

High-resolution metocean modelling at EMEC's (UK) marine energy test sites

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Abstract

To support and improve the evaluation of the test results of wave energy and tidal energy generators, it is important to understand the detailed physical conditions at the test sites. EMEC has chosen DHI's MIKE modelling technologies for studying water levels, currents and waves at their test sites. DHI has assisted EMEC in constructing numerical hydrodynamic and wave models of the Orkney Islands using the flexible mesh version of MIKE 21. This model permits spatial varying resolution, so that the complex tidal channels and local topographic features that may influence the tidal and wave dynamics can be sufficiently resolved. This paper highlights the modelling activities for EMEC's two test sites.

Keywords: EMEC, Orkney, test sites, tidal, metocean, wave-current interaction, numerical modelling, MIKE by DHI

1 Introduction

The European Marine Energy Centre (EMEC) in Orkney is the world's first purpose built wave and tidal energy test facility. EMEC was established in 2004 with the aim of stimulating and accelerating the development of marine power devices, initially through the operation of a testing centre in Orkney [1]. The location is shown in Fig. 1.

Construction of the wave test facility was completed in 2003 and the Pelamis 'sea snake' wave device first delivered energy to the UK grid in 2006. The tidal test facility opened later with the OpenHydro turbine delivering energy to the grid in 2008.

The facility provides a unique location for offshore testing of marine energy devices, demonstration of new

technologies, and benchmarking the operation of such devices [2].

The open-sea test facilities for wave energy converters consist of four berths situated along the 50m-water depth contour off Billia Croo on the Orkney mainland (some 2km offshore). The site typically experiences significant wave heights of the order of 2m, and maximum significant wave heights larger than 10m.

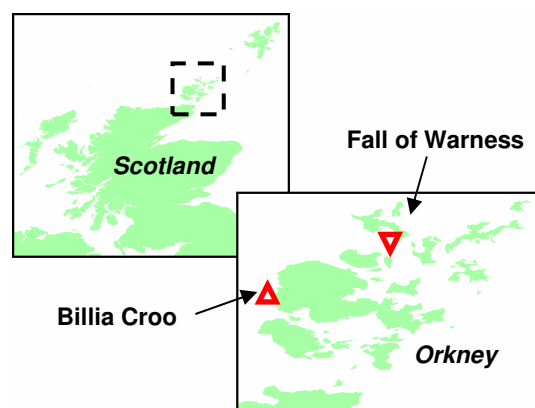


Figure 1: General location of EMEC's marine renewable energy test sites.

Armoured cables link each berth to a substation onshore. This links to an 11kV transmission cable connecting to the national grid and to a data/communications centre located in nearby Stromness. The Centre provides a comprehensive range of electronic monitoring and support systems for developer testing, and meteorological data are collected nearby with a remote weather station.

The tidal test facilities provide five berths in the Fall of Warness, to the south-west of Eday. Peak tidal flows up to 7 knots are experienced, and notable wave-

current interaction is also found in this region during certain metocean conditions. Similar grid connections and data communication facilities are provided, and a weather station is also located near the site.

To provide detailed support to marine operations at the EMEC sites, DHI has been commissioned to supply calibrated MIKE 21 tidal and wave models of the Orkney region focussing on EMEC's present two test sites; Billia Croo and Fall of Warness. An overview of the bathymetry and topography is shown in Fig. 2.

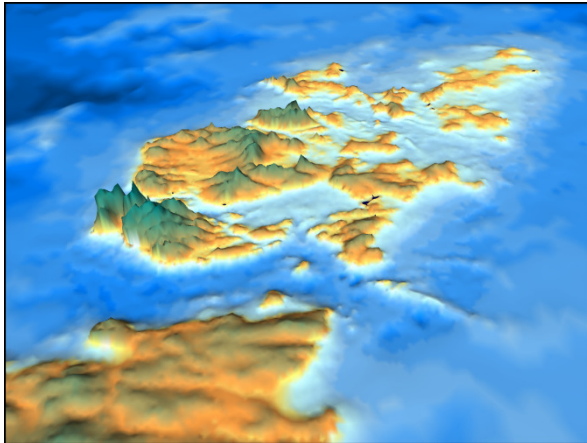


Figure 2: Overview of bathymetry used in the modelling and computational mesh.

The tidal and wave models have been implemented with the flexible mesh code with a minimum grid spacing of approximately 75m in Fall of Warness and 200m at Billia Croo. The spatial resolution offshore is 5-7km. The tidal model is driven with tidal constituents supplied from the DHI's global tidal database, and has been calibrated with current profiler data supplied by EMEC and UKHO. The 3rd generation wave model is driven by directional spectral wave and wind data from Oceanweather Inc's GROWFAB database (1986-2005). The wave model has been calibrated with wave data supplied by EMEC.

The models have also been implemented as an operational metocean forecasting system, which can be made available to assist EMEC clients with marine planning.

2 Modelling technologies and data

EMEC has decided to use DHI's MIKE modelling technologies for studying water levels, currents and waves at their test sites.

A numerical hydrodynamic model of the Orkney Islands was built using MIKE 21 Flow Model FM (Flexible Mesh) module. The flow model solves the 2D Reynolds-averaged Navier-Stokes equations on an unstructured mesh using a finite volume technique, see [3] and [4]. The flexible mesh model permits spatially varying resolution in the geographical space, so that the complex tidal channels and local topographic features that may influence the tidal dynamics in areas of

interest (eg. Fall of Warness) can be sufficiently resolved.

DHI's fully spectral wave model, MIKE 21 Spectral Waves FM, is used for modelling of the waves, [5]. The wave model, MIKE 21 SW, is part of the MIKE 21/3 Coupled Model FM. It is a truly dynamic modelling system for application within coastal and estuarine environments. The flow and spectral wave models are the basic computational components of the modelling system. The flow model permits both 2D and 3D flows to be simulated, and the combined wave-current system simulates the mutual interaction between waves and currents using a dynamic coupling [6]. The same system can also be coupled to a sediment transport model to provide feedback between bed level changes and the hydrodynamics. The numerical approach applied in both the wave and flow models is based on a cell-centred finite volume technique on an unstructured grid. DHI was the pioneer on spectral wave modelling using finite volume and flexible mesh numerical techniques initiated in 2000.

2.1 Computational mesh and bathymetry

Construction of the model mesh required selecting a model area that is large enough to capture regional tidal flow patterns and sufficiently refined in the narrow channels to accurately predict the current speeds, waves and potential wave-current interaction phenomena.

Bathymetry data were available from a number of sources including EMEC (UKHO, Osiris and Fathoms data). All of these data sets, collected at different times and often at different vertical datum, needed to be adjusted to a single datum. It was also important that the newer and more accurate data sets were given precedence over older, less accurate, data. Fig. 3 shows the extent of high-resolution bathymetry data.

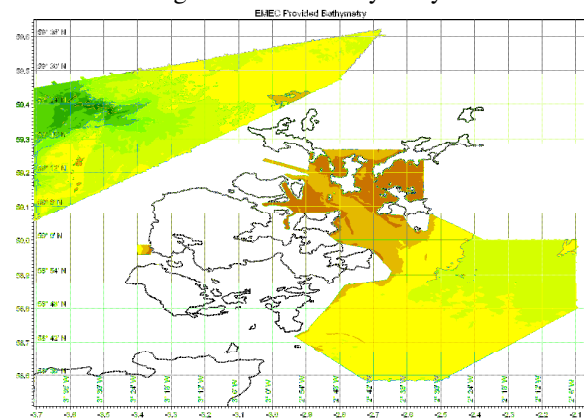


Figure 3: Data coverage from bathymetry data available at EMEC (including UKHO, Fathoms and Osiris).

This was achieved by interpolating all of the data onto a high-resolution mesh (0.0001 deg.) The grid used for the interpolation can be seen in Fig. 4 below (notice the higher resolution grid areas mirror the higher resolution data provided by the UKHO through EMEC). Finally, the datum was corrected to Mean Sea Level based on available tidal information across the domain. The overall computational mesh is shown in

Fig. 4. Also a high-resolution sub-domain model covering the Fall of Warness area has been developed for more efficient studying of wave-current in this complex strait. This is shown in Fig. 5.

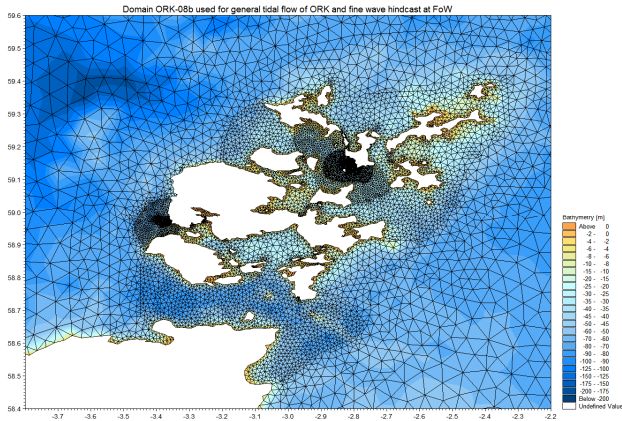


Figure 4: Overview of computational mesh and bathymetry covering the entire Orkney Islands.

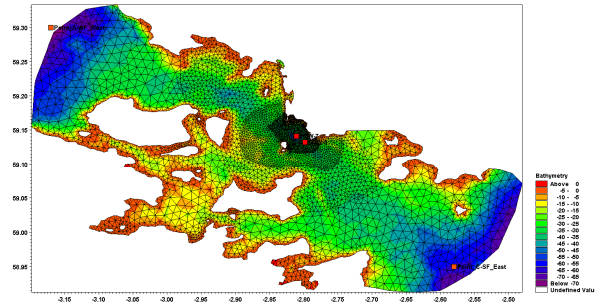


Figure 5: Overview of computational mesh and bathymetry covering Stronsay Firth (South East), Fall of Warness and Westray Firth (North West).

2.2 Measurement data

A number of wave and current measurements are available at EMEC's test sites, which have been used for model calibration and validation. The locations of the measurement devices are indicated in Figs. 6 and 7. The recorders were deployed for periods of between 15 and 30 days, recording at 20 minute intervals.

UKHO's Admiralty Total Tide (ATT) data, derived from historic observations, were also used for the calibration and validation of the hydrodynamic model. The ATT was used in order to complete the current measurements which were made only locally in Fall of Warness. Additional hourly current information was therefore extracted from the ATT database at several points all over the domain (see Fig. 8). These additional data were used to assess the overall tidal flow model performance to predict tidal current in the Orkney Islands.

Tidal level information at the stations shown in Fig. 9 was also used for calibration and validation of the modelled water level.

2.3 Model forcing

The tidal flow model and the wave model are driven by external forcing of different nature. The availability, the location and the quality of the forcing are of utmost importance and determine the extension of the numerical model domain. The model domain is shown in Fig. 10 including the location of the essential boundaries.

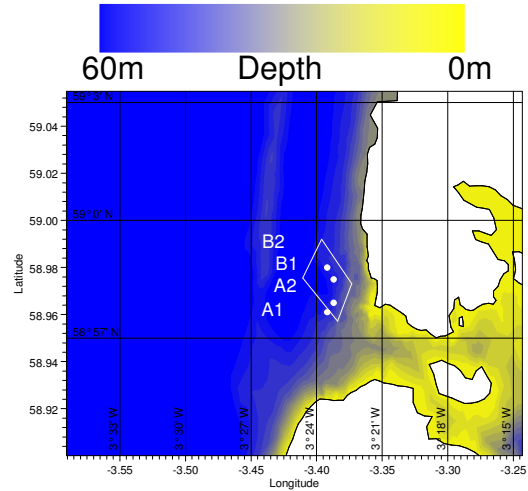


Figure 6: Billia Croo wave test site. Positions of the four Cardinal Buoys (CB), four berths and four directional waverider measurement stations: A1, A2, B1 and B2.

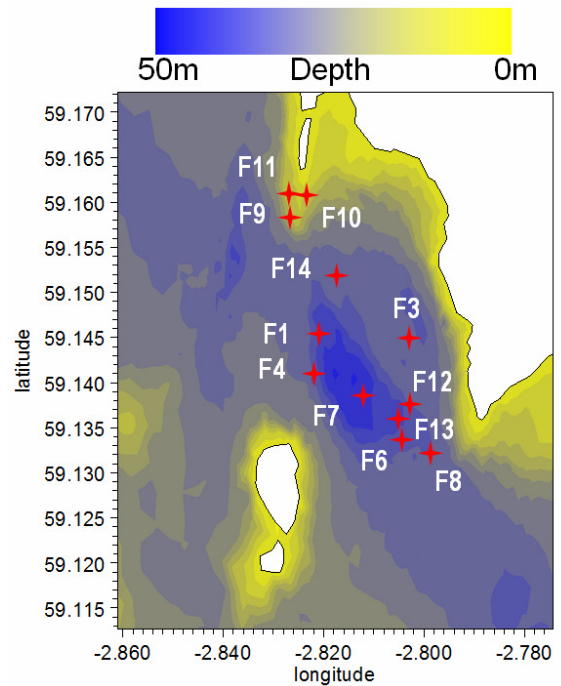


Figure 7: Fall of Warness tidal test site. Position of ADCP measurement stations.

Water level

DHI's global tidal database, KMS, provides boundary conditions for tidal current flow model. The global model is based on the four major diurnal constituents (K1, O1, P1 and Q1) and the four semi-

diurnal constituents (M2, S2, N2, K2) with a spatial resolution of $0.25^\circ \times 0.25^\circ$. The model has been validated using TOPEX/POSEIDON altimetry data.

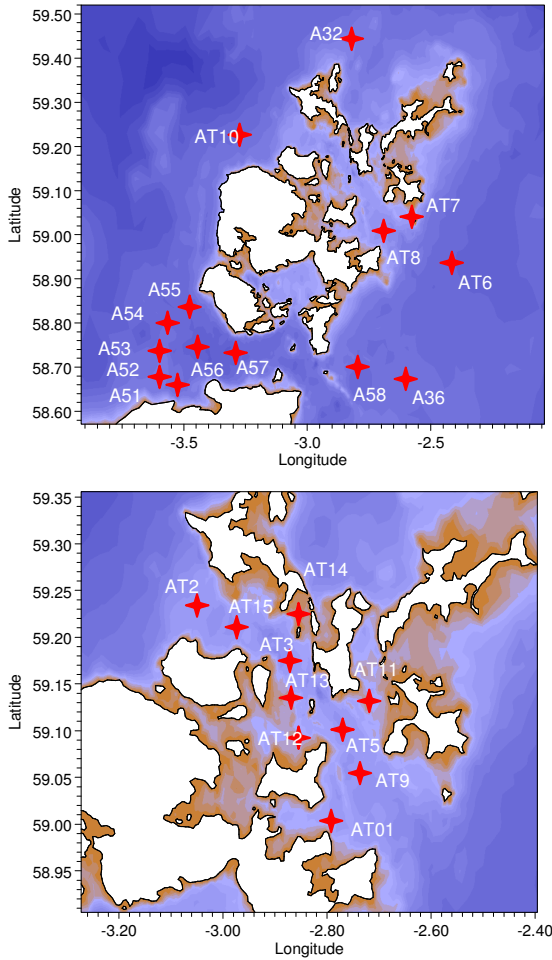


Figure 8: Position of the UKHO's Admiralty Total Tide (ATT) points used for the calibration and validation of the hydrodynamic model.

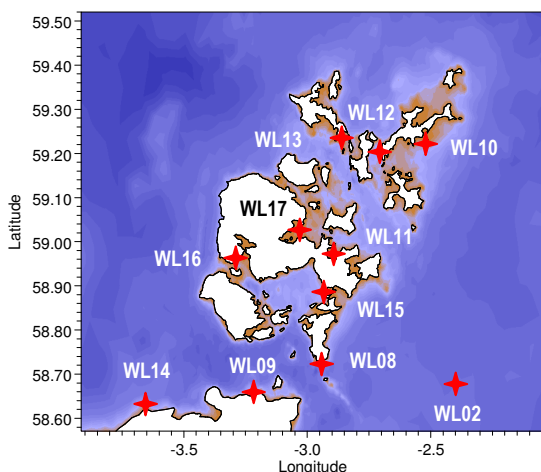


Figure 9: Position of tidal stations used for the calibration and validation of the hydrodynamic model (water level).

Waves

Accurate boundary conditions need to be provided at the open essential boundaries of the wave model unless its extension is large enough to be driven only by a

corresponding wind field. The Orkney Islands are subject to waves generated in the North Atlantic Ocean and North Sea, and it was beyond the scope of this project to incorporate the local wave model in the DHI operational high-resolution North Atlantic or North Europe wave models, which have been in operation since 2002.

Oceanweather Inc (OWI) has provided EMEC with hindcast data from their GROWFAB database (GROW Fine North Atlantic Basin) available from 1986 to the end of 2005. Oceanweather's 3rd generation wave model (OWI3G) was adopted onto a 0.5 degree grid, and wind and wave fields were archived at all active model points at 3-hourly intervals. Four points (O1 to O4, see Fig. 10) have been selected which cover the Orkney model domain, and the provided directional wave spectra have been interpolated and imposed as essential boundary conditions in the MIKE 21 SW model.

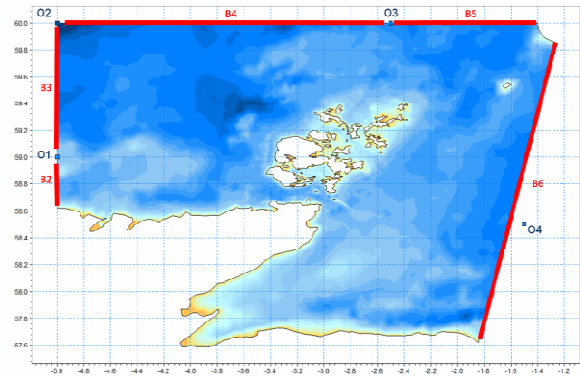


Figure 10: Model domain extension used for the numerical models of the Orkney Islands and identification of the open boundaries.

Wind

The wind forcing is of utmost importance for a wave model like the one considered in this study, in particular in sheltered areas behind islands, etc. The OWI point data cover a period of 20 years. The point data have been interpolated and extrapolated to cover the entire modelling domain, and have been validated against available measured wind data provided by EMEC.

3 Tidal flow modelling – model results

The tidal model covers an area over $3\frac{1}{2}^\circ$ longitude, and nearly $3\frac{1}{2}^\circ$ latitude. The full extent of the model is shown in Fig. 4.

A harmonic analysis of the tidal constituents shows the variation of tidal range and velocity throughout the islands, and can be used to assess the suitability of sites for tidal power. Tidal stream information is also of interest to wave developers for the estimation of tide-induced loads on device moorings, to allow for provision of satisfactory mooring equipment, etc. A good characterisation of tidal streams is essential for tidal device developers to enable satisfactory device design.

The modelled tidal water level has been compared to predicted tide at 18 stations depicted in Fig. 9. Time series comparison for two selected stations (Stromness and Loth) is shown in Fig. 11. The RMS error for the two stations is 13cm.

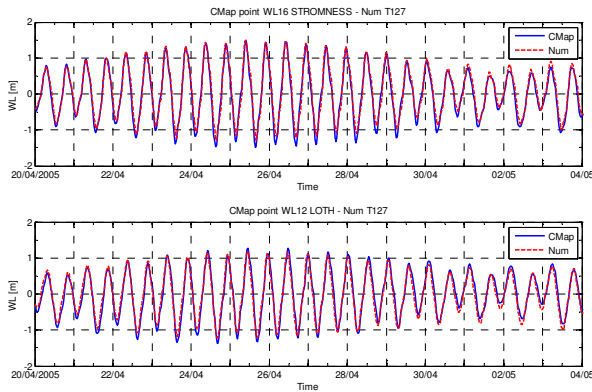


Figure 11: Comparison of predicted and modelled water level at Stromness (upper) and Loth (near Fall of Warness).

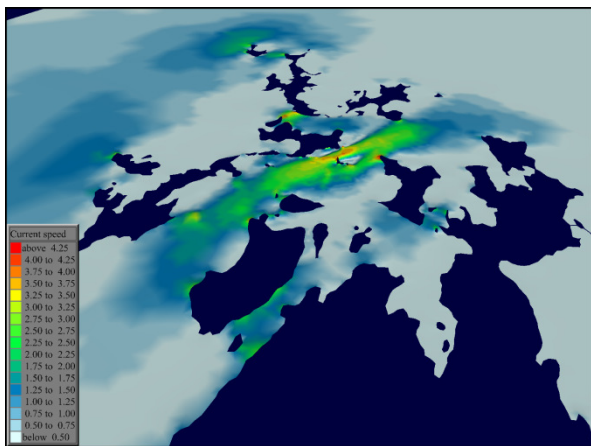


Figure 12: Example of flow field around the Orkney Islands. Fall of Warness is in the centre.

2.1 Fall of Warness

The tidal energy resource in Fall of Warness is exceptionally good. As illustrated in Fig. 13, the tidal flow pattern is complex. Comparisons of modelled and measured tidal currents at the measurement stations FOW-8 and FOW-3 are shown in Figs. 14 and 15, respectively. The agreement is exceptionally good at FOW-8. At FOW-3, the model calibration is complicated by the fact that the ADCP was located close to the large local tidal eddy and velocity gradient (see Fig. 13). The position of this eddy and the severe gradient in the current field is sensitive to the local water depth and to the flow separation point at the nearby Warness Point. This means that a very high resolution mesh is required around the headlands to resolve the flow separation and resulting velocity gradient and downstream eddy. The resolution required is thus much higher than can be afforded in the present study due to the long run time it would produce. Interestingly, however, it was possible to obtain a reasonable match between the measured and modelled current speeds at FOW-3 by shifting the location of the station in the model, i.e. by extracting model data from

a slightly shifted lateral position (100-200m). The flow separation at Warness Point injects vorticity into the tidal flow which culminates in an eddy forming on the downstream side of the headland (in this case to the north west of Warness Point). The vorticity persists in the headland wake and is dispersed by friction during the late flood and early ebb periods. In the wake of the headland, therefore, the early ebb current speed is very low because it is retarded by the persisting eddy on the upstream side of the headland. This is apparent in the measurements at FOW-3, which show a large disparity between flood and ebb velocities.

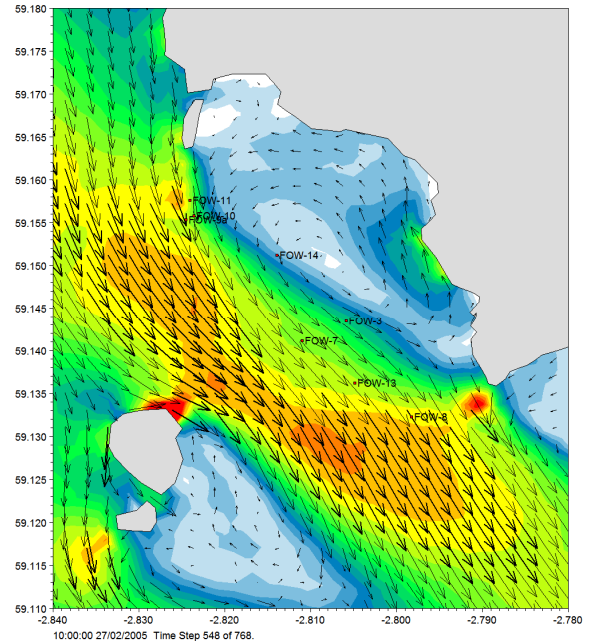


Figure 13: Example of flow patterns in Fall of Warness during high (upper) and low tide. Measurement stations are also indicated.

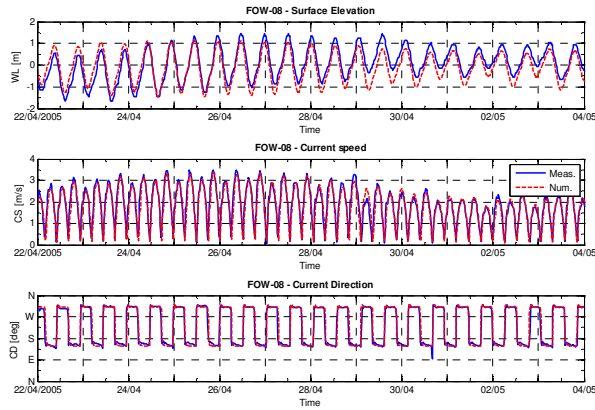


Figure 14: Comparison of modelled and measured tidal currents in at FOW-8, see Fig. 13 for station location.

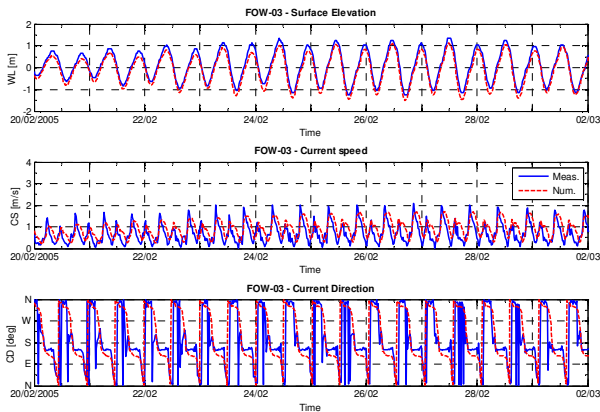


Figure 15: Comparison of modelled and measured tidal currents at FOW-3, see Fig. 13 for station location.

Comparison of modelled current speeds and ATT predicted current speed at a number of stations (from Westray Firth in north west towards Stronsay Firth in south east) in Fall of Warness is shown in Fig. 16. Very good agreement is obtained at ATT 04 (near FOW-8). Further southwards at ATT 05, the tidal model tends to overestimate the predicted ATT current speed.

Results (current speed and water level) of a one-year flow simulation are shown for station FOW-08 in Fig. 17 including a hindcast time series of wind speed.

It may be concluded that the developed hydrodynamic model is able to capture the most important flow features with fairly good accuracy around EMEC's test site.

4 Wave modelling – model results

The wave model covers the same extent as the tidal model. Calibration has been performed against the wave data recorded by EMEC with a Datawell Waverider at the Billia Croo site, and with a RDI Workhorse Monitor ADCP at the Fall of Warness site. The model has been run to provide a 20-year hindcast of the Orkney waters for the period 1986 – 2005, using boundary data sourced from OWI.

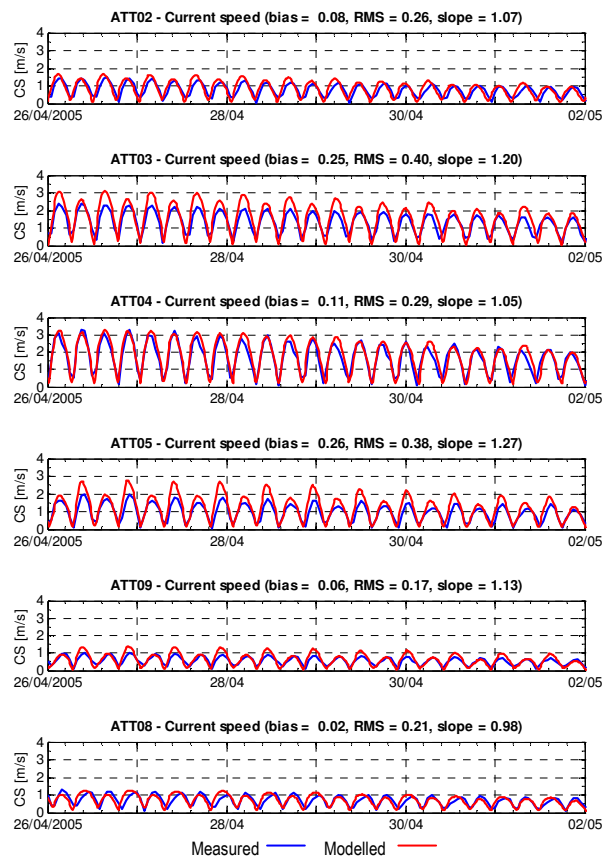


Figure 16: Sample comparison of modelled and ATT based current speed prediction through Fall of Warness.

4.1 The Billia Croo test site

The wave test site at Billia Croo has a water depth of the order of 50m, and experiences wave action from west and north west.

A 20-year time series of hindcast significant wave height at EMEC's test site (A1, northern part) is shown in Fig. 18. The maximum wave height is well above 20m, and significant wave heights of 11-12m have been hindcast over the considered 20-year period.

A comparison of modelled and measured significant wave heights at Billia Croo (station A2) is shown in Fig. 19.

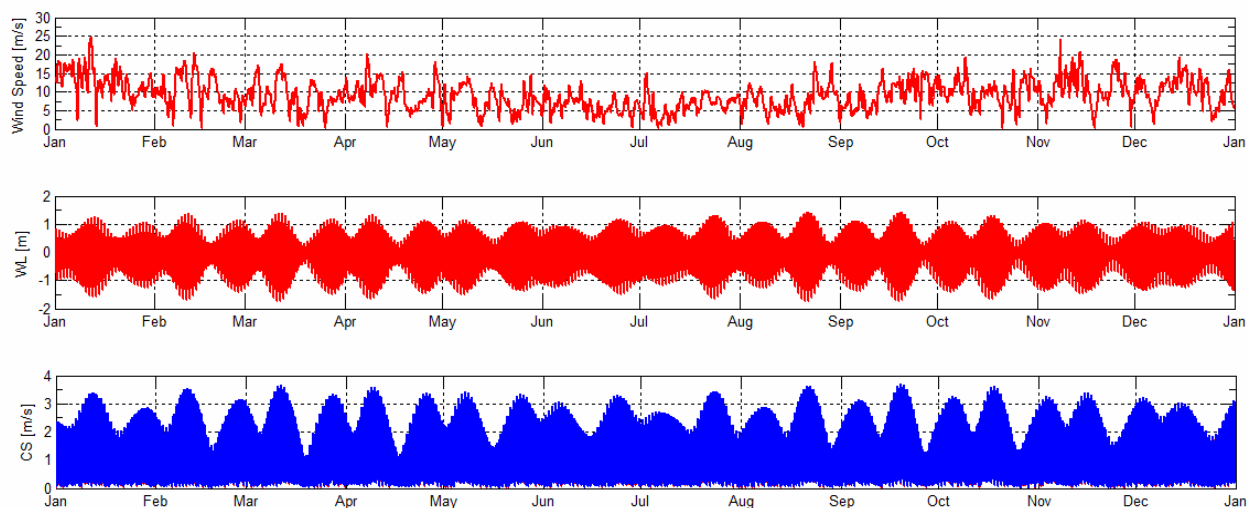


Figure 17: Time series of wind speed (upper panel) and modelled water level and current speed at FOW-8 during the year of 2005.

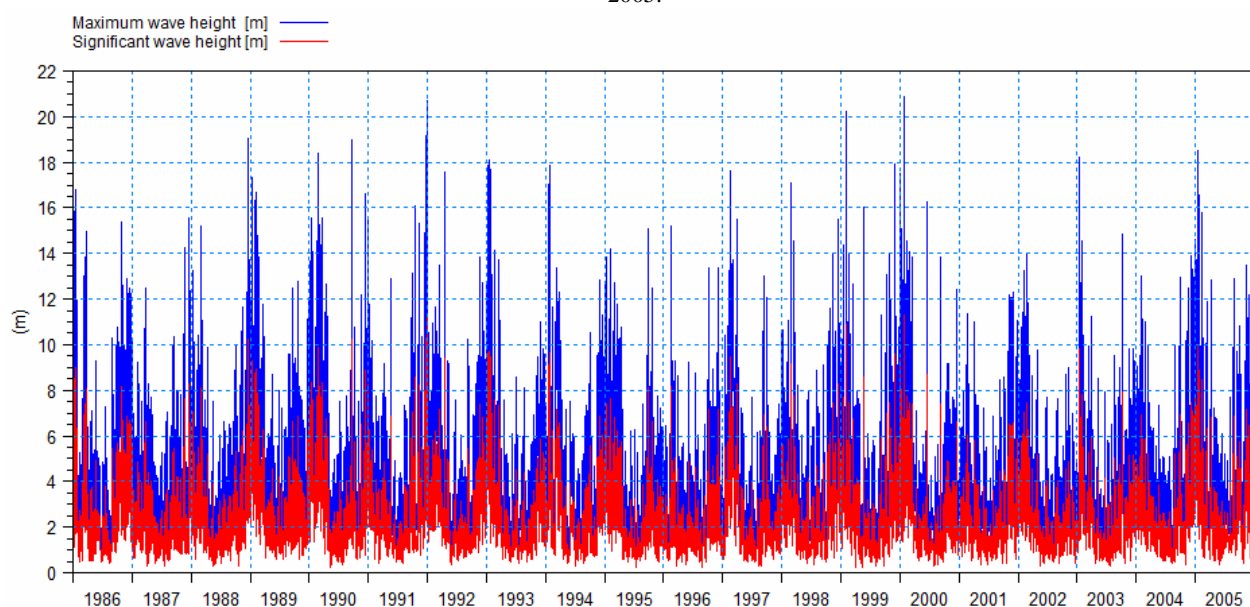


Figure 18: Time series of hindcast significant wave height and maximum wave height in the northern part of the Billia Croo test site.

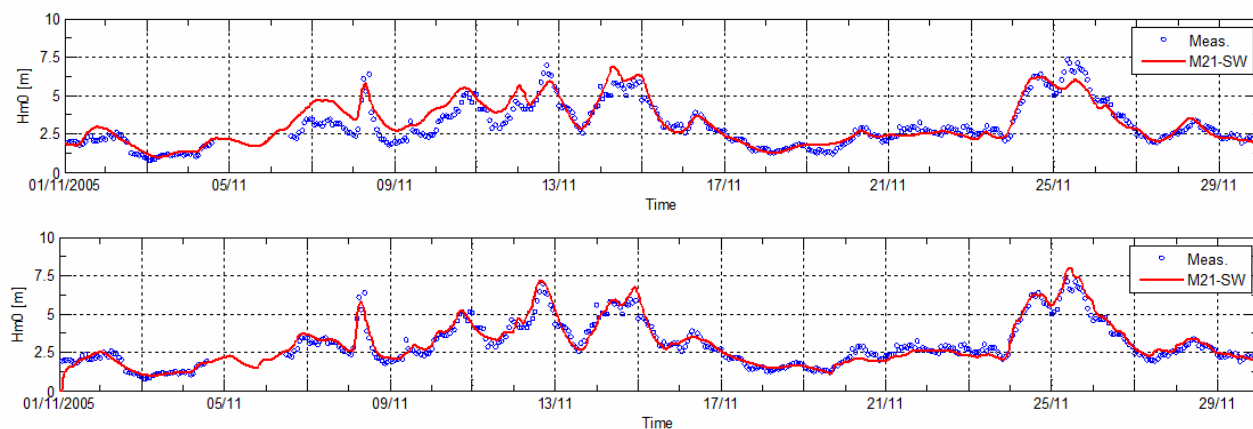


Figure 19: Time series of hindcast and measured significant wave height at Billia Croo test site (station A2) during November 2005. Upper panel with wind/spectral data forcing based on OWI data and lower forcing from DHI's operational North Atlantic / Northern European wave model and 0.15° (presently 0.10°) wind field.

The hindcast data are in good agreement with measurements. However, if the Orkney wave model is forced by even higher resolution directional wave spectra obtained from DHI's operational North Atlantic (NA) / Northern European wave model (NEU), and a 0.15° resolution wind field, then exceptionally good results are obtained. In this case, the scatter index is 0.12. By using OWI forcing the scatter index is 0.18 for November 2005. This demonstrates the accuracy and robustness of the calibrated wave model.

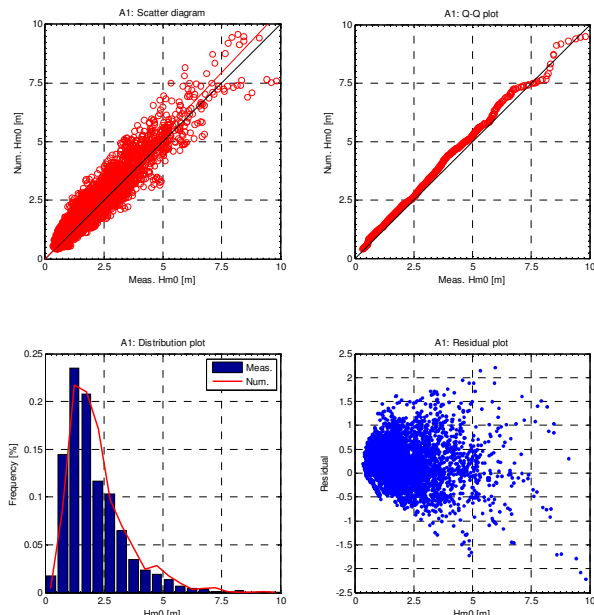


Figure 20: Statistical comparison of hindcast and measured significant wave height at Bilia Croo (station A1).

Fig. 20 shows scatter diagram, QQ plot, distribution and residual plots of measured and hindcast wave height data at station A1. The model results are in excellent agreement with the measurements. The QQ (*Quantile-Quantile*) plot is a graphical technique for determining if two data sets come from populations with a common distribution.

The model results include wave parameters at individual elements in the model, and full directional wave spectra at half hourly intervals for the full 20-year period. A sample spectrum is shown in Fig. 21.

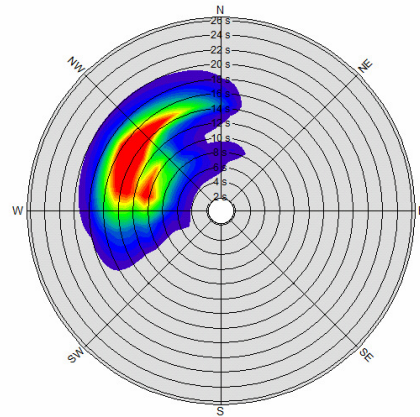


Figure 21: Example of a (bi-modal) directional wave spectrum at Bilia Croo.

An extreme value analysis of the 20-year hindcast significant wave height data for a deepwater location (near the model offshore boundary, North Atlantic) and at Bilia Croo (northern part) is shown in Fig. 22. This preliminary statistical analysis indicates an extreme significant wave height (1 hour value, return period 1 in 50 yr) of 15.3m offshore Orkney (North Atlantic) and 11.6m at Bilia Croo (northern part of test site).

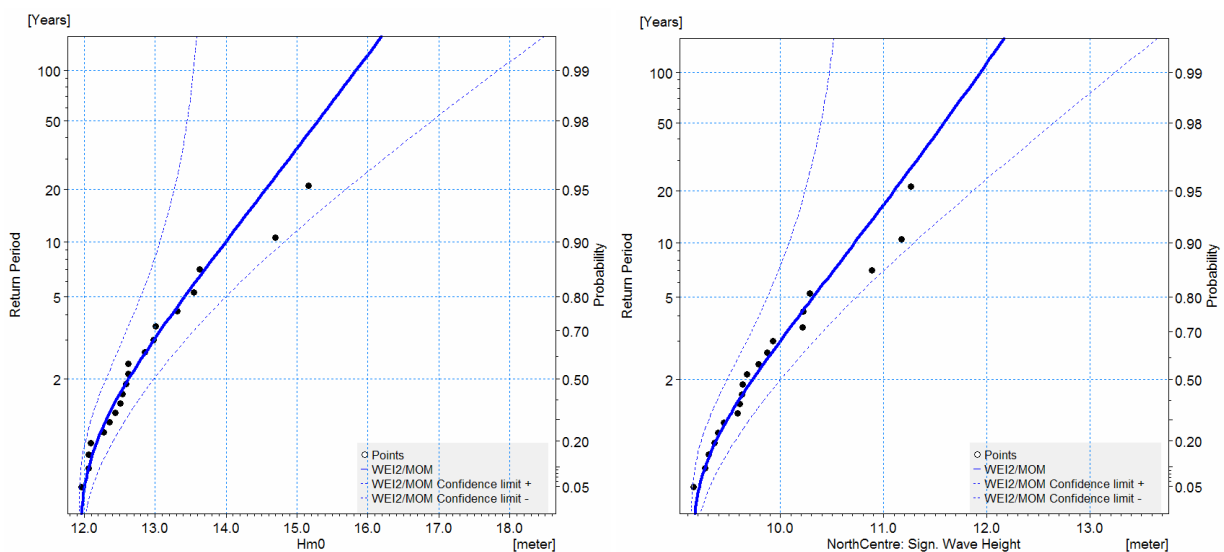


Figure 22: Results of an extreme wave height analysis for a deepwater location (North Atlantic, left panel) and at Bilia Croo (northern part). The dashed lines indicate the upper and lower 95% confidence band limits derived from the statistical analysis.

4.2 The Fall of Warness test site

The Fall of Warness strait is mostly sheltered from oceanic conditions, but waves from north-westerly and south-easterly directions are able to propagate into this region. The area is exposed to the south east, through the Stronsay Firth and the north west, via the Westray Firth. Large swells can build up - their size depending upon the strength of the wind and the length of time that wind is blowing from the SE and NW quarters.

When the tide is running in the opposite direction to the waves, very steep waves are created, which are known locally as "tide lumps". These waves are very hazardous to small craft and difficult to operate in with larger vessels, the waves often reaching heights of over 5m. These waves are especially prevalent to the south of the Point of Warness when there is an incoming swell or wind from the SE running against the flood tide as it flows towards the SE. Similar conditions will occur in the north of the Falls of Warness with the NW going (ebb) tide running into waves propagating from the NW. The worst areas for tide lumps with SE and NW wind are shown in Fig. 23. Also the photos shown in Fig. 24 clearly show the influence of the currents on the wave field. Hence accurate modelling of waves in this area requires an accurate flow field in time and space.

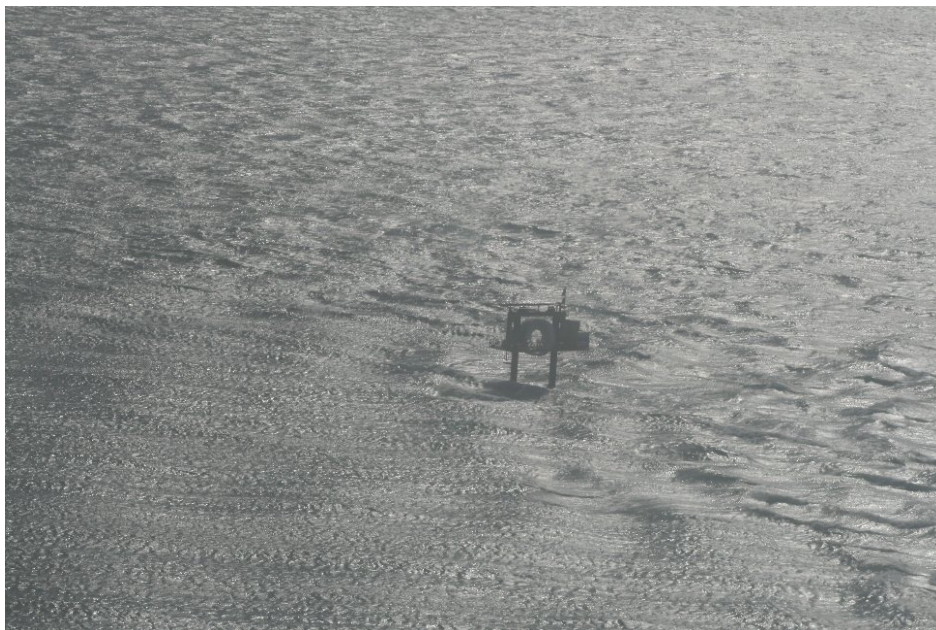


Figure 24: Open Hydro's prototype open-centre tidal turbine installed at EMEC's tidal test site in Fall of Warness in combined waves and currents. The device is located close to FOW-8 (see Fig. 13). Photos: ©EMEC.

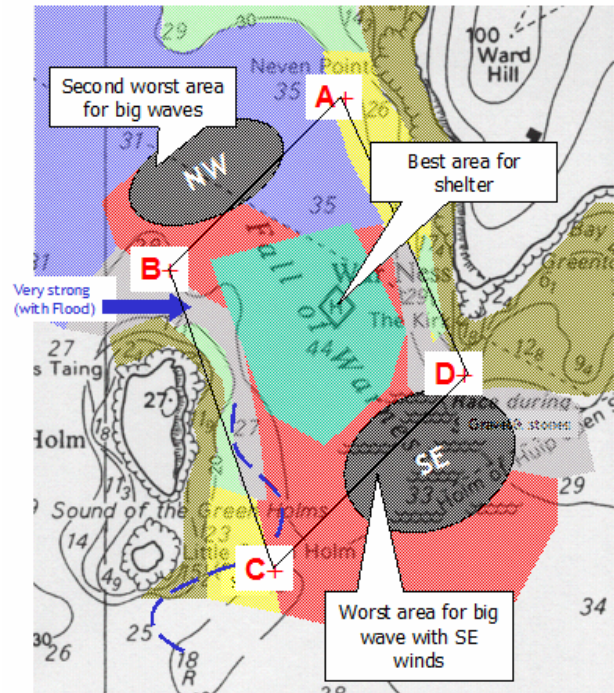


Figure 23: Observed locations with strong wave-current interaction (so-called "tide lumps"). Points A, B, C & D are the approximate boundaries of the test area. From [7].

To improve the understanding of the interaction of waves and currents in the Fall of Warness, the strait has been modelled by coupling the overall Orkney model together with the sub-domain model of Fig. 5.

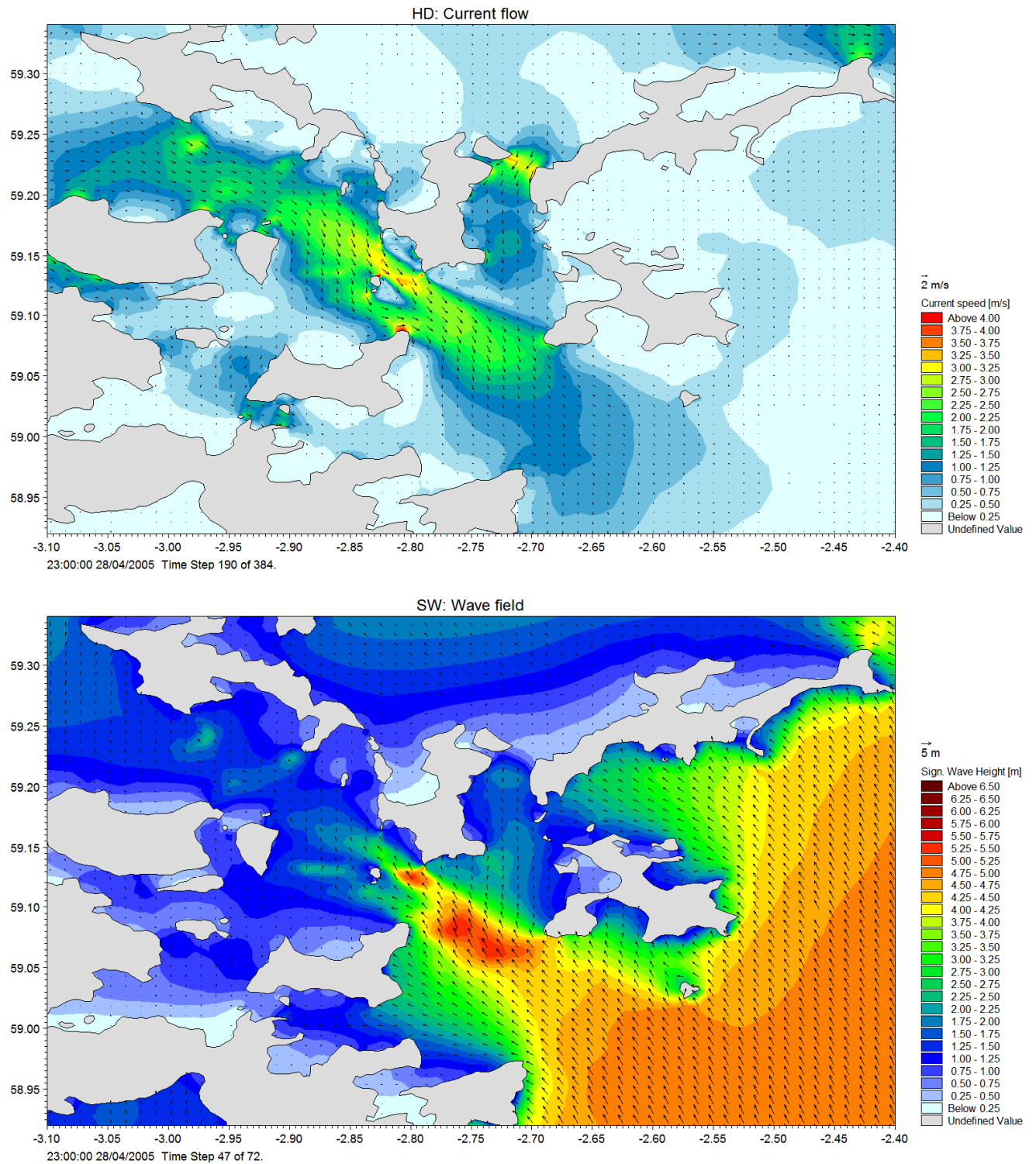


Figure 25: Simulated current flow field (upper panel) and wave field take into account the spatially/temporally varying current field, 23:00 April 28th 2005.

One event of particular interest has been recorded at the end of April 2005 at FOW-8. The maximum wave height measured was 5.1m at 23:00 April 28th. Offshore waves and wind were coming from S-SE. The modelled flow and wave field is shown in Fig. 25. Apparently, two “tide lumps” occur S-SE of Point of Warness. A comparison between measured and modelled waves and currents at FOW-8 is shown in Fig. 26. From the figure, it is seen that the model captures the high waves measured at 23:00 April 28th though the peak value is slightly underestimated. The modelled current speed and phase are in good agreement with measurements. As shown in Fig. 25, the spatial gradient of the significant wave height is very high in the “tide lumps”. Within a very short

distance from FOW-08, even higher modelled waves occur. The model underestimation may also be explained by current speed further southwards being predicted too high, which will affect the wave propagation and transformation towards the test site.

Fig. 27 clearly shows the importance of taking into account the influence of currents on the wave modelling in Fall of Warness.

Fig. 28 shows the wave field around the Orkney Islands at 23:00 April 28th 2005. Also substantial wave-current interaction is seen to take place at the entrance to Pentland Firth resulting in very high and choppy sea states.

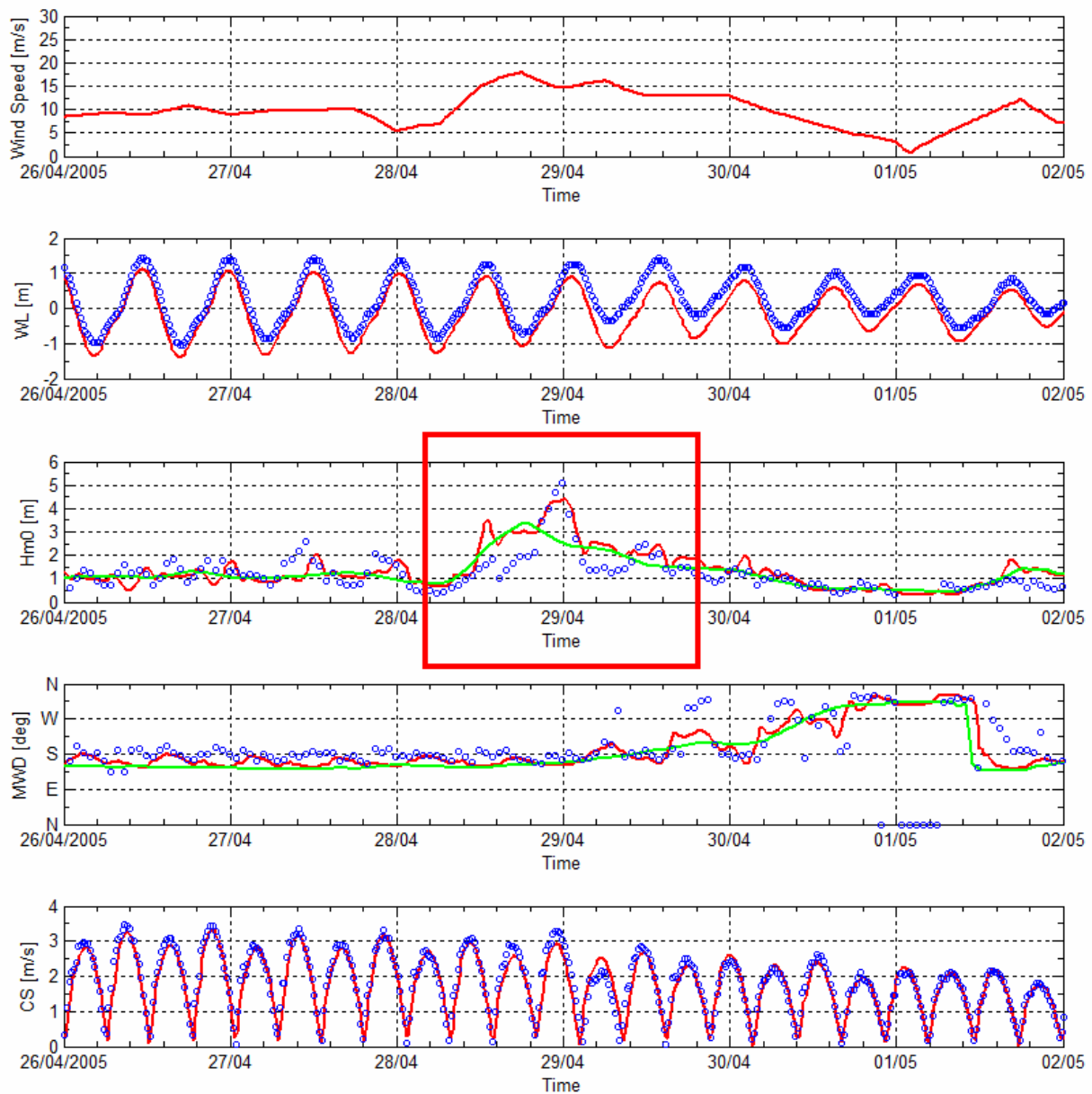


Figure 26: Time series of hindcast wind (upper panel), modelled and measured water level, significant wave height, mean wave direction and current speed around April 28th 2005 (indicated by the red box) at FOW-8. Key: Red curve: model; Green curve: model excluding wave-current interaction; Blue circles: measurements.

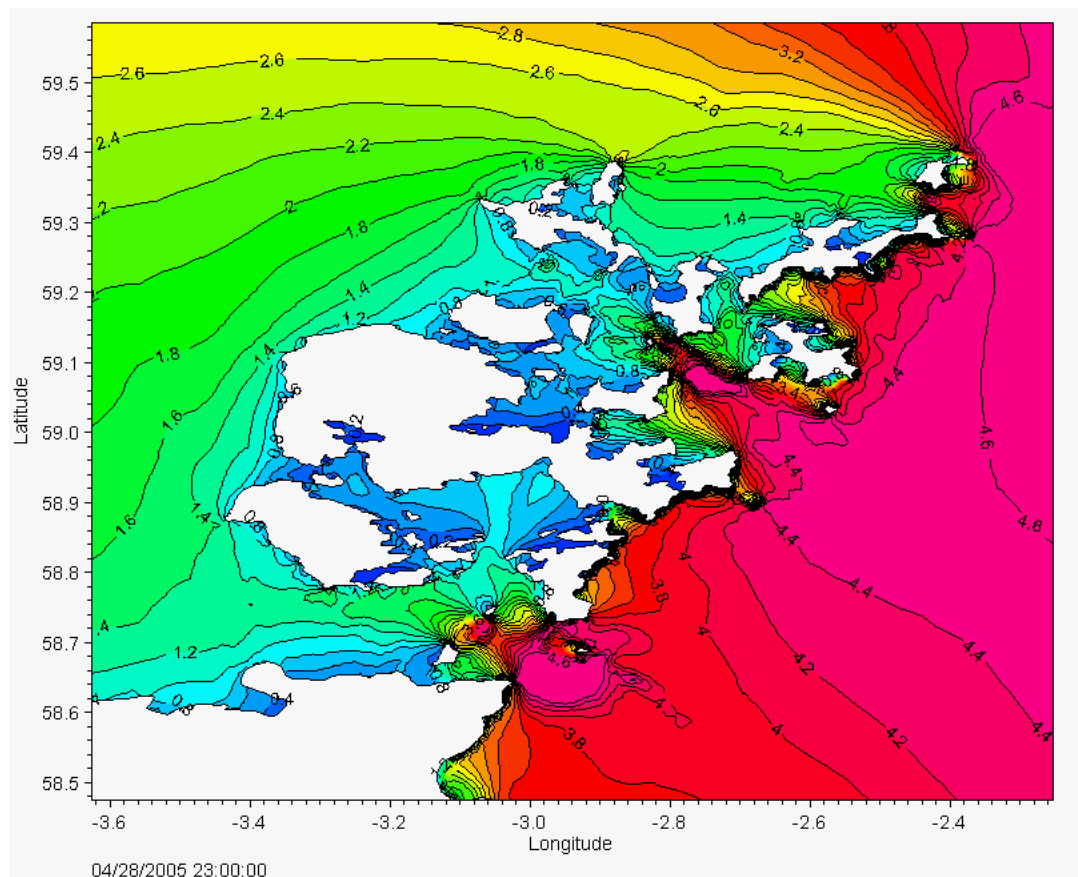


Figure 27: Simulated wave field (significant wave height) around the Orkney Islands taking into account a spatial/temporary varying current field. 23:00 April 28th 2005.

5 Operational metocean data forecasting

DHI has used the developed models to operate the Orkney model in a real-time operational forecasting mode. This provides hourly overview maps of selected metocean parameters from the model, and also a detailed forecast for 48 hours (can be extended to 120 hours) at selected points as shown in Fig. 28. The operational model is forced by 0.1-0.15° wind field data and directional spectral wave data from DHI's operational Northern European wave model which is dynamically linked to a North Atlantic wave model.

A storm event, in the winter of 2008/9 that had particularly high waves, was chosen for comparison with observed wave data at the Billia Croo test site. The observed data were obtained with the regular Waverider buoy deployed at the site.

The event covers 19-24 December 2008, with two peaks in wind strength during a south-westerly dominated wind flow. The first peak had wind speeds just over 25m/s and the second peak had sustained wind speeds of about 20m/s. The forecast (best cast) and observed significant wave height and spectral peak period is shown in Fig. 29. The agreement is quite close, with wave heights underestimated for the first peak and overestimated on the second peak.

Fig. 30 shows a map of forecast significant wave heights on 20 December 2008 01:00 UTC around the Orkney Islands.

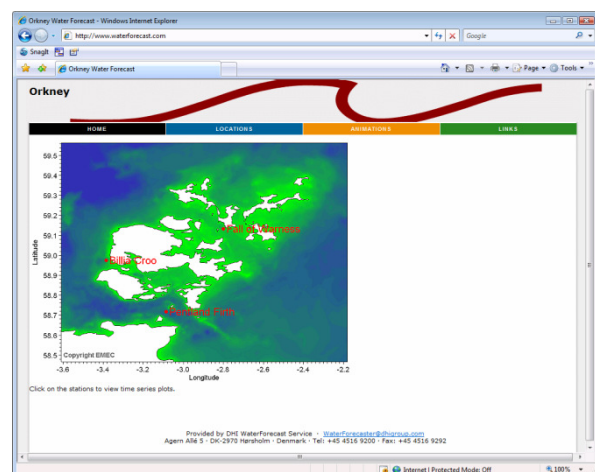


Figure 28: Website of the operational metocean forecast system for the Orkney Islands.

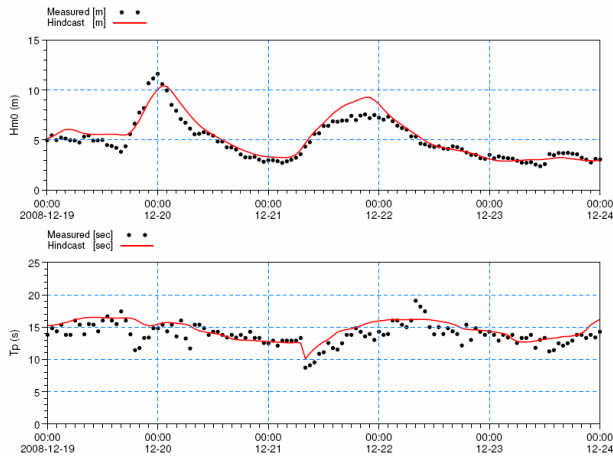


Figure 29: Forecast (best cast) and measured significant wave height and spectral peak period at Billia Croo during the 19-24 December 2008 storm.

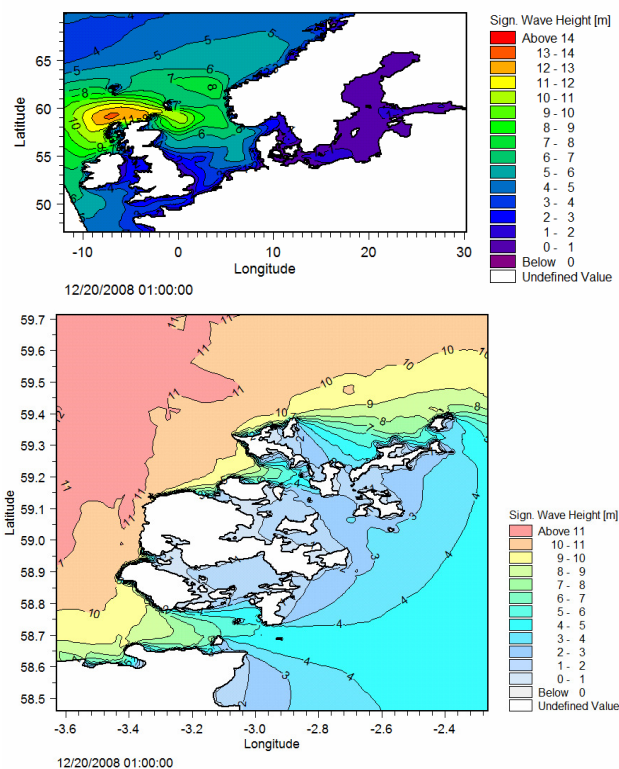


Figure 30: Map of forecast significant wave height during the 19-24 December 2008 storm (20th December 2008 01:00 UTC). Upper panel shows DHI's Northern European Operational Wave Model (NEU) and lower panel the Orkney model.

6 Conclusion

High-resolution numerical models for the marine energy test sites in Orkney have been developed and have been calibrated against a varied dataset of observations.

The tidal model has been used to study the hydrodynamic regime within the Fall of Warness, in particular the nature of special tidal features within the region. The wave model has been used to develop a 20-year hindcast dataset, which can be used to justify

decision making in marine operations planning at the test sites. The coupled models have been used to study wave/current interaction at sensitive locations in Fall of Warness.

The applicability of these state-of-the-art numerical flow and wave models for studying and predicting metocean conditions at EMEC's wave and tidal energy test sites has been demonstrated, and these models will contribute to the ongoing program of works for EMEC and EMEC's clients.

Acknowledgements

The modelling technology and assistance was commissioned with funds granted by the Carbon Trust, UK. The support is gratefully acknowledged.

Many thanks are due to Oliver P. Jones for his early involvement and enthusiasm in this project.

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