Assessment of significant wave height in UK coastal waters – 2011 update

Report for Maritime and Coastguard Agency Research Proposal RP626

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Executive Summary

This document describes analyses made by the Met Office on behalf of the Maritime and Coastguard Agency (MCA) under research proposal RP626 to provide an update to the study 'Assessment of significant wave height in UK coastal waters' which had been originally conducted in 1998 under RP422.

The project provided as a main deliverable sets of Annual and Summer (defined April to October inclusive) contours indicating the position at which 1m, 1.5m, 2.0m, 2.5m, 3.0m, 4.0m and 5.0m significant wave heights are exceeded for either 10% or 1% of the time. These contours were derived from a 10 year archive of Met Office wave model data generated on a 12km resolved grid, and were assessed for accuracy against records from 24 wave buoy observation sites around the UK.

Included in this report are commentaries regarding the confidence that can be placed in the contours based on the assessment against wave buoys, known limitations in the wave model and comparison with the 1998 study. To aid visualization in near coastal areas the contours have been supplemented with subjectively interpreted extension lines; however it is recommended that neither these lines or visual estimates of contour positions interpolated between the supplied thresholds are used for decision making.

Since the source data for this study is a model designed to predict waves over large offshore areas, a particular limitation relates to the ability to accurately provide contours within a few kilometres of complex coastlines or areas with highly detailed shallow water (less than 20m) bathymetric features. As a result areas of particular importance and where this study's contours are liable to give a limited representation are identified as needing further analysis based on improved data.

This study and the 1998 study are compared and discussed against present thinking in terms of the effects of climate change, in particular a proposed increase in storminess in the North Atlantic. The comparison shows high levels of inter-annual variability in wave heights and an improvement in the resolution at which waves are represented closer to the coast in the new study. These sources of variability in the data mean that inferences about change to the wave climate cannot be made simply from comparison of the two MCA studies. A critical factor that will also influence the wave environment around the UK is the sensitivity of different sea areas to the track of storms as well as frequency and

intensity, since areas such as the North Sea, Irish Sea and English Channel are can almost be considered as distinct semi-enclosed basins which can have entirely different exposures under given storm conditions. A gross observed indicator of patterns in the North Atlantic storm track may be given by the North Atlantic Oscillation, and comparison with the long term past record suggests that the past 20 years are not majorly inconsistent with the longer term and so changes may presently be limited. Looking forward, the science that positions the storm track accurately in climate projections is still undergoing development and a well evidenced discussion of future change in the UK's wave climate will only be possible when this is mature.

Contents

1. Scope of study

In 2011 the Met Office were commissioned by the Maritime and Coastguard Agency (MCA) under research proposal RP626 to provide an update to the study 'Assessment of significant wave height in UK coastal waters' which had been originally conducted in 1998 under RP422.

The primary deliverable of the study is a set of GIS shapefiles comprising contour data that describe the significant wave height likely to be exceeded for 10% of the time in an average Annual or Summer (defined as April to October inclusive) period. Contour intervals were specified in consultation with the MCA and set at 1m, 1.5m, 2.0m, 2.5m, 3.0m, 4.0m and 5.0m. In addition a series of 1% exceedence contours were provided for the same contour thresholds.

The 2011 update study was triggered because of a concern that climate change may have modified the wave climate around the UK since 1998. The 2011 study has exploited improved observed and model data generated since 2000, which are believed to represent the UK's wave climate more accurately than the data available to the 1998 study. Both climate change and revised data impacts on the exceedence contours generated in the two studies will be discussed.

Data from numerical wave models were used to provide the necessary geographic coverage and estimates of variability in the wave field based on representation of physical processes (rather than simply interpolating between observation points). Data from a portfolio of UK in-situ wave observations were compared with the model outputs in order to generate confidence information that forms the basis for guidance statements on how to interpret the 2011 contours.

This study also identifies areas of the UK coast where resolution of the model background dataset remains insufficient to correctly estimate variation in significant wave height exceedence. These areas are generally near-coastal and estuarine waters pertinent to the vessel operations defined in MSN-1827. Methodology and requirements for a separate package of work to establish contours for these areas and the MSN-1827 application are discussed.

The structure of the report is as follows:

- Section 2 describes the data sources and method used for the study and draws a contrast with the 1998 study data.
- Section 3 discusses the confidence that can be placed in the contours based on model limitations and comparisons with observed data.
- Section 4 discusses how climate change and the data used in both the 2011 and 1998 study might affect the contours.
- Section 5 identifies key areas requiring more detailed study and proposes methods to generate the necessary data.

2. Background data and method

This study describes the wave climate in terms of a 'significant wave height' (Hs) statistic. Hs was originally developed as a mathematical expression of the wave height most likely to be estimated by a trained manual observer at sea following work on sea-state forecasting during World War II (Sverdrup and Munk, 1946). The parameter and relationships from which it is derived have since been adopted as a de-facto standard by the scientific community and World Meteorological Organisation. Specifically, Hs values are assumed representative of the average of the highest one-third of waves observed. For both the buoy observations and model data used in this report, Hs is determined from the wave energy spectrum – this is generally believed to be consistent with the manual observation within 10% (Holthuijsen, 2007, p68-75).

2.1 Generation of significant wave height contours

The contours were generated based on hourly time-series of significant wave height from Met Office operational wave model archives. In order to obtain the best available spatial resolution around the UK, the data were taken from two 12km resolved models:

a) the Met Office 2nd Generation wave model (Golding, 1983) 'UK Waters' configuration; which was operational between June 2000 and November 2008
b) a Met Office implementation of the WAVEWATCH III model (Tolman, 2007) over a 'North Atlantic European' (NAE) domain; which replaced the UK Waters model in December 2008 and is presently the operational model used for wave forecasting around the UK.

In both cases the models were forced by 'analysis winds' from the Met Office Unified Model; i.e. the wind data used to generate the waves are spatially coherent fields derived from seeking the best balance between a modelled estimate and available atmospheric observations. The wind fields were scaled similarly to the wave model grid at 12km.

Since the wave and atmospheric model domains and physics parameterizations will have varied over the course of the record, the dataset cannot be considered homogeneous – however it is expected from ongoing verification of operational wave forecasts that in general the systematic biases in both wave models will be small enough not to have had a major effect on the contours. The reference against measurements provided along with the contour data in Section 3 is intended to confirm this assumption.

Seasonal discrepancies were avoided by only using ‘full years’ from each model archive – on this basis the contours were generated from the following records covering a 10 year period:

- Winter; UK Waters data from June 2000 to May 2008, plus November 2008 (extra month in 2008 accounts for a missing record from November 2006); NAE data from June 2009 to May 2011.
- Summer (defined as April to October inclusive); UK Waters data from June 2000 to October 2008; NAE data from April 2009 to May 2011. Since the 12km model resolution was not expected to capture coastal sea breeze effects well, no account was taken for daylight hours in favour of using the larger data sample created from analysing full days.

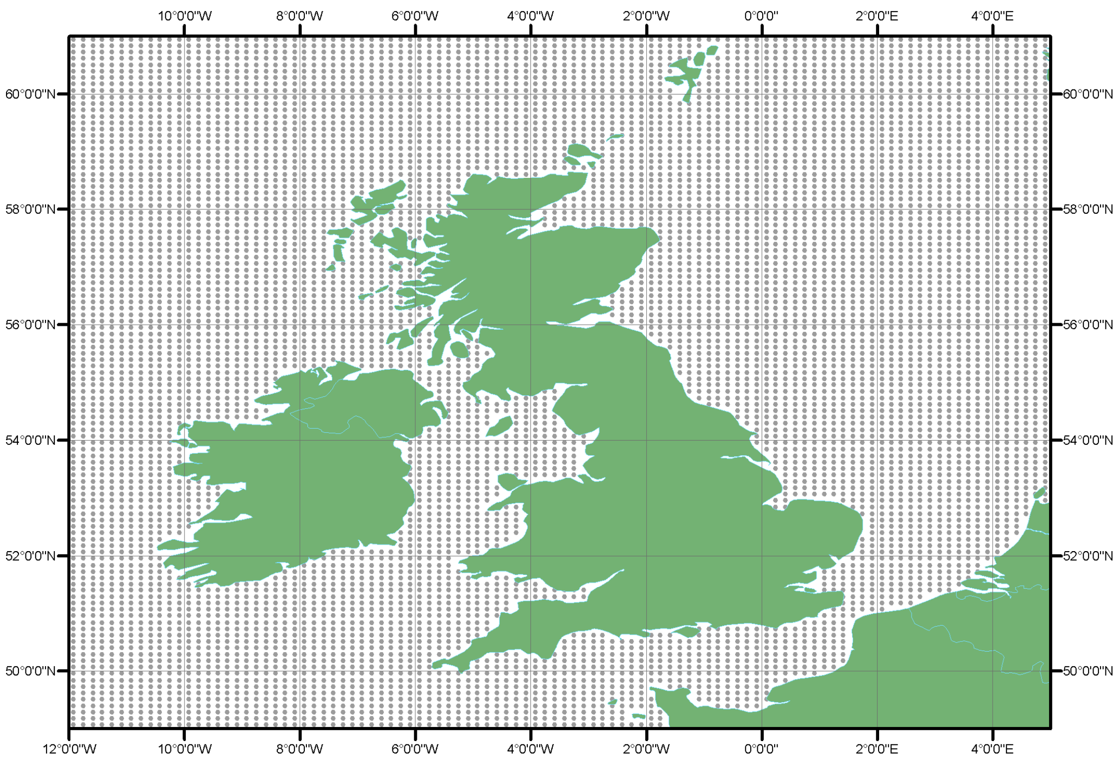

Figure 2.1 Grid definition around the UK, cell resolution is approximately 12km.

The common model grid used for the analysis is shown in Figure 2.1, and comprises 10125 cells. Contours were generated following a 4-step process. First the time-series record at each grid cell was analysed to generate a frequency of exceedence table for Hs based on thresholds at every 0.25m up to 5m, then every 0.5m up to 15m. Second, for each exceedence table Hs bins with exceedence values crossing the 10% and 1% thresholds were identified, and a final Hs value was derived for each percentage threshold by linear interpolation. In the third step the gridded Hs values were contoured using a spline fit tool within ARC GIS spatial analyst. Contours were set at 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0m levels. The final step was to make a manual edit of the derived contours in order to deal with coastal discontinuities in the gridded data. In this process contour sections within the model grid but crossing land (as defined in a high resolution UK shapefile provided by MCA) were removed, and any contours artificially introduced by the contouring program shoreward of model grid cells were removed since no certainty can be placed on the exact position of these contour lines where they are not informed by any data.

Adopting this approach has meant that the data driven contours do not fully close to shoreward in a number of instances, and so a subjectively interpreted 'extension layer' was also provided to aid use of the contours. <u>However it must be stressed that the extension data is an educated best guess at best and as such has very low confidence associated with it. Similarly, a visual interpolation to contour levels between those given is not recommended</u>.

2.2 Reference against measured data

In order to quality control and provide confidence guidance on the contours, the model data were assessed against available wave buoy observations made around the UK during the last 10 years. These data do not include measurements taken at lightvessels, which are believed to have a low bias in their measurements due to their large hull size. Figure 2.2 shows the locations of the buoys cross-referenced against the annual 10% exceedence contours and indicates both the geographic extent of the buoy coverage and also that the buoy data cross references against a range of high and low energy wave regimes.

Buoy data were co-located with cells in the model grid using a nearest cell approach, and the exceedence statistics from both datasets compared at percentile levels from 50% to 90% at 5% intervals, and 90% to 99% at 1% intervals. This type of comparison is generally termed as 'quantile-quantile' or 'q-q' analysis, and is of direct use in this study as it compares exceedence properties. The results of the analysis are included in Appendix A and inform the commentary accompanying each area map.

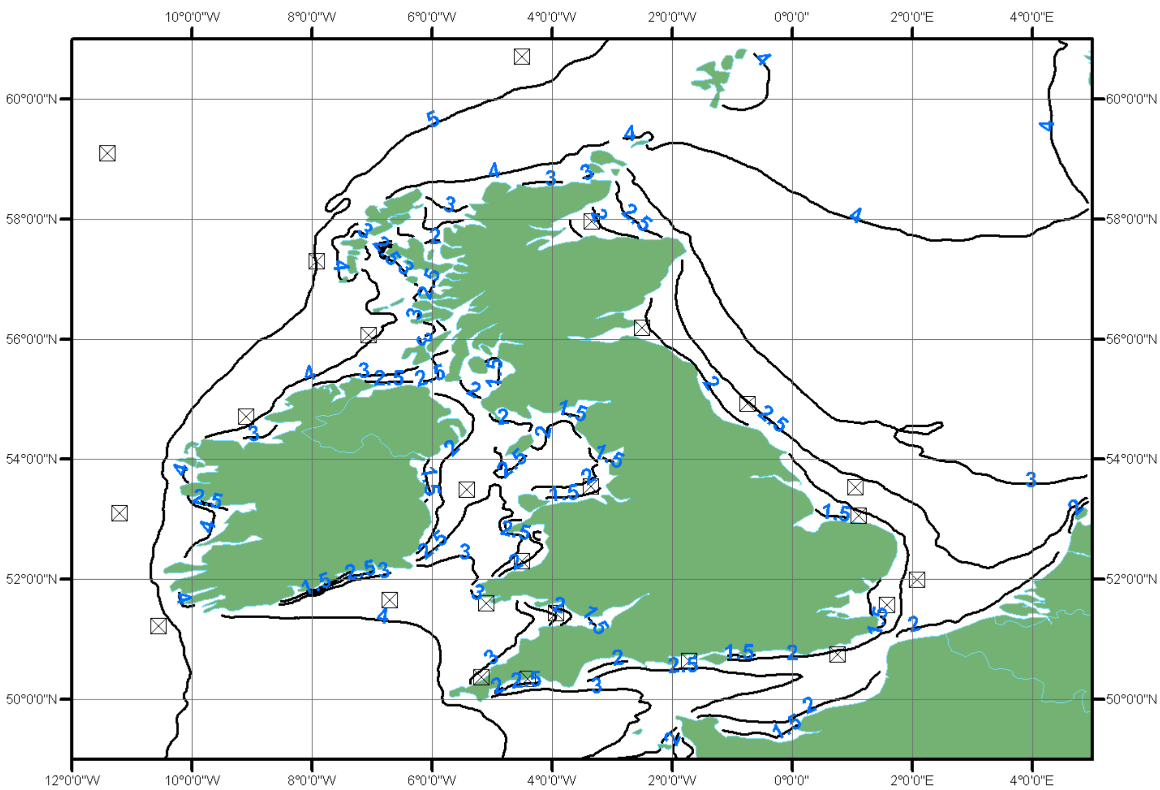

Figure 2.2 Data buoy locations (crossed squares) and 10% annual exceedence contours derived from the model data. The buoy coverage includes both coastal low wave height regimes and offshore high energy locations.

2.3 Contrast with 1998 study

The 2011 study has used a similar method for its UK regional contour generation as for the 1998 study, i.e. the contours are generated from model data with a series of observations used to provide confidence data. However, some significant differences exist between the two background data sources:

1. The 2011 model data were sourced over a 10 year period from 2000-2011 rather than the 1986-1997 sample used in the 1998 study. The different sampling periods may allow some contrasts to be drawn in terms of sampling inter-decadal variability in the wave climate (i.e. we now have two periods potentially comprising a different mix of stormy and more benign periods).

2. The 2011 data were sampled hourly rather than 3-hourly in the 1998 study. Higher frequency sampling increases the likelihood of including storm peak values in the data. This is unlikely to affect the 10% exceedence contours but may have some impact on the 1% contours.

3. The 2011 model data aims to provide a genuine representation of mesoscale (order 10s kms) variability in the wave climate. In order to achieve this both the atmospheric models providing wind forcing and the wave models are scaled at approximately a 12km resolution – this is particularly important for representation of wind structures in frontal zones and for the waves to provide a sensible description of the coastline and short fetch areas. This contrasts with model data for the 1998 study, where the wave model was resolved at approximately 25km and the wind data came from a global atmospheric model scaled between 75km and 60km. The impact of these differences is most keenly felt in and around the more complex areas of coastline.

4. Recent years have seen an unprecedented level of in-situ wave monitoring around the UK coastline. The campaigns include work by the Met Office, Irish Marine Institute, CEFAS/Environment Agency and Channel Coast Observatory. The deployments are summarized on the WaveNet website[1]. In terms of data return, accuracy, precision and consistency the in-situ measurements are believed to provide a significantly improved observed baseline relative to the manual ship observations used in the 1998 study. In addition, each observation site is at a fixed location, which enables a direct spot comparison between the model statistics and the observed data. In the 1998 study such a comparison was not available since the ships data produced an Hs derived over an area.

[1] http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx

One drawback of the in-situ dataset is that at some locations the sampling period is comparatively short (approximately 1-2 years).

3. Area contour maps and confidence

This section presents area maps showing:

- Hs exceedence contours provided in the shapefiles
- the gridded model data on which the contours are based
- extension lines inferring the likely trajectory of contours shoreward of the model grid – <u>these are provided to aid visualization only</u>
- locations of in-situ observations.

The purpose of presenting the data in this manner is to allow a discussion of the confidence placed in each set of contours. This is primarily based on comparison of collocated model data with the in-situ observations, known model issues in shallow water, and extent of the gridded dataset.

To enable comparison with the 1998 study maps are presented using a similar geographic breakdown, i.e. :

- Figures 3.1 – 3.4, North East
- Figures 3.5 – 3.8, North West
- Figures 3.9 – 3.12, South East
- Figures 3.13 – 3.16, South West
- Figures 3.17 – 3.20, Orkney and Shetland

The Isles of Scilly are not presented explicitly in this section, but are discussed along with the South West and again in Section 5.

High energy wave regimes outside of the regions shown in the figures, but important to verifying the models' performance in the North Atlantic, were assessed at M1, M3, M4 and K5 buoys. In all cases the data exhibited a small to moderate (less than 10% of significant wave height) error at exceedence thresholds between 50% and 1%, with the model data generally over-estimating at the M-buoys and under-estimating at the K-buoy. This level of performance in open waters surrounding the UK demonstrates that the models accurately represent waves generated by storms tracking toward the UK. Details of the verification can be found in Appendix A.

3.1 North East

Contours and extension lines, gridded data and buoy locations are shown in Figures 3.1 - 3.4. Extension lines are provided for visual continuity only and should be treated with low confidence. Similarly visual interpolation to contour levels between those given is not recommended.

Relevant verification sites and the errors between model and observed Hs exceedence quantiles are described in Table 3.1. Errors are discussed based on the verification plots provided in Appendix A. In the table errors are termed small if within the larger of 0.2m or 5% of Hs, moderate if up to 0.5m or 10% of Hs, and large otherwise. The term positive bias is used if the model consistently over-estimates, and negative bias is used if the model under-estimates. A description of varying bias is given if the errors are inconsistent (e.g. positive bias at lower quantiles becoming negative bias at higher quantiles).

Site Name	Latitude (deg.dec)	Longitude (deg.dec)	Annual Error Description	Summer Error Description
Moray Firth	57.96 N	3.33 W	Small	Small negative bias above 90%
Firth of Forth	56.19 N	2.50 W	Small negative bias to 10%; large negative bias at 1%	Small negative bias to 10%; large negative bias at 1%
Tyne Tees	54.92 N	0.75 W	Small	Small to 5%; varying to moderate negative bias at 1%
Dowsing	53.53 N	1.05 E	Small positive bias to 5%; varying small negative bias to 1%	Small positive bias

Table 3.1 Location and error description for buoys relevant to the North East region.

The small errors at the 10% exceedence threshold and the near coastal location of the observation sites suggest that good confidence can be placed in the contours up to the 2.5m value for the 10% threshold in this region. South of Peterhead the position of 3m and 4m contours are generally expected to be reliable; the slightly lower wave heights over Dogger Bank which give rise to a ‘kink’ in the contours are expected to be physically consistent although the contours are liable to be slightly less precise in their position here. Contours between Peterhead and Orkney are expected to be conservative (i.e. positioned shoreward of their most likely location) due to the model grid potentially allowing too much Atlantic wave energy to flow between Orkney and Shetland into the northwest of the North Sea. Grid definition limitations preclude drawing 1m and 1.5m contours along large stretches of this coast.

At the 1% exceedence threshold the model appears to under-estimate in Summer and in particular for the Firth of Forth. On this basis the 3m Summer contour running between Arbroath and Spurn Head might be considered to be placed too far offshore. Further north and in the Annual data the 1% contours can be considered slightly more reliable.

It is suggested from these data that the Firth of Forth might be considered a particular site for higher resolution assessment of the wave climate.

Comparing 10% exceedence values with the 1998 study, both Annual and Summer contours appear reasonably consistent although the new contours are positioned several kilometres shoreward, suggesting more energetic waves in the new data. The 1998 contours indicate a stronger curvature in toward the Moray Firth than the more recent data. This is believed to be due to the different ways in which the different models may have blocked wave energy flowing into the northwest North Sea. If the present data are considered conservative then in the Moray Firth approaches the 1998 data can probably be considered even more so.

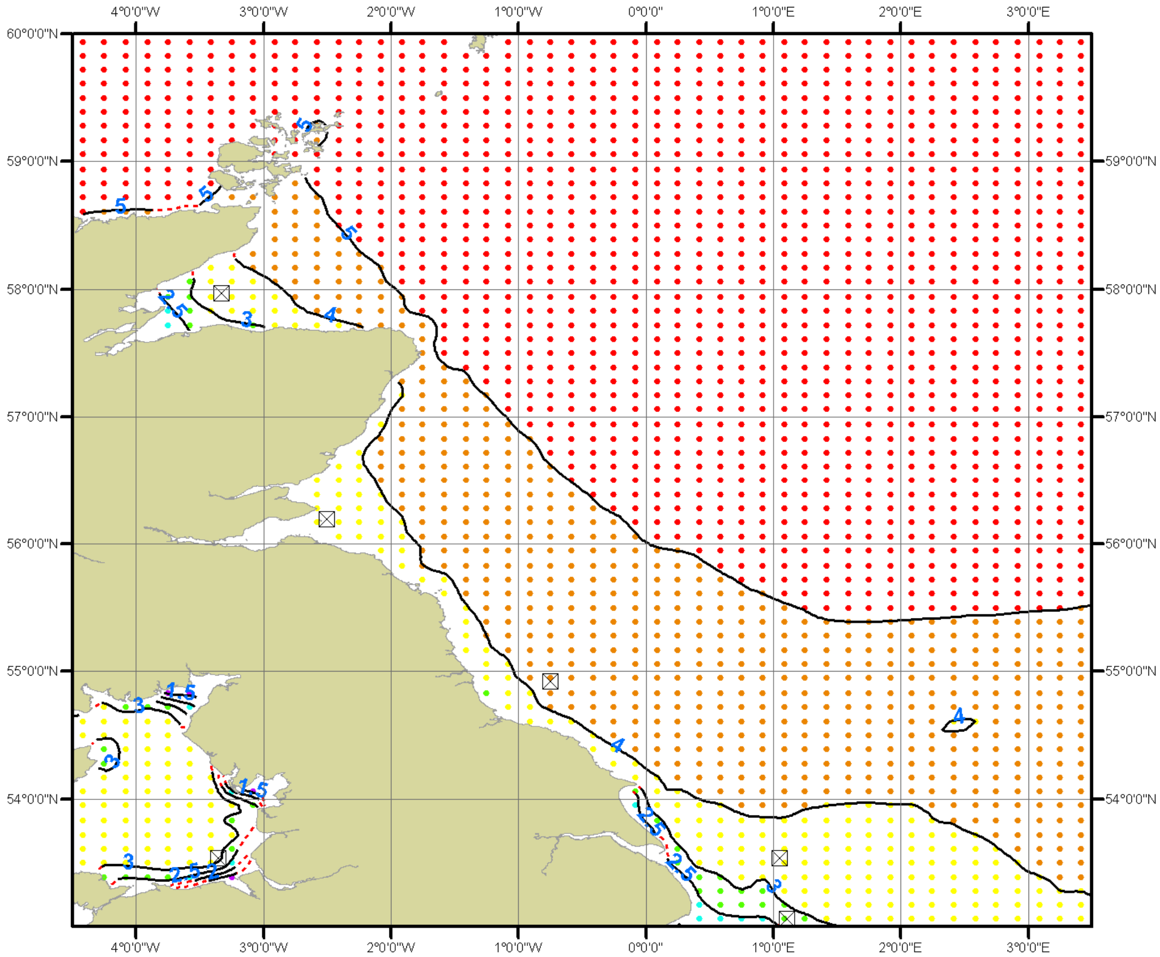

Figure 3.1 Significant wave height 1% exceedence contours for Annual period.

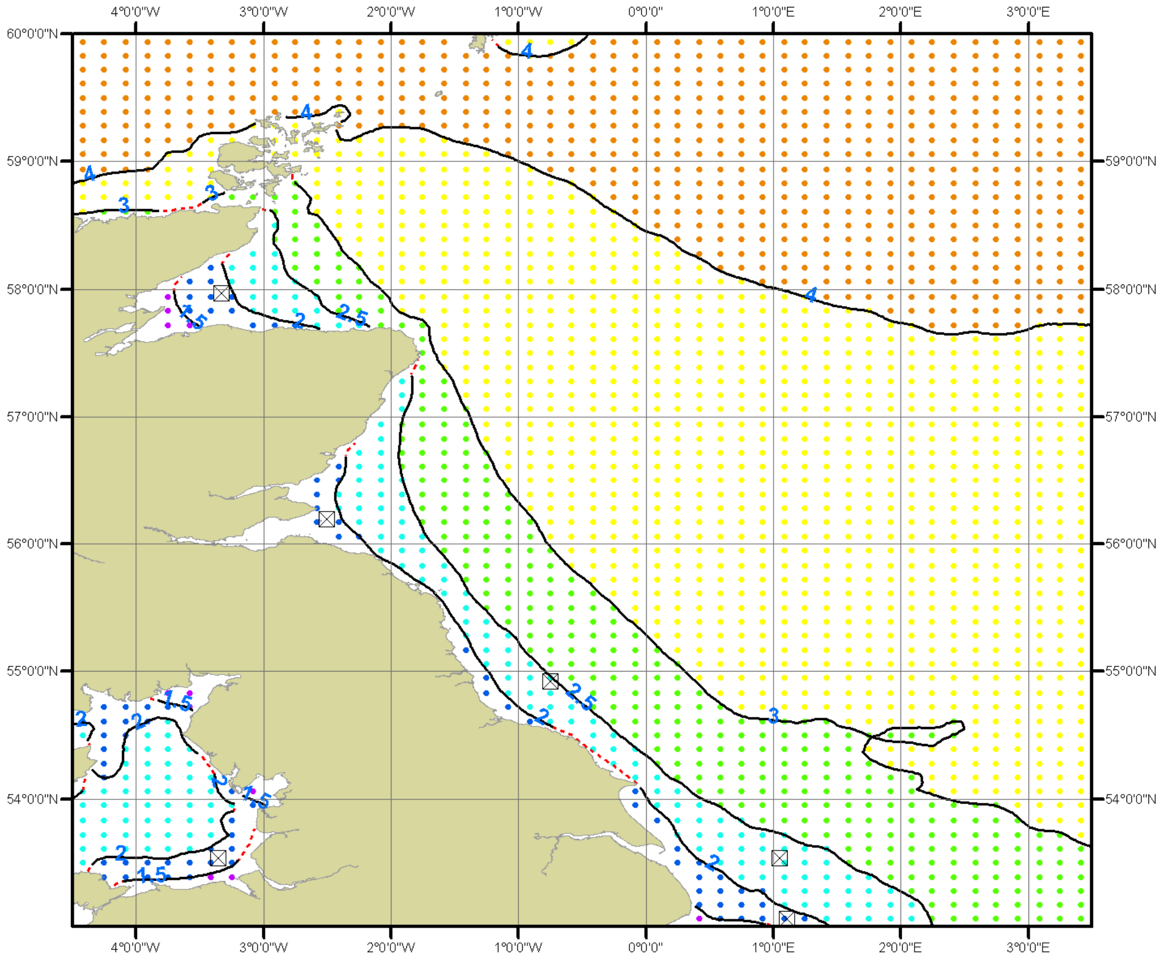

Figure 3.2 Significant wave height 10% exceedence contours for Annual period.

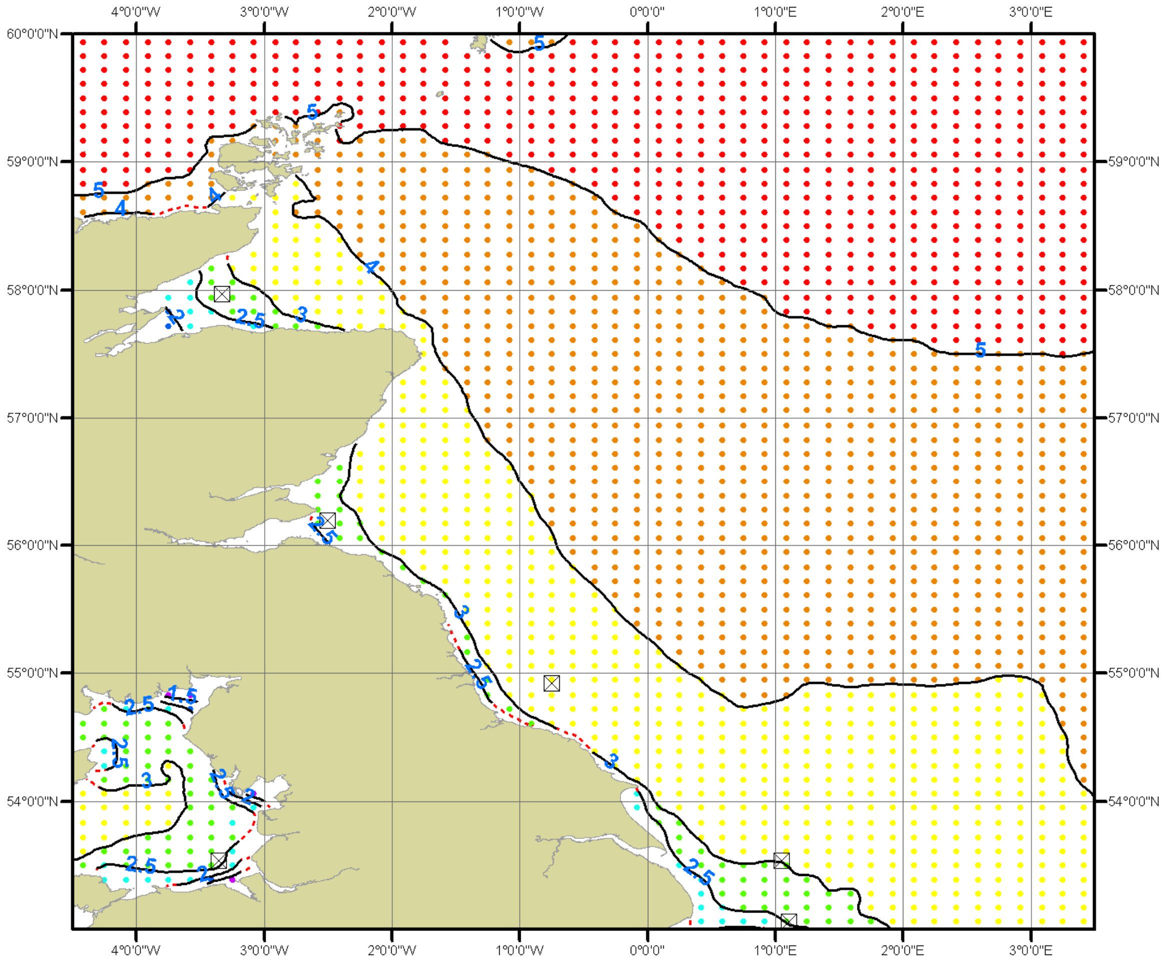

Figure 3.3 Significant wave height 1% exceedence contours for Summer period.

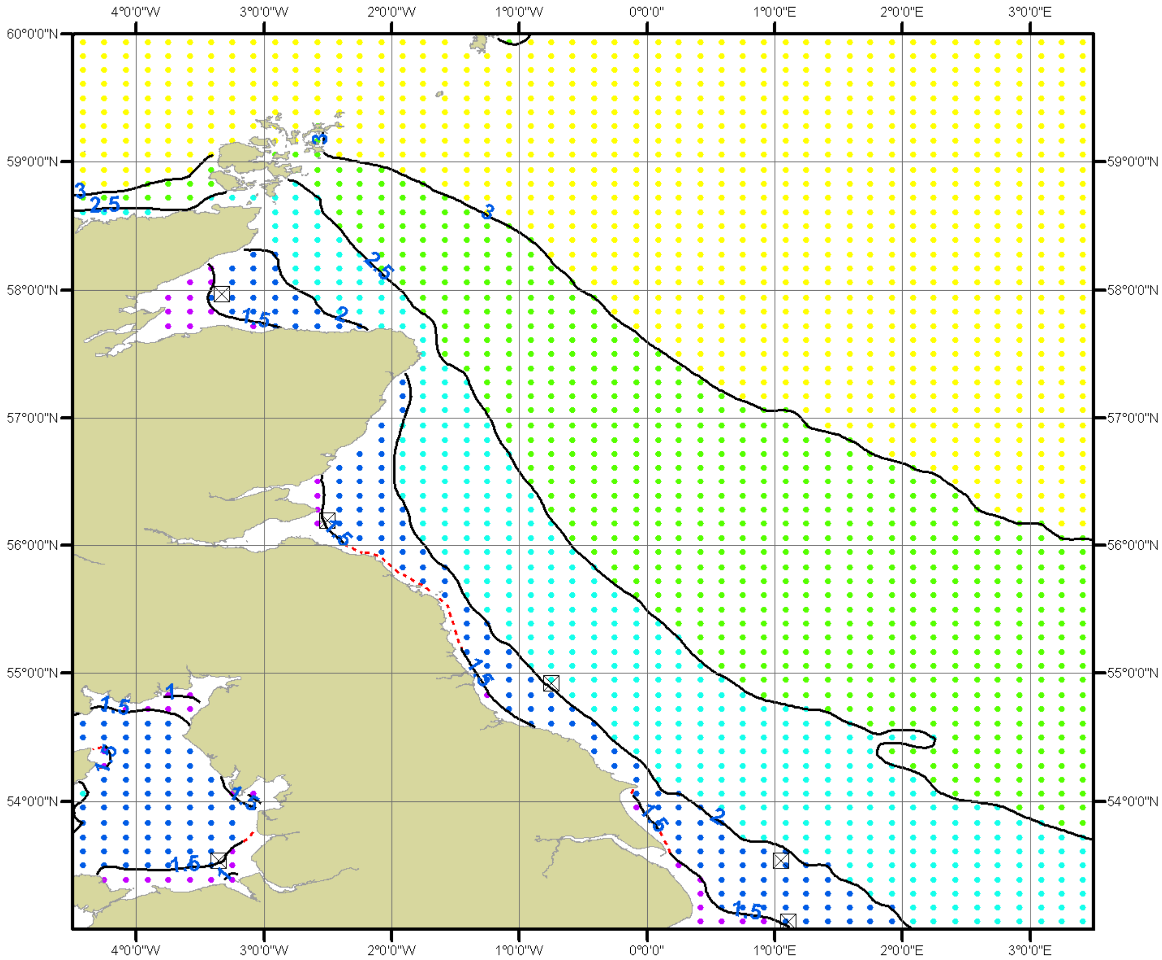

Figure 3.4 Significant wave height 10% exceedence contours for Summer period.

3.2 North West

Contours and extension lines, gridded data and buoy locations are shown in Figures 3.5 - 3.8. Extension lines are provided for visual continuity only and should be treated with low confidence. Similarly visual interpolation to contour levels between those given is not recommended.

Relevant verification sites and the errors between model and observed Hs exceedence quantiles are described in Table 3.2. Errors are discussed based on the verification plots provided in Appendix A. In the table errors are termed small if within the larger of 0.2m or 5% of Hs, moderate if up to 0.5m or 10% of Hs, and large otherwise. The term positive bias is used if the model consistently over-estimates, and negative bias is used if the model under-estimates. A description of varying bias is given if the errors are inconsistent (e.g. positive bias at lower quantiles becoming negative bias at higher quantiles).

Site Name	Latitude (deg.dec)	Longitude (deg.dec)	Annual Error Description	Summer Error Description
W. Hebrides	57.29 N	7.91 W	Small positive bias	Small positive bias
Blackstones	56.06 N	7.06 W	Small	Small negative bias
M2	53.48 N	5.42 W	Small positive bias	Small positive bias
Liverpool Bay	53.53 N	3.35 W	Small positive bias	Small positive bias

Table 3.2 Location and error description for buoys relevant to the North West region.

The small errors at both the 10% and 1% exceedence thresholds and for observation locations in both northwest approaches and the Irish Sea suggest that good confidence can be placed in the contours a grid point or more away from the coast. The main limitations around the North West region are therefore based on the detail at which the model grid resolves the coastline, particularly around the Inner and Outer Hebrides, Isle of Man and approaches to the Mersey, Morecambe Bay and the Solway Firth. This is mostly an impact for the 1% threshold data and it is recommended that positions of contours less than 3m in the Annual 1% contours and 2.5m in the Summer 1% contours are treated as an approximation in these regions.

For the Summer data, comparison of 1998 study and 2011 study contours in the north west approaches from the Atlantic are reasonably consistent. In the Annual data the 2011 study contours at 3m and higher are shifted further offshore suggesting a slightly more benign wave climate. Since we might expect the two models to perform most consistently in open waters this might suggest some change in wave climate (see Section 4).

Comparing the contours less than 2.5m, which are located in the North Minch, Inner Minch, North Channel, Firth of Clyde and Irish Sea, significant extra detail is provided by the 2011 dataset. In the North and Inner Minch this is due to the 2011 data explicitly modelling the region, where in the 1998 study the contours were derived from land wind observations and manual estimation of fetch. In the Firth of Clyde and Irish Sea it is also expected that the 2011 data is more likely to be correct in these regions, since even at 12km the number of grid cells making up local fetches are relatively small (2-5 grid points) and the 1998 25km data will have therefore poorly resolved these. Nevertheless a number of these areas would benefit from an even higher resolution treatment.

For the North West, key locations that might require a more detailed study are the stretch of coast from Luce Bay to Solway Firth in Liverpool Bay, the Firth of Clyde and the Inner Hebrides.

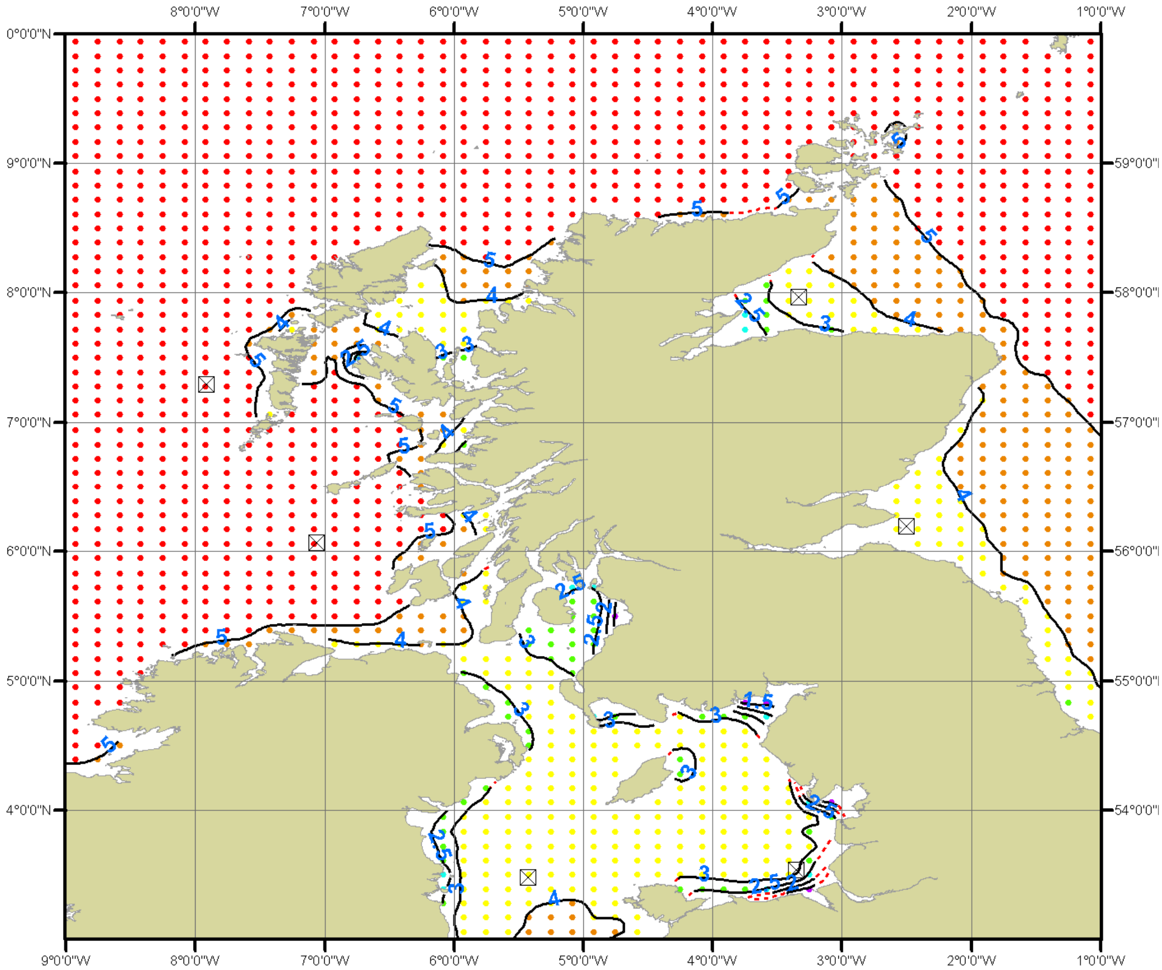

Figure 3.5 Significant wave height 1% exceedence contours for Annual period.

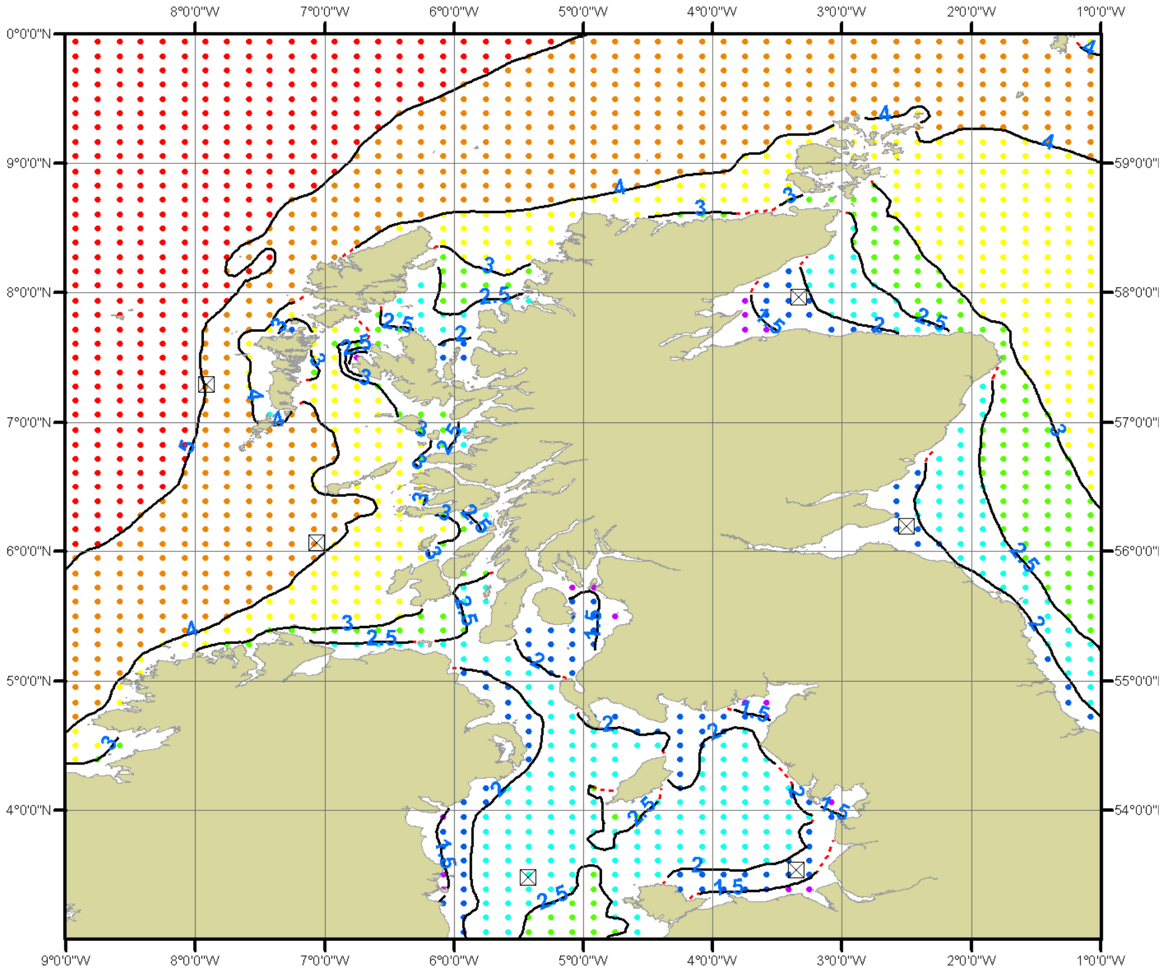

Figure 3.6 Significant wave height 10% exceedence contours for Annual period.

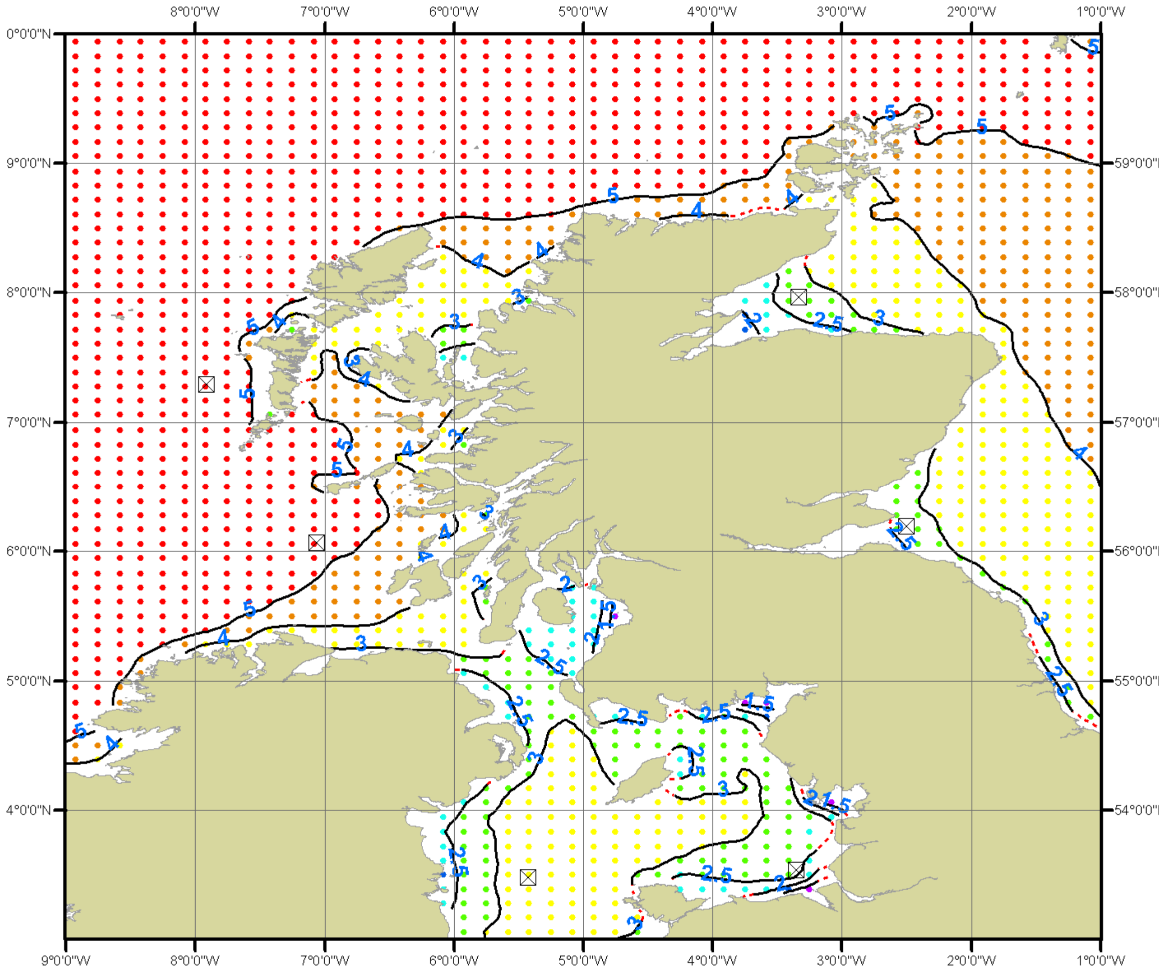

Figure 3.7 Significant wave height 1% exceedence contours for Summer period.

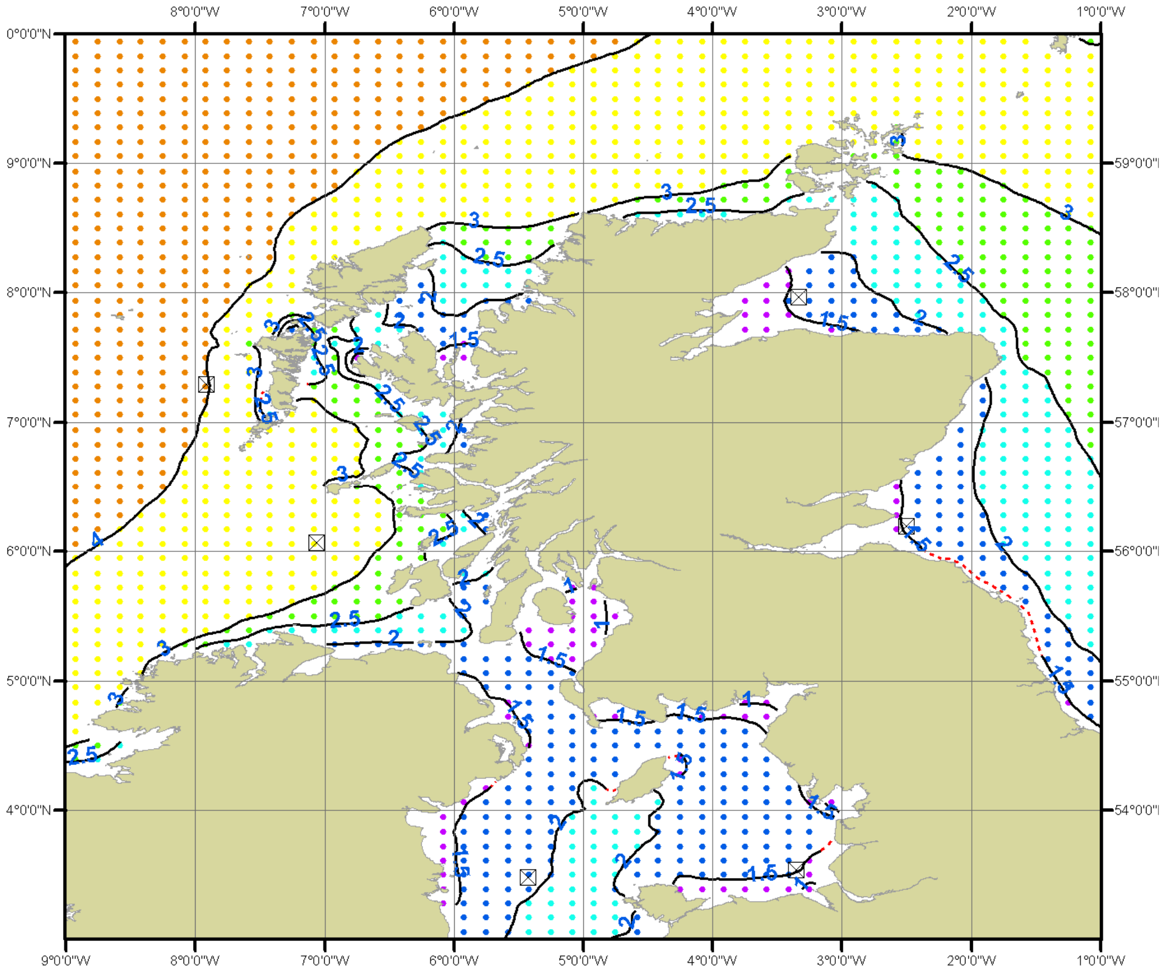

Figure 3.8 Significant wave height 10% exceedence contours for Summer period.

3.3 South East

Contours and extension lines, gridded data and buoy locations are shown in Figures 3.9 - 3.12. Extension lines are provided for visual continuity only and should be treated with low confidence. Similarly visual interpolation to contour levels between those given is not recommended.

Relevant verification sites and the errors between model and observed Hs exceedence quantiles are described in Table 3.3. Errors are discussed based on the verification plots provided in Appendix A. In the table errors are termed small if within the larger of 0.2m or 5% of Hs, moderate if up to 0.5m or 10% of Hs, and large otherwise. The term positive bias is used if the model consistently over-estimates, and negative bias is used if the model under-estimates. A description of varying bias is given if the errors are inconsistent (e.g. positive bias at lower quantiles becoming negative bias at higher quantiles).

Site Name	Latitude (deg.dec)	Longitude (deg.dec)	Annual Error Description	Summer Error Description
Dowsing	53.53 N	1.05 E	Small positive bias to 5%; varying small negative bias to 1%	Small positive bias
Blakeney Overfalls	53.06 N	1.11 E	Small positive bias	Small positive bias
W. Gabbard	51.98 N	2.08 E	Small positive bias	Small positive bias
South Knock	51.57 N	1.58 E	Small positive bias to 10%; varying moderate positive bias to 1%	Small positive bias to 10%; varying moderate positive bias to 1%
Hastings	50.75 N	0.75 E	Small positive bias to 10%; varying moderate positive bias to 1%	Small positive bias to 10%; varying moderate positive bias to 1%
Poole Bay	50.63 N	1.71 W	Small positive bias	Small positive bias

Table 3.3 Location and error description for buoys relevant to the South East region.

The generally small positive errors at the 10% exceedence thresholds against observations at both offshore and near coastal locations suggest that good confidence can be placed in the contours a grid point or more away from the coast. 1% contours may be placed slightly conservatively, i.e. shoreward of their actual position. Less certainty is placed in the position of contours running very close to the coast, for example from Beachy Head to the Isle of Wight, and into the Wash and Thames Estuary. This is due to resolution limitations of the model grid. The Solent is not resolved at all in the data. Sheltering and strong tidal effects around the Channel Islands, Isle of Wight, Poole Bay and Weymouth Bay are not fully resolved.

The contours in this study and the 1998 study are consistent for this region.

Key locations that are recommended for more detailed study are approaches to the Thames, the Solent and the Isle of Wight, and Poole Bay. It is worth noting that a significant number of observing platforms deployed as part of the WaveNet (http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx) program and Channel Coast Observatory (http://www.channelcoast.org) network are available shoreward of the model grid in this region.

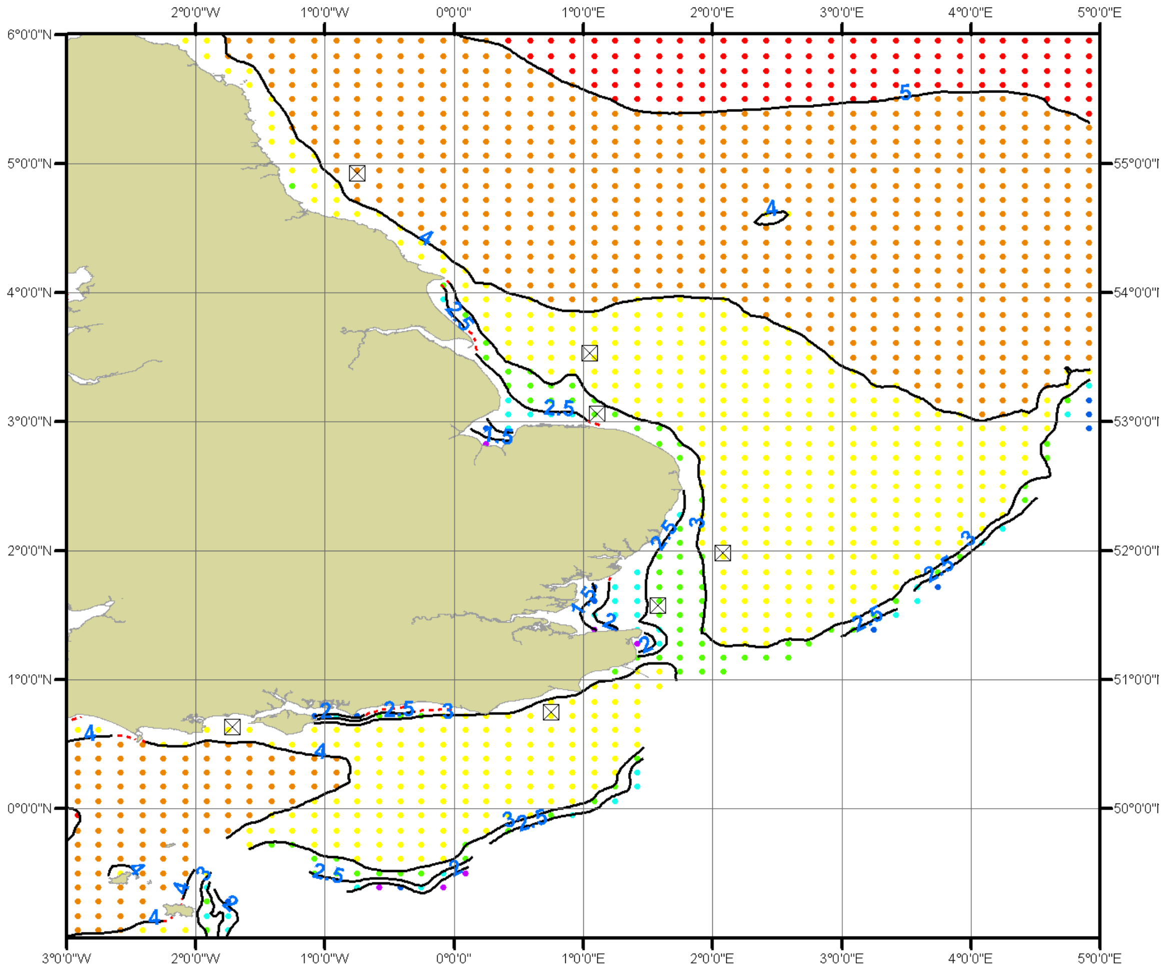

Figure 3.9 Significant wave height 1% exceedence contours for Annual period.

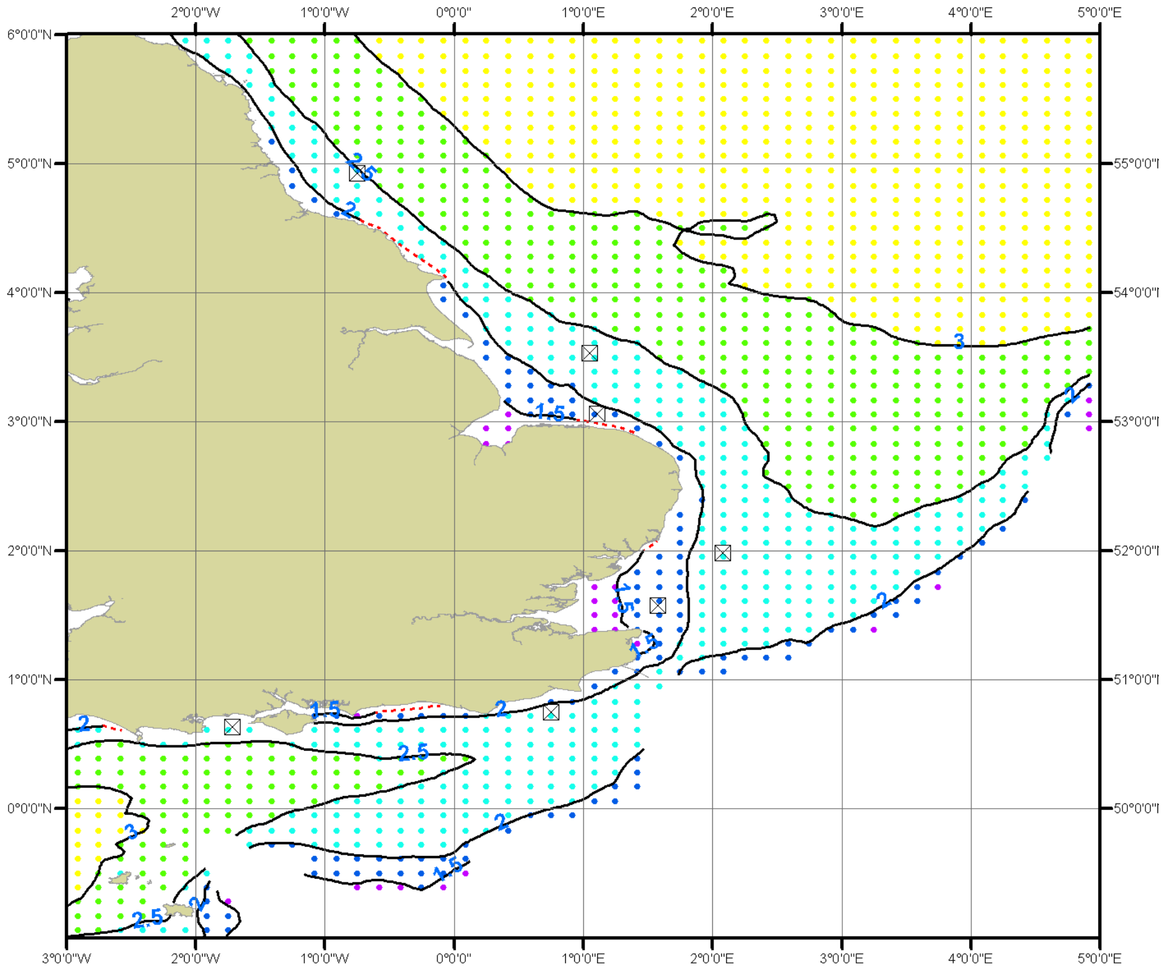

Figure 3.10 Significant wave height 10% exceedence contours for Annual period.

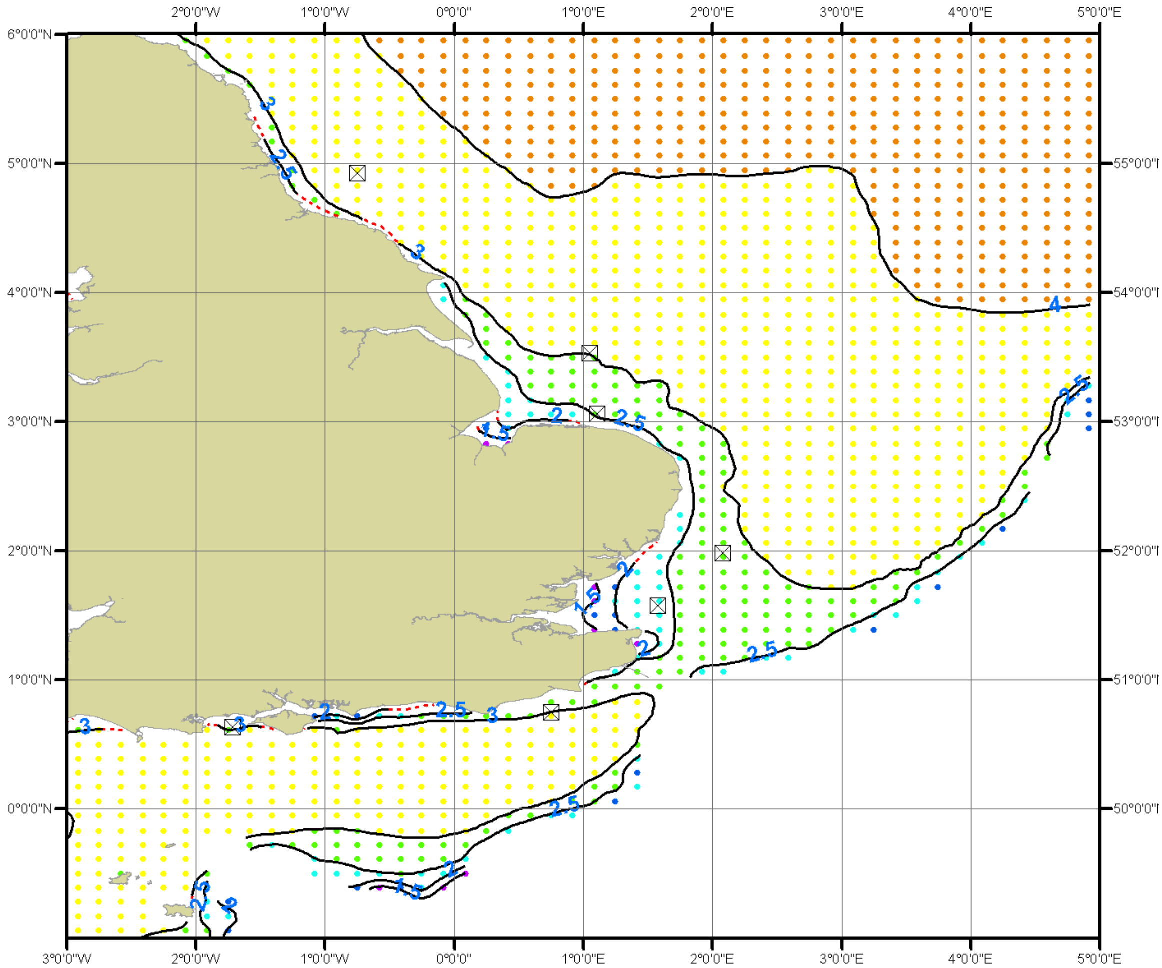

Figure 3.11 Significant wave height 1% exceedence contours for Summer period.

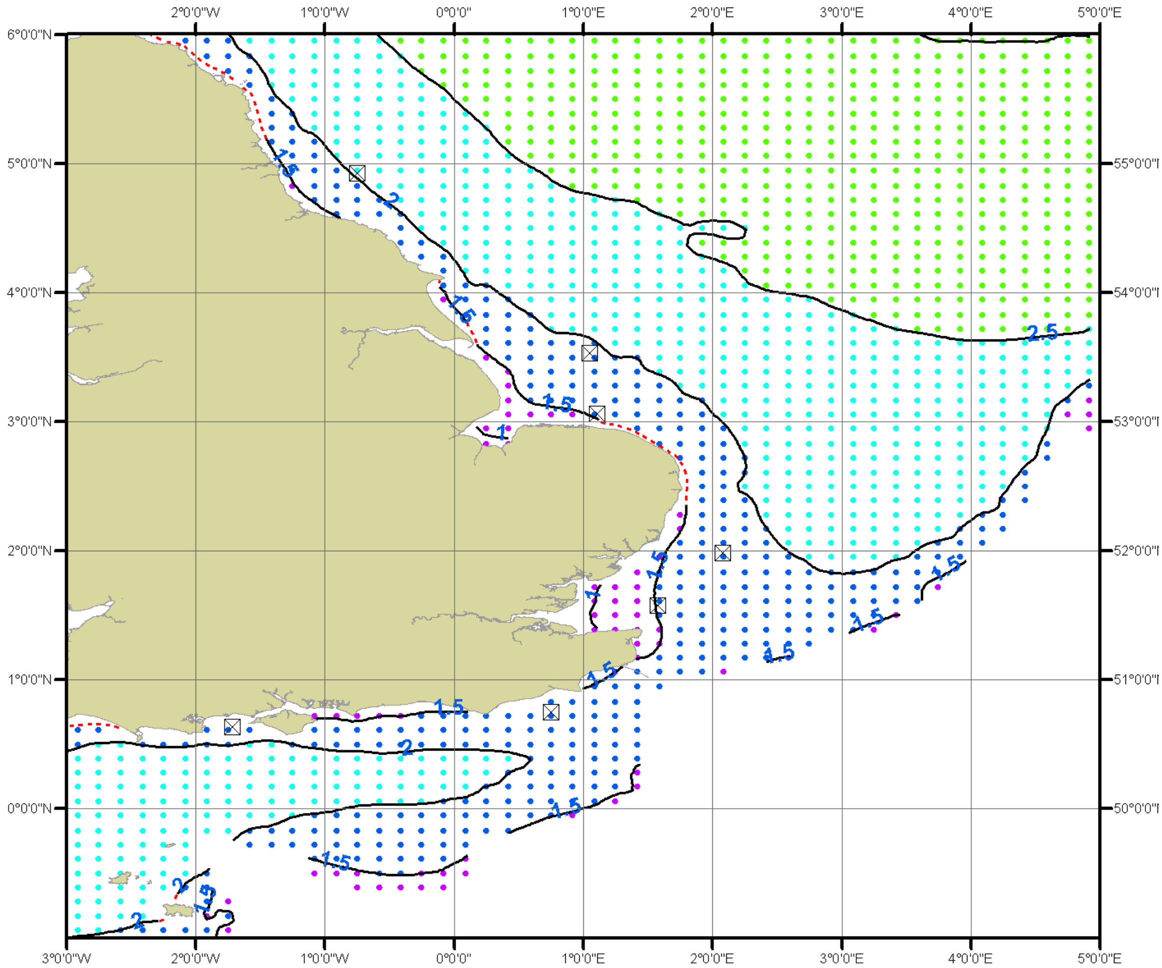

Figure 3.12 Significant wave height 10% exceedence contours for Summer period.

3.4 South West

Contours and extension lines, gridded data and buoy locations are shown in Figures 3.13 - 3.16. Extension lines are provided for visual continuity only and should be treated with low confidence. Similarly visual interpolation to contour levels between those given is not recommended.

Relevant verification sites and the errors between model and observed Hs exceedence quantiles are described in Table 3.4. Errors are discussed based on the verification plots provided in Appendix A. In the table errors are termed small if within the larger of 0.2m or 5% of Hs, moderate if up to 0.5m or 10% of Hs, and large otherwise. The term positive bias is used if the model consistently over-estimates, and negative bias is used if the model under-estimates. A description of varying bias is given if the errors are inconsistent (e.g. positive bias at lower quantiles becoming negative bias at higher quantiles).

Site Name	Latitude (deg.dec)	Longitude (deg.dec)	Annual Error Description	Summer Error Description
Looe Bay	50.33 N	4.41 W	Large positive bias	Large positive bias
Perranporth	50.35 N	5.17 W	Small	Small positive bias
Scarweather Sands	51.43 N	3.93 W	Small positive bias	Small positive bias
Turbot Bank (Pembroke)	51.6 N	5.10 W	Small variable bias	Small variable bias
M5	51.65 N	6.70 W	Large positive bias	Moderate positive bias at 10% varying large at 1%
Aberporth	52.30 N	4.50 W	Small positive bias	Small positive bias

Table 3.4 Location and error description for buoys relevant to the South West region.

Comparison with observations at locations along the north Cornwall and Devon coast, and Welsh coastline suggest a reasonable confidence can be placed in contour positions in these areas at both 10% and 1% levels. A caveat is placed on interpretation of the data east of Scarweather Sands into the upper reaches of the Bristol Channel, where strong tidal flows may heavily influence wave height and steepness. Large positive biases are noted at M5 (approaches to St George's Channel) and in Looe Bay (Cornwall south coast). The Looe Bay errors are explained by the shallow water (10m) location of the buoy, and particularly the short time observed period (1 year) available to compare with the 10 year model climatology (errors are eliminated when a direct year to year comparison are used; see figures A.10 versus A.25). However, headland blocking along the south coast may also not be entirely resolved in the 12km model grid and as a result the 2m, 2.5m and 3m contours in the southwest approaches to the English Channel are considered conservative (i.e. erring toward a shoreward position).

The longer sampling period at M5 rules out aliasing due to sample size, and since biases in waters further west in the Celtic Sea (e.g. at M3) are small it is most likely that the model has poorly represented a combination of blocking effects around the southern-most tip of Ireland and refraction and dissipation on the Nymphe Bank. Since the impacts are limited north of St George's channel the main effect of this bias is expected to be applicable to the most seaward contour running between approximately 8.00W and 5.50W. Contours running between St Govans Head (Wales) and Carnsorpe Point (Ireland) should be considered as placed conservatively to the north, but probably only by one or two grid points (10-25km).

Comparison of 10% contours from the 1998 and 2011 studies indicate that 3.0m and 4.0m contours are similarly positioned for both Summer and Annual data. For contours at 2.5m, 2m and 1.5m the 2011 data appears more conservative, generally placing these further shoreward. In general the agreement between observations and the model plus the extra detail at which the coast is resolved in the new data suggests that the new contours can be leant more credence.

The 1998 study generated separate maps for the Scilly Isles and surrounding waters based on analysis of wind data and estimation of fetch lengths. Since no improved data source existed to use in the 2011 study the assumption has been made that the 1998 figures still provide a best estimate. In making this assumption, two issues should be recognised:

1. There will be significant variations in wave climate in the waters between islands at a detail over and above that given in either the 2011 or 1998 contours. Generating information at this level requires downscaling.

2. Neither the 1998 or 2011 studies recognise the role played by the Scillies in blocking wave energy travelling toward southwest Cornwall. This suggests that the proximity of contours to Lands End and the Lizard may be slightly conservative.

In the South West, other key locations that might require more detailed study are identified as Mounts Bay and the Bristol Channel east of Minehead. It is worth noting that a significant number of observing platforms deployed as part of the Channel Coast Observatory (http://www.channelcoast.org) network are available shoreward of the model grid in this region.

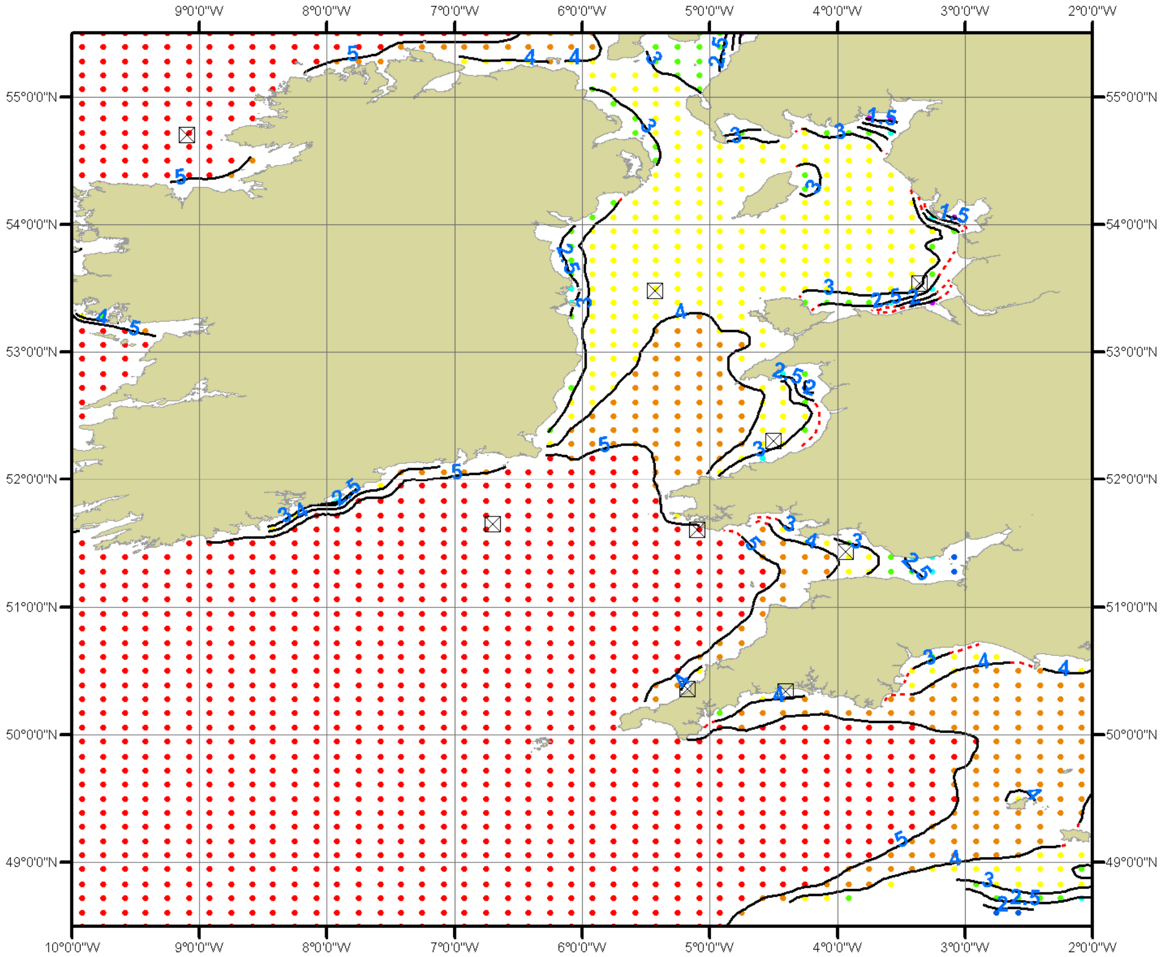

Figure 3.13 Significant wave height 1% exceedence contours for Annual period.

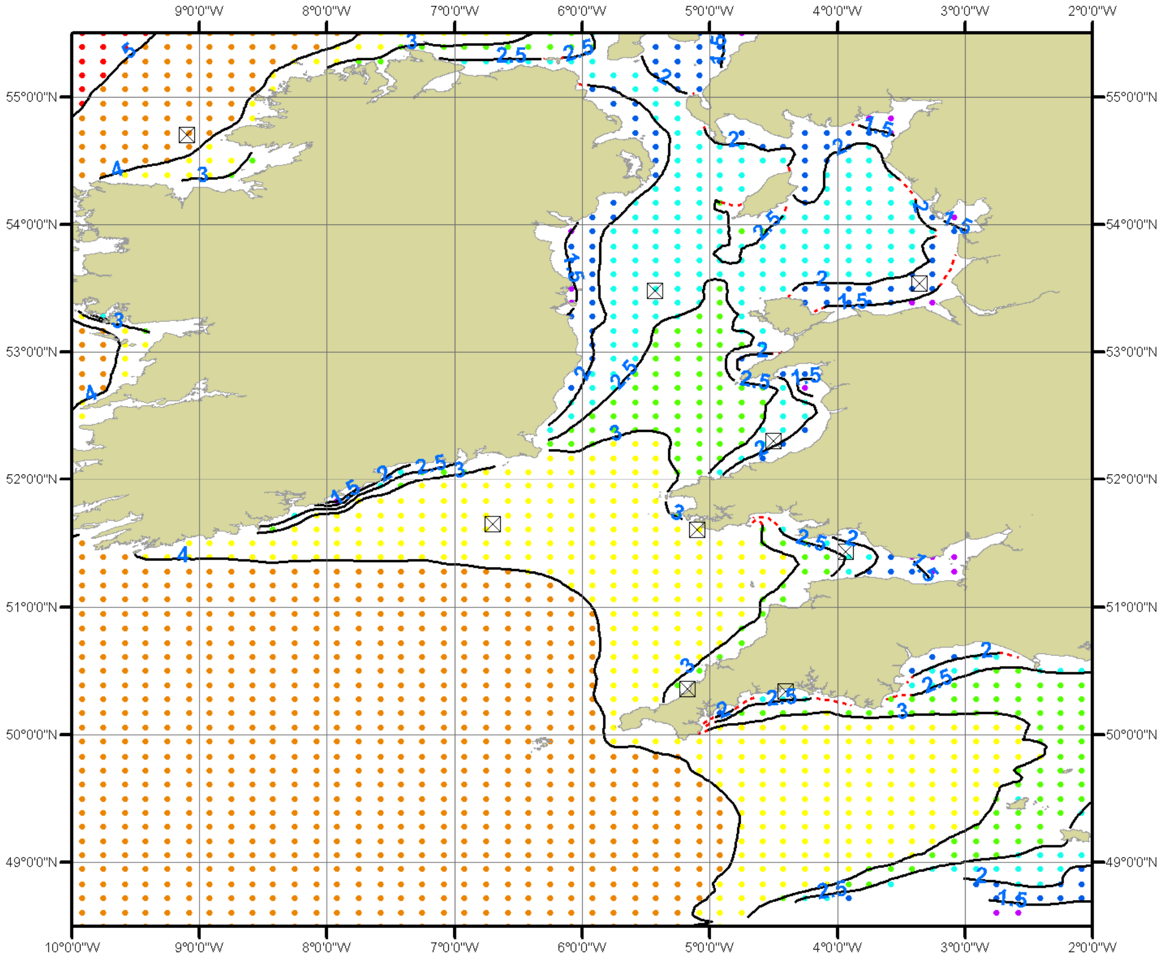

Figure 3.14 Significant wave height 10% exceedence contours for Annual period.

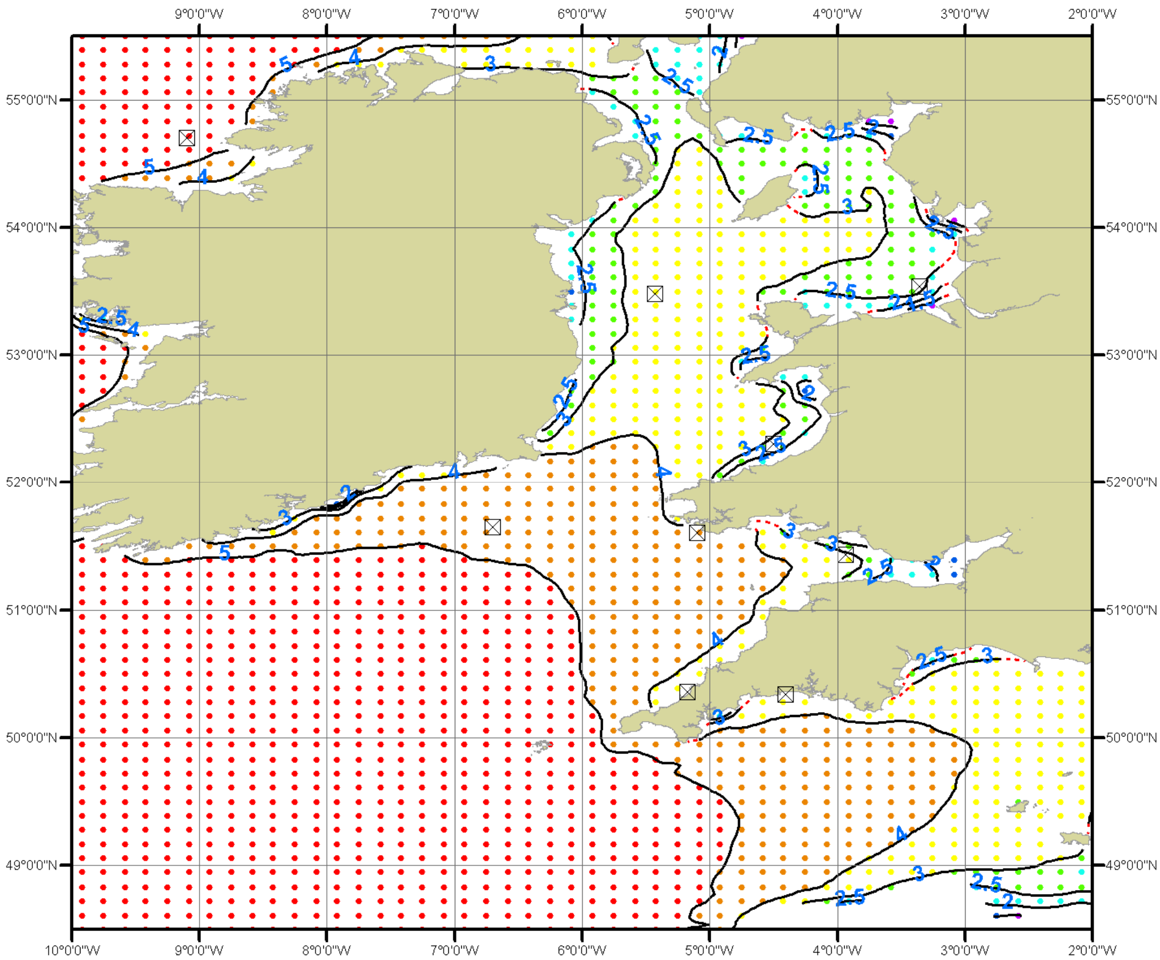

Figure 3.15 Significant wave height 1% exceedence contours for Summer period.

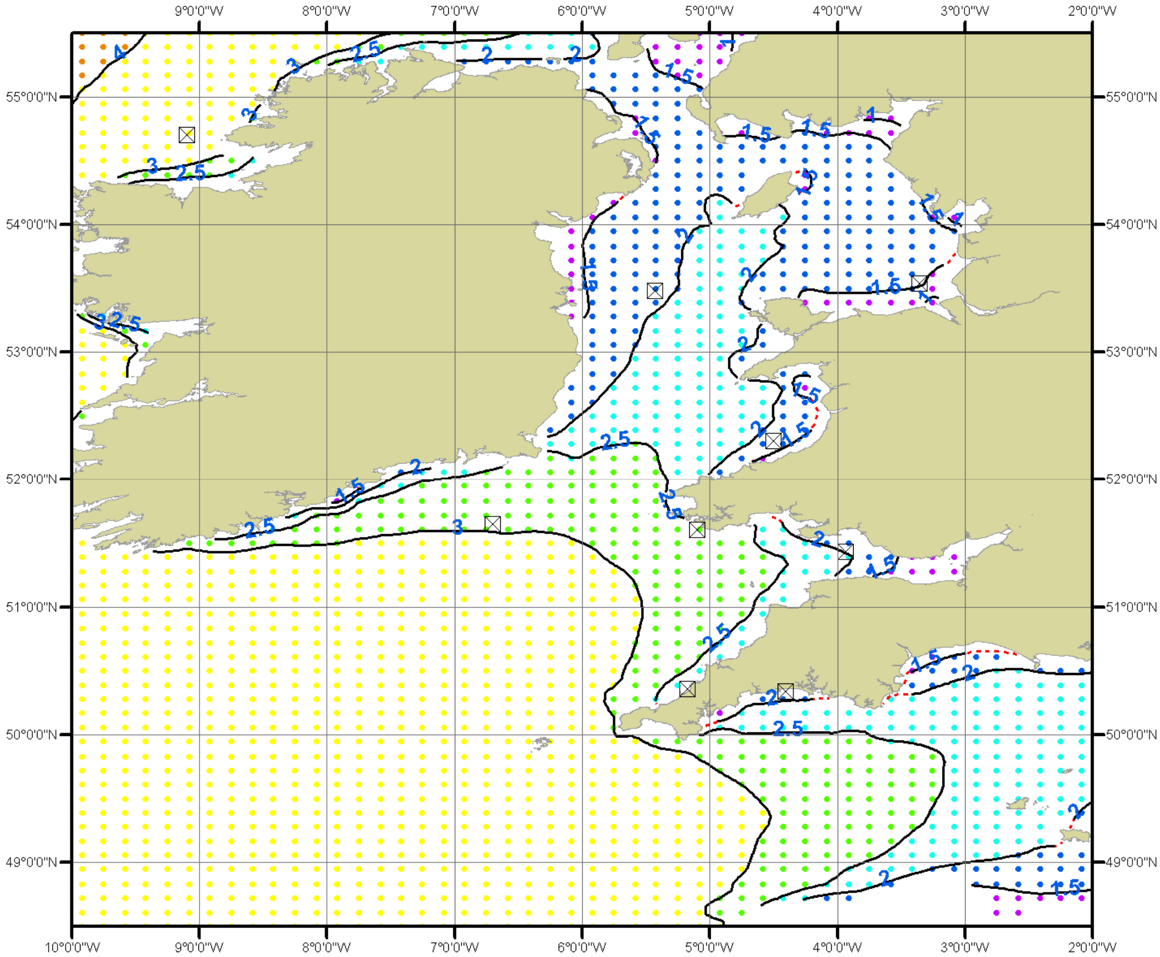

Figure 3.16 Significant wave height 10% exceedence contours for Summer period.

3.5 Orkney and Shetland

Contours and extension lines, gridded data and buoy locations are shown in Figures 3.17 - 3.20. Extension lines are provided for visual continuity only and should be treated with low confidence. Similarly visual interpolation to contour levels between those given is not recommended.

Relevant verification sites and the errors between model and observed Hs exceedence quantiles are described in Table 3.5. Errors are discussed based on the verification plots provided in Appendix A. In the table errors are termed small if within the larger of 0.2m or 5% of Hs, moderate if up to 0.5m or 10% of Hs, and large otherwise. The term positive bias is used if the model consistently over-estimates, and negative bias is used if the model under-estimates. A description of varying bias is given if the errors are inconsistent (e.g. positive bias at lower quantiles becoming negative bias at higher quantiles).

Site Name	Latitude (deg.dec)	Longitude (deg.dec)	Annual Error Description	Summer Error Description
K7	60.70 N	4.50 W	Small negative bias at 10% varying moderate negative bias at 1%	Small positive bias

Table 3.5 Location and error description for buoys relevant to the Orkney-Shetland region.

The K7 buoy is located in deep open waters to the west of the region, and is therefore only a useful indicator of the wave energy flowing toward the islands rather than how the model deals with waves close to the island. The negative bias at 1% in the annual data reflects limitations of the model at very high wave heights (over 8m), but these will have no impact on this study. As a result good confidence can be placed in contours to the north and west of the islands, but it is harder to give confidence levels for the sheltered areas downstream. In particular this applies to waters immediately to the south east of Orkney since Westray-Sanday are not well masked in the model grid, and waters through and immediately downstream of the Pentland Firth (where strong tides will also have an effect). Waters within the boundaries of the islands are not resolved in this study.

The contours in this study are conservative compared to the 1998 study, particularly immediately to the east of Shetland.

More detailed work around Orkney to generate data for inter-island waters is necessary.

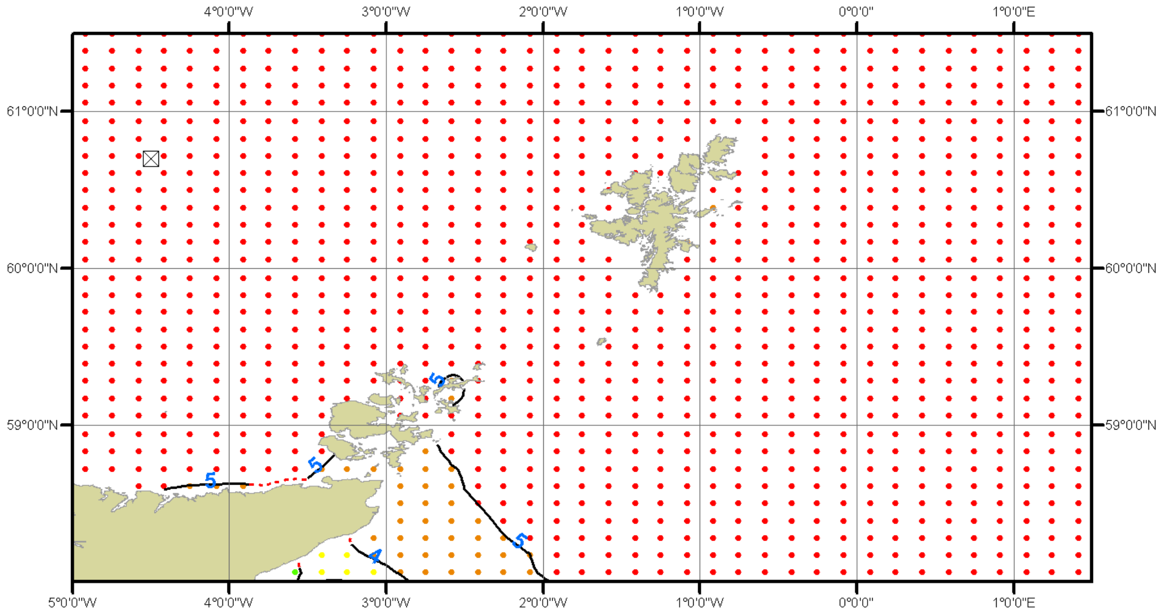

Figure 3.17 Significant wave height 1% exceedence contours for Annual period.

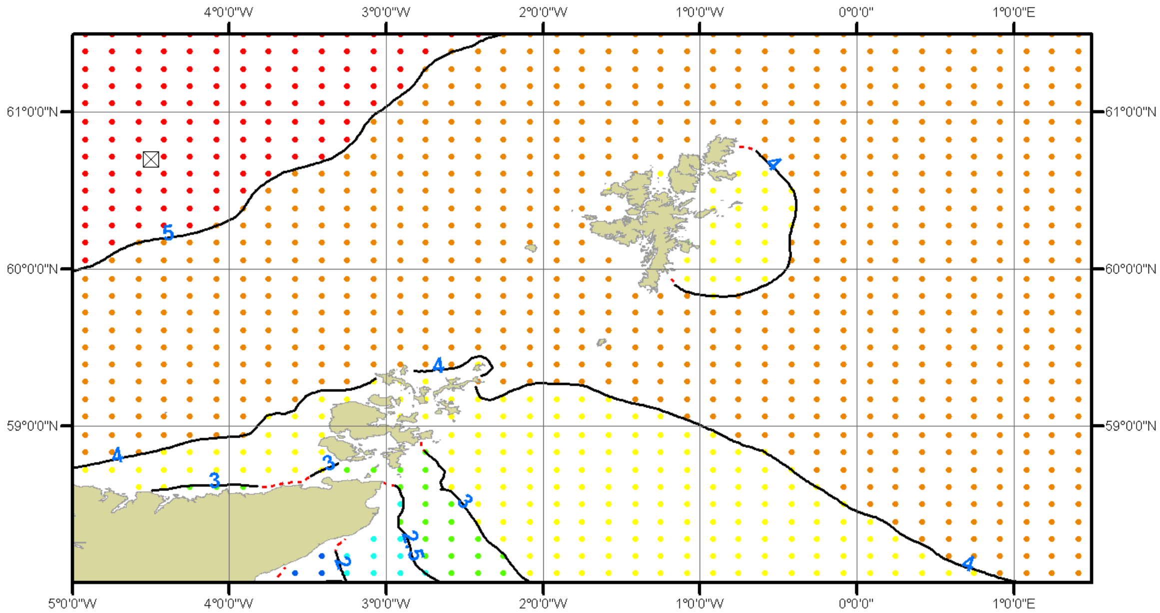

Figure 3.18 Significant wave height 10% exceedence contours for Annual period.

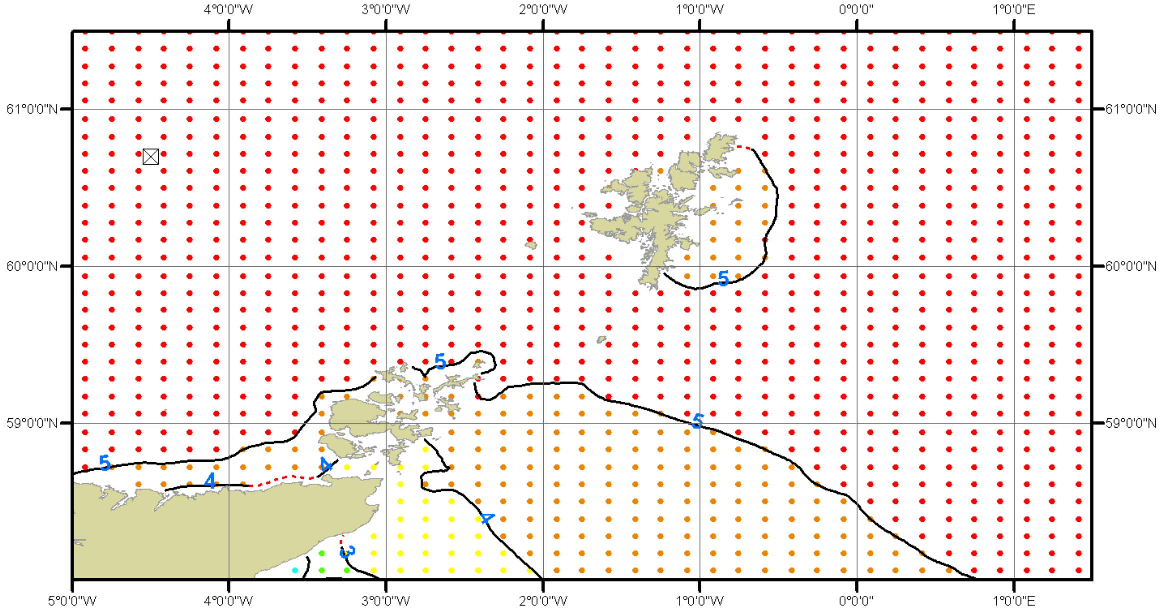

Figure 3.19 Significant wave height 1% exceedence contours for Summer period.

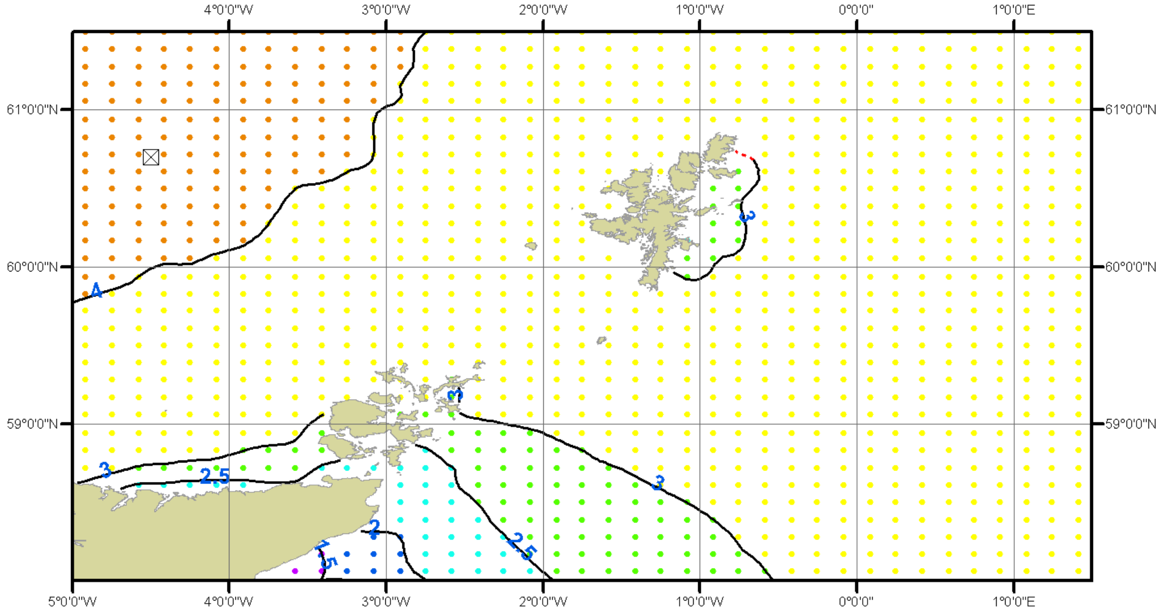

Figure 3.20 Significant wave height 10% exceedence contours for Summer period.

4. Evidence for climate change

In order to discuss how climate change might have affected data in the two studies it is important to recognise several factors that could influence the conclusions.

Wave climate in different regions of the UK is sensitive to not only to storminess, but also the latitudes along which storms propagate (also known as the storm track). This is because the major sea basins around much of the UK coast (North Sea, English Channel and Irish Sea) are effectively distinct semi-enclosed basins, which for a given storm can potentially have very different exposures to winds and incoming waves from the North Atlantic. An example of this effect would be that a season with a higher population of lower latitude storm tracks leads to the wave climate in the English Channel being substantially higher than for a season with more intense and regular storms but which generally track north of Scotland.

These sensitivities lead to significant inter-annual and inter-decadal variabilities which are believed to have some association with known climate signals such as the North Atlantic Oscillation (NAO). Figure 4.1 shows the observed NAO signal over the last 150 years. In very general terms the positive phases are more likely to be associated with higher wave energy which particularly affects the North West, Scotland and North Sea. Negative phases are more likely to be associated with generally calmer conditions, but can also be associated with more a southerly storm track that will more frequently direct wave energy toward the South West approaches and the English Channel.

Both 1998 and 2011 study periods are dominated by positive NAO phases but also comprise some negative phase data, so are expected to have sampled the climate's inter-annual variation reasonably similarly and should therefore exhibit only a limited change due to inter-decadal variability. Negative phases tend to be relatively short lived throughout the observed record (with the exception of a period in the 1960s), so the ratio of positive to negative phase seasons sampled in the studies appears consistent with the longer record. Inter-annual variability common to the longer term climate should therefore have been reasonably captured in both studies. Examining inter-annual variability in some of the longer buoy records suggests that this is of the order 10-25% at the 10% and 1% exceedence levels (see Figure 4.2).

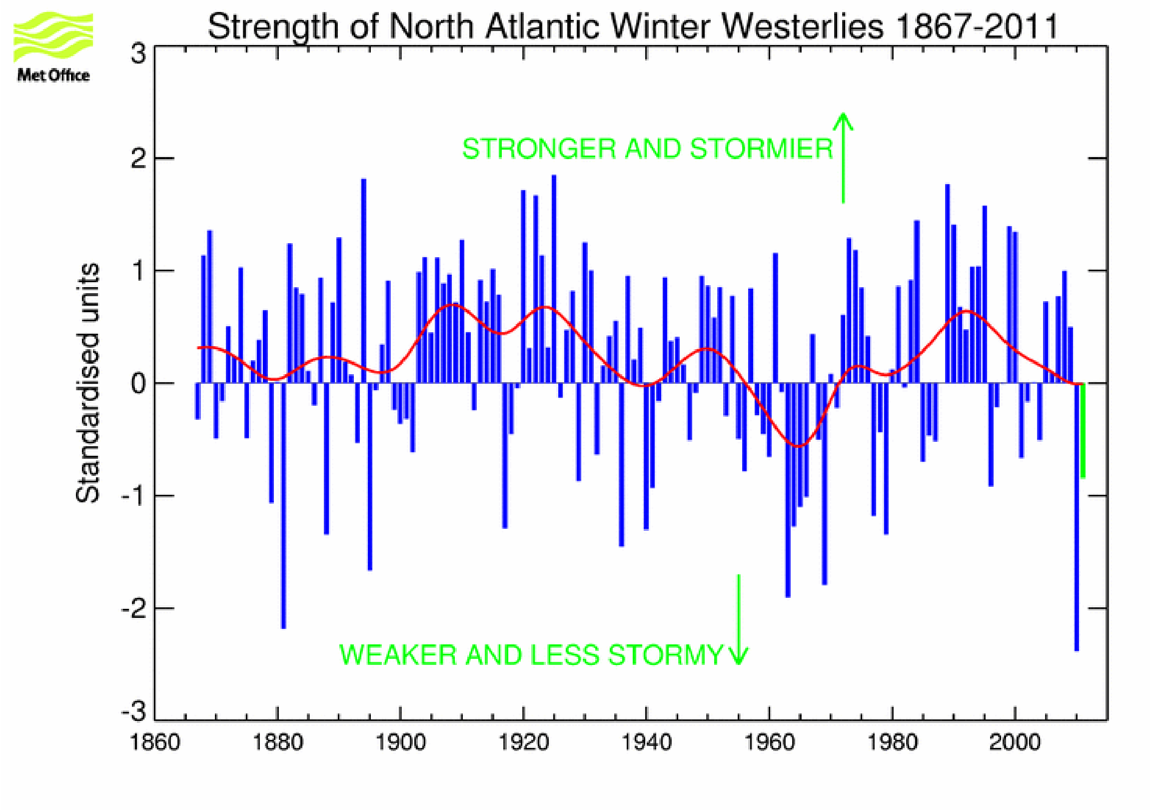

Figure 4.1 Observed North Atlantic Oscillation record from 1867-2010. In terms of affecting the wave climate positive phases are usually associated with an energetic northerly storm track that particularly affects the North West, Scotland and the North Sea; negative phases are more benign but have also been associated with a shift toward a more southerly storm track that affects the South West and English Channel.

The background datasets for the 2011 and 1998 studies used different models for wind and wave estimates. Regarding the model changes, other previous studies carried out with these data such as the 'BERR Atlas of UK Offshore Renewable Energy Resources' (2008) and 'Forecaster Guidance Notes for Improved Use of Met Office Wave Forecasts and Observations' (Bunney et al., 2009) suggest approximately 5-15% variability may be introduced between different models.

The changes in contours described in Section 3 suggest that open waters in the North West approaches and northeast Scotland were subject to somewhat higher energy conditions during the 1986-1997 period than in 2000-2011. This may be consistent with the number of strong positive phase NAO events occurring in the two different samples, and the existence of a known high wave energy period in the North Sea in the early 1990s. However, the 2011 study consistently places its lower wave height (1m to 2.5m) contours closer to the coastline than in the 1998 study. This somewhat contradicts the offshore data in the north, and is believed to be due to better model resolution around the UK coast allowing the contours to be placed with greater precision rather than any climate effects.

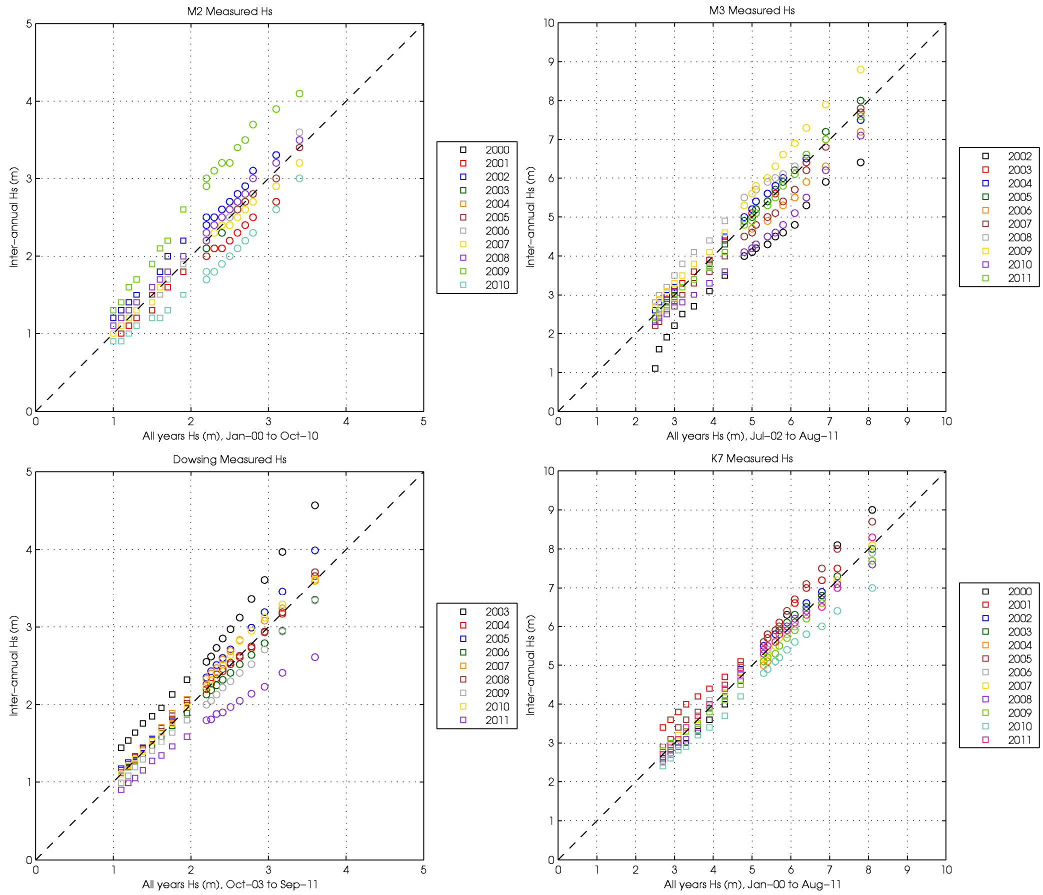

Figure 4.2 Inter-annual variability in wave climate at four long term buoy deployments; the plots show quantile-quantile data (squares every 5% from 50% to 15% exceedence, circles every 1% from 10% to 1% exceedence) where the x-axis represents quantiles from the whole record and the y-axis quantiles from individual years.

The discussed estimates of the variability that both short term climate change and use of a revised dataset contribute to the contours are clearly approximate and are also unlikely to apply completely consistently across the geographic domain. However, they indicate that regimes sampled in the two studies were similar in terms of inter-annual variability and were likely to have been generally consistent with much longer term climatology. In addition, using datasets derived from models of differing resolution has introduced a number of changes that make drawing more detailed conclusions regarding long term climate change effects on the UK shelf seas wave field from their differences unreliable. It is therefore difficult to conclude any major changes in wave climate around the UK over the course of the two studies.

This position needs to be viewed against the evidence that in atmospheric terms a warmer climate is liable to lead to increased levels of storminess in the North Atlantic in future. Such changes would be expected to affect the wave field in regions along and adjacent to the storm track. As discussed previously however, the UK shelf seas wave climate's sensitivity to storm track latitude means that good information on future changes to storm frequency, intensity and track are all required to make sensible inferences regarding how the UK's waves will be affected. At present the science required to provide all of this information remains under development.

As a result it is recommended that the present study's contours are taken as a valid representation of the climate around UK waters, since in general there are limited differences in the contours offshore and the coastal contours are provided in more detail than in the 1998 data. The use of the 10 year sample in the 2011 study should also make the contours robust in respect to inter-annual variability effects. It is recommended that the contours at a regional level are revisited should evidence of a significant change to both position and intensity of the North Atlantic storm track come to light (e.g. in Intergovernmental Panel on Climate Change reports or UK Climate Projection reports, which are generally updated every 4-5 years), for example with evidence of increased regularity of negative phase NAO, or consistent strong positive phase NAO.

5. Coastal zones identified for further study

Section 3 identified a number of important coastal or estuarine areas for which it was recommended that further detailed studies be carried out. In this respect the term 'detailed' implies use of local observations or a better resolved model that will correctly represent sheltering by headlands and wave refraction and dissipation processes influenced by complex shallow water bathymetry. In some cases, inclusion of the effects of tidal elevation and currents may also be important.

Assuming that observations are not available, or that a mapped view of an area similar to that provided in this study is required, the most rigorous technique to obtain an estimate of significant wave height exceedence in these areas would be to downscale model the full time period used in this study for each area, i.e. the time-series of wind and wave data underpinning this study are used as boundary conditions to force higher resolution limited area models. Bearing in mind the number of areas identified this could be prohibitive in terms of time and expense due to the number of runs required for each area. Such a study would be recommended to evaluate a 10% exceedence criteria, for example if a comparison was needed relative to conditions set out in Merchant Shipping Notice MSN 1747, since the 10% condition can plausibly be achieved from a large range of boundary scenarios with different combinations of wind, waves and tide.

However to evaluate less common conditions, for instance the criteria set out in MSN 1827 which states that Category C and D waters are based on a significant wave height that 'could not be expected to be exceeded at any time', implies that a much smaller subset of boundary scenarios could be used in analysis, particularly if the downscaling areas are kept small.

For example, the 1 in 1 year return period criterion can be used to generate significant wave height values that would plausibly occur only once per year in the area of interest. The most simple case is an inland water – in this instance the once per year significant wave height values can be generated based on 1 in 1 year return period wind speed for each of the body's major directional axes. Coastal locations are more complex, but generally experience their most energetic conditions when offshore storm waves arrive from exposed directions – in this instance the 1 in 1 year return period boundary conditions would be based on wave height and period combinations from the key directional sectors.

In many cases tidal elevation effects can be accounted for by using elevation at Mean High Water Springs, since deeper water generally implies higher wave heights as dissipation is minimised. Where shoals or bars are known to cause high waves at particular stages of the tide, running scenarios at other standard water levels (e.g. MLWS, MSL) can provide a check on refraction 'hotspots' causing wave energy to focus in particular locations. Tidal currents have a less linear affect on the wave field, and areas with known high currents would require a more complex study including set up of a high resolution tidal flow model.

For the locations identified in this study as needing more detailed modelling, Table 5.1 estimates the minimum data requirements for further modelling study. These are preliminary requirements only, and would likely be subject to change.

Location, area size and extent	Requirements
Firth of Forth Approx 45km x 75km; BLC at Leith, TRC at Arbroath	Minimum bathymetry resolution: 500m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS Tidal currents: No
Luce Bay to Solway Firth Approx 93km x 73km; TLC at Stranraer, BRC at Millom	Minimum bathymetry resolution: 1km Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS, Flmax Tidal currents: Spring peak flows
Firth of Clyde Approx 108km x 97km, TLC at Islay, BRC at Stranraer	Minimum bathymetry resolution: 500m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS Tidal currents: No
Inner Hebrides 114k x 282km; BLC at Malin Head, TRC at Rubha Reid NB this is a large area and probably best broken into a series of smaller areas	Minimum bathymetry resolution: 500m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS, Flmax Tidal currents: Spring peak flows

Thames Approx 24km x 43km; left extent at Southend, BRC at Herne Bay, TRC at Clacton	Minimum bathymetry resolution: 250m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS, MSL, MLWS Tidal currents: No
Swanage to Selsey Bill Approx 83km x 53km; southern extent approx 50km into English Channel to capture tidal effects	Minimum bathymetry resolution: 1km Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS, Flmax Tidal currents: Spring peak flows
Solent Approx 38km x 18km; BLC at Needles, BRC at Bembridge	Minimum bathymetry resolution: 250m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS, Flmax Tidal currents: Spring peak flows
Mounts Bay Approx 31km x 22km; north extent at Penzance, west extent at Porthcurno, BRC at Lizard	Minimum bathymetry resolution: 500m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS Tidal currents: No
Isles of Scilly (inter-island waters) Approx 18km x 17km	Minimum bathymetry resolution: 250m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS Tidal currents: No
East Bristol Channel Approx 61km x 37km; BLC at Minehead, TLC at Nash Point, east extent at Avonmouth	Minimum bathymetry resolution: 250m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MHWS, Flmax Tidal currents: Spring peak flows
Orkney (inter-island waters) Approx 68km x 89km;	Minimum bathymetry resolution: 250m Offshore wave boundary: Required Intra-model wind forcing: Required Tidal elevations: MSL, Flmax Tidal currents: Spring peak flows

Table 5.1 Requirements for detailed modelling studies aimed at improving coastal waters contours. Abbreviations used are MHWS – mean high water springs; MSL – mean sea level; MLWS – mean low water springs; Flmax – water level at peak tidal flow;

BLC – bottom left corner; BRC bottom right corner; TLC – top left corner; TRC – top right corner.

6. References

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Appendix A – Quantile-Quantile comparisons of observed and model significant wave height

The following figures show a comparison of the 10 year modelled wave climate used for threshold exceedence contouring versus observed wave climate at 24 in-situ wave monitoring sites around UK waters.

The plots present the wave climate via significant wave height exceedence ‘quantiles’, i.e. the significant wave height value that is exceeded for a given percentage of the time. In each plot square symbols represent quantiles at 5% intervals from 50% to 15% exceedence, and the circle symbols represent quantiles at 1% intervals from 10% to 1% exceedence.

Annual data, comparing all months, are shown in the left hand side plots with green symbols; Summer data using months from April to October inclusive are shown in the right hand side plots with blue symbols.

Sample periods for each location are given in the plot titles. In general the sampling period available from the buoys has been deemed long enough to allow a direct comparison against the 10 year model period. One exception is the buoy at Looe Bay (Figure A.10), which effectively comprised a single year sample and was tested for ‘aliasing’ against the model by re-analysing the observations against the matching model year. The revised comparison is shown in Figure A.25.

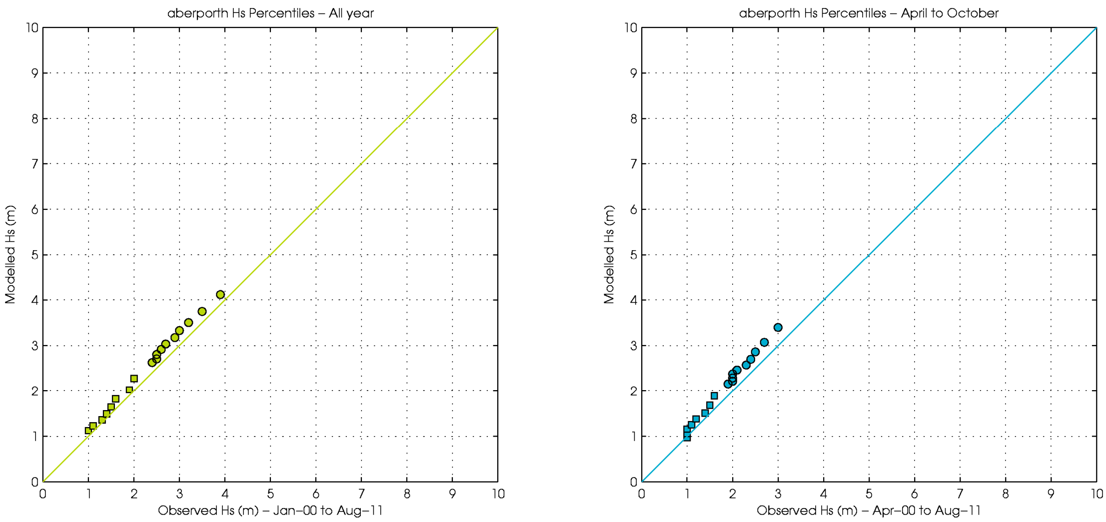


Figure A.1 Hs quantile-quantile comparison at Aberporth buoy

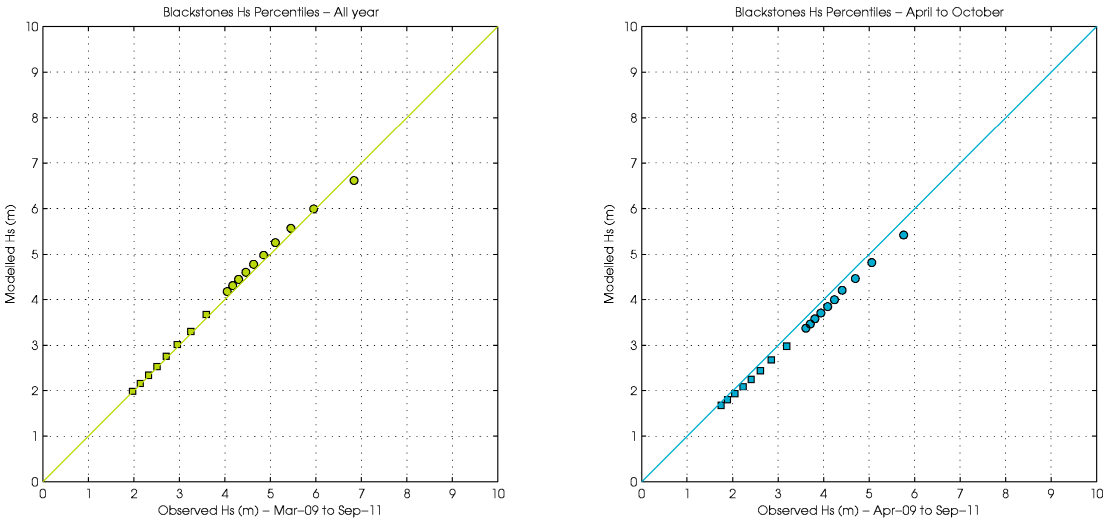


Figure A.2 Hs quantile-quantile comparison at Blackstones buoy

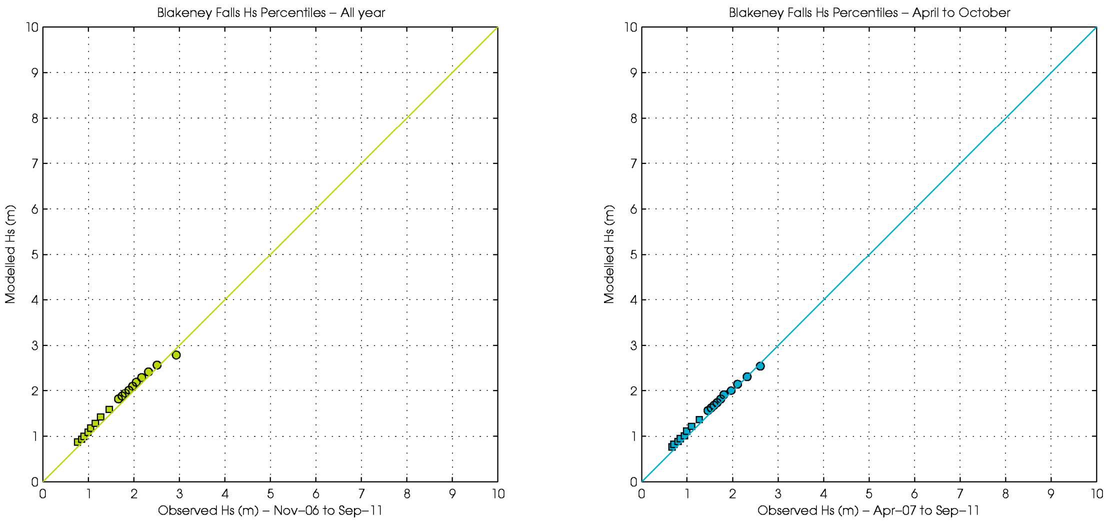


Figure A.3 Hs quantile-quantile comparison at Blakeney Falls buoy

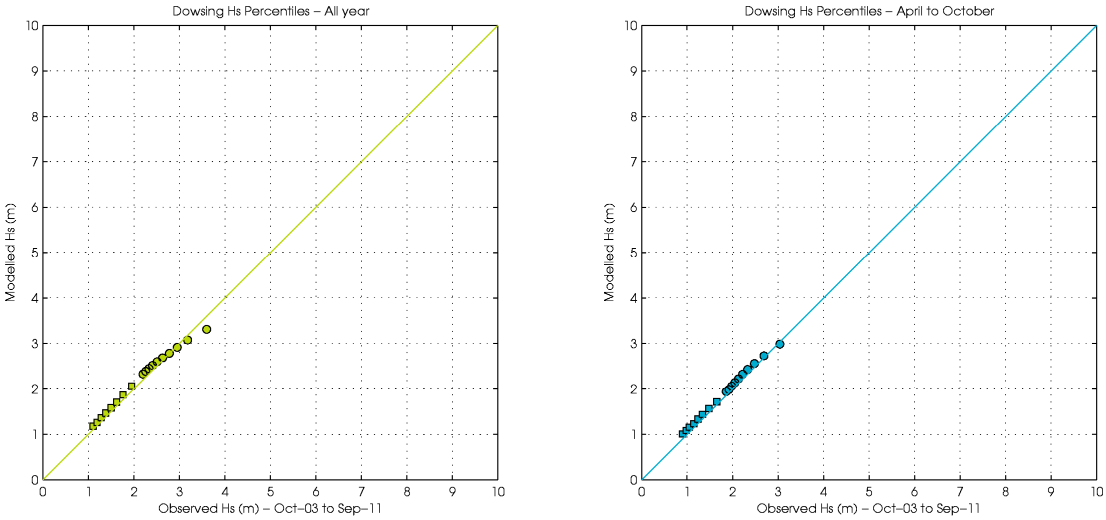


Figure A.4 Hs quantile-quantile comparison at Inner Dowsing buoy

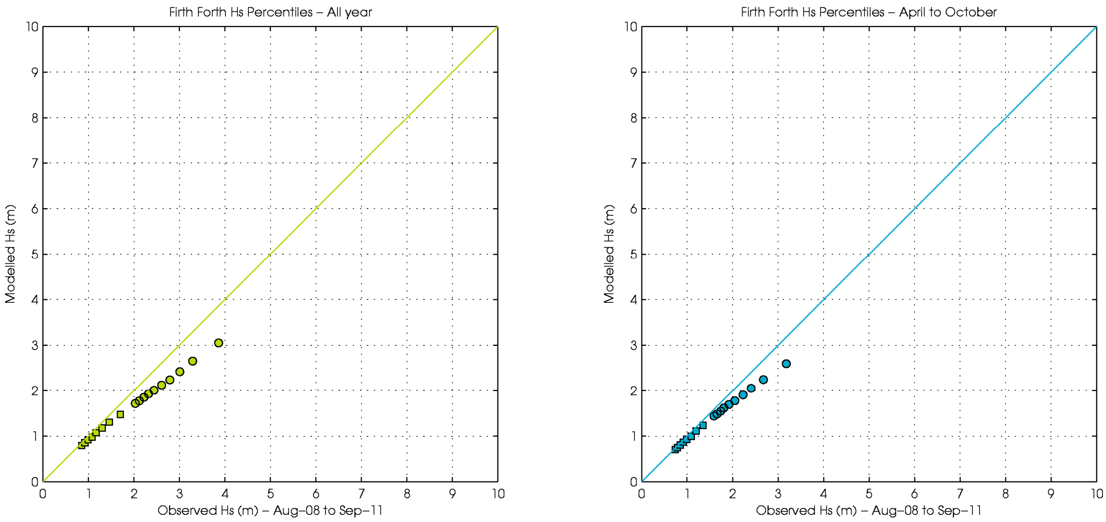


Figure A.5 Hs quantile-quantile comparison at Firth of Forth buoy

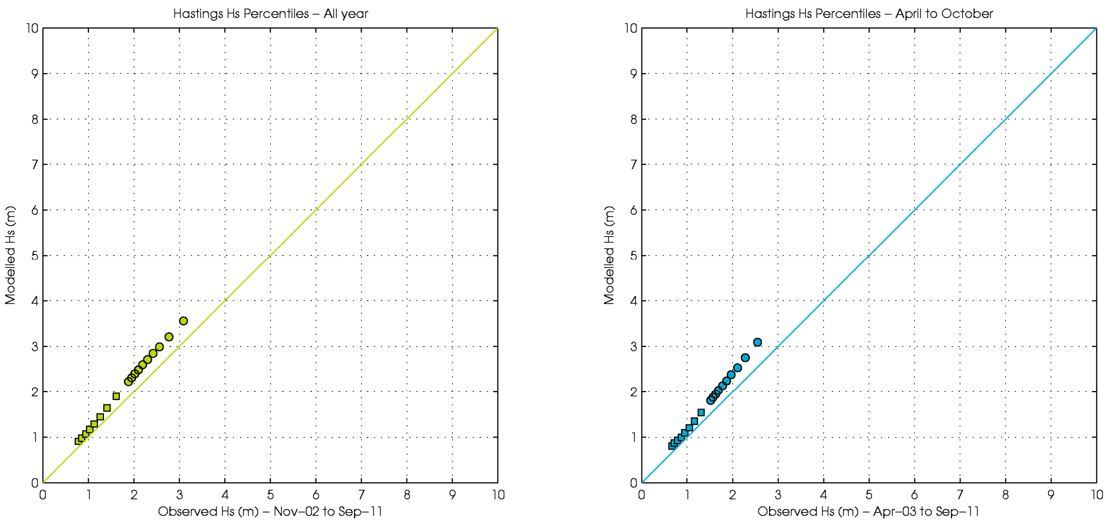


Figure A.6 Hs quantile-quantile comparison at Hastings buoy

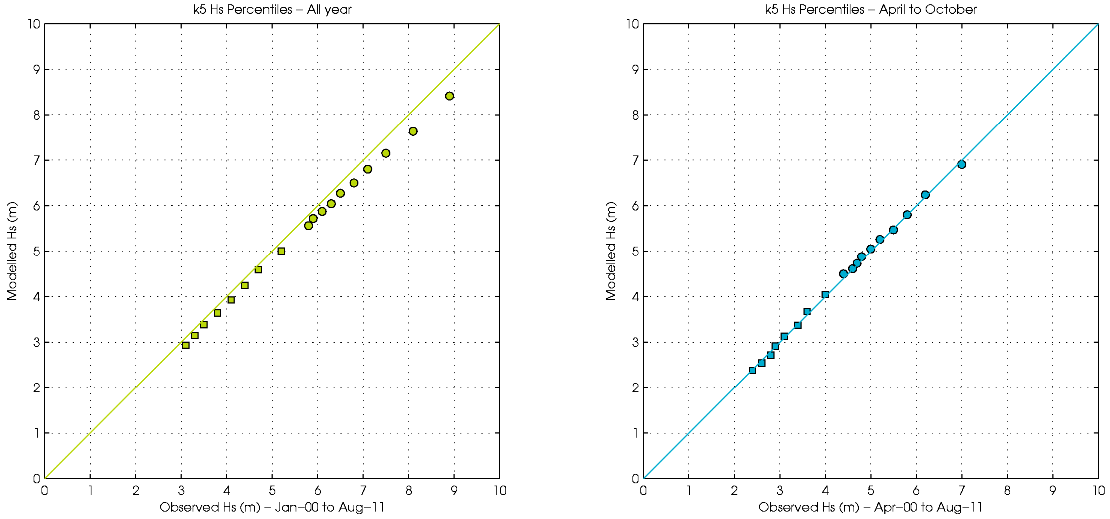


Figure A.7 Hs quantile-quantile comparison at K5 buoy

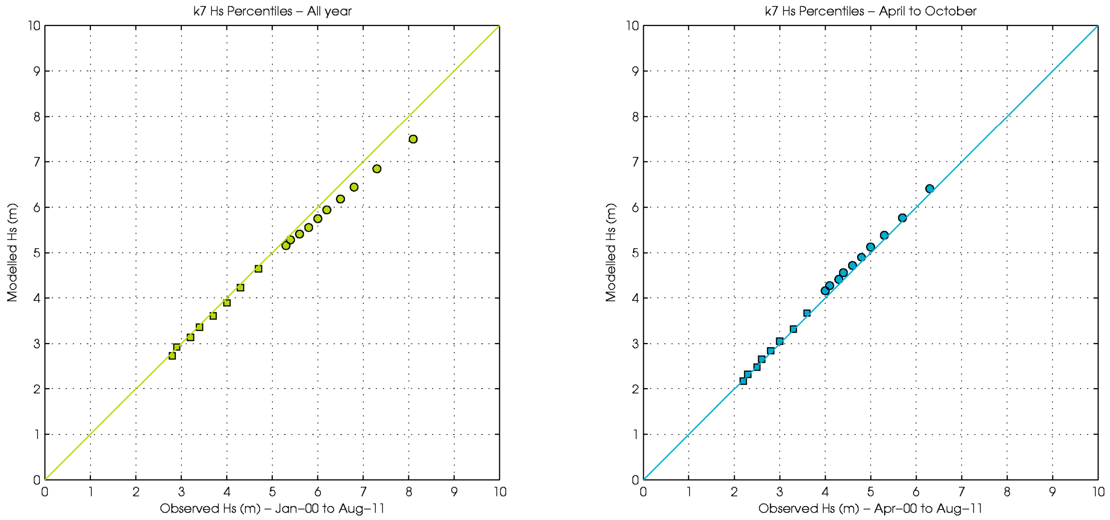


Figure A.8 Hs quantile-quantile comparison at K7 buoy

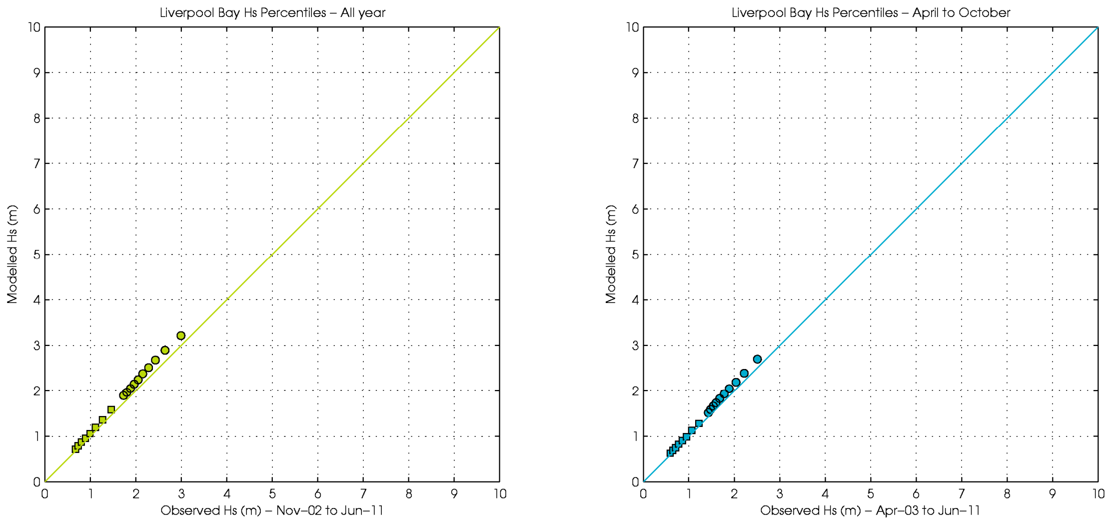


Figure A.9 Hs quantile-quantile comparison at Liverpool Bay buoy

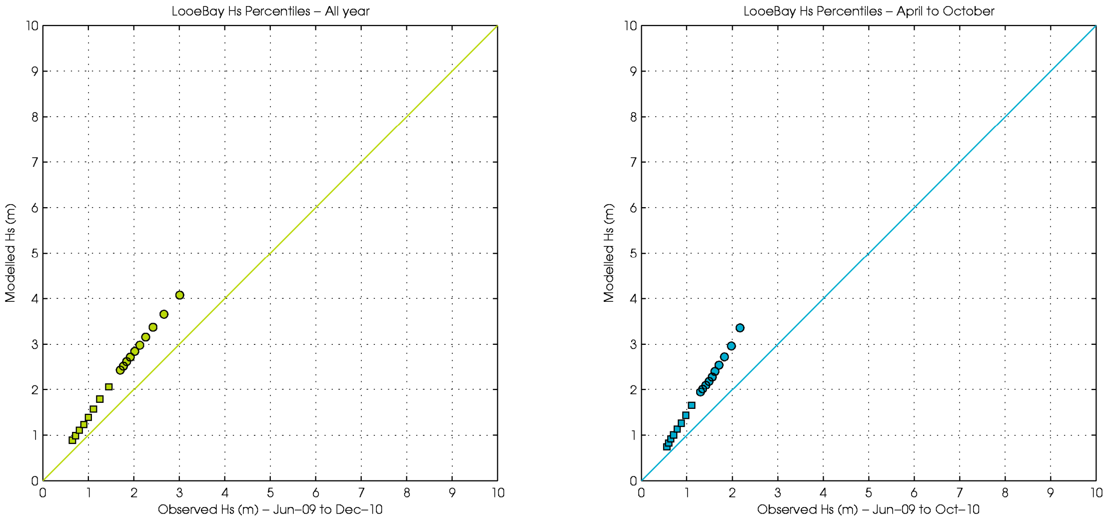


Figure A.10 Hs quantile-quantile comparison at Looe Bay buoy

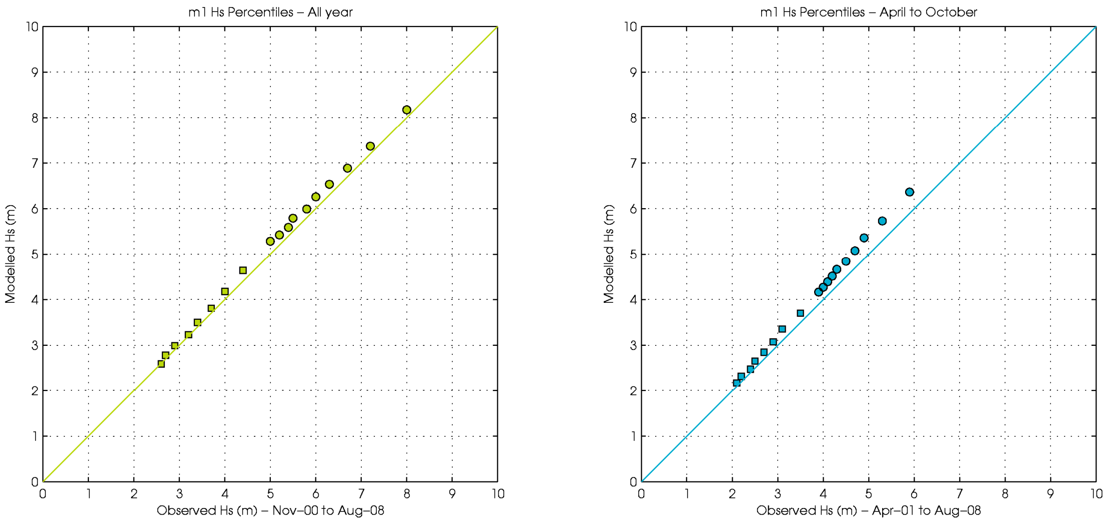


Figure A.11 Hs quantile-quantile comparison at M1 buoy

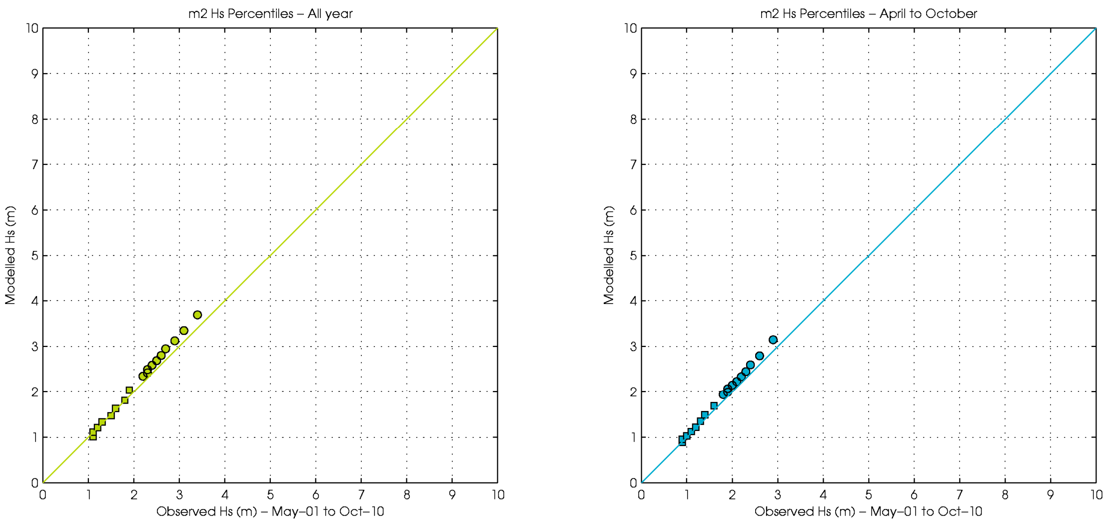


Figure A.12 Hs quantile-quantile comparison at M2 buoy

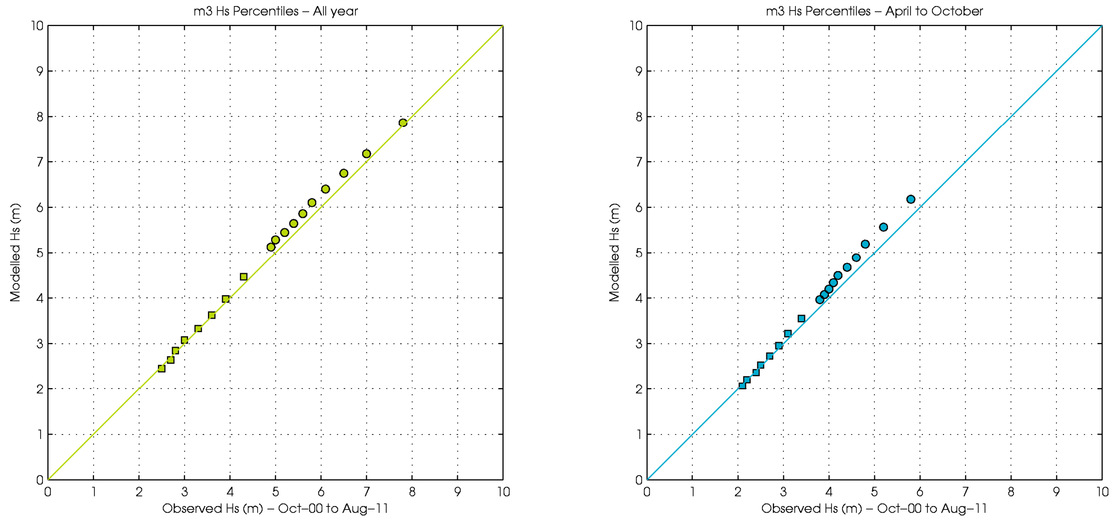


Figure A.13 Hs quantile-quantile comparison at M3 buoy

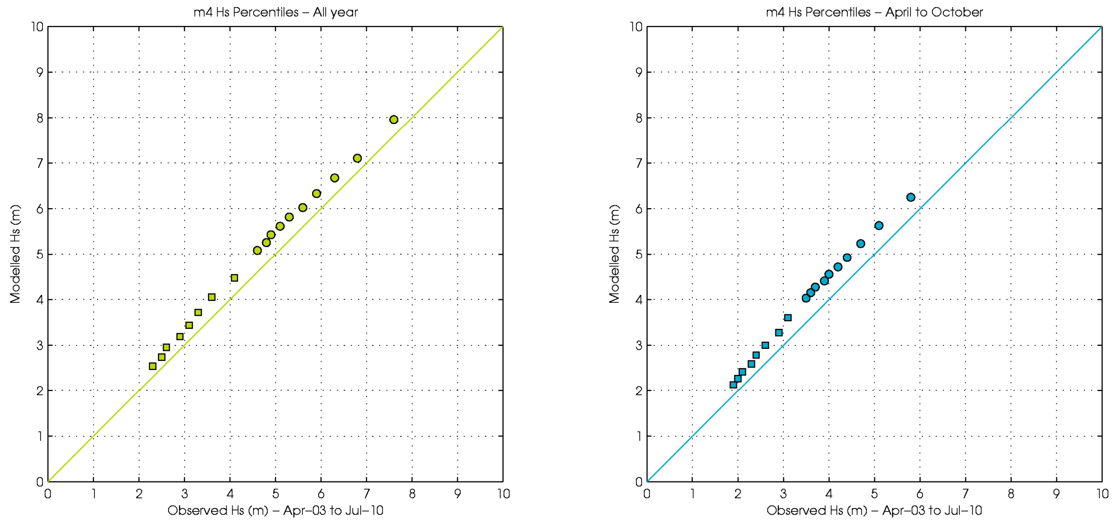


Figure A.14 Hs quantile-quantile comparison at M4 buoy

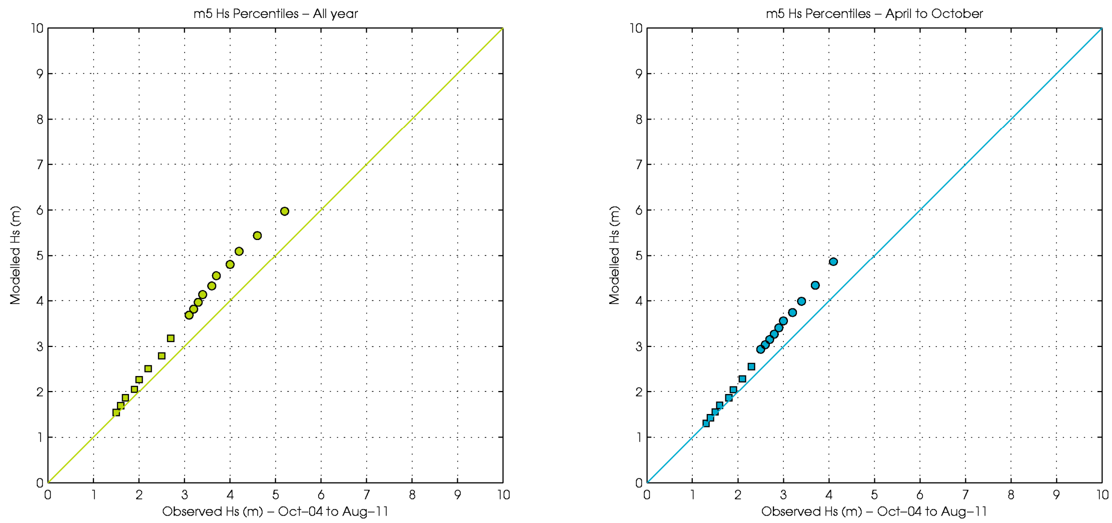


Figure A.15 Hs quantile-quantile comparison at M5 buoy

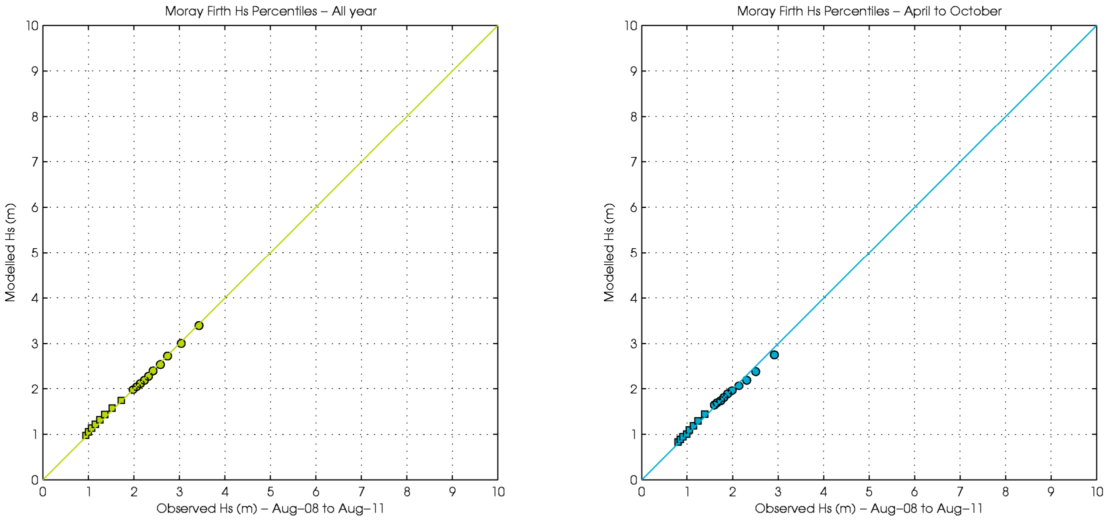


Figure A.16 Hs quantile-quantile comparison at Moray Firth buoy

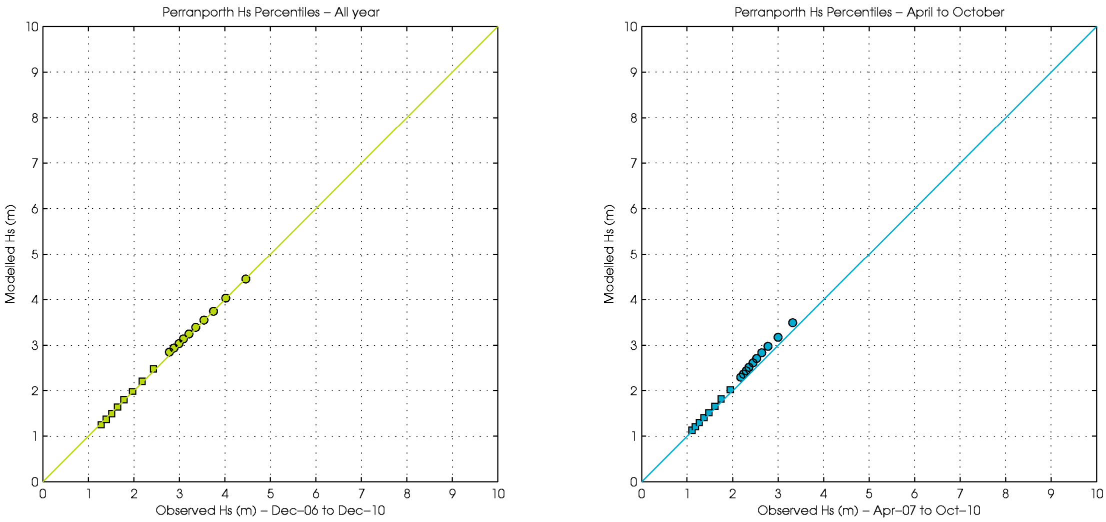


Figure A.17 Hs quantile-quantile comparison at Perranporth buoy

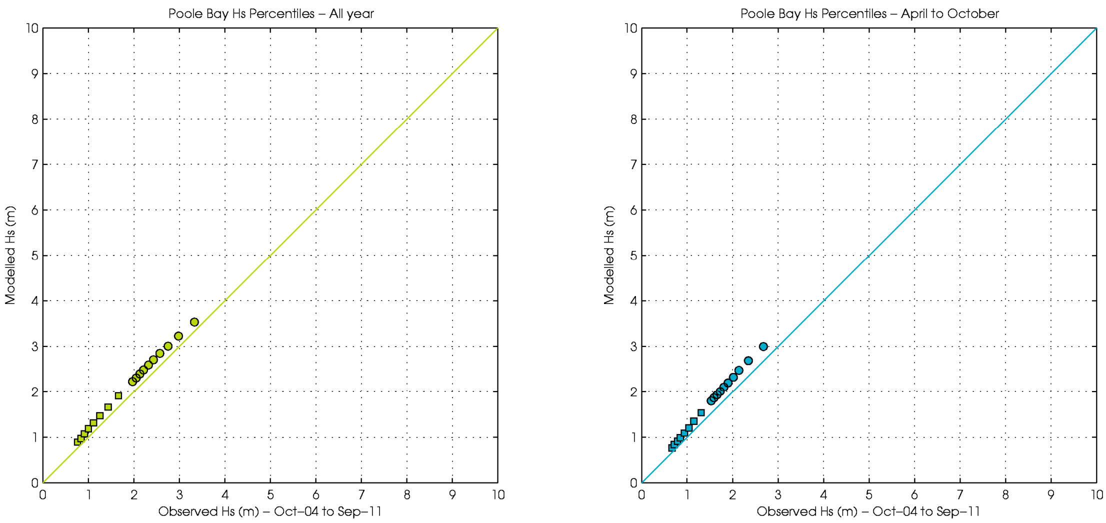


Figure A.18 Hs quantile-quantile comparison at Poole Bay buoy

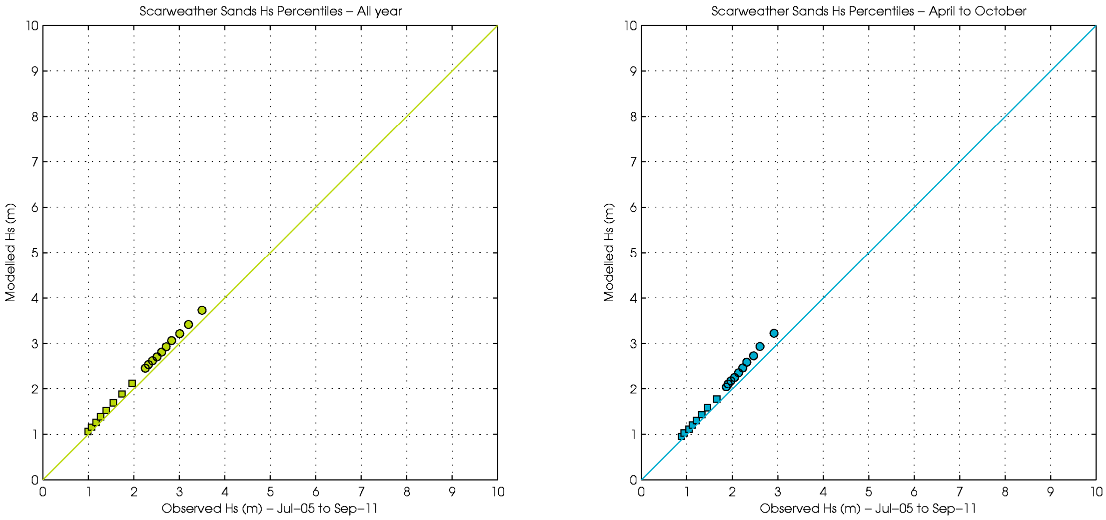


Figure A.19 Hs quantile-quantile comparison at Scarweather Sands buoy

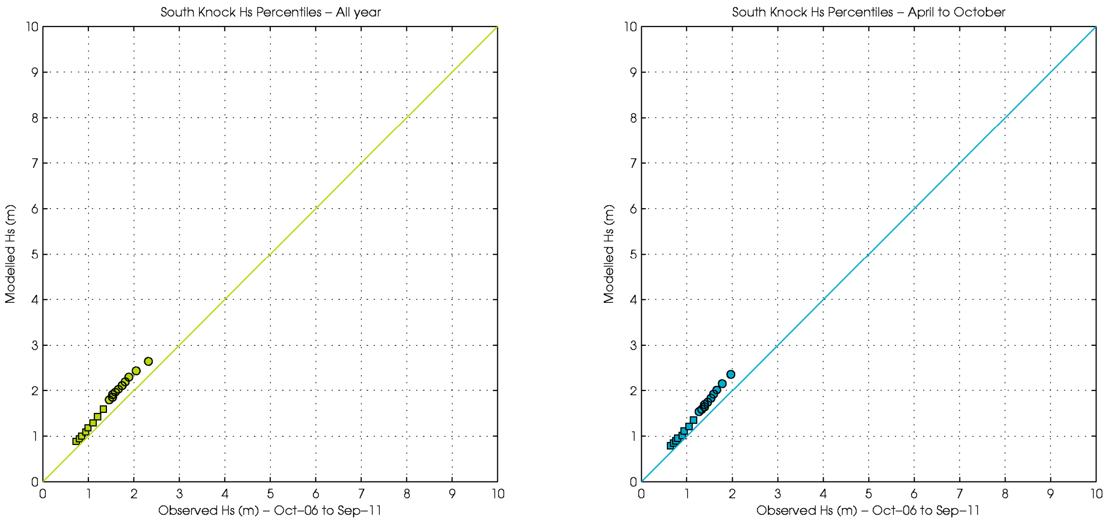


Figure A.20 Hs quantile-quantile comparison at South Knock buoy

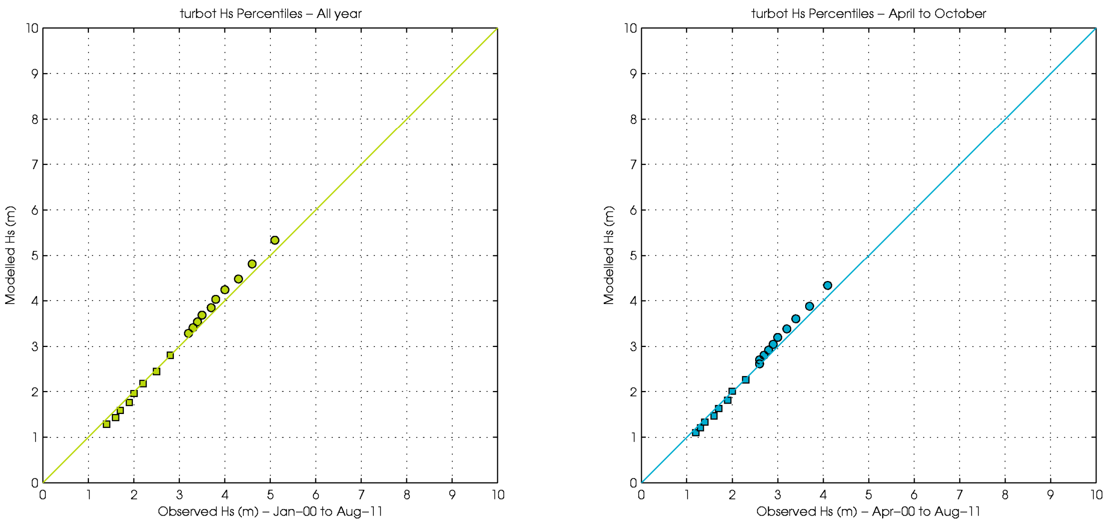
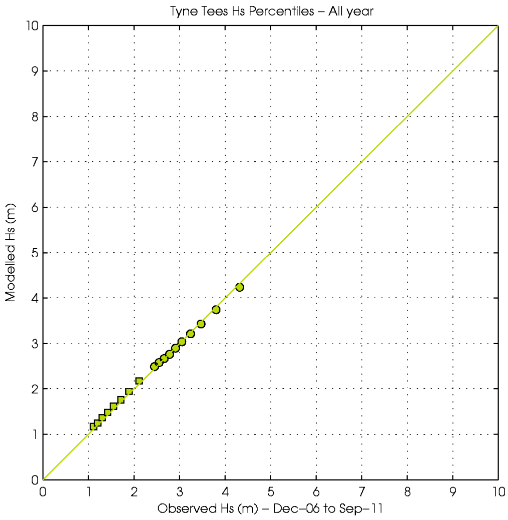


Figure A.21 Hs quantile-quantile comparison at Turbot Bank buoy



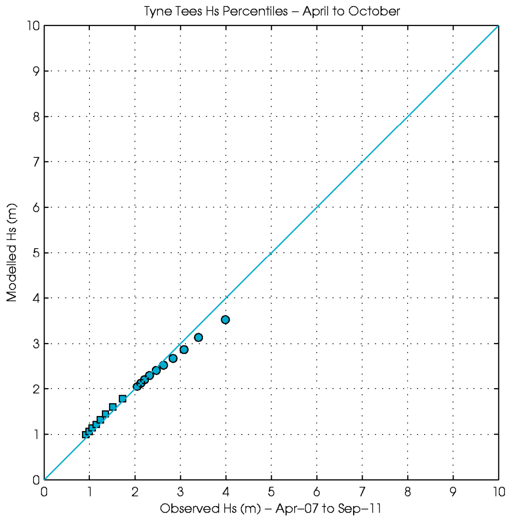
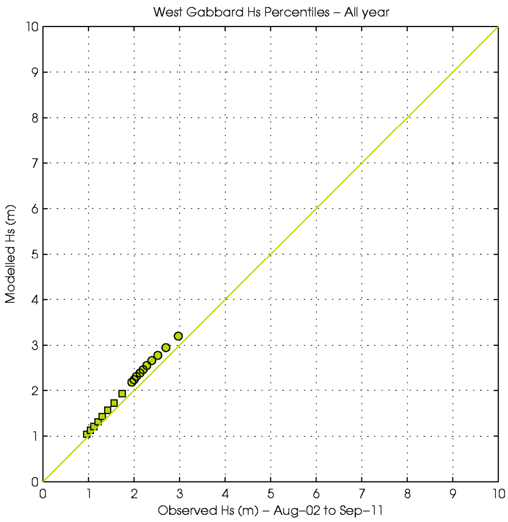


Figure A.22 Hs quantile-quantile comparison at Tyne Tees buoy



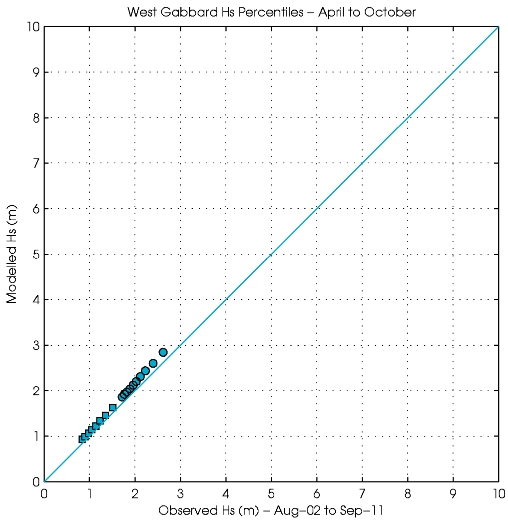
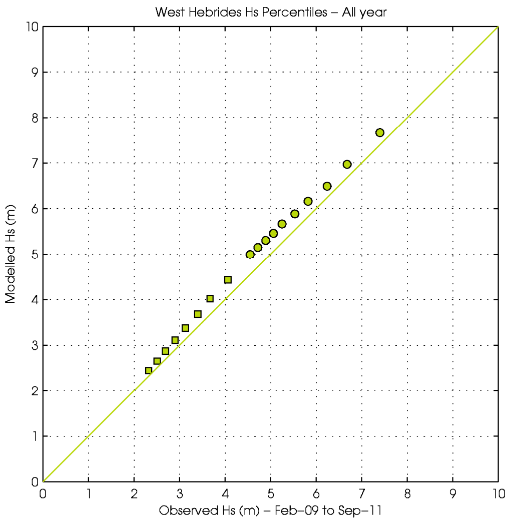


Figure A.23 Hs quantile-quantile comparison at West Gabbard buoy



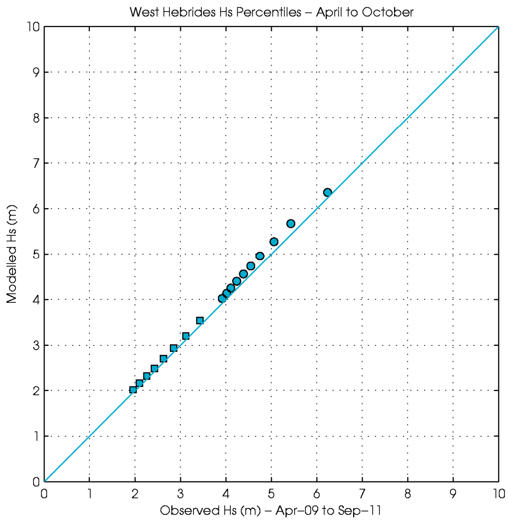


Figure A.24 Hs quantile-quantile comparison at West Hebrides buoy

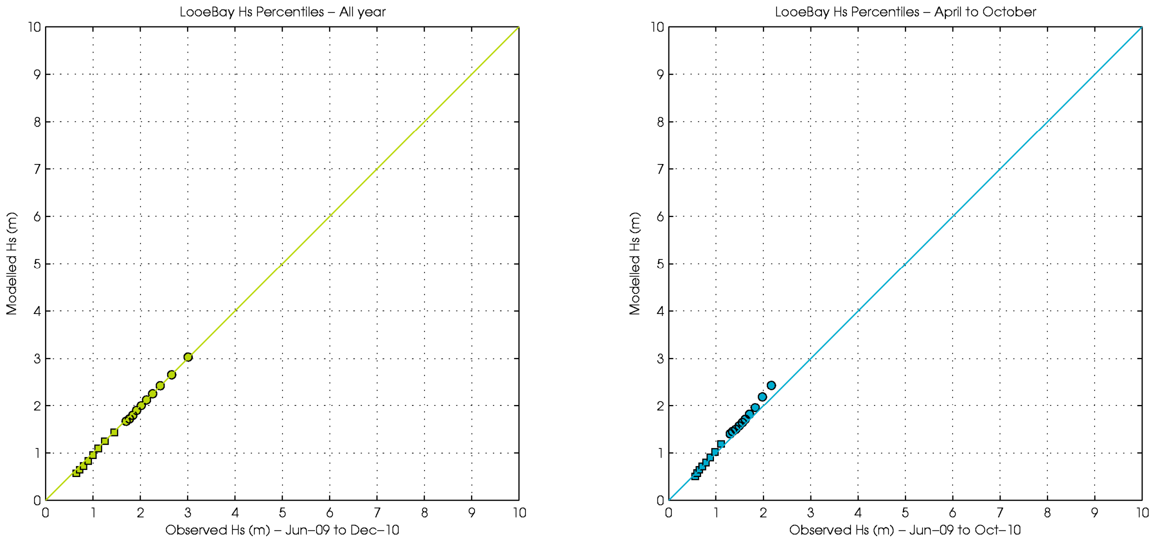


Figure A.25 Hs quantile-quantile comparison at Looe Bay buoy using matching 1 year model climatology

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