Inter-comparison of operational wave forecasting systems.

Jean-Raymond Bidlot

European Centre for Medium range Weather Forecasts,
Shinfield Park, RG2 9AX, Reading, UK.

+44-118-9499-708

and

Jian-Guo Li,
the Met Office, UK.
Paul Wittmann,
Fleet Numerical Meteorology and Oceanography Centre, USA.
Manon Fauchon,
Meteorological Service of *Canada*, Canada.
Hsuan Chen,
National Centers for Environmental Prediction, USA.
Jean–Michel Lefèvre,
Météo France, France.
Thomas Bruns,
Deutscher Wetterdienst, Germany.
Diana Greenslade,
Bureau of Meteorology, Australia.
Fabrice Ardhuin,
Service Hydrographique et Océanographique de la Marine, France.
Nadao Kohno,
Japan Meteorological Agency, Japan.
Sanwook Park,
Korea Meteorological Administration, Republic of Korea.
Marta Gomez,
Puertos del Estado, Spain.

Abstract

The monthly exchange of operational ocean wave model data has successfully been taking place for over 12 years. Nowadays, model data from twelve operational centres are compared with observations obtained from moored buoys and platforms. This paper briefly reviews the status of this inter-comparison.

1. Introduction

A routine inter-comparison of wave model forecast verification data was first informally established in 1995 following discussions at the WISE meeting in Ensenada (Mexico). It was intended to provide a mechanism for benchmarking and assuring the quality of wave forecast model products.

This original inter-comparison was developed around the exchange of model analysis and forecast data at an agreed list of moored buoy sites at which observations of significant wave height, wave period and wind speed are available over the Global Telecommunication System (GTS) from the World Meteorological Organization (WMO). Five centres (ECMWF), the Met Office (United Kingdom), FNMOC (USA), NCEP (USA) and the Meteorological Service of Canada (MSC)) routinely running wave forecast models contributed to the original exchange. The usefulness of this type of data collection was presented during WAVES97 (Bidlot et al. 1998).

The exchange was subsequently expanded with the addition of Météo France in 2001. A paper discussing results from the exchange was published in 2002 (Bidlot et al. 2002). The Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) via its Expert Team on Wind Waves and Storm Surges, during its first meeting (ETWS-I, Halifax, Canada, June 2003) noted the value of the exchange, and endorsed the further expansion of the scheme to include other wave forecast systems. In recent years, this project has expanded to include Deutscher Wetterdienst (DWD), the Australian Bureau of Meteorology (BoM), the Service Hydrographique et Océanographique de la Marine (SHOM) and Japan Meteorological Agency (JMA). In 2007, contributions from the Korea Meteorological Administration (KMA) (Republic of Korea), and Puertos del Estado (Spain) were received. All twelve centres actively contribute data on a routine basis. Some participants are also providing observations that are not commonly available on the GTS.

The mechanism for the data collection is similar to the one set up for the original exchange. On a monthly basis, each centre provides files of model data collocated with the buoy locations in an agreed format to ECMWF, where the data are collated for subsequent access. The combined datasets are then processed to provide statistics for each centre at each buoy. Observation data are also added at ECMWF, and are quality controlled, with wind speeds adjusted to 10m height. A technical report on the inter-comparison was submitted following the JCOMM Services Coordination Group SCG-I meeting, and was published in 2006 (Bidlot and Holt, 2006). This report provides a description of the project activity, and includes a full technical specification of the data exchange process.

At the second JCOMM Expert Team on Wind Waves and Storm Surges (ETWS-II, Geneva, March 2007), it was agreed that this activity should continue and that it needs to be consolidated. It was also recognised that it should also be more visible to the wider community at large.

It is now opportune to review what has been achieved so far. Improvements in wave forecasting are clearly visible. At the same time, from the slow, yet steady increase in available wave observations, the inter-comparison is extending to more locations. Finally, it is hoped that the current results will motivate participants to discuss possible new avenues for expanding this inter-comparison.

This paper is intended to show some of the results of the inter-comparison. It is however not the intention of the authors to try to explain the possible reasons for the differences between the different systems.

In the next section, data involved in this inter-comparison are briefly reviewed, followed by examples of some recent results.

2. Data

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 usually exchanged via GTS. The geographical coverage of the wave data is still very limited (yet expanding), and at the present wave model resolution, only a subset of all these stations is within the wave model grids. Most measurements are taken in the Northern Hemisphere (Figure 1).

The hourly wave and wind data are transferred continually via the GTS to national meteorological centres and are usually archived with all other synoptic 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.

Before using observations for verification, care has to be taken to process the data to remove any erroneous observations. It is also necessary to match the scale of both model and observations. This scale matching is achieved by averaging the hourly data in 4 hourly time windows centred on the four major synoptic times corresponding to the usual model output times. The original quality control and averaging procedure was discussed in Bidlot et al. (2002). It was extended to include platform data as described in Sætra and Bidlot (2004).

The inter-comparison relies on the exchange of model output at buoy locations. An agreed upon list of locations is used where observations are known to be available. Because buoy networks are changing with time, as witnessed by a rapid increase in the number of buoys available since the mid-nineties (Figure 1), updates to the list have been necessary. Not all participating centres have been able to update their list at the same time however. Other participants are only running limited area model(s) or use a coarser grid. Because of the limited number of buoys, a fair comparison between the different systems can only be achieved if the same number of buoys and the same number of buoy-model collocations are used.

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 (Bidlot et al. 2002). 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, wave measurements are not made by the National Meteorological Service. As a consequence, there is no, or only limited access, to the GTS for dissemination. Nevertheless, it was possible to gather and exchange monthly datasets of observations in some cases. 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 complement the data already received by GTS. Recently, Oceanor has made their detailed buoy observations available via the web and monthly data sets are retrieved to supplement the GTS data (http://www.oceanor.com/Barents_Sea/).

Similarly, the Australian Bureau of Meteorology is kindly providing wind and wave buoy data it has collected from different institutes around Australia (Figure 1). The buoy data are sent to ECMWF every month together with the model data. Likewise, SHOM has recently deployed a directional buoy off the west coast of France (buoy 62064) and has attached the relevant buoy data to its model data contribution. Puertos del Estado is maintaining a network of buoys along both Atlantic and Mediterranean Iberian coasts (Figure 8). Their wave spectral data should soon become available on the GTS. In the mean time, as part of joining the inter-comparison, they have enabled access to their ftp site where the hourly observations can be fetched.
(http://www.puertos.es/en/oceanografia_y_meteorologia/index.html)

Twelve operational centres are currently contributing data. All are running global wave models except for MSC and Puertos del Estado, albeit with different wave model(s), different wind forcing, and different model configurations. MSC has one model set up for the North Pacific and another one for the North Atlantic. Puertos del Estado has different models for the Atlantic and the Mediterranean Sea. MF global wave model considered for this inter-comparison is not used by forecasters over the Pacific due to lack of resolution of the forcing winds (see appendix)
Forecasting systems are evolving with time, it is therefore hard to keep an up-to-date description of each system. We have tried to provide a list of recent publications and dynamic links in the appendix if a reader is interested in a detailed description.

3. Examples of recent results

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 UTC) if available and at the day 1 up to day 5 forecasts from 0 and 12UTC (when available). In order to facilitate the data exchange, a simple fixed ASCII text format is used. There is a file for each forecast step and all buoys and times have to be included. These files are transferred via FTP to 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 server.

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 atmospheric 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 (most plots are also visible on the internal web pages at ECMWF). Summary reports have also been recently posted on the ETWS part of JCOMM web site. A few examples are presented below.

The monthly comparison with the buoy data is performed by looking at basic statistics - assuming that the quality controlled 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). 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. Time series of the different observed parameters at all buoy locations are provided as well but with 12 participants, the plots are quite often hard to decipher (not shown).

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 10 centres with a global wave model for June to August 2007. The corresponding statistics are given in Table 1. Note that at the time of writing, not all participants had updated their buoy list to the latest one, hence the relative small number of buoys that were used when compared to Figure 1 (the buoy list roughly corresponds to the original list used in Bidlot et al. (1998 and 2002), besides Japanese buoys that are no longer available). Recall that a fair comparison between the different outputs can only be made if the same observations are used. Table 2 and 3 show similar statistics for wind speed and peak period.

The evolution of the scatter index and the bias in terms of the forecast step can also be plotted as presented in Figure 3 for the same period as in the previous Figure. From these types of plots, it is pretty clear that some forecasting systems have quite different characteristics. It is not the intention of this paper to review the possible reasons why it could be so. Note however that discussions are taking place to resolve (understand) some of the outliers.

This global picture of the performance of each system should be complemented with the seasonal variation of the different statistics. The time series of the 3-month running average of the day 1 and day 3 forecast wave height, wind speed and peak period scatter indices are presented in Figure 4. The plots clearly illustrate the seasonal variation of the error, as well as the seasonal rate of degradation of the forecasts. Note the arrival of many new participants in 2006-2007, overwhelming the clarity of the plot. Clearer longer trend analysis can be shown by using a 12 month running mean of the seasonal statistics, as shown on the right hand side of Figure 4. It appears that, generally, nice improvements of the quality of wave forecasts have been taking place for the last 10 years.

Regional variations of the fit to the data can also be studied as shown for buoys around Hawaii in Figure 5, compared to European buoys in the North East Atlantic in Figure 6 for December 2006 to February 2007. A slightly more extended list of locations than the original one is used in these plots.

Similarly, regional models can be compared to global ones in each of the regional model area of interest as illustrated in Figure 7 for MSC. The general trend in these scatter index time series confirms the ongoing improvements in wave forecasting, even at regional scale. It also shows that the error characteristics can be rather different from one ocean basin to the next.

Wave forecasts can have quite different quality in open ocean conditions or in enclosed sea environments. The newly acquired Spanish buoy data, together with the data already available via GTS can be compared to forecasts from Puertos del Estado and the few global systems that have a sufficiently fine resolutions for the European Atlantic area and the Western Mediterranean Sea (Figure 8). As expected, enclosed seas are harder to predict in terms of wave height and wind speed but not necessarily in terms of mean periods.

Finally, as seen in Figure 1, the number of available buoys has increased in the past 10 years. A new list of locations has recently been suggested in which new areas have become available for comparison. Figure 9 shows a recent example of forecast scores for buoys around India and Australia respectively.

4. Conclusions

Every month, wave model analysis and forecasts from the participating centres are compared with buoy observations at selected locations. The buoy data are obtained from the GTS and a few other sources. A basic quality control and averaging procedure is used to produce observations which can be compared to the equivalent model values. The resulting comparison serves as an additional validation tool for the operational wave forecasting system of each collaborating centre (winds and waves). As such, it 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 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 (or a consensus) 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 more widely available, it will stimulate a larger wave data exchange with organizations which collect wave data but do not make them available on GTS.

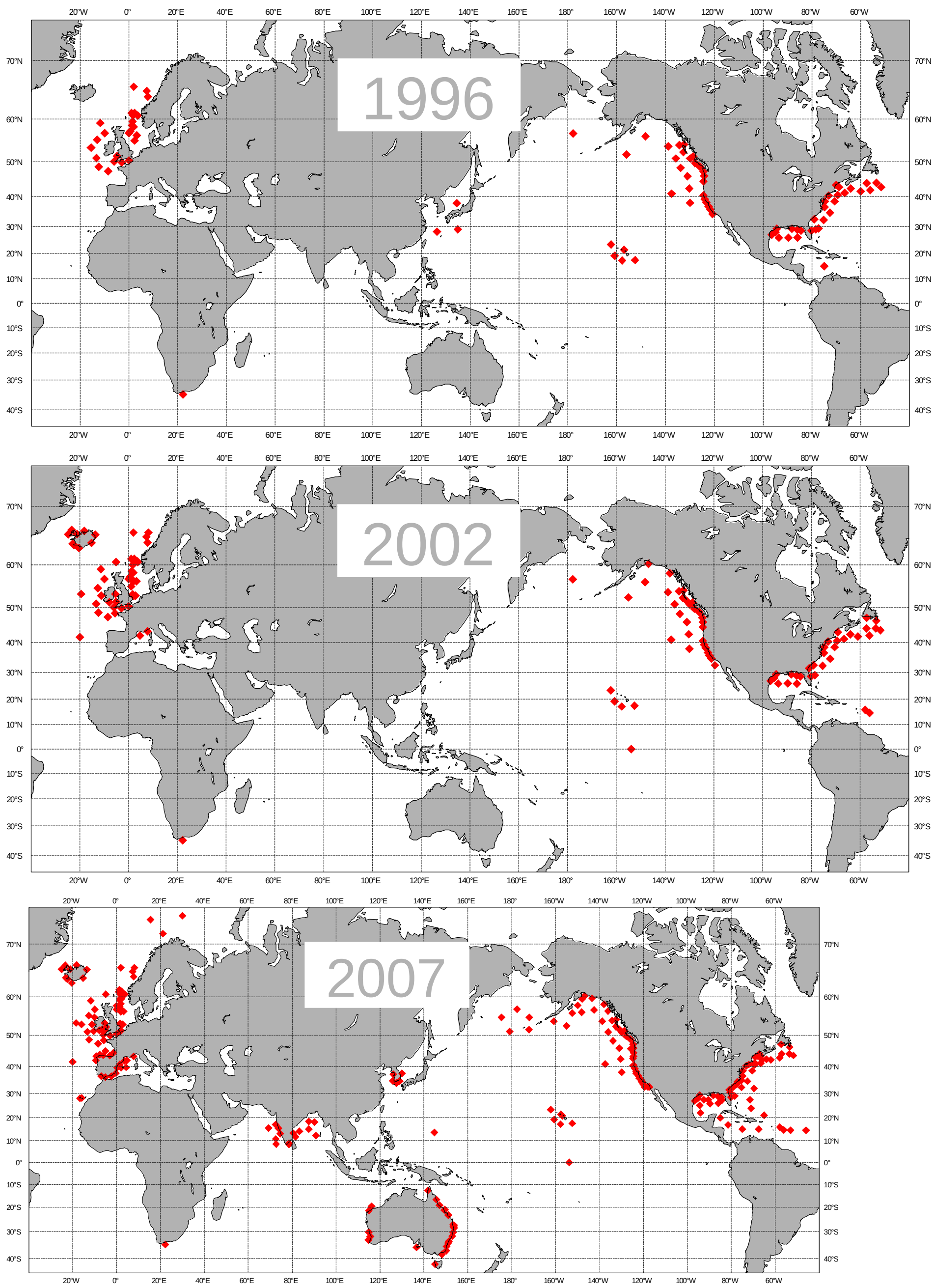


Figure 1: Locations where wind and wave data were collocated with the ECMWF model in 1996, 2002 and 2007. Most data were obtained via the GTS, except for data around Spain, Australia and the Barents Sea (see text).

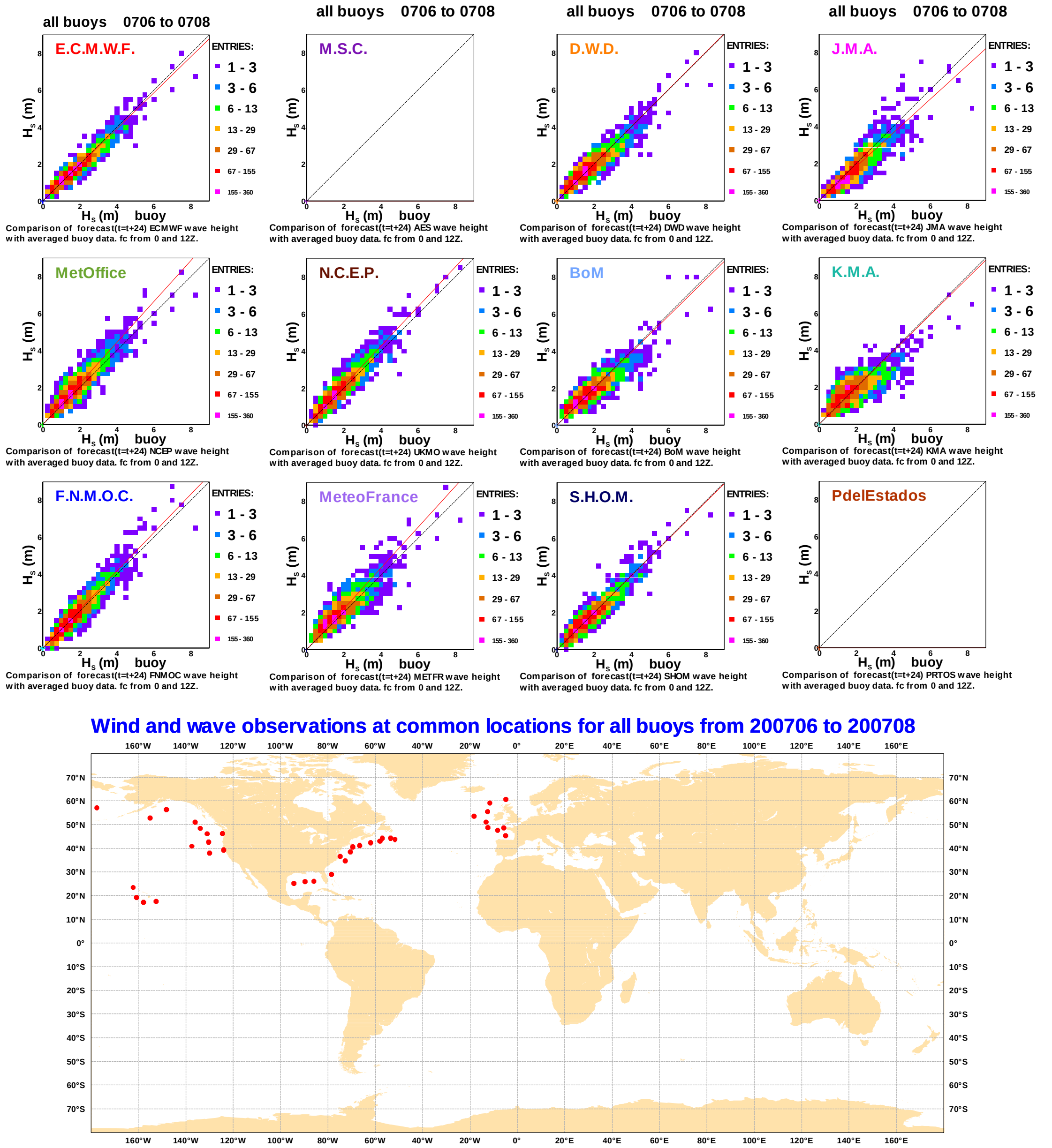


Figure 2: Scatter diagrams for the day 1 wave height forecasts at all common active buoys as shown on the map above from June to August 2007. Only global models are used.

Table 1: Wave height statistics corresponding to Figure 2:

N=2456	ECMWF	MetO	FNMOC	NCEP	MF	DWD	BoM	SHOM	JMA	KMA
SI (%)	15.1	21.0	19.2	18.6	23.1	20.2	22.6	18.0	20.9	30.5
Bias (m)	-0.02	0.20	0.04	0.11	0.22	0.04	0.03	0.00	-0.18	0.05
CC	0.95	0.92	0.94	0.94	0.89	0.92	0.89	0.93	0.91	0.79
RMSE (m)	0.25	0.40	0.32	0.33	0.44	0.34	0.38	0.30	0.40	0.50

Table 2: Forecast day 1 wind speed statistics for the same period as in Figure 2:

N=3250	ECMWF	MetO	FNMOC	NCEP	MF	DWD	BoM	SHOM	JMA	KMA
SI (%)	22.5	23.2	26.1	27.9	24.9	25.0	27.8	22.2	25.9	31.0
Bias (m/s)	-0.03	0.23	-0.14	0.23	-0.41	-0.01	0.11	-0.06	0.13	-0.44
CC	0.87	0.87	0.82	0.81	0.84	0.83	0.81	0.87	0.84	0.74
RMSE (m/s)	1.43	1.49	1.67	1.79	1.63	1.59	1.77	1.41	1.65	2.02

Table 3: Forecast day 1 peak period statistics for the same period as in Figure 2:

N=2750	ECMWF	MetO	FNMOC	NCEP	MF	DWD	BoM	SHOM	JMA	KMA
SI (%)	26.8	44.8	31.5	24.5	----	----	40.1	36.9	----	----
Bias (s)	0.40	1.65	-0.21	-0.66	----	----	0.68	1.14	----	----
CC	0.63	0.40	0.54	0.65	----	----	0.34	0.51	----	----
RMSE (s)	2.18	3.94	2.53	2.06	----	----	3.27	3.16	----	----

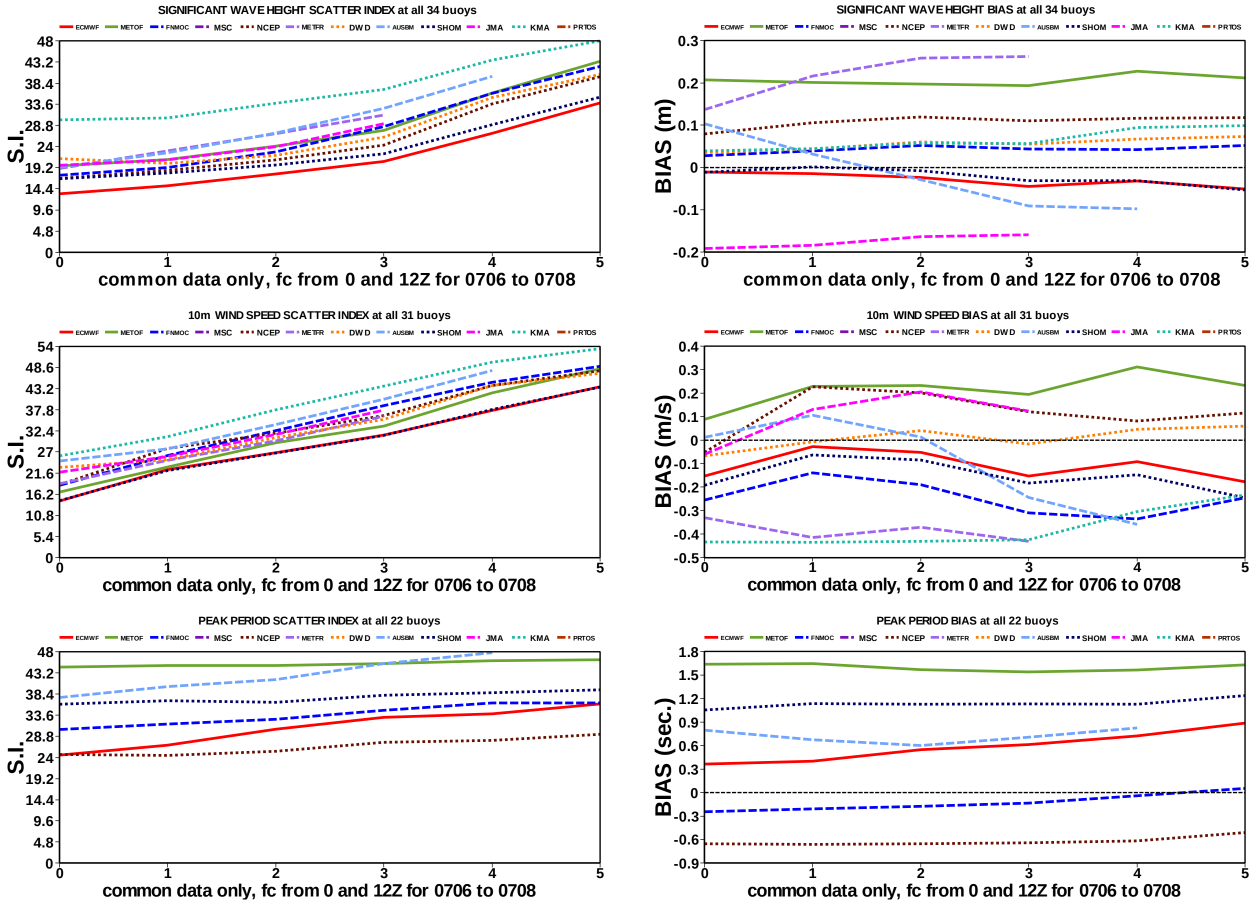


Figure 3: Forecast scores in terms of scatter index (left panels) and bias (model-buoy) (right panels) for wave height (top panels), wind speed (middle panels) and peak period (bottom panels) for all common active buoys as shown in Figure 2 for June to August 2007. Only global models are shown. Not all participants provide peak periods.

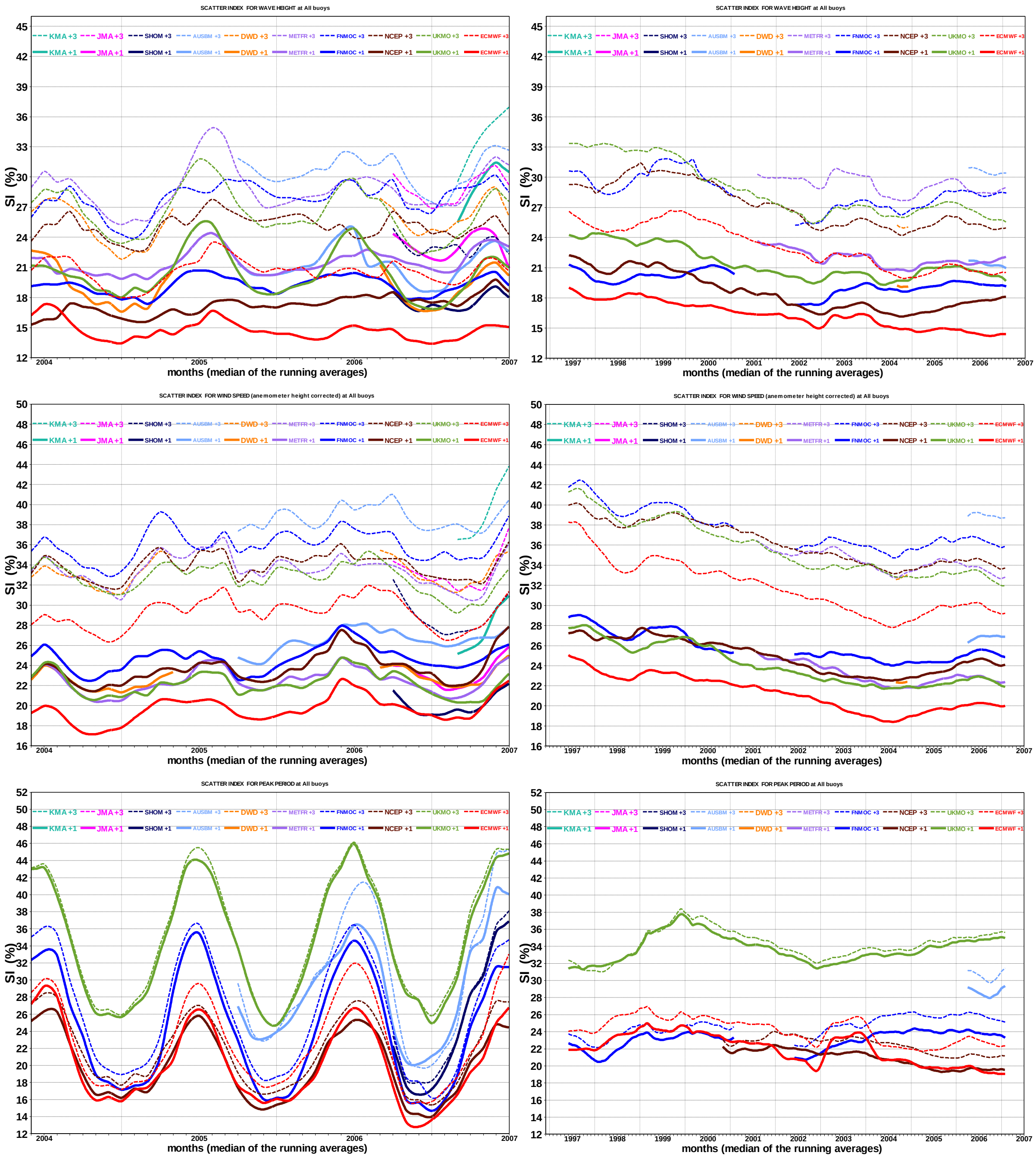
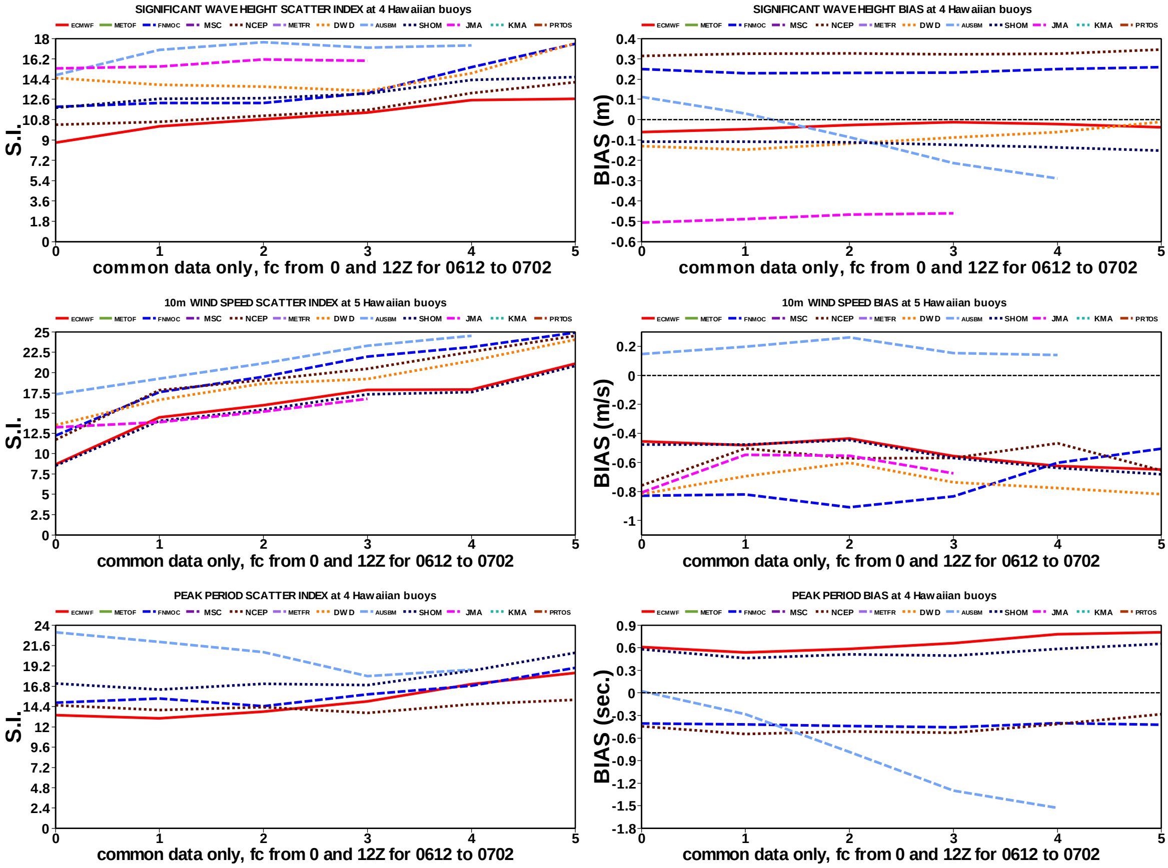


Figure 4: Scatter index time series for wave height (top panels), wind speed (middle panels) and peak period (bottom panels) for all buoys common to 10 centres with a global model (when available). Thick solid lines are used to display day one scores and thin dashed lines correspond to day 3 statistics. For clarity, a 3 month running average of the statistics was used to display the data on the left (recent period when all 10 centres contributed data) and a 12 months running mean of the 3 month running average was used to display longer time series on the right (since Dec. 1996). Note that buoy data coverage has changed over time. Not all participants provide peak periods. FNMOC did not provide data for a few months in 2001 and DWD interrupted data dissemination for over a year in 2005-2006.



Number of common observations for Hawaiian buoys (HW) from 200612 to 200702 (wind, Hs, Tp)

1	51001	155	155	155	Hawaii North West		4	51004	155	136	136	Hawaii South East
2	51002	152	152	154	Hawaii South West		5	51028	153	0	0	Christmas Island DWA
3	51003	74	74	75	Hawaii West							

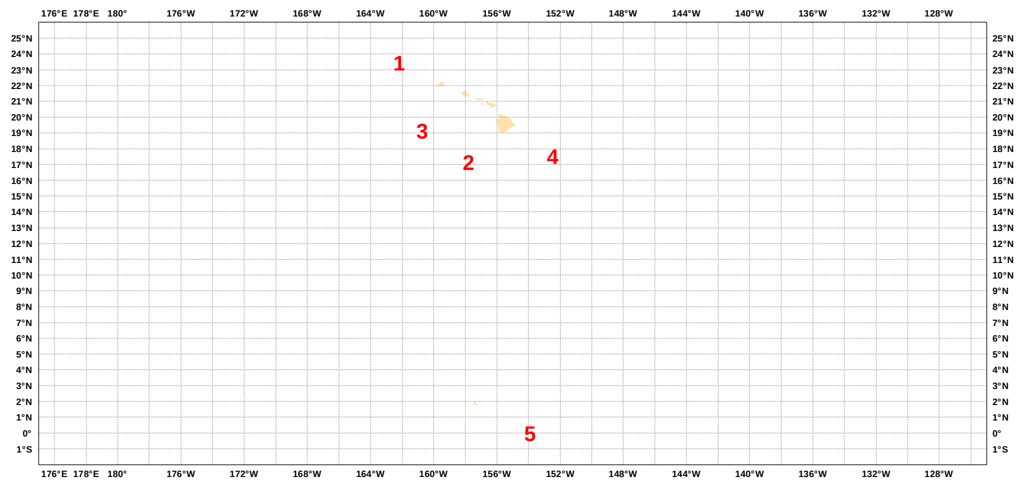
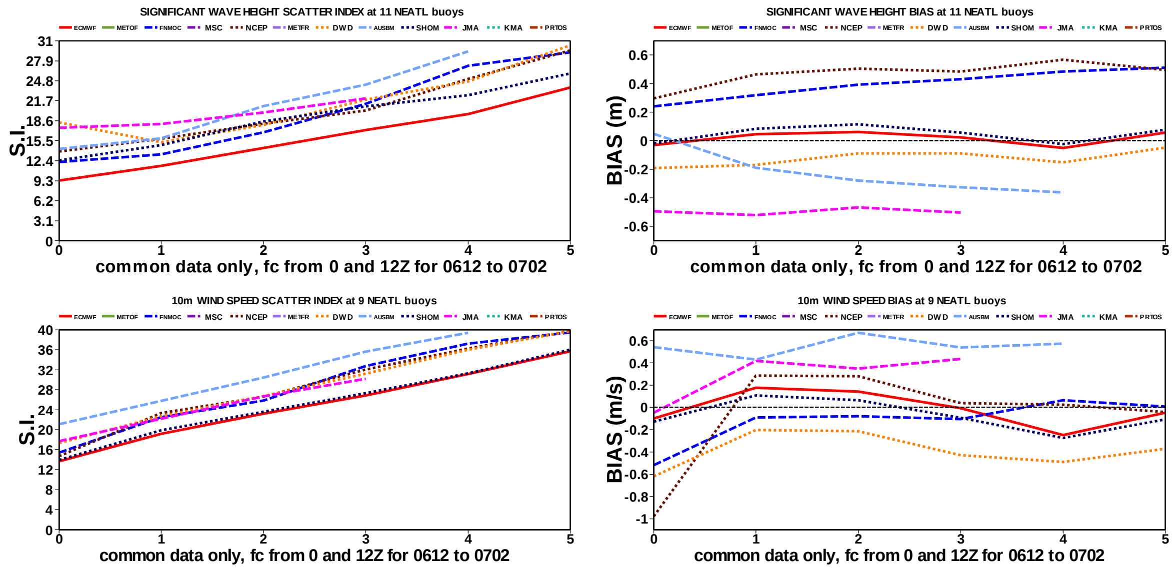


Figure 5: Forecast scores in terms of scatter index (left panels) and bias (model-buoy) (right panels) for wave height (top panels), wind speed (middle panels) and peak period (bottom panels) for all common active buoys from the second list in and around Hawaii as shown on the map for December 2006 to February 2007. Only global models, excluding the metoffice, Météo France and KMA, are shown. The table on top of the map gives the number of collocations at each buoy for wind speed, wave height (Hs) and peak period (Tp).



Number of common observations for North East Atlantic buoys (NEATL) from 200612 to 200702 (wind, Hs, Tp)

1	62001	155	155	0	Gulf of Biscay, Gascogne	7	62107	154	154	0	Isle of Scilly (7 stones)
2	62029	155	155	0	UK Celtic Sea shelf break (K1)	8	62108	3	97	0	UK East Atlantic (K3)
3	62052	80	64	0	CETMEF Ouessant (Brest)	9	62163	155	155	0	UK Celtic Sea shelf break (Brittany)
4	62081	75	145	0	UK East Atlantic (K2)	10	64045	133	136	0	UK North-East Atlantic (K5)
5	62090	150	154	0	West Ireland (M1), Aran Islands	11	64046	0	149	0	UK North-East Atlantic (K7)
6	62105	0	155	0	UK East Atlantic (K4)						

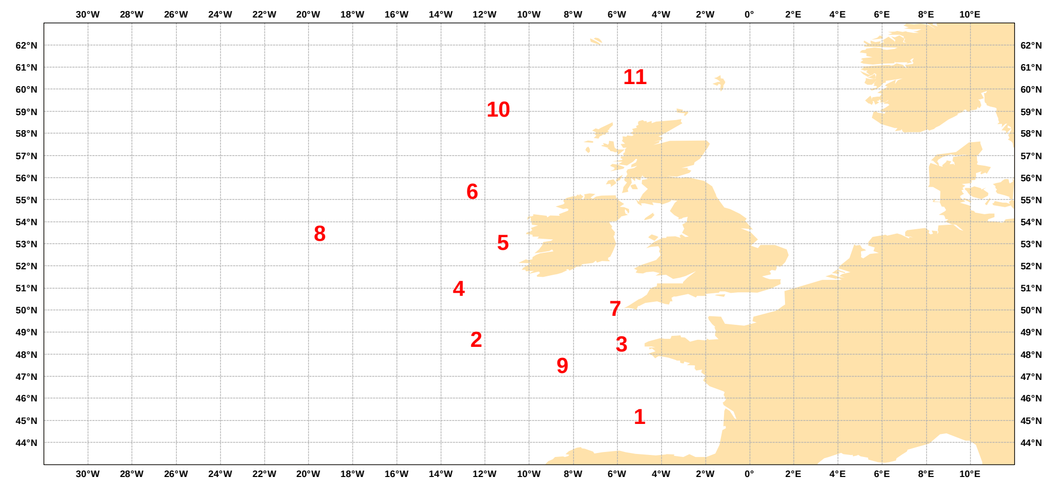
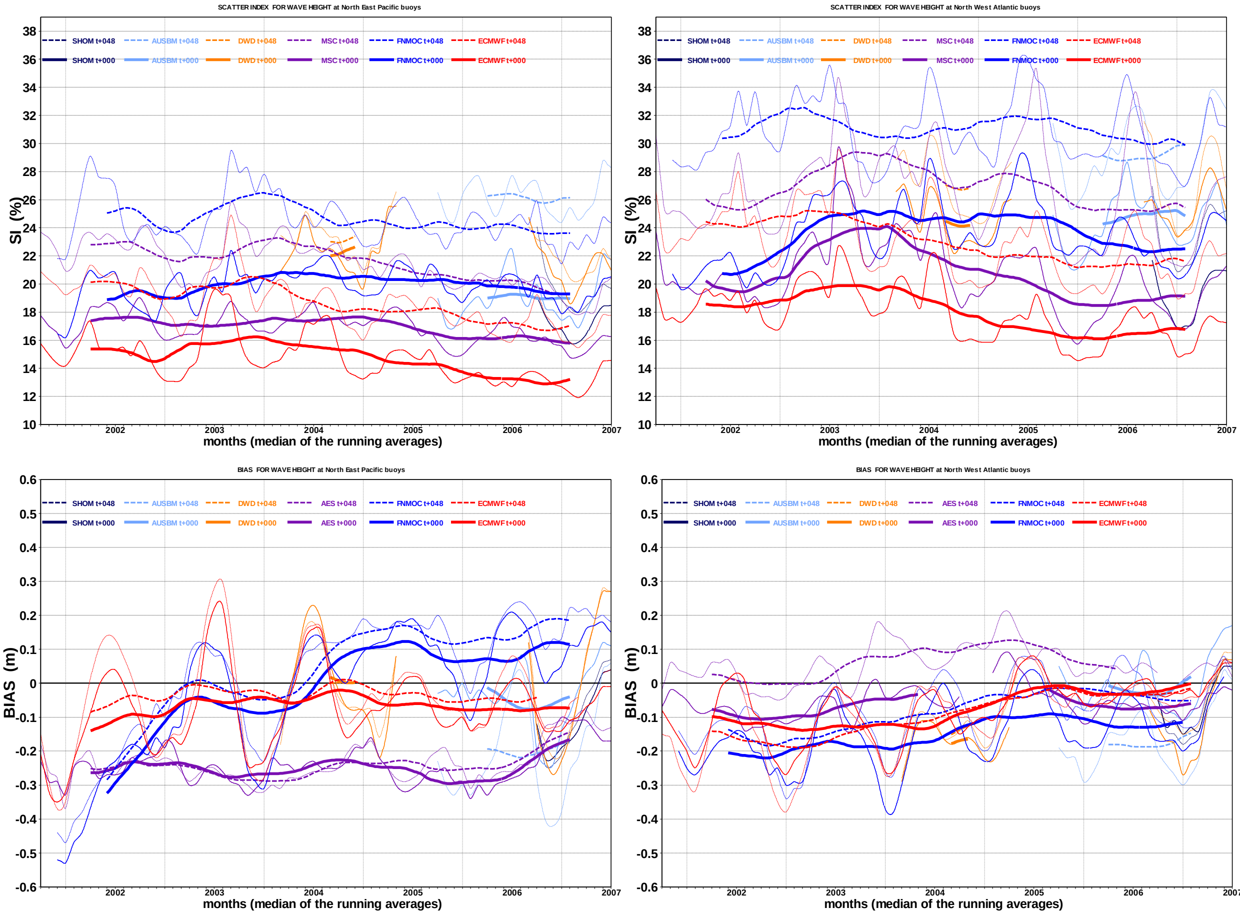


Figure 6: Forecast scores in terms of scatter index (left panels) and bias (model-buoy) (right panels) for wave height (top panels), wind speed (middle panels) and peak period (bottom panels) for all common active buoys from the second list as shown in the North East Atlantic area (British, Irish and French buoys) as shown on the map for December 2006 to February 2007. Global models, excluding the metoffice, Météo France and KMA, are shown. The table on top of the map gives the number of collocations at each buoy for wind speed, wave height (Hs) and peak period (Tp).



Number of common observations for North East Pacific buoys (NEPAC) from 200706 to 200708 (wind, Hs, Tp)

1	46001	40	40	40	Gulf of Alaska	12	46042	179	178	178	US South-West Coast, Monterey
2	46002	123	152	152	US West Coast,Oregon	13	46050	180	180	180	US West Coast, Yaquina Bay
3	46004	180	171	171	Canada West Coast, Middle Nomad	14	46059	180	180	180	US West Coast, California
4	46005	180	180	180	US North-West Coast, W Astoria	15	46066	180	180	180	Gulf of Alaska, S Aleutians
5	46006	34	28	28	US West Coast, SW Astoria	16	46083	165	167	167	Gulf of Alaska, Fairweather Grounds
6	46013	146	179	179	US South-West Coast, Bodega	17	46132	154	154	154	Canada West Coast, South Brooks
7	46014	100	100	100	US South-West Coast, Point Arena	18	46147	180	180	180	Canada West Coast, South Moresby
8	46023	180	180	180	US South-West Coast, Point Arguello	19	46205	170	161	161	Canada West Coast, W. Dixon Entrance
9	46029	163	180	180	US West Coast, Columbia River Bar	20	46206	152	152	152	Canada West Coast, La Perouse Bank
10	46035	6	6	6	Bering Sea	21	46207	157	157	157	Canada West Coast, East Dellwood
11	46036	180	177	177	Canada West Coast, South Nomad	22	46208	178	175	175	Canada West Coast, West Moresby

Number of common observations for North West Atlantic buoys (NWATL) from 200706 to 200708 (wind, Hs, Tp)

1	41001	178	177	177	US East Coast, E Hatteras	10	44025	0	179	179	US North East Coast, Long Island
2	41004	101	100	100	US South-East Coast, Edisto	11	44137	178	118	118	Nova Scotia, East Scotia slope
3	41010	178	179	179	US East Florida , Cape Canaveral East	12	44138	64	178	178	Newfoundland, SW Grand Bank
4	44004	180	179	179	US North East Coast, Hotel	13	44139	178	177	177	Newfoundland, Banquerau
5	44005	55	129	129	US North East Coast, Gulf of Maine	14	44140	179	117	117	Newfoundland, Tail Of The Bank
6	44008	180	180	180	US North-East Coast, Nantucket	15	44141	180	180	180	Nova Scotia, Laurentian Fan
7	44009	180	179	179	US North-East Coast, Delaware bay	16	44251	71	143	143	Newfoundland, Nickerson Bank
8	44011	180	180	180	US North-East Coast, Georges Bank	17	44255	180	179	0	Newfoundland, NE Bugeo Bank
9	44014	179	176	176	US East Coast, Virginia Beach						

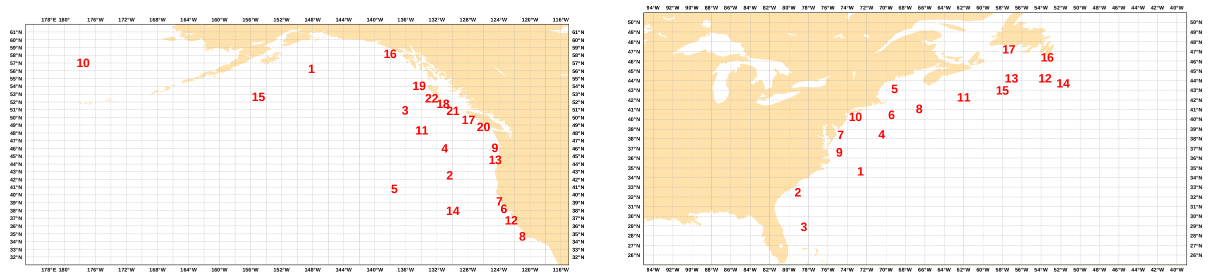
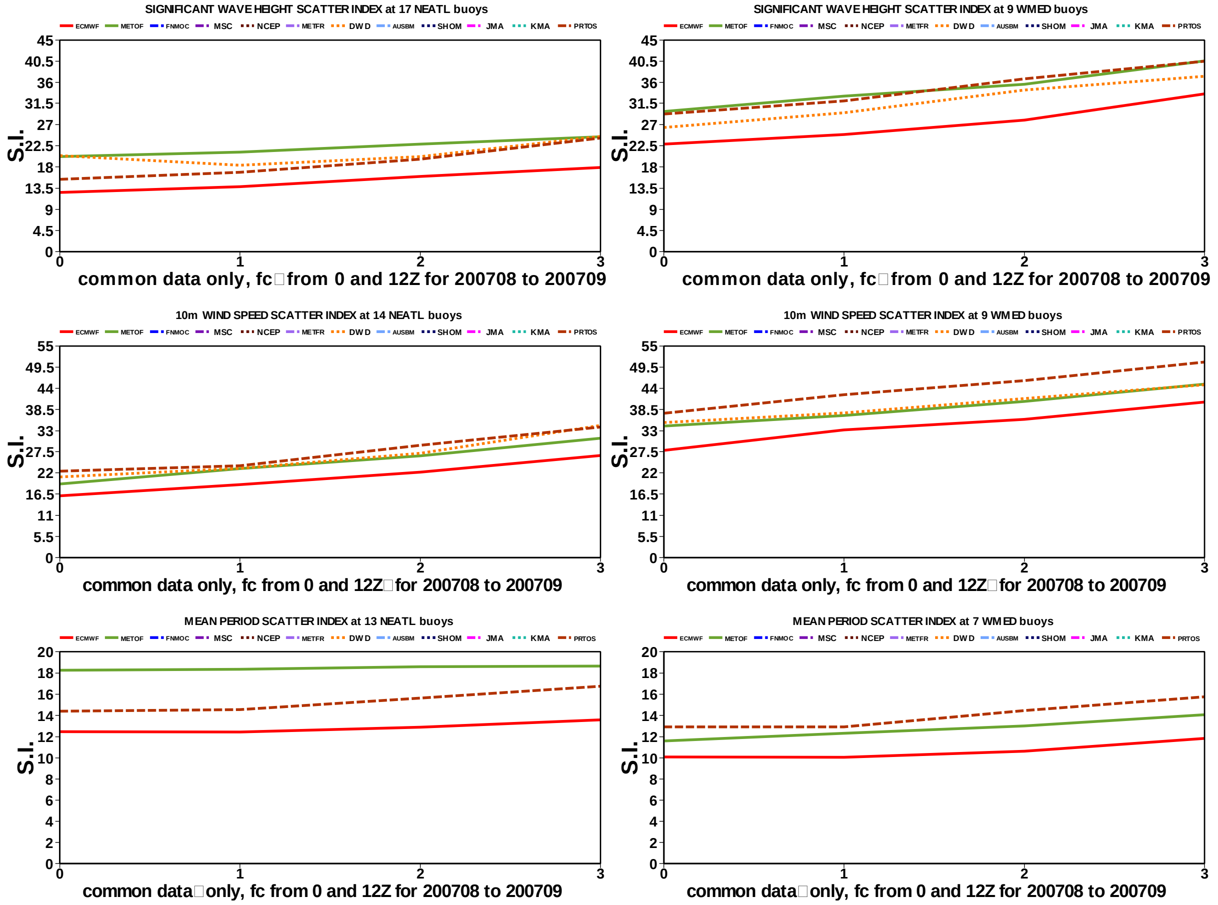


Figure 7: Time series of scatter index (top panels) and bias (bottom panels) since 2001 for wave height for all buoys common to ECMWF, FNMOC, MSC, DWD, BoM and SHOM (when available). Thick lines are used to display day one scores and thin lines correspond to day 2 statistics. A 3 month running average of the statistics was used to display the data and a 12 months running mean of the 3 month running average is overlaid. All common buoys in the North East Pacific (left) and in the North West Atlantic were used (right) as shown in the attached maps. The tables on top of the maps give the number of collocations at each buoy for wind speed, wave height (Hs) and peak period (Tp).



Number of common observations for North East Atlantic buoys (NEATL) from 200708 to 200709 (wind, Hs, Tz)

1	62001	118	118	0	Gulf of Biscay, Gascogne		10	62084	115	115	115	Silleiro Spain)
2	62024	65	115	115	Bilbao (Spain)		11	62090	1	0	0	West Ireland (M1), Aran Islands
3	62025	115	115	115	Cabo de Penas (Spain)		12	62092	118	118	118	South West Ireland (M3), Mizen Head
4	62029	168	168	0	UK Celtic Sea shelf break (K1)		13	62095	118	118	0	West Ireland (M6), West Coast
5	62052	113	118	0	CETMEF Ouessant (Brest)		14	62105	0	134	117	UK East Atlantic (K4)
6	62064	0	117	117	SHOM (Cape Ferret)		15	62107	118	118	118	Isle of Scilly (7 stones)
7	62081	169	169	117	UK East Atlantic (K2)		16	62108	0	168	118	UK East Atlantic (K3)
8	62082	94	94	94	Estaca de Bares (Spain)		17	62163	69	118	118	UK Celtic Sea shelf break (Brittany)
9	62083	89	89	89	Villano-Sisargas (Spain)		18	64045	0	118	118	UK North-East Atlantic (K5)

Number of common observations for Western Mediterranean Sea (WMED) from 200708 to 200709 (wind, Hs, Tz)

1	61001	108	116	0	Ligurian Sea (Cote d'Azure)	6	61280	114	14	14	Tarragona (Spain)
2	61002	115	115	0	Gulf of Lion	7	61281	91	91	91	Valencia (Spain)
3	61196	97	114	114	Begur (Spain)	8	61417	114	114	114	Cabo de Palos (Spain)
4	61197	53	53	53	Mahon (Spain)	9	61430	114	111	111	Dragonera (Spain)
5	61198	113	114	114	Cabo Gata (Spain)						

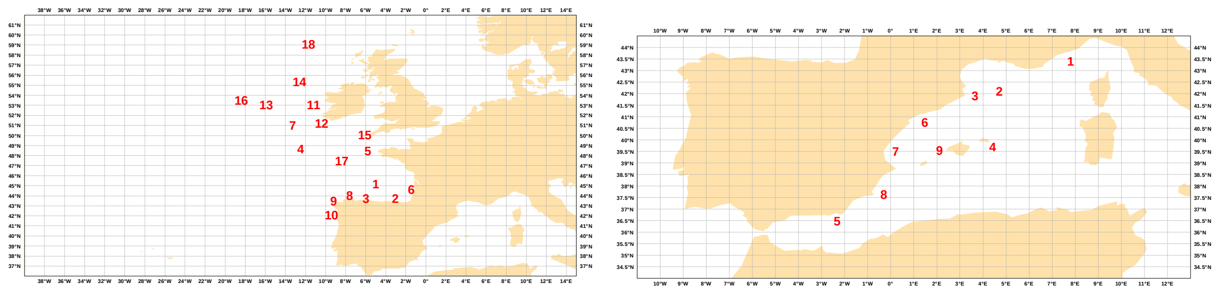


Figure 8: Forecast scores in terms of scatter index for wave height (top panels), wind speed (middle panels) and mean wave period (bottom panels) for all common active buoys to ECMWF, the metoffice, DWD and Puertos del Estado for European Atlantic buoys (left hand side) and western Mediterranean buoys (right) as shown on the map for August and September 2007. The tables on top of the maps give the number of collocations at each buoy for wind speed, wave height (Hs) and mean wave period (Tz).

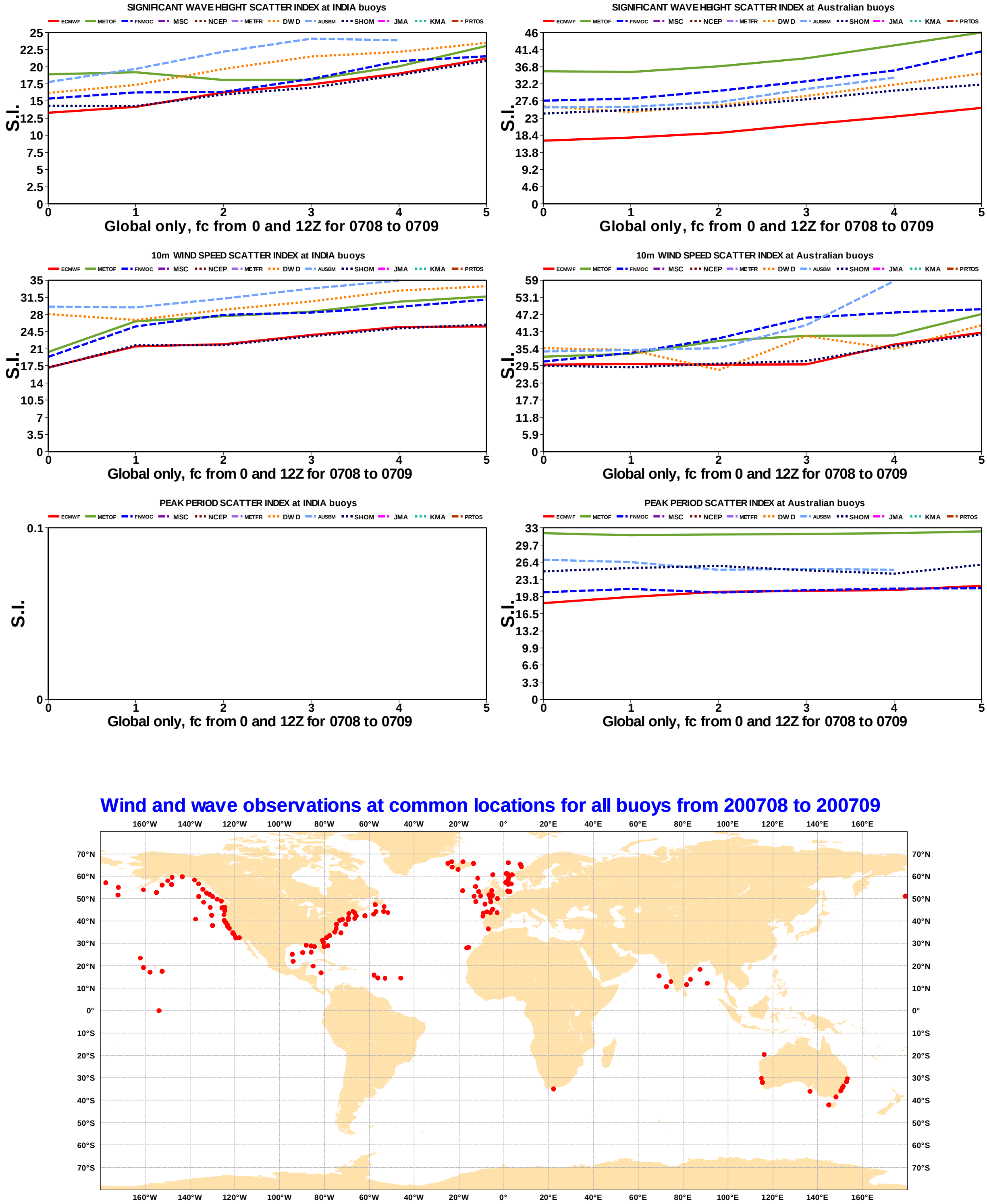


Figure 9: Forecast scores in terms of scatter index for wave height (top panels), wind speed (middle panels) and peak period (bottom panels) for all common active buoys to ECMWF, the metoffice, FNMOC, DWD, BoM and SHOM for all Indian buoys (left hand side) and all Australian buoys for August and September 2007. The map shows all common locations of the latest list, including data from around India and Australia. Peak periods are not available for the Indian buoys. Only one Australian buoy reports wind speed.

Acknowledgments

Without easy access to wind and wave observations such continued work would not be possible. We would like to thank all data providers in their effort to supply data on the GTS. We would also want to thank Ian Hunter from the South African Weather Service for his effort in providing data from platform ZSWAV. Similarly, Oceanor has to be commended for his Barents Sea data that are easily available on their web pages.

References

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 Engineers. http://www.jcomm-services.org/modules/documents/documents/waves97_proceeding.pdf

Bidlot J.-R., D. J. Holmes, P. A. Wittmann, R. Lalbeharry, H. S. Chen, 2002: Intercomparison of the performance of operational ocean wave forecasting systems with buoy data. *Wea. Forecasting*, **17**, 287-310.

Bidlot J.-R. and M.W. Holt, 2006: Verification of operational global and regional wave forecasting systems against measurements from moored buoys. JCOMM Technical Report, 30. WMO/TDNo.1333. http://www.wmo.ch/pages/prog/amp/mmop/documents/Jcomm-TR/J-TR-30/J-TR-30.pdf

Sætra, Ø. and J.-R. Bidlot, 2004: On the potential benefit of using probabilistic forecast for waves and marine winds based on the ECMWF ensemble prediction system. *Wea. Forecasting*, **19**, 673-689.

Annex:

Model information:

A1 European Centre for Medium range Weather Forecasts (ECMWF):

The wave model is a modified version of WAM, cycle4. It is fully coupled to the global atmospheric model. Altimeter wave height and ASAR data are used in the wave model assimilation.

Information on the atmosphere and wave models
http://www.ecmwf.int/products/forecasts/guide/index.html

Detailed documentations:
http://www.ecmwf.int/research/ifsdocs/

Recent publications:

Janssen, P., 2004: *The interaction of ocean waves and wind*, 300pp. Cambridge Univ. Press, Cambridge, UK.

Janssen P, J.-R. Bidlot, S. Abdalla and H. Hersbach, 2005: Progress in ocean wave forecasting at ECMWF. ECMWF Tech. Memo. **478**. ECMWF, Reading, United Kingdom, 27pp. Available online at: http://www.ecmwf.int/publications/

Bidlot J.-R., P. Janssen, S. Abdalla and H. Hersbach, 2007: A revised formulation of ocean wave dissipation and its model impact. ECMWF Tech. Memo. **509**. ECMWF, Reading, United Kingdom, 27pp. Available online at: http://www.ecmwf.int/publications/

Richardson, D. J. Bidlot, R. Buizza, L. Ferranti, A. Ghelli, G. van der Grijn and E. Zsoter, 2006: Verification statistics and evaluations of ECMWF forecasts in 2005-2006. ECMWF Tech. Memo. **504**. ECMWF, Reading, United Kingdom, 44pp. Available online at: http://www.ecmwf.int/publications/

A2 The Met Office (MO):

A web link with details of the system is
http://www.metoffice.gov.uk/research/ncof/wave/index.html

Relevant publication:

Golding, B., 1983: A wave prediction system for real-time sea-state forecasting. *Quarterly Journal Royal Meteorological Society*, **109**, 393-416.

A3 Fleet Numerical Meteorology and Oceanography Centre (FNMOC):

General information can be found at:
http://www.nrlmry.navy.mil/atcf_web/wavewatch/ww3.html

A4 Meteorological Service of Canada (MSC):

http://www.weatheroffice.gc.ca/model_forecast/wave_e.html

Useful references:

Lalbeharry, R., S. Desjardins, H. Ritchie, A. Macafee and L. Wilson, 2005: Wave simulation of hurricanes using blended winds from a parametric hurricane wind model and the CMC weather prediction model. Proc. 5th Intl. Symposium on Ocean Wave Measurement and Analysis. Madrid, Spain, 3-7 July 2005.

Lalbeharry, Roop, 2002: Evaluation of the CMC regional wave forecasting system against buoy data. *Atmosphere-Ocean*, **40**(1), 1-20.

Lalbeharry, R., J. Mailhot, S. Desjardins and L. Wilson, 2000: Examination of the impact of a coupled atmosphere and ocean wave system. Part II: Ocean wave aspects. *J. Phys. Oceanogr.*, **30**, 402-415.

Desjardins, S., J. Mailhot and R. Lalbeharry, 2000: Examination of the impact of a coupled atmosphere and ocean wave system. Part I: Atmospheric aspects. *J. Phys. Oceanogr*., **30**, 385-401.

A5 National Centers for Environmental Prediction (NCEP):

http://polar.ncep.noaa.gov/waves/

Recent publications:

Tolman, H. L., B. Balasubramaniyan, L. D. Burroughs, D. V. Chalikov, Y. Y. Chao, H. S. Chen, and V. M. Gerald, 2002: Development and implementation of wind generated ocean surface wave models at NCEP. *Weather and Forecasting*, **17**, 311-333.

Tolman, H. L., 2002: Alleviating the Garden Sprinkler Effect in wind wave models. *Ocean Modelling*, **4**, 269-289.

Tolman, H. L., 2003: Treatment of unresolved islands and ice in wind wave models. *Ocean Modelling*, **5**, 219-231.

Chao, Y. Y., J. H. G. M. Alves and H. L. Tolman, 2005: An operational system for predicting hurricane-generated wind waves in the North Atlantic Ocean. *Weather and Forecasting*, **20**, 652-671.

A6 Météo France (MF):

No web link in English

The system used in this inter-comparison consists of a 2G Global Wave Model at 1° resolution driven by ARPEGE winds (stretched grid). This will change soon – work has started with a 3G model.

MF global wave model considered for this inter-comparison is not used by forecasters over the Pacific and is mainly used to provide boundaries conditions to nested models over the Atlantic because it is driven by winds from ARPEGE model which has a stretched grid with a coarse resolution over the Pacific (up to 1.25°) where many buoys are part of the common data set, and a relatively fine resolution over the Northern Atlantic (0.5° on the average). Moreover, all winds are interpolated over a 1.5° global grid before being used in the wave model grid (1°). The outputs of the nested models (European seas and France) are not yet considered in this inter-comparison.

Useful references:

Fradon B., Hauser D., Lefèvre J.M., 2000: Comparison study of a second-generation and of a third-generation wave prediction model in the context of the SEMAPHORE experiment, *J. Atmos. and Ocean. Technology*, **17**, pp197-214.

Lefèvre J.-M. and Cotton D., 2001:” Ocean Surface Waves”, in Fu L.L and Cazenave, A., Editors, Satellite Altimetry and Earth Sciences”, Academic Press/, International Geophysics Series, Vol 69, 463p.

Hauser D, H. branger, S. Bouffies-Cloché, S. Despiau, W. M. Drennan, H. Dupuis, P. Durand, X. Durrieu de Madron, C. Estournel, L. Eymard, C. Flamant, H. C. Graber, C. Guérin, K. Kahma, G. Lachaud, J.-M. Lefèvre,J. Pelon, H. Petterson, B. Piguet, P. Queffeulou, D. Tailliez, J. Tournadre, and A. Weill : The FETCH Experiment : An overview, J. Geophys. Res., 108 (C3), 8053, doi :10.1029/2001JC001202, 2003.

Skandrani C., J.-M. Lefèvre and P. Queffelou, 2001: "Impact of multi-satellite altimeter data assimilation on wave analysis and forecast", Marine Geodesy, 27: 511-533, 2004.

Courtier P., C. Freydier, J.-F. Geleyn., F. Rabier and M. Rochas, 1991:The ARPEGE project at Météo-France, In ECMWF 1991 Seminar Proceedings: Numerical methods in atmospheric models.

A7 Deutscher Wetterdienst (DWD):

No web link.

The system consists of a 3GWAM-based (cycle 4.0) Global Model (GSM) and two regional models for North sea and Baltic Sea (LSM) and Mediterranean Sea (MSM)

GSM : area: 72°N to 72°S, grid 0.75°, forecast from 00UTC and 12UTC up to 174 hours, Assimilation of altimeter data will soon be implemented LSM : 66°N to 40.5°N spaced by 0.1°, 3.75°W to 30.75°E spaced by 0.167°, 00UTC and 12UTC, 78 hours
MSM : 46°N to 30.25°N, 5.75°W to 36.25°E spaced by 0.25°, 00UTC and 12UTC , 174 hours.

Products are used internally for maritime weather forecasts and ship routing.

A8 Bureau of Meteorology (BoM):

The wave model is a version of WAM4 with some WAM3 physics. Altimeter wave heights are assimilated with spatially varying background errors.

The operational atmosphere and wave forecasting systems are described in NMOC Operations Bulletins:
http://www.bom.gov.au/nmoc/bulletins/nmc_bulletin.shtml

Relevant publications:

Bender, L.C. 1996. Modification of the Physics and Numerics in a Third-Generation Ocean Wave Model, J. Atmos. Oc. Tech., **13**, 726 - 750.

Greenslade, D.J.M. and I.R. Young, 2005: The impact of inhomogenous background errors on a global wave data assimilation system, *J. Atmos. Oc. Sci.*, **10**, No. 2 doi:10.1080/17417530500089666

Greenslade, D.J.M. 2004: Marine Forecasting at the Bureau of Meteorology, In *"The Past, Present and Future of Numerical Modelling": extended abstracts of presentations at the sixteenth annual BMRC Modelling Workshop, 6-9 December 2004*, Melbourne, Australia, November 2004.

Greenslade, D.J.M., E. W. Schulz, J. D. Kepert and G.R. Warren, 2005: The Impact of the Assimilation of Scatterometer Winds on Surface Wind and Wave Forecasts, *J. Atmos. Oc. Sci.*, **10**, No 3, doi:10.1080/17417530600784976

Schulz, E. W., J. D. Kepert, and D. J. M. Greenslade, 2007: An Assessment of Marine Surface Winds from the Australian Bureau of Meteorology Numerical Weather Prediction Systems, *Wea. and Forecasting*, **22**, No. 3, pp 609 - 632.

A9 Service Hydrographique et Océanographique de la Marine (SHOM) :

The wave model is a version of WAVEWATCH III with some WAM4 physics, forced by ECMWF winds. No data are assimilated. Until June 2007 the output provided for this comparison combined only the global 1° and North Atlantic 0.5° domains. As of July 2007, in order to allow a meaningful comparison at the Spanish buoys, the 0.1° Mediterranean grid output is used when and where available.

Thanks to this comparison exercise, and questions from P. A. E. M. Janssen and J. R. Bidlot, errors in the implementation of the ECWAM version of WAM4 have been found. The corrected model, based on version 3.13-beta of WAVEWATCH III is now used as of October 22, 2007. The source term package used will be part of the official 3.14 version of WAVEWATCH III released by NCEP, and activated by the ‘ST3’ switch.

The model set-up used in the present paper is described at:
http://surfouest.free.fr/NYMPHEA/

and its ongoing upgrade is described at:
http://surfouest.free.fr/CAPARMOR/

Model hindcast results can be found at:
ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/wavewatch3/HINDCAST/

Relevant publications:

Ardhuin, F., T. H. C. Herbers, G. Ph. van Vledder, K. P. Watts, R. Jensen et H. Graber, Slanting fetch and swell effects on wind wave growth, *J. Phys. Oceanogr.*, **37**, 908—931.

A10 Japan Meteorological Agency (JMA):

The wave model is the 'MRI-III' which was originally developed at Meteorological Research Institute (Ueno and Kohno, 2004). This model is a third generation wave model in deep water and observed data are not assimilated. The previous version of the MRI-III had been in operation since 1998, but it was replaced by the current version on 30th May 2007. The outline of the operational wave model is described in the following notes (JMA, 2007), and the latest topics are presented in the session 17 (Model improvement) of this workshop.

The operational wave forecast based on model data are available at:
http://www.data.kishou.go.jp/kaiyou/db/wave/chart/fwpn_e.html

Information on the atmosphere and wave models
http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline-nwp/index.htm

Related publications:

Ueno, K. and N. Kohno, 2004: The development of the third generation wave model MRI-III for operational use. *in Proc. 8th Int. Workshop on Wave Hindcasting and Forecasting*, G2, 1-7.
(also available at: http://www.waveworkshop.org/8thWaves/Papers/G2.pdf)

A11 Korea Meteorological Administration (KMA):

General information can be found at

http://web.kma.go.kr/eng/wis/gws_04.jsp

Recent publication:

Park S., Lee D.-U., Seo J.-W., 2007: Operational wind wave prediction system at KMA. Proceedings to the JCOMM Scientific and Technical Symposium on Storm Surges, 2-6 October 2007, Seoul, Republic of Korea.
Available at
http://www.ioc-goos.org/index.php?option=com_oe&task=viewEventDocs&eventID=126

A12 Puertos del Estado (PRTOS):

Modelling effort and observation networks are described at
http://www.puertos.es/en/oceanografia_y_meteorologia/index.html

Recent publication:

M. Gómez Lahoz and J.C. Carretero Albiach, 2005: Wave forecasting at the Spanish coasts. *Journal of Atmospheric and Ocean Science*. **10**, No. 4, December 2005, 389-405.

Catalogue of wave data on the web:

http://www.jcomm-services.org/Wave-and-storm-surge-data.html