Present Status of wave forecasting at ECMWF

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1. Introduction

In this note I shall give a brief overview of the ECMWF wave forecasting system. Firstly, the present applications of wave forecasting model are described, followed by a discussion of some developments of the wave model after the operational introduction of WAM cy4 in 1991. Extensive validation of wave analysis and forecast is performed at ECMWF. I discuss analysed/first-guess wave height verification against buoy data and altimeter data, while verification of the 10 day forecasts against the analysis is given as well. Conclusive evidence is found of the sensitive dependence of wave forecasting results on the quality of the surface wind field. Since independent validation of the surface winds suggests that in the past five years there are considerable improvements in the quality of the surface wind field on a global scale, the time seems ripe to reconsider numerics and physics of the wave prediction model. Finally, the main reason is given why the present version of the atmospheric model with spatial resolution of 40 km and 60 layers in the vertical shows a sensitive dependence on the two-way interaction between wind and waves.

2. Present Status

The present version of the ECMWF wave forecasting system is based on WAM cy4 as described by Komen et al (1994). The WAM model was introduced in operations 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 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, an number of changes of a numerical nature were introduced over the past 9 years, which will be discussed in Section 3. A documentation of the present version of the ECMWF wave model may be found on the web (http://www.ecmwf.int/; choose *research*, choose *Integrated Forecasting System Documentation* 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. I concentrate here on the global domain. The global model covers an area of 81° S to 81° N. Since the 29th of June 1998 the wave model is part of the IFS model enabling a two-way interaction between wind and waves. Hence, the sea surface roughness, as seen by the atmosphere, is sea state dependent. The spectrum consists of 30 frequencies and 24 directions, and shallow water effects are switched on.

For the globe two applications are run:

a) *Deterministic Forecast*

The resolution of the wave model is 55 km. In order to avoid violation of the CFL criterion in the polar regions an irregular lat-lon grid was introduced in such a way that in the latitude direction the distance between grid points is more or less constant. This has the additional benefit that compared to normal spherical coordinates the number of grid points reduces by 30%. The integration and propagation time step are 15 minutes. The wave model is coupled to the 10 m winds of the TL 511 atmospheric model and the coupling time step is 15 minutes. Benefits of two-way interaction are reviewed in Janssen et al (2001). In the analysis step ERS-2 wave height data are assimilated using the OI scheme of Lionello et al (1992). Every day 10 day forecasts are issued from 12Z and 00Z.

b) Probabilistic Forecasts

ECMWF produces ensemble weather forecasts since December 1992. With the introduction of two-way interaction of wind and waves it was relatively straightforward to introduce ensemble forecasting of ocean waves. An ensemble of forecasts is realised by perturbing the atmospheric initial state with a set of the most unstable singular vectors, while the initial sea state is not perturbed. Presently, everyday 50 ensemble members and one control forecast are produced. The resolution of the wave model is 110 km and it is coupled to the 10 m winds of the TL 255 atmospheric model. Ensemble wave products are helpful in assessing the uncertainty in the wave forecast, in estimating probabilities of high sea states in the medium-range and in practical applications such as ship routing (Hoffschildt et al, 1999)

3. 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 WAM software have been introduced as well. These have been mainly of a numerical nature, i.e. there are no changes to the Physics formulation, nor to the choice of the parameters. The only parameter that has been changed is the von Karman constant (from 0.41 to 0.40) which was done in order to agree with the choice made in the atmospheric model.

The major changes that have been introduced are:

1. Rotation of the spectrum by 1/2 its angular resolution. This change was introduced in order to alleviate problems with wave energy propagation along the coordinate axes. As discussed by Bidlot et al (1997), this change resulted in occasionally large improvements in the shadow zones of islands such as Hawaii. Overall, it gave a small improvement on the scores of large areas such as the Tropics.

2. A more liberal, dimensionally correct limiter of wave growth was introduced following the work of Hersbach and Janssen (1999). This change is in particularly relevant in fetch-limited, rapidly varying circumstances.

3. Limit the explicit determination of the spectrum up to a revised cut-off frequency. In WAM cy4 the cut-off frequency was

   $\mathrm{Max}(2.5*f_{mean}, 4*f_{PM})$

   while the new choice is simply $2.5*f_{mean}$. This change resulted in a more realistic dependence of the rms slope and the Charnock parameter on the surface wind speed, while first-guess wave height standard deviation errors, as compared to Altimeter wave height data, were reduced by 5% (cf Janssen et al, 2001).

4. Altimeter wave heights are obtained from the wave form by assuming that the sea state is Gaussian. However, owing to nonlinearity deviations from the Gaussian state occur. For this reason there is a need of correcting the Altimeter Range measurement, and there is also a small correction to the Altimeter wave height. In coastal areas this may give an increase in wave height of 10%, but over all cases the correction is only 3% (Janssen, 1999).

Overall, it is estimated that these numerical changes have reduced the rms error of wave height by 10%. For example, the impact of the changes in item 3 and 4 were explicitely studied for the month of February 1998. When compared to buoy data the rms error of wave height reduced from 0.58 m to 0.53m.

4. 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).

In addition, regarding the validation of analysis and forecast against buoy data, ECMWF is involved in an intercomparison project with centres such as UKMO, FNMOC, AES, NCEP and MeteoFrance. In comparison with other centres, the ECMWF wave forecasting system shows a relative slow deterioration of the forecast. A more detailed discussion of this may be found in Bidlot et al (2001).

As reported by Janssen et al (2000), since 1995 we have seen a steady improvement in forecast skill of waveheight. From the comparison of forecast surface winds and wave heights with the verifying analysis it turns out that the standard deviation of error in wind speed and wave height has been reduced by 25% in the Northern Hemisphere, while improvements in the Southern hemisphere have been even larger. Also, when comparing first-guess wave height and analysed wind speed with the counterparts measured by the ERS-2 Altimeter, considerable reductions in the standard deviation of error are found.

It is believed that a considerable part of the improved skill in wave forecasts is caused by the improvements in surface winds. This follows from Janssen (1998) who established, based on the verification results of forecast wind and waves against the analysis, a close relation between the wave height error and the wind speed error. According to Janssen et al (2000) the improvements in the quality of the surface winds were caused by the introduction of CY13R4 (which included a number of physics changes such as the reintroduction of mean orography, 3DVAR (including the use of Scatterometer data), the formulation of the new Jb, 4DVAR (which allowed a better treatment of Satellite data from e.g. (A)TOVS) and the two-way interaction of wind and waves.

The standard deviation of error in wind speed has reduced over the past 5 years by 25%. As a consequence 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 in 1995 (Janssen et al,1995). Hence, the time seems ripe to reconsider the formulation of the Physics Source terms of the wave model and to reconsider the way advection is done in the model.

5. Two-way interaction of wind and waves

In Janssen et al (2001) a review is given of the impact of two-way interaction on the atmosphere. The main point of this review is 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 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 at best illustrated by the operational introduction of the TL511 atmospheric system. At the same time it was decided to increase direction 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 TL 319 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, in the context of TL511 impact was much more pronounced, as discussed in more detail in Janssen et al (2001). The main reason for this is probably that in TL 511 the subsynoptic scales are better represented, which follows from comparing for TL511 and Tl319 plots of the Kinetic Energy spectrum near the surface as function of total wave number.

6. Conclusion

At ECMWF there has been a considerable improvement in wave forecasting skill, in particular during the past five years. Although numerical improvements have contributed to the improved skill it is argued in this note that the major reason of the improvement comes from a higher quality wind field. In view of the significant improvements in driving wind fields the time seems ripe to contemplate on wave model improvements.

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