VERIFICATION OF OPERATIONAL GLOBAL AND REGIONAL WAVE FORECASTING SYSTEMS AGAINST MEASUREMENTS FROM MOORED BUOYS

by

J.-R. Bidlot and M.W. Holt

WMO/TD-No. 1333

2006

JCOMM Technical Report No. 30

WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (OF UNESCO)

VERIFICATION OF OPERATIONAL GLOBAL AND REGIONAL WAVE FORECASTING SYSTEMS AGAINST MEASUREMENTS FROM MOORED BUOYS

by

J.-R. Bidlot and M.W. Holt

WMO/TD-No. 1333

2006

JCOMM Technical Report No. 30

C O N T E N T S

1. INTRODUCTION

Regional or basin-scale wave forecast model systems have been developed and run at various forecast modelling centres since the late 1970s, and as computer power grew during the 1980s, with the availability of global numerical weather prediction (NWP) models, global wave forecast models were established, often with nested regional wave models. Since that time, with increasing supercomputer capacity, the resolution of both global and regional wave models has increased, so that in 2004 a global wave model will typically have a grid spacing of ~50 km, close to or matching the resolution of the global NWP model providing the forcing winds. The models are typically run twice daily for a five-day forecast, in line with the available numerical weather prediction models.

The wave model systems provide forecasts for offshore operations, ship routing, and, now via Global Maritime Distress and Safety System (GMDSS), for safety of life at sea.

Initial verification work was based on comparison with available in situ observations, and verification was carried out independently at each modelling centre (Günther *et al.*, 1984; Zambresky, 1989; Khandekar *et al.*, 1994; Khandekar and Lalbeharry, 1996; Lalbeharry, 2002; Janssen *et al.*, 1997; Jensen *et al.*, 2002; Wittmann, 2001; Tolman, 2002; Cardone *et al.*, 1996).

With the advent of operational satellite altimeters in the early 1990s (ERS-1), it was possible to consider assimilation of along-track wave height values from the altimeter, using the collocated wind speed observations as required (Lionello *et al.*, 1992; Foreman *et al.*, 1994). Some modelling centres, though not all, continue to assimilate satellite data into the global wave model.

A verification exchange activity and inter-comparison was established in 1995 by the wave modellers from AES (now MSC), ECMWF, FNMOC, NCEP and the Met Office as a research and development activity for comparison of ocean wave forecast systems. In particular the verification is of the operational system, using operational forcing winds and the operational wave model configuration "as run". The intention is to provide a benchmark of performance, to establish best practice and guide the future development of the wave forecast systems. The exercise is not configured as a wave model inter-comparison. It is realized that for this, a common model set up is required.

In 2004 the verification exchange also includes contributions from Meteo-France and DWD.

The verification activity has been described in several published papers, and results have been written up or presented at various conferences (Bidlot *et al.*, 1998; Bidlot and Holt, 1999; Bidlot *et al.*, 2002).

The purpose of this JCOMM Technical Report is to document the global wave model verification activity, giving details of the working mechanism and file formats so that modelling centres not yet engaged may judge whether or not they should participate.

2. FORECAST MODELS AND FORCING WINDS

The details of wave model, configuration and resolution at each centre will change with time, as do the details of the forcing NWP winds used, so are not given here. Summary details are available in the annual WMO GDPS report (http://www.wmo.ch/web/www/DPS/Annual-Tech-Progress/2004/COVER.html).

3. OBSERVATIONS

Sea state and ocean surface meteorological observations are routinely collected by several national organizations via networks of moored buoys or weather ships and fixed platforms deployed in their near- and offshore areas of interest. The data are exchanged via GTS (or as otherwise made available under WMO Resolution 40). The geographical coverage of the wave data is still very limited, and at the present wave model resolution, only a subset of all these stations is within the wave model grid. Nevertheless, about 79 stations that report both wind and wave data were selected for the comparison. The data coverage can be seen in Figure 1, which shows the positions of all the observations. Except for one platform located off the South African coast and one buoy on the equator near Christmas Island in the Pacific, all measurements are taken in the Northern Hemisphere.

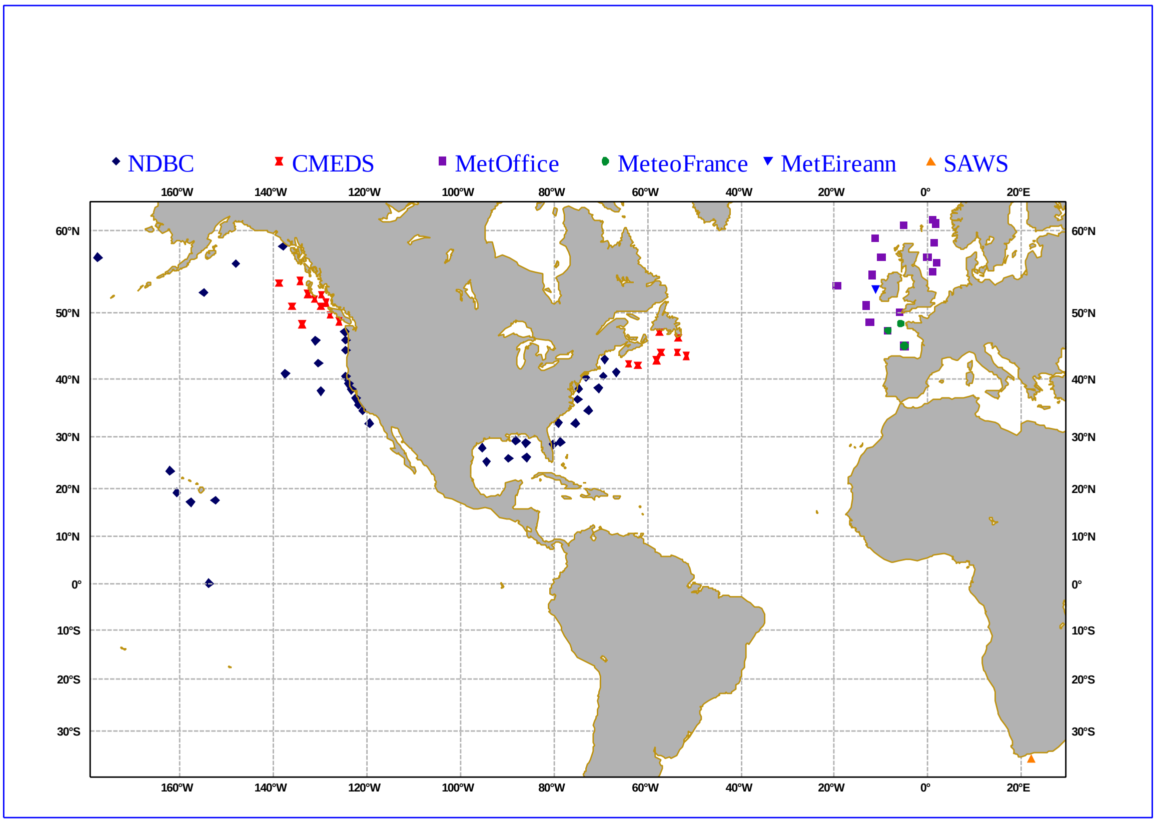

Figure 1: Buoy and platform locations currently used in the inter-comparison. The data providers are indicated above the map.

The hourly wave and wind data are transferred continually via the GTS to national meteorological centres and are usually archived with all other synoptic ship observations. In the remainder of the paper, the word buoy will be used to refer to the selected moored buoys, weather ships or platforms since most of the reliable observations come from moored buoys. Note however that the observation principle for waves from moored buoys is quite different from that used from platforms. Buoys usually rely on time series analysis of the buoy motion to derive wave spectra whereas radar imaging of the sea surface is employed by platforms to derive the wave spectra. Collocations between these observations and the corresponding model values interpolated to the buoy locations can easily be obtained. A direct comparison between model values and buoy and platform observations is however undesirable as some measurements may still be erroneous. Furthermore, model and observed quantities represent different time and spatial scales.

From the buoy records, time series are reconstructed and used to perform a basic quality check on the data (Bidlot *et al.*, 2002). Spatial and temporal scales are made comparable by averaging the hourly observations in time windows of 4 hours centred on the main synoptic times. It should be emphasized that buoy observations and the model represent different scales. Typically the buoy observation represents an average over an interval of 20 minutes, and buoys exhibit high frequency variability on a time scale of one hour, which is absent in the model because the model value represents a mean value over a grid box of size 50-150 km. In other words, since waves propagate across the area where the instrumental sensors are located, one should not consider a single observation at any given time to be equivalent to the actual statistical wave height computed at each model grid box. Averaging of the observed wave height is therefore preferable where the averaging period should match the scales still represented by the model. With a mean group velocity of 10 m/s, an averaging time of 4 hours thus seems appropriate to represent a 100-150 km box averaged observation. Not averaging the data will result in increased scatter between the model and observations, which can be linked to the high frequency variability, not present in the model (Janssen *et al.*, 1997). GTS data are unfortunately provided with some truncation. Wave heights are rounded to the closest 0.1 meter, wave periods to the closest second and wind speed to the closest meter per second. Averaging will diminish the effect of these truncations. The resulting errors for wave data are well within what can be expected from buoy measurements (Monaldo, 1988). It is however unfortunate that wind speed observations are encoded with such a large truncation error (up to 0.5 m s-1) since most of them still need to be adjusted to the standard height of 10 m.

Buoy anemometers are not usually at an average height of 10 meters. However, the wind observations used here will be compared to model wind 10 meters above mean sea level. Therefore the height of the anemometers was obtained from the data providers and the wind speed statistics were produced by adjusting the buoy winds to 10 m. The wind speed is corrected assuming that on average the wind profile in the planetary boundary layer is neutral. Winds from platforms are usually adjusted to 10 m by the data providers. A reduction factor is used even though the height of the anemometer could be in the several tens of meters. Winds from platforms are therefore less reliable than buoy observations.

Besides wave heights, buoys also report wave period measurements. There is however, no consensus on what type of period should be reported. Canadian and US buoys report the period corresponding to the peak in the one-dimensional wave spectrum, the peak period (Tp), whereas the other data providers use a mean period, usually the zero mean crossing period (Tz) which can roughly be equated to the reciprocal of the square root of the normalized second moment of the frequency spectrum.

In some countries the wave measurements are not taken by the National Meteorological Service so there is no, or only limited access, to the GTS for dissemination. Here it has in some cases proven possible to collate and exchange a monthly dataset of observations. This is currently the case with the South African Weather Service. On a monthly basis, hourly time series of the observations from the platform ZSWAV are sent via email to a list of interested people. These data are used to supplement the data already received by GTS.

4. THE VERIFICATION DATA EXCHANGE: TECHNICAL DETAILS

At the beginning of each month, buoy data are processed at ECMWF based on the analysis of time series of hourly data of the previous month. At the same time, ECMWF model data are collocated with the observations. Besides the necessary quality check on the data as well as on the buoy positions (moored buoys are known to be drifting), a quick inspection of data is performed to remove any suspicious data records. Because of the general good quality of present wave model analyses, large departures from the model usually indicate problems with the observations. Information about the status of the buoy networks (when available) is also regularly used to eliminate wrong data.

Other participating centres have built similar buoy-model collocation files or have agreed to provide corresponding model values at as many buoy locations as possible (Figure 1).

Flexibility is desirable as buoy locations are likely to change over time. Every month, each participating centre creates files that contain model monthly time series of 10-m wind speed and direction, wave height, and wave period at the selected locations. It was agreed to look at the analyses at the four major synoptic times (0, 6, 12, 18 GMT) if available and at the day 1 up to day 5 forecasts from 0 and 12Z (when available). In order to facilitate the data exchange, a simple fixed ASCII text columns format is used. There is a file for each forecast step and all buoys and times have to be included (a missing data indicator should be used if some model data cannot be produced, see Annex I). These files are transferred via FTP to a designated server at ECMWF (password required). The contributions from all participants are combined with the corresponding buoy data and the resulting files are made available to all participants via the same FTP site (for simplicity the file format is still organized in column in ASCII text).

It is the responsibility of each participant to retrieve the combined files from the ECMWF server. The statistical analysis of the data is left to each centre (i.e. scores are not exchanged as is done for NWP models). However, ECMWF has a semi automatic procedure to analyze the monthly results from which comparative tables and summary plots are produced. The tables and plots are also available every month from the ECMWF server.

At this time, the data remain confidential to the participants, except for agreed summaries that are published on the JCOMM web site or in occasional published papers. It is possible that some results might also appear on the public web pages from ECMWF.

If anybody is interested in joining this intercomparison, he or she should get in touch with Jean Bidlot (Wave Model development scientist) at ECMWF. The latest list of selected locations will be provided and access to the FTP server will be granted. The interested party should then provide a sample set of files with their data following the format as described in Annex I. ECMWF will then modify its processing scripts to accommodate the newcomer and if the results are satisfactory then the new participant will be notified. Note that from then on, each participant is responsible to send his or her contribution at the beginning of each month (first 10 days preferably) since it is the aim of the group to have the combined data set and the summary statistics by the middle of the month.

5. SUMMARY DATA PRODUCTS AND EXAMPLES OF RECENT RESULTS

The monthly comparison with the buoy data is performed by looking at basic statistics assuming that the buoy data represent the truth such as the mean of the difference between model and observations (bias), the root mean square error (RMSE), the scatter index (SI) defined as the standard deviation of the difference normalized by the mean of the observations, linear correlation coefficient (CC) and the mean square slope (SS) defined as the ratio of the variance of the model and the variance of the observations. The model analyses and the different forecast steps are compared.

These tabulated statistics are supplemented by plots of time series of the different parameters as well as plots of the evolution of the different quantities in function of the forecast range. A general perception of the fit of the model data with the buoy observations is also presented in scatter diagrams. Figure 2 is such an example for wave height day one forecasts for the six centres with a global wave model for 2 boreal winter months in 2004. The evolution of the RMSE in terms of the forecast step is also presented at the centre of the plot. A similar plot is shown in Figure 3 for three boreal summer month for buoys that are well within the regional models in use at MSC.

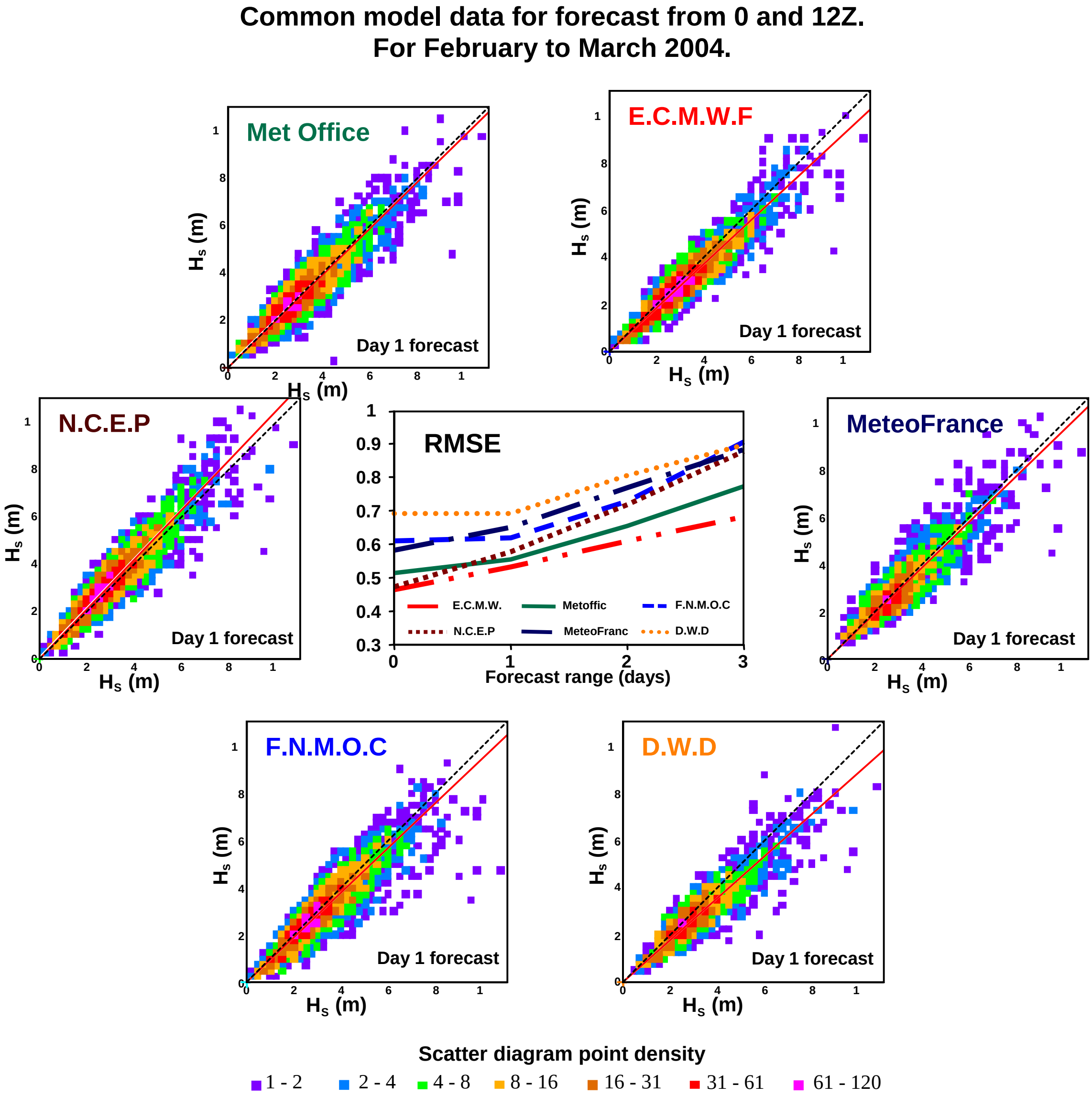

Figure 2: Scatter diagrams for the day 1 wave height forecast from 0 and 12Z valid from February 1st to March 31st 2004 with respect to buoy data at all locations for which the six global wave models provided data. Also shown is the evolution of the root mean square error (RMSE) as a function of the forecast range (up to day 3).

Common model data for forecast from 0 and 12Z.
For June to August 2004.

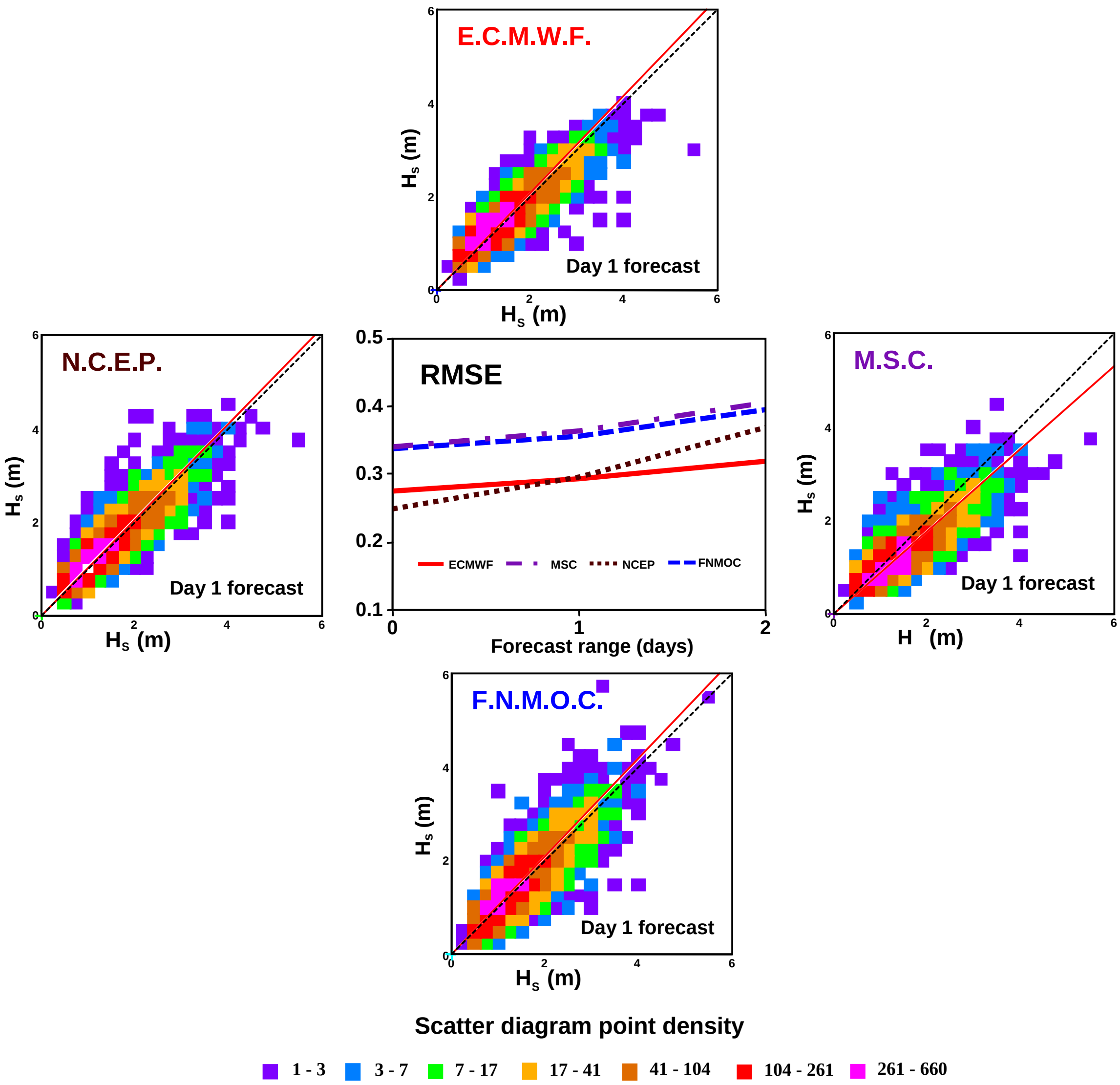

Figure 3: Scatter diagrams for the day 1 wave height forecast from 0 and 12Z valid from June 1st to August 31st 2004 with respect to buoy data at all locations for which the four wave models provided data. Also shown is the evolution of the root mean square error (RMSE) as a function of the forecast range (up to day 2).

REFERENCES

Bidlot J-R and M Holt, 1999: Numerical wave modelling at operational weather centres. Coastal Eng. 37 409-429.

Bidlot J-R, Holt MW, Wittmann PA, Lalbeharry R and Chen HS, 1998: Towards a systematic verification of operational wave models. Proc Third Int. Symp. on ocean wave measurements and analysis. Waves97 Virginia Beach VA American Society of Civil Engineers.

Bidlot J-R, Holmes DJ, Wittmann PA, Lalbeharry R and Chen HS, 2002: Intercomparison of the performance of operational ocean wave forecasting systems with buoy data. Weather and Forecasting 17 287-310.

Cardone, VJ, RE Jensen, DT Resio, VR Swail, AT Cox, 1996: Evaluation of contemporary ocean wave models in rare extreme events: the “Halloween Strom” of October 1991 and the “Storm of the Century” of March 1993. J. Atm. Oceanic. Tech., 13, 198-230.

Foreman SJ, Holt MW and Kelsall S 1994: Preliminary assessment and use of ERS-1 altimeter data. J. Atm. Oceanic. Tech. 11 No. 5 pp 1370-1380.

Günther H, Komen GJ and Rosenthal W, 1984: A semi-operational comparison of two parametrical wave prediction models. Citation Deutsche Hydrographische Zeitschrift, VOL. 37 No. 3 pp.89-106.

Janssen PAEM, Hansen B and Bidlot J-R 1997: Verification of the ECMWF wave forecasting system against buoy and altimeter data. Weather and Forecasting, VOL. 12 No. 4pp.763-784.

Jensen RE, PA Wittmann, and JD Dykes, 2002: Global and regional wave modelling activities. Oceanography, 15, No. 15, 57-66.

Khandekar, ML, Lalbeharry R and Cardone V, 1994: The performance of the Canadian Spectral Ocean Wave Model (CSOWM) during the Grand Banks ERS-1 SAR wave spectra validation experiment.
Atmosphere-Ocean, VOL. 32 No. 1 pp.31-60.

Khandekar ML and Lalbeharry R, 1996: An evaluation of Environment Canada's operational Ocean Wave Model based on moored buoy data. Weather and Forecasting, VOL. 11 NO. 2 pp.137-152.

Lalbeharry R, 2002: Evaluation of the CMC regional wave forecasting system against buoy data.
Atmosphere-Ocean, VOL. 40 NO. 1, 2002.

Lionello P, H Gunther and PAEM Janssen 1992: Assimilation of altimeter data in a global third generation wave model. JGR C97, 14453-14474.

Monaldo, F., 1988: Expected difference between buoy and radar altimeter estimates of wind speed and significant wave height and their implications on buoy-altimeter comparison. J. Geophys. Res., 93C, 2285-2302.

Tolman HL, B Balasubramaniyan, LD Burroughs, DV Chalikov, YY Chao, HS Chen and VM Gerald, 2002: Development and implementation of wind-generated ocean surface models at NCEP. Weather and Forecasting (NCEP Notes), 17, 311-333.

Wittmann PA, 2001: Implemetation of WAVEWATCH-III at Fleet Numerical Meteorological and Oceanography Center. Conference proceedings: MTS.IEEE Conference and Exposition: An Ocean Odyssey: November 5-8, 2001, Honolulu, Hawaii, 1474-1479.

Zambresky L, 1989: A verification study of the global WAM model December 1987- November 1988. ECMWF Tech Report 63, ECMWF, Reading, 86pp.

Annex I

Each centre should prepare its files following a simple ASCII text format. One file for the analysis and one file for each forecast step provided. Note that because monthly time series of buoy data are used (from the 1st 0Z to the last day of the month 18Z) model analysis and forecast data are to be provided with verifying date and time corresponding to those buoy date and time. We rely on the exact prescription of the data to combine the different files from the different participants. This means that if for some reason, model data are missing then entries should still be produced with missing data indicators instead.

The format is as follows

ccccc bbbbb ttt yyyy mm dd hh ww.w ddd hh.h pp.p WW.W DDD HH.H PP.P p

where:
ccccc: centre identifier (!! 5 long !!)
bbbbb: buoy identifier as defined by WMO (!! 5 long !!)
ttt: forecast step (0,24,48,...)
yyyy: year in 4
mm: month in 2
dd: day in 2
hh: hour in 2

and for model quantities (lower case)

ww.w: wind speed (in m/s) (**** if missing)
ddd: wind direction (in degree, meteorological convention) (*** if missing)
hh.h: wave height (in m) (**** if missing)
pp.p: period (in second) (**** if missing)

the upper case entry are for the buoy data in case you were to provide data that ECMWF cannot get otherwise fill these columns with missing data indicators (**** or ***). the last entry, p , indicates which model period is used: 0: zero mean crossing, 1: peak period, 2: $T_{1/3}$. Most buoys used here report the peak period but the UK and Irish buoys use a zero mean crossing period and French buoys encode $T_{1/3}$. Most people in the exchange only provide the peak period and therefore so far we have limited the analysis to those data. If you are able to provide different type of periods, let Jean Bidlot know he will send you the list of buoys for which we need the zero mean crossing periods or $T_{1/3}$, otherwise, provide the peak period.

Also note that the date and time used in these files correspond to the verifying time.
Namely if date and time are 2003 10 1 0

with ttt=24, it means it was a forecast that was issued on 2003 09 31 0Z

etc.

Also note that for the analysis, model data are provided 4 times per day where as for the forecasts at most 2 times a day (forecast from 00 and 12Z) because most global wave forecast are only available from 0 and 12Z. If you have only one forecast per day, just provide that one.

Examples:

for the analysis:

```
ccccc bbbbb ttt yyyy mm dd hh ww.w ddd hh.h pp.p WW.W DDD HH.H PP.P p

DWD   41001   0 2003 10  1  0  6.8  19  1.4 10.1 **** *** **** **** 1
DWD   41001   0 2003 10  1  6  6.4  10  1.3 10.2 **** *** **** **** 1
DWD   41001   0 2003 10  1 12  6.1  20  1.3 10.2 **** *** **** **** 1
DWD   41001   0 2003 10  1 18  5.4  28  1.2 10.2 **** *** **** **** 1
DWD   41001   0 2003 10  2  0  5.4  46  1.1 10.2 **** *** **** **** 1
DWD   41001   0 2003 10  2  6  5.2  16  1.1 10.2 **** *** **** **** 1
DWD   41001   0 2003 10  2 12  6.2  20  1.1  9.5 **** *** **** **** 1
DWD   41001   0 2003 10  2 18  4.4   9  1.4 10.5 **** *** **** **** 1
DWD   41001   0 2003 10  3  0  7.6 349  1.3 10.2 **** *** **** **** 1
DWD   41001   0 2003 10  3  6 10.6   8  2.1  6.3 **** *** **** **** 1
```

and for the forecast:

```
DWD   41001  24 2003 10  1  0  7.6  15  1.4  9.9 **** *** **** **** 1
DWD   41001  24 2003 10  1 12  5.4  15  1.1 10.2 **** *** **** **** 1
DWD   41001  24 2003 10  2  0  5.4  41  1.1 10.2 **** *** **** **** 1
DWD   41001  24 2003 10  2 12  5.9  15  1.1  9.5 **** *** **** **** 1
DWD   41001  24 2003 10  3  0  9.3 346  1.6  8.7 **** *** **** **** 1
DWD   41001  24 2003 10  3 12  9.7  16  2.1  6.9 **** *** **** **** 1
```

Annex II

ACRONYMS AND OTHER ABBREVIATIONS AND SYMBOLS

AES	Atmospheric Environment Service
CC	Correlation Coefficient
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-range Weather Forecasts
ERS	European Remote Sensing
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GDPS	Global Data Processing System
GMDSS	Global Maritime Distress and Safety Systems
GTS	Global Telecommunication System (WWW)
JCOMM	Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology
MSC	Meteorological Service of Canada
NWP	Numerical Weather Prediction
RMSE	Root Mean Square Error
SI	Scatter Index
SS	Mean Square Slope
Tp	Peak Period
Tz	Zero Mean Crossing Period
$T_{1/3}$	Significant Wave Period
WMO	World Meteorological Organization
WWW	World Weather Watch (WMO)