Validation of the ECMWF analysis wave data for the area around the Faroe Islands

Samanbering av alduforsøgnum frá ECMWF við aldumátingar gjørdar á føroyaleiðini

Bárður A. Niclasen[1] and Knud Simonsen[2]
Faculty of Science and Technology at the University of the Faroe Islands
P.O. Box 2109, FO-165 Argir, Faroe Islands. Email: [1]bardurn@setur.fo, [2]knuds@setur.fo

Úrtak

Úrslit frá virkandi aldumyndlinum, ið liggur hjá ECMWF, verða her borin saman við aldumátingar, sum eru gjørdar á føroyaleiðini. Fýra tíðarskeið, hvørt ein mánað til longdar, verða nýtt til henda samanburð. Hesi ávísu tíðarskeiðini eru vald, tí tey hava hægstu mátaðu alduhæddir við Føroyar í tíðarskeiðinum 1999-2004.

Myndilin gevur góð úrslit samanborið við mátaðu alduvirðini, men alduhæddin er nakað undirmett, tá ið harðast leikar á. Í miðal er myndlaða alduhæddin eitt sindur betur endurgivin í summartíðarskeiðunum enn í vetrartíðarskeiðunum. Alduskeiðið er í miðal yvirmett, tí myndilin undirmetir alduorkuna hjá teimum hægru tíddunum nakað. Myndlaðu alduróðirnar líkjast nógv teimum mátaðu, tó so, at skjótar broytingar í teimum lægru tíddunum ikki altíð eru endurgivnar í myndlaðu alduróðunum.

Samanumtikið er virkandi myndilin hjá ECMWF førur fyri at endurgeva mátaðu alduna nóg væl, til at hesin myndin hóskar til at reka ein háloystan staðbundnan aldumyndil fyri Føroyar.

Abstract

Results from the limited area wave model running operationally at ECMWF are compared against buoy measurements around the Faroe Islands. The hindcast spans four periods, each of one-month duration, which cover the roughest sea states recorded on the Faroese shelf in the period 1999-2004.

The model results are generally close to the measured values in most inspected parameters, but there is some under-estimation of the peak wave height in the individual storms. A seasonal variation in the model performance is observed with larger negative bias in the predicted wave height in the winter months. A consistent positive bias is observed in the predicted mean wave period in all events and at all locations, indicating a slight underestimation of the high-frequency content of the modelled wave-spectra. Otherwise, the modelled spectra correspond well to the observed spectra, but are found to be slightly smoother in the low frequency range.

Overall, the model is found to give good comparison with measured data, and is therefore a good candidate for providing forcing to a high resolution local wave model.

Introduction

The Faroe Islands are situated in the eastern part of the North Atlantic Ocean. Being close to the common cyclone tracks in the North Atlantic region, the Islands have a windy climate. Intensive cyclone developments frequently give unstable weather, especially in autumn and winter. Due to its location with long fetches, especially in the southwesterly direction, swells play an important role in the local wave conditions. Several regional wave models cover the Faroese area. The existing operational models are, however, not currently able to include the effects of the fine-scale bathymetry and relatively strong tidal currents in the Faroese coastal area.

Here, analysis values from the limited area wave model from the European Centre for Medium-range Weather Forecasts (ECMWF) are validated against measurements on the Faroe Islands and the surrounding waters. The primary emphasis is on validating integrated wave parameters, but some inquiries into the shape of the modelled wave spectrum and the performance of the forcing wind model, are also performed. The purpose of the inquiries is

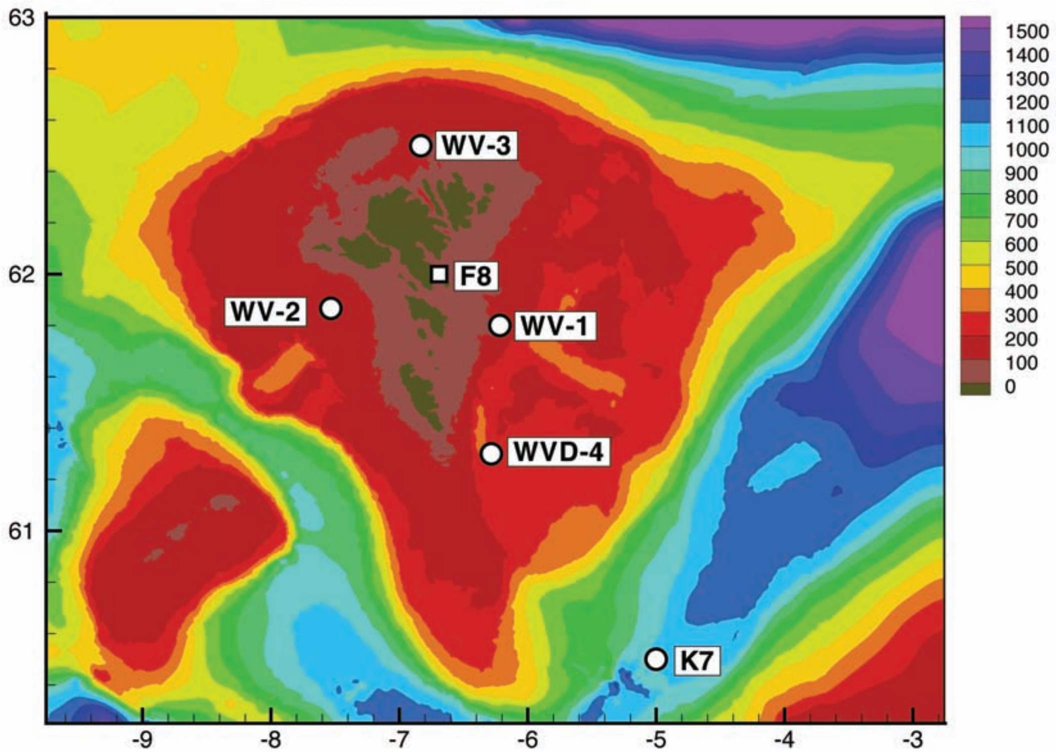

Figure 1. Location of waverider buoy's (WV-1, WV-2, WV-3 and WVD-4), one MetOffice UK buoy measuring meteorological and wave data (K7) and one land based, meteorological station at Glivursnes (F-8). Vertical axis gives degrees North, and horizontal axis gives degrees East. Background colours indicate bottom depth in m.

to verify that the ECMWF wave model (henceforth called EW4) is well suited to provide boundary conditions and forcing for a high-resolution local wave model.

The four periods, which are chosen for this validation, are centred around the largest wave heights, recorded in the deployment time of the directional waverider WVD-4 south of Faroe Islands (Figure 1). Each period spans one month, such that the general skill of the EW4 model can be investigated in average and extreme circumstances.

The ECMWF wave model

The wave model at ECMWF is a slightly adapted version of the WAM cycle 4 model (ECMWF, 2004, Janssen, 2004, Janssen *et al.*, 2005). WAM is a third generation wave model, which solves the wave transport equation explicitly without any ad hoc assumption on the shape of the wave energy spectrum. The basic transport equation in Cartesian co-ordinates is:

$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial x}(c_x F)+\frac{\partial}{\partial y}(c_y F)+\sigma\frac{\partial}{\partial \sigma}(c_\sigma F)+\frac{\partial}{\partial \theta}(c_\theta F)=S_{tot} \quad (1)$$

where $F(\sigma,\theta)$ is the wave energy spectrum, t is time, σ is the intrinsic angular frequency, θ is the wave direction measured clockwise from true north, c_x and c_y are propagation velocities in geographical space, c_σ and c_θ are the propagation velocities in frequency and directional space respectively. If $S_{tot}=0$, Eq. 1 gives the local rate of change of wave energy density due to spatial propagation, and depth induced shoaling and refraction. The effects of currents on the wave transport equation are omitted here as the effects of currents on oceanic scales are usually negligible (Komen *et al.*, 1994).

The right hand side of Eq. 1 represents all effects of generation, dissipation and wave-wave interactions. The total source term can be expressed as $S_{tot}=S_{in}+S_{ds}+S_{nl}$, where S_{in} is the wind input, S_{ds} is the wave dissipation and S_{nl} is the Discrete Interaction Approximation (DIA) to the non-linear quadruplet wave-wave interactions. More detailed information on the WAM model and its source terms can be found in Komen *et al.* (1994).

Direct application of the WAM model to global scales will result in numerical difficulties with the areas close to the poles (as the distance in latitude direction decreases, this causes problems with the CFL-criterion). This problem is solved in the ECMWF-WAM (EW4) model by using an irregular spherical grid, where the distance in latitude direction is more or less fixed to its value at the equator (ECMWF, 2004). As the model results validated here are derived from a regular spherical 0.25° by 0.25° grid as disseminated by ECMWF, some interpolation has been made in the parameter values. The 2D-wave spectra are not interpolated, but set equal to the closest point from the staggered grid (find more information on the ECMWF wave model interpolation schemes on http://www.ecmwf.int).

A weather or sea state forecast is essentially an initial value problem. Given the initial state, the further development in time can be calculated. The problem is, however, that the initial state is never known exactly. To overcome this problem in operational forecasts, the initial state for the forecast is obtained by a combination of the latest forecast and all available new observations. This procedure, where the observations 'push' the initial state towards reality (measurements at the given time), is known as analysis.

The model results validated here are the 6-hourly analysis data from the ECMWF operational archive of the limited area wave model (wave parameters and wind speed) and the atmospheric model (wind). The integrated wave parameters generated by this model (e.g. H_{m0}, T_{m02} etc.) are based on the predicted wave spectrum, with a padded 'diagnostic' f^{-5} tail in the frequencies above the model resolution. The wind speed parameter from the wave model corresponds to the winds that are actually seen by the wave model. In the case of the limited area wave model, it is essentially the same wind as provided by the archived atmospheric model fields, except that the data have been interpolated onto the wave model grid. Therefore it does not contain any values over land points (missing data). When interpolating such field, the closest grid point is used whenever missing data are present; otherwise bi-linear interpolation is used.

Available metocean data

The validation is performed against all suitable buoy data in the region. The non-directional waverider buoys WV-1, WV-2, and WV-3 are part of the Faroese buoy measuring program which was started in 1979 (Davidsen and Hansen, 1981) and are operated by the Office of Public Works (OPW) on the Faroe Islands. The directional waverider buoy, WVD-4, is operated by the company DataQuality, on the behalf of a consortium of oil companies (FOIB). The meteorological buoy K7 (also known as 64046) is operated by the MetOffice UK. Data from the land based meteorological station at F8 are also used. This station is also operated by OPW. Table 1 gives the locations of the measuring sites and the closest respective model points.

The periods of validation (Table 2) are the four months that contain the highest recorded wave heights at WVD-4 site so far. The WVD-4 buoy is chosen as the main reference as this site is less influenced by sheltering and other fine scale features compared to the OPW buoys. The WVD-4 buoy is also the only directional buoy, and the only buoy where the complete data-set (raw data etc.) are made available. Another factor that also might complicate the model comparison at some of the OPW sites is the mooring type used there (Niclasen and Simonsen, 2005b).

		WV-1	WV-2	WV-3	WVD-4	K7	F8
Site	Lat.	61.80˚N	61.87˚N	62.50˚N	61.30˚N	60.50˚N	61.97˚N
	Long.	6.22˚W	7.53˚W	6.83˚W	6.28˚W	4.90˚W	6.75˚W
	Depth	100m	130m	100m	240m	1000m	–
Model	Lat.	61.75˚N	61.75˚N	62.50˚N	61.25˚N	60.50˚N	62.00˚N
	Long.	6.25˚W	7.50˚W	6.75˚W	6.25˚W	5.00˚W	6.75°W

Table 1. Location and depth of the measuring sites and their respective closest model points.

Event number	Start date	End date
1	20/8-2000	20/9-2000
2	15/1-2002	15/2-2002
3	1/6-2002	1/7-2002
4	1/1-2003	1/2-2003

Table 2. Duration of the inspected events

The data from WVD-4 are quality checked for all events by the data provider. On top of this check, different manual inspections of the raw data from the peak of the storms are performed, which resulted in rejection of a few measurements in the January 2003 storm. Data from the other locations are only quality checked by parameter behaviour; that is outliers are removed if they are not supported by several measurements etc.

The time tags connected to measured wave parameter values have been adjusted so they correspond to real-time, rather than completion times of the measured time series (data-burst) which generate the wave spectra.

Wave buoys can only accurately measure waves up to some fixed cut-off frequency f_{high}, and the calculation procedures of the buoys do not add a diagnostic upper frequency tail above f_{high}. For this reason integrated wave parameters, especially those based on higher order momentums of the spectrum (e.g. T_{m02}), are affected by this upper frequency limit of the buoy measuring system. At WVD-4 $f_{high}=0.58$ Hz (Heinesen, 2005), at K7 $f_{high}=0.25$ Hz (Peter Fenna at Met Office UK, pers. com., 2006) and at the OPW buoys f_{high} is estimated to be in the region of 0.5 Hz (Heinesen, 2001).

In order to compensate for the effect of f_{high} on the measured wave parameters, the wave parameters from WVD-4 are recalculated from the measured spectrum padded with an f^{-5} high frequency tail. As the spectra are not available for the OPW buoys or the K7 buoy, it is not possible compensate for the influence of the cut-off frequency on the measured wave parameters from these sites.

In relation to the wave measurements from K7 it ought to be mentioned that the wave height and wave period (labelled H_{m0} and T_{m02} here), are in fact calculated directly from the time series as root-mean-square wave height and zero-crossing wave period T_z, and not from the measured wave spectra as at the other buoys used here. According to the operator, the difference between using the root-mean-square value instead of the wave spectra to compute the wave height has been found to be insignificant (Peter Fenna at Met Office UK, pers. com., 2006). The two wave periods T_{m02} and T_z should in average be directly comparable as they both correspond to the period of the mean wavelength, or alternatively if the wave field is assumed to be a random Gaussian process, then these two periods have been shown to be equal (Rice, 1944; 1945).

Wind measurements are available for comparison from the meteorological station F8 and the K7 buoy. Numerical investigations of stable circumstances suggest that the measured wind speed at the F8 station is on average comparable to the offshore 10-meter wind (Heinesen, 2002). Nevertheless direct comparison of wind-speed time series at F8 must be done with caution as the effects of topography and air/sea temperature gradients are expected to be significant. The wind measured on the K7 buoy is measured at 3 m height and ought to be converted to 10 m height before it is compared to the modelled 10 m wind. Inspection of the temperature gradient between air and sea reveals that the atmospheric stratification is predominantly unstable in all the inspected events. In such circumstances, it requires more information than available to do a proper height conversion. If the conditions had neutral stability, the increase in the wind speed from 3 m to 10 m height would be in the region of 10-15% depending on the roughness length of the sea. The K7 and F8 wind speeds are therefore not used to derive statistical parameters from the performance of the wind model, but only used for visual inspection of possible general trends in the predicted wind speed.

Events

The events chosen for this validation contain the largest observed wave heights recorded so far on the WVD-4 location, and are long enough to give a general impression of the EW4 model performance. The meteorological circumstances leading up to the different storms are linked to the passages of one or several low pressures in the NE Atlantic. The dynamics leading up to the winter storms is quite complex and the reader is referred to analyzed weather charts (e.g. the NCEP reanalyzed weather charts available at http://www.wetterzentrale.de/topkarten/fsreaeur.html). The main observed characteristics of the peak storm events are summarized in Table 3.

From Table 3 it is clear that the observed wave fields at WVD-4 in the summer events (1 and 3) correspond quite well to fully developed wind sea, whereas swells play an important role in the winter events (2 and 4).

	Event 1	Event 2	Event 3	Event 4
Date	8/9 2000	2/2 2002	17/6 2002	15/1 2003
ΔP (hPa/hour)	36/50 at F8	29/36 at F8	12/6 at K7	28/12 at F8
ΔH_{m0} (m/hour)	4.3-10.2/12	4.5-14.1/18	2.8-10.7/8	4.0-11.7/16
Max-wind (m/s)	19 (F8)	20 (F8), 27 (K7)	18 (K7)	8 (F8)
Dir-wind	S to W	W to S to SW	SE to S	SW to N
Max-H_{m0} (m)	10.2	14.1	10.7	11.7
Max-T_p (s)	15.4	20.0	16.7	20.0
PM-T_p (s)	16.0	18.8	16.4	17.1
PM-wind (m/s)	20.3	23.9	20.8	21.8

Table 3. Some general information related to the development of the peak storms in the four events. Date gives the date of the largest observed wave height, ΔP gives the drop in atmospheric pressure, ΔH_{m0} gives the increase in wave height from the beginning to the climax of the particular storm, *Max-wind* gives the maximum observed wind speed, *Dir-wind* gives the observed wind directions throughout the event, *Max-*H_{m0} and *Max-*T_p give the largest observed wave heights and peak periods at WVD-4, *PM-*T_p and *PM-wind* give the peak wave period and wind speed corresponding to the case where the observed wave height at WVD-4 is due to fully developed wind sea.

Validation procedure

The validation will consist of two steps. The first step is the comparison of time series of model-results vs. measurements of relevant parameters and spectra. The second step is the computation of statistical parameters from the fit of the two time series. Time series give a qualitative impression, where the temporal fit of peak events etc. can be inspected. The strength of the statistical parameters is to give objective information on the model performance, which can be used to compare different sites and different time intervals.

As the model results correspond to real-time values (analysis values of the wind/wave model are assimilated to real time data), the measured time series will not be filtered/averaged before comparison with the model results. The statistics are derived from model output at locations as close to the buoy positions as possible. The comparison is made at model output times vs. the closest measurement time. This non-averaged time series comparison is used here as it favours the point of view of the end user, that it exemplifies how well the model replicates the sea state at a particular location at a particular time. The downside of this type of time series comparison, is that it does not take into account the spatial and temporal resolution of the wave model (Bidlot *et al.*, 2002), nor reduce the inherent randomness of wave parameters derived from a point time series.

The wave parameters, which are used for the model validation, are significant wave height H_{m0}, peak wave period T_p and average wave periods T_{m01} and T_{m02}. The average wave period can be defined in many ways and depend on different spectral moments e.g. $T_{m02} = \sqrt{m_0 / m_2}$ where $m_n = \int_0^\infty f^n E(f) df$, f is frequency and $E(f)$ energy spectrum. T_{m02} is more sensitive to the higher 'wind-sea' frequencies, which adjust to the local wind speed much faster than the lower frequencies compared to the alternative mean wave periods. For this reason a higher level of scatter is to be expected in modelled T_{m02} values vs. measurements compared to T_{m01} values vs. measurements.

Statistical parameters

Given a set of N model predicted m and observed o scalar values. If we assume that the measured data are error free, an unrealistic but necessary assumption, the following statistical parameters can be computed: Mean error also known as bias:

$$Bias = \frac{1}{N}\sum_{i=1}^{N}(m_i - o_i) = \overline{m} - \overline{o} \qquad (2)$$

where $\overline{m}$ and $\overline{o}$ represent the mean values of the modelled and observed values. The scatter index, which is the normalized root mean square error, is given as:

$$ScI = \frac{1}{\overline{o}}\sqrt{\frac{\sum_{i=1}^{N}(m_i - o_i)^2}{N}} \qquad (3)$$

Another frequently used parameter to quantify the relation between m and o is the correlation coefficient:

$$Cor = \frac{\sum_{i=1}^{N}(o_i - \overline{o})(m_i - \overline{m})}{\sqrt{\sum_{i=1}^{N}(o_i - \overline{o})^2 \sum_{i=1}^{N}(m_i - \overline{m})^2}} \qquad (4)$$

The last parameter is the skill index (also known as reduction of variance):

$$SkI = 1 - \frac{\sum_{i=1}^{N}(m_i - o_i)^2}{\sum_{i=1}^{N}(\bar{o} - o_i)^2} \quad (5)$$

The bias value is good to reveal general trends in the model performance, that is if the model consistently over- or under-predicts the measurements. It can nevertheless be misleading in cases where both over- and under-estimations occur. The scatter index does not reveal general trends, but is good to evaluate the average model performance. The correlation coefficient is +/-1 if there is a consistent linear relation between *m* and *o*, and 0 if *m* and *o* are independent. If the correlation coefficient is close to one this suggests that there is good correlation between model and data (low random error), but it does not mean that there is no systematic error. The skill index has similar properties as the scatter index, but is included since it in many cases is more sensitive than the scatter index. If there is a good fit between model results and data, then bias and scatter index will tend to zero, whereas the skill index will tend to one. If the skill index is less than zero, this indicates that the measured mean value of a parameter represents the measured time series better than the modelled parameter time series.

Results

The wind series from the K7 (Figure 2) suggest that the ECMWF wind speed is underestimated in the two winter events (2 and 4), whereas the ECMWF wind speed correlates better with measurements in Event 3 (if the modelled values at 10 m height are expected to be 10-15% higher than the measured values at 3 m height). As expected, both wind speed parameters give identical results at this location (K7) since the impact of different interpolations is very small for point away from land. Note also that wind observations from K7 are provided to the atmospheric model assimilation scheme.

The measurements from the F8 station show good correlation to the ECMWF model winds (Figure 3). The clear difference in data-fit between winter and summer events seen in the K7 series is not obvious at F8. The two model parameters give slightly different wind speeds at this location due to the differences introduced by interpolations, but visual inspection of the series does not find one of them superior to the other.

The time series from locations WV-1 and WV-3 (omitted here) show surprisingly good correlation between measured and EW4 wave parameters, considering the coarse resolution of the EW4 model and the often sheltered position of the buoys. The measured time series do nevertheless reveal considerable fluctuations in the wave height, which most probably are due to the mooring issue discussed in Niclasen and Simonsen (2005b). These series are therefore not included in the EW4 validation.

The time series from the WV-2 and K7 buoys show good correlation with the

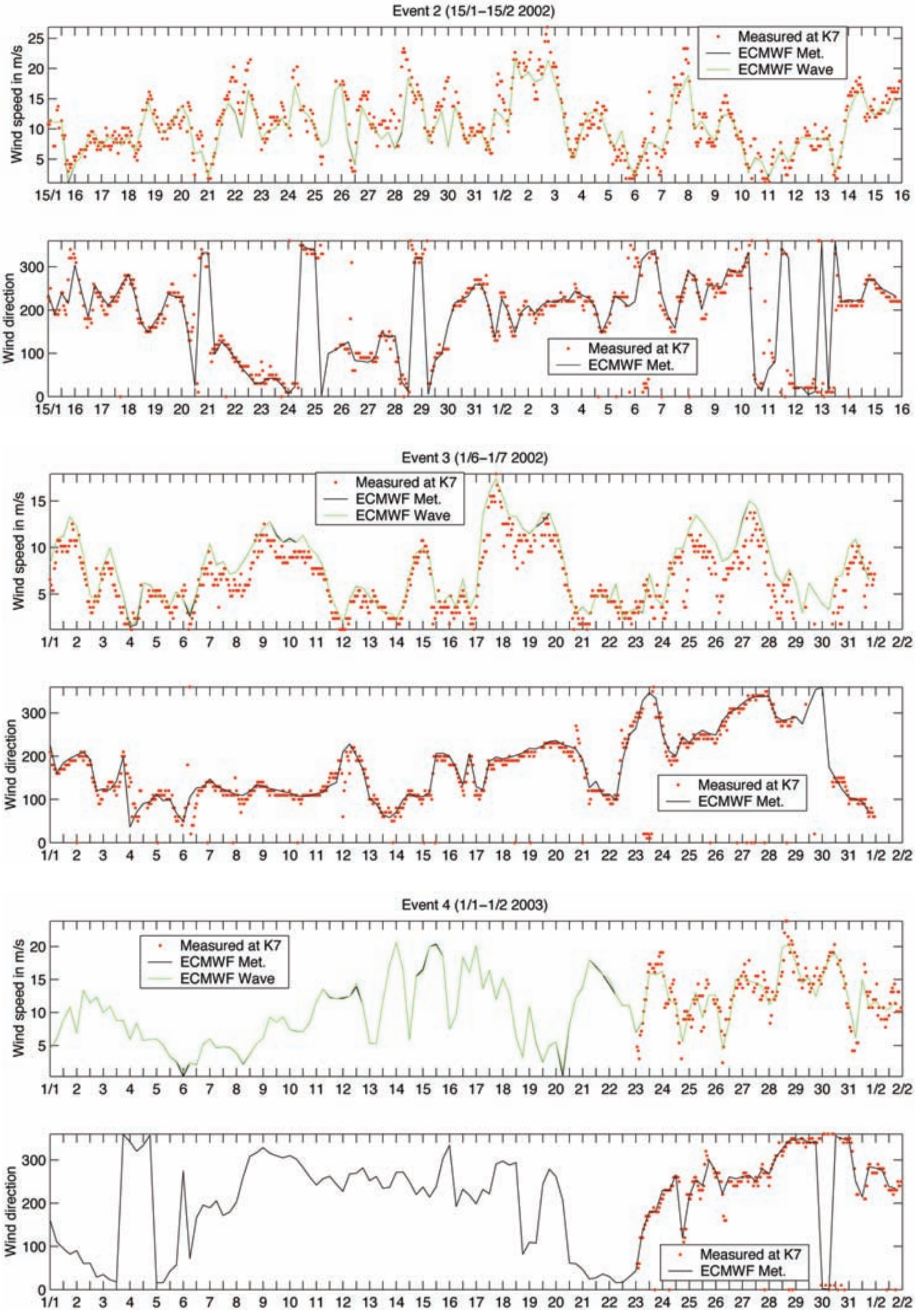

Figure 2. The recorded and predicted wind speed and direction at the MetOffice K7 station for the second, third, and fourth hindcasted periods respectively. Note that the wind observations are not adjusted to 10m.

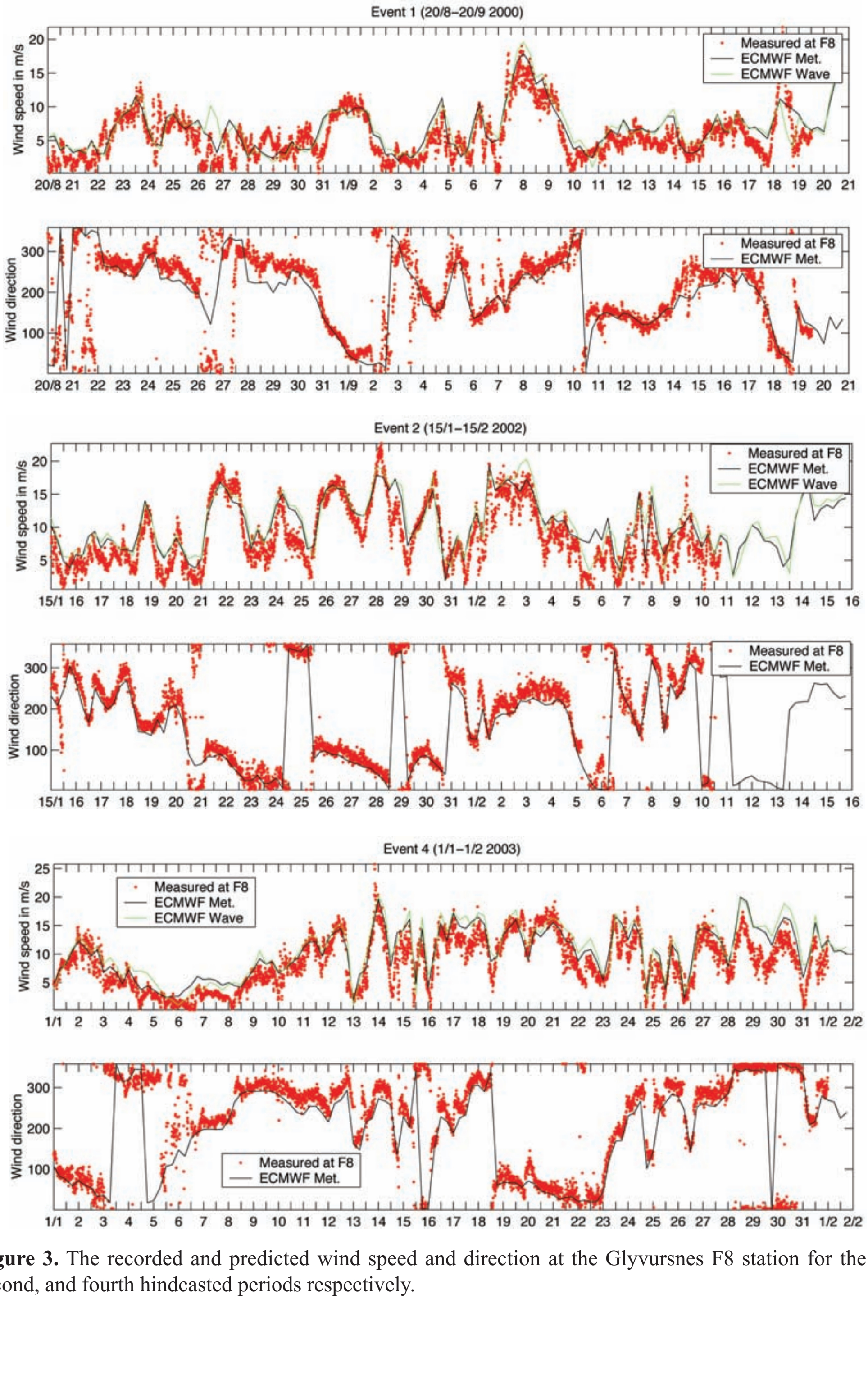

Figure 3. The recorded and predicted wind speed and direction at the Glyvursnes F8 station for the first, second, and fourth hindcasted periods respectively.

Site	Event	Size	DC	Param	Bias	ScI	Cor	SkI
WV-2	1	78	0.61	H_{m0}	0.00	0.19	0.97	0.95
				T_p	1.12	0.21	0.65	0.01
				T_{m02}	0.74	0.23	0.67	0.21
WV-2	3	120	0.97	H_{m0}	-0.09	0.21	0.95	0.89
				T_p	0.94	0.20	0.58	-0.26
				T_{m02}	0.46	0.17	0.63	0.15
WV-2	4	122	0.95	H_{m0}	-0.28	0.19	0.96	0.87
				T_p	1.61	0.19	0.76	-0.07
				T_{m02}	0.67	0.17	0.73	0.23
WVD-4	1	127	0.98	H_{m0}	0.01	0.19	0.96	0.92
				T_p	0.07	0.17	0.65	0.42
				T_{m01}	0.78	0.18	0.78	0.28
				T_{m02}	1.01	0.25	0.71	-0.12
WVD-4	2	117	0.91	H_{m0}	-0.54	0.16	0.91	0.65
				T_p	0.32	0.16	0.69	0.42
				T_{m01}	0.74	0.12	0.84	0.31
				T_{m02}	0.96	0.16	0.77	-0.25
WVD-4	3	124	1.00	H_{m0}	-0.08	0.22	0.94	0.87
				T_p	0.07	0.19	0.55	0.24
				T_{m01}	0.57	0.16	0.74	0.33
				T_{m02}	0.70	0.19	0.69	0.11
WVD-4	4	96	0.75	H_{m0}	-0.57	0.18	0.91	0.72
				T_p	0.07	0.14	0.70	0.36
				T_{m01}	0.40	0.09	0.89	0.68
				T_{m02}	0.57	0.12	0.84	0.47
K7	2	128	1.00	H_{m0}	-0.81	0.22	0.92	0.65
				T_{m02}	-0.20	0.10	0.78	0.56
K7	3	123	0.99	H_{m0}	-0.13	0.15	0.97	0.91
				T_{m02}	-0.10	0.10	0.75	0.51
K7	4	39	0.30	H_{m0}	-0.57	0.14	0.93	0.75
				T_{m02}	-0.34	0.08	0.86	0.66

Table 4. Statistical parameters derived from comparing model values to closest data values. The abbreviations are Event:event number, Size:number of comparison points, DC:data coverage of event, Param:parameter name, Bias:bias between data and model, ScI:Scatter index, Cor:Correlation coefficient, and SkI:Skill index.

EW4 parameters. The time series plots from these sites are omitted as the same observed trends in these series are also visible in the WVD-4 time series.

The clearest difference between the EW4 fit to K7 and WVD-4, is that the underestimation of the wave height in the peak storms is more pronounced at K7. The difference between the EW4 fit to WV-2 and WVD-4, is that an overestimation of the peak period T_p is present at WV-2. This can partly be explained by the fact that the WV-2 site is more sheltered from swell arriving from the ocean North to

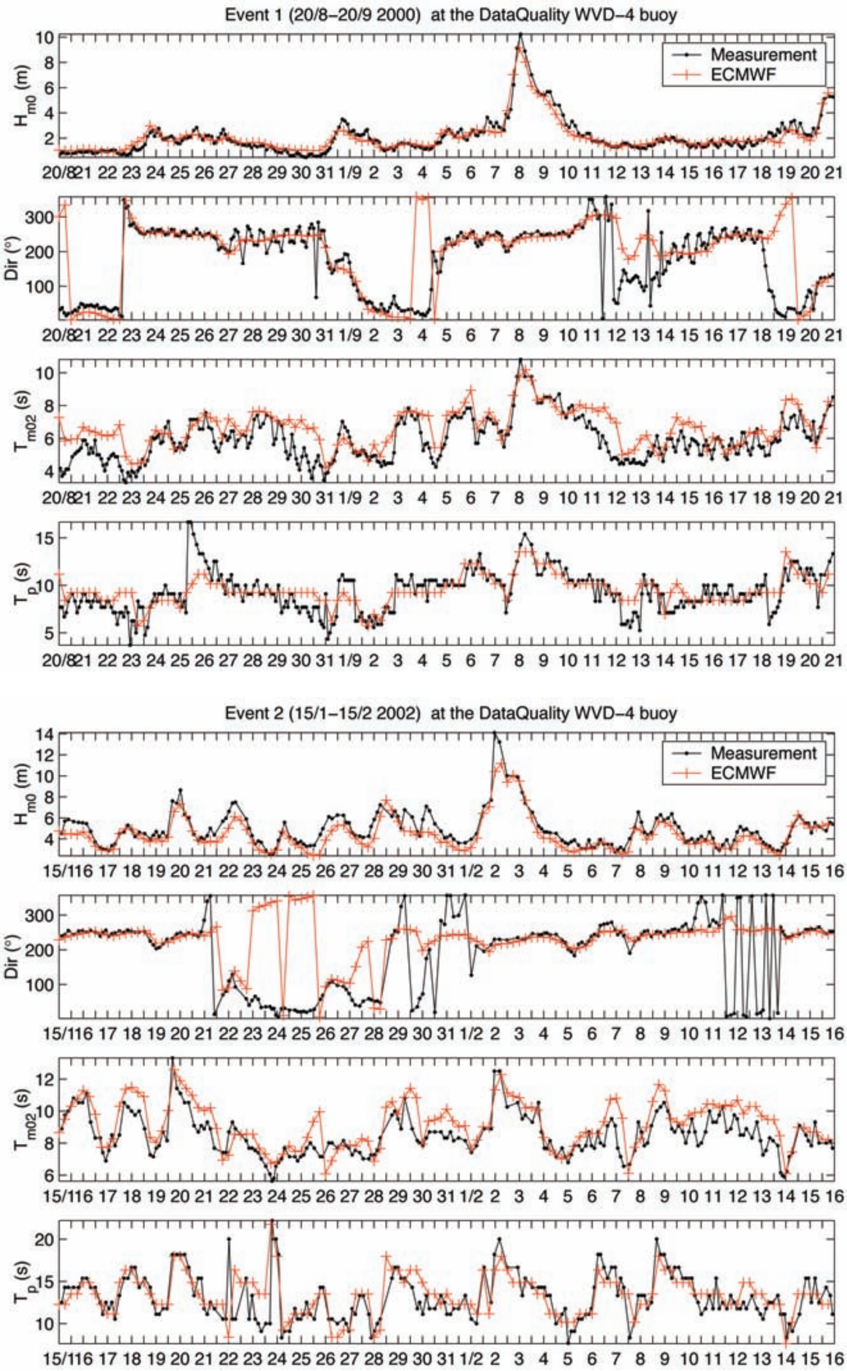

Figure 4. Recorded and predicted wave parameters H_{m0}, *Dir*, T_{m02} and T_p at location WVD-4, for Event 1 and 2 respectively.

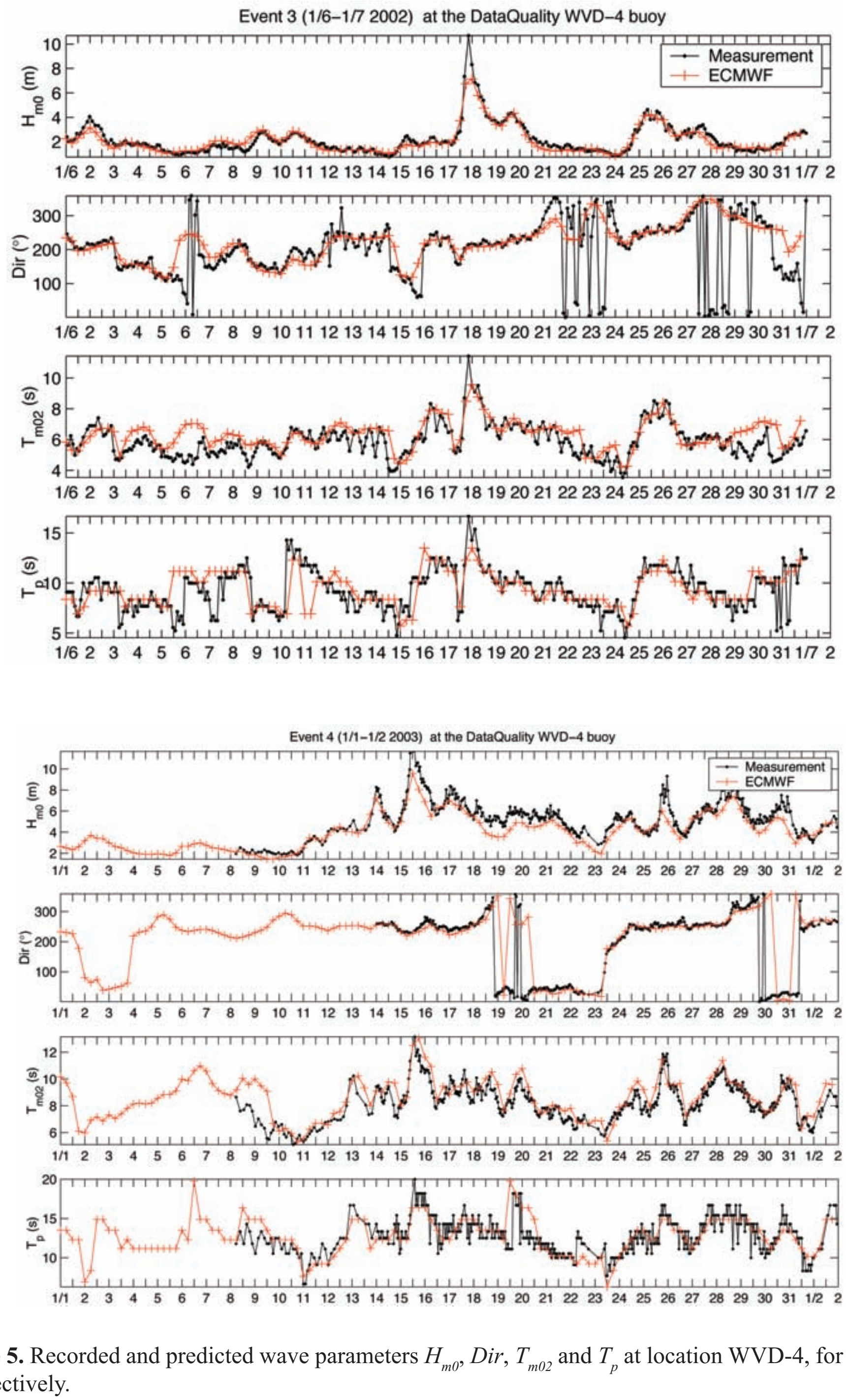

Figure 5. Recorded and predicted wave parameters H_{m0}, Dir, T_{m02} and T_p at location WVD-4, for Event 3 and 4 respectively.

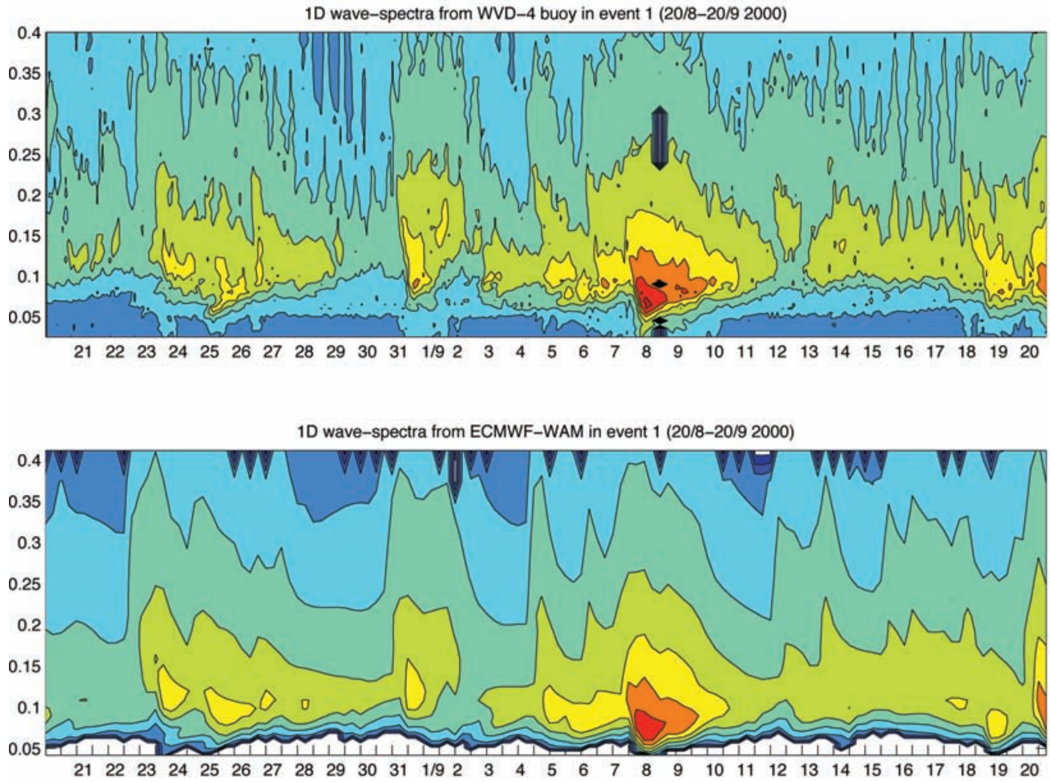

Figure 6. All recorded 1D wave spectra at WVD-4 in Event 1 vs. 1D-wave spectra from ECMWF. y-axis gives frequency, x-axis gives time and colours give the logarithm of the spectral energy density. The spurious spectral feature occurring in the WVD-4 spectra on the 8/9 is due to data error.

Southeast of the Faroe Islands, and secondly the EW4 model most likely does not resolve the bathymetric features that cause negative shoaling at WV-2. The effect of negative shoaling is significant on low frequencies at the WV-2 site, according to idealized tests, some of which are reported in Niclasen and Simonsen (2005c).

The statistical parameters derived from WV-2, WVD-4 and K7 are given in Table 4, and the time series of EW4 and measured parameters at WVD-4 are given in Figures 4 and 5. In order to get a general comparison of the spectral shape of the EW4 model vs. observed spectra at WVD-4, the 1D-spectra time series for Event 1 are displayed in Figure 6. No effort is made here to investigate the fit between observed and modelled 2D-spectra as pitch/roll buoys have intrinsically poor directional resolving power (Young, 1994; Arntsen and Tørum, 2005).

One clear feature is the underestimation of the wave height in the peak of the storms in all events, and general underestimation of the wave height in the winter

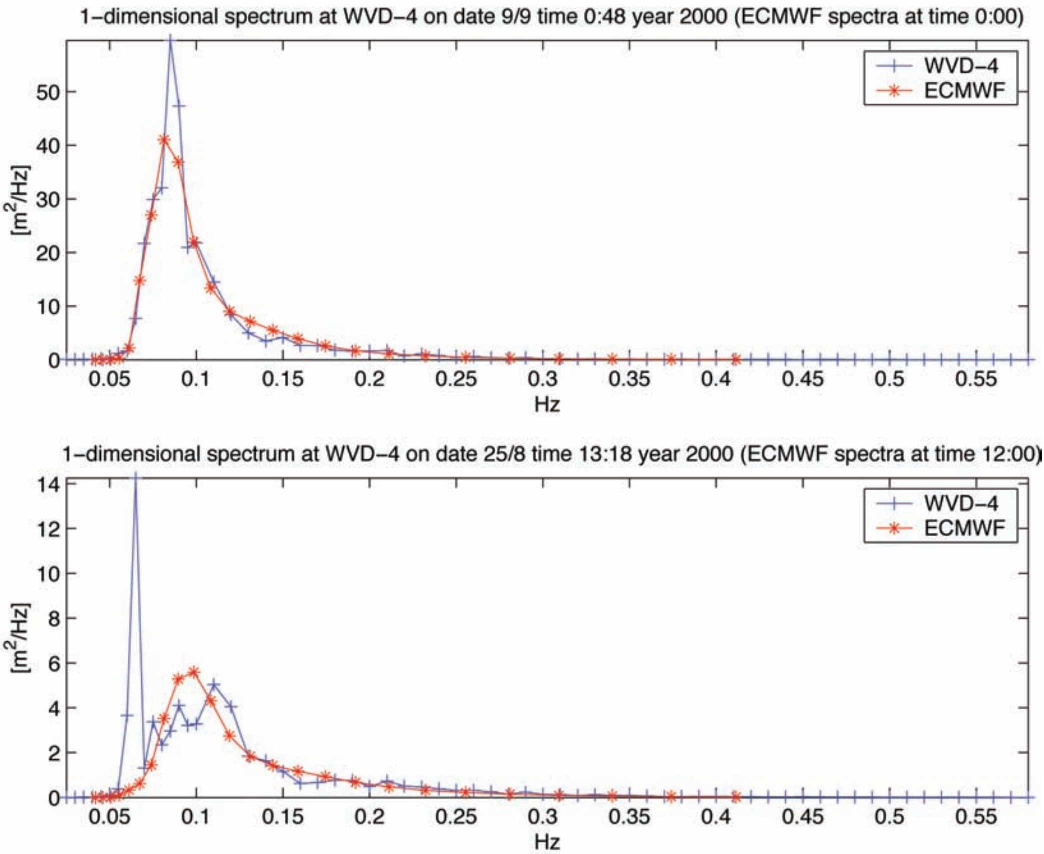

Figure 7. Two recorded 1D wave spectra at WVD-4 in Event 1 vs. 1D-wave spectra from ECMWF.

events. The measurements on the Faroe shelf suggest a consistent positive bias in the T_{m02} wave period, but this trend is not supported by the measurements at K7.

Clear half-daily variations occur in wave height, direction, period and spectral shape in the summer events. One example of this is the period 27/8-31/8 2000 in Figures 4 and 6. Some speculations on the causes for these variations are presented in Niclasen and Simonsen (2005a).

The modelled 1D spectra resemble the measured 1D spectra quite well. The EW4 spectra are smoother, in time and frequency, than the observed spectra, and double peaked spectra are much rarer in the modelled spectra (Figure 6). Much of this can be explained by the coarser time and frequency resolution of the EW4 model compared to the WVD-4 buoy, but not all. On the 25/8 2000 a clear arrival of incoming swell is apparent in the buoy spectra, but the corresponding feature in the EW4 spectra is vague and diffuse (Figure 6 and lower plot in Figure 7). The observed spectra have a tendency to have more energetic peak frequencies, and a slightly narrower peak, one such example is given in the upper plot in Figure 7.

Discussion

Before going into the detailed discussions of the fit of the modelled wave parameters at the different locations, a closer look into the effect of the cut-off frequency f_{high} on the measurements is needed. Using all the measured wave spectra at WVD-4 (17196 measurements spanning from 10/2-1999 to 13/2-2004) as a reference database, it was investigated what the effect of different values for f_{high} were on the wave parameters H_{m0} and T_{m02}. The inspection showed that f_{high}=0.50 Hz, corresponding to f_{high} at WV-2, introduced a positive bias (artificial overshoot) of 0.43 s in T_{m02} and a negative bias in H_{m0} of -0.01 m. If f_{high}=0.25 s, corresponding to f_{high} at K7, the artificial positive bias in T_{m02} would be 1.43 s and the bias in H_{m0} would be -0.09 m. The parameters from the WVD-4 site are, as mentioned earlier, compensated for the effect of f_{high} whereas the measurements at WV-2 and K7 are not. When compensating for the effect from f_{high} on T_{m02}-measurements at WV-2 and K7 it becomes apparent that the true T_{m02}-bias is in the region of 1 s at all sites for most of the events. It is therefore clear that the EW4 model seems to consistently over-predict the T_{m02} wave period.

Due to inherent random properties in wind and wave fields, there is a lower limit to the scatter index of wave parameters. For the wave height this lower limit of the scatter index, lies on average in the region of 10-20% (Komen *et al.*, 1994). As reported by Cardone *et al.* (2000), a generally accepted high skill level for continuous hindcasts of H_{m0} is represented by a scatter index of less than 0.25 associated with bias of less than 0.25 m and a correlation of 0.90 or greater.

Looking at Table 4, and comparing it to other operational models (Bidlot *et al.*, 2002; Nielsen, 2002, 2003a, 2003b, Janssen *et al.*, 2005), it is clear that the EW4 model prediction is good for all locations and events.

When this is said, it is quite clear that the modelled wave height performance is seasonally dependent, having larger negative bias and smaller skill index in the winter events. This seasonal performance variation in H_{m0} of the EW4 model is also documented in Bidlot *et al.* (2002). Due to the skill of the present wave models, poor model performance says more about the driving wind fields than the model itself (Komen *et al.*, 1994). This claim seems in the present case to be supported by the general under prediction of the wind fields observed at K7 in the winter events (Figure 2).

Another trend which is visible in all events is the under prediction of the wave height, in the peak of the storms. This problem is well known from different applications, and the major source for error can usually be traced back to deficiencies in the forcing wind field (Cardone *et al.*, 1996).

The model prediction of H_{m0} and T_p are not affected by the same order of consistent bias as it is seen in T_{m02} and the bias of

T_{m02} is generally larger than the bias of T_{m01}. This suggests that the wave-period-bias is not primarily due to shortcomings in the wind field, but rather due to underestimation of the energy in the high frequency part of the spectrum by the EW4 model. The EW4 underestimation of the energy content in the higher frequencies is also apparent in the spectral time series (Figure 6).

The fact that the seasonal under prediction is not clear in the F8 wind series but is present in the WVD-4 H_{m0} series, could indicate that the F8 station does not always represent the 10 m wind correctly.

It was observed that the spectral peak had a tendency to be broader than the observed peak (Figures 6 and 7). This is a commonly observed mismatch between operational wave models and observed spectra, and can to a large extent be attributed to the deficiencies in the DIA approximation (van Vledder, 1990; Forristall and Greenwood, 1998).

It was also noted that some swell incidences (see example in Figure 6) were smooth and diffuse in the EW4 results. The missing swell event in the EW4 data, such as the one on the 25'th August 2000, can be caused by different causes. Previous inspections have found that shortcomings in operational wind models are a common reason for underestimation of wave events (Komen *et al.*, 1994; Cardone *et al.*, 1996). Detailed investigations omitted here, indicate that the swell generating area is estimated to be some 1700 Km west to southwest of WVD-4, that is roughly to 60 EW4 model grid lengths of 0.25°, so propagation effects might also play a role in this case. The arriving swell is also observed to be quite narrow in frequency and direction (Figure 7), which again could make the representation and advection of the swell more difficult within the limitations of the EW4 resolution and numerical propagation. It has previously been mentioned e.g. by Wingeart *et al.* (2001), that underreported swell events by operational WAM models can be due to the diffusive 1st order propagation used in WAM. In this particular case inspected here, the missing swell energy is so evident that the primary cause must be due to an underestimation in the forcing wind field.

Recent model improvements at ECMWF

At ECMWF, there is a sustained effort at improving model performances and assimilation techniques. For this reason, it is necessary to give an outline of the most important model upgrades introduced into the operational model after the time periods inspected here.

In March 2004, a scheme for the inclusion of the effect of unresolved bathymetric features on wave propagation was introduced. The impact of this scheme is better model predictions downwind from sub grid features such as the Faroe Islands (Janssen *et al.*, 2005). A re-formulation of the wave dissipation source term was implemented in April 2005. The impact of this re-formulation on spectral wave parameters such as mean wave periods was highly beneficial (Janssen *et al.*, 2005 and Bidlot *et al.*, 2007). Finally in February 2006, the atmospheric model spectral resolution was increased so it now is roughly equivalent to 25 km horizontal resolution, and the associated coupled global wave model resolution was increased to 40 km. This new model configuration has been found to be better able at predicting intense storms (Untch *et al*., 2006). Moreover, additional wave observations from the radar altimeter onboard Jason-1 and from ASAR on board ENVISAT were added to the wave model data assimilation resulting in better wave model analysis and short range forecasts (Abdalla *et al.*, 2005). Overall, it should therefore be expected that the present implementation of the EW4 model would generate analysis data that relate even better to buoy data, than the analysis values used in this investigation.

Planned wave model changes at ECMWF in the near future are, increased model resolution in the limited area model, and inclusion of more shallow water physics (Jean-Raymond Bidlot at ECMWF, pers. com., 2007).

Conclusions

Analysis values from four one-month periods, of the limited area wave model are found to give satisfactory results when compared to wave data from the Faroe area. There is a general under-prediction, especially of the wave height, at the peak of all the extreme storms. A seasonal variation is observed with larger negative bias in the modelled wave height in the winter months compared to the summer months. This seasonal bias seems to be connected to a similar bias in the forcing wind model.

The shape of the modelled spectra correlates well with the observed spectra, but the behaviour in the lower frequencies in the model spectra are found to be slightly smoother than the observed, and with examples of missing swell events.

It is observed that the predicted wave periods have a consistent positive bias compared to the measurements and that the EW4 model has a tendency to under-predict the energy content in the high frequency range of the spectrum.

Overall the model performance is found suitable to force a nested high resolution wave model for the Faroese area. Due to recent improvements in the EW4 model formulation and wind forcing, it is expected that the model performance, especially in average wave period, would be even better with the recent implementation of the model.

In this investigation, only analysis values and not forecasted values are used for the model validation, but a comparative global test of five operational models (Bidlot *et al.*, 2002) finds the ECMWF model to have the lowest forecast error in wind and waves. The ECMWF model is therefore not only a suitable candidate to force high resolution local hindcasts, using analysis data, but also a suited candidate to force high resolution forecasts for the area.

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