Working group on modelling

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The discussion and the conclusions have focused on three main subjects: 1) coupling, 2) how to deal with multiscale, 3) dangerous sea states. While by and large the group has followed this logical sequence, unavoidably the three subjects are, partly at least, interconnected. Therefore in the following discussion we will smoothly pass from one subject to another one with frequent cross-references.

We have, where possible, indicated the future actions ECMWF should take to keep itself at the front line of research and operational products. However, in several cases the matter is not well defined, either because of a lack of sufficient knowledge or because the decision on how to proceed may depend on factors external to the specific technicality of the matter. In these cases we have highlighted the problem, framing it within the present knowledge and expectations.

Having said that, for an easier following of the discussion we itemize the subjects sequentially touched.

Energy and action balance equations

These equations have been the backbone of spectral wave modelling since its beginning. The underlying hypothesis is that the spatial and time scales of the changes in the fields are much larger than the ones of the waves we are considering (wavelength and wave period). This assumption needs to be reconsidered when moving to higher resolutions. So the question is which resolution the Centre is expected to move to within the next decade. This point is discussed below in greater details (see “Resolution”). If, as they indicated, the solution will not go beyond 2 or 3 km, we do not expect any problem with the present spectral approach. Should the Centre decide to go further, i.e. at resolution of the order of 100 m, the matter will have to be reconsidered.

Scientific and pragmatic (operational) approaches

A purely scientific approach to wave modelling would imply to implement the best known physics for each of the processes that we consider as influential on the final results. Given our present limited knowledge or limitations, errors are to be expected. At the same time ECMWF, as any other operational centre, is expected to provide the best possible results. Unavoidably, this is achieved with a variable degree of tuning, still keeping the solid physical background. Our opinion is that both these approaches should be kept alive at the Centre. While research has always been here alive, this will necessarily be more and more the case in the future. The increasing level of sophistication of wave models, together with their present remarkable accuracy and the growing difficulty for further improvements, imply that the extensive tests required for testing any possible improvement can effectively be done only at the large, typically operational, centres.

Where to act for further improvements

Although simple in its conceptual structure (generation, dissipation, advection, nonlinear interactions), an advanced operational wave model is a rather sophisticated machine. It is not always obvious where, on each process, to invest for further improvement. However, apart from the just mentioned distinction (see previous item) between scientific and operational approaches, there is at present an intense international effort aimed at improving, where possible, the physical aspects of a wave model. Therefore in a way the question we have posed is rhetoric. With one exception: nonlinear wave-wave interactions. The limits of the present DIA approach are well known, although their overall implications on the final results (Hs, Tm, etc.) are not similarly clear. Given the more complete, but correspondingly expensive, methods available (including the EXACT-NL), the question is if the next increase of computer power should be used as a further, as usual, increase of resolution, or it should be devoted, partly at least, to a more sophisticated estimate of the nonlinear interaction source term. Two tests should be done: A) a global simulation using first DIA and then EXACT-NL to check if the latter results are indeed better and, if so, how much. If this were indeed the case, B) to run the same simulation with DIA, but with an increased resolution implying the same increase of computer power used for the EXACT-NL. The output statistics and the analysis of single events should clarify how to best invest the future computer resources. A compromise solution may come with the use of unstructured grids (see “Resolution”).

Coupling

It is progressively accepted by the meteorological and oceanographic communities that any realistic simulation of the atmosphere and the ocean should include both the media. Wave generation and feed-back to the atmosphere, wave-currents interactions, currents and relative wind, waves modulating all the exchanges at the air-sea interface, are just a few, although relevant, examples of the processes involving the ocean and the atmosphere. There is a whole hierarchy of interaction processes. Which ones to consider in operational application depends on the time scale one has in mind. In the middle range, and focusing on wind wave generation, we consider spray and heat exchange as two elements that could have a rapid impact (we expect more on this in the report by the “Physics” group). Part of this is already included in the mixed-layer modelling the Centre is working on.

On the same time scale there is an obvious interaction with currents, both for the wave current interactions as for the effective wind relative to the moving sea surface. The influence of waves on the atmosphere (once generation is over), although locally non-dominant, will probably have to be considered as the long distance swell generated along the storm belts is an effective mean to transport atmospheric momentum towards the equatorial zone. All these processes act at their extreme in hurricane conditions, a subject the increasing resolution and the quality of the ECMWF results will imply that more attention needs to be given to.

Moving to monthly and seasonal predictions, more processes need to be taken into account, the dominant one being the exchange of gases. We stress that their proper consideration implies in principle quantification of the spray and of the bubble clouds following any breaking. We also stress that the sensitivity of the long term forecasts to the situation in the early days of the forecast suggests that these once considered second order processes should be taken into account since the start.

A substantial problem with coupling is that all the coupled models should be at the same level of accuracy and reliability. At present, while meteorological and wave models share a similar level of quality of the results, this is not the case with circulation models. There are good reasons for this: the 3D structure of the ocean, a complicated physics, a substantial lack of data, just to mention the basic ones. However, this is the situation and it is not a problem that can be solved at short term. We will come back to this on the final item of this document.

Coupling implies also proper consideration of the related numerics. Models run generally on different grids, with different time steps. Which approach to use (e.g., a) all the models run with the same Δt , b) each model with its own optimal Δt, with intermittent exchanges of information) is strongly dependent on the coupling tool that is used and on the architecture of the computer system.

Ensemble and data assimilation

Presently the middle range ensemble approach is used only on the meteorological model. Although physically coupled, in this respect the wave model acts as a slave. A deeper level of coupling, including the ocean since the start, possibly implies that the concept of ensemble will have to be revisited. The ensemble should be considered as perturbations, physically consistent, of the overall system. This is an open problem, but likely to appear in the near future.

A similar problem exists for data assimilation. When the atmosphere and ocean are conceived as a single fully interactive system, it seems natural that a correction, e.g. on the wave field, should be reflected into the whole system. Carrying on the example, if we find that the modelled wave heights are too large, this should be considered also as information on the driving wind field.

Resolution

While sufficiently good for most of the storms in the open ocean (hurricanes and similar phenomena are a different matter), the present global resolution of the WAM wave model run at the Centre (28 km) is too coarse when focusing on the coastal areas. This is a) for the geometry of the coasts, b) for the required accuracy of the bathymetry, c) for the larger field gradients found in coastal areas, d) for a proper consideration of the shallow water processes. A substantial increase of resolution is strongly recommended, also the one of the European model (11 km) being not sufficient for the accuracy required by the strong economic and human interests in coastal areas.

The resolution required depends on the processes the Centre means to consider. Were it only for waves, we believe that a resolution of the order of kilometres would be sufficient, a closer look being probably within the realm of coastal engineering.

It is obvious that such a resolution cannot be considered at the global level. Then there are two possible approaches: a) nested modelling, b) unstructured grid. Nesting seems viable only at one level, beyond which it loses numerical efficiency for large scale applications. Besides in a coupled system it should probably act as a slave of the global model. In this respect unstructured grids seem a more viable and efficient solution, allowing relatively coarse resolution in the open ocean and a finer one where required.

The "relatively coarse" resolution in the oceans may leave the problem open for hurricanes and similar phenomena. A possible solution could be a nested movable grid, a solution followed or planned at other centres. However, apart from the implications for coupling (the nested grid should talk in both directions), the problem remains that the continuous interpolations required could lead to an excessive smoothing of the fields.

While we can increase the resolution of the wave model where required, the question is if it makes sense to run (locally) a high, e.g. 2 km, resolution model with the input provided by a necessarily coarser resolution global meteorological model. This is more the case close to the coasts where stronger gradients are usually present, but smoothed by both the nominal resolution of the atmospheric model and its further smoothing regularly introduced during its numerical integration. The reply is partly positive because many processes not strictly depending on the wind information can be locally at work. Of course wind input to waves in coastal areas may have a large degree of approximation.

Currents

We have mentioned in the "Coupling" section the problem of the lower accuracy of the circulation models with respect to meteorological and wave modelling. This is more the case in coastal areas where currents are often intensified and with dimensions, e.g. 1 km width or less, smaller than the model resolution (we are not talking about the shore currents due to bottom induced breaking). These currents, often associated to stormy conditions, hence to waves, may have a substantial effect of the wave fields. Given the wave resolution we anticipate at ECMWF, this can be a strong limitation to the achievable accuracy.

A longer term problem that brings us back to coupling is the physics of generation of currents. Apart from the thermohaline circulation, the so-called "wind driven currents" are in reality "wave driven currents". Most of the energy and momentum from wind go into waves that rapidly transfer most of them to currents and turbulence via the white-capping. The apparently local and short scale of the process allows the shortcut. However, as also experiments at ECMWF have shown, this is not always the case, typical examples being the areas with strong special and temporal gradients, e.g. fronts. Both the intense coupling expected in the near future and the closer approach to the coastal zone imply a substantial revision of this fundamental point.

Dangerous sea states

The definition of "dangerous" may change from place to place and depend also on the user. This is more the case approaching the coastal zone with higher resolution. Given the situation, the best approach by the Centre is to provide, place by place, an objective picture of the situation leaving the implications to the user. However, the range of products needs to be expanded. Presently ECMWF estimates, at each grid point and each output time, the distribution of wave heights (not distributed) and the likely Hmax (distributed). Several more parameters or situations need to be added.

Steepness is recommended as crucial information. High waves with low steepness (e.g. a large swell) are easily navigable. Relatively low, but steep, waves may be much more dangerous. Breaking is an essential characterization of the sea surface. An estimate of the frequency of white-capping and of its severity would be very useful information. Directionality, meant as the angular spread of the main wave system, would be much welcome as a significant information on the characteristics of a storm. Crossing sea goes along the same line of thinking, but it refers to the case of two, or more, separate wave systems, typically wind sea and the other one(s) swell. This is one of the most difficult conditions to handle in the sea. Wave-current interactions can substantially increase the severity, both as wave height and steepness, of a storm. However, here we go back to the already mentioned problem of a lack of sufficient accuracy in the description of the actual current distribution in the ocean and, more so, in coastal areas.

Freak wave have been for many years one of the activities where ECMWF has been the leader. We have mentioned above the estimate of the kurtosis, hence of the likely distribution of wave heights and of the expected Hmax. These estimates should always be based on the full 2D spectrum. Some of the characteristics of a dangerous sea state we just quoted, i.e. steepness and directionality, are crucial to evaluate the instability of the wave system, hence the increased probability of freak waves.

Recent results also indicate that cross-sea conditions are a favourable situation for instabilities, hence for freak waves. This is especially the case when two crossing systems have similar frequencies and are at a well defined angle range. Besides, as there is no indication that the above situations exhaust the possibilities for instability, we recommend that the Centre maintains this as an area of active research. In this respect we suggest to use the reanalysis data to explore the long-term statistics of the number and severity of freak waves on the globe and if, and how, they vary along the years.

Meteorological and oceanographic centres

We close this discussion and list of suggestions with a very general consideration.

ECMWF was conceived and founded in the ‘70s, when meteorology was conceived as a self-standing and autonomous science. Inputs from the oceans were a few and parameterised in what nowadays can be considered a very crude way. At the same time the oceanographic community produced their own centres, obviously focused on the oceans, and with some single parameterised inputs from the atmosphere (see, one for all, the “wind driven currents”).

Especially during the last two decades we have progressively realised that atmosphere and ocean are strongly coupled and that any successful modelling of the system implies a continuous exchange of communications between the two media.

In this situation it makes less and less sense to have half of the system, or so, modelled at one location, and the other half somewhere else. Truly enough, ECMWF has its oceanographic group, but both as human and computer resources this is only a fraction of the local work force. At the heart, this limits the quality of the performance of the Centre, especially in the longer range.

How to proceed? The problem is technical, but mainly political. One possibility is the continuous exchange of information with an operational oceanographic centre. However, this would be a far cry from the continuous coupling and cross-talking during the integration of a fully coupled model. No full immediate solution is at hand, but we strongly recommend this crucial aspect of the problem to be deeply discussed looking for a future solution. In the USA, the solution presently considered is to concentrate the computer power at one physical location with each different centre, located somewhere else, operating on the various aspects of the problem. Still with a lack of human contact, this solution makes feasible to run a fully coupled system. Something to think about at the European level.

Working group on physics

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Dissipation

The formulation of the whitecapping dissipation source function currently used in ECWAM acts both on windsea and swell. It is recognised that many processes might be involved in the dissipation of windsea and swell. It is therefore recommended to split windsea and swell dissipation formulation. In this framework, it would become easier to include newer physically based mechanisms in accordance with progress in the understanding of wave generation, interaction and dissipation. Note however that any addition to the parameterisation should aim at explicitly describing the possible interaction that might exist between the different mechanisms. A set of minimum requirements for a new formulation were identified. It should handle the case of long swell attenuation. The performance of the new parameterisation should be particularly analysed with respect to the windsea/swell transition as waves propagates away from storm but also in cases of diminishing winds. There are sufficient observational evidences that the loss of energy by whitecapping has threshold behaviour. Moreover, it is not local in spectral space but depends on the wave breaking history of other spectral components (cumulative impact).

Wind input

The working group questions the behaviour of the current wind input source term under strong wind forcing (young windsea). Based on observations, it is now known that the wind input is influenced by flow separation/sheltering around the waves. There are some evidences that wave growth depend on steepness. It is therefore recommended that an alternative formulation is sought (Donelan 2006, or something else). The impact and success of any such formalism will have to be determined in the context of the coupled system (atmosphere-waves). A better modelling of the high frequency part of the spectrum should be achieved (i.e. more than just a parameterised f**-5 tail) with the aim of improving air-sea fluxes specification. It is unclear whether the coupling mechanism between the atmosphere and the waves should be enhanced with the exchange of the actual surface stress vector as modified by the waves rather than the current practice of returning an update to the surface roughness. Impact of the directional spread specification in the wind input should be studied.

Nonlinear source term

Alternative efficient schemes (multi dia, GQM) should be tested. A careful evaluation of the impact should not limit itself to wave height but to all aspects of the waves. It is expected that such a change will mostly be visible for parameters that are more sensitive to the actual shape of the spectrum. Knowing the respective impact will help the decision on how to best allocate future computer resources to the model upgrade. In shallow water, the current practice is to rescale the deep water interaction coefficients. The actual shallow water interaction coefficients should be derived and used.

Interaction with the ocean

On top of what is already planned for the mixed layer model, the impact of mixing of the ocean turbulence by wave orbital motion should be considered.

When considering wave-current interaction, the centre should consider running a hydrodynamic model (tides, surge). Tidal currents are after all the dominant currents in many seas.

Once currents are used, the issue of what might need to be added/modified to the wave action equation should be studied (propagation effect, diffraction, dissipation,).

Address the ocean current vertical shear on wave propagation.

Bottom friction

The old bottom friction formulation has shown its limit. More advanced ones exists. To a minimum, it should include information on bottom roughness.

Waves ice interactions

This issue is worth investigating but will require better knowledge of sea ice characteristics.

Extreme winds

The working group encourages the Centre to look into the issue of observed reduced drag for the evolution of tropical cyclones.

Extreme waves

It is known that current/wave interaction can result in dangerous wave conditions. Adapt the freak wave warning system to include those dangerous sea states.

Working group on data

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General

1. Going from integrated wave parameters, derived over the whole spectrum, to following individual wave fields in terms of mean parameters of individual systems as a first step and ultimately, at a later stage, in terms of the whole spectra. This would have implications for assimilation, validation and product generation.

Future Data Availability

2. The available in-situ measurement stations are very limited both in coverage and in number. Additional in-situ measuring stations (preferably in the form of 2-D spectra) at various locations around the globe (especially in the Monsoon and trade wind areas, the Tropics in general and the Southern Hemisphere) are needed. The locations should be far from land or islands. It is recommended that JCOMM and WMO lobby national and international funding organisations for inclusion of observations within capacity building programmes for developing countries.

3. In order to produce accurate wave analysis, an order of magnitude more satellite data are needed. We, as the wave forecasting community, live in a world similar to the world that meteorologists used to live 20-30 years ago as far as data availability is concerned. This may be alleviated through a constellation of low-cost satellite measurements, e.g. GNSS Reflectometry, but to get up to the level of meteorology for the boundary layer we need wide swath observations.

4. As the realisation of 2 and 3 above can be rather expensive and may take a long time to achieve, an intermediate solution to meet the data demands through the addition of wave measurements to the available drifters, TAO, TOGA, ... etc. This may be advocated through JCOMM. Note that this has become much more feasible through the application of low cost and low weight accelerometers.

5. It is recommended the consideration, by e.g. JCOMM, of reprocessing existing in-situ wave observations as a means for deriving new validation reference data.

6. It is time to start thinking out of the box in relation to data. “Targeted observations” are a possible option. The use of innovative technologies like UAV/ UUV [both ocean surface gliders and airborne], and instruments like LIDAR and WSRA. Spatial coverage (something similar to HF-radars used for currents) of integrated parameters may be better than detailed point measurements (spectra). Other examples include Ferrybox Accelerometer. Collecting specialised data sets to serve special research needs to improve the model are of interest.

7. Support, by showing interest and by making use of existing datasets, e.g. the NOAA flight detailed (full 2-D spectra) measurements during the hurricanes using WSRA (and example of targeted observations, ECMWF interest will help assure NRT availability). The availability of such NRT data is important for data assimilation and verification.

Data Assimilation

8. It is recommended to add a partitioning and individual partition tracking facilities. This may be useful for data assimilation. Replacing the OI scheme for data assimilation with a more sophisticated scheme may not add much to the current system. A greater impact is anticipated by moving towards using error covariance estimates for individual wave systems.

9. Quantification of the measurement errors is required for both data assimilation and interpretation of the model errors.

Validation and Verification

10. Validation is not an "objective science". Therefore, it should not be based on a fixed standard set of validation measures (as this community has been doing during the last few decades). Such standard measures cause the models to evolve so that they beat these measures, rather than becoming more physically realistic. Therefore, metrics need to evolve as we better identify and understand model weaknesses. It is recommended that effort is made to adopt techniques that make use of more holistic set of metrics, e.g. the use of "Taylor diagram" and "target diagram" (Jolliff et al., J. Mar. Sys. 76, 2009, p. 64-82) for model verification.

11. It is recommended that additional metrics are adopted that relate to the end user requirements e.g.

    a. The use of the "hit-miss" statistics for the forecast products.

    b. The use of peak over thresholds (POT) for the verification of extreme-condition forecasts,

    c. Quantile-quantile (Q-Q) plots are very useful for many end-users.

12. We recommend a move to validation of whole spectra rather than the limited integrated parameters. For example, this can be done in stages from:

    a. evaluating integrated parameters of partitions (e.g. IMEDS, Hanson et al., JTECH, 26, 1614-1633, 2009), or

    b. verification based on the full 1-D or 2-D spectrum (e.g. Wingeart et al., 4th Int. Sym. Ocean Wave Meas. & Analysis, 2001, p.590-599).

13. Distribute all model match-up data from satellite data as being done for the buoy inter-comparison.

14. Work towards self-consistency in terms of scales, both temporal and spatial, between model verification and data products.

Forecast Products

15. Improving the partitioning scheme to provide proper information regarding various wave systems (e.g. swells), including spatial and temporal tracking.

16. Wave steepness and direction of each partition (e.g. for the identification crossing seas) can be more important than total SWH itself to describe dangerous sea-states. New products like breaking occurrence and intensity are also needed to describe dangerous sea-states.

17. Details of the shape of the spectrum need to be improved, including increased spectral resolution. This will enable more reliable derivation of several related products like the swell front arrival time and extreme wave prediction.

18. We, as wave scientists and engineers, need to work with the end-users on the generation, education and dissemination of products that are relevant to them. The direct interaction with the end-users is very important. It is also recommended that some of the more advanced forecast centres e.g. the JCOMM members, to come together and explore this issue.

19. We recognise that we did not give enough attention to the ensemble predictions (EPS) during the last couple of decades. Therefore, we need to start assessing the quality and characteristics of the EPS. We need to promote the use of EPS and educate the forecasters and end users on using and understanding them. We need also to address the validation and portrayal of EPS from the wave model point of view and from the end-user point of view.

20. Combining EPS wave products from various meteorological organisations into one data base (maybe within the framework of the THORPEX Interactive Grand Global Ensemble, TIGGE, project) is deemed very useful.