Introduction

Developments in wave forecasting methodology have been considerable in the last fifteen years. The surge in interest in the problem can be identified with the establishment of the, largely European, WAM group under the auspices of the Scientific Committee for Oceanic Research (SCOR).

By the end of its active life in 1992 a prescription for significant advances in wave forecasting had been laid down and was published two years later in the "WAM book" by Cambridge University Press. Some years before members of the WAM model community had begun to develop a global wave model at ECMWF, placing this relatively young weather forecasting centre at the forefront of wave prediction. ECMWF has maintained this position over the intervening years and the impressive improvements in global wave forecasting, especially at ECMWF, as well as the demonstrated effects on weather forecasting have earned the status of full partner for wave forecasters in the marine weather forecasting community. At the same time, the steady improvements in wave forecasting skill owe much to the improved skill in forecasting marine winds.

Global wave prediction has now moved from adolescence to maturity and the time is ripe to focus on the special conditions of severe storms, coastal effects, interactions with currents, freak waves, etc, that have a direct impact on life and commerce. In addition, the improved accuracy of surface winds warrants a reconsideration of all aspects of the wave prediction model.

The workshop followed the usual format of invited lectures and discussions in working groups and concluded with a plenary session. Groups were set up to consider the fields of wave modelling, physics and wave data assimilation. The discussions and recommendations of these groups are summarised in the following three reports. In order to speed up the production of the workshop proceedings, the invited lecturers were requested to provide extended abstracts only, which are presented in this volume.

ECMWF thanks all the participants for contributing to a successful and stimulating workshop.

Working group 1: Modelling

Present: Heinz Gunther(chairman), Jim Doyle, Damian Holmes, Peter Janssen, Hendrik Tolman

1. Numerical Scheme

Advection Scheme

- Investigate the benefits of alternative propagation schemes of increased accuracy, such as higher order, semi-Lagrangian, positive definite, energy conserving, reduce wiggles (TVD filter).
- Extend CFL criteria for refraction (+ filter on refraction)

Integration Scheme

- Investigate possible convergent limiters and study why they are necessary.

Choice of Grid

- Explore alternative computational grid configurations, e.g. reduced grid, finite elements, conformal mapping, icosahedral grid, two-way nesting, moving high-resolution grids, adaptive grids

Balance between spatial and spectral resolution

- High resolution in frequency and direction requires a new non-linear transfer algorithm and vice versa.
- Improved prediction of swell propagation (fronts, dispersion) requires higher frequency, direction resolution

Subgridscale Process

- Parametrise unresolved island and partial ice cover.
- Gustiness and mesoscale transients need to be included. Also, gustiness due to convection and down draughts from deep convection should be considered because they may affect sea state.

2. Coupling

- Improve coupling by investigating the importance of processes not currently considered, such as stability effects, density, gustiness, sea spray, rainfall, Stokes drift etc.
- Explore the impact of ocean parameters such as currents, SST on wave model performance as a step towards a fully coupled ocean wave, circulation and atmospheric prediction system.
- Unify the physical description between the atmospheric and oceanic circulation and wave models and across the model interfaces

3. Verification and Data Issues

- It is necessary to assess the performance of the wave model by using all data available including the spectral information.
- New validation methods and metrics must be developed to use the information available such as spectral data.
- It is essential to ensure the continuous availability of buoy data because it is the only independent ground truth available for models and remotely sensed data.
- More buoys are required, in particular in the Southern Hemisphere.

- It should be ensured that proper air-sea interface parameters are used in satellite retrieval algorithms
- Currently available and forthcoming sources of 2-d spectra should be exploited such as HF radar, ship radar, oil platform instrumentation.

4. Ensemble Forecasting and Extreme State Prediction

- Investigate the relationship between the occurrence of freak wave phenomena and atmospheric / sea state parameters with the aim to start probabalistic forecasting of extreme sea states.
- Study the vast body of information from the EPS wave forecasts to assess the uncertainty in the forecasts. Consider applications such as ship routing, coastal shore protection, workability, etc.
- Validate the EPS wave forecast against data, e.g. buoy and altimeter data.

Working group 2: Physics

Present: Luigi Cavaleri (chairman), Saleh Abdalla, Stephen Belcher, Mark Donelan, Michael Stiassnie, Gerbrant van Vledder

Recommendations

1. The current practice of treating the source functions as independent is at variance with new understanding of physical wave processes. The effect of wave breaking on enhancing the momentum transfer and swell on modifying the wind-sea has been demonstrated and therefore raises the possibility of interactive source terms. These need to be considered in further model developments. The current practice patching a 'tail' on to the predicted spectrum limits the ability of the longer wave spectral region to respond correctly to the source terms. A correct description of the source terms admits the possibility of calculating the equilibrium region (offline) and for consistency this should be done.

2. By now, it is acknowledged that the nonlinear quadruplet wave-wave interaction as approximated by the Discrete Interaction Approximation (DIA) is in poor agreement with exact computations of the Boltzmann integral. Therefore, the DIA needs to be replaced by a more accurate algorithm consisting of additional generally shaped interacting wave number configurations. For shallow water the present depth scaling should be replaced by a direct computation of the finite depth effects on the nonlinear transfer.

3. The present system of model verification gives general statistics of general parameters only. It fails to diagnose specific limitations of the model. We make two recommendations to address this point. Firstly, we recommend that verification be done for selected conditions, especially for high wind conditions (e.g. mid-latitude cyclone) or frontal zone, in selected areas. Secondly, we recommend that further parameters of verification and statistics be used. The mean wave direction, the directional spread and the swell properties are of growing interest to users, particularly for coastal applications, and so should be verified. The long term aim should be toward verifying the whole 2-D spectra generated by the model, although we recognise that new techniques would be required to attain this goal. The ECMWF archive will provide a valuable resource in producing these new verification statistics.

4. The present representation of various source terms does not presently represent the situations encountered during extreme wind conditions (e.g. > 30m/s). This has strong consequences on the accuracy of the forecast in these situations.

5. The growing international concern about extreme conditions should prompt ECMWF to have a better prediction, and possibly a warning system, for extreme wave events in the open sea and in coastal waters. Beside the pure meteorological forcing, such events arise for a number of reasons, especially: a) wind gustiness, introducing random variability in the forcing field (not to be confused with the mean enhancement effect), b) interaction with current, and c) nonlinear instabilities leading to freak waves. Item b) requires an operational circulation model with a sufficient spatial resolution. Items a) and c) can be approached only in statistical terms, providing, for given conditions, the encounter probability of different wave heights.

6. Care must be taken when going to higher resolutions, with associated small time and space scales, since the basis for some of the theoretical formulations can be violated and different approaches need to be followed. A higher special resolution also implies that more attention should be given to coastal areas where shallow water processes become important, and to a better prediction of the spatial variation of the coastal winds.

7. In view of new applications and of the move toward higher resolutions, the possibility of formulating explicitly the wave model in wave number, rather than frequency, space should be considered.

Working group 3: Wave Data Assimilation

Present: Martin Holt(chairman), Jean Bidlot, Jim Gunson, Daniele Hauser, Hans Hersbach, Jean-Michel Lefevre

1. Objectives

The group on wave data assimilation believes the following objectives should be addressed:

- In the 0 to 5 year term assimilation should aim at improving significant wave height and spectral components in the vicinity of the observations in order to obtain a better estimate of extreme events. In the longer term, methods should be developed to use the discrepancies between model and observations to correct the low frequency spectral components such that it is consistent with their propagation.
- In a relatively short time, the feasibility of using an adjoint of WAM should be explored.
- The potential use of wave observations in improving the coupled atmospheric/WAM should be assessed. Work should take place on how to improve the coupled atmosphere/WAM assimilation system. Recognising that a fully coupled variational formulation might not be directly available, simpler schemes should be explored on how to bring about wave information on the wind into the atmospheric assimilation.
- Future requirement on wave observations, both as far as data type and coverage are concerned should be addressed and feedback to the space agencies should be made.

2. Data

Data assimilation goes hand in hand with the actual data available (currently and in the future):

- The group would like to recommend that the centre takes an active role in indicating that wave data assimilation might be more successful in the future if collocated data were available (i.e. Hs, spectrum, wind speed and direction). For this reason it might be necessary to run impact studies to confirm this view. Furthermore, required sampling and coverage of satellite data could be ascertained that way.
- Could the centre take a role in encouraging the distribution (and production) of in-situ spectral wave observations needed for any kind of validation.
- The operational status of satellite wave data has been questioned, as it seems that data producers are not aware of the type of impact they have when they `play' with the instruments. The continued requirement of spectral wave observations should be communicated to the space agencies.

3. Methods

Some attention has been given to the type of method the centre should develop and use for wave data assimilation:

- It is believed that the current sequential method (OI) should be sufficient to reach some impact for the first objective to improve Hs and spectra locally, provided some work is done in trying to improve the knowledge of spatial covariances. In the longer term an ensemble Kalman filter (EKF) approach may be better, provided a sequential assimilation scheme is kept.
- It might also be necessary to explore how a variational approach can be worked out if WAM is integrated further into the 4dvar formulation. In the longer term a variational scheme could include the instrument model transfer function to assimilate directly the satellite observations.
- In line with the recommendation of collocated satellite observations, the group feels that a multivariate analysis scheme is necessary.

4. Other issues

- There is a need to continue data monitoring.

- The group has discussed whether there is any need to improve wave data analysis in the context of seasonal forecasting and climatology but it was concluded that it would not have much impact to justify the effort.