WIND WAVES IN THE GLOBAL OCEAN OBSERVING SYSTEM

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ABSTRACT - *Measuring and forecasting ocean waves are key elements of marine services. This has stimulated the continuing development of observational networks and operational forecasting systems. But waves are also highly relevant for all other modules of GOOS, in particular for the Climate Module. So far the importance of ocean wave observations for the GOOS Climate Module has been somewhat overlooked. However, sea state is an important element of the coupled atmosphere/ocean system, affecting many human activities. Knowledge of its climatology is of great importance therefore, and its variability on interannual and decadal time scales should be studied, understood, predicted - to the extent possible - and* ***validated****. In addition, there are indications that waves can play a dynamical role in the climate system: they affect air-sea interaction, so that the sea state is a parameter in flux parameterizations, and they have a strong effect on the albedo. Waves also affect mass exchange across the sea surface. GOOS wave observations must build on the existing infrastructure, which was originally set up mainly in relation to real-time wave forecasting. Visual observations from ships, instrumental in situ measurements of significant wave height and of the wave spectrum, and satellite observations of waves and wind (altimeter, SAR and scatterometer) are complementing each other and deserve high priority. The analysis of long-term global satellite datasets can complement information obtained from operational model archives (analysis* ***and*** *reanalysis) of assimilated wind and wave fields. To obtain the best possible input observations from existing networks should be distributed through GTS, and additional wave sensors should be standard on all operational moored buoys (e.g. TAO, TRITON, PIRATA, etc). The present paper begins with an overview of the status of wave observation, and wave prediction and specific climate issues. It also discusses the overlap with other modules of GOOS. It is suggested that the WMO CMM Subgroup on Wave Modelling, now part of JCOMM, be given the task of overviewing all wave-related GOOS activities, and that s scientific group, perhaps under SCOR, be established to address some or all of the scientific issues addressed in this paper.*

1. INTRODUCTION

Wind waves affect many human activities and have great geophysical significance. Therefore, their study, observation and prediction and the corresponding climatological data services are relatively well developed, and have been used in practice since the mid 1950s. Highlights were the increasing sophistication of wave observations, which now allow the routine measurement of two-dimensional wave spectra, the enormous increase of spatial observational coverage by the launch of a whole series of wave observing satellites, and by the development of advanced theories of wave dynamics and the development of computers which allow advanced wave models to be used for real time forecasting and hindcasting. Nevertheless, there are some very basic needs which are not addressed in a satisfactory manner at present. For example, very little is known about the decadal variability of the wave climate. Also, our understanding of the dynamical role of waves in the climate system is still rudimentary.

The establishment of a Global Ocean Observation System provides an important opportunity to optimize and rationalize the observation of ocean waves and all related data services. According to the GOOS Strategic Plan, the GOOS goals are:

i. to serve the marine data and information needs of humanity for the efficient, safe, rational and responsible use and protection of the marine environment, and for climate prediction and coastal management, especially in matters requiring information beyond that which individual national observation systems can efficiently provide, and which enable smaller and less-developed nations to participate and gain benefit;
ii. to establish an international system to provide the required coordination and sharing of data and products that otherwise would not be possible.

More specifically the GOOS objectives are:

i. to specify in terms of space, time, quality and other relevant factors, the marine observational data needed on a continuing basis to meet the common and identifiable requirements of the world community of users of the oceanic environment and ocean knowledge;
ii. to develop and implement an internationally coordinated strategy for the gathering or acquisition and the archiving of these data and synthesizing them for common use and practical application;
iii. to facilitate the development of uses and products of these data, and encourage and widen their application in the sustainable use and protection of the marine environment;
iv. to facilitate means by which less developed nations can increase their capacity to contribute, acquire and use marine data;
v. to coordinate GOOS activities and ensure their integration with other global observation and environmental management strategies.

These goals and objectives may be used as a checklist when defining priorities for the development of ocean wave activities. In fact they form a challenging list of tasks: concerning wind wave observations, data collection, distribution, processing and archiving. They also raise the issue of capacity building, and integration with other marine meteorological and oceanographic activities.

In a recent paper Komen and Smith (1999) have discussed wave monitoring and prediction in the Service Module of GOOS. The present paper broadens this discussion by focusing on the issue of how various wind wave related applications can benefit from and contribute to the development of the global sustained observation and data processing system, as a whole. We will begin with a short overview of the current status of wave observation and modelling. This will be followed by a discussion of wave climatological aspects and the role of wind waves in the Climate Module of GOOS. We also include a section describing the relevance of waves for other GOOS modules. The paper ends with a set of recommendations, taking into account the potential benefits the global sustained, systematic oceanographic observation and data processing system can provide for wind wave modelling, prediction and related data services and to derive recommendations how to maximize the benefits.

2. OPERATIONAL WIND WAVE OBSERVATION, MODELLING, AND DATA SERVICES

2.1. Wind wave observations

2.1.1. Visual observations

Visual observations of wind speed and direction, significant wave height, wave period, and wave direction (wind sea and swell) have always been of great importance, and will continue to be important. However by their nature these observations are subjective, and whilst useful in assessing marine forecast products - since the ships themselves may be receiving routing advice, the data are not sufficiently precise to permit assimilation or direct application in numerical wave models.

Further insight into the problem of ship observation quality was achieved by the Voluntary Observing Ships Special Observing Project for the North Atlantic (VSOP-NA). Some persistent biases and systematic errors were revealed in the study, particularly regarding near-surface winds. It was concluded that errors in true wind could be decreased by the provision of dedicated computer programs or calculators. The results of the project make it possible to introduce more sophisticated ship report processing techniques that will extract more useful information from the observations. However, the ratio benefit/effort for such an undertaking is unclear. The corresponding biases and typical errors of visual wave observations also remain unclear. Gulev *et al.* (1998) showed considerable scatter in comparisons of VOS significant wave height, altimeter waves and modelled waves. However, the differences in the mean wave height climatologies were generally less than about 0.5m. Probably, an experiment like VSOP-NA could be useful for learning more about the quality of visual wave observations. At the same time the development of remote sensing techniques and corresponding data assimilation is clearly of higher priority.

A possible limitation of visual wave observations is that ships may try to avoid storm areas, although studies done previously failed to show any evidence of such a fair-weather bias. If this were the case, however, the better the storm forecasts the fewer visual observations from ships in storms would be available. In addition, according to the widely accepted seafaring practice, meteorological observations in storm conditions may be not conducted. This limitation emphasizes the value of instrumented observations. Automatic data coding and transmission is not less important.

At the same time visual wave observations represent, and for many years to come will represent the basis for feedback of mariners to wind wave data services provided to them. A question arises, can the development of GOOS and corresponding observational techniques make ship observations more useful? One obvious answer to it would be automation of VOS shipboard instrumentation and data transmission facilities including software for message compilation, archival, and transmission.

2.1.2. Instrumented observations

Instrumented observations of wave height and wave period are available from a network of moored buoys operated by National Agencies, or by the offshore oil industry. However this network of buoys that are routinely available via the GTS (Figure 1), is too sparse to give any more than a local impact from assimilation into a global wave model. Many of the buoys are in coastal waters, and the network aims to sample "incoming" waves for coastal applications - any impact in model assimilation will therefore be short-lived.

In recent years, instrumental observations from buoys and platforms of the (two-dimensional) wave energy spectrum have grown in importance. Certain areas, such as the North Sea, coasts of Canada, US, Australia, are covered reasonably well. Instrumental observations in other areas, and mostly in the Southern Hemisphere are rare. It is important to adequately sample the different wave climate regimes that exist in different regions, such as the central Pacific, NE Pacific, NW Atlantic, NW Pacific.

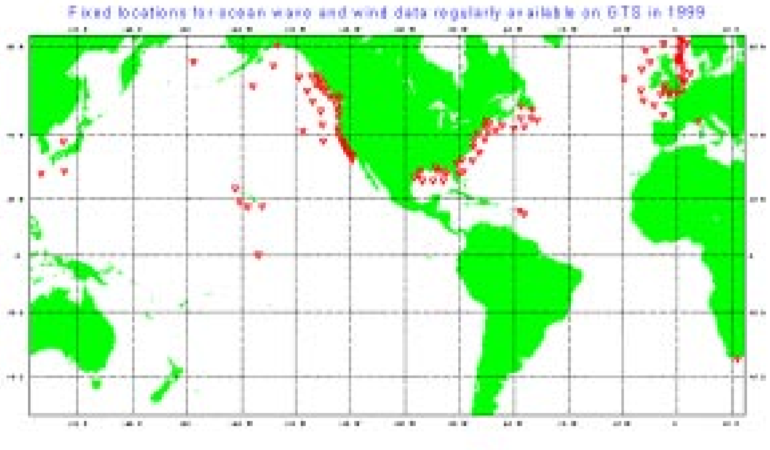

Fig.1. Fixed locations for ocean wave and wind data regularly available on GTS in 1999.

Long-term moored buoy systems TAO/TRITON and PIRATA in the tropical Pacific and Atlantic provide high quality subsurface observations of temperature/salinity/currents, which are of great value for future long-term weather forecasting and climate change studies. However, a question arises whether in future it will be possible to interpret the data in terms of surface fluxes without corresponding information on wind wave spectral characteristics. Simulated wave fields would serve this purpose but in addition, the TAO/TRITON and, potentially, PIRATA arrays could be useful for obtaining better data on wave growth for large fetches under condition of more or less uniform and steady wind.

Instrumented wave observations are the main source for wave hindcast and forecast verification and predictive model tuning. They will probably represent the observational basis for off-shore industry feedback to wind wave data services. The majority of instrumented wave observations provide one-dimensional, i.e. frequency spectrum data. Freely available (i.e. non-proprietary) directional wave spectrum measurements, i.e. 2-D, which would correspond to the output of modern wind wave models, are extremely scarce.

2.1.3. Satellite observations

Satellite altimetry. A wealth of ocean wave observations has become available from satellites such as Geosat, Topex-Poseidon, ERS-1 and ERS-2. The radar altimeter has proven reliable for measurement of the significant wave height, but does need careful calibration against co-located moored buoy measurements (Cotton & Carter, 1994; Challenor and Cotton, 1999), before the data can be fully utilized in assimilation into models. The accuracy of present-day global wave models, when measured against moored buoy wave heights, is better than that of the uncalibrated altimeter.

For application in real-time modelling, it is the so-called "fast-delivery" data that must be calibrated. For climate assessment purposes, the offline geophysical record is well calibrated.

Synthetic Aperture Radar (SAR). Altimeters do not provide directional or spectral information. This type of information can be obtained from SAR (Heimbach *et al.*, 1998). Short waves can not be detected by this instrument, and first-guess wave model information is normally used for conversion of the SAR-image spectrum into a wave spectrum, although new techniques being developed will permit retrieval of long period swell energies without the need for a priori assumptions or a first guess wave field. The SAR instruments potentially provide almost global coverage of observations of the wave energy spectrum. The data from ERS-2 are at approximately 200km intervals along the satellite track, from ENVISAT (to be launched November 2000) the observations will be at 100km intervals, and will be processed to provide the cross-spectrum, rather than the Fast Fourier Transform. This helps remove the directional ambiguity from the post processing of the observation. Assessment of global wave models against SAR spectral observations is increasing in importance, as specialist users of wave model forecasts demand detail of the low-amplitude long-period long-travelled swell energy.

Satellite wind observations. Wind observations with a radar scatterometer are becoming increasingly important. Scatterometers are unique among satellite remote sensors in their ability to determine the wind speed **and** direction. Scatterometers measure the backscatter from the sea surface. A dominant mechanism is Bragg scattering from short gravity capillary waves. These waves are in near local equilibrium with the boundary layer, but they are modulated by the longer ocean waves and by other ocean features (slicks). The rms differences found for the NSCAT scatterometer were 2.3 m/s and 15°, although most of this difference comes from low wind speeds (Bourassa *et al.*, 1999). Results from the SeaWinds sensor flying aboard the Quikscat satellite are expected to be as good or better, with double the coverage of NSCAT, covering 90% of the world’s oceans in one day with a footprint of 25 or 50 km. The altimeter and microwave radiometers provide information on wind speed only. The radiometer provides wind speed data over a wide swath; the altimeter provides information only on the sub-satellite track. Accuracy is about ± 1-2 m/s for the altimeter, and about ± 2 m/s for the radiometer for most cases (Cardone *et al.*, 1999). Little or no calibration has been done for high wind speed cases. The SAR also provides wind speed information with errors of about ± 1 m/s for low to moderate wind speeds (Vachon and Dobson, 1995). Radiometer data (SSM/I) is routinely assimilated into most operational NWP models.

Future satellite missions. Present and future satellite observations on ocean surface waves are available or are expected from the following missions ((see The GOOS Strategic Plan, 1998): TOPEX/POSEIDON, Okean-01, JERS-1, ERS-1 & 2, Envisat, Priroda (SAR), RADARSAT, RLSBO on Okean-O, RLSBO on Sich-1M, Jason-1, EOS-LAM-1, RADARSAT-2, ALOS, future missions by NOAA and ESA). More flights of satellites with oceanographic sensors will lead to better meteorological data needed for forcing of wind wave models and for more frequent acquisition of wave data stripes from polar-orbiting satellites.

Satellite wave observations will serve as the main input for global, and basin scale data assimilation systems. The ability of future satellites to carry additional instruments will remain limited for a sufficiently long time, and this raises an important question. Which has higher priority: more wave data from satellite altimeter or SAR to measure wave parameters directly, or more wind data from scatterometer to ensure better forcing data for wave models?

Wind waves are strongly dependent on wind, and it is unclear at the moment what would be the most beneficial development in terms of GOOS observations. It is important to realize that this question interests not only wave modellers but other specialists as well, such as climatologists and physical oceanographers. The answer to it should be based on mutual consensus, better if supported by cost/benefit considerations. For wind wave applications more wind data will facilitate wave hindcasting while more wave observations will be helpful to improve data assimilation and model validation.

From the perspective of operational real time sea state forecasting, wave experts from leading centres would prefer more wave data from SAR (or altimeter) rather than more scatterometer winds. The impact of assimilating scatterometer winds into NWP was small - alongside all the other data that go into NWP. However, the value of scatterometer wind data should not be underestimated. Recent results described by Atlas *et al*. (1999) showed that significant improvements in NWP model forecasts in general will be realized from an operational satellite remote wind vector sensing capability (from NSCAT, which can also be expected from QUIKSCAT). Also, on the climate side, one of the most important analyses is kinematic analysis of the surface wind fields to drive wave models. Here the scatterometer data has proved to have a large impact on the quality of surface wind analysis. This is not inconsistent with the NWP experience - the scatterometer has a positive effect on the analysis cycle, but the effect diminishes rapidly with forecast time, mostly because of the small impact of this single level data on the initial geopotential fields. In the hindcasting mode the positive effects are generated every 6 hours.

At least the present coverage of satellite altimeter wave and wind observations, SAR wave spectral observations, and scatterometer surface wind observations should be maintained. Where possible the instruments should be considered for implementation on "operational" satellites, to provide an ongoing continuous data stream. Further development for **both** satellite observations of winds and waves should be promoted. What is also needed is increased international coordination of satellite monitoring programs to ensure that the optimum balance of sensors is achieved.

2.1.4. Coastal radar.

There are several wave measurement techniques that can be grouped into “coastal radars”. The MIROS wave radar, which also measures currents, has been used operationally in the North Sea for several years to measure wave parameters and spectra. A recent evaluation of a MIROS wave system is given by Dobson and Dunlap (1999), showing good results compared to a directional wave buoy. Shipborne HF radars have also been used to measure wave height and spectra, although this technology is less well developed. Ground-wave radar is a new, very impressive method of simultaneous high resolution wind wave and current observations. It is usable in the coastal waters and should be particularly valuable for support of near-coastal shipping, port operations and other activities. At present the method is approaching operational use and there are some reports on experiments, in the course of which the radar data will be used in conjunction with hydrodynamic models for waves and coastal currents, and supplementary *in situ* data will be provided to verify the radar data.

2.1.5. Other surface marine observations.

Wind wave forecasting is quite unique in that the quality of wave forecast depends more on quality of forecast wind data than on direct wave observations. Thus, the contribution of GOOS to improve the quality of wind data should lead to better accuracy of wind wave simulations. Hence all expected developments in the atmospheric and marine meteorological observations in general, and observation of the surface winds over sea in particular, will contribute to the development of better surface wave-data services. Fort example, the recommendations expressed by other papers in this Conference (e.g. Taylor *et al*., 1999) for a subset of automated Voluntary Observing Ships (VOS) would greatly benefit future wave information. This is an area where interests of wave modelling intersect with such bodies as CEOS, DBCP, ASAP.

2.1.6. Some general considerations on wind wave observations in relation to GOOS.

1) GOOS must provide a coherent approach to development of marine observing systems on a series of scales. At present, the co-ordination of different types of wind wave observations seems to be insufficient. However, visual, instrumented, and remote observations mostly serve different purposes.

2) A thorough study is required on the further development of satellite observations that would meet the major requirements of all interested parties. This study could result in a balanced proposal on combination of different types of observations including satellite scatterometry, altimetry, and SAR.

3) At present it is unclear whether it is cost beneficial to supplement existing moored buoy observation systems with sensors measuring wave parameters. However, the concern is that future re-analyses of surface variables and re-construction of instantaneous fluxes between ocean and atmosphere would be insufficiently accurate for future requirements if proper information on surface waves is not used in the analysis. Increasing accuracy requirements of such GOOS activities as GODAE may also eventually require use of surface wave data in oceanographic data assimilation schemes.

2.2. Data transmission

Making observations and products available to users is one of the major GOOS objectives. Quasi-real time dissemination of surface marine observations is obviously an issue of crucial importance. The WMO GTS continues to play an important role for this. In case of satellite observations specialized data links are gaining importance, but again many types of data are disseminated through the GTS (e.g. ERS altimeter and SAR wave data).

The satellites carrying altimeters are not designated "operational", and have differing methods for disseminating data. In the case of ERS1 and ERS2 the fast delivery data are put onto the GTS, for access by National Meteorological Services. Timeliness of delivery is essential if the data are to be used for assimilation into operational real-time global wave forecast models.

Many of the moored buoy measurements are transmitted in near-real time via the WMO GTS. There now seems to be a trend towards greater international exchange of spectral wave data, for which the main format for the data transmission is WAVEOB.

Offline datasets of moored buoy observations are available from the NOAA Data Buoy Centre Web site (http://seaboard.ndbc.noaa.gov/data/). The IOC published in 1987 a “User Guide for the Exchange of Measured Wave Data”. It provides a good insight into the scope of the problem, but, in some parts, has become technically obsolete.

The main issues regarding wave data transmission and archiving seem to be:
- enforcement of standards for wave data and information transmission,
- facilitation of transmission in real-time of the remotely sensed wave data,
- setting up modern standards for instrumented data archiving that would ensure easy data retrieval and its use in multi-disciplinary applications,
- the need to establish a centre (or centres) for the collection and archiving of wave observations and gridded (level III) wave parameter fields,
- evaluation of the need for a project aimed at wave data rescue.
- encouragement for ALL observing centres to distribute real-time data via the GTS
- free (or at least minimal cost) and easy access to GTS data

2.3. Wind wave forecasting and related services

2.3.1. Wind wave models

The status of wind wave modelling is reviewed in many publications and in a recent comprehensive monograph (Komen *et al*., 1994; see also Komen, 1999a,b). Numerical wave modelling dates back to the 1950s. By the end of the 1980s the first third generation model WAM (WAMDI, 1988) had been developed, and it became possible to use third generation models for real time wave hindcasting/forecasting as well as for wave climate studies. At present almost all prediction centres around the world run operationally second or third generation spectral wave models. A decisive advantage of the third generation models is that they do not employ any explicit limitations on the shape of the wave energy spectrum and hence are by definition more general and better capable to resolve wave fields responding to arbitrary atmospheric forcing.

Several centres run global wave models in real time (http://www.ecmwf.int/; http://www.ncep.noaa.gov/). The higher resolution global wave models such as those run at ECMWF or UK Meteorological Office now include shallow water physics. Regional wave models can also be run, nested into global or basin scale wave models. These are often at higher resolution to include a better definition of the coastline and of shallow water processes. Surface wind forcing may be provided by regional NWP models. It is important to maintain *in situ* monitoring, and particularly in areas of strong tidal current, to have co-located measurements of wave and surface current. This is possible with a medium range (ground wave) HF radar. Support should be given, by region, to further investigation of pre-operational trialling of these instruments.

Physical packages of wind wave models are getting more and more comprehensive. It is possible to produce very accurate representations of wind wave conditions in individual storms (e.g. Cardone *et al*., 1995), and in long term wave climatologies (Swail and Cox, 1999). Nevertheless, there still are unresolved scientific and practical issues in treatment of almost all factors affecting wave spectrum evolution. Here is a non-exhaustive list of the problems (a much more comprehensive description can be found in Komen *et al*. (1994).

- A set of questions on the wind input term, which remains acute because the turbulent flow of air and water in the surface wave layer and affected zones below and above is not yet fully understood and still too simply parameterized. In addition, a lack of “ideal wind/wave data sets” does not allow us to derive general growth curves of wave spectrum parameters and to achieve comprehensive representation of atmospheric forcing in terms of measured/simulated parameters. Explicit modelling of water-air flow provides a promising avenue to future findings. At the same time it is also restricted by the use of parameterizations for the smaller scale turbulent motions.
- The discrete interaction approximation (DIA) parameterization (Hasselmann S. *et al*., 1985 a,b) of the non-linear interactions was extremely important because it made the operational use of the third generation models a reality. It provides “good looking” results in terms of total wave energy and mean frequency. At the same time the shape of simulated spectrum and the energy flux between some wave numbers come up distorted. In addition, the use of the DIA for shallow water (with corresponding modifications) and under rapidly and irregularly varying wind is much less studied. It is possible that other combinations of wave numbers are dominating the non-linear interaction energy exchange in high frequency part of the spectrum. There are some promising studies showing that in future it will be possible to compute the full non-linear integral in operational wave models, at least for deep sea applications.
- Wave energy dissipation is still mostly parameterized as the spectral energy balance closing term. The challenge of the research here is to represent quite generally several of the most

important dissipation mechanisms in all parts of the wave frequency domain via spectral densities and integral wave spectrum parameters. The deficiency of the “closure approach” emerges because the other source terms are not precisely expressed and hence errors in their modelling are affecting representation of the dissipation term. Lack of ideal observational data sets also hampers the research.

- Account for shallow water effects, wave – current interaction (modification of surface current fields by surface waves may be a significant effect, thus becoming a factor in heat and freshwater transport), interaction with tides and storm surges, sea ice; etc.
- A variety of issues related to the numerical implementation:

- multiple consequences of spectrum discretization in terms of spatial variables, time, wave number or frequency – direction including the well-known garden sprinkler effect,
- classical problems of solution of the advection equation ranging from excessive numerical diffusion to various types of numerical instability,
- difficulties of achieving fully implicit treatment of so called “right hand side terms” requiring frequent inversion of a large matrix or leading to the use of too short time steps,
- implications of limited model frequency range (usually the range is insufficient for resolving spectrums corresponding to light winds),
- specific problems of numerical solution of motions on a spherical surface (particularly for long swell waves),
- consequences related to the use of numerical stabilizers such as the high frequency tail and of model tuning,
- problems in representation of bottom topography and its effect on wave propagation in shallow water leading to complicated wave paths,
- problems associated with the use of nested models,
- efficiency of the wave models coding on vectorized multi-CPU computers,

In addition to further refinement of source term parameterizations of “pure” wind wave models, the most important direction of future research will be associated with development of coupled models of atmosphere, ocean, sea ice, and wind waves.

2.3.2. Data assimilation

Traditionally, data-assimilation of wave observations in wave models received little attention, until the advent of the first satellite altimeter data (SEASAT 1978, GEOSAT 1985). An early development was the technique to partition the increments of significant wave height between the spectral components used in a wave model (Thomas, 1988). However, recently considerable progress was made. The presently operational, simple wave data-assimilation schemes based on optimum interpolation ("O/I", Lionello *et al*., 1992; see also Foreman *et al*., 1994) are being extended to include more wave parameters. Recent progress was made by Young and Glowacki (1996), Voorrips *et al*. (1997) and Voorrips (1999) who extended the O/I approach and successfully assimilated two-dimensional spectra, obtained from directional buoys and the SAR. In addition, so-called four-dimensional variational methods should be further developed. A promising method is based on use of the adjoint of the WAM model (de las Heras and Janssen, 1992; Hersbach, 1998). Kalman filtering approaches seem also to become feasible (Voorrips, 1998; Voorrips *et al*, 1999). The possibilities should be further investigated. It is important that corrections made to wave estimates are consistently introduced in the forcing wind fields. Therefore, future models should attempt to have two-way coupling between atmosphere and waves. As long as this is not achieved one may expect the greatest impact of wave data-assimilation to occur for swell. Once the coupling has been realized, one may also expect a beneficial impact on wind sea forecasting.

It is also possible to expect that existing relations of wind and waves, wind and vertical mixing rate, wave breaking and vertical mixing rate, mixing rate and SST variation and, possibly others, can be utilized for primary data checking, or even in a multi-variate objective analysis scheme in a coupled atmosphere/ocean model. Such scheme does not exist so far.

2.3.3 Verification of operational wave forecasting models against GTS data

For any operational centre involved in wave prediction, there is a need for monitoring the quality of wave model analysis and forecasts. Prior to the end of 1995, no systematic comparative study of the different global wave forecasting systems existed. Earlier work on operational North Sea predictions (Bouws *et al*, 1980, 1986; Günther *et al.*, 1984) had shown how useful these comparisons can be. Therefore, in late 1995, the European Centre for Medium range Weather Forecasts (ECMWF), the United Kingdom Meteorological Office (UKMO), the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the Atmospheric Environment Service of Canada (AES) started a project aimed at exchanging model data at given geographical points. They were joined, in May 1996, by the National Centers for Environmental Prediction (NCEP). The methodology and preliminary results of this data exchange were discussed in Bidlot *et al.* (1998).

Sea state and surface meteorological observations are routinely collected by several national organisations via networks of moored buoys and platforms deployed in their near- and offshore regions. These wave data are transferred continuously via the GTS to most national meteorological centres and are usually archived locally. It is therefore a simple matter to build collocations between these observations and the corresponding model values.

Every month, each participating centre creates files which contain analysed and forecast model monthly time series of 10m wind speed and direction, wave height and wave period at the selected buoy locations. These files are exchanged via the internet.

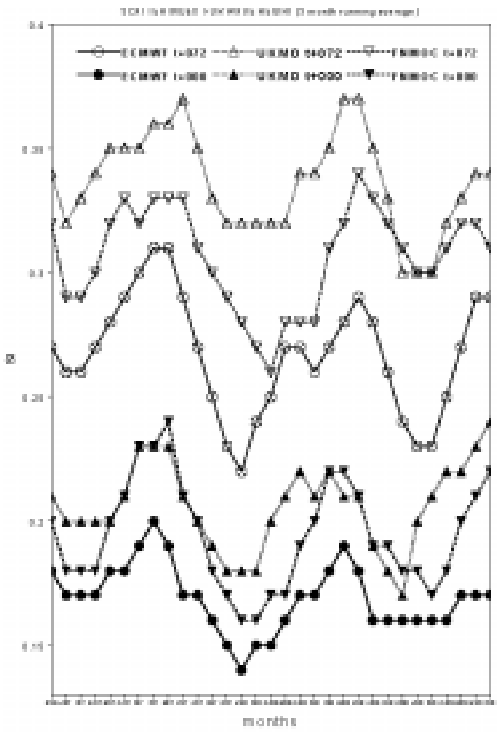

Fig. 2. Monthly time series of 12Z analysis and the corresponding day 3 forecast scatter index (standard deviation of the difference normalized by observation mean) for model wave heights when compared to observations from off-shore buoys located around Hawaii, Japan, the North American west and east coasts and around the British Isles.

It is up to each individual centre and any interested individual to retrieve the combined files. The statistical analysis of the data is left to each centre which may decide to look at it from their own perspective. For example, Figure 2 shows the time series of the monthly wave height scatter index (standard deviation of error normalized by the buoy mean) for centres which provide medium range wave forecasts (ECMWF, UKMO, FNMOC). It clearly shows the seasonal variation of the error, as well as the seasonal rate of degradation of the forecasts. Larger errors occur in winter when waves are higher.

The resulting comparison serves as an additional validation tool for the operational wave forecasting system of each collaborating centre. The comparison provides an independent reference for operational changes or problems which could otherwise go unnoticed. This information is also being used to identify wave modelling shortcomings and ultimately, it should lead to improvements of future wave models.

It is believed that centres engaged in wave forecasting will benefit from this activity in the same way as weather centres benefit from the exchange of forecast verification scores. In that matter, everyone involved in the project knows the actual skill of the model forecasts, and sees what kind of errors should be tackled first.

The wave buoy data set is usually not included in the operational wave data assimilation scheme, it therefore constitutes an independent reference. Its geographical coverage is however very limited. In the future, the collaboration could be extended to include other types of wave data (satellites) as well as model forecast scores verified against their own analysis as it is done with numerical weather prediction models. In that case, greater geographical coverage will be gained at the cost of totally independent data.

We also hope that by making the information widely available, it will stimulate a larger wave data exchange with organisations which collect wave data but do not make them available on the GTS.

3. WIND WAVES AND CLIMATE

3.1 Wave climatology

Knowledge of the wave climate, its trend and variability are of great importance for a wide range of marine activities. These activities include the safe and economical design and operation of offshore oil and gas facilities, design of ships, strategic planning for long ocean towing operations. In addition to these open ocean applications, knowledge of the wave climate is vital for coastal infrastructure including design of ports and harbours, shoreline erosion and protection, sediment transport and wave scour for seabed pipelines.

The degree of complexity of the wave information required also varies considerably. Some applications require only knowledge of the long term mean significant wave height, on a monthly seasonal or annual basis. Wave period and direction may similarly be required. Design applications typically require information on the extreme conditions, the so-called “hundred year wave”, that is, the individual wave which could be expected to occur on average once in 100 years. This type of analysis requires a record of at least 25 years time series of wave information at a given location. Increasingly, design studies are being based on the 10^{-4} frequency wave, or the 10,000 year return period. This will require an even longer period of record with better quality data. More sophisticated applications require detailed knowledge of the climate of the full 1-D or 2-D wave spectrum. Design of floating drilling platforms or coastal protection are examples of these applications.

Several studies have triggered the interest in long term trends (Carter and Draper, 1988: Bouws *et al.*, 1996). An important scientific issue is whether these trends are natural or related to Greenhouse warming (WASA, 1998). Knowledge of these trends has also considerable practical importance. For example, a 5% increase in the design wave height leads to a 10% increase in the cost of steel in a platform (Shaw, 1999). The ramifications of a non-stationary climate on the existing infrastructure are obvious – increased probability of failure and/or costly refitting. For obvious safety reasons, the offshore industry will avoid under-designing an offshore installation, hence the price paid for not having the right design data available when it is needed is essentially the cost of over-designing facilities for the future. However these arguments must be balanced by considering the use of design criteria which are deliberately conservative for today's solution but which will allow additional facilities to be added to the structure in the future without the need, and associated high costs, for major offshore structural modifications (Shaw, 1999).

Aside from these very important engineering aspects, there are other reasons why knowledge of the wave climate is important. The study of trends and variability of waves gives a good indication of the tendencies of storms over the oceans. Waves naturally integrate the wind field over time and space, and thus the climate signal is much less obscured by high frequency, local variability. This makes climatological wave height fields much more suitable for analyses relating trends and variability to large scale atmospheric circulation features such as the North Atlantic Oscillation (NAO). Techniques such as canonical correlation analysis (CCA) and redundancy analysis thereby allow us to effectively extend the record back more than 100 years, whereas reliable wave (or wind) data go back only a few decades (e.g. Wang and Swail, 1999; Kushnir *et al.*, 1997).

In terms of long term wave climate information, wave hindcasts, based on high quality wind fields and a proven spectral ocean wave model, are increasingly the preferred source of wave information on regional, basin-wide and global scales. This is apt to remain the case for at least the next 100 years, since we will always have at least 40 years more modelled data than any other global source. When driven by high quality wind fields, present day wave models are capable of producing almost perfect specifications of the significant wave height (Cardone *et al.*, 1995). As noted above in Section 2.3.1, there are still improvements to be made in wave models, especially in extreme storm seas (Cardone *et al.*, 1996), but overall the results are impressive. Therefore, one of the primary requirements for a good long term wave climatology is a good set of high quality marine wind fields.

The presently recommended approach to such long term wave hindcasts is to start with a high quality surface wind field derived from one of the global reanalyses, either the National Centers for Environmental Prediction (NCEP) 40-year reanalysis (NRA40, Kalnay *et al.*, 1996), or the European Centre for Medium Range Weather Forecasting (ECMWF) reanalysis (ERA15). Wave hindcasts based on the NRA40 hindcast are described by Cox and Swail (1999); hindcasts based on the ERA15 reanalysis are given by Sterl *et al.* (1998). The new 40-year ECMWF reanalysis (Uppala *et al.*, 1999) will soon be available, and will contain wave information directly, whereas the two earlier wave hindcasts were run independently. Swail and Cox (1999) describe the generation of a high quality, high resolution wave hindcast for the North Atlantic Ocean, which included re-assimilation of all surface data accounting for wind measurement height and type (measured/estimated), included detailed tropical storm wind fields, carried out an intensive kinematic reanalysis of all 6-hourly wind fields, and utilized satellite scatterometer wind fields where available. The resultant wave fields compared very well with high quality, *in situ* measurements from moored buoys and platforms, and with satellite altimeter wave measurements.

This brings us to the next important aspect of wave climatology: as important as the surface wind fields from reanalysis and satellite scatterometer are, it is equally important that we have sufficient high quality wave measurements to validate the model results. The existing network of moored buoys and offshore drilling platforms, shown in Figure 1, provide relatively consistent time series of significant wave height and period (some national differences are noted by Challenor and Cotton, 1999). Many of these buoys provide 1-D wave spectra, and a few provide full 2-D spectra. As is readily seen, the existing network of moored buoys and offshore drilling platforms is mainly limited to the vicinity of continental margins, and primarily on the east and west coasts of North America and western Europe. Coverage of the southern ocean is practically non-existent. Not only must we maintain the existing networks, it is important to try and broaden the geographical coverage to non-coastal areas, and the southern ocean. It is important to sample as many diverse wave regimes as possible to confirm the validation of model and satellite data in all types of conditions.

It is impractical to consider large arrays of moored buoys covering global oceans. Yet global wave information is required to validate model output. This is the role of satellite wave measuring instruments, altimeter and synthetic aperture radar (SAR). A significant volume of altimeter wave data is being assembled, which is starting to give some idea of global wave climate on its own (Cotton and Challenor, 1999). However, altimeter data alone are too short a period for trend or extremal analysis, the present temporal frequency of coverage is inadequate to properly sample the wave height distribution, and there remain questions about the instrument's ability to measure the higher sea states (as there are questions about buoys' ability to measure very high, or breaking seas). Nevertheless, the altimeter is a very important tool in the validation of model output in open ocean areas (see Cox *et al*., 1999).

While SAR wave data are now being introduced into operational NWP models, they are not routinely used in wave hindcast studies. Future reanalyses may incorporate these data. SAR wave spectra could be used for model verification in open ocean areas. SAR can also produce wind speed information (Vachon and Dobson, 1995), although its development is not as mature as scatterometer winds.

A good description of the global and North Atlantic wave climate, its trend and variability is given by Swail *et al*. (1999). Figure 3 shows some significant results from this analysis.

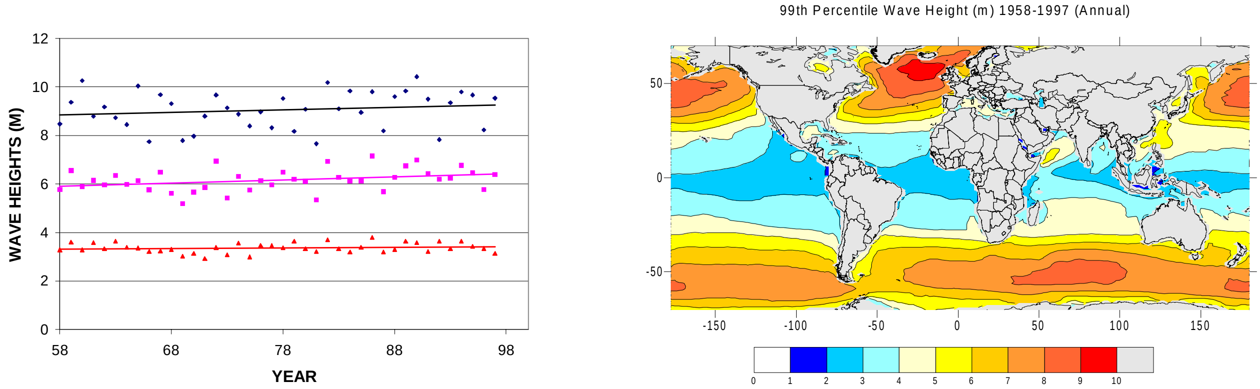

Fig. 3. (left) Annual 50th, 90th and 99th percentile wave heights at OWS Juliet; (right) annual 99th percentile wave height. (see Swail *et al*., 1999).

One important concern in long term trend and variability studies is that the data are homogeneous. Swail *et al*. (1999) showed that the trends derived from the modelled waves probably have a slight artificial positive bias due to "creeping inhomogeneities" caused by increased data densities in recent decades. However, the bias is not large, implying that the results could serve as a useful upper bound on probable "true" trends. The biases were considerably smaller than those obtained from ship wind data even when those winds were adjusted to account for anemometer height and observation type following Cardone *et al*. (1990). It is important to note that even buoy and satellite data contain temporal biases due to changes in instrumentation, processing, platforms, etc. This highlights another important concern: data measured as part of a climate monitoring program must be accompanied by a comprehensive metadata description. This applies to *in situ*, satellite and model data. The WMO CMM (now JCOMM) Sub Group on Marine Climatology is presently developing a metadata standard for buoys; a similar standard should also be developed for satellite systems. Furthermore, when new systems are introduced there should be a substantial period of overlap between the old system and new ones for homogeneity adjustment. It is recognized that this is not always possible.

The problem of homogeneity is complicated by sensor drift, for waves as it is for sea surface temperature. For example, Challenor and Cotton (1999) advise that “ the drift in the TOPEX altimeter has shown the need for continual monitoring of satellite systems throughout their life rather than simply relying on the calibration phase at the start of the mission. Calibration should be against well maintained and calibrated buoy networks, and not ad hoc deployments of buoys for special purposes”.

To summarize, the requirements for data to provide the wave climate information necessary for science and engineering fall into two distinct categories: high quality wind fields to drive proven spectral ocean wave models, and equally high quality wave measurements, both satellite and *in situ*, for validation of the hindcast model output, and cross-validation with each other. The measured waves may also be useful in themselves for specific applications.

3.1.1 Wind

Specific requirements for wind data will also be described elsewhere in the Global Ocean Observing System; here we will only deal with the specific wind data which are necessary to drive wave models.

- Reanalysis wind fields provide long term, extensive spatial coverage necessary for homogeneous wave fields; higher spatial resolution is required to properly resolve the peaks in extreme storms. Operational NWP wind fields may be used in future to extend reanalysis data sets but inhomogeneities arising from model changes are a serious concern.
- Scatterometer winds already play an important role in kinematic reanalysis of marine wind fields for input to wave models; advances in data assimilation techniques to 4-D variational methods may be able to make better use of this information so that its impact is not lost in the first few hours of the forecast cycle. Nevertheless, the analysis cycle should maintain the improvements. This is a mature data source, which is now showing impressive results (Atlas *et al.*, 1999).
- SSM/I winds play an important role in current NWP model data assimilation, but are little used in kinematic analysis. These data will likely be important data sources in future reanalysis efforts.
- Ship winds are presently used in both NWP data assimilation, albeit with low weights, and in kinematic analysis schemes. Automated shipboard wind systems would greatly improve the utility of these data.
- Buoy winds remain an important source of input to atmospheric models and kinematic analysis, although the restricted domain is limiting. Additional buoys, especially in data sparse areas such as the Southern Ocean should be a priority, although cost limitations mean that increases in numbers will be modest.
- Altimeter winds are a useful source, but the very limited spatial coverage makes them far less desirable than scatterometer or SSM/I winds. However, the instrument will be used extensively for waves, so we should not overlook the wind information.

- Platform winds should be encouraged wherever possible, although the spatial extent is very limited, and some of the newer generation platforms may have serious flow distortion problems.
- SAR winds provide another viable source of wind data for assimilation into models and for kinematic analysis. Only wind speed is at present produced objectively. As with the altimeter, if the instrument is being used for wave data we should not overlook the wind data.

3.1.2 Waves

- Modelled wave data, using carefully constructed homogeneous wind fields, and rigorously validated with high quality *in situ* wave data from buoys and platforms, and satellite altimeter and SAR data will provide the basis for most engineering uses and scientific analyses of long term trend and variability. Due care must be taken to ensure that the model can account for the high end of the wave height distribution.
- Moored buoys and platforms will continue to be of critical importance for validation of wave model output and satellite-based wave measurements. These data may also be very useful for local climate purposes, especially for near-coastal applications.
- Altimeter waves represent a mature data technology, which provides an invaluable data resource on global scales. These data are proving to be useful in their own right for wave climate applications, as well as for validation of model waves in open ocean areas, and cross-validation with buoy data. Because of the limited coverage available from individual orbits, a number of satellites must be flying concurrently to provide adequate coverage. Even then, the temporal coverage of individual locations may not be sufficient to adequately sample extreme conditions, and there is still some uncertainty as to the ability of the altimeter to accurately measure the most extreme sea states (due to very limited calibration cases).
- Ship wave observations should continue to be encouraged as a long term data base. Ship wave observations have been shown to be surprisingly consistent when treated as an ensemble, but should only be used for description of mean conditions (Cotton *et al*., 1999).
- Coastal radar, ship RF radar, microwave radar on board platforms all provide potentially useful information, particularly in coastal areas, but are more varied in data quality and documentation than the other systems described. The MIROS microwave radar, for example, has shown the ability to provide very good wave height and spectral information, but can be prone to substantial errors if not continuously monitored (Dobson and Dunlap, 1999).

3.1.3 General

- It is critical for climate uses that each data set be accompanied with a comprehensive set of metadata describing the instrumentation, its characteristics, processing, calibration, and changes in those elements, for example sensor drift.
- Wherever possible, new measurement systems should have an overlapping period with the systems they replace.
- R&D is required into 4-D variational assimilation systems to effectively handle assimilation of SAR spectra and winds, altimeter and scatterometer data, for future reanalysis systems; this also has obvious application to present real-time NWP forecasting.
- R&D into calibration and validation of satellite winds and waves in extreme storm seas (winds > 20 m/s; waves > 8 m) is required.
- R&D concerning homogeneity assessment of all data sets used for climate trend and variability analysis, including model waves, satellite waves and measured waves from buoys and platforms is required.

3.2 The role of wind waves in the coupled atmosphere/ocean system

Wind waves play an important role in many physical processes both at the ocean surface and in the adjacent boundary layers: the marine boundary layer and the oceanic mixed layer. These processes affect winds, currents, turbulent mixing, the density structure, and the transport of momentum, heat, moisture and mass. Waves also influence the radiative properties of the sea surface, which is of relevance for remote sensing and for the determination of the albedo of the sea surface.

Given these facts, several questions arise:

- How do wind waves affect physical parameterizations? This question has been addressed in many studies both from theoretical and experimental perspectives.
- Are there any dynamical consequences for the coupled atmosphere/ocean system? Are wind waves important for weather prediction? Are wind waves relevant for climate studies? To answer these questions numerical experiments with GCMs are performed and diagnosed, in order to study the impact of the wave dependence on the model behaviour on different time scales.
- Do wind wave observations provide useful information about the state of the atmosphere/ocean system? There have been some attempts to use wind wave observations in an inverse modelling approach, in which wave observations were used to make statements about the quality of modelled near surface winds and surface stresses. This latter approach opens up the possibility of including wind wave observations in a multivariate data assimilation system in coupled atmosphere/wave/ocean models.

In this section we will briefly review each of these approaches.

3.2.1 Physical parameterizations

Several basic theoretical studies (Janssen, 1982, 1989; Makin *et al.*, 1995) suggest that wind waves play an essential role in the air/sea exchange of momentum. In these theories the stress is a function of both the wind speed at a given height and the two-dimensional wave spectrum. An important parameter is the ratio of the wave-supported momentum flux and the total momentum flux. This quantity can be determined experimentally, but, unfortunately, this is only rarely done. A question that has not been settled is whether the wave effect can be parameterized in terms of the local, instantaneous wind speed alone. At first sight, this seems unlikely, because in general the wave spectrum is a very complex function of the (non-local) wind field history. However, in the theories the stress is mainly controlled the by the short waves. These short waves have a shorter time scale than the energy containing long waves, which allows for a quasi-instantaneous equilibrium between the short waves and the turbulence in the boundary layer. This enhances the importance of the local wind for roughness parameterizations and explains the success of Charnock's relation. Yet Charnock's constant is not a constant ("which it was never meant to be"). It is unclear what causes its variations (see Figure 4).

For the wind stress there is an increasing number of valuable observational data sets (HEXOS, ASGAMAGE, TOGA-COARE, FASTEX, SWS-2). Unfortunately, in most cases, their analysis in terms of wave effects is hampered for lack of detailed observations of the 2-D wave spectrum. There is increasing observational evidence that surface waves have an effect, but the exact nature and significance of that effect is still a subject of debate (Smith *et al.*, 1992; Janssen, 1992; Yelland *et al.*, 1998; see also review papers by Donelan *et al.*; 1993; Komen *et al.*, 1997; and Taylor *et al.*, 1999). Most observations have been analysed in terms of the wave age. A widely held view is that the wave age is important with "younger" seas (that is those which are still developing) being rougher and therefore increasing the wind stress. For a given wind speed, this theory predicts higher wind stresses at short fetches or in intense storms where the seas are strongly duration limited.

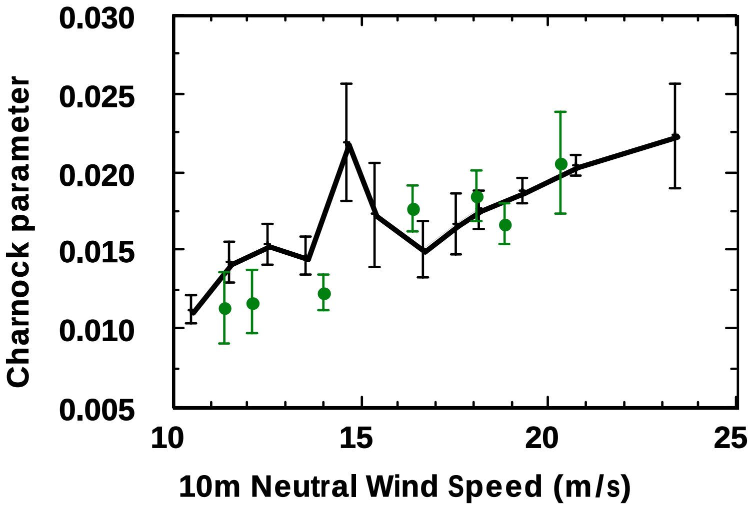

Figure 4.Values of the Charnock "constant" as a function of wind speed: Eddy correlation data from Hare *et al*. (1999) (points); inertial dissipation method data from Yelland & Taylor (1996) (line).

Unfortunately the present evidence for these effects is not unequivocal. For example, alternative sea state variables such as the height and steepness of the waves may affect the wind stress in a different manner from the predictions based on wave age (Anctil & Donelan, 1996, Taylor & Yelland, 1999). In this case duration or fetch may have less effect whereas the presence or absence of swell may be an important factor. Indeed, some recent observations apparently detect significant changes in wind stress in the presence of swell. Swell is practically omni-present in the open ocean but may be absent in enclosed sea areas, particularly for offshore winds, and this may change the wind stress in some coastal regions.

Even if waves have an influence on instantaneous stress values one may ask whether their effect on average fluxes cannot be parameterized in terms of wind speed. Illuminating is a recent study of Sterl and Bonekamp (1999). They compared the ERA15 momentum fluxes (which did not consider wave effects) with a set of fluxes computed from the WAM model forced with ERA15 winds. They obtained significant differences for daily-averaged wind stresses, but the effect on the monthly averages was almost negligible.

The effect of waves on heat and moisture fluxes, on mass transport (CO2 fluxes) and the albedo of the ocean deserves further study. Whitecapping presumably plays an important role, but again the question arises whether parameterization in terms of wind speed is possible. We refer to Janssen, Becker and Morcrette (1996) for a discussion of the effect of waves on the albedo.

Makin (1998) discusses the effect of wind waves on the heat flux. Presently, ocean buoys are capable of providing monthly mean heat flux measurements with accuracy generally better than 10 W/m^2. This threshold meets the requirements of most ocean climate studies. Further increase of accuracy may be feasible but at considerable increase in cost. Also, in this case, the effect of wind waves is expected to be present for short averaging periods, particularly for cases of growing seas, but for longer periods the effect is expected to get smaller and smaller.

Wind waves are known to enhance the ocean/atmosphere transfer of CO2 and other gases considerably. However, the mechanism of this enhancement is poorly understood (Jähne and Haussecker, 1998). Recently considerable progress has been made in directly observing CO2 fluxes in the field (Jacobs *et al*., 1999; Wanninkhof and McGillis, 1999). One may hope that this will also lead to an improved understanding of the role of waves.

3.2.2 Dynamical consequences

Several authors have used GCMs to study the dynamical impact of a wave dependent drag formulation. For example, Mastenbroek *et al.* (1993) and Burgers *et al*. (1996) obtained a beneficial effect on North Sea storm surge predictions. Other studies (Doyle 1995; Janssen and Viterbo, 1995 and Lionello *et al*., 1998) addressed cyclogenesis in an atmospheric GCM and obtained a marked effect. Janssen (private communication) made a large number of numerical simulations. On the basis of his analysis of these simulations ECMWF is using a coupled atmosphere/wind-wave model for its operational 10-day forecasts. The justification came from an improved forecast skill (for wind and waves) and from an improved comparison with scatterometer winds. This same coupled model is being used for the new ECMWF 40-year reanalysis. Of course, it should be remembered that the parameterizations used in these studies need confirmation. Typically they allow the Charnock constant to vary with wave age, but one might obtain similar qualitative behaviour by allowing the Charnock constant to vary with wind speed, (which is however unappealing from a dimensional point of view). Even if waves have an impact on the high-frequency behaviour one may wonder whether there is an effect on the slower climate variations. The above mentioned results of Sterl and Bonekamp (1999) suggest that this is not the case, unless scale interactions play a role. According to Janssen waves had a small but significant effect on the climatology of the ECMWF model. This would mean that scale interactions are important. We believe that this aspect deserves further investigation.

3.2.3 Wave observations as a source of information about the atmosphere

It is well known that wave observations can provide information about the atmosphere. Hurricanes can be detected from the very long swell they generate, and wave observations have been successfully used to determine subjective corrections to a objective surface wind field analysis (Cardone, private communication). So far this has not led to the development of multivariate data assimilation systems for the joint assimilation of atmospheric observations and wave observations. However, there are several indications that this approach could be beneficial. For example, Sterl *et al*. (1998) showed that the quality of ERA-15 winds can be assessed by comparing the wave model response with wave observations; Swail and Cox (1999) showed similar results from the NRA 40-year reanalysis. There are also indications that first-guess wave information may be used for improved retrieval of scatterometer winds.

3.2.4 Conclusions and recommendations

In summary, there is some evidence that the variable roughness associated with wind-generated surface waves has dynamical consequences for the atmosphere. This has led ECMWF to introduce waves into their operational suite for 10-day weather forecasting, and in their new reanalysis project. There is less evidence for the effect of wind waves on climatic time scales, because then many of the wave effects average out and parameterization in terms of mean wind speed may be adequate. This is probably not the case when scale interactions are important, in the case of westerly wind bursts, acting as triggers for ENSOs, for example. The effect of waves on seasonal forecasting deserves further study, therefore.

There are several reasons why wind waves should be considered in GODAE. First of all they may have an effect on the forcing fields, as illustrated by simulations with the operational ECMWF model. Also, wave information may be needed if improved physical descriptions of upper-ocean mixing become available. Ultimately, the models used in GODAE should give a consistent description of fluxes in the lower atmosphere, the upper ocean and through the interface.

To make progress in this field there is an urgent need to combine flux and other routine measurements with observations of the 2-D wave spectrum and to better quantify the effect of waves on air/sea fluxes. In particular, we recommend that instruments capable of measuring the 2-dimensional wave spectrum be installed at the Surface Reference Sites. There is also a need for further analysis and documentation of the impact of wave dependent parameterizations in coupled models on different time scales. Finally, one should not forget the potential advantages of comprehensive multivariate data assimilation methods combining observations of the atmosphere, the upper ocean and the air/sea interface.

Summarizing:

- Wind wave observations should be conducted (as a rule) in parallel with other basic marine surface observations. The combined implementation of wind wave and ocean observing components under GOOS will obviously be more economical than the development of the two separate systems.
- The effect of waves on air/sea fluxes should be further quantified.
- The use of running a wind wave model in a coupled mode with ocean/atmosphere models both in the data assimilation cycle and forecast modes should be further investigated, as should be the benefit of using wave information in a multivariate objective analysis.

4. WAVES IN THE DIFFERENT GOOS MODULES

So far we have given a fairly general discussion of wind waves, with some emphasis on global wave observations, modelling and forecasting (section 2) and climatic aspects (section 3). We will now consider wind waves from the perspective of the different modules of GOOS. Clearly, when it comes to GOOS implementation it would be rational to do this in such a way that the basic wave data needs of the different modules are satisfied simultaneously.

4.1 The Climate Module

According to the GOOS Strategic Plan the goals of the Climate Module (identical with the ocean component of Global Climate Observing System) are:

- to monitor, describe, and understand the physical and bio-geochemical processes that determine ocean circulation and its influence on the carbon cycle as well as the effects of the ocean on seasonal to multi-decadal climatic changes.
- to provide the observations needed for the prediction of climate variability and climate change.

It is obvious from the discussion in section 3 that wind waves should form an integral part of this module. Moreover, the wind wave spectrum itself should be considered an important variable of the global climate. Basically, there is a need for four types of activity:

- process studies, aimed at improving parameterizations in coupled A/O GCMs and numerical studies with these models,
- the establishment of one or more data centres making available historic wave observations, (re)analysis products and wave hindcast results,
- co-ordination of satellite missions for balanced coverage by a variety of sensors,
- the implementation of wave observations and their assimilation as an internal part of GODAE.

4.2 The Coastal Module

The Coastal Module of GOOS, which is being designed by the IOC-WMO-UNEP-ICSU Coastal Panel of GOOS, will concentrate on the following areas of activity:

- preservation and restoration of healthy ecosystems,
- sustainable use of living marine resources,

- mitigation of coastal hazards,
- ensuring safe and efficient marine operations.

These goals cannot be achieved without properly addressing various wave climatological issues and real time forecasting. Waves also play a role in the physics of the models that are used for the simulation of coastal processes.

Coastal GOOS will likely develop parallel sets of global core measurements and more extensive regional/coastal observing networks. No doubt, both real time prediction of surface waves and delayed mode wind wave data services are in the heart of the coastal GOOS. In coastal areas different processes should be observed simultaneously: wind waves, currents, storm surges, and river outflow. Account of tides is important for many locations. Multiple model nesting is usually required to resolve wave field variation at a series of scales. There are several observing tools that are of particular value in coastal areas. An example is the HF radar which provides simultaneous measurements of waves and currents.

Storm surges represent a phenomenon which is driven mostly by the same force as wind waves (storm surges in addition are driven by atmospheric pressure differences), and storms in coastal zones are almost always associated with simultaneous effect of waves and sea level variations. An obvious shortcoming of many on-going projects devoted to protection of coastal areas from storm surges is insufficient attention to wind wave prediction. Wind waves are not only important because they represent an additional threat to coastal life and property but because they affect the drag to be applied on the sea surface. Reciprocally, variations of sea depth in the course of a storm surge may significantly change wind wave patterns in shallow waters. In the light of this, better coordination of the WMO Wave Programme, which also takes care of storm surge forecasting activities, and the Coastal GOOS Panel is desirable.

4.3 The Living Marine Resources Module (LMR)

The objective of this module is to develop a system to monitor living marine resources and marine ecosystems including the biological, chemical and physical parameters controlling their variability on useful time scales. Aquaculture is a good example of an activity which can be very dependent on wave conditions. It requires both wave forecast services and climatological data. Usually, in many locations, coastal ecosystems have the ability to restore themselves after the impact of extreme storm wind waves. However, changes in storm and/or wind wave patterns associated with climate trend or variability, may, in principle, alter this ability.

A symbiosis of wind wave services and LMR may be found in the coordinated design and implementation of observing systems. Common benefits may accrue from exchange of information on the development of satellite remote sensing and moored buoys instrumentation. A proposal (see LMR Panel First Session Report, 1998) has been made for setting up LMR monitoring stations at several locations (Baltic Sea, California Current, Japan/East Sea, NW and NE Atlantic, Benguela Current, Black Sea). It would be useful and possible to expand this proposal with wind wave observations, most possibly in connection with the establishment of the surface reference sites (see Taylor *et al*., 1999).

4.4 Health of the Ocean

A central goal is to determine prevailing conditions and trends in the marine environment, also in relation to the effects of anthropogenic activities, particularly those resulting in the release of contaminants to the environment. Examples of such activities include aquaculture, forestry/logging, coastal development, marine transportation, industrial discharge, sea dumping, agricultural practices, mineral extraction processes and municipal and urban waste discharge. The module's primary objective is to provide information on the nature and extent of adverse effects, including increased risks, on human health, marine resources, natural change and ocean health.

Several biological systems are used to monitor the health of the ocean. The GOOS Coastal Module Workshop, 1997 gives a list of physical parameters also affecting these biological systems. Table 1 is a slightly modified version of this table, giving information connected to wind wave height and period, sea level, and coastline change data. The activities which are of concern for HOTO are often strongly dependent on wind wave data services, examples being coastal development, marine transportation, industrial discharge, sea dumping, mineral extraction processes, aquaculture, municipal and urban waste discharge.

	Wave height	Wave period	Sea level	Coastline change
Coral reef ecosystems	relevant		relevant	
Wetlands incl. mangroves			relevant	relevant
Spawning and nursery areas	may be relevant	may be relevant	relevant	
Macrophyte communities	may be relevant	may be relevant	relevant	
Habitat change	may be relevant	may be relevant	relevant	relevant
Genetic change	wave climate change may be relevant			
Community Structure				relevant
Eutrophication / HAB				relevant

Table 1 Biological sensors of the health of the ocean and their sensitivity to physical parameters

Another evident interest of the HOTO Module in wind wave data is connected to forecasts of wind wave parameters needed for oil clean-up operations in the case of an accident. Development of coastal radar observation techniques can be also useful because they provide all data types needed for prediction of the oil spill instant velocity. Of course, longer prediction of oil spills will need to rely on prediction of wind, waves, and current. The choice of oil localisation / gathering / combat means depends to a great extent subject on the surface wave conditions. Statistical data on wind waves play a considerable role in preparation of various contingency plans.

4.5 Ocean Services

The purpose of this module is twofold: on the one hand it should maintain, expand and optimize existing marine meteorological and oceanographic services; on the other hand it should assist the other Module panels in establishing services.

Wind waves are an essential element of the traditional marine meteorological services. In line with the safety needs, which are expressed in international conventions such as the SOLAS Convention of 1974, WMO requires the inclusion of wind wave forecast data in marine weather bulletins. The number of national meteorological services providing such forecasts is steadily growing. Real-time data services are important for ship routing, and offshore activities (oil/gas rig operations), shore protection/beach nourishment, etc. These same activities also require climatological information, in particular for the design of ships, offshore and coastal structures.

In section 2 we have given a rather comprehensive discussion of the modern approach to wave prediction, and section 3.1 summarized recent developments in wave climatology. Where possible the quality of these, already existing products should be improved. In addition the need for new products should be explored. Ensemble wave forecasts may become an important new product.

Forced by initially slowly diverging meteorological forecasts, corresponding wave forecasts will also diverge with time and will exhibit a measure of uncertainty of wave forecasts at different ranges. This measure is a statistical parameter, which can be used in ocean weather routing and in a wide range of services to offshore industry.

4.6 Ongoing wave projects and programmes

Since waves are important to all modules of GOOS there is need for coordination at a sufficiently high level. Tables 2 and 3 give an overview of the many relevant projects, programmes, and bodies. We recommend that the WMO CMM Subgroup on Wave Modelling under the supervision of JCOMM should be made responsible for overviewing all GOOS-related wind wave activities. We also recommend that it would be made responsible for storm surge forecasting as this is closely related to wave prediction. It would also be desirable to establish a scientific group, perhaps under SCOR, which should address some or all of the scientific issues addressed in this paper.

Projects, programmes, bodies	**Potential desirable activities, areas of co-operation, benefits**	**Value**
CMM, IGOSS, JCOMM	Wind wave observations and data services form core activity. The WMO Wave Programme should be co-sponsored also by the IOC and should highlight matters associated with storm surges	High
VOS/SOOP	Activities could be aimed at improvement of visual wave observation quality, increased automation of marine meteorological observations and reporting, and better weather routing services.	High
OOPC	To review further the contribution of wind wave observations and data services in implementing ocean observing systems for climate	High
CEOS	Contribution to design of optimal future observing system, particularly in view of future mission payload	High
Moored buoys (TAO, TRITON, PIRATA)	To consider the need to supplement the networks with surface wave meters	High
DBCP, GODAE, XBT, ARGO	Joint contribution of data to such experiments as GODAE, the effect comes via the dependence of surface fluxes on wind waves	High
IODE	To increase wave dimension in the IODE, to consider the need to establish a project like GODAR for waves, a RNODC for wind waves	Ave-rage
GLOSS	Consider joint benefits from developments in satellite altimetry	Ave-rage
GTSPP	Consider the use of GTSPP end-to-end-data-management procedures such as data tracking, quality assessment, feedback to data suppliers for wave data services provision	Ave-rage
GIPME MARPOLMON	To better specify wave data requirements for pollution clean-up operations and for increased safety of potential environmentally risky activities	Ave-rage
LOICZ	Better co-ordination and liaison	Ave-rage
Capacity building activities, TEMA	To continue capacity building activities with focus on how wind wave observations and data services contribute to the GOOS development	High

Table 2 Major environmental programmes with a wind wave component

GOOS Programme	Wave observations and data services activities – status and prospects
EuroGOOS	Wind wave data requirements of various activities were specified in the programme planning documentation. This information is useful for other programmes and activities. The BalticOOS (BOOS) has a wave data services component. The EuroROSE Project develops HF coastal radar systems. The Mediterranean Forecasting System Project has a wave data services component which could be potentially re-enforced.
NEARGOOS	Wind wave observations are exchanged in the real time data-base of NEAR GOOS and are stored in the delayed mode data-base.
USA GOOS	A wide scope of wave services exists.
MedGOOS	Likely of high priority, liaison required. Well developed wind wave climatological data projects have been completed there.
Black Sea	Well developed wind wave climatological data projects have also been completed for the area, real-time wave data services development was envisaged in some project proposals.
C-GOOS storm surge forecasting system for the east coast of South America	In initial stage, liaison with the WMO Wave Programme may be required.
PacificGOOS	In initial stage, liaison required.
GOOS-Africa	In initial stage, liaison required.
Caribbean GOOS	In initial stage, liaison required.
SEA – GOOS	In initial stage, liaison required.

Table 3: GOOS regional programmes with a wind wave component

5. RECOMMENDATIONS TO GOOS AND WAVE MODELLERS

Wind wave observations and data services should be a core activity of the GOOS Services module. They also are of great value for the GOOS Coastal and Climate modules. The interests of wave data services and of GOOS HOTO and LMR modules coincide in that they mostly require the same types of sensors onboard satellites.

On the basis of our discussions we have formulated a number of recommendations, which will help optimize the benefit of wave observations in GOOS and minimize costs.

In situ observations. Good quality in-situ measurements are important. There is a need for co-locations of radar altimeter and moored buoy wave heights to adequately calibrate the altimeter. All operational moored buoys (e.g. the TAO, TRITON, PIRATA arrays) should include wave instrumentation, in order to improve coverage and enable better data interpretation in future. There is a strong need for spectral observations, including 2-D spectra, not simply wave height.

Remote observations. The importance of satellite observations of wave height and co-located surface wind speed should be emphasized, and it is desirable that radar altimeter missions become established on "operational" polar orbiting satellites. The science (engineering) and applications are now mature. It is also important to emphasize the need for spectral wave observations from wave-mode SAR. Again it is desirable that these instruments be given "operational" status.

Real time wave data assimilation and forecasting. Wave modelling can benefit from improved atmospheric modelling. A point that requires particular attention is the quality of forecast sea level winds in the medium-range. Wave modelling itself can also be improved. This requires higher resolution, improved numerics and a better representation of the physics. Assimilation of wave observations can lead to better predictions, and may be an important element in such programmes as GODAE.

Wave climate studies. Sea state is an important element of the coupled atmosphere/ocean system, affecting many human activities. Knowledge of its climatology is of great importance therefore, and its variability on interannual and decadal time scales should be studied, understood, predicted - to the extent possible - and **validated**. As with operational forecasting, wave climate studies can benefit greatly from improved atmospheric modelling (and monitoring), and continued reanalysis efforts.

The dynamical role of waves in the climate system. There are indications that waves play a dynamical role in the climate system: they affect A/S interaction, so that the sea state is a parameter in flux parameterizations, and they have a strong effect on the albedo. Waves also affect mass exchange across the sea surface, in particular the exchange of Carbon Dioxide, Methane, DMS etc. There is a need for observational process studies addressing these issues.

Coordination and cross cutting issue with other GOOS modules. It is suggested that the WMO CMM Subgroup on Wave Modelling, now part of JCOMM, be given the task of overviewing the wave-related GOOS activities. We also recommend establishment of a scientific group, perhaps under SCOR, which should address some or all of the scientific issues addressed in this paper.

Capacity building could include assistance to developing countries with technical support in establishing an *in situ* monitoring network and making data available to the GTS in near real time. Existing networks of moored buoys should be encouraged to insert data onto the GTS, and technical assistance should be given to help achieve this.

Requirement	Priority	Incremental Cost
Maintain existing level and coverage of VOS wave observations	Medium	$0
Enhanced *wind* observations from selected automated VOS subset	High	$85K/ship[1]
Maintain existing moored buoy networks for wind and waves	High	$0
Add 1-D wave sensors to existing moored buoy arrays TAO, TRITON, PIRATA (and additional power)	High	$3K/buoy[2]
Add 2-D wave sensors to some existing moored buoy arrays	High	$30K/buoy[2]
Extend moored buoy coverage in South America, Bay of Bengal, Africa	Medium	$200K/buoy[2]
Operational altimeter wave measurements	High	High[3]
Operational scatterometer wind measurements	High	High[3]
Operational SAR spectral wave measurements	Medium	High[3]
Operational SSM/I wind speed measurements	Medium	High[3]
Improved spectral wave models	Medium	Medium
Improved data assimilation methods for scatterometer, SAR winds, waves	High	Medium
Improved scatterometer algorithms for high wind speed conditions	Medium	Medium
Improved altimeter algorithms for high wave conditions	Medium	Medium

[1] Coincident requirement with Surface Fluxes and Surface Reference Sites (Taylor et al., 1999)
[2] Assumes deployment on an opportunity basis
[3] Based on sensor cost, not including launch and ground-based infrastructure

Table 4: Requirements for wave (and wind) information within GOOS.

Table 4 outlines our perceived requirements for wave (and wind) information to support the various activities within GOOS. Approximate costs are estimated where possible; it is difficult to quantify the costs associated, for example, with a scatterometer or altimeter, which has associated launch costs, and ground-based infrastructure.

Finally, it should be noted that the determination of the optimum global observing system for waves is still a work in progress. Input from the global waves community continues to come in, but hopefully this will mostly represent fine-tuning of the initial requirements described in this paper.

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6. REFERENCES

Anctil, F. and M. A. Donelan, 1996: Air-water momentum flux observations over shoaling waves. *J. Phys. Oceanogr.*, **26**, 1344 - 1353.

Atlas, R., S.C. Bloom, R.N. Hoffman, E. Brin, J. Ardizzone, J. Terry, D. Bugnato and J.C. Jusem, 1999: Geophysical validation of NSCAT winds using atmospheric data and analyses. *J. Geophys. Res.*, **104**, C5.

Bidlot J.-R., M. Holt, P. A. Wittmann, R. Lalbeharry, H. S. Chen, 1998. Towards a systematic verification of operational wave models. *Proc. Third Int. Symposium on WAVES97:* November 3-7, 1997, Virginia Beach, Va, USA, edited by B. L. Edge and J. M. Hemsley. American Society of Civil Engineer.

Bourassa, M.A., D.M. Legler and J.J. O'Brien, 1999. Scatterometry data sets: high quality winds over water. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C., p. 139-148.

Bouws, E., B.W. Golding, G.J. Komen, H.H. Peeck and M.J.M. Saraber, 1980. Preliminary results on a comparison of shallow water wave predictions. *KNMI Scientific Report 80-5*.

Bouws, E., G.J. Komen, R.A. van Moerkerken, H.H. Peeck and M.J.M. Saraber, 1986. An evaluation of operational wave forecasts on shallow water in: *Proceedings IUCRM Symposium on Wave Dynamics and Radio Probing of the Ocean Surface*. Phillips and Hasselmann, eds. Plenum, , p. 639-660.

Bouws, E., D. Jannink, G.J. Komen, 1996. On the increasing wave height in the North Atlantic Ocean. *Bulletin of the American Meteorological Society*, 77. 2275-2277.

Burgers, G., P.A.E.M. Janssen and D.L.T. Anderson, 1996. Impact of sea-state dependent fluxes on the tropical ocean circulation. *Proceedings of the International Scientific Conference on the Tropical Ocean Global Atmosphere (TOGA) Programme,* 2-7 April 1995, Melbourne, Australia, WCRP-91 - WMO/TD No. 717, p 643-646.

Cardone, V.J., J.G. Greenwood and M.A. Cane, 1990. On trends in historical marine wind data. *J. of Climate*, 3, 113-127.

Cardone, V.J., H.C. Graber, R.E. Jensen, S. Hasselmann, and M.J. Caruso, 1995. In search of the true surface wind field in SWADE IOP-1: ocean wave modeling perspective. *The Global Ocean Atmosphere System,* **3**, 107-150.

Cardone, V.J., R.E. Jensen, D.T. Resio, V.R. Swail and A.T. Cox, 1996. Evaluation of Contemporary Ocean Wave Models in Rare Extreme Events: "Halloween Storm of October, 1991; "Storm of the Century" of March, 1993". *J. Atmos. Ocean. Tech.*, **13**, 1, 198-230.

Cardone, V.J., A.T. Cox and V.R. Swail, 1999. Evaluation of NCEP reanalysis surface marine wind fields for ocean wave hindcasts. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99)*, 8-15 September 1999, Vancouver, B.C., p. 210-222.

Carter, D.J.T. and L. Draper, 1988. Has the northeast Atlantic become rougher? Nature, 332, 494.

Challenor, P. G. and P. D. Cotton, 1999: The joint calibration of altimeter and *in situ* wave heights, *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C.

Cotton P. D. and D. J. T. Carter, 1994: Cross calibration of TOPEX, ERS-1 and Geosat wave heights, *J. Geophys. Res.,* **99**, 25025-25033. (correction *J. Geophys. Res.,* **100**, 7095).

Cotton, P. D. and P. G. Challenor, 1999: North Atlantic Wave Climate Variability and the North Atlantic Oscillation Index, *Proc Ninth (1999) ISOPE Conf,* Brest, France, May 30-June 4, 1999, **3**, pp 153-157.

Cotton, P.D., P.G. Challenor, L. Redbourn-Marsh, S.K. Gulev, A. Sterl and R.Bortkovskii, 1999: An intercomparison of *in situ,* voluntary observing, satellite data, and modelling wind and wave climatologies. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C., p. 110-120.

Cox, A.T., and V.R. Swail, 1999. A global wave hindcast over the period 1958-1997: validation and climate assessment. *Submitted to JGR (Oceans).*

Cox, A.T., V.J. Cardone and V.R. Swail, 1999. On the use of *in situ* and satellite wave measurements for evaluation of wave hindcasts. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C.

Dobson, F.W. and E. Dunlap, 1999. MIROS system evaluation. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C., p.

Donelan, M.A., F.W. Dobson, S.D. Smith and R.J. Anderson, 1993. On the dependence of sea surface roughness on wave development. *J. Phys. Oceanogr.* 23, 2143.

Doyle, J.D., 1995. Coupled ocean wave/atmosphere mesoscale model simulations of cyclogenesis. *Tellus,* 47A, 766-778.

Foreman, S.J., M.W. Holt, S. Kelsall, 1994. Preliminary assessment and use of ERS-1 altimeter data. *JAOT October 1994.*

GOOS Coastal Module Planning Workshop, 1997. Univ. of Miami, February 24-28, 1997, 53 pp.

Gulev, S. K., D. Cotton and A. Sterl, 1998: Intercomparison of the North Atlantic wave climatology from voluntary observing ships, satellite data and modelling. *Physics and Chemistry of the Earth,* **23**, No. 5/6, pp 587-592.

Günther, H., G.J. Komen and W. Rosenthal, 1984. A semi-operational comparison of wave prediction models. *D. Hydr.Z.* 37, 89- 106.

Hare, J. E., P. O. G. Persson, C. W. Fairall and J. B. Edson, 1999: Behaviour of Charnock's relationship for high wind conditions. *Preprint volume: 13th Conf. on Boundary Layers and Turbulence,* Dallas, Texas, 10-15 January, 1999, American Meteorological Society.

Heimbach, P., S. Hasselmann and K. Hasselmann, 1998. Statistical analysis and intercomparison of WAM model data with global ERS-1 SAR Wave Mode spectral retrievals over three years. *J. Geophys. Res.* 103, 7931-7978.

Heras, M.M. de las, and Janssen, P.A.E.M. 1992. Data assimilation with a coupled wind-wave model. *J. Geophys. Res.* 97, 20261-20270.

Hersbach, H., 1998. Application of the adjoint of the WAM model to inverse wave modelling. *J. Geophys. Research,* 103, 10,469-10,487.

Jacobs, C.M.J., W. Kohsiek and W.A. Oost, 1999: Air-sea flux and transfer velocity of CO2 over the North Sea: results from ASGAMAGE. *Tellus* 51B, 629-641.

Jähne, B. and H. Haussecker, 1998: Air-water gas exchange. *Annu. Rev. Fluid Mech.,* 30, 443-468.

Janssen, P.A.E.M, 1982. Quasilinear approximation for the spectrum of wind-generated water waves. *J. Fluid Mech.* 117, 493 - 506.

Janssen, P.A.E.M, 1989. Wave-induced stress and the drag of air flow over sea waves. *J. Phys. Oceanogr.* 19, 746 - 754.

Janssen, P.A.E.M., 1992. Experimental evidence of the effect of surface waves on the air flow. *J. of Phys. Oceanogr.* 22, 1600-1604.

Janssen, P.A.E.M. and P. Viterbo, 1995. Ocean waves and the atmospheric climate. *J. of Climate,* {\bf 9} 1269 - 1287.

Janssen, P.A.E.M., B. Becker and J.-J. Morcrette, 1996. Note on the sea-state dependence of the ocean surface albedo. *ECMWF, Techn Memorandum No. 228.*

Janssen, P.A.E.M., H. Wallbrink, C.J. Calkoen, D. van Halsema, W.A. Oost and P. Snoeij, 1998. The VIERS-1 scatterometer model. *J. Geophys. Res.*, 103, 7807-7831.

Kalnay, E., *et al*, 1996. The NCEP/NCAR 40-Year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77**, 3, 437-471.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, 1994. Dynamics and Modelling of Ocean Waves. *Cambridge University Press,* 532p.

Komen, G.J., P.A.E.M. Janssen, V. Makin and W.A. Oost, 1998. On the sea state dependence of the Charnock parameter. *The Global Atmosphere and Ocean System,* 5, 367-388.

Komen, G.J. and N. Smith, 1999. Wave and sea level monitoring and prediction in the service module of the Global Ocean Observing System (GOOS). *J. of Marine Systems,* 19, 235-250.

Komen, G.J., 1999a. The physics of ocean waves. *Proceedings of 1997 ECMWF Seminar on Atmosphere-Surface Interaction,* p67-84.

Komen, G.J. 1999b. Forecasting wind-driven ocean waves. *To appear in Ocean forecasting, conceptual basis and applications.* Nadia Pinardi (ed). Also available as *KNMI Preprint 97-27.*

Kushnir, Y., J. G. Greenwood and M. A Cane, 1997: The recent increase in North Atlantic wave heights. *J. Climate,* **10**, 2107-2113.

Lionello, P., H. Günther and P.A.E.M. Janssen 1992. Assimilation of altimeter data in a global third generation wave model. *J. Geophys. Res.* 97, 14253-14474.

Lionello, P. Malguzzi and A. Buzzi, 1998: Coupling between the Atmospheric Circulation and the Ocean Wave Field: An Idealized Case. *J. Phys. Ocean.*, 28, 161-177

Living Marine Resources Panel (IOC-WMO-UNEP-ICSU-FAO) of the Global Ocean Observing System (GOOS). First Session Report. GOOS Report No. 54, UNESCO, Paris, Oct. 1998.

Makin, V.K., 1998. Air-sea exchange of heat in the presence of wind waves and spray. *J. Geophys. Res.* 103, 1137 - 1152.

Makin, V., V. Kudryavtsev and K. Mastenbroek, 1995. Drag of the sea surface. *Boundary-Layer Meteorology,* 73, 159-182.

Mastenbroek, C., G.J.H. Burgers and P.A.E.M. Janssen, 1993. The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer. *J. Phys. Oceanogr.* {\bf 23}, 1856-1866.

Shaw, C.J., 1999. Offshore industry requirements and recent metocean technology developments. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C., p. 324-329.

Smith, S.D., R.J. Anderson, W.A. Oost, C. Kraan, N. Maat, J. DeCosmo, K.B. Katsaros, K.L. Davidson, K. Bumke, L. Hasse and H.M. Chadwick, 1992. Sea surface wind stress and drag coefficients: the HEXOS results. *Boundary-Layer Meteorol.* 60, 109-142

Sterl, A. and H. Bonekamp, 1999. Comparison of wind stress from ERA and from WAM. To appear in the *Proc. of the 2nd International Conference on Reanalyses,* Reading, UK.

Sterl, A., G.J. Komen and P.D. Cotton, 1998. Fifteen years of global wave hindcasts using ERA winds: Validating the reanalysed winds and assessing the wave climate. *J. Geophys. Research,* 103, No. C3, 5477-5492.

Swail, V.R. and A.T. Cox, 1999. On the use of NCEP/NCAR reanalysis surface marine wind fields for a long term North Atlantic wave hindcast. *Accepted in J. Atmos. Ocean. Tech.*

Swail, V.R., A.T. Cox and V.J. Cardone, 1999. Analysis of wave climate trends and variability. *Proc. WMO Workshop on Advances in Marine Climatology (CLIMAR99),* 8-15 September 1999, Vancouver, B.C., p. 245-256.

Taylor, P. K. and M. J. Yelland, 1999: The dependence of the surface roughness on the height and steepness of the waves. *Journal of Physical Oceanography (submitted).*

Taylor, P. K., E. F. Bradley, C. W. Fairall, D. Legler, J. Schulz, R. A. Weller, G. H. White, 1999. Surface fluxes and surface reference sites. *This volume.*

The GOOS Strategic Plan and Principles for the Global Ocean Observing System (GOOS). GOOS *Report No. 41, IOC/INF-1091,* UNESCO, ii+23 pp., Paris, January 1998.

The WAMDI-group. S. Hasselmann, K. Hasselmann, E. Bauer, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionello, A. Guillaume, V.C. Cardone, J.A. Greenwood, M. Reistad, L. Zambresky and J.A. Ewing, 1988. The WAM model - a third generation ocean wave prediction model. *J. Phys. Ocean.* 18, 1775 - 1810.

Thomas, J.P. 1988 retrieval of energy spectra from measured data for assimilation into a wave model. *QJ Royal Met Soc* **114** 781-800

Uppala, S., J.K. Gibson, M. Fiorino, A. Hernandez, P. Kallberg, Xu Li, K. Onogi and S. Saarinen, 1999. ECMWF's second generation reanalysis – ERA40. *Proc. 2nd International Conference on Reanalyses,* 23-27 August, 1999, Reading, UK.

Vachon, P. and F. Dobson, 1995: Validation of wind speed retrieval from ERS-1 SAR images. *Fourth International Workshop on Wave Hindcasting and Forecasting*. October 16-20. Banff, Alberta, Canada.

Voorrips, A.C., 1998. Sequential data assimilation methods for ocean wave models. *PhD-Thesis, Technical University of Delft,* The Netherlands, 175p.

Voorrips, A.C., 1999. Spectral wave data assimilation for the prediction of waves in the North Sea. *Accepted by Coastal Engineering.*

Voorrips, A., V.K. Makin and S. Hasselmann, 1997. Assimilation of wave spectra from pitch-and-roll buoys in a North Sea wave model. *J. Geophys. Res.* 102, 5829-5849.

Voorrips, A.C., A.W. Heemink and Komen, G.J., 1999. Wave data assimilation with the Kalman filter. *Journal of Marine Systems*, 19, 267-291.

Wang, X.L. and V.R. Swail, 1999. Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. *Submitted to J. Climate.*

Wanninkhof, R. and W.R. McGillis, 1999: A cubic relationship between air-sea CO2 exchange and wind speed. *Geophys. Res. Letters* 26, 1889-1892.

WASA group: J.C. Carretero, M. Gomez, I. Lozano, A. Ruiz de Elvira, O. Serrano, K. Iden, M. Reistad, H. Reichardt, V. Kharin, M. Stolley, H. von Storch, H. Günther, A. Pfizenmayer, W. Rosenthal, M. Stawarz, T. Schmith, E. Kaas, T. Li, H. Alexandersson, J. Beersma, E. Bouws, G. Komen, K. Rider, R. Flather, J. Smith, W. Bijl, J. de Ronde, M. Mietus, E. Bauer, H. Schmidt and H. Langenberg, 1998. Changing waves and storms in the Northeast Atlantic? *BAMS,* 79, 741 - 760.

Yelland, M. J. and P. K. Taylor, 1996: Wind stress measurements from the Open Ocean. *J. Phys. Oceanogr.,* 26, 541 - 558.

Yelland, M. J., B. I. Moat, P. K. Taylor, R. W. Pascal, J. Hutchings and V. C. Cornell, 1998: Measurements of the open ocean drag coefficient corrected for air flow disturbance by the ship. *J. Phys. Oceanogr.,* **28**(7), 1511 - 1526.

Young, I.R. and T.J. Glowacki, 1996. Assimilation of altimeter wave height data into a spectral wave model using statistical interpolation. *Ocean Engng.* 23, No. 8, 667-689.