return signal. This work will be carried out in collaboration with Dr Seymour Laxon (University College London) and Dr Nobuhito Mori (Osaka City University).

Finally, we note that freak wave prediction is an example of severe weather forecasting. The Ensemble Prediction System will no doubt play an important role in assessing the uncertainty of the prediction of these extreme waves.

Effects of currents and coastal zone modelling

The WAM model has an option to allow for the effects of ocean currents on wave propagation. Currents may affect ocean waves in the following ways. First, the frequency of the waves gets a Doppler shift, given by the wavenumber times the current velocity (see Box A). Second, when the current has a horizontal gradient then waves are refracted in a similar way as in the case of depth refraction. However, the most dramatic effects may be found when waves propagate against an ocean current. For sufficiently high current and high frequency, wave propagation is prohibited and wave breaking and wave reflection occurs. The most prominent example of the process of wave blocking is found in the Agulhas current, east of South Africa. The combined effect of current refraction and wave steepening (just prior to wave blocking) is thought to play a role in the formation of freak waves, which occur fairly frequently in the Agulhas current.

We have investigated the impact of currents on the significant wave height field by doing a standalone run with the wave model using monthly mean currents provided by the seasonal forecasting group. Figure 8 shows the monthly mean difference in wave height field from an experiment with and without currents. All major current systems are visible in this difference plot except perhaps the Gulf Stream. However, the amplitude of the differences is fairly small, of the order of 10 cm at best. A comparison with results from *Komen et al.* (1994) suggests that in the North Atlantic the modelled current is most likely too weak. Nevertheless, it is expected that in the near future the effects of currents will be included in the seasonal forecasting version of the wave prediction system.

Although on a global scale effects of the current may be fairly modest, it is known that in the coastal zone, in the presence of large tidal currents and surges, currents may modulate wave spectra to a considerable extent. A proper modelling of the sea state in the coastal zone, will require therefore the introduction of a coupled storm-surge, ocean wave prediction system. In addition, near the coast additional shallow water effects need to be taken into account. Examples are bottom-induced wave breaking, refraction and perhaps even quasi-resonant three wave interactions.

Part of the scientific development (for example the coupling of a storm-surge model and the WAM model) has already taken place during the European Union project Promise. Therefore, an operational version of the coastal zone, wave forecasting system (presumably replacing the present European Shelf Model) is expected to be ready in a time frame of 5 years. This work will be done in collaboration with the Proudman Oceanographic Laboratory and other partners of the Promise project.

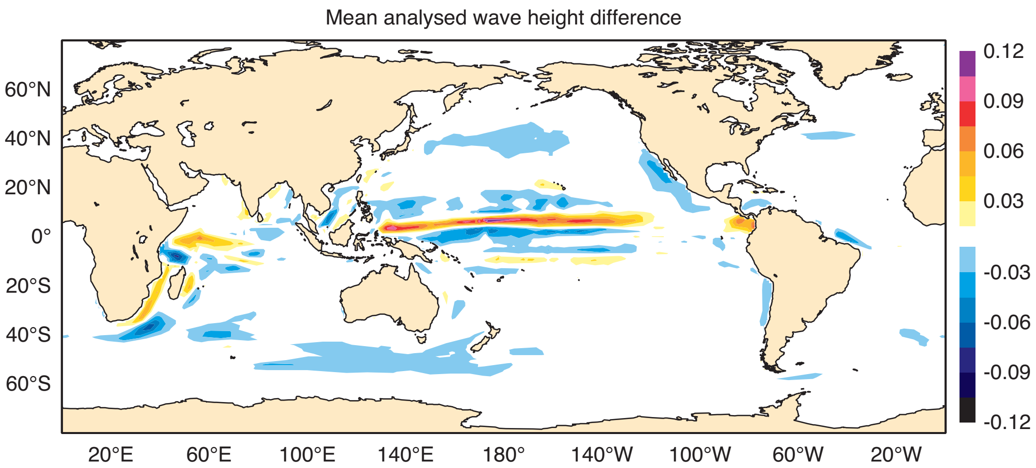

Figure 8 Impact of monthly mean currents from the seasonal forecasting system on the monthly mean significant wave height field for the period 00 UTC on 1 December to 18 UTC on 31 December 2003. All major current systems are visible except perhaps the Gulf Stream.

Need there be further wave model improvements?

At ECMWF there has been a considerable improvement in wave forecasting skill, in particular during the past ten years. Although wave model improvements have contributed to a considerable extent to the improved skill for predicting significant wave height and parameters such as the mean period it is argued that the major reason of the improvement comes from a higher quality wind field.

Clearly wave model results are sensitive to errors in the forcing wind speed. We have utilized this property of ocean waves to our advantage by using wave model forecast results as a tool to diagnose problems in the atmospheric model (*Janssen et al.,* 2000). Examples are the inconsistency between surface wind and stress, the over-activity of the atmospheric forecast, and the lack of small-scale variability. Combined with the two-way interaction of wind and waves this has contributed to maintaining a high quality weather forecasting system.

One may ask the question whether there is any further need for wave model improvements. Evidently, there is, at least if one is interested in a realistic representation of the properties of the sea surface. Examples are the coupling of wind and waves which had a beneficial impact on the forecast and the recent improvements seen in the mean frequency of the ocean waves. It is emphasized that forecasting of significant wave height is only one aspect of the wave forecasting problem, the final aim is to obtain a reliable and accurate two-dimensional wave spectrum. This is relevant for many practical applications ranging from ship response studies to sea state effects on altimeter measurements.

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