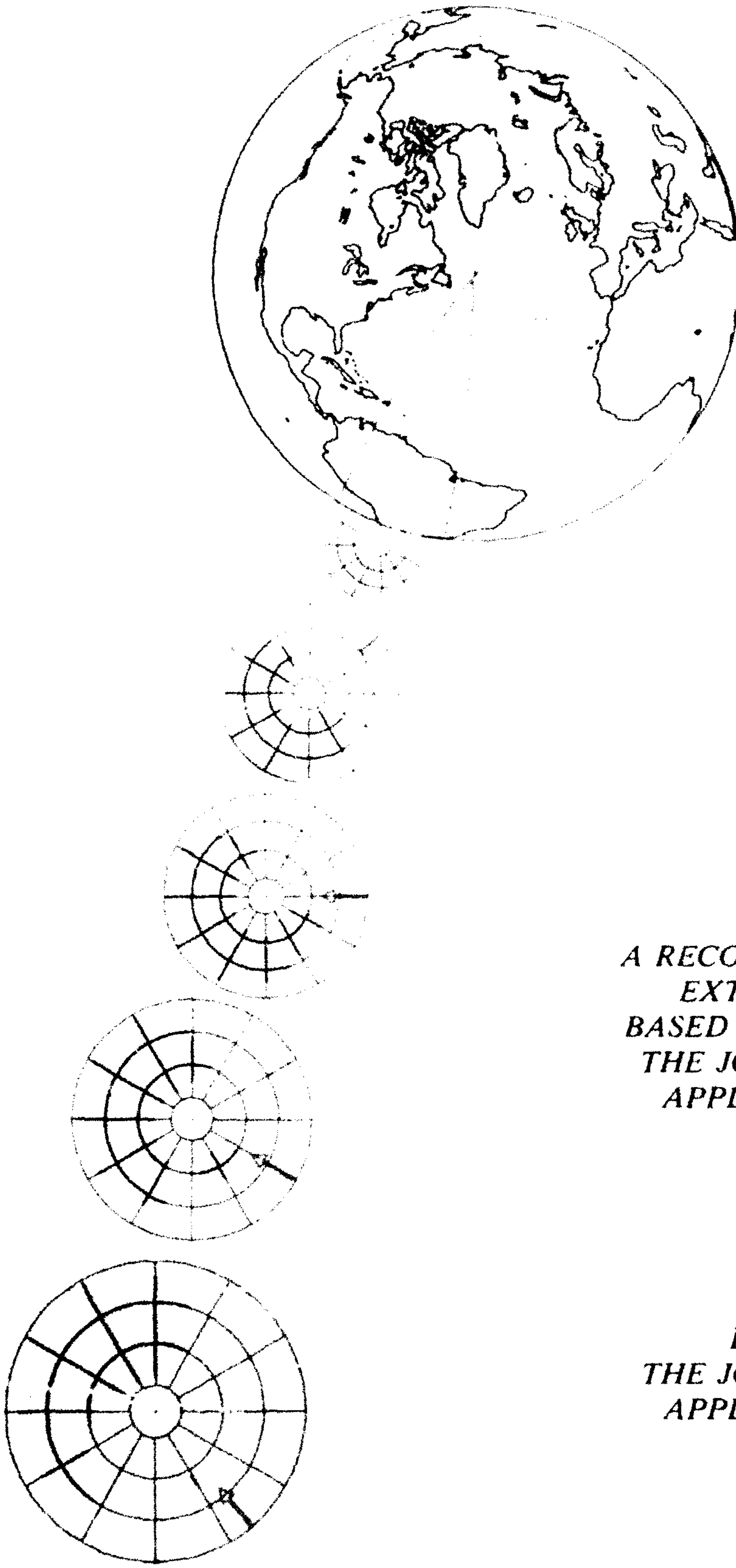

MEASURING
MODELING
PREDICTING
AND APPLYING

DIRECTIONAL OCEAN WAVE SPECTRA

A RECORD OF THE LABRADOR SEA
EXTREME WAVES EXPERIMENT
BASED ON A SYMPOSIUM HELD AT
THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
APRIL 18-20, 1989

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EPILOGUE: WAVES, DREAMS, AND VISIONS

By Klaus Hasselmann

As a guest at this conference who has not been directly involved in LEWEX [Labrador Sea Extreme Waves Experiment], I can genuinely and convincingly extend my congratulations to all of its participants for carrying through this ambitious project so successfully. It has long been a goal of wave research to compare detailed *in situ* directional wave buoy measurements with various, potentially very powerful, remote sensing methods of measuring the two-dimensional wave spectrum, to make such measurements simultaneously at a sufficiently large number of stations to reconstruct the space–time history of the two-dimensional spectrum, and to combine all measurements in a comprehensive wave model intercomparison study. I think LEWEX is the first experiment that has really succeeded in bringing these three important aspects together. There is clearly still a long way to go to completely analyze all the many data sets and model simulations that have been presented at this meeting, but what we have already seen has been very impressive. The successful completion of the field exercise, and the collection and presentation of the extensive suite of *in situ* measurements, remote sensing data, and model hindcasts in a common format together represent major accomplishments. This well-organized analysis has provided a unique and impressive overview of the entire experiment and has set a clearly defined frame within which all participants will be able to interact effectively in their further in-depth investigations.

It is still too early to predict whether it will be possible to successfully disentangle the significant differences we have seen among the various model hindcasts, and whether one will succeed in attributing these differences uniquely to particular shortcomings in particular models. As often in the past, a major challenge will be to reconstruct the wind field with sufficient accuracy. Nevertheless, there is no doubt that this experiment has provided the best data set to date for testing two-dimensional wave models in real, complex wind situations, and one can safely predict that the experiment will generate many interesting new ideas and open up new avenues of research. Let me therefore extend my sincere congratulations to the entire LEWEX group.

I thought this might be a good excuse to indulge in some personal fantasies and visions, particularly about the future role of wave modeling in the evolving geosciences of the nineties. I have attempted this sometimes in the workshops of the WAM [Wave Model] Group. My inspired visions of the future were usually received with some bemusement, but only muted enthusiasm. However, I thought perhaps, in the pervasive atmosphere of satiated contentment following this excellent banquet, that I could invite you to join me in a little speculative dreaming about where we may be going in future wave research.

Let me first summarize briefly what I think we have achieved in ocean wave modeling in the last forty years and explain then why I believe that wave modeling will play a completely different and far more central role in the geophysical sciences in the future.

There have been major landmarks in our understanding of wave dynamics and in the development of wave models since the pioneering paper of Sverdrup and Munk in 1947 [see the boxed insert for other landmark publications]. I need not dwell on the various stages of this development. But the development in our understanding of wave dynamics and our ability—or, more precisely, our belief in our ability—to model ocean waves have not always coincided.

Each landmark in wave research led to a significant increase in our understanding of wave dynamics. However, our confidence in our models suffered a severe setback in the early seventies. At this time we realized, through detailed field measurements, that the first-generation wave models developed in the sixties on the basis of the linear Phillips-Miles wave growth theories and Phillips's concept of a universal saturation spectrum were fundamentally incorrect. The growth of wind waves was found to be much more strongly controlled by the nonlinear transfer than we had hitherto believed.

The second-generation models that were introduced in the second half of the seventies to represent this revised spectral energy balance, then, essentially brought us right back, regarding the description of the wave field, to the original concepts of Sverdrup and Munk. The wind sea was again reduced to two characteristic parameters, the significant wave height and significant period, which could be represented as a function of a single parameter, the wave age. The dynamics were, of course, more sophisticated than in Sverdrup and Munk, in the sense that the evolution of these scale parameters was now determined by a transport equation. Also, the scale parameters were now used to define the full, two-dimensional windsea spectrum, and the swell was described independently by an additional arbitrary spectrum without any shape restrictions, as in a first-generation model.

In a talk I gave at a symposium to honor Walter Munk's sixty-fifth birthday in 1982 entitled "The Science and Art of Wave Prediction: An Ode to HO 601," I plotted the Sverdrup and Munk windsea data from their original report together with the JONSWAP [Joint North Sea Wave Project] data. The Hydrographic Office [HO 601] data were based almost entirely on visual observa-

Adapted from the LEWEX banquet address.

SOME LANDMARK PUBLICATIONS IN WIND-WAVE MODELING

Wave Heights and Period

1947 Sverdrup, H. U., and Munk, W. H., "Wind, Sea, and Swell. Theory of Relations for Forecasting," Hydrographic Office Publication No. 601, U.S. Naval Oceanographic Office, Washington, D.C.

1952 Bretschneider, C. L., "Revised Wave Forecasting Relations," in *Proc. 2nd Conf. Coastal Engineering*, Council of Wave Research, Engineering Foundation, Berkeley, Calif., pp. 1-5.

Spectrum

1955 Pierson, W. J., Neumann, G., and James, R. W., *Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics*, U.S. Navy Hydrographic Office Publication No. 603, Washington, D.C.

Dynamics

1957 Miles, J. W., "On the Generation of Surface Waves by Shear Flows," *J. Fluid Mech.* **3**, 185-204.

1957 Phillips, O. M., "On the Generation of Waves by Turbulent Wind," *J. Fluid Mech.* **2**, 417–445.

1958 Phillips, O. M., "The Equilibrium Range in the Spectrum of Wind-Generated Ocean Waves," *J. Fluid Mech.* **4**, 426–434.

1961 Hasselmann, K., "On the Non-Linear Energy Transfer in a Wave Spectrum," in *Ocean Wave Spectra*, Prentice-Hall, Englewood Cliffs, N.J., pp. 191-197.

Transport Equation

1957 Gelc', R., Cazale, H., and Vassal, J., "Prevision de la houle, la méthode des densities spectroangulaires," *Extr. Bull. Inf. Com. Cent. Oceanogr. Etude Cotes* **9**, 416–431.

First-Generation Models

1964 Pierson, W. J., and Moskowitz, L., "A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii," *J. Geophys. Res.* **69**, 5181-5190.

1967 Barnett, T. P., and Wilkerson, J. C., "On the Generation of Ocean Wind Waves as Inferred from Airborne Radar Measurements of Fetch-Limited Spectra," *J. Mar. Res.* **25**, 292-321.

1969 Ewing, J. A., "Some Measurements of the Directional Wave Spectrum," *J. Mar. Res.* **27**, 163-171.

Joint North Sea Wave Project (JONSWAP)

1973 The JONSWAP Group, Measurement of Wind Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP), *Dtsch. Hydrogr. Z.* **12**, Suppl. A.

Second-Generation Models

1976 Hasselmann, K., Ross, D. B., Muller, P., and Sell, W., "A Parametric Wave Prediction Model," *J. Phys. Oceanogr.* **6**, 200-228.

Seasat

1982 Seasat Special Issue 1: Geophysical Evaluation, *J. Geophys. Res.* **87**, No. C5.

1983 Seasat Special Issue 2: Scientific Results, *J. Geophys. Res.* **88**, No. C3.

Sea Wave Modeling Project (SWAMP)

1985 The SWAMP Group, Sea Wave Modeling Project (SWAMP): An Intercomparison Study of Wind-Wave Prediction Models, Part 1: Principal Results and Conclusions, *Ocean Wave Modeling*, Plenum Press.

Third-Generation Models

1988 The WAMDI (Wave Model Development and Implementation) Group, "The WAM Model—A Third Generation Ocean Wave Prediction Model," *J. Geophys. Oceanogr.* **18**, 1775-1810.

Labrador Sea Extreme Waves Experiment (LEWEX)

1991 Beal, R. C., ed., *Directional Ocean Wave Spectra*

tions from highly heterogeneous sources—including waves on the lake in Hyde Park and the observations of a ship's officer crossing the English Channel during D-Day—while the JONSWAP data were obtained under highly selective fetch-limited, uniform wind conditions using modern spectral wave instruments. Yet the agreement was astounding!

We have clearly still not entirely removed the art from wave prediction. However, today we have passed another significant landmark, the introduction of third-generation wave models following SWAMP [the Sea Wave Modeling Project, 1979-81], and I believe we have now finally shifted the art to where it belongs—to the discussion of the source functions, rather than the manipulation of the spectrum itself.

In SWAMP, four first-generation and five second-generation models were intercompared. SWAMP clearly demonstrated that second-generation models, although representing a significant improvement over first-generation models, still suffered from basic shortcomings. The simplified parametrical description of the windsea spectrum was simply inadequate to treat the complex windsea spectrum generated in more complicated real wind field situations. This motivated the WAM Group to develop a third-generation wave model in which the wave transport equation was integrated from first principles only, using prescribed source functions, without any additional assumptions regarding the shape of the resultant spectrum. After several years of joint efforts, an extensively tested and verified third-generation wave model is now available. We are thus finally in a position to seriously investigate competing hypotheses regarding the form of the input and dissipation source functions, and to compute the response of the wave field to extreme or unusual wind conditions, as documented in detailed field experiments such as LEWEX or the planned SWADE [Surface Wave Dynamics Experiment] project.

This development is particularly timely if I turn now to the tasks facing wave modelers in the future. For the scientist, the primary motivation for ocean wave research has undoubtedly always been its intellectual attraction as a field of fluid dynamics, which is both inherently complex and, at the same time, amenable to a certain level of rigorous mathematical-physical analysis. The support for research in this field, however, has traditionally been rooted in more mundane engineering and economic concerns: the great practical importance of wave forecasts or hindcasts for ship routing, offshore activities, coastal engineering, design criteria, risk assessment, accident investigations, and numerous other applications. Although these areas will continue to remain major drivers for wave research, particularly as the economical pressure to extend offshore activities into environmentally more hostile regions of the ocean increases, we may expect wave research and wave modeling in the future to assume a completely new role as an essential component of the expanding world climate research and global change programs (cf. Fig. 1). This will bring a new focus into wave research, with a much stronger emphasis on the symbiosis between basic wave research and wave modeling.

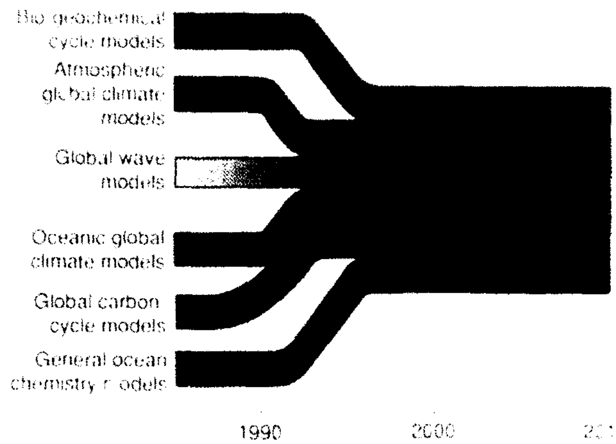

Figure 1. Future role of wave models as an essential coupling component for ocean–atmosphere–carbon-cycle models developed in the context of the *World Climate and Global Change* programs.

Ocean waves represent the interface between the ocean and the atmosphere, the two most important subsystems governing the dynamics of climate and global change. A realistic description of the physical processes occurring at the ocean–atmosphere interface is essential for a reliable determination of the air–sea fluxes of momentum, sensible and latent heat, CO_2 and other trace gases, and aerosols, which together determine the coupling between these two systems. We know that the wave field is intimately involved in these exchange processes, although this knowledge has yet to find its expression in most air–sea bulk formulae. In the future, wave models, therefore, will be needed to compute not only the wave spectrum itself, but also the processes at the air–sea interface that govern, in addition to the growth and the decay of the wave spectrum, the fluxes across the interface.

Third-generation wave models are an essential prerequisite for this task. We will need to look closely, for example, not only at the form of the high-frequency equilibrium spectrum, but also at the source functions determining this equilibrium, since these determine the momentum extracted from the atmosphere, the fraction of the momentum flux transferred to currents, and the energy dissipation available for mixing. We are only just beginning to investigate these problems seriously.

Nobody has as yet attempted to couple an ocean model to an atmosphere model via an explicit model of the air–sea interface, that is, via a wave model. The coupling is still realized today using simple standard bulk formulae. Numerical climate simulation with coupled ocean–atmosphere models is a field that is still in its infancy, but one that can be expected to expand rapidly. Reasonably realistic global circulation models of both the ocean and the atmosphere now exist. The problem of model drift—the fact that the coupled system, when freed from the boundary conditions that constrain the individual subsystems in the uncoupled mode, slowly drifts into another, often unrealistic, equilibrium climate state—that has long plagued coupled model experiments, has now been largely resolved for response simulations by coupling the two systems through the flux anomalies rather than the net fluxes. Finally, the enhanced computer resources needed for coupled model experiments have now become available and will continue to be upgraded. In the next years, simulations of the coupled ocean–atmosphere system with high-resolution general-circulation models can be expected to yield a significantly better understanding—and, hopefully, useful predictions—of natural climate variability, such as the El Niño/Southern Oscillation phenomenon and decadal and century-scale climate variations. Still more importantly, they will provide an essential tool for the urgent task of assessing the time-dependent climate change induced by man's activities.

The problem of man's impact on climate will require coupled models, including not only the physical ocean–atmosphere system, but also the carbon cycle. Models of the carbon cycle based on realistic three-dimensional descriptions of the ocean and atmosphere circulation have now been developed, and it is, in principle, technically straightforward to combine such models with coupled ocean–atmosphere models to predict the impact of CO_2 emissions on climate, taking into account all relevant feedbacks between variations in the ocean–atmosphere circulation and changes in the ocean–carbon constituents and the atmospheric CO_2 concentration.

As more experience with such coupled ocean–atmosphere and ocean–atmosphere–carbon-cycle models is gained, the details of the coupling at the air–sea interface will naturally begin to receive more attention. The need to introduce an explicit model of the interface, namely, a wave model, into coupled models may, in fact, arise sooner than some may anticipate. First experiments with coupled models have already clearly revealed the discrepancy between the relatively simple bulk formulae used to parameterize the fluxes across the air–sea interface in present atmospheric circulation models and the more sophisticated treatment of the dynamical processes at the air–sea interface commonly invoked in the interpretation of detailed field and laboratory experiments. Whereas the atmospheric circulation does not appear to be overly sensitive to the precise formulation of the air–sea transfer rates, the ocean circulation, carbon cycle, and surface wave field all respond strongly to small perturbations in these fluxes. A significant improvement of the present bulk flux parameterizations needed to drive these systems reliably can be achieved only by using a wave model with explicit, realistic representations of the dynamical source functions.

Technically, it is quite feasible to run an ocean wave model together with an atmospheric circulation model. This is indeed currently being pursued in several weather forecast centers. We can, therefore, expect future atmospheric circulation models to include wave models as a standard extension of their ocean boundary-layer packages, just as snow, soil moisture, and land vegetation must be included in a consistent treatment of the terrestrial boundary layer.

Looking farther down the road (cf. Fig. 1), coupled models will undoubtedly be extended within the context of the International Geosphere-Biosphere Programme and the activities of the World Climate and Global Change programs to include more sophisticated models of the hydrological and global biogeochemical cycles. But these models will still continue to be built on coupled ocean–atmosphere models as their core component, and the proper representation of the exchange processes at the air–sea interface will continue to remain a high priority concern. Thus, the need to develop coupled ocean–atmosphere models, complete with a dynamical ocean wave interface model, applies not only for climate studies, but holds generally for the evolving Global Change programs.

Finally, ocean wave research and wave models also have an important role to play in the global observing system planned for the World Climate and Global Change programs. An essential component of this observing system is the measurement of ocean surface properties from space. However, the retrieval of geophysical parameters from many ocean satellite sensors—in particular, from all-weather microwave systems—depends critically on knowledge of the sea state and the associated dynamical processes at the sea surface that directly or indirectly affect the signals measured by these sensors. Reliable ocean wave models will therefore be needed in the future to routinely process ocean satellite data. For ERS-1 and ERS-2 [European Remote Sensing Satellites], an extensive program for the simultaneous analysis and assimilation of altimeter, scatterometer, and SAR [synthetic aperture radar] wave model data in near real time, using both atmospheric general circulation and global ocean wave models, is already being developed. In the long term, a comprehensive data analysis and processing system, combining data quality procedures, sensor algorithms, and data assimilation in a single processing suite, will need to be developed for all available ocean surface data.

From the global viewpoint, if mankind is to meet the challenge of understanding and managing the resources of the finite planet on which we all live, we will need to install and maintain a permanent global Earth observation system, consisting of space, land, and ocean segments, in conjunction with an operational data assimilation system based on sophisticated models to process the enormous data volumes continuously generated by such a system. Wave models will represent an important component in this model suite.

Thus, we may expect in the nineties an evolution of ocean wave studies from a discipline that has tended to live rather in the wings of traditional oceanographic and atmospheric scientific research, supported mainly by offshore, oceanic, and coastal engineering applications, to a pivotal discipline in the mainstream of Earth system science.