and vitamins from foods whose growth efficiency is far below that of tomatoes (for example, domestic animals); and people require things besides food (for example, inedible materials, energy and absorption of wastes).

This controversy about a particular ecological question raises a broader problem. Ecological information is important in evaluating many other questions of public policy as well as human population growth and use of resources. Scientists are becoming increasingly troubled that governments and the public often ignore them. Yet the scientific community itself often places a low value on ecology and population biology. The recent report[3] that minimizes biological limitations on economic development was not issued by industry but by a committee of the National Research Council of the National Academy of Sciences including economists but no ecologists or population biologists. Scientists can hardly expect the public to listen to them when their own professional organizations fail to do so. □

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Meteorology

Interactions of wind and waves

Gerbrand Komen

RESEARCH on ocean waves is evolving rapidly: for the first time an understanding of physical processes responsible for the generation of ocean waves has reached a level at which it can be (and is) used to infer the large-scale response of the ocean surface to wind forcing. At the same time application of ocean-wave modelling is going beyond traditional objectives (such as the routing of shipping) as it is becoming increasingly clear that good global knowledge of the sea state can help in the understanding weather and climate. This can work in two ways. First, measurements of wave heights can be used to modify estimates of wind speed. Second, the effect of wind–wave interactions on the boundary layer over the sea can be dramatic, and this in turn has an impact on weather patterns. These developments were the topic of a recently held workshop* of the international WAM collaboration.

Traditionally, numerical wave-prediction models are based on a mixture of theory, empiricism and *ad hoc* assumptions. But wave growth is the result of a rather delicate balance between input of energy from the atmosphere, dissipation to the underlying ocean and hydrodynamic nonlinear redistribution of energy between different wave components. The usual distinction between wind, sea and swell turns out to be highly artificial and arbitrary. As a result, models were not very accurate in complex or extreme situations, unless they had been tuned to reproduce observations under particular conditions. (See, for example, Robert Long's News and Views article in *Nature* **313**, 182–183; 1985.)

In 1984, on the suggestion of Klaus Hasselmann (Max-Planck Institut für Meteorologie, Hamburg), an international group of wave researchers (40 people from 10 countries), not satisfied with this state of affairs, started a collaboration to develop and implement a model based on best-known expressions for input, dissipation and nonlinear transfer. They have now produced a model (WAM, for wave modelling) which has run successfully on several large computers, notably on the Cray-XMP/48 of the European Centre for Medium Range Weather Forecasting (ECMWF) in Reading, United Kingdom.

The original prototype of the model has now grown into a flexible system of programs that includes all the necessary pre- and post-processing software. The model has been tested in many hindcasts: six storms on the north-west European shelf; a comprehensive North Sea study; three hurricanes in the Gulf of Mexico; several storms in the Mediterranean; and an extended global hindcast. The results compare favourably with observations, although the model may be somewhat overpredicting in the early stage of wind sea development, when waves have just begun to grow and are still relatively low. This is being fixed now, but it suggests that our ideas about white cap coverage in these early stages of development need revision. Also, the model has been run in real time, to make actual forecasts, using wind forecasts of ECMWF as input. After tests on a regional version, the global model was run for the first time on 7 March. Since then, a wave analysis and a five-day forecast have been made each day, producing detailed global wave charts.

Other work has focused on more general wave-dynamical problems. One group is reanalysing all existing observa tions of fetch-limited growth. They find for example, that air–sea temperature dif ferences are an important factor in wav growth. The effect of changing wind direc tion on ocean waves can be drastic, a tragically illustrated by the Fastnet sailin race disaster in 1979. The calculation are complicated by nonlinear coupling between waves moving in different direc tions, but are possible now using the effici ent codes of the WAM model. Also it ca now be shown how in shallow water, lon waves become dissipated while sho waves continue to propagate.

Last, but not least, the group addresse the data-assimilation problem. It is her that the relationship to weather predictio is most clear. The general idea of dat assimilation is to improve the initial mode fields (resulting from earlier forecasts) b incorporating observations, with the hop of improving subsequent predictions. I weather forecasting this is common prac tice, as forecasting skill is known to rel heavily on having high-quality initi fields. Assimilation of data on ocea waves is now becoming possible becaus of the development of remote sensin especially with the use of satellite (Geosat, ERS-1) that can measure wav heights to an accuracy of 0.5 metre These data, together with ripple-densit measurements (also from satellites), ca be used to obtain accurate estimates c wind speeds over the sea.

As it happens, ocean-wave prediction i intimately related to wind prediction. If computed wave height has to be modified the computed winds may have to b changed as well. Therefore, the problem of data assimilation in numerical wave an atmospheric models is coupled. In addi tion, the state of the sea influences th atmospheric boundary layer and th momentum flux to the ocean; it als affects satellite observations of wind above the sea. Ultimately, it is to be hope that real-time data assimilation of a observations in combined wave an atmosphere models will be available. Thi would also ensure that best use is made c satellites for climate studies. Only by com bining measurements and models ca accurate global-stress fields, essential i climate modelling, be compiled.

The effectiveness of the WAM grou may be related in part to the way in whic it arose. Its work evolved in an iterativ way as a result of a series of meetings i which individual plans and group task were presented alternately. In this wa different interests and abilities, person and institutional, were merged withou any strong power structure, but with gre success.

* The WAM group met at Woods Hole Oceanographic Institution, 2–5 May 1987.

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