ABP Marine Environmental Research Ltd

SEASTATES Wave Hindcast Model: Calibration and Validation Report

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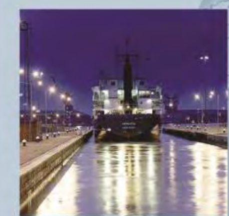



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ABP Marine Environmental Research Ltd
Quayside Suite, Medina Chambers, Town Quay, Southampton, Hampshire SO14 2AQ

Tel: +44 (0) 23 8071 1840 Fax: +44 (0) 23 8071 1841
Web: www.abpmer.co.uk Email: enquiries@abpmer.co.uk

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Non-Technical Summary

The ABPmer SEASTATES Wave Hindcast Model (SWHM) has been developed to provide wave parameter time-series around the UK and European coastal seas spanning a period of 34.5 years. Calibration of the model has been demonstrated using observational wave data from a wide geographical spread of locations and for a wide range of wave conditions. A high level of model performance has subsequently been confirmed through independent validation of SWHM results against observational data. On this basis it is considered that the SWHM provides wave hindcast data with high accuracy.

Although present levels of SWHM performance are considered to be very good overall, there are still some locations where slight improvements might be achieved from further planned enhancements to the SWHM. In this respect local downscaling is the preferred option to address tidal influences (e.g. the Bristol Channel) and such downscaling will be structured into the planned future enhancements and improvements to all SEASTATES products.

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1. Introduction

In order to offer metocean services to a wide range of clients, numerous Companies and Agencies currently offer hindcast and forecast data products derived using diverse numerical modelling approaches (e.g. Met Office UK, DHI in Denmark, BMT ARGOSS, RPS Group PLC etc.). However, owing to the use of different numerical models, and to differences between the data sources used for model calibration and validation, the spatial and temporal resolution, and the quality of hindcast and forecast data from each provider is variable. As a result the metocean data market can be a confusing place for clients unfamiliar with the limitations of numerical models and observational data.

To address these deficiencies, and to demonstrate clearly the high performance of a new wave hindcast service offered by ABPmer, this report presents the calibration and validation results for the SEASTATES Wave Hindcast Model (SWHM). SWHM is one component of the SEASTATES metocean information toolbox developed by ABPmer to support coastal and offshore projects. SWHM provides wave hindcast information for the European Continental Shelf using a state-of-the-art spectral wave model, respected bathymetric data and the most up-to-date long-term wind field data spanning a 34.5 year period from 1979 to 2012. The present SWHM application is focused on the European Continental Shelf, and from inception, purposefully recognises the broad range of end-user requirements as well as new technical standards for the marine renewable energy market in relation to wave energy resource predictions (e.g. PEL 114[1]). The data from SWHM provides the information necessary to characterise (with high statistical confidence) the wave climate at a selected location within the model domain as well as the time-series data required for extreme value analysis.

The aim of this calibration and validation report is to show the accuracy and reliability of ABPmer's SWHM. In the section reporting on model calibration, comparisons made between model result time-series and measurements from wave buoys demonstrate very good agreement at 28 widely dispersed geographical locations during a period 12 November 2009 to 1 January 2010. It is shown that the SWHM provides regional scale, long-term prediction of waves across European waters with high spatial and temporal resolution. This assertion is backed up with validation evidence obtained at 12 sites across the model domain for the period 1 November 2008 to 31 December 2008.

The SWHM calibration and validation report is structured as follows:

- Section 2 provides background information about the SEASTATES approach.
- Section 3 describes the wave hindcast model methodology and includes a description of the numerical model, meteorological forcing used to generate wave hindcast data and the approach and data sources used to calibrate and validate the model outputs.

1 http://standardsdevelopment.bsigroup.com/Home/Committee/50176875

- Section 4 describes the performance statistics used in the calibration and validation process to objectively compare the accuracy of output from the SWHM against observational wave data.
- Section 5 presents calibration results for SWHM from 28 widely dispersed and diverse geographical locations. Here the model performance is judged against measured data using a range of statistics as well as visual comparisons.
- Section 6 presents results of the model validation undertaken using data from a further 12 locations. Here the comparisons between SWHM outputs and observation validation data are undertaken without further adjustments to model parameters.
- Section 7 discusses the SWHM calibration and validation results, highlighting both the strengths of SWHM and areas where further improvements to the model performance remain the subject of local down-scaling.
- Section 8 presents conclusions from the model calibration and validation work.

2. Background

The SWHM is one component of the metocean hindcasting and forecasting service provided by ABPmer. The wave model used in the SWHM is driven by hindcast wind data obtained from the NCEP[2] Reanalysis 2 Data Set, supplemented from 2010 by the complementary NCEP Reanalysis 1 Data Set. Following extensive analysis against a range of alternative data sources, these wind data have been 'tuned' by ABPmer using bespoke methods to better describe winds in nearshore areas. This has enabled an improvement in the accuracy of the wave model calibration for such locations.

The essential features of the SWHM and characteristics of the output data include:

- Hindcast waves obtained from a MIKE by DHI third generation Spectral Wave model[3];
- A model spatial extent that includes the North Atlantic in relatively coarse detail, and the North-Eastern European continental shelf at higher resolution;
- A flexible mesh providing:
  - 5 km equivalent rectilinear spatial resolution for the majority of UK coastal waters;
  - 15 km to 20 km equivalent rectilinear resolution elsewhere on the shelf; and
  - Gradually increasing mesh element size from the shelf break into the North Atlantic.

2 National [American] Centers for Environmental Prediction
3 http://www.dhisoftware.com/Products/CoastAndSea/MIKE21/Waves.aspx

- Time-series model outputs of key wave spectral parameters separated into wind sea and swell sea components (e.g. Hs, Tz, Tp, mean direction etc.) for up to 34.5 years (1979 to near present) at:
  - The same spatial resolution and extent as the model (as above); and
  - Hourly time-steps.

3. Modelling Approach

3.1 Overview

In developing the SWHM using a flexible mesh, state-of-the-art spectral wave model (DHI Mike SW[4]) to describe wave growth and propagation, ABPmer are targeting hindcast predictions of waves at a regional-scale. In the present case the model grid extends across the North Atlantic to capture long fetches and to resolve the propagation of remote swell moving towards the UK (Figure 1). In the hindcast, the long time-series of spatial wind data used to drive the wave model includes: the NCEP Reanalysis 2 Data Set (1979-2009); and the complementary NCEP Reanalysis 1 Data Set (2010 to present).

3.2 Extent of the Model

The extent of the model covers the North Atlantic Ocean. The western boundary of the SWHM is defined by the east coast of North America while the southern boundary of the model extends to 23°N (Figure 1). To the north and east the grid extends to 80°N and 50°E to include Greenland and the Barents Seas. Although the Skagerrak between Denmark and Norway is included, the Kattegat between Denmark and Sweden is excluded. The Baltic Sea and other regional enclosed seas such as the Mediterranean Sea are also excluded from the model. The largest individual element sides of the flexible mesh model grid are 115 km in the deep offshore areas of the North Atlantic Ocean. To better present shallow water regions where bathymetric effects on the wave field become important, the spatial resolution in shallower coastal areas is reduced to 5 km. The transition into the continental shelf from deep water is smoothed carefully during construction of the model mesh. Figure 2 shows the detail of the model grid across the European Continental Shelf.

3.3 Model Parameters

3.3.1 Bathymetry

The following data sources are used to define bathymetry for the SWHM:

- 1° GEBCO[5] bathymetry (North Atlantic); and
- 1' GEBCO bathymetry (European Shelf).

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4 http://www.dhisoftware.com/Products/CoastAndSea/MIKE21/Waves.aspx

5 http://www.gebco.net/

These bathymetric data sets are used extensively in regional scale models and are based on depth values defined relative to mean sea level (MSL).

3.3.2 Meteorological Forcing

The SWHM is driven by winds derived from the NCEP Reanalysis 2 Data Set. These data provide complete coverage of the globe at a spatial resolution of 0.5°, and with a temporal resolution of one hour for the period 1979 to 2009, inclusive. In addition, to allow extension of this data to the present time, use is also made of the NCEP Reanalysis 1 Data Set.

In the SEASTATES approach, temporally averaged wind speed maps of the NCEP boundary data are compared with the contemporaneous mean wind speed data available from the Atlas of Marine Renewable Energy Resources[6]. Although at many locations it was found that the mean NCEP Reanalysis and Marine Renewable Atlas wind speeds matched very closely, there were some areas where the data diverged significantly (e.g. some coastal locations). By subtracting the mean NCEP Reanalysis wind speed map from mean Marine Renewable Atlas wind speed map a difference map was produced to guide the application of local correction factors to the NCEP wind speed data and thereby improve SWHM performance. Following standard procedure, the resulting mean wind speed difference maps were normalised and a number of iterative model calibration runs were undertaken in which the absolute magnitude of the nearshore wind speed correction factors were adjusted to optimise the performance SWHM across the model domain. By these means ABPmer has been able to refine the wave modelling methodology and provide a more accurate hindcast data product.

3.3.3 Numerical and Spectral Formulation

In order to achieve good agreement between model predictions of wave conditions and observational wave data at a range of locations across the model domain, the model was run in fully-spectral mode. In this condition, the time formulation of the model was set to ***in-stationary***, so that wave conditions calculated at each time-step were dependent on the previous conditions as well as the meteorological forcing. This allowed realistic wave propagation across the model domain, an issue which is fundamental to the age of swell which can travel long distances.

The model resolved the spectral distribution of the seastate within 36 component wave periods ranging between 30.3 s to 1.08 s (Table 1). The spectra were split into 24 sectors of 15° equal increments. It is note here that although higher directional resolutions are possible, the present model has been shown to run most efficiently with 24 directional sectors and meets the IEC standard.

6 http://www.renewables-atlas.info/

Table 1. Wave period bins for wave calculation by the SWHM

Bin	Wave Period (s)	Bin	Wave Period (s)	Bin	Wave Period (s)
0	30.30	12	9.66	24	3.08
1	27.55	13	8.78	25	2.80
2	25.04	14	7.98	26	2.54
3	22.77	15	7.25	27	2.31
4	20.70	16	6.59	28	2.10
5	18.82	17	6.00	29	1.91
6	17.11	18	5.45	30	1.74
7	15.55	19	4.95	31	1.58
8	14.14	20	4.50	32	1.44
9	12.85	21	4.09	33	1.30
10	11.68	22	3.72	34	1.19
11	10.62	23	3.38	35	1.08

3.3.4 Water Levels

The majority of locations tested in the SWHM calibration process did not demonstrate strong tidal influence. For improved computational efficiency, the model was therefore run without any variation in water levels or associated tidal currents. However, there are a number of discrete locations around the UK where the tidal effects (variations in water depth and currents) are sufficient to influence local wave behaviour and where model down-scaling is appropriate. A further discussion of these locations, and the associated results from the SWHM calibration and validation, is given in Section 7.

3.3.5 Wave Breaking, Friction and White Capping

MIKE SW default parameters for wave breaking were used in the SWHM. These include: Gamma = 0.8 (to control the limiting water depth condition); and Alpha = 1 (to control the rate of energy dissipation due to shoaling). Bottom friction was set to the default Nikuradse roughness of 0.04. The white capping term, Cdis, was set to 4.5 across the model domain. A spatially uniform DELTAdis value of 0.5 was used to define the weight of dissipation in the energy/action spectrum.

3.3.6 Separation of Wind Sea and Swell

Being fully-spectral the SWHM can resolve wind sea and swell. A dynamic threshold method is used by the model to discriminate between these sea states according to the speed and direction of waves in relation to the speed and direction of the wind. Specifically, the model identifies swell by applying the following test:

$$\text{if } \frac{U}{c}\cos(\theta_{wave} - \theta_{wind}) < 0.83 \text{, then} \qquad \text{Eq. 1}$$

waves are defined as swell. Here, U is the mean wind speed, c the wave's phase speed and θ is the mean direction of the wind or wave. Thus, waves that deviate significantly from the speed or direction of the wind will be identified as swell.

4. SWHM Calibration

4.1 Approach

In common with the majority of numerical wave model calibration approaches, calibration of the SWHM has been achieved by varying the model coefficients to obtain the best achievable fit between measured and predicted wave characteristics at locations across the model domain. The degree of agreement between model and observational data defines the level of model calibration. Poor agreement indicates poor calibration, while good agreement indicates the model is calibrated accurately. Depending on local conditions, and how well these can be represented in the model, the degree of agreement between measured and predicted wave parameters will vary from location to location.

As it is widely acknowledged that no single method provides a full assessment of model performance, here the level of agreement between the SWHM and the observational data has been assessed in two ways:

- Visual comparisons between the model output and the observed data to assess the shape, trend, range and limits of model output and observed data; and
- Statistical comparison of the differences between SWHM output and observed data to determine the degree to which the model fits the observations within defined calibration limits (e.g. ABPmer, 2013). These statistics include bias, scatter, correlation coefficients and regression coefficients and are defined below.

The approach to assess model performance used here follows guidelines set out in ABPmer (2013) and is described in detail below. However, it is important to recognise that under certain conditions, models can meet the statistical calibration standards but visually appear to perform poorly. Conversely, seemingly accurate models assessed on a visual basis can sometimes fall short of the statistical guidelines. In such cases the model performance guidelines cannot be used solely to assess the performance of the model, and it is necessary for experienced modellers and oceanographers to offer a critical assessment of model performance based on the overall weight of evidence and taking all the information into account. Here ABPmer has employed their own experience gained from calibrating a wide range of models over many years in order to resolve any residual calibration issues. In addition, comparisons between model performance statistics from a total of 29 model calibration runs have enabled convergence to the performance targets defined in Table 2.

The statistical performance targets used to define an acceptable calibration of the SWHM are shown in Table 2 (*cf.* ABPmer, 2013) and defined below. These statistics allow a rigorous assessment of the similarity between a series of discrete observational data and equivalent values predicted by the SWHM.

Table 2. Guideline statistical targets for wave model performance

Measure	Guideline Statistical Score
Wave Height Bias (mean error)	< 10% mean observed height
Wave Period Bias (mean error)	< 20% mean observed period
Wave Height Scatter Index (SI)*	< 35
Wave Height Correlation (R)	> 0.8
Wave Period Correlation (R)	> 0.65
Wave Direction (Mean) Bias (mean error)	< 30° observed direction
* The SI requirements are also used to assess wave period	

Tabulated model calibration and validation statistics are presented in Appendices A and B, respectively, and include: (1) The Pearson product-moment correlation coefficient, R, defined as the (sample) covariance of the variables divided by the product of their (sample) standard deviations. R values quantify the strength and direction of the linear relationship between measured and observed wave parameters with values of 1 indicating a perfect linear relationship; (2) the regression coefficient, β_0, associated with the regression analysis of observed and modelled wave parameters; (3) bias; and (4) scatter index, SI. These statistical quantities are now defined and explained.

R is defined as:

$$R = \frac{\sum_{i-1}^{N_i}(S_i - \overline{S}_i)(O_i - \overline{O}_i)}{\sqrt{\sum_{i=1}^{N_i}(S_i - \overline{S}_i)^2}\sqrt{\sum_{i-1}^{N_i}(O_i - \overline{O}_i)^2}} \qquad \text{Eq. 2}$$

where O_i and S_i are the observed and modelled data, respectively, and N_i is total number of data. β_0 is defined as:

$$\beta_0 = \frac{\sum_{i=1}^{N_i}(S_i - \overline{S}_i)(O_i - \overline{O}_i)}{\sum_{i=1}^{N_i}(S_i - \overline{S}_i)^2} \quad and \quad \beta_1 = \overline{O}_i - \beta_1\overline{S}_i \qquad \text{Eq. 3}$$

where β_1 is the regression intercept.

Both β_0 and R provide the similar information: both define the strength of the linear relationship between observed and modelled wave parameters (e.g. Hs). However, they also provide quite distinct information:

- The R value gives a bounded measurement that can be interpreted independently of the scale of the two variables. The closer the estimated correlation is to ±1, the closer the two are to a perfect positive or negative linear relationship. The regression slope, in isolation, does not provide that information.

- The β_0 value provides a useful quantity expressing the estimated change in the expected value of a modelled wave parameter for a given observed wave parameter. Specifically, the regression coefficient expresses the change in the expected value of a modelled wave parameter corresponding to a 1-unit increase in an observed wave parameter. This information cannot be deduced from the correlation coefficient alone.

'Bias' measures the extent of the deviation, or scatter, of the modelled values away from the observed values. It therefore indicates the variance in the model predictions expressed as the difference between modelled and measured datasets. Bias is defined as

$$\text{Bias} = \sum_{i=1}^{N_i} \frac{1}{N_i}(S_i - O_i); \qquad \text{Eq. 4}$$

The difference between O_i and S_i can also be quantified using the statistical Scatter Index, SI expressing the root-mean-square error normalised with the mean value. SI is defined as

$$SI = \frac{\sqrt{\frac{1}{N_i}\sum_{i=1}^{N_i}(S_i - O_i)^2}}{\frac{1}{N_i}\sum_{i=1}^{N_i} O_i} \times 100 \qquad \text{Eq. 5}$$

Specifically, SI is used to quantify the mean absolute deviance of the model values away from the observed values and is expressed as a percentage of the observed mean. For example, a SI value of 0% would be achieved when each modelled value matched the corresponding observed value exactly. In practice this is unachievable and here we accept all model predictions with an SI value no greater than 35% of the observed mean. A scatter index is also used along with R and β_0 to test the statistical significance of the linear relationship between the measured and observed datasets.

4.2 SWHM Calibration Data

The performance of the SWHM has been tested against observational records from 28 separate locations spread around the UK and Europe (Table 3). These data have been sourced from:

- 18 WaveNet[7] devices;
- 4 CCO[8] wave devices;
- 2 FINO[9] project wave records from the North Sea;
- 4 Ifremer[10] recorded sites from the French west coast and Spanish north coast; and
- Irish Marine Weather Buoy Network.

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7 http://cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx
8 http://www.channelcoast.org/
9 http://www.oceanwaves.org/start.html?http://www.oceanwaves.org/projects/fino.html
10 http://wwz.ifremer.fr/iowaga/Scientific-activities/Wave-observation-and-forecasting

The location of these sites is shown in Figure 3 and the site depth and mean tidal range are also given in Table 3 for context.

Table 3. Wave measurement locations used in SWHM calibration, local water depths and mean tidal ranges

Area	Location	Local Water Depth (m MSL)	Mean Tidal Range (m)
Scottish West Coast	West Hebrides	99	3.2
	Blackstones	97	3.1
Irish Sea	Liverpool Bay	24	7.0
	M2 (Ireland)	73	3.2
Bristol Channel	Scarweather	35	8.8
	Hinkley	10	11.0
Celtic Sea	Seven Stones	69	5.0
	M5 (Ireland)	65	4.1
English South Coast	Poole	32	1.3
	Rustington	10	4.8
	Hastings	43	6.8
	Bracklesham	10	3.8
	Hayling	10	3.7
UK East Coast	Moray Firth	54	3.3
	Firth of Forth	65	4.3
	Tees	63	3.9
	Dowsing	22	4.4
	West Gabbard	33	2.1
Irish West Coast	M3	126	3.6
	M4	50	3.7
Offshore	K7	650	2.0
	M6	3,000	2.9
North Sea	FINO1	28	2.5
	FINO3	23	1.2
France	Gascogne	4,520	4.2
	Brittany	2,265	3.9
Spain	Penas	450	4.1
	Tarra	1,065	4.3

4.3 Calibration Period

The SWHM has been calibrated using observational wave data covering an 8-week period between 12 November 2009 and 1 January 2010. This period was selected as it represents a wide range of wave events and directions, including both calm and storm periods and complex combinations of wind sea and swell. The SWHM resolves events over this period with a time-step of 1-hour.

5. Results: Model Calibration

The summary statistics of the SWHM calibration performance are shown in Appendix A (Tables A1 to A5) and include information on: significant wave height, Hs, (bias, SI, β_0 and R); wave period, Tz, (bias, SI, β_0 and R); and wave direction (bias and SI). Model calibration is grouped by geographical location and shading is used to indicate where a statistic falls outside of the performance targets defined in Table 2. Reasons for apparent underperformance of the model at a few locations are discussed below.

To facilitate a convenient visual comparison of the model performance, a graphical presentation of SWHM output and contemporaneous observational wave data is shown in Figure 4 through to Figure 31. In each figure the three panels on the left show model (red) and observational (black) Hs, Tz and wave direction time-series at the location indicated in the small outline map of the UK in the top right hand corner of the figures. In addition, scatter plots for these three wave parameters are shown in the three panels on the right.

Together Tables A1 to A5 and Figure 4 to Figure 31 demonstrate that the SWHM achieved the performance targets defined in Table 2 for the majority of the observational records tested. This is considered to provide sufficiently convincing evidence to support the view that the SWHM performs exceptionally well across the model domain.

Minor discrepancies (discussed below) remain at some locations with slight over-predicted wave heights in some exposed areas and under predicted wave heights in sheltered areas, while generally under-predicting wave periods by a small amount. There are also some discrepancies in areas dominated by strong tidal currents.

5.1 Significant Wave Height, Hs

Bias in Hs for 25 of the 28 calibration locations tested exceeded the performance target (Table 2) demonstrating very good model performance. The three sites where the bias statistic did not achieve the performance target (Hinkley, Figure 9; Seven Stones, Figure 10; and Gascogne, Figure 28) are discussed in Section 7. Similarly the wave height scatter index at all sites was found to be within the performance target, with the exception of Hinkley (Table A1). The correlation between the observed and modelled data (Table A2) was found to be statistically significant at greater than the 95% confidence level at all 28 model calibration sites.

5.2 Wave Period, Tz

In general, wave period predictions fall within the performance targets defined for bias for the majority of sites, with the comparisons from Hinkley being the only exception (Table A3). Generally, the SWHM tends to very slightly underestimate wave period (i.e. 22 of the 28 sites exhibit slight negative bias). However, there is no geographical trend evident in this behaviour. Scatter index percentages shown in Table A4 are less than 35% at all sites without exception. The highest scatter index of approximately 31% is found at Hinkley. Correlation coefficients for the observed and modelled data (Table A4) was found to be statistically significant at greater than the 95% confidence level. Only Hinkley, Hayling and Penas had correlation coefficients outside of the performance target (Table A4).

5.3 Wave Direction

At all locations where wave direction was measured (Table A5) the mean wave direction bias values are all less than 30°. The only exceptions to this are at Firth of Forth and Penas. It is noted also that although Hinkley, Moray Firth and Tees also show high bias, these statistics are not outside the performance target. Scatter index values for the majority of the calibration sites meet or exceed the performance target and are therefore judged to be accurate. However, Table A5 shows that Moray Firth, Firth of Forth and Tees (all from the same geographical region), have a scatter index that is outside of the desired limit of 35%. The proximity of these sites to the coast is likely to make them very sensitive the effects of coastal winds and how well these are described by the wind boundary. They are also locations where wind sea dominates and the swell component is small. The scatter index for all other locations where wave direction is recorded is low.

6. Results: Model Validation

The SWHM has been validated using observational wave data from 12 locations (Table 4) spanning a two month period from 1 November 2008 to 31 December, 2008. In common with the calibration period selected this period represents a wide range of wave events and directions, including both calm and storm periods and complex combinations of wind sea and swell.

Table 4. Wave measurement locations used in SWHM validation, local water depths and mean tidal ranges

Area	Location	Local Water Depth (m MSL)	Mean Tidal Range (m)
Irish Sea	Liverpool Bay	24	7.0
English South Coast	Poole	32	1.3
	Rustington	10	4.8
	Hastings	43	6.8
UK East Coast	Moray Firth	54	3.3
	Firth of Forth	65	4.3
	Dowsing	22	4.4
	West Gabbard	33	2.1
North Sea	FINO1	28	2.5
France	Gascogne	4,520	4.2
	Brittany	2,265	3.9
Spain	Penas	450	4.1

The summary statistics of the SWHM validation performance are shown in Appendix B (B1 to B5) and include information on: significant wave height, Hs, (bias, SI, β_0 and R); wave period, Tz, (bias, SI, β_0 and R); and wave direction (bias and SI). Shading is used to indicate where a statistic falls outside of the performance targets defined in Table 2. Visual comparison of the model performance, a graphical presentation of SWHM output and contemporaneous observational wave data is shown in Figure 32 through to Figure 43.

6.1 Significant Wave Height, Hs

Bias in Hs for 11 of the 12 validation locations tested (Table B1) exceeded the performance target (Table 2) demonstrating very good model performance. The only site where the bias statistic did not achieve the performance target was the Moray Firth on the UK east coast. The reasons for this are discussed in Section 7. The scatter index at all the validation sites (Table B2) exceeds the performance target value (Table 2). Scatter index values greater than 35 are noted for the Firth of Fourth and the FINO1 site in the North Sea for the reasons discussed in Section 7. With the exception of R values for the Firth of Fourth, R and βo values exceed the performance target. Together, when taking in consideration the reasons for slight model under-performance at a few sites, these statistics provide good validation evidence for model predictions of Hs. This is further reinforced by the time-series and scatter plots of model and observational data shown in Figures 32 to 43 for each model validation site.

6.2 Wave Period, Tz

At all model validation sites the wave period bias (Table B3) falls well within the performance target (Table 2). Scatter index values (Table B4) meet or exceed the performance target (Table 2) at all validation locations except FINO1 in the North Sea. Correlation and regression coefficients for the observed and modelled data (Table B4) were found to meet the performance target at eight validation locations. A discussion of model underperformance at the other four validation locations is given in Section 7.

6.3 Wave Direction

At five of the 12 model validation locations, mean wave direction bias values are less than 30°. However, Table B5 also shows that at five model validation locations Bias lies in the range 30° to 40°, and in two further locations bias values are 44.8° and 49.3°. However, scatter index values for 10 of the model validation sites meet the performance target and are therefore judged to be accurate. Only the Moray Firth and the Firth of Forth (Table B5) have scatter index vales that exceed the performance target (Table 2).

7. Discussion

The model calibration and validation results presented above have largely demonstrated that wave conditions predicted by the SWHM meet the performance targets defined in Table 2. This provides clear evidence that the model is fit for purpose. However, model performance does not meet the strict performance targets at a few locations and as indicated above, this section now provides an explanation for under-performance of the SWHM at some of the model calibration and validation locations.

When considering model calibration results and model performance it is important to remember that the quality of the observed data is a significant factor governing the modelling outcome. The quality of these data depend on the type of observation data, instrument type, accuracy, post-processing methods, resolution, deployment location, environmental conditions and human error (*cf.* ABPmer, 2013). Whilst every care has been taken here to assess the accuracy of the field data used for model calibration and validation, there may still remain some residual errors that cannot be detected, corrected or improved.

The first potential limitation to model performance is imposed by the bathymetric data used in the SWHM. Here the principal errors may arise from the level of detail resolved in the shallow nearshore areas. A lack of precision in the representation of the local bathymetry in shallow water can affects the modelled wave field behaviour and introduces a range of potential errors associated with wave refraction (affecting wave direction) and bed friction (affecting wave height and period). Thus in shallow water areas it is recommended that a local model is built with an appropriate spatial resolution of the bathymetry. ABPmer can offer bespoke solutions to address this issue.

As noted above, the SWHM does not presently include any tidal currents as these have little impact on the wave field across the majority of the model domain. However, there are some areas where tidal currents are so strong that they can influence wave propagation. With regards to the present model calibration/validation these areas include, for example, Hinkley in the Severn Estuary and Seven Stones where tidal flows exceed 2 m/s. Flow speeds of this magnitude are sufficient to influence wave behaviour and the use of model down-scaling is recommended so that tidal flow effects can be correctly represented in the wave model. An improvement in model performance would also be achieve in these cases through the use of higher resolution bathymetric data to enable these areas to be better represented in the model. Again, ABPmer can offer bespoke solutions to address this issue.

As noted above the greatest out-of-range bias is exhibited at Seven Stones (Figure 10). This site is located at the offshore tip of the south west of England and is exposed to a wide range of directional sectors including the North Atlantic Ocean. In contrast to all other wave measurements sites considered in this report, these wave data were obtained through post-processing of shipborne accelerometer data which recorded the motion of a large vessel at sea. Since there is some uncertainty about the accuracy of these data in truly resolving the position of the sea surface in a storm, when the vertical distance between 100% water and 99% air can exceed 1 m (Draper *et al*, 1974), wave data from the Seven Stones location must be treated with caution. Further, the frequency response of shipborne accelerometers and wave buoys are quite different making comparisons between wave data and model outputs problematic (*cf.* Crisp, 1987). It is also noted that the bathymetry in the vicinity of Seven Stones is highly variable and the Seven Stones light vessel is situated around 4 km approximately north east of the Seven Stones reef. The local seabed is not highly resolved in the current version of the SWHM grid and therefore any local attenuating effect the reef may not be fully described. This again highlights the need for accurate representation of bathymetry in any model of complex areas like Seven Stones.

Discrepancies between measured and predicted wave parameters remain at locations with slight over-predicted wave heights in some exposed areas and under predicted wave heights in sheltered areas. There is also a small under-prediction of wave periods at these locations. Further, the Firth of Forth, Penas, Hinkley, Moray Firth and Tees locations exhibit high bias in wave direction (although not exceeding the performance target in the case of the latter three locations). At all these locations it is possible that the model's spectral weighting between the onshore and offshore directed waves is incorrect (i.e. a bias towards wind sea). Where these are generally opposing one another, the mean wave direction becomes unrepresentative of the total wave field. At Moray Firth particularly these two wave directions are directly opposed to one another due to the shape of the Firth. Table A5 shows that Moray Firth, Firth of Forth and Tees (all from the same geographical region), have a scatter index that is outside of the desired limit of 35%. The proximity of these sites to the coast is likely to make them very sensitive the effects of coastal winds and how well these are described by the wind boundary. The scatter index for all other locations where wave direction is more exposed to swell dominance. In the case where sites of interest are subject to land effects of the type described above, a local scale model is required to improve accurate representation of the local wave field.

It is also noted that Gascogne (Figure 28) exhibits a high bias in Hs of 0.42 m. A visual check upon the model's performance here suggests that wave heights are represented least well during periods of switching direction (such as when weather systems track over the area). The performance during these times will be highly dependent upon the accurate representation of the NCEP wind boundary conditions. Without recourse to wind data with a higher spatial and temporal resolution it is not possible to reconcile local errors of this nature in wave model predictions. However, this issue is unlikely to affect long-term statistics or extremes since any deviations average out through time.

However, despite the few locations where the SWHM slightly under-performed, the overall calibration and validation results demonstrate that the SWHM provides accurate regional scale wave hindcast data for areas of interest and meet the requirements of a wide range of end-users. Indeed, when considering comparisons between other wave model hindcast data observational data (e.g. Bradbury *et al*., 2004), the SWHM model performance demonstrated here is very good for the key wave parameters Hs, Tz and direction. Our analysis of the very few locations where the model fails to meet performance targets has identified the reasons why the model under-performs and bespoke solutions to these issues can now be provided by ABPmer for specialist applications.

8. Conclusions

Following successful calibration, SWHM has been used to generate a 34.5 year wave time-series around the UK and European coastal seas. Accurate calibration of the model is clearly demonstrated at a wide geographical spread of 28 sites and for a wide range of meteorological forcing conditions and far field wave propagation during the two month period between 12 November 2009 to 1 January 2010.

Model validation at 12 sites for the two month period 1 November 2008 to 31 December 2008 has shown independently that the SWHM generally performs exceptionally well and is therefore judged to be fit-for-purpose.

Although present levels of SWHM performance are considered to be very good overall, local model down-scaling is the preferred option to address tidal influences (the Bristol Channel). Such down-scaling will be structured into the planned future enhancements and improvements to SEASTATES.

9. References

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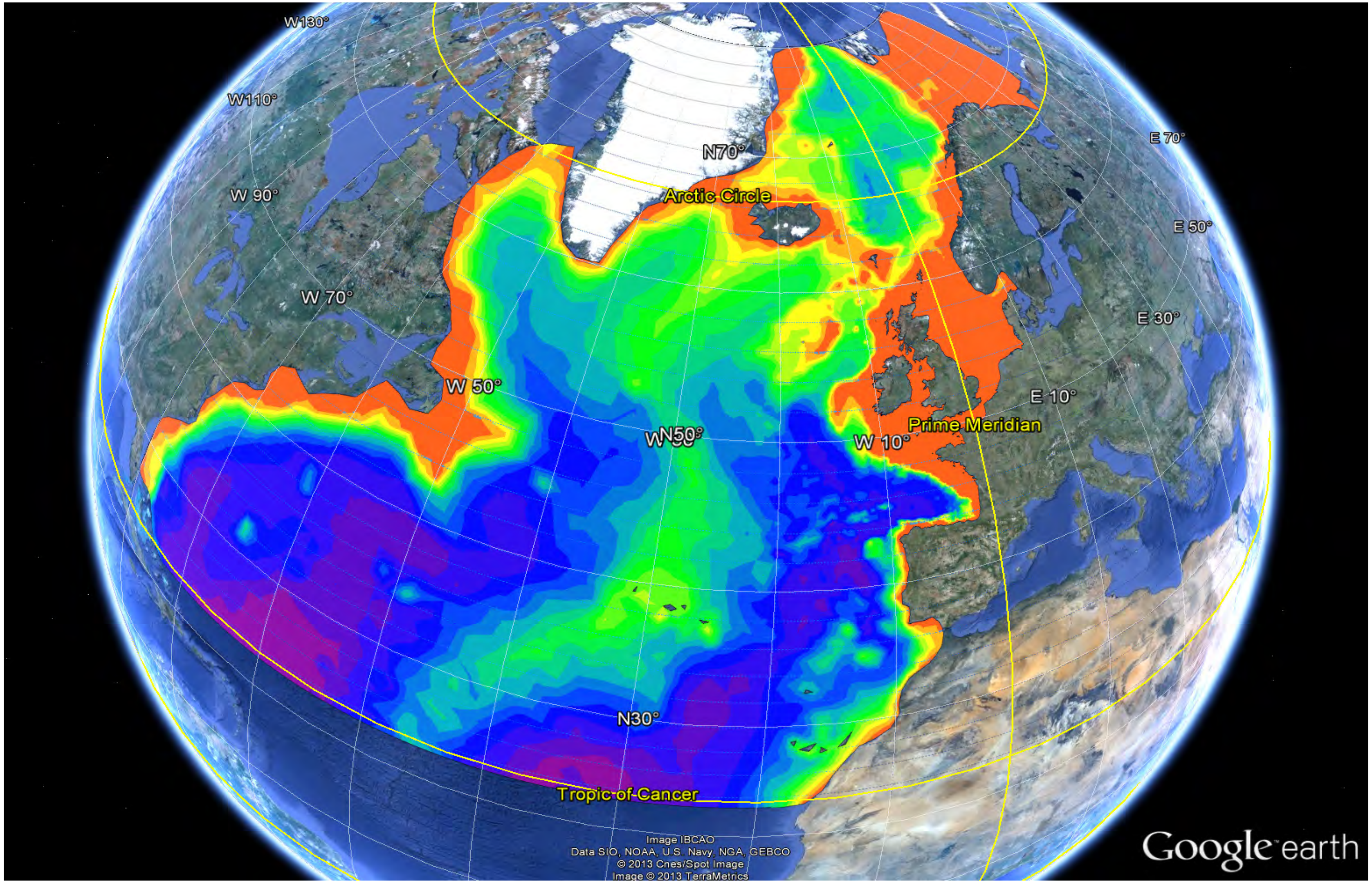
Figures



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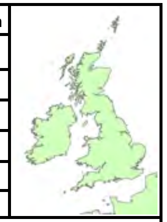

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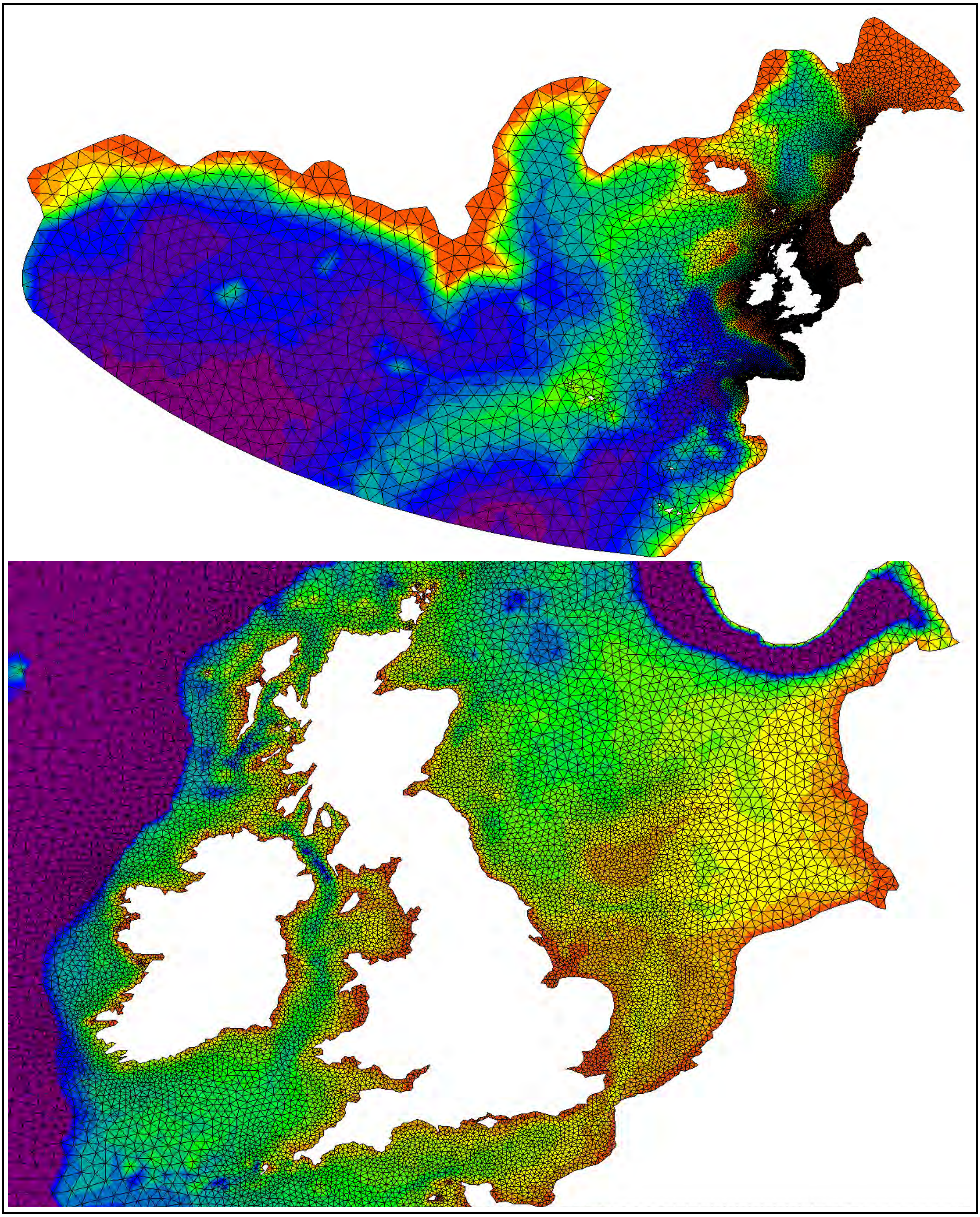
Model Extent

Figure 1



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Model Mesh Detailed View

Figure 2

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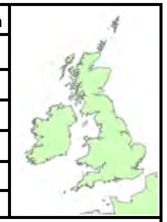

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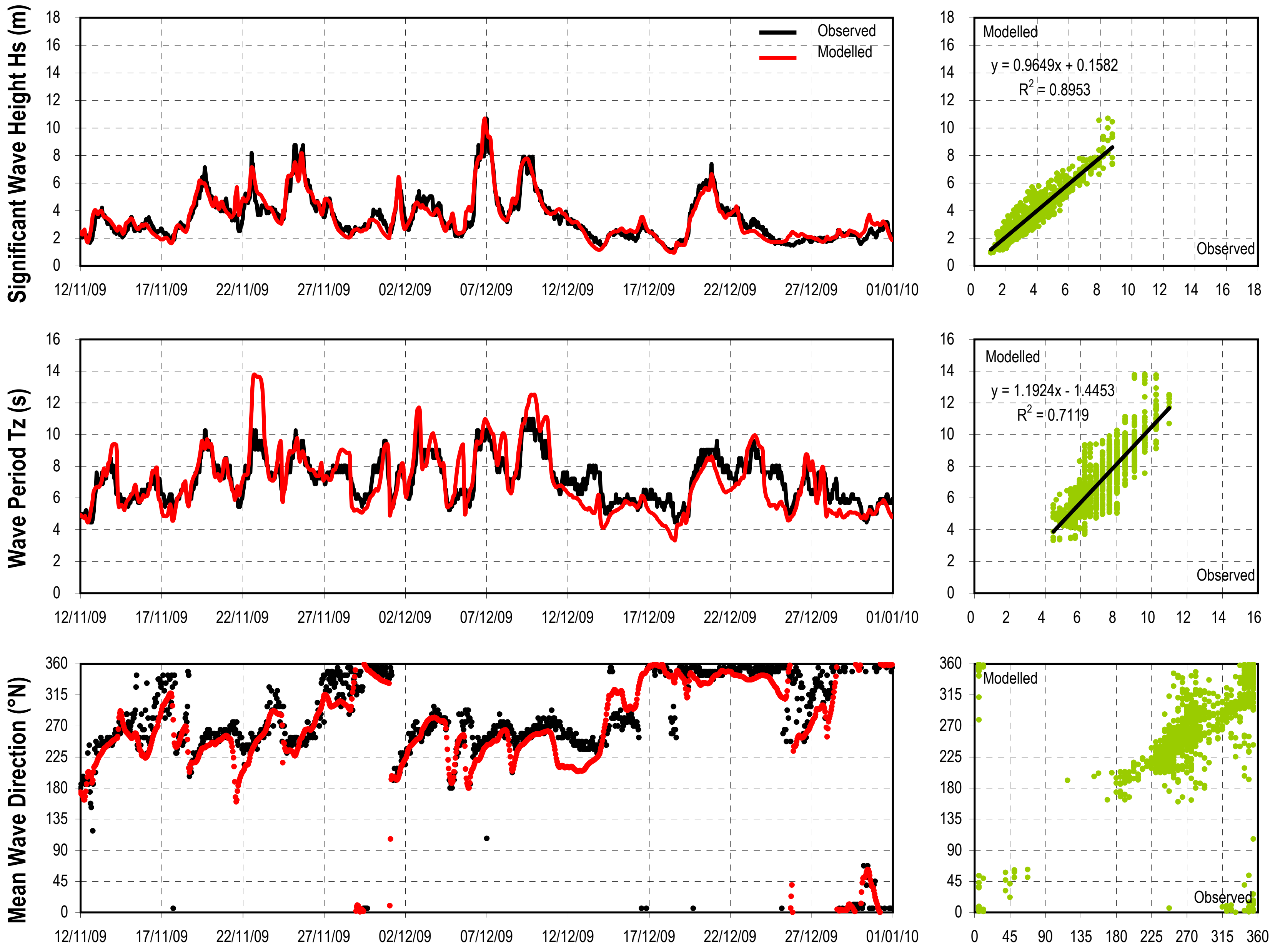
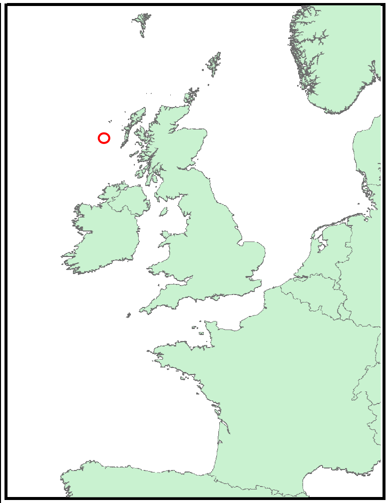
Locations of the Wave Records for Calibration

Figure 3

West Hebrides





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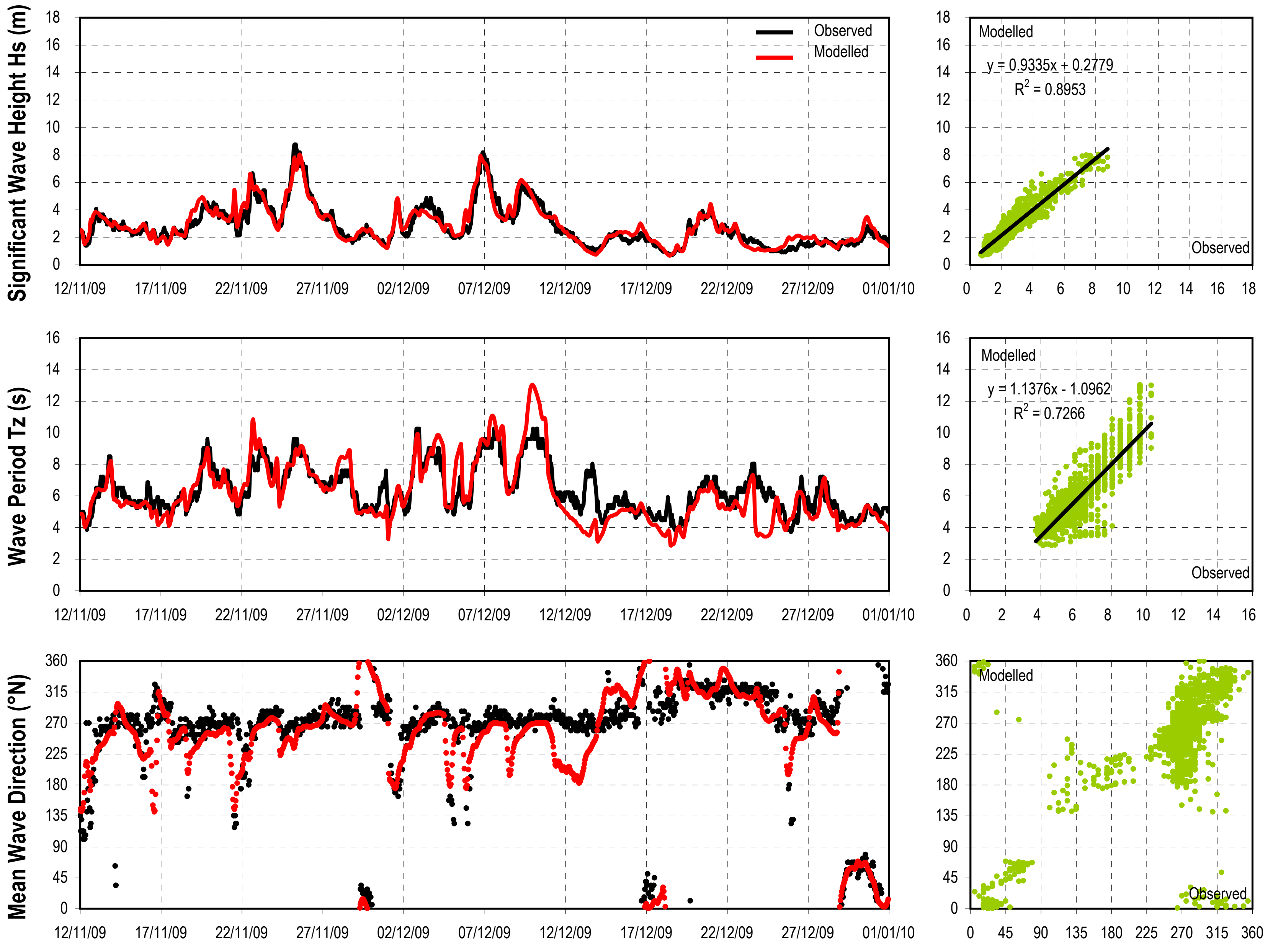
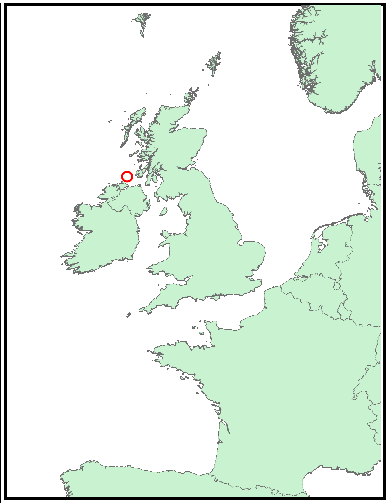
Calibration Summary: West Hebrides

Figure 4

Blackstones





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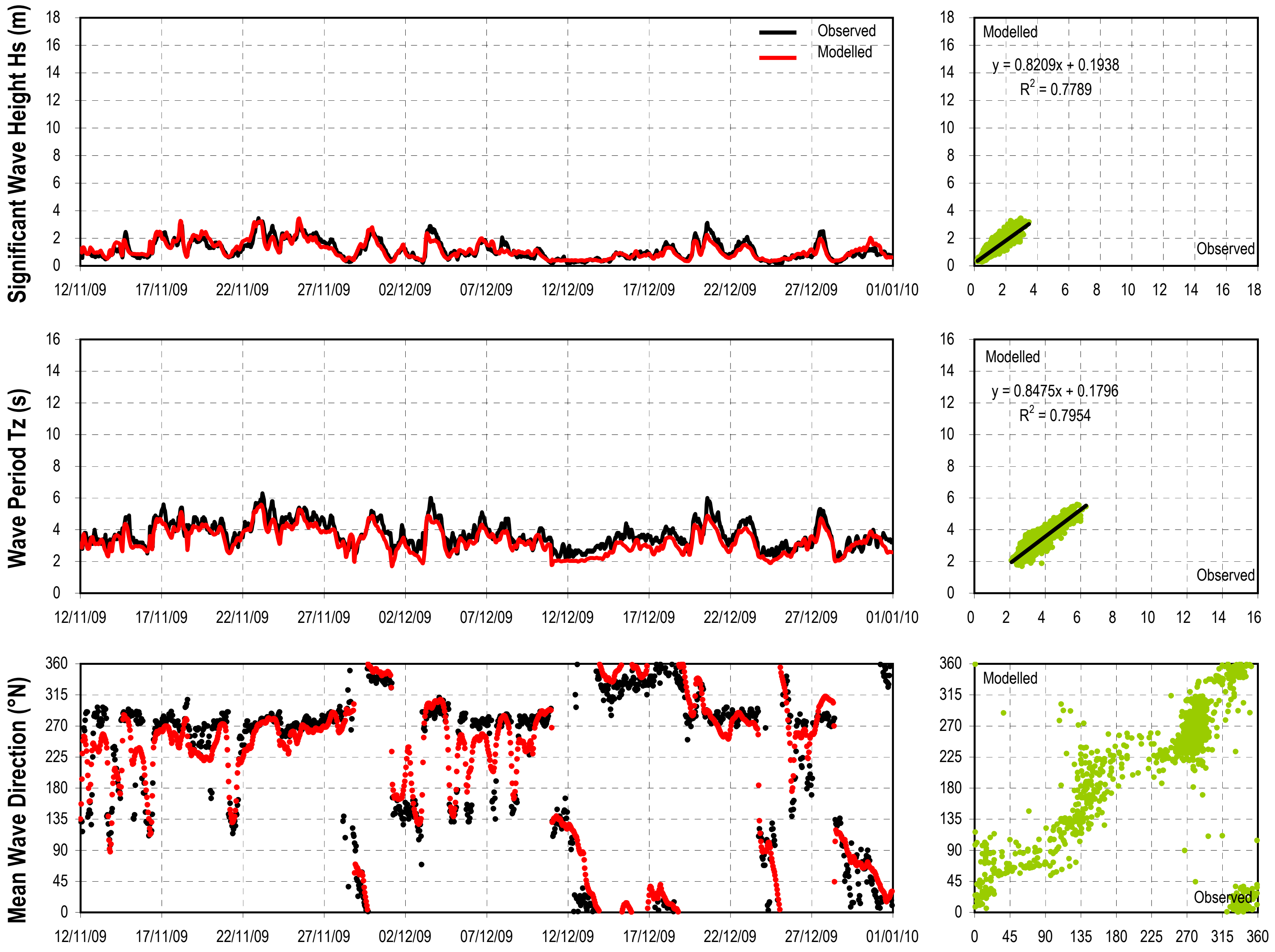
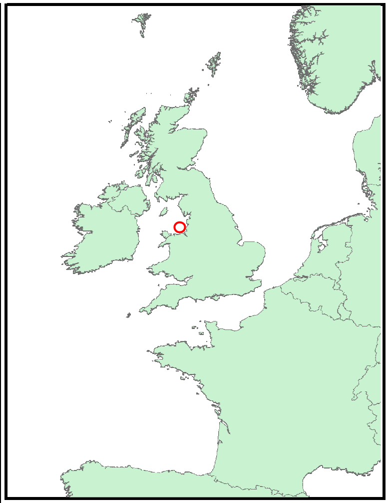
Calibration Summary: Blackstones

Figure 5

Liverpool Bay





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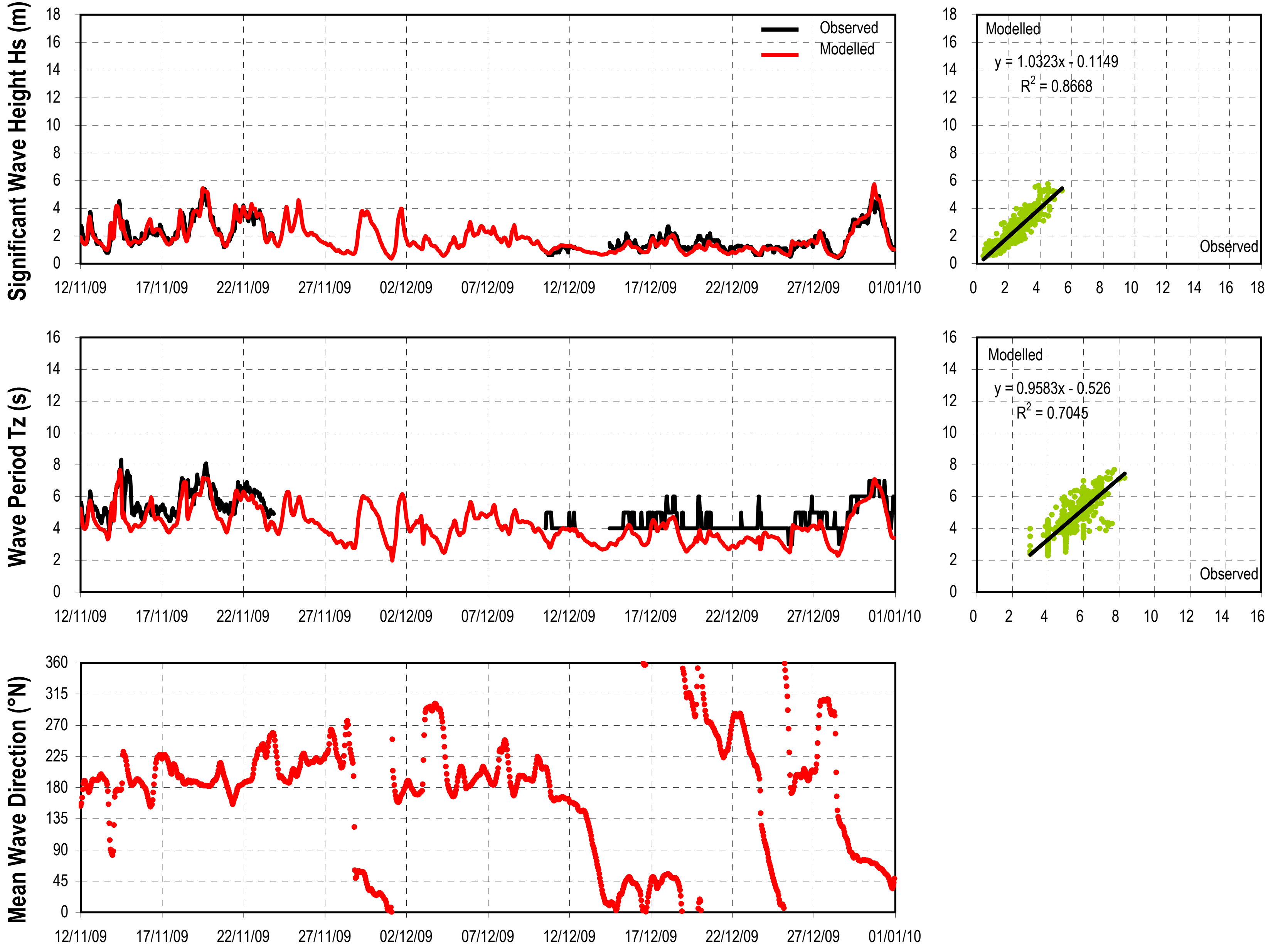
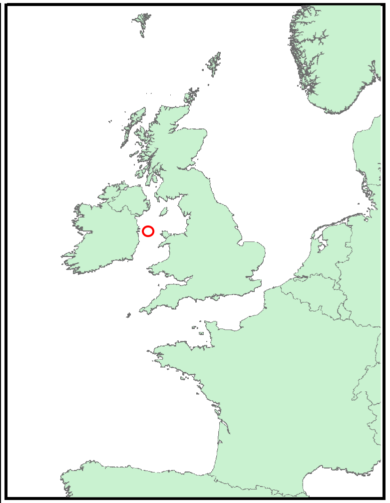
Calibration Summary: Liverpool Bay

Figure 6

M2





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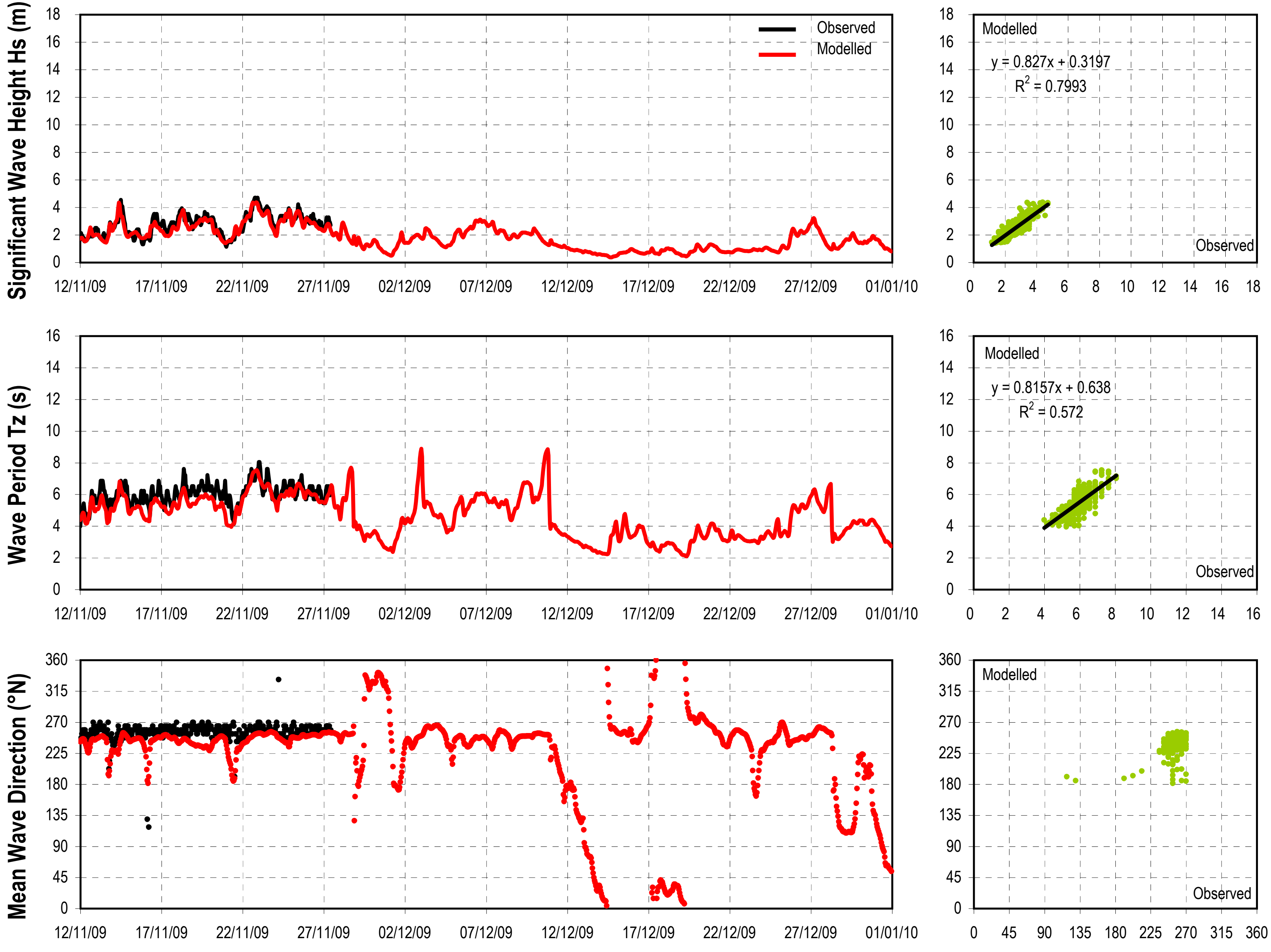
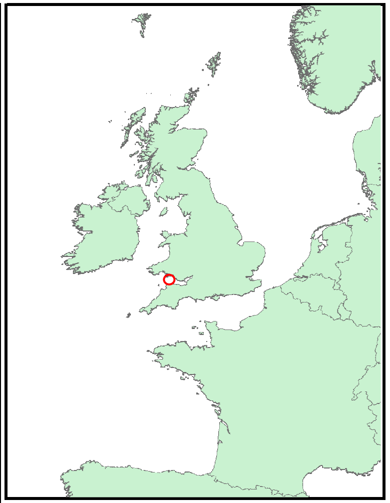
Calibration Summary: M2

Figure 7

Scarweather





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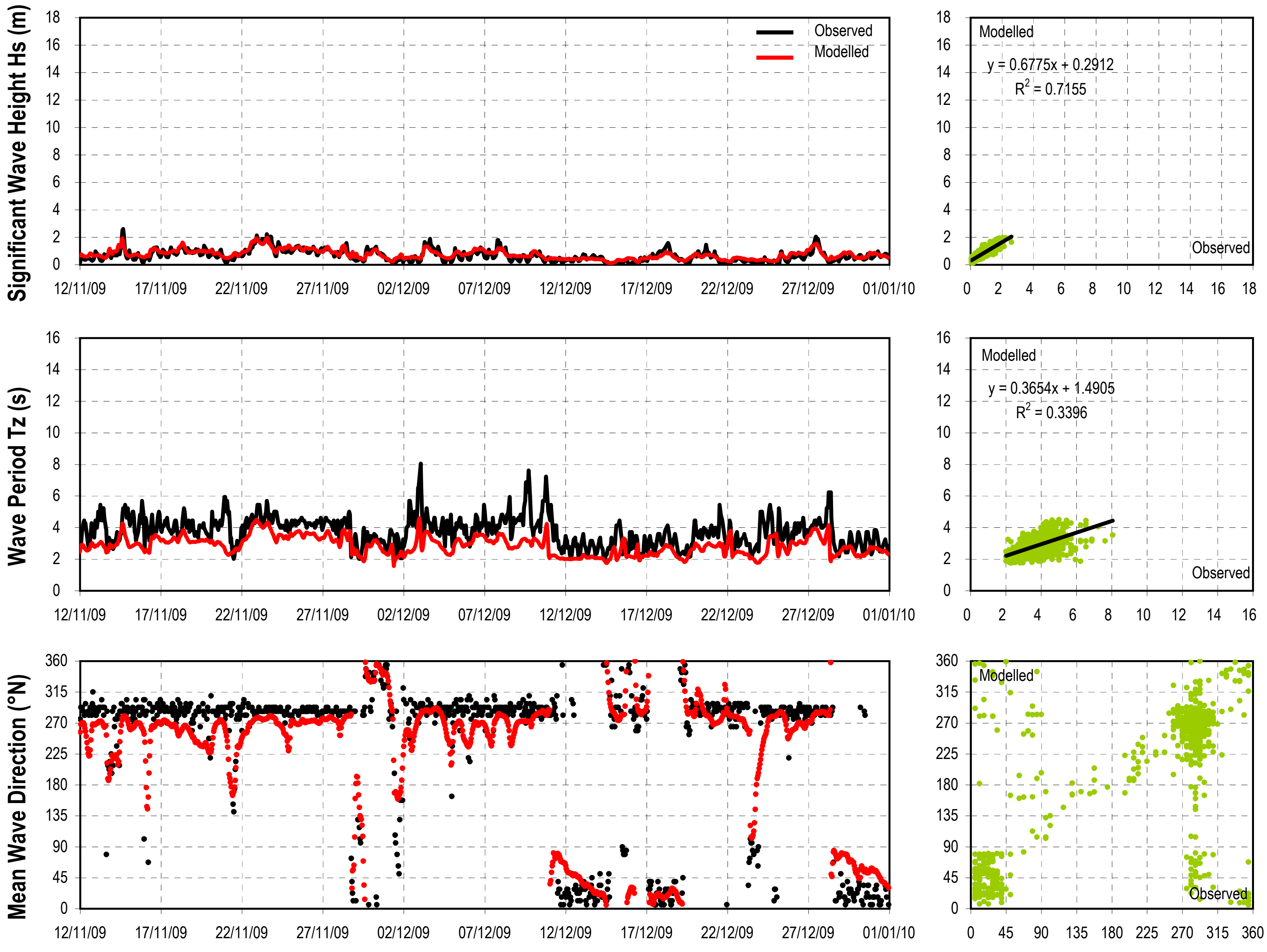
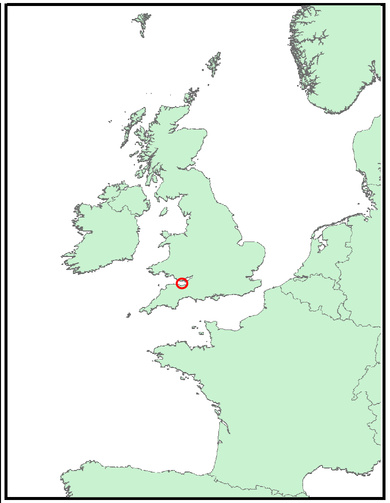
Calibration Summary: Scarweather

Figure 8

Hinkley





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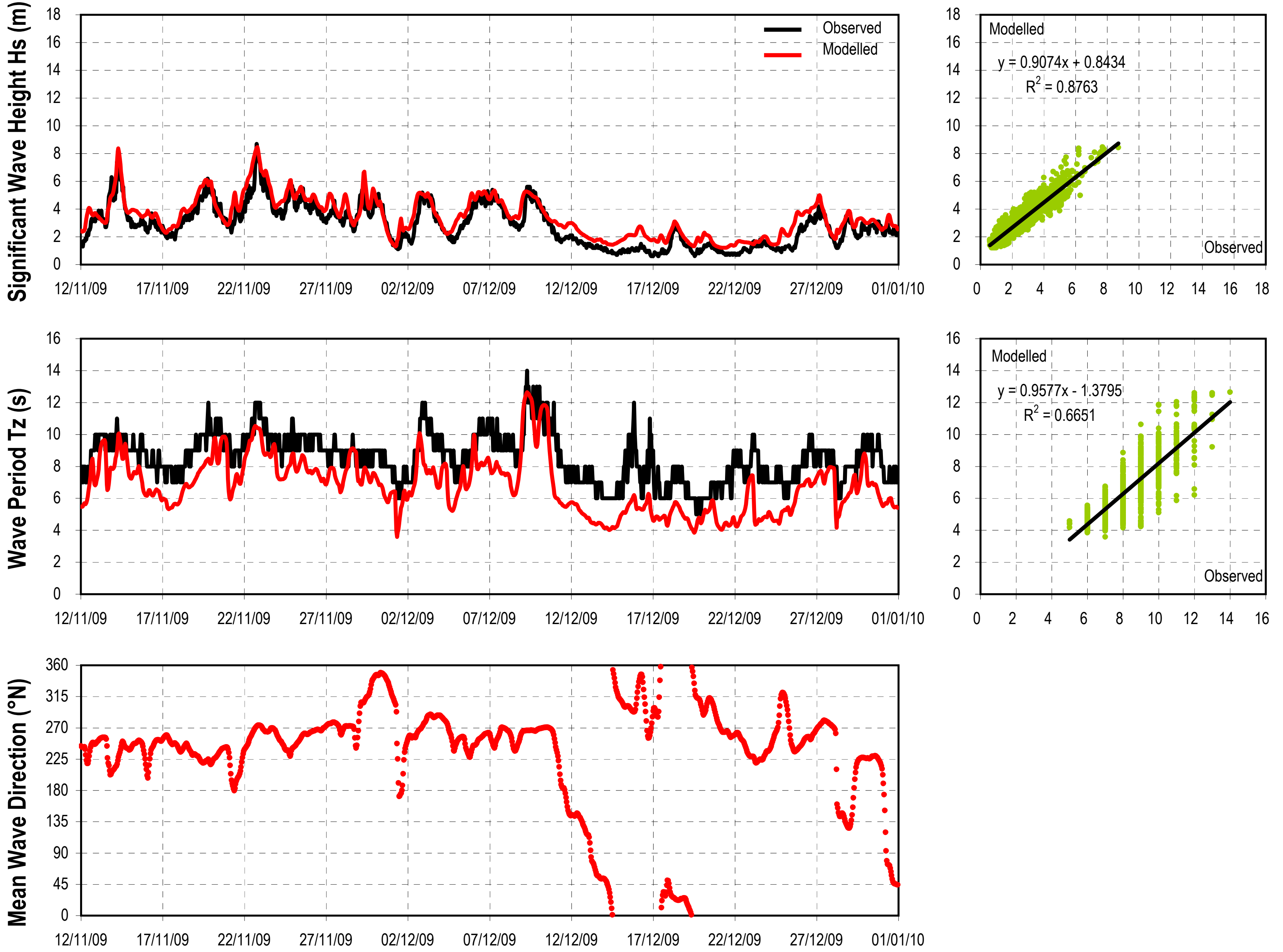
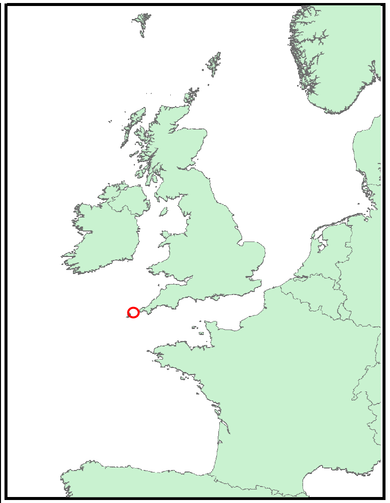
Calibration Summary: Hinkley

Figure 9

Seven Stones





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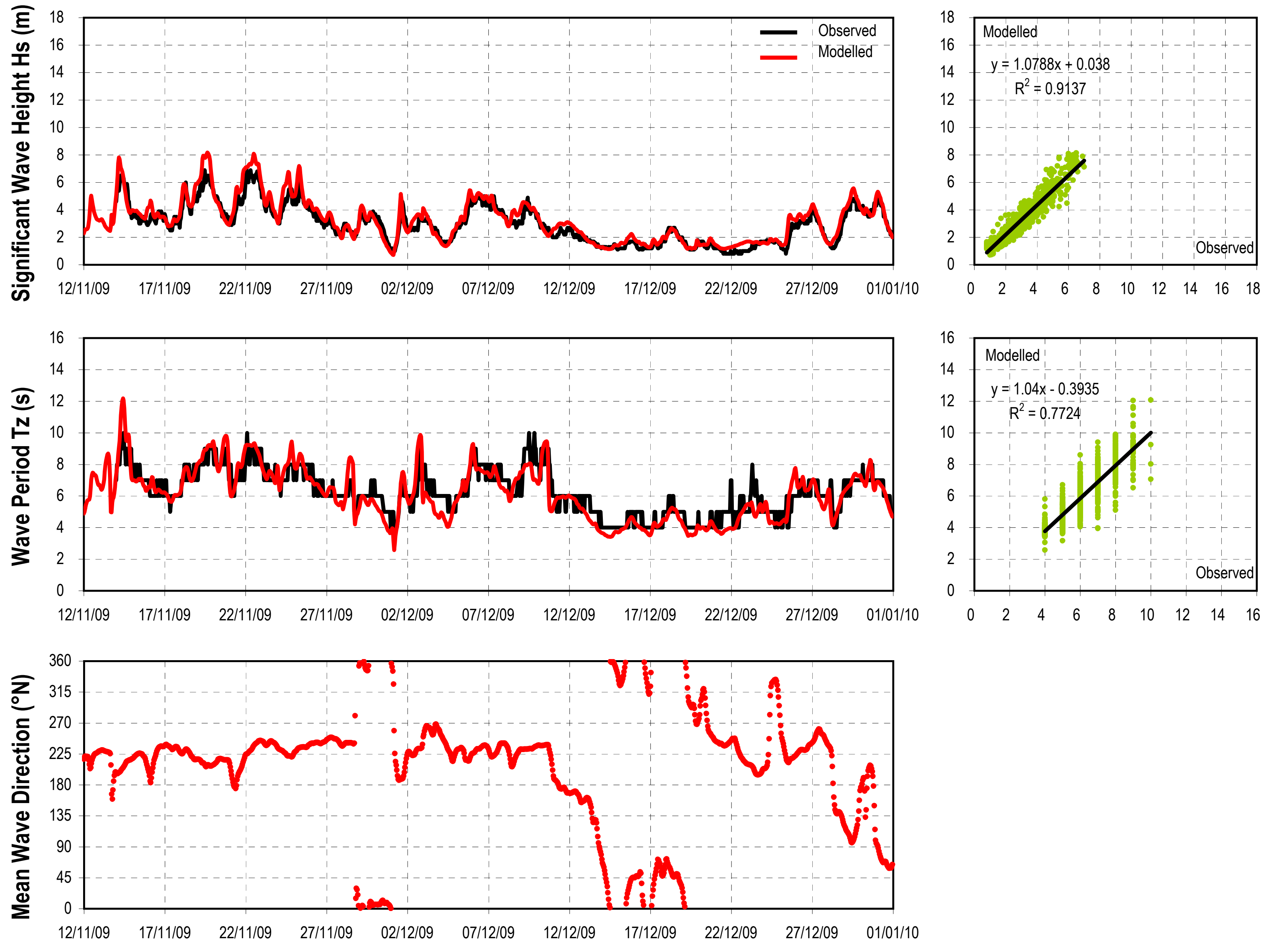
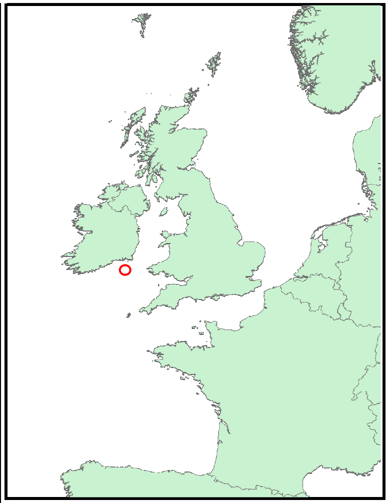
Calibration Summary: Seven Stones

Figure 10

M5





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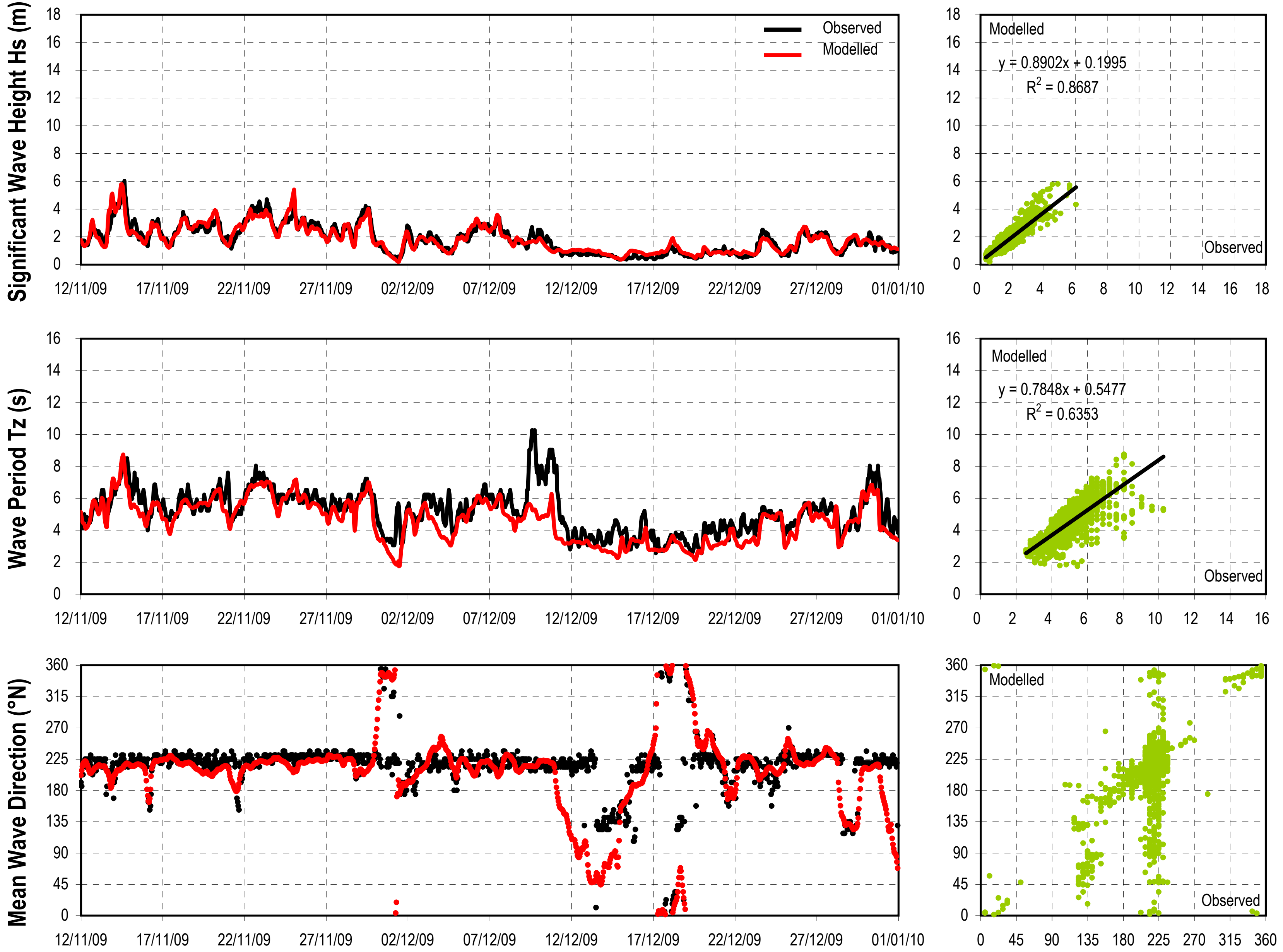
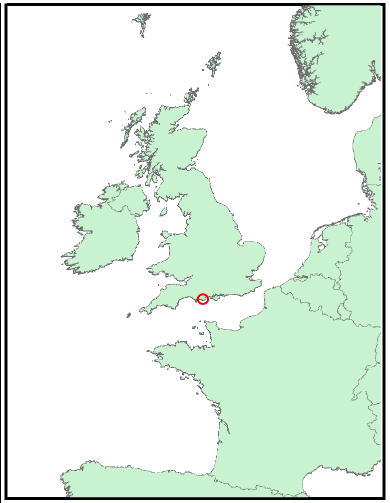
Calibration Summary: M5

Figure 11

Poole





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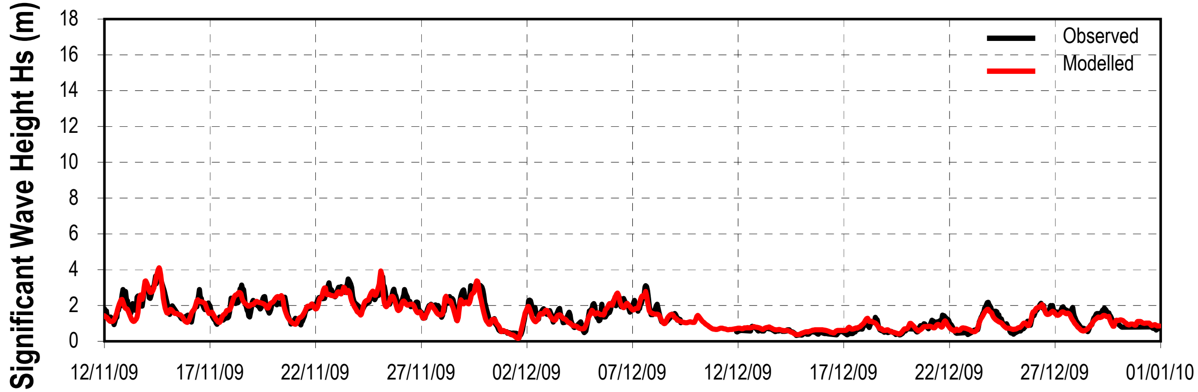
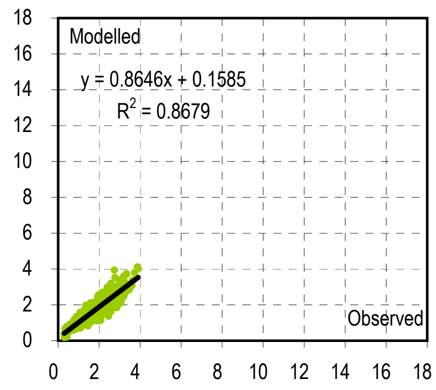
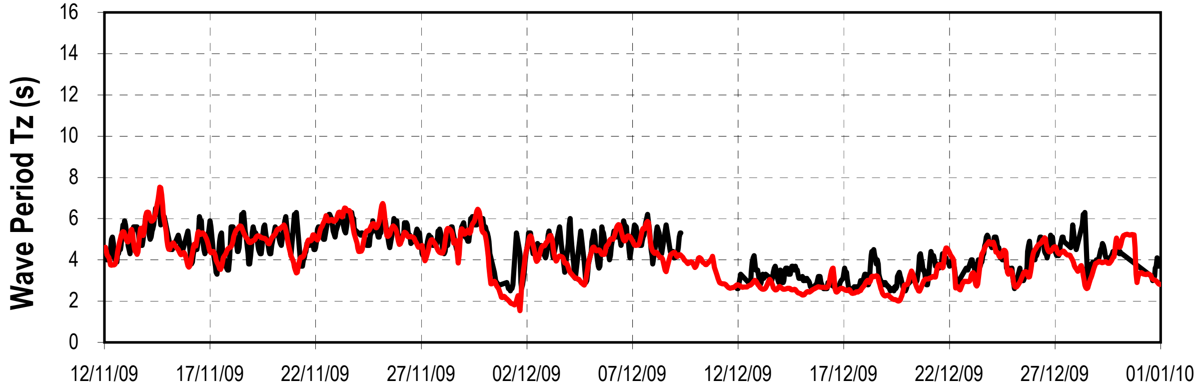
Calibration Summary: Poole

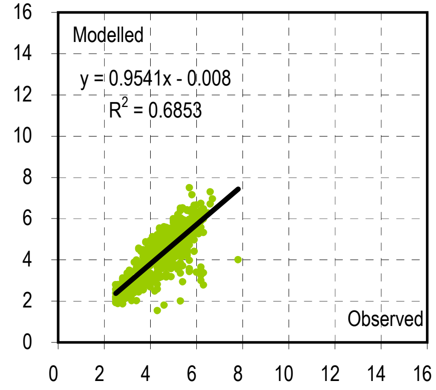
Figure 12

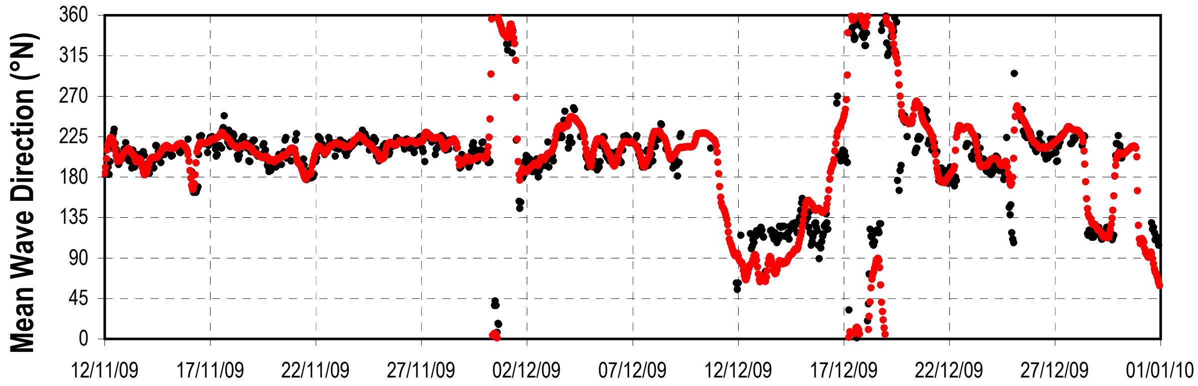
Rustington

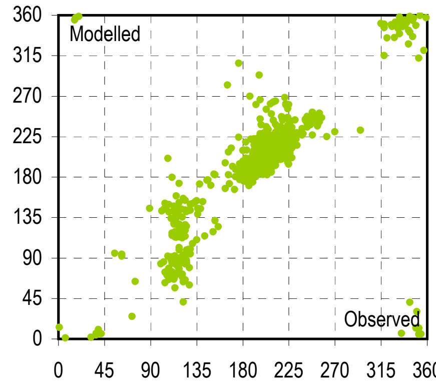


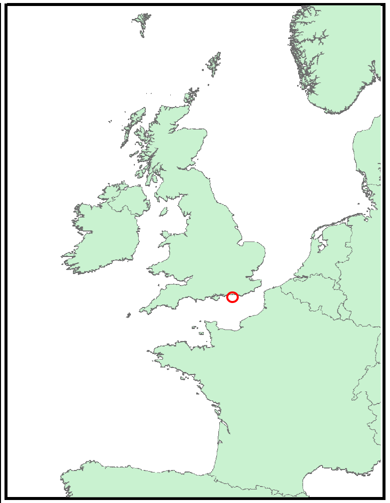












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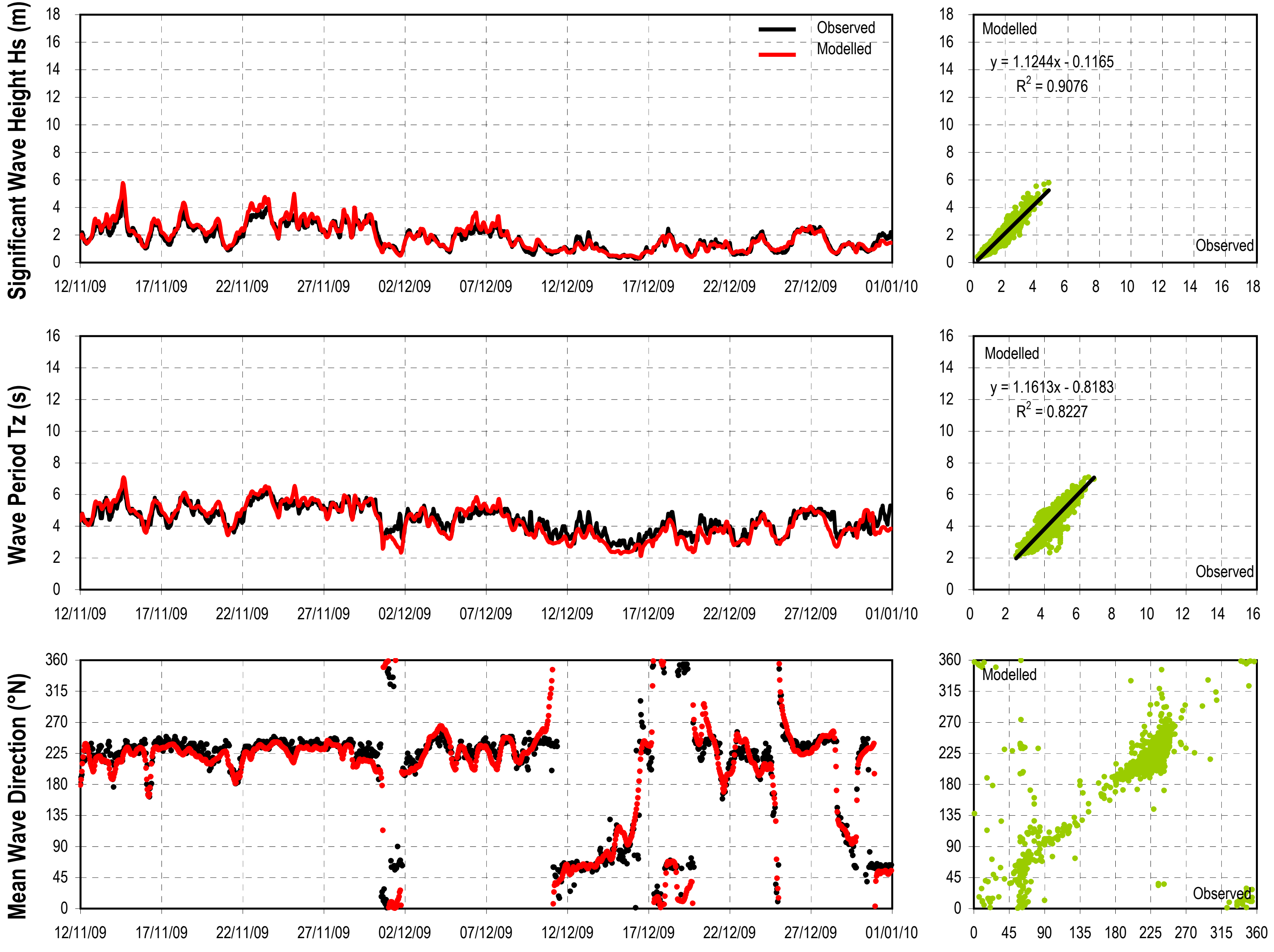
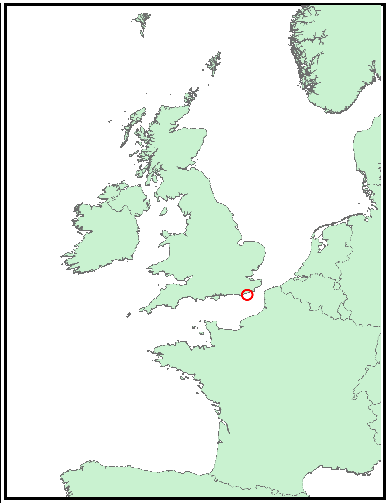
Calibration Summary: Rustington

Figure 13

Hastings





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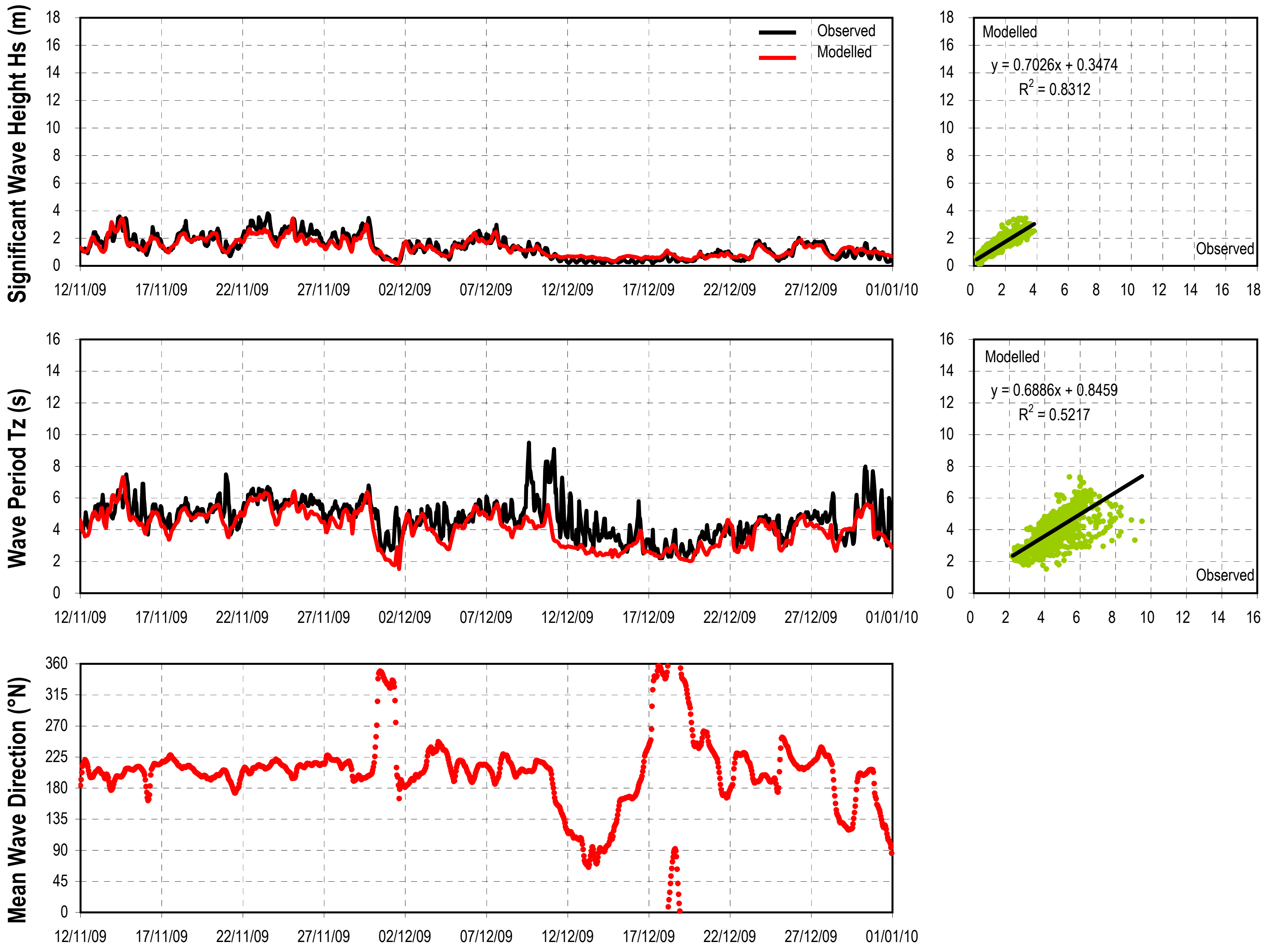
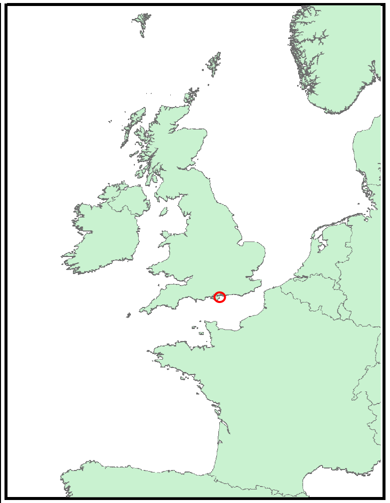
Calibration Summary: Hastings

Figure 14

Bracklesham





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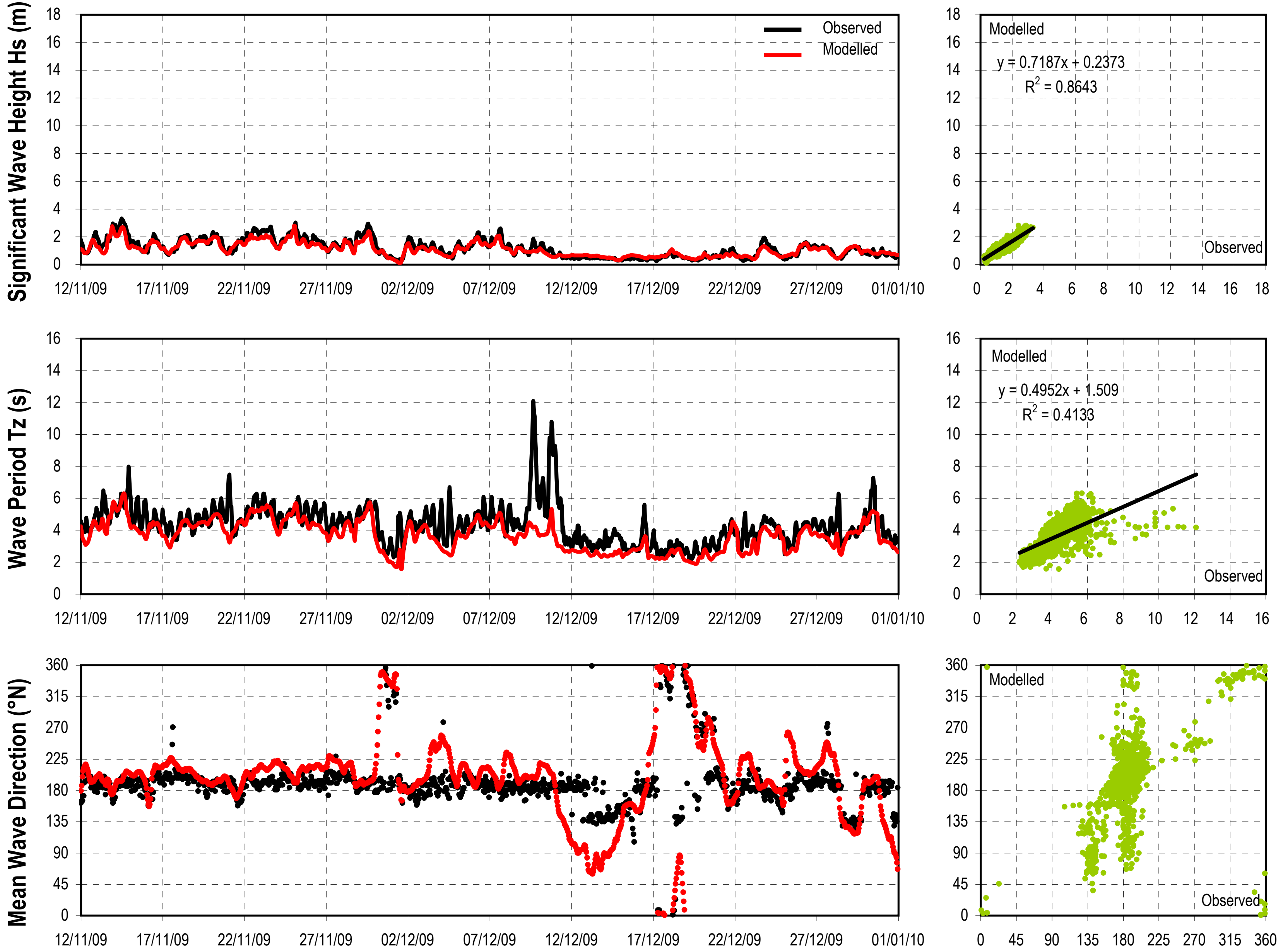
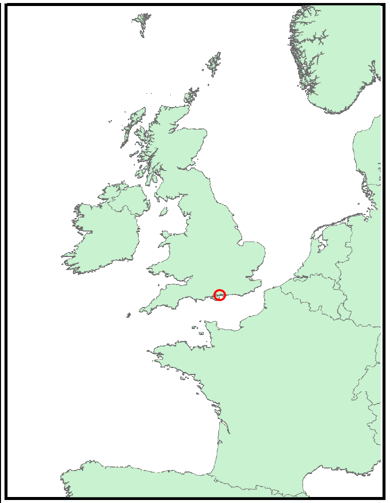
Calibration Summary: Bracklesham

Figure 15

Hayling





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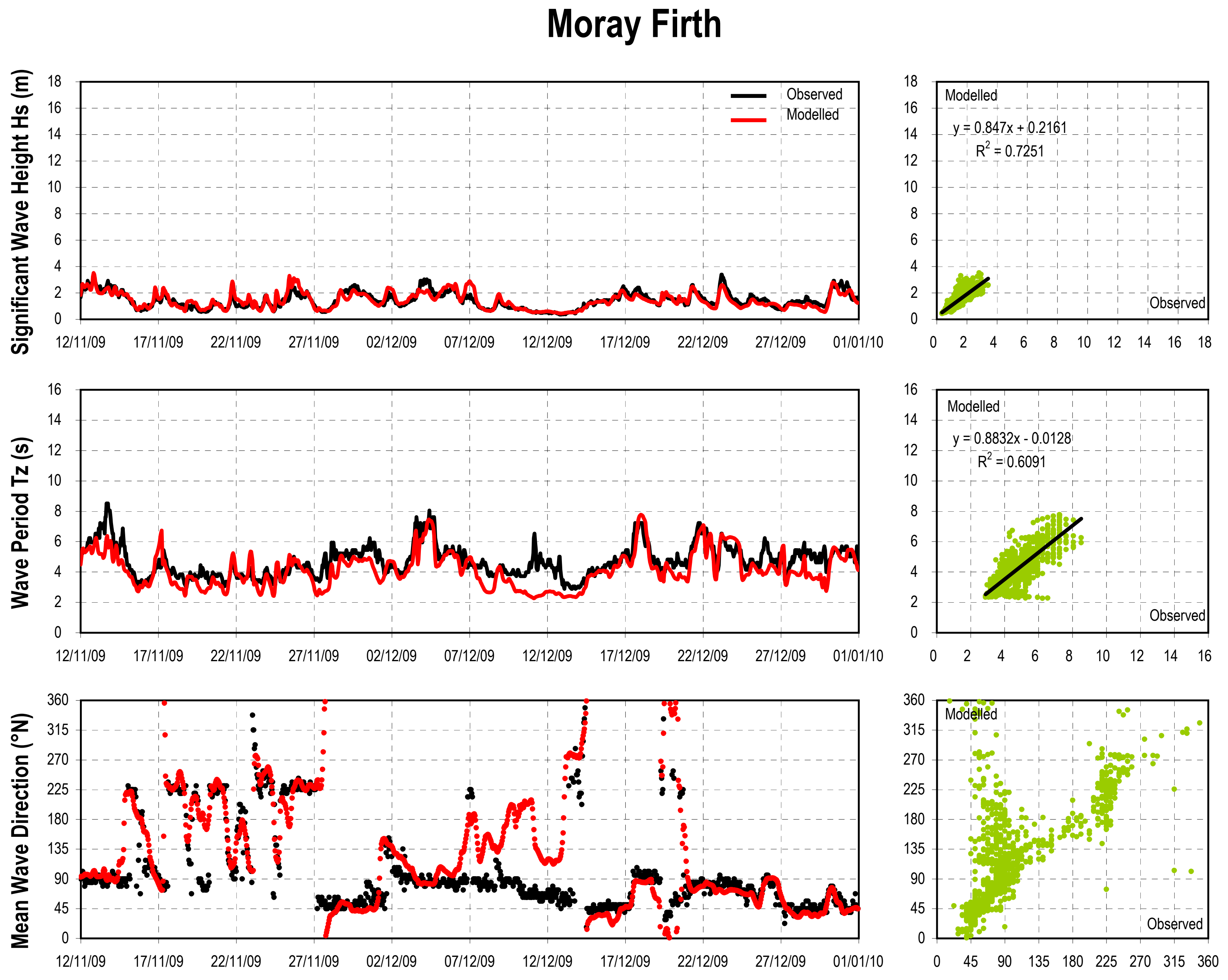
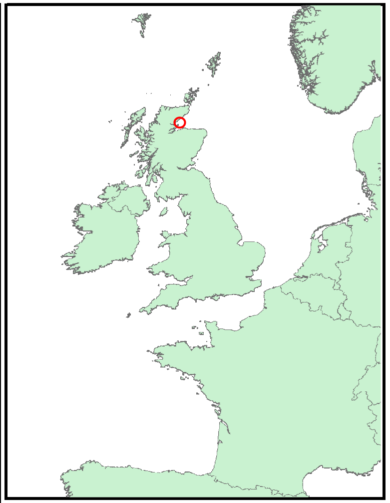
Calibration Summary: Hayling

Figure 16





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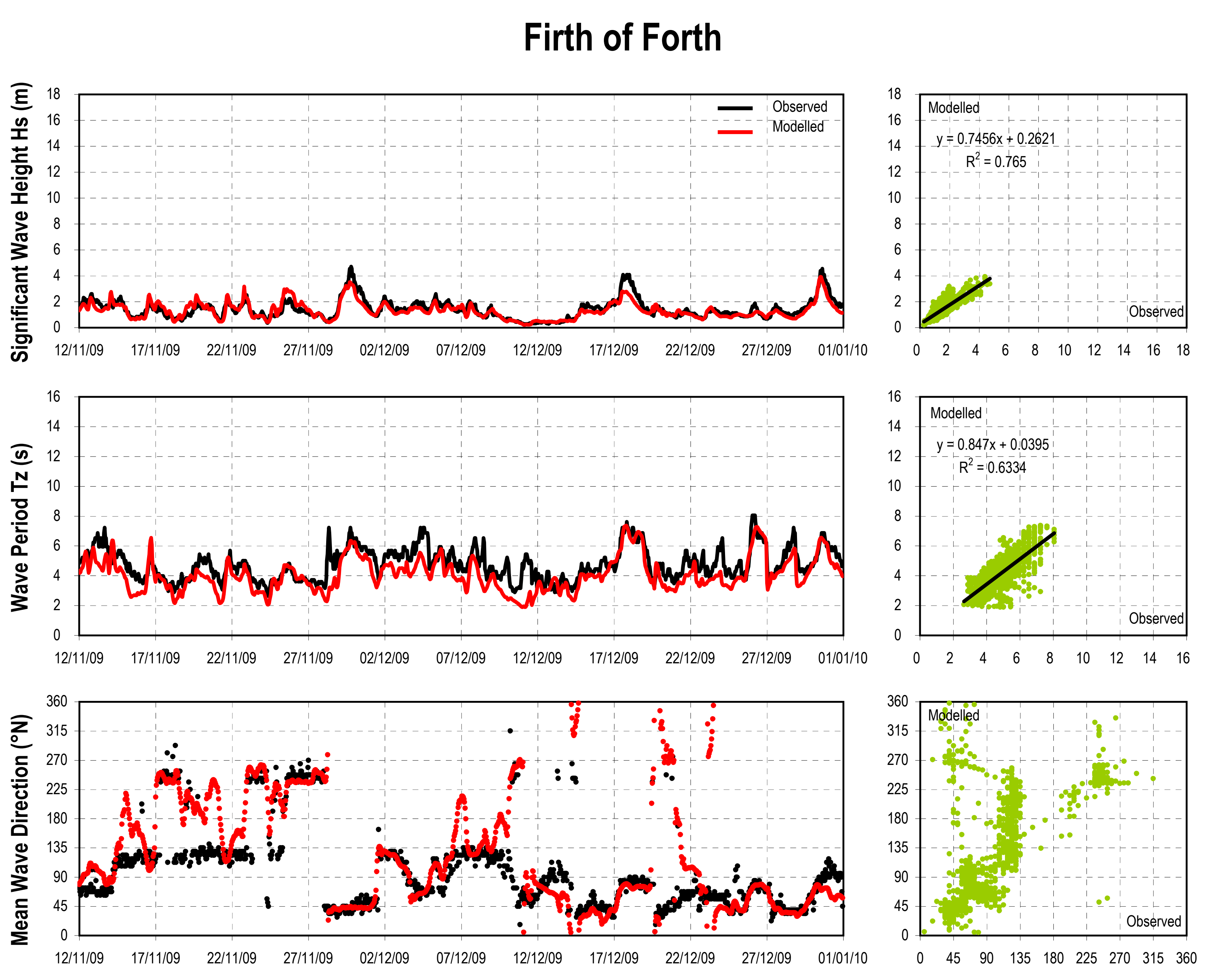
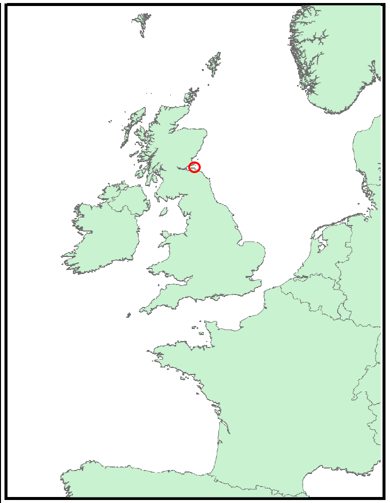
Calibration Summary: Moray Firth

Figure 17





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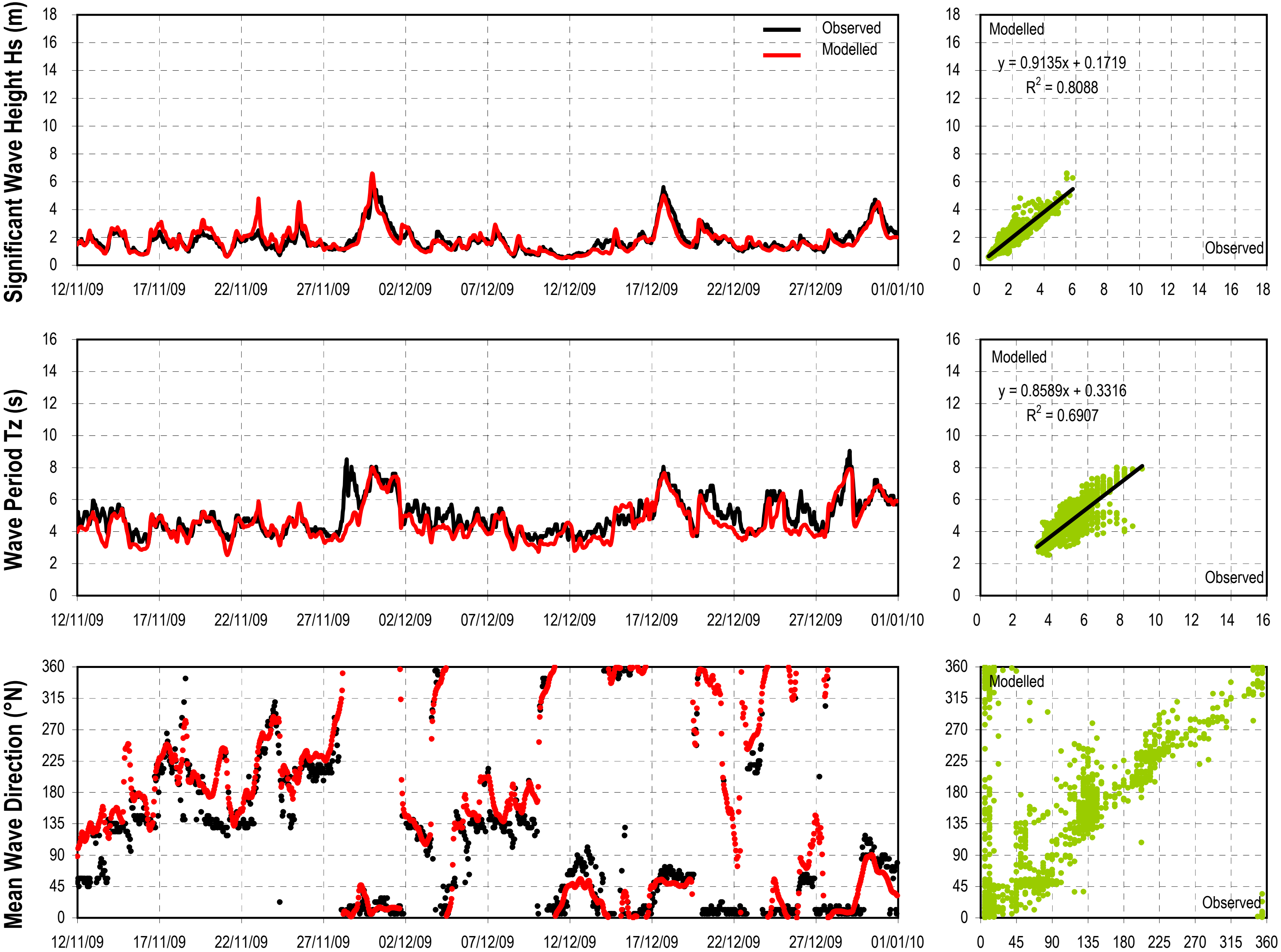
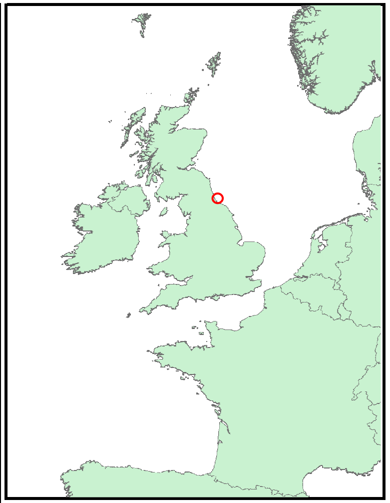
Calibration Summary: Firth of Forth

Figure 18

Tees





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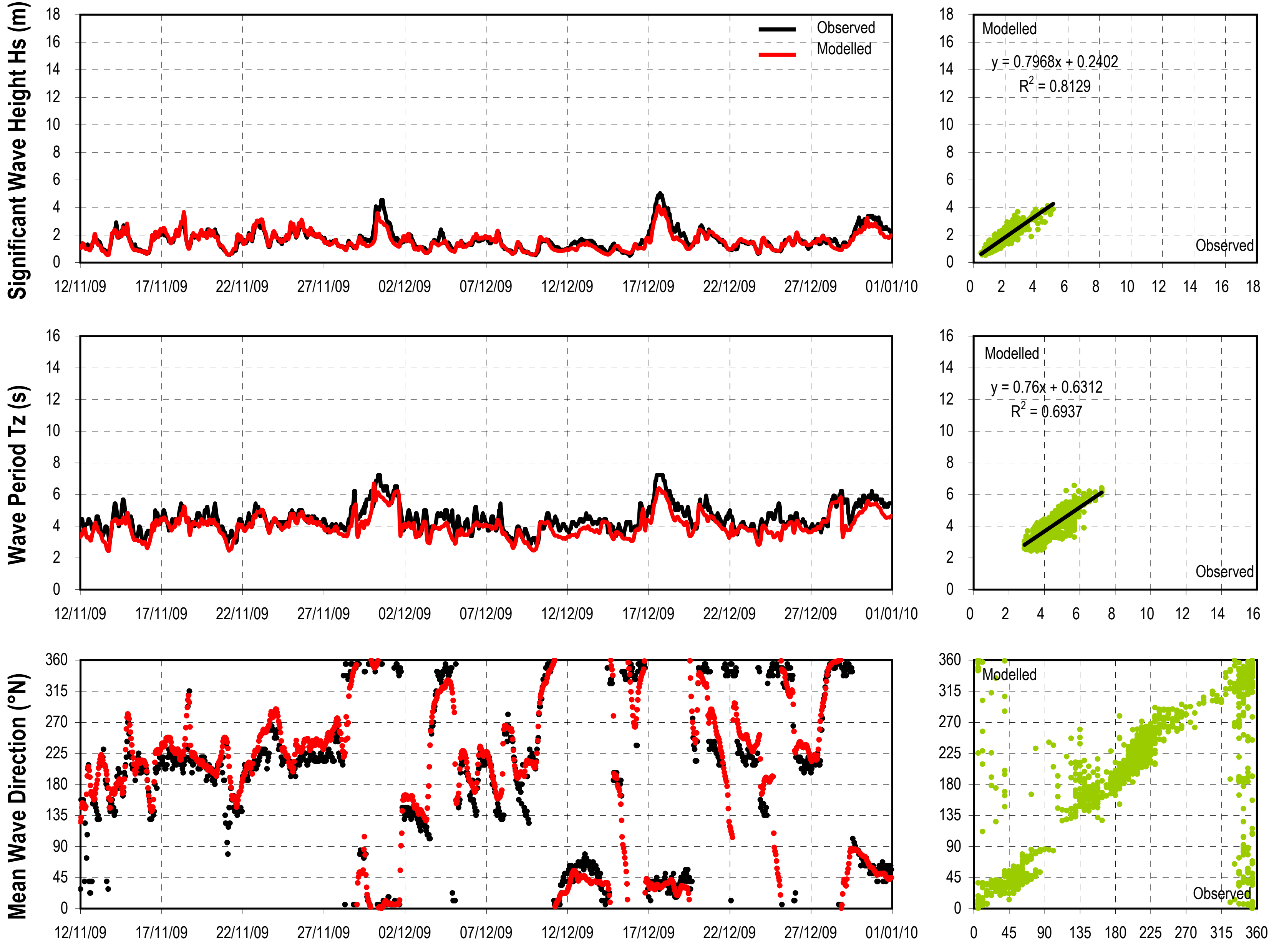
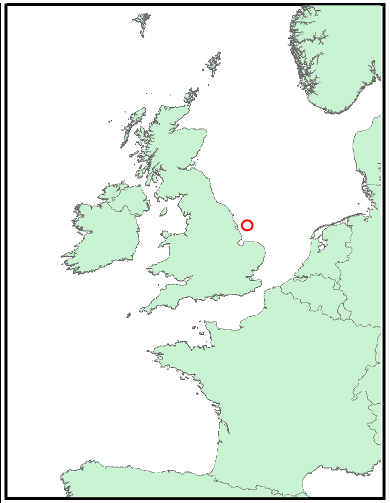
**Calibration Summary:
Tees**

Figure 19

Dowsing





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Scale		n/a	
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Produced by ABPmer			

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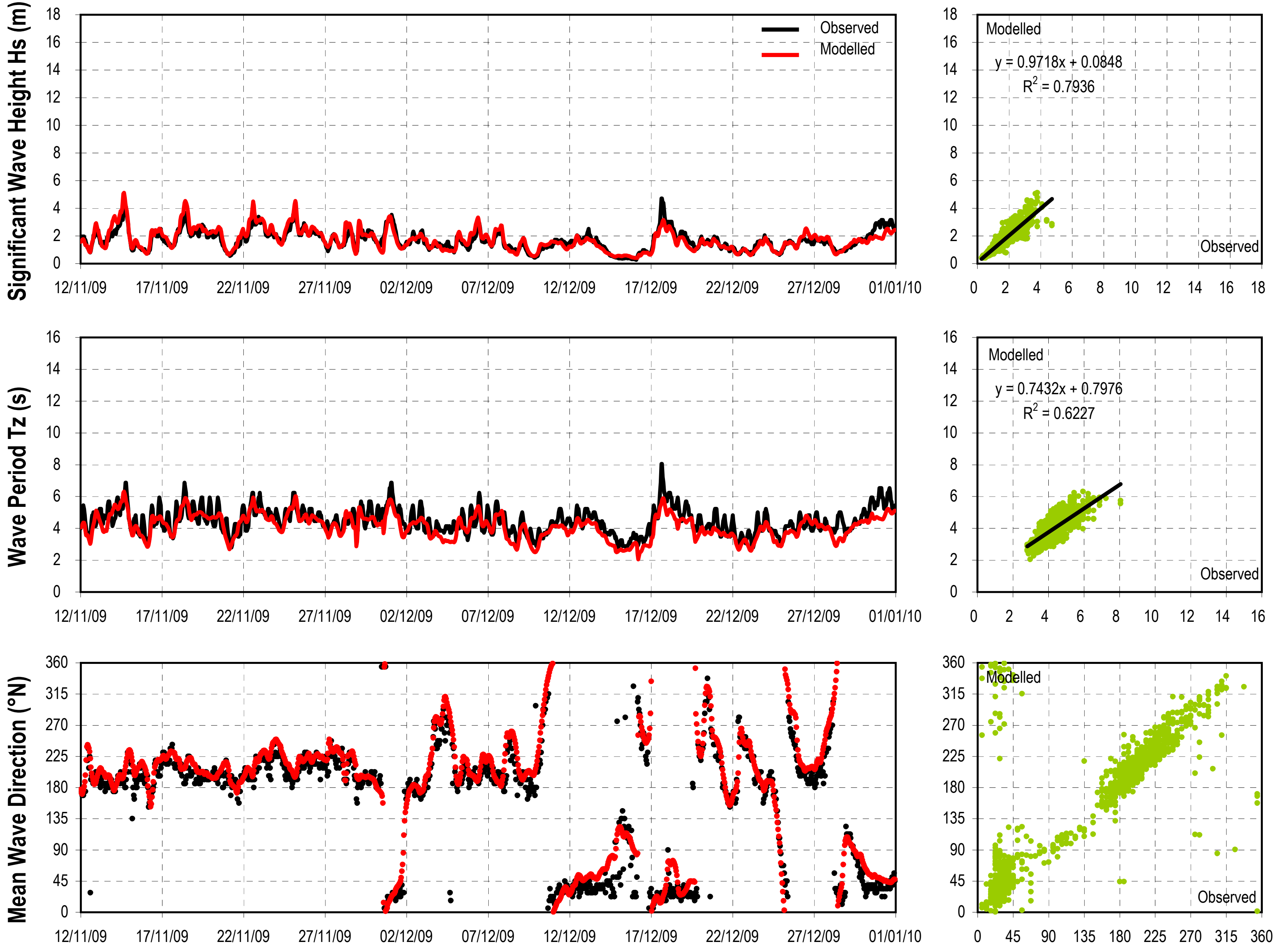
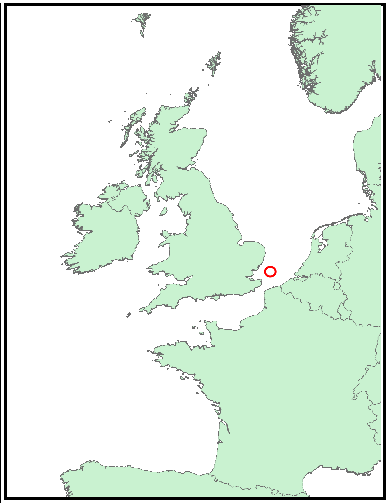
Calibration Summary: Dowsing

Figure 20

West Gabbard





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Produced by ABPmer			

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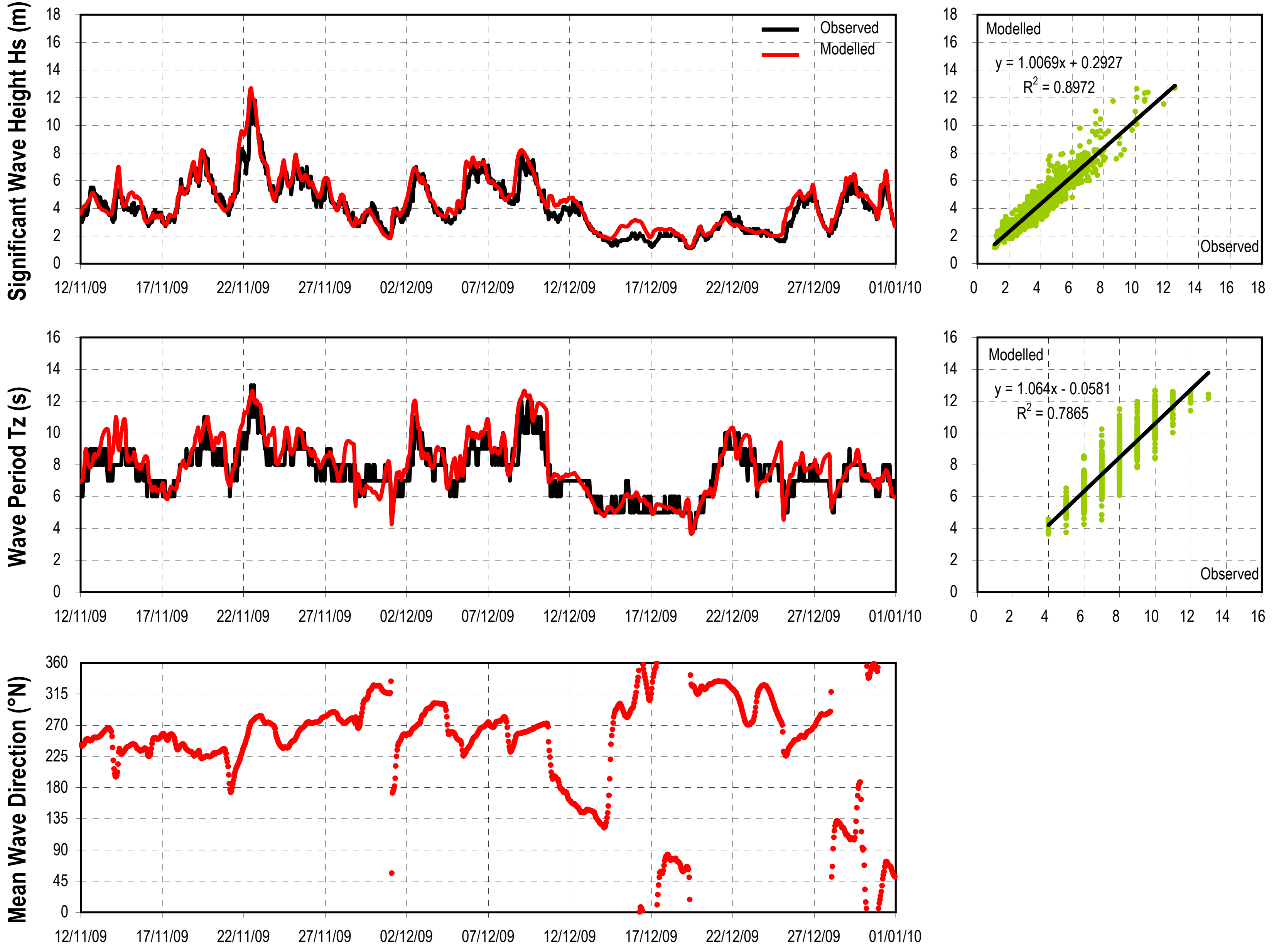
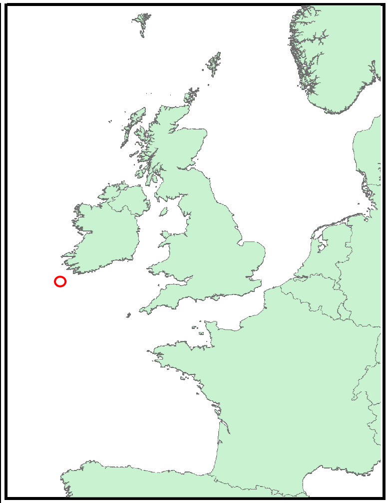
Calibration Summary: West Gabbard

Figure 21

M3





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Produced by ABPmer			

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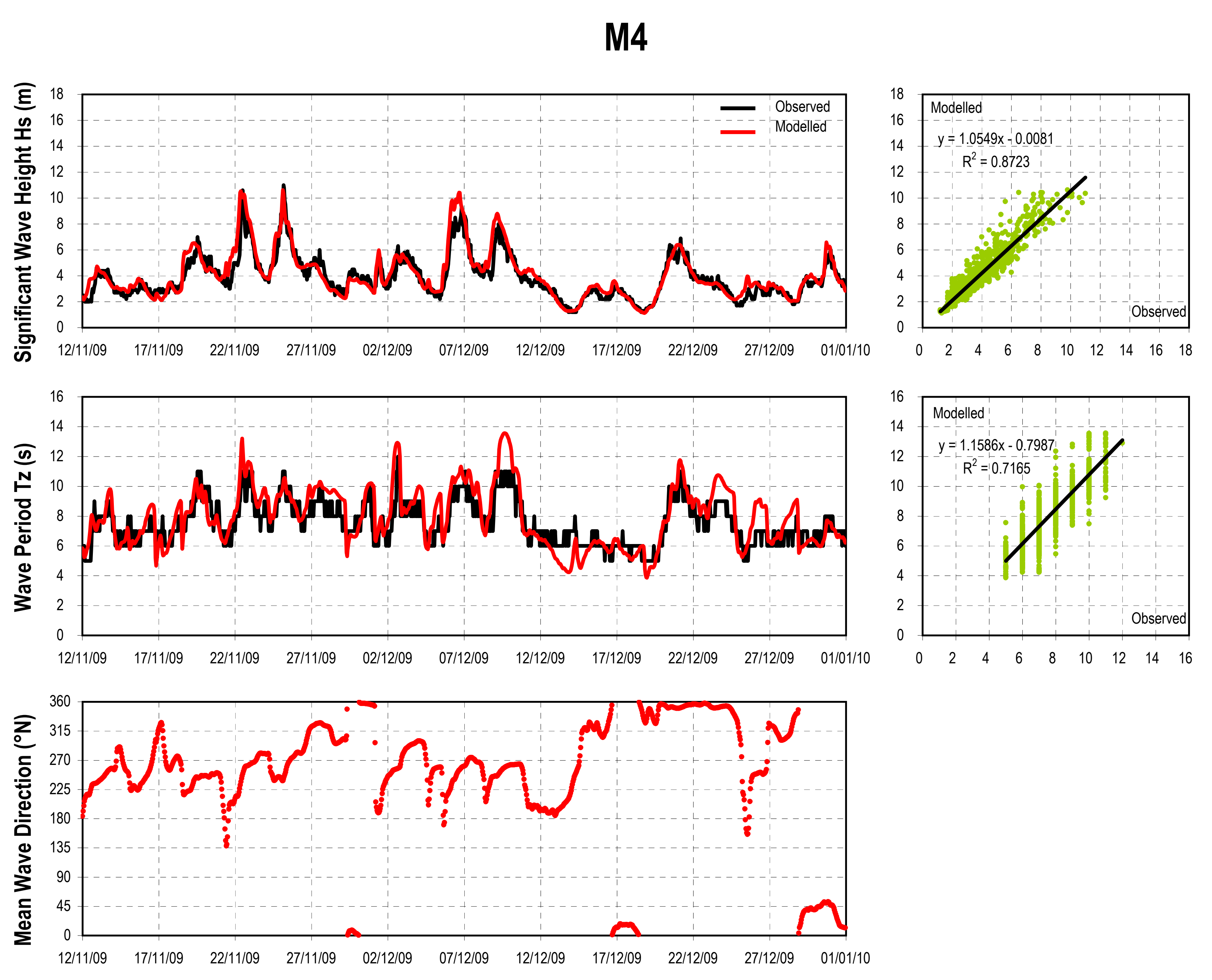
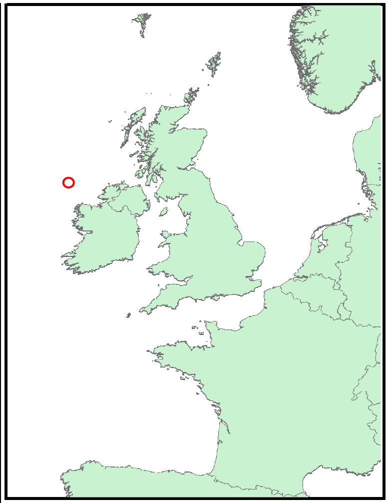
Calibration Summary: M3

Figure 22





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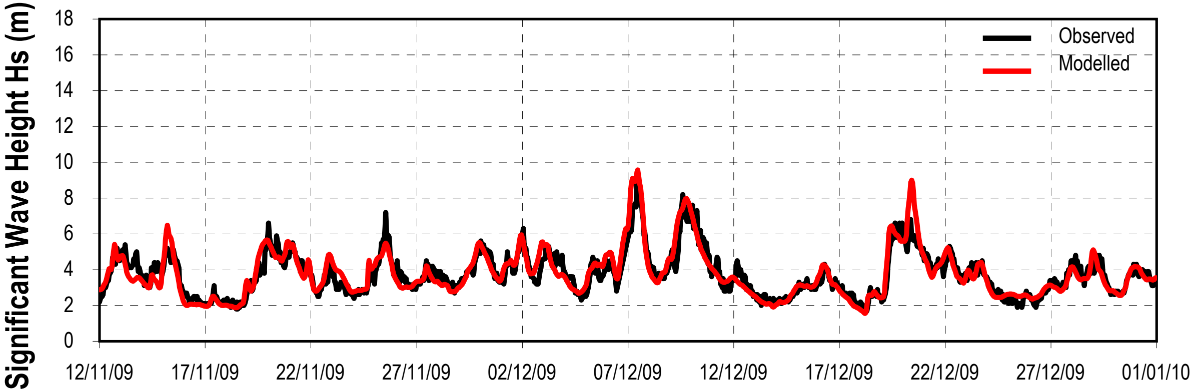
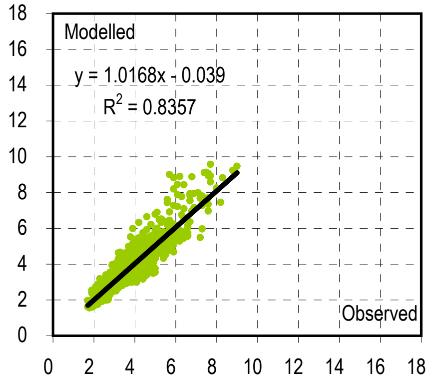
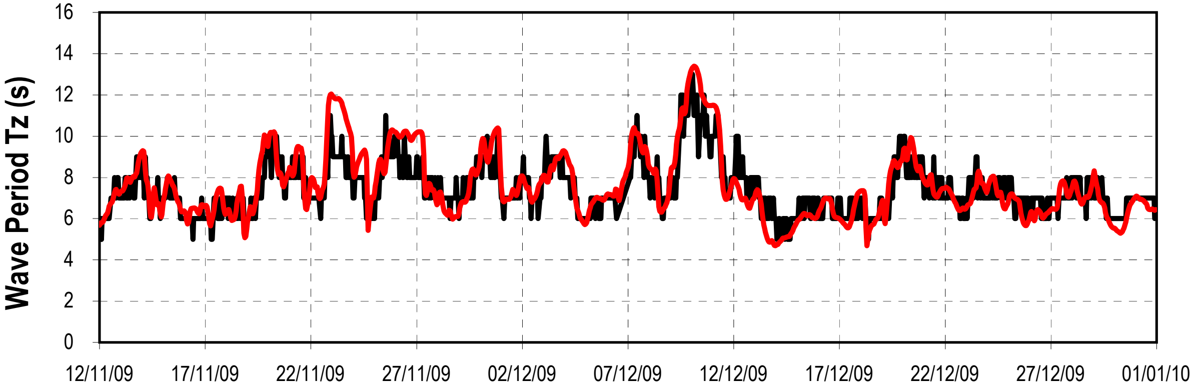
Calibration Summary: M4

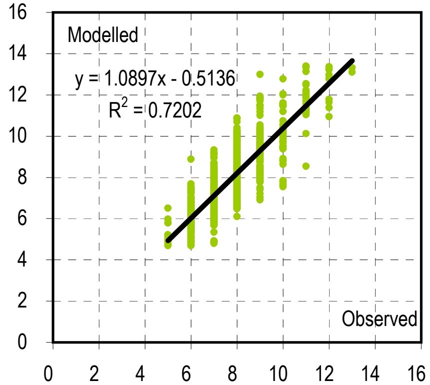
Figure 23

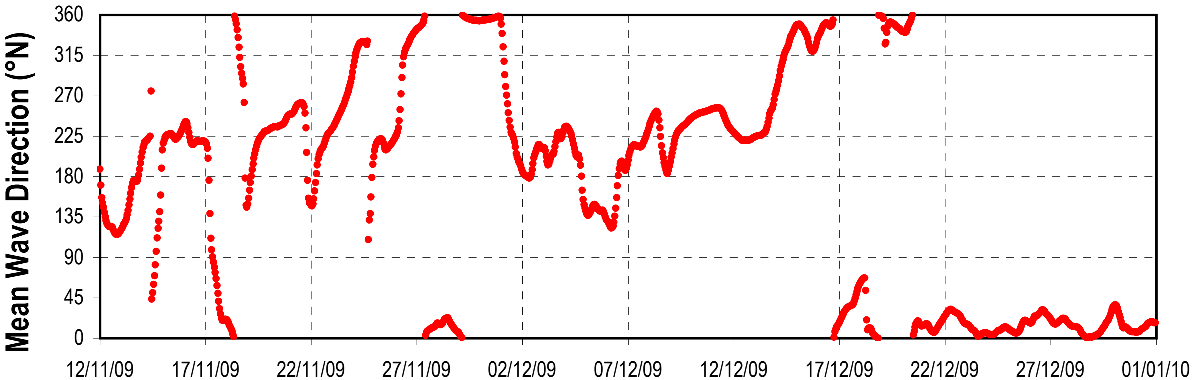
K7

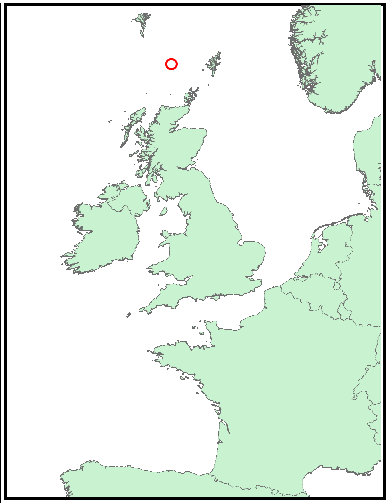












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Scale		n/a	
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Produced by ABPmer			

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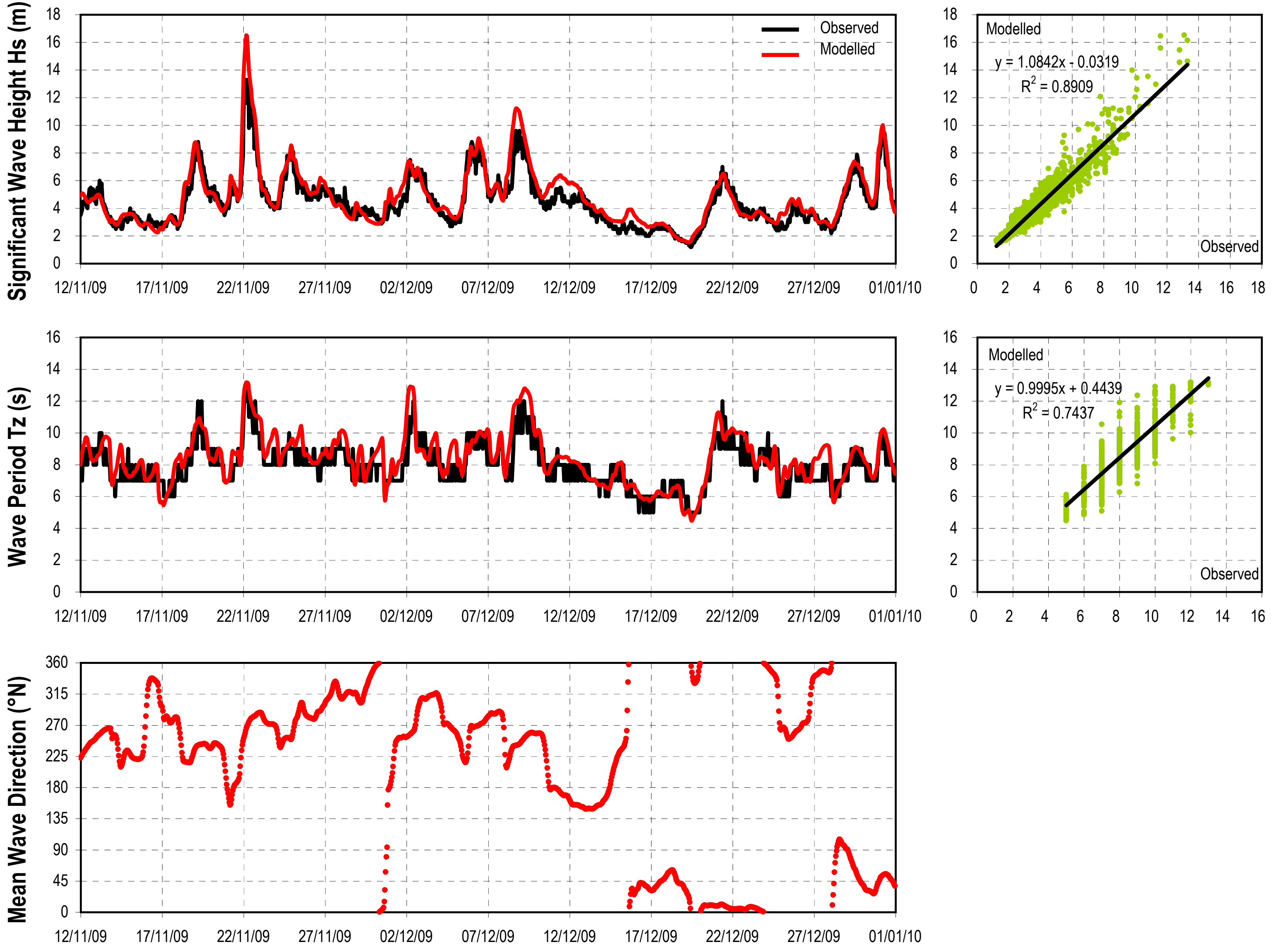
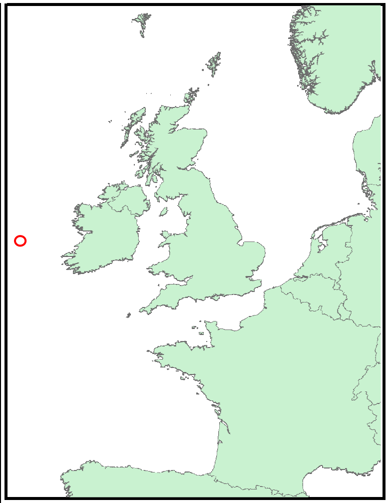
Calibration Summary: K7

Figure 24

M6





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Scale		n/a	
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Produced by ABPmer			

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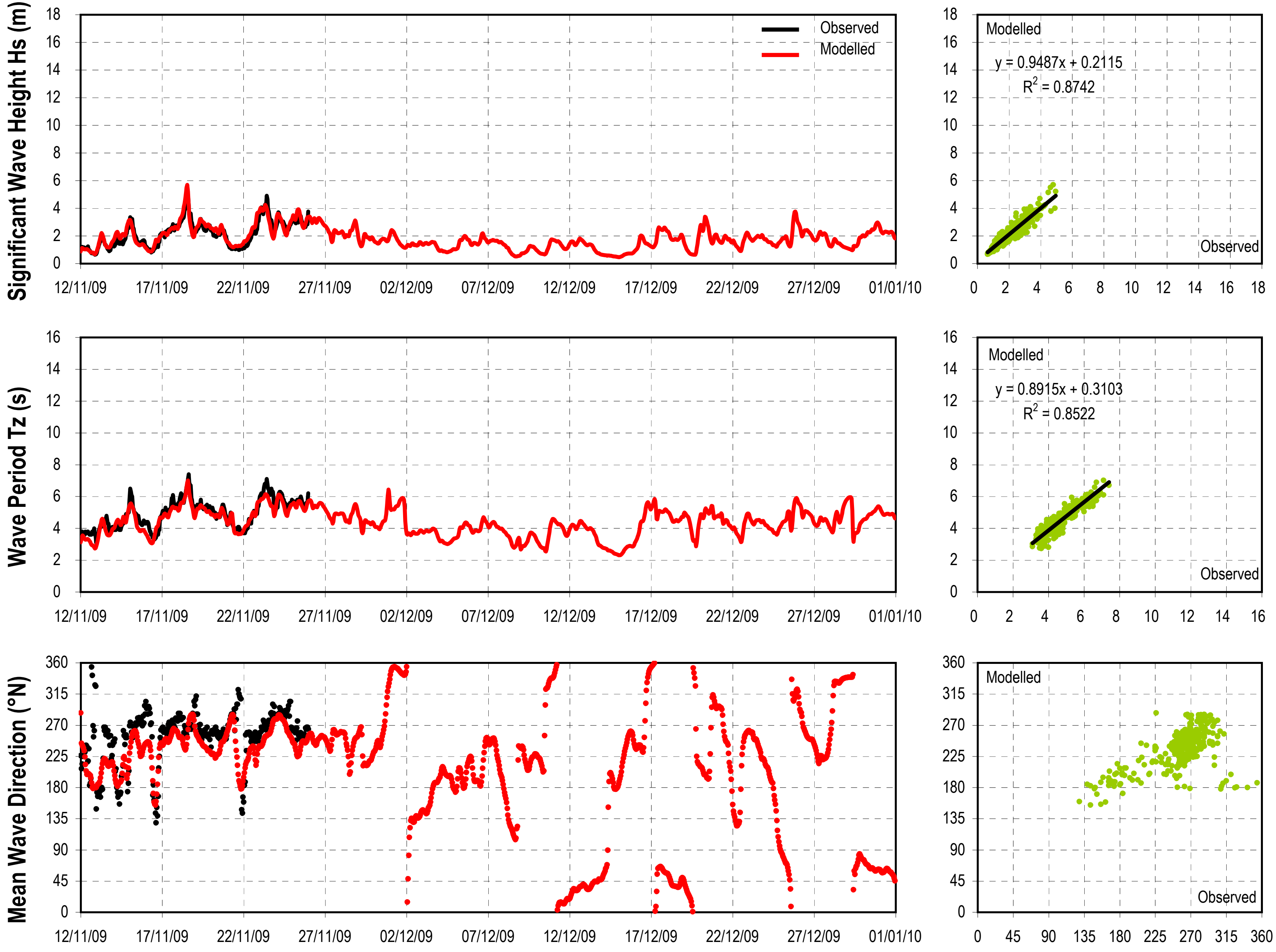
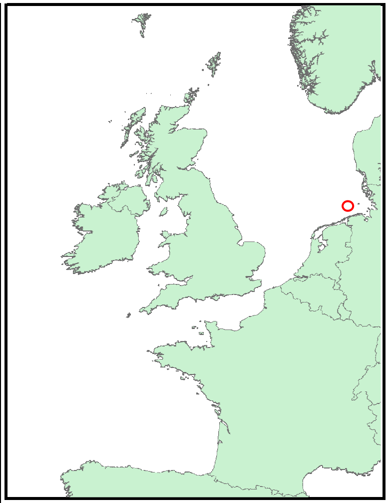
Calibration Summary: M6

Figure 25

FINO1





Observed data are incomplete in the calibration period

Date	By	Size	Version
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Scale		n/a	
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SEASTATES_fig-control4.xls			
Produced by ABPmer			

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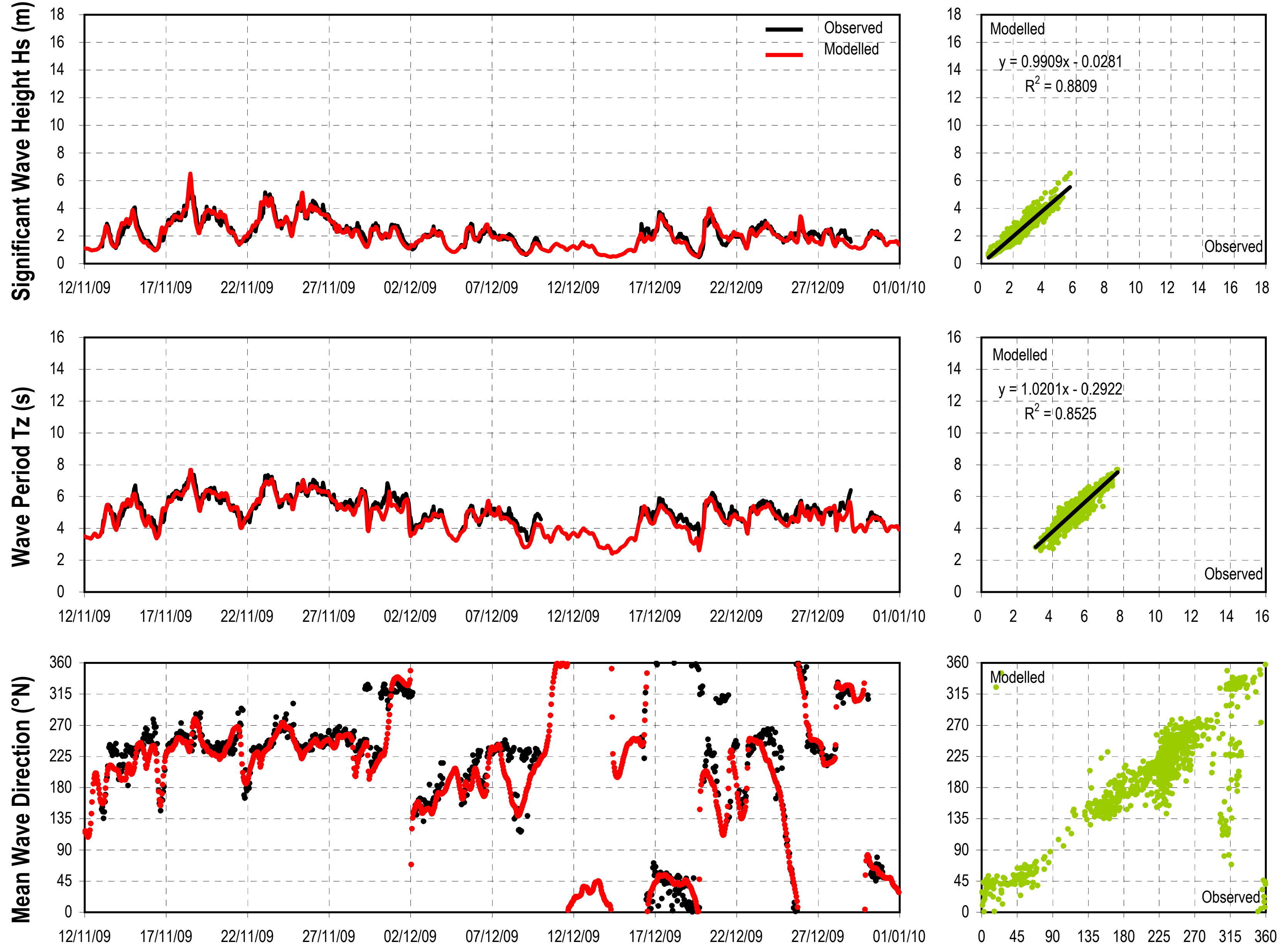
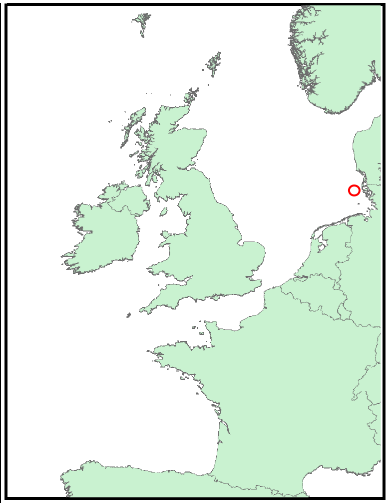
Calibration Summary: FINO1

Figure 26

FINO3





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Scale	n/a		
QA	DOL		
SEASTATES_fig-control4.xls			
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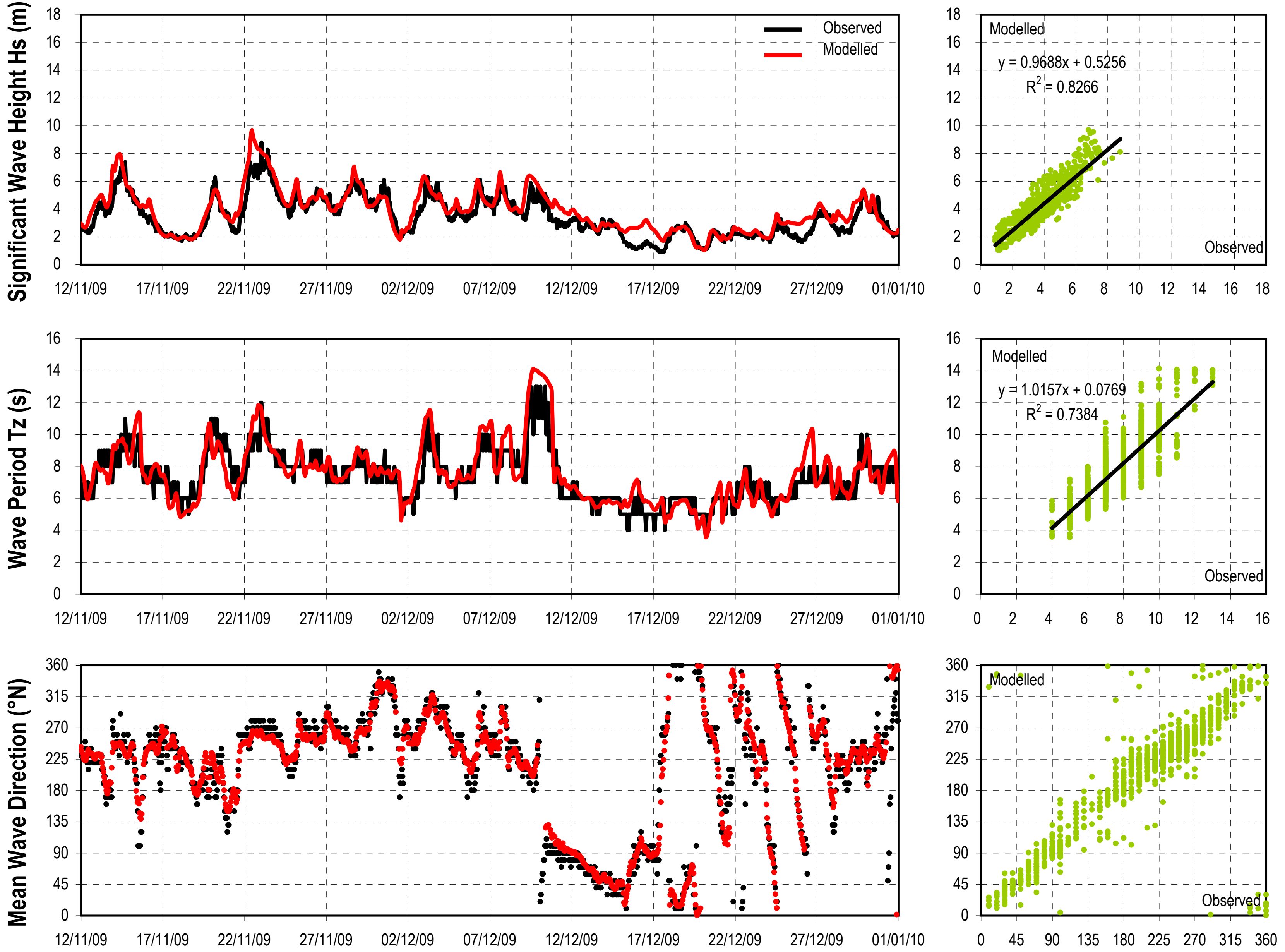
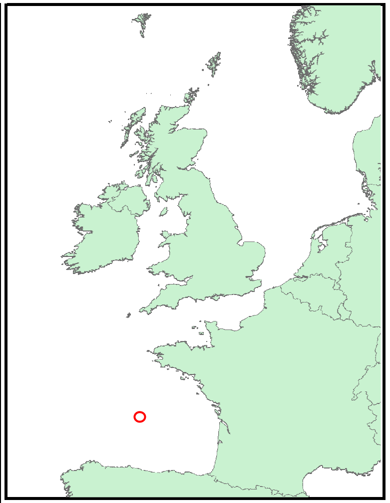
marine environmental research

Calibration Summary: FINO3

Figure 27

Gascogne





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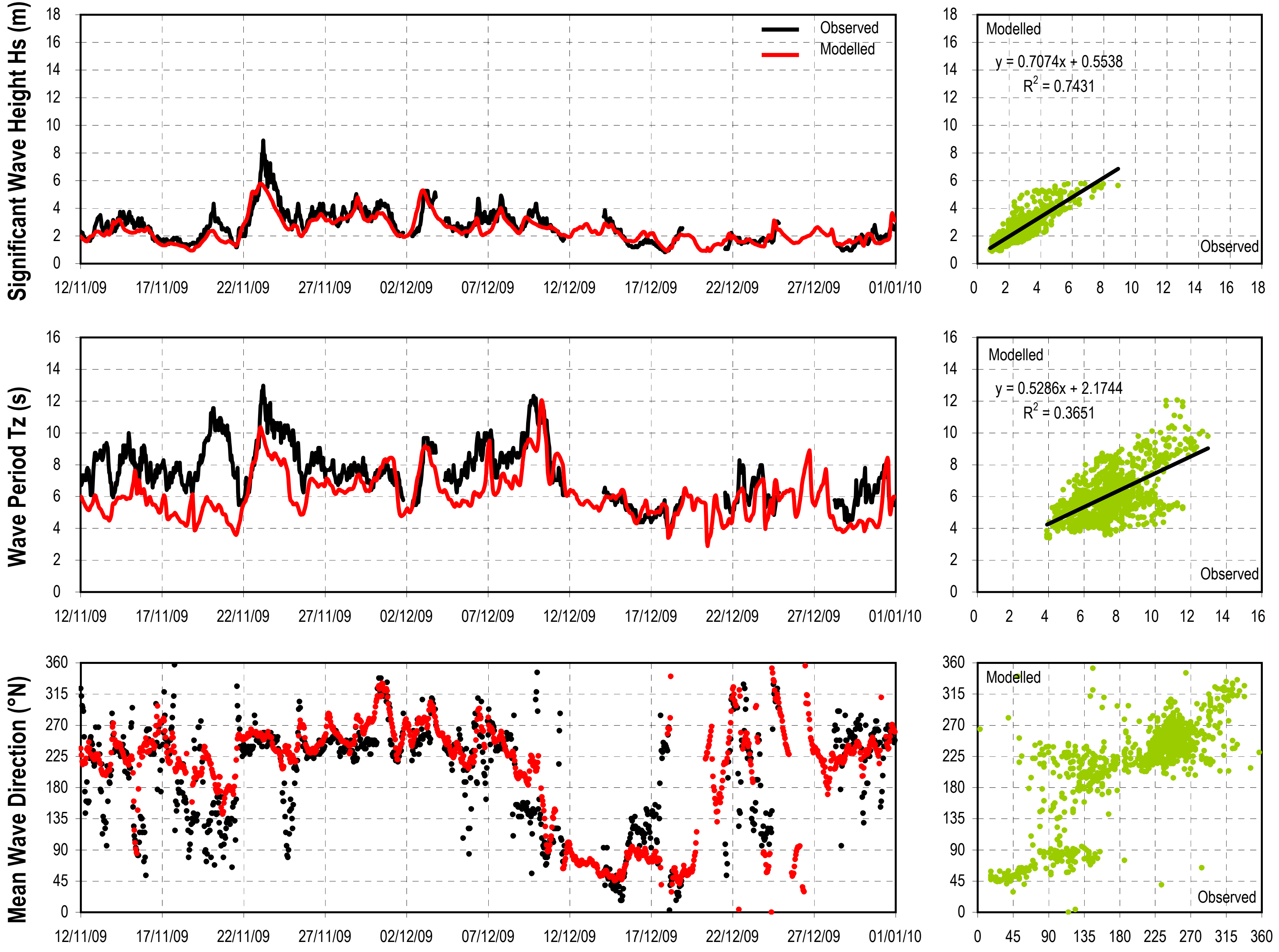
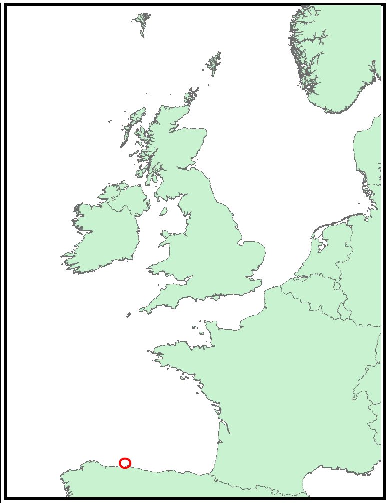
Produced by ABPmer			

Calibration Summary: Gascogne

Figure 28

Penas





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Scale		n/a	
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Produced by ABPmer			

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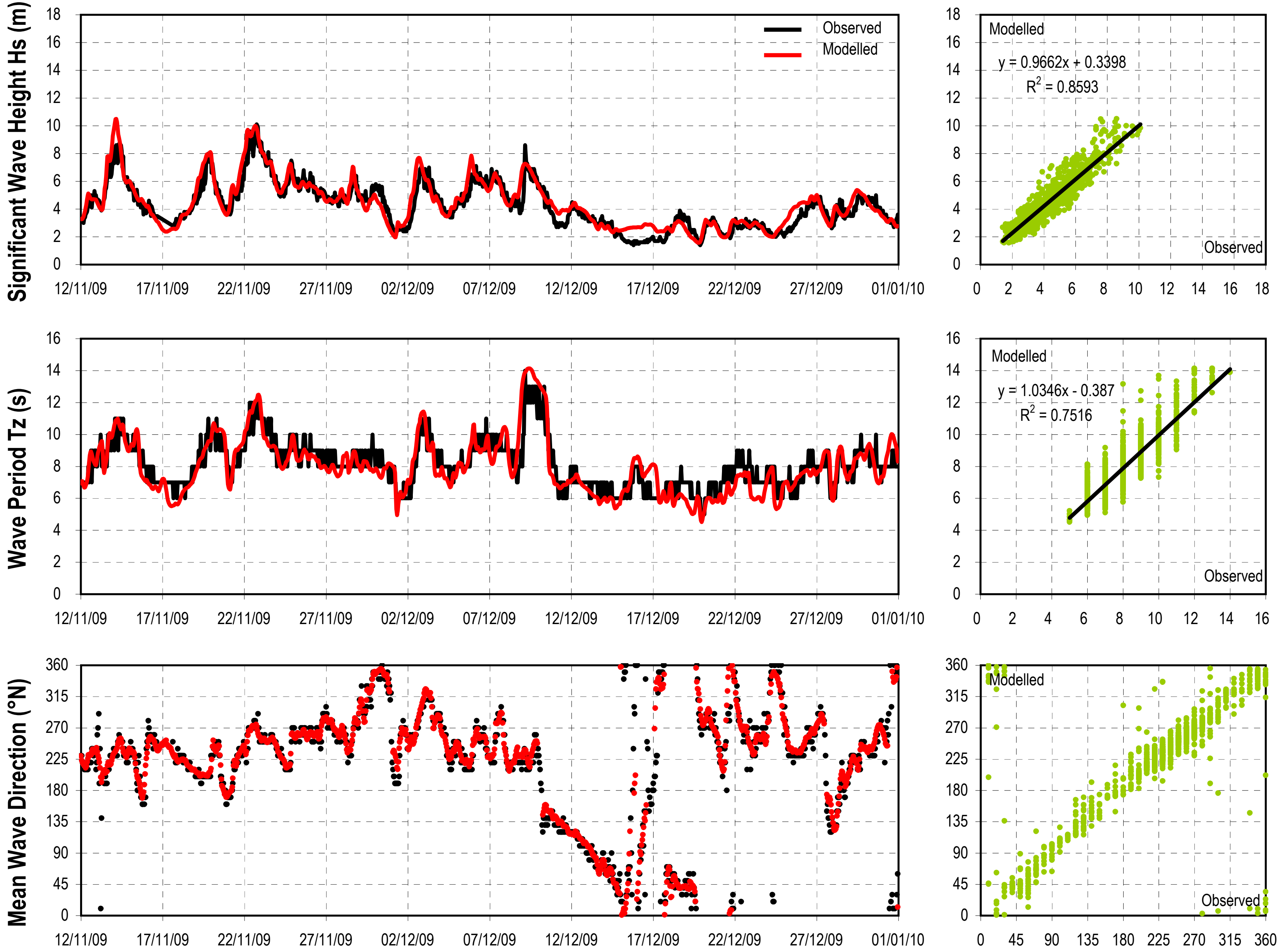
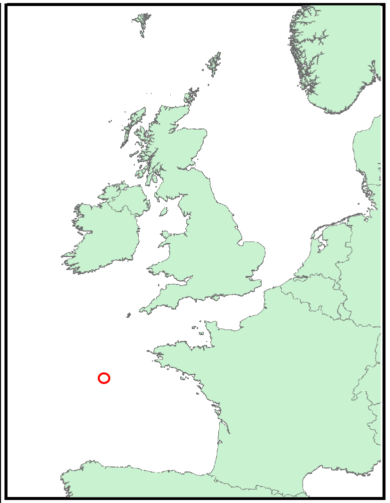
Calibration Summary: Penas

Figure 29

Brittany





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Scale		n/a	
QA		DOL	
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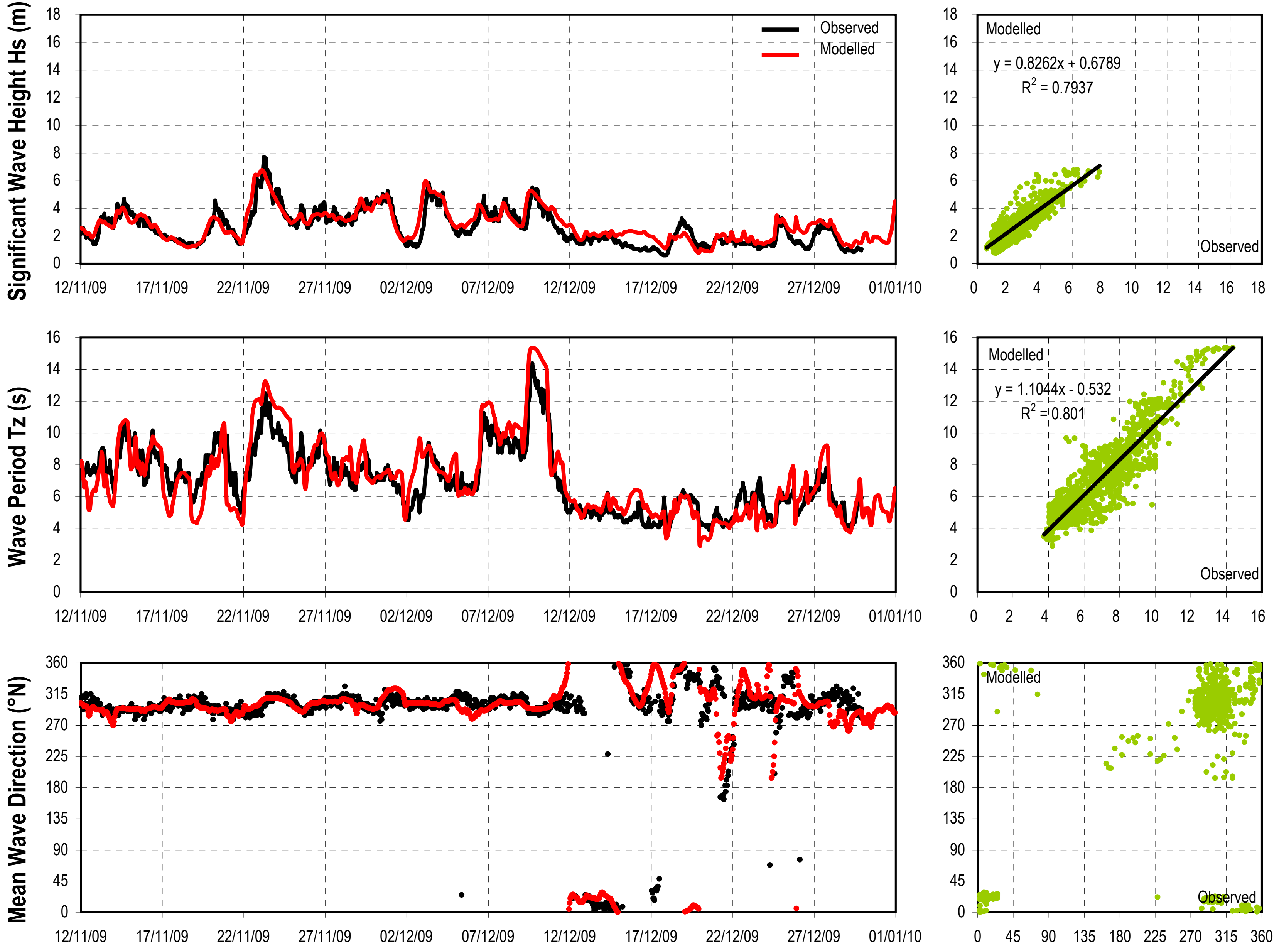
Produced by ABPmer			

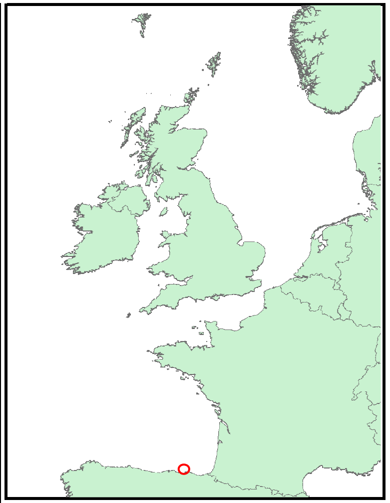
ABPmer marine environmental research

Calibration Summary: Brittany

Figure 30

Tarra





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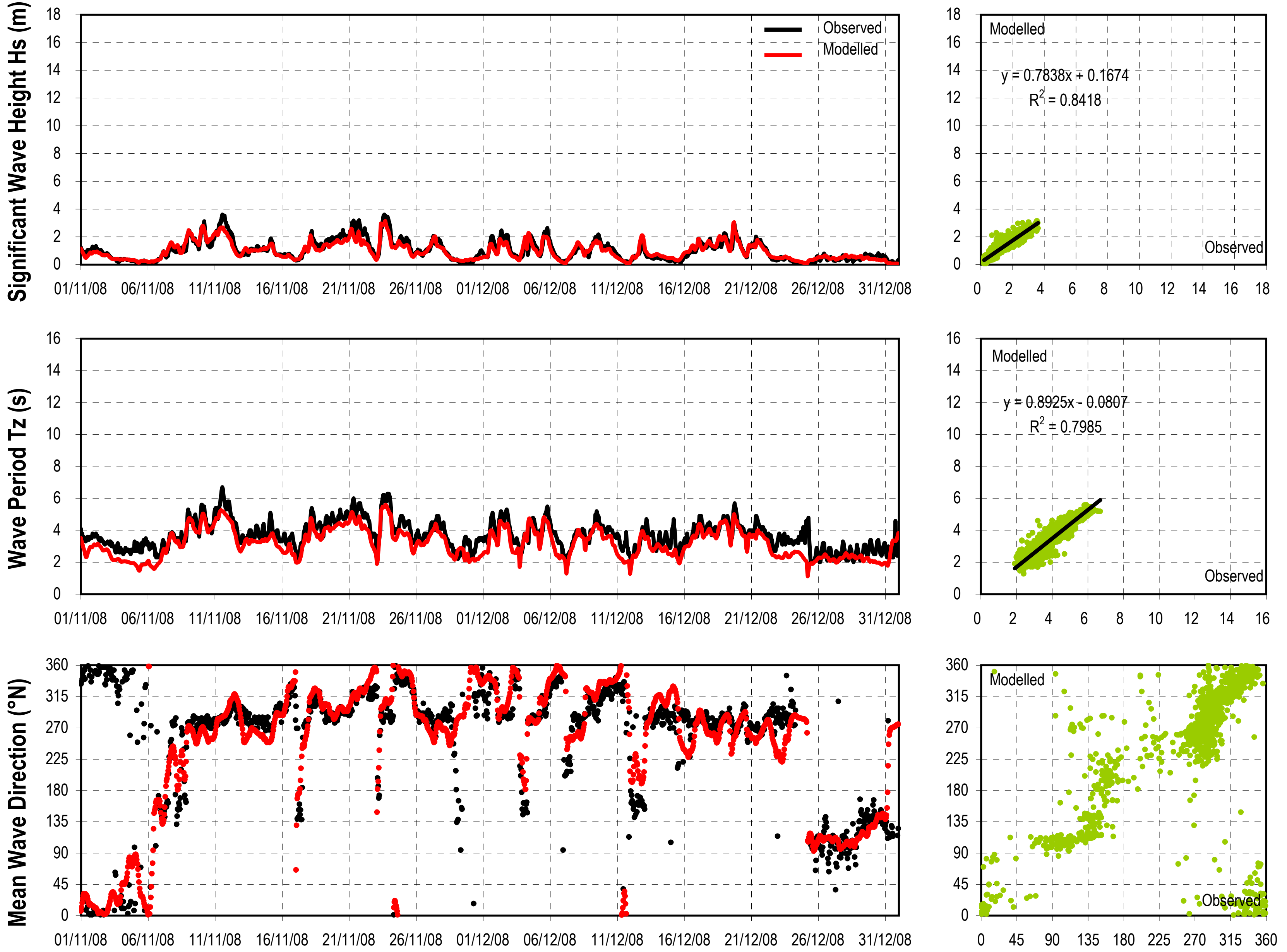
Produced by ABPmer			

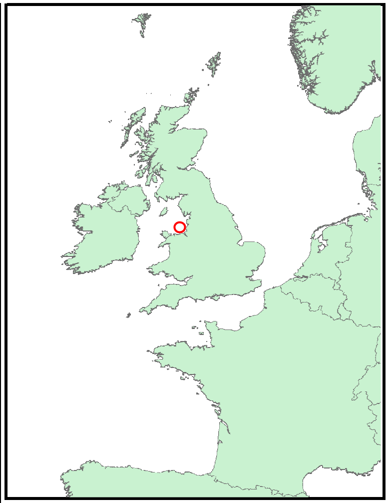
ABP mer marine environmental research

Calibration Summary: Tarra

Figure 31

Liverpool Bay





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Scale		n/a	
QA		DOL	
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Produced by ABPmer			

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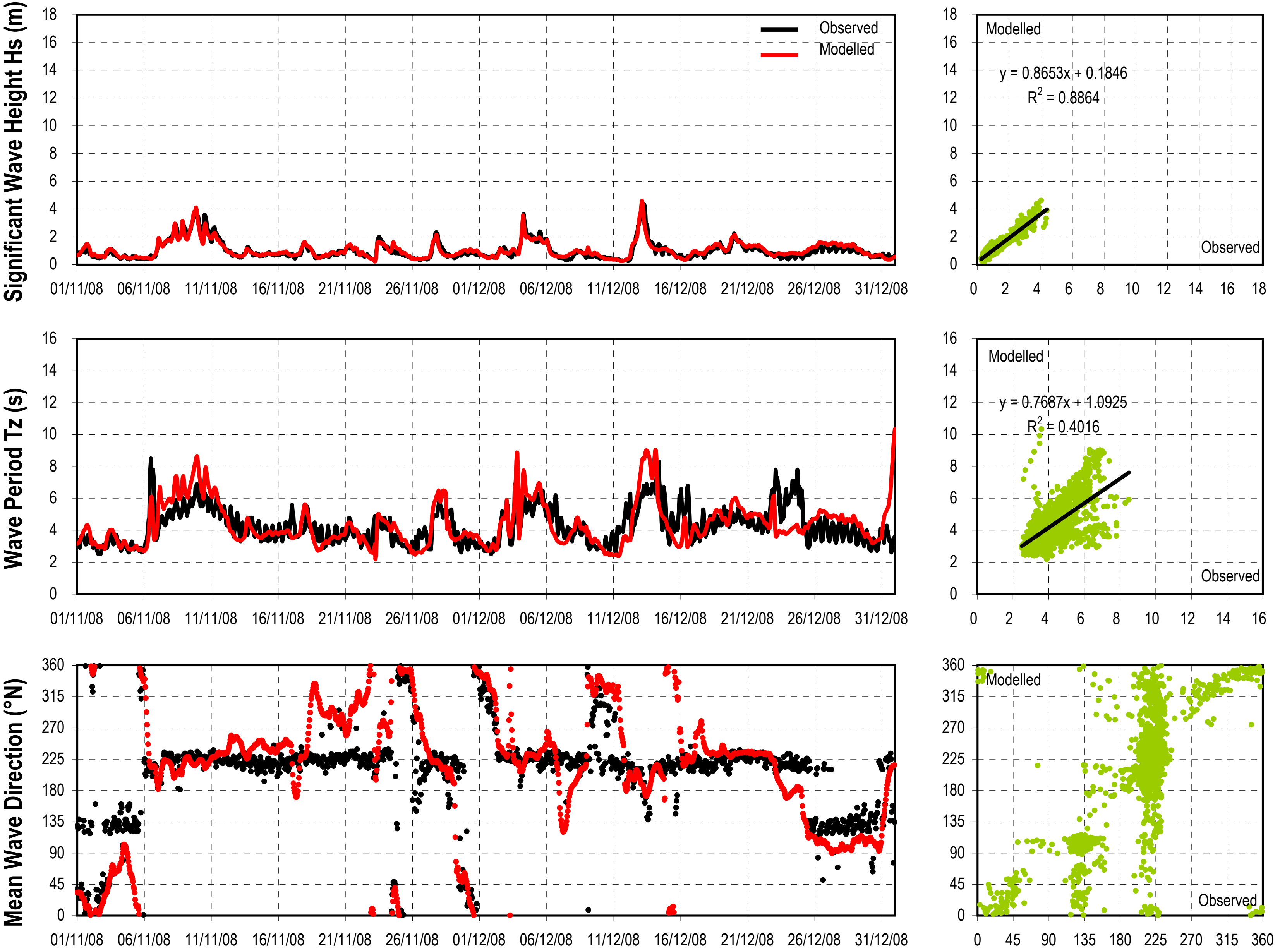
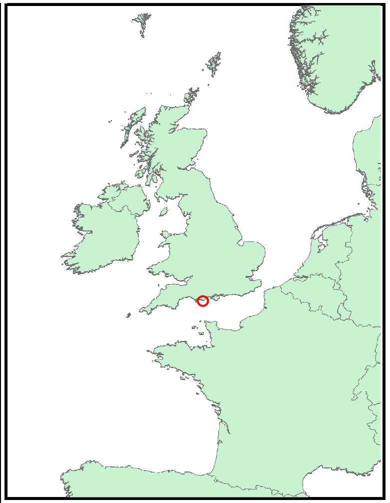
Validation Summary: Liverpool Bay

Figure 32

Poole





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Scale		n/a	
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Produced by ABPmer			

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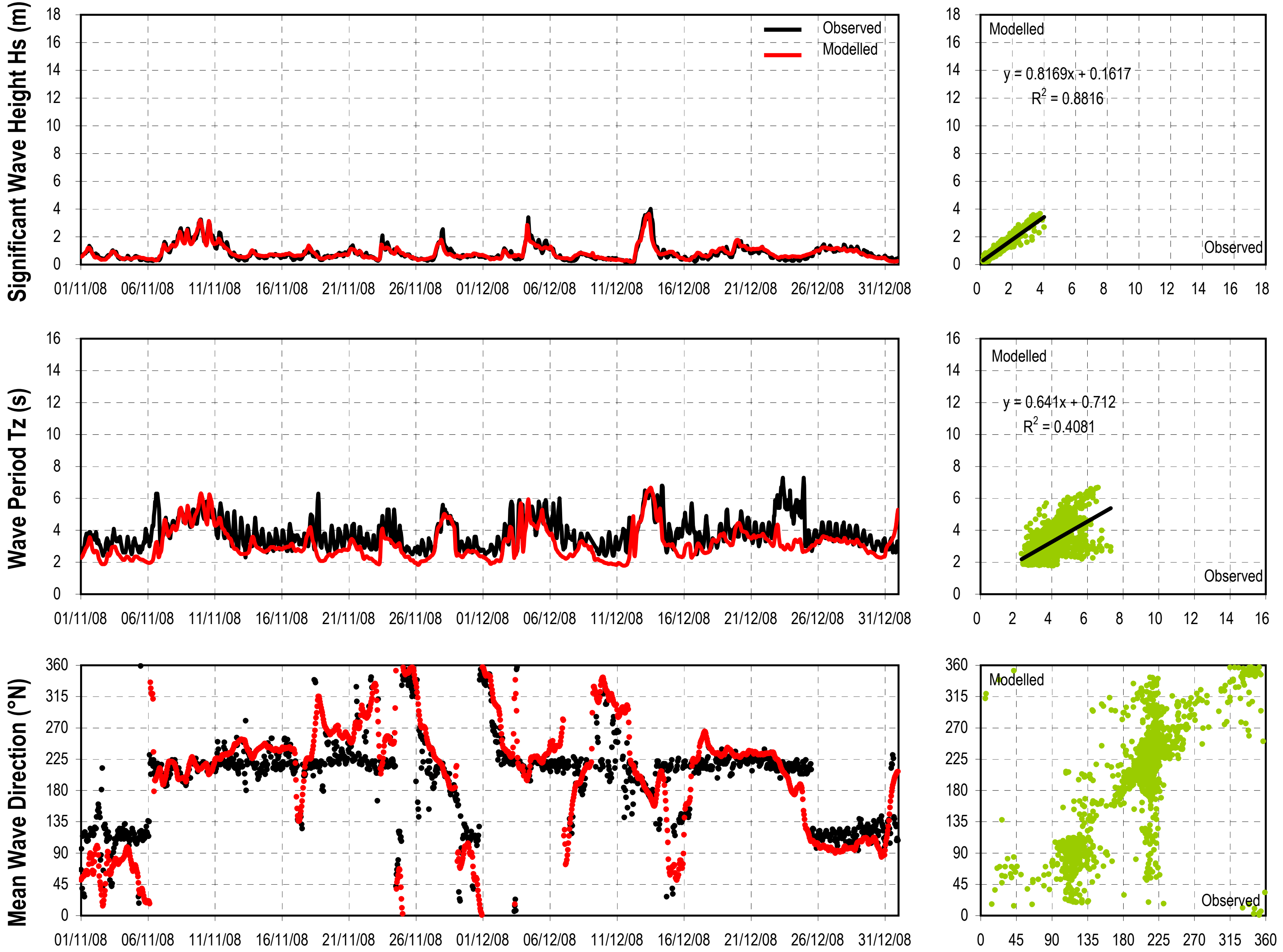
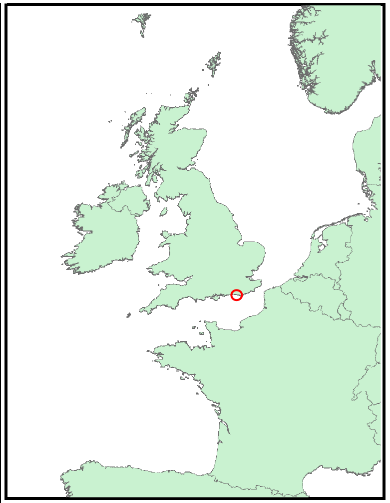
Validation Summary: Poole

Figure 33

Rustington





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Scale		n/a	
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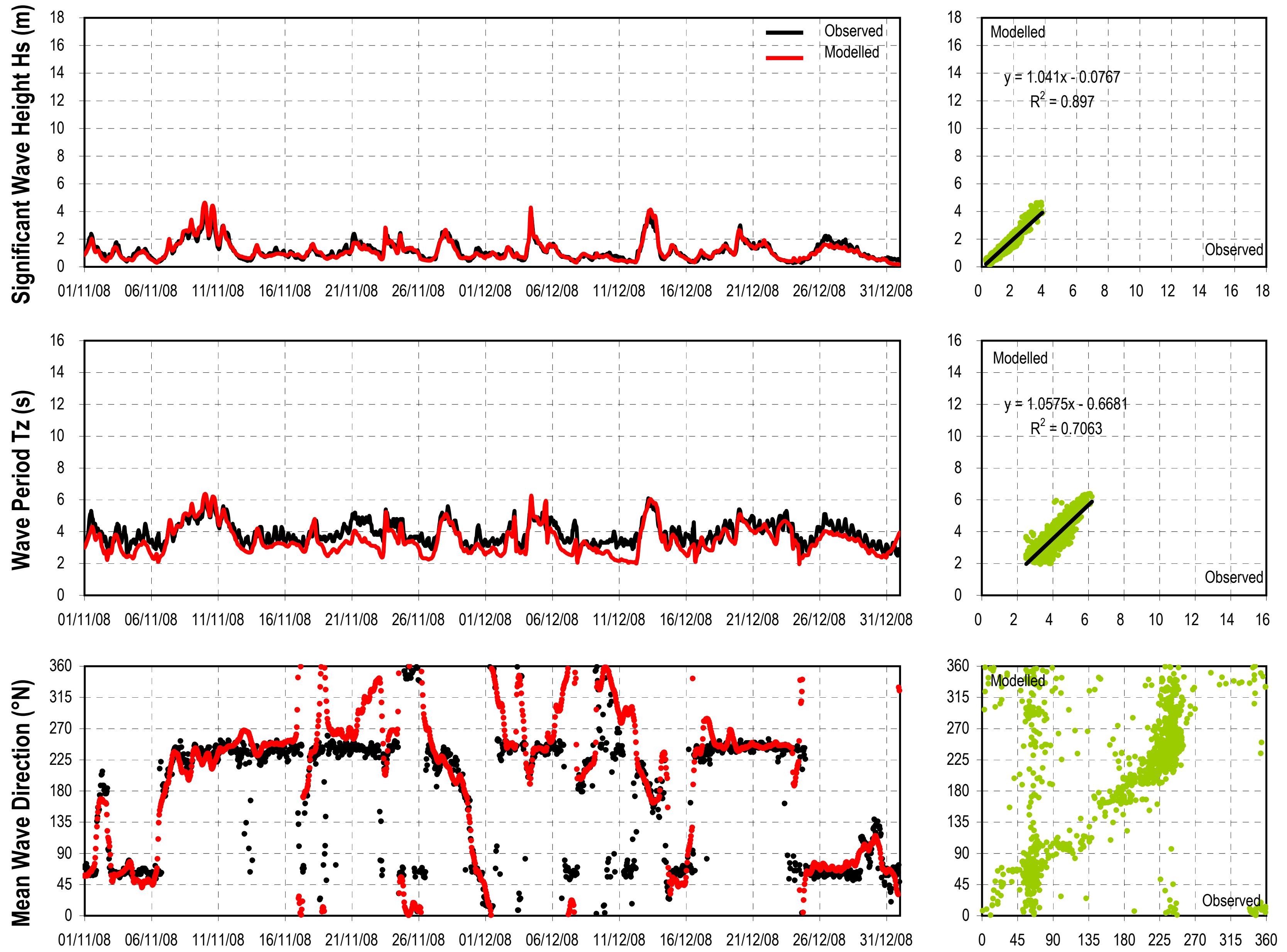
Produced by ABPmer			

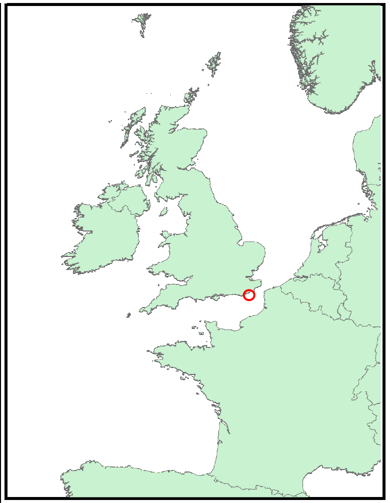
ABP mer marine environmental research

Validation Summary: Rustington

Figure 34

Hastings





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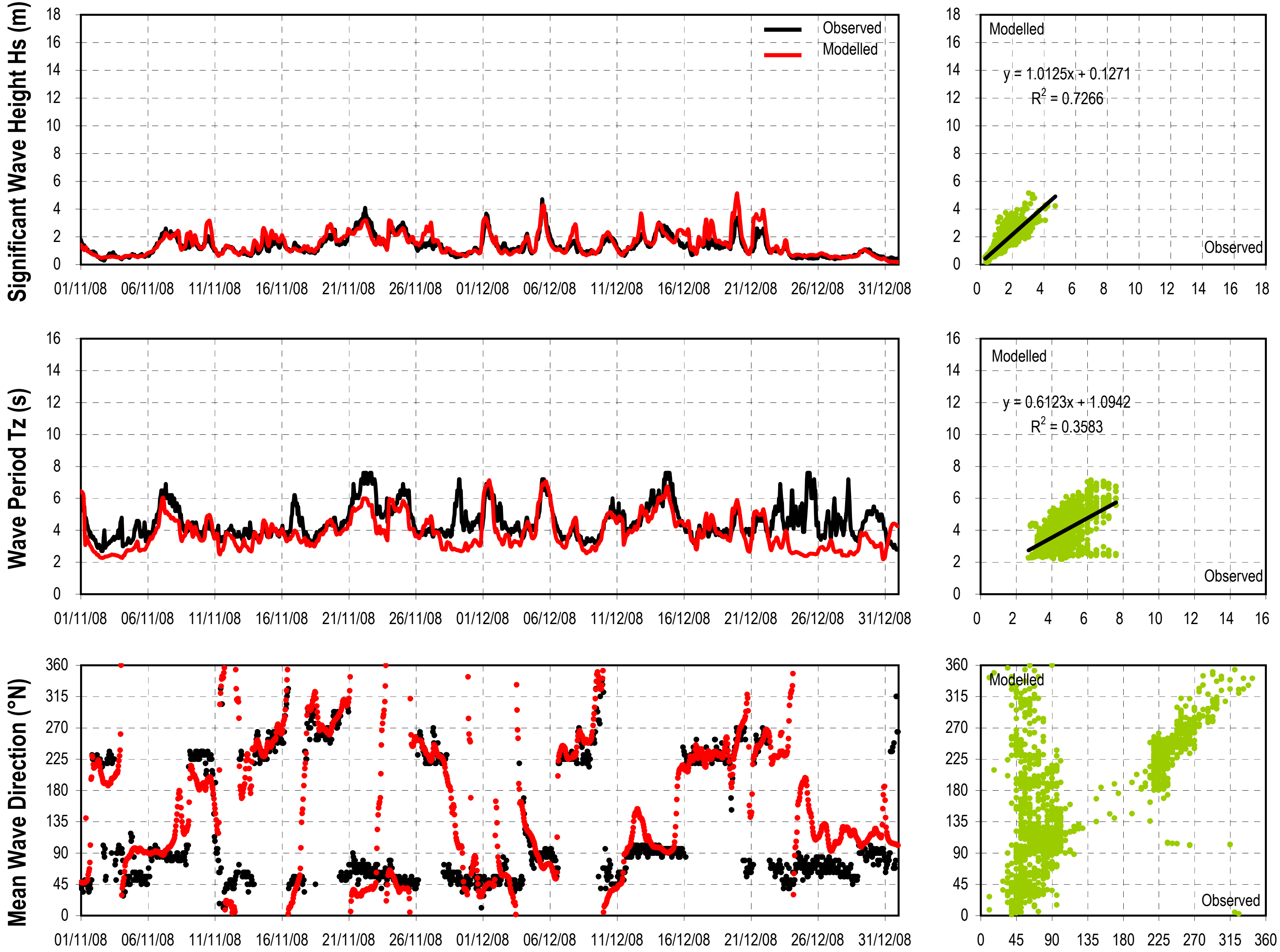
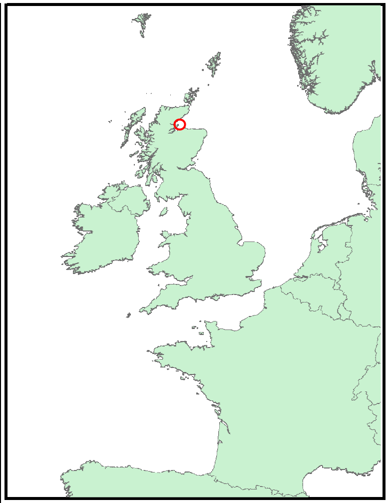
Produced by ABPmer			

Validation Summary: Hastings

Figure 35

Moray Firth





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Produced by ABPmer			

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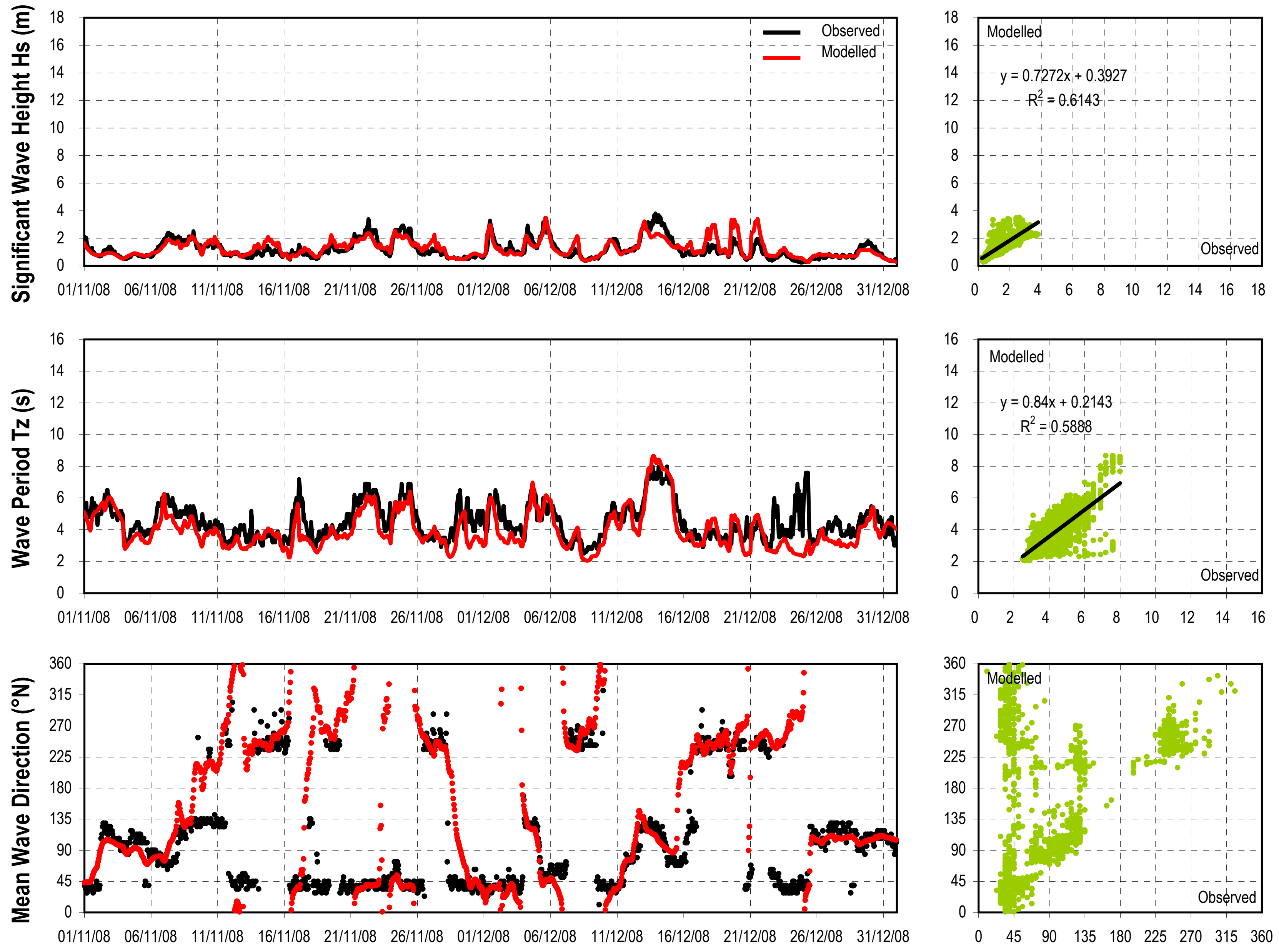
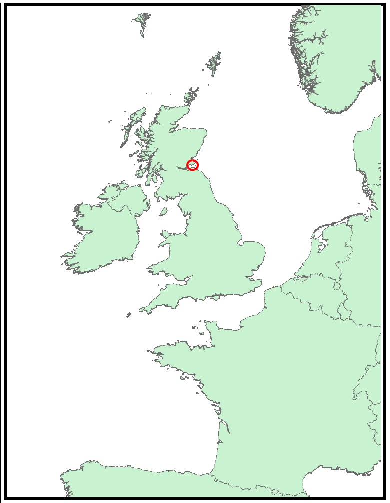
Validation Summary: Moray Firth

Figure 36

Firth of Forth





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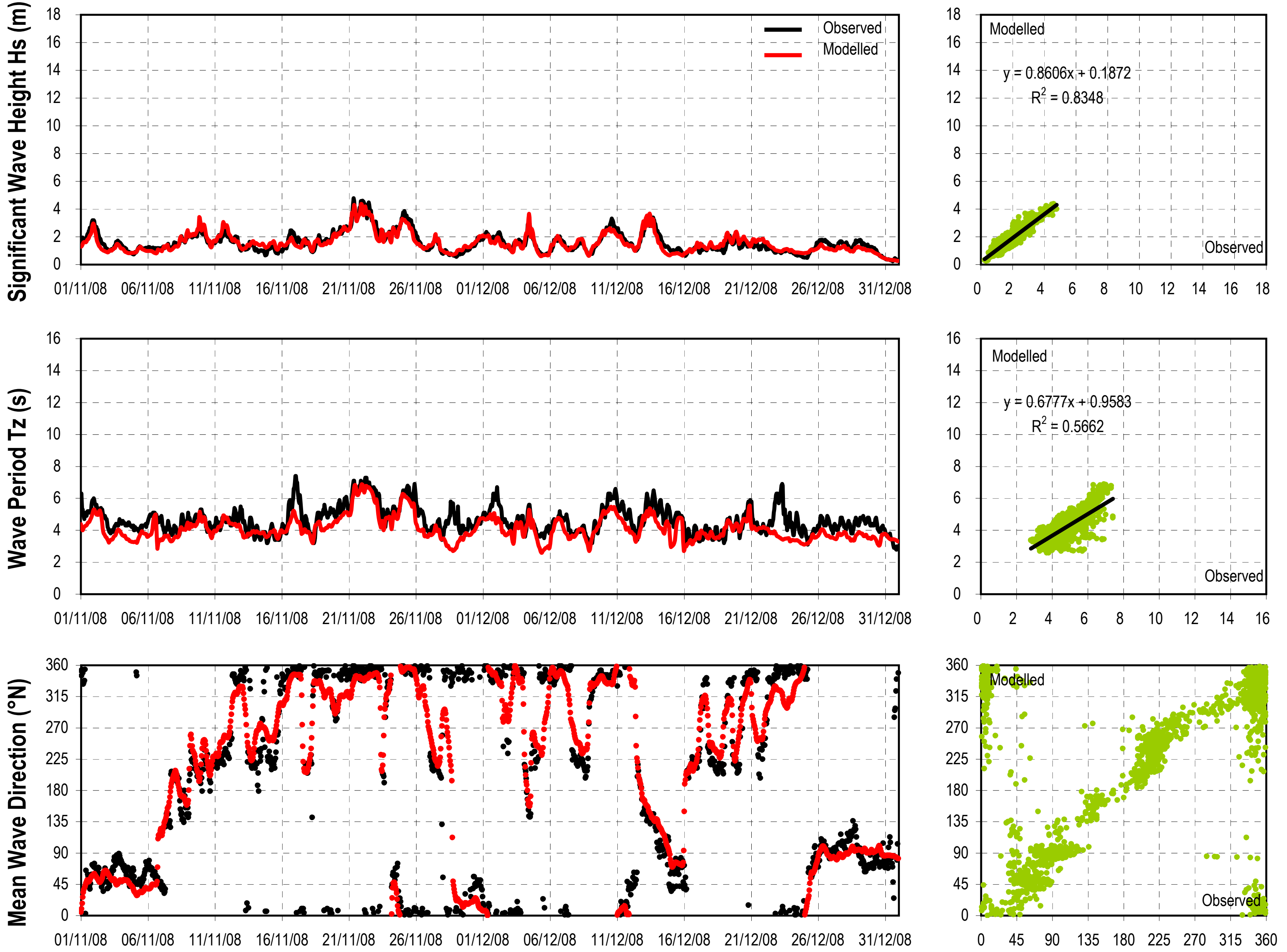
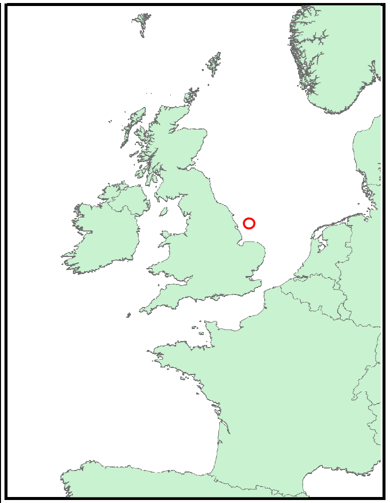
Produced by ABPmer			

Validation Summary: Firth of Forth

Figure 37

Dowsing





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Scale		n/a	
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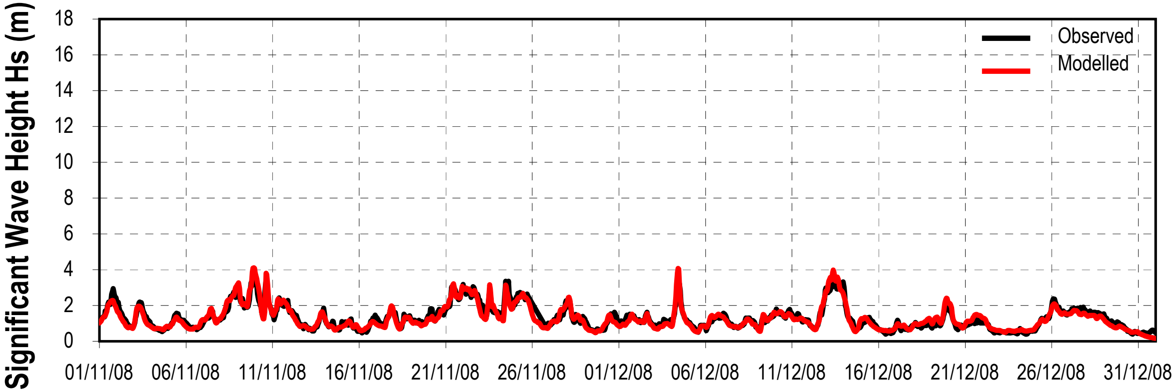
Produced by ABPmer			

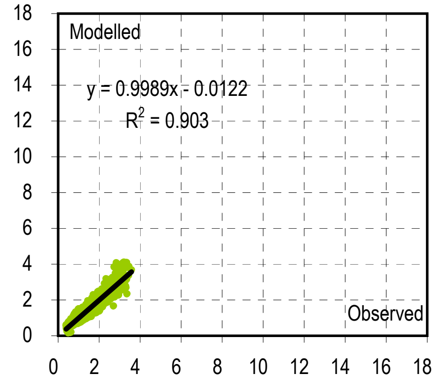
ABP mer marine environmental research

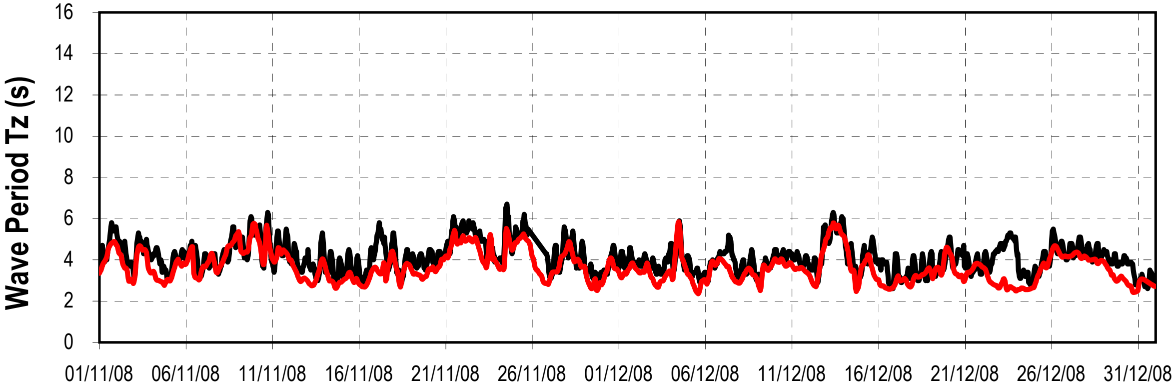
Validation Summary: Dowsing

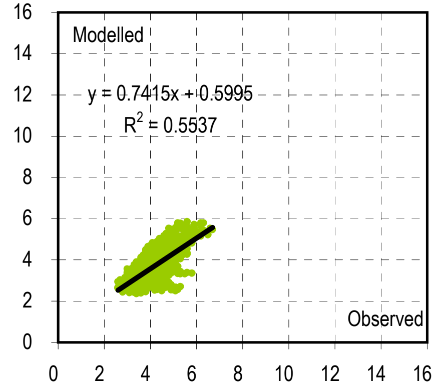
Figure 38

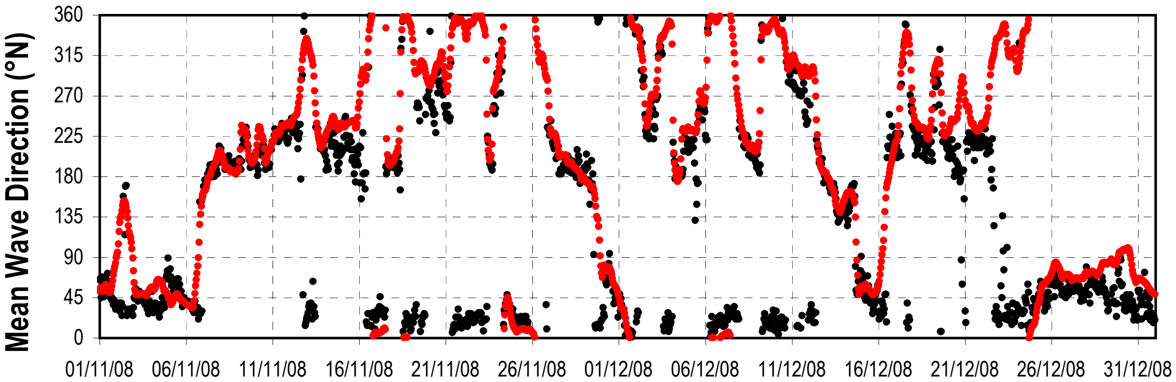
West Gabbard

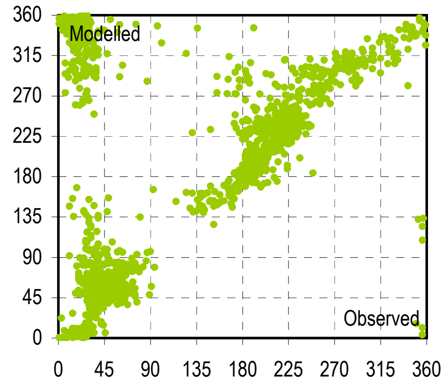


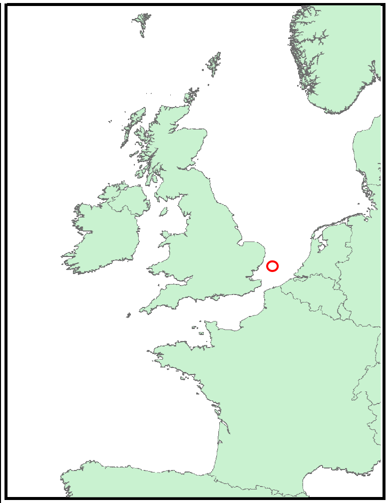












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Scale		n/a	
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Produced by ABPmer			

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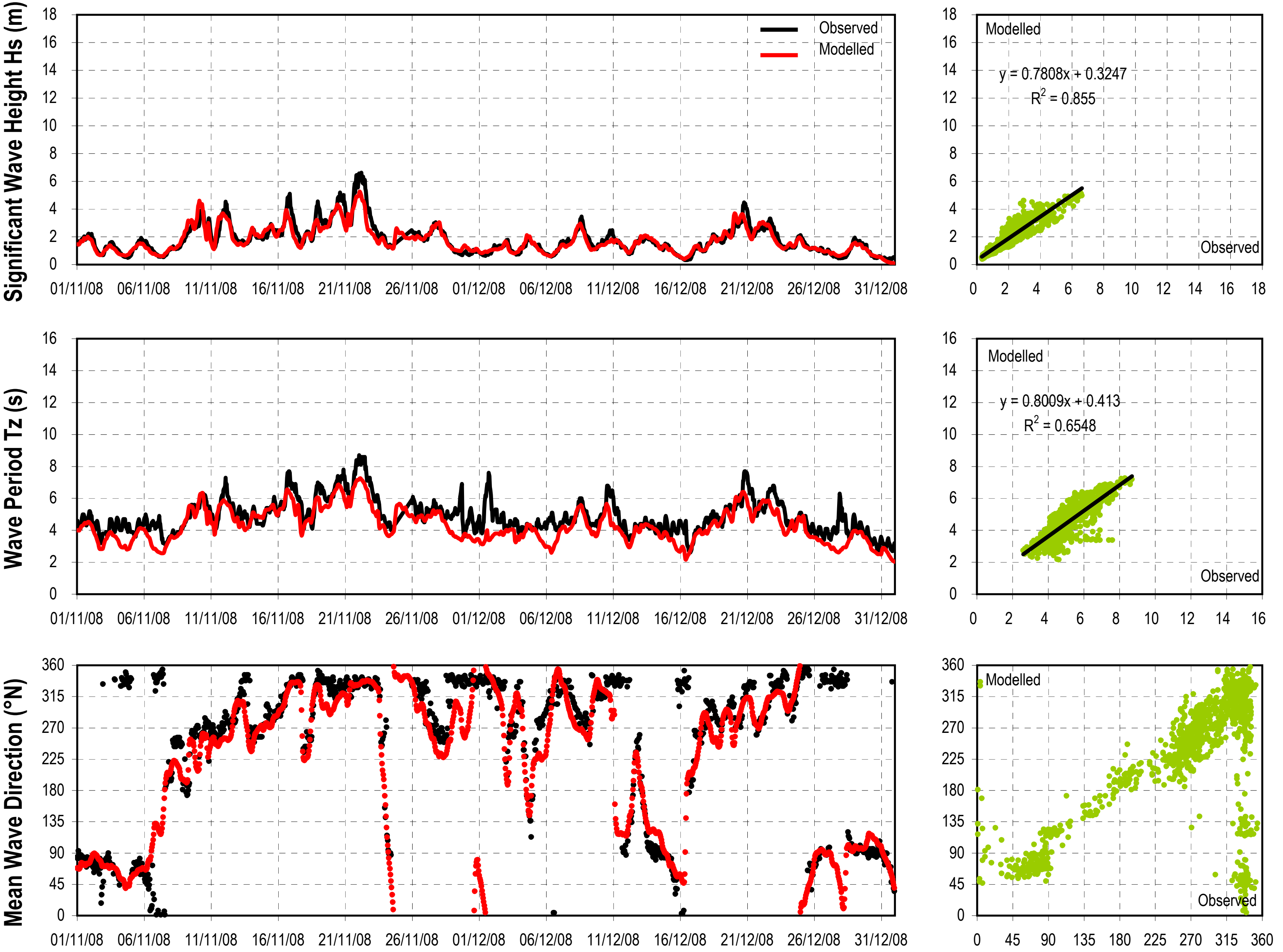
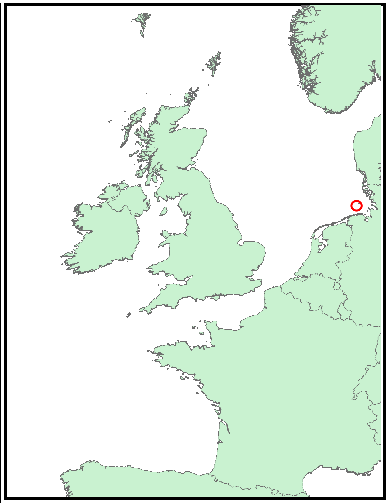
Validation Summary: West Gabbard

Figure 39

FINO1





Date	By	Size	Version
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Scale		n/a	
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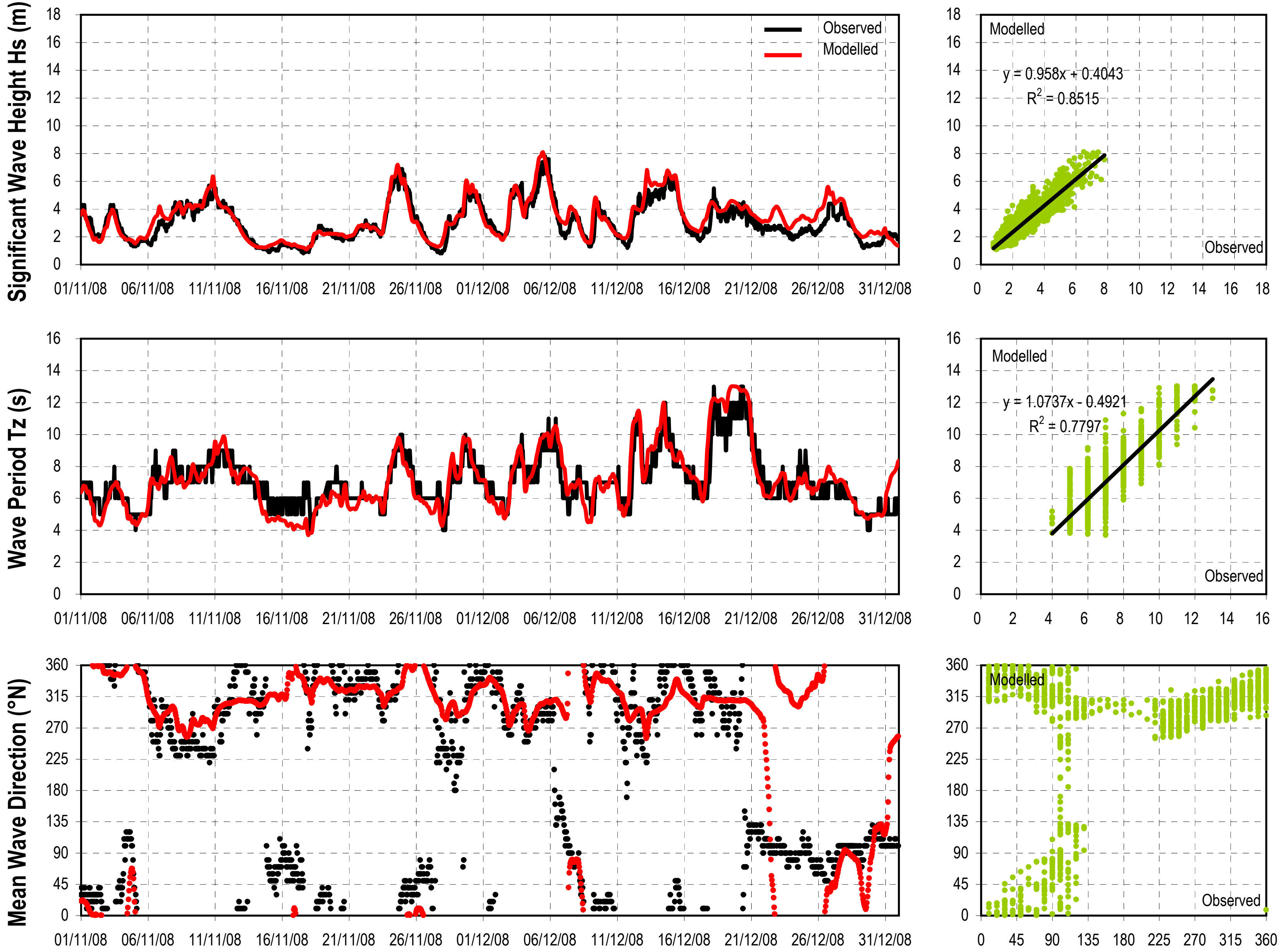
Produced by ABPmer			

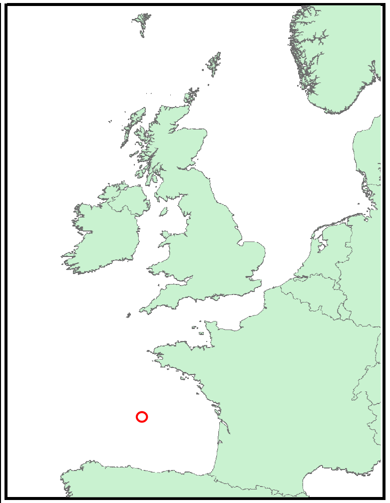
ABP mer marine environmental research

Validation Summary: FINO1

Figure 40

Gascogne





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Scale		n/a	
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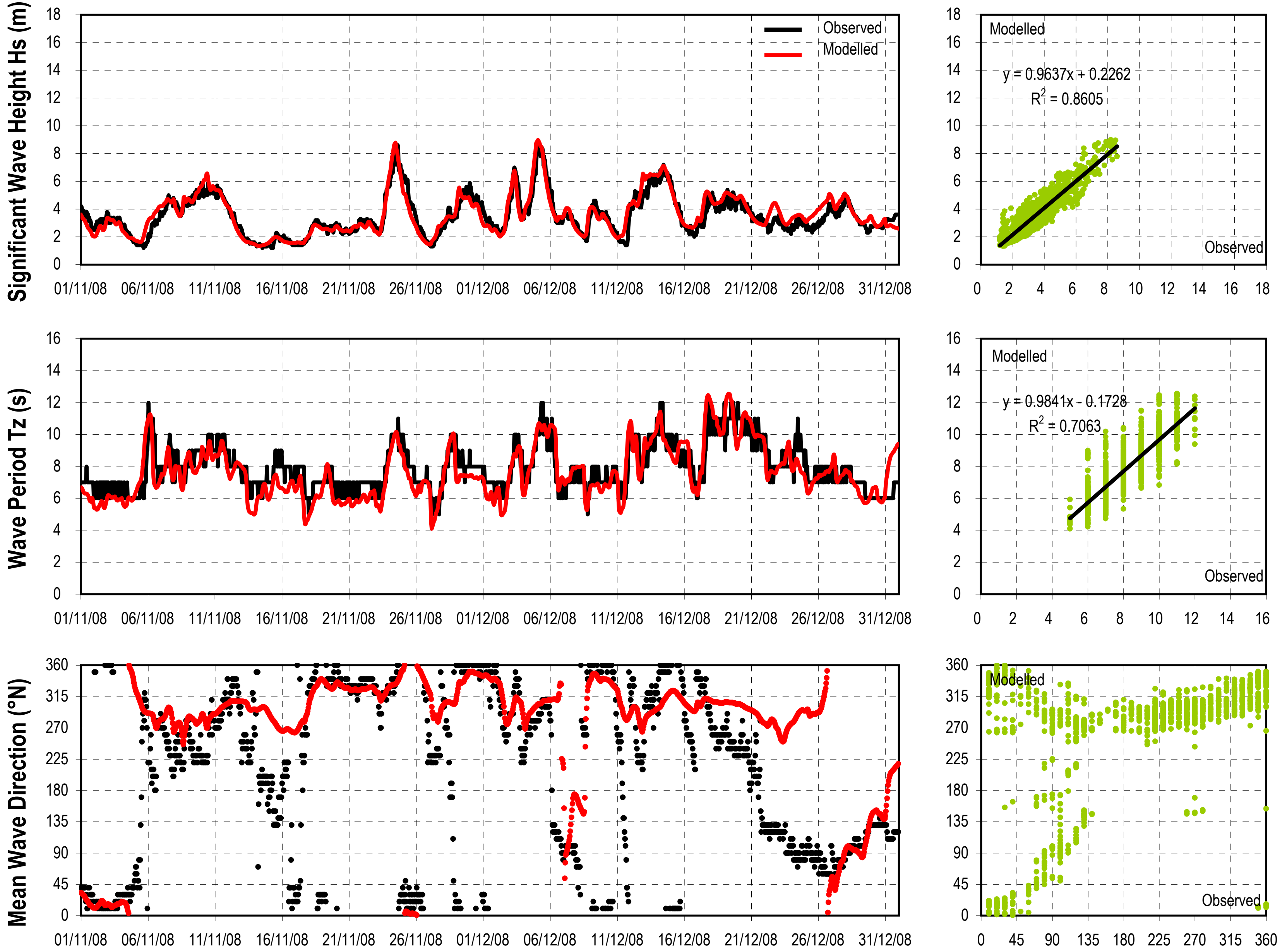
Produced by ABPmer			

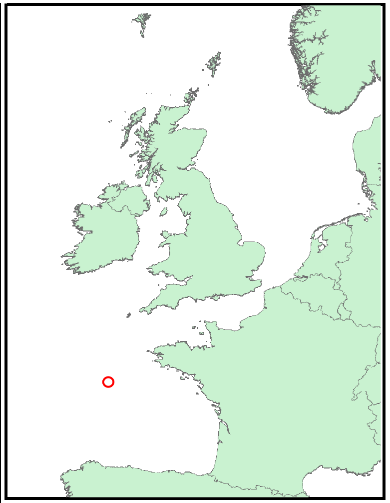
ABP mer marine environmental research

Validation Summary: Gascogne

Figure 41

Brittany





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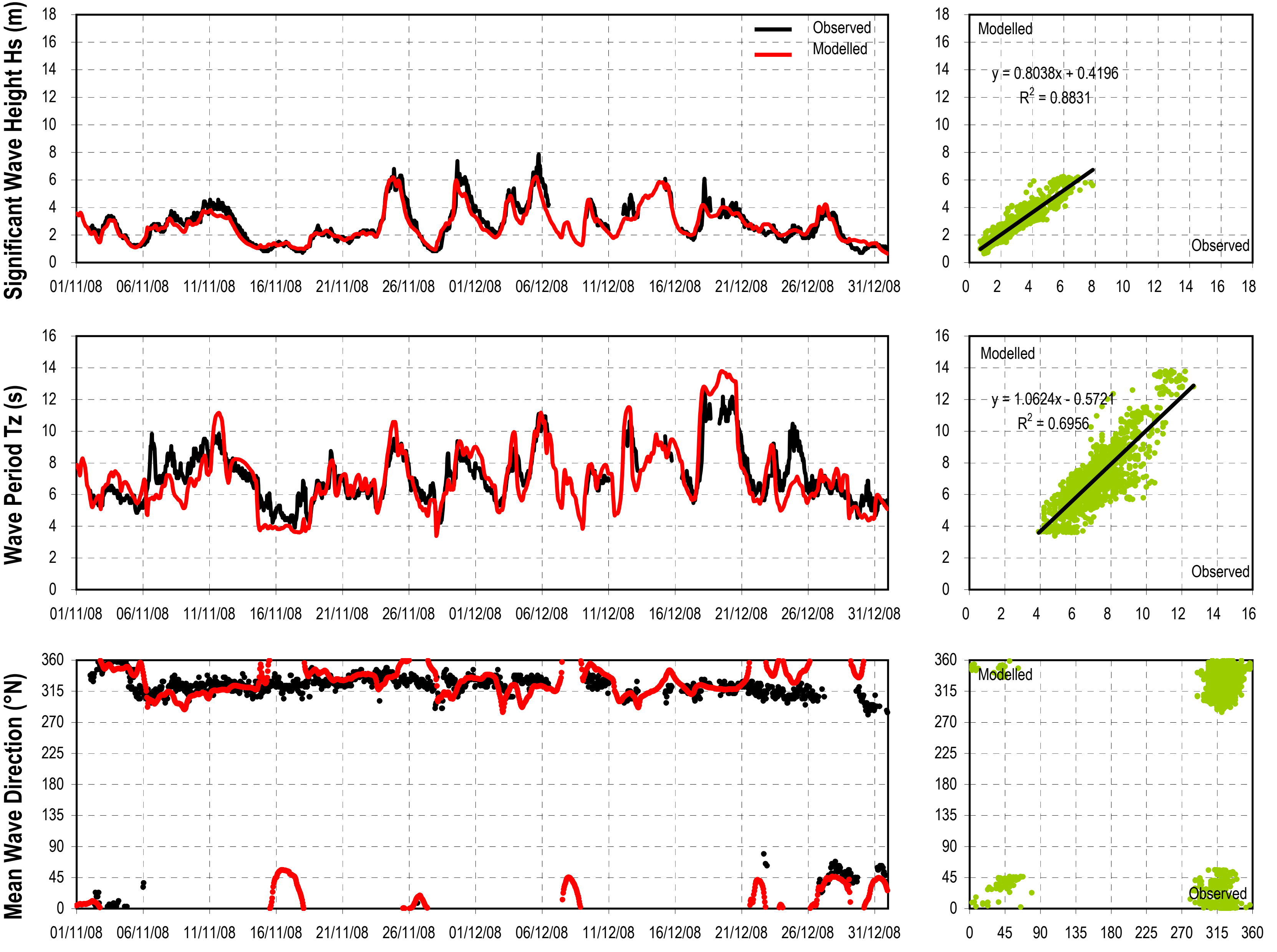
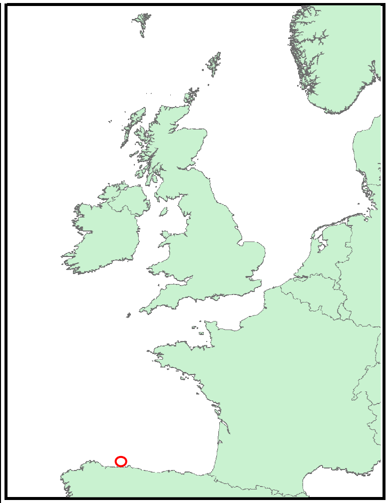
Validation Summary: Brittany

Figure 42

Penas





Date	By	Size	Version
Aug '13	NW	A4	6
Projection		n/a	
Scale		n/a	
QA		DOL	
SEASTATES_fig-control5.xls			
Produced by ABPmer			

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Validation Summary: Penas

Figure 43

Appendices

Appendix A

SWHM Calibration

Appendix A. SWHM Calibration

Table A1. Model calibration: Significant wave height, Hs, bias

Area	Location	Bias (m)	Bias as a Percentage of the Mean Observed Hs (%)	Mean Observed Hs (m)	10% of Mean Observed Hs (Hs Bias Performance Target) (m)
Scottish West Coast	West Hebrides	0.04	1.1	3.16	0.32
	Blackstones	0.09	3.8	2.41	0.24
Irish Sea	Liverpool Bay	-0.01	-1.5	0.95	0.10
	M2	-0.05	-3.2	1.67	0.17
Bristol Channel	Scarweather	-0.16	-5.7	2.82	0.28
	Hinkley	0.07	11.8	0.63	0.06
Celtic Sea	Seven Stones	0.58	20.7	2.80	0.28
	M5	0.27	9.1	3.00	0.30
English South Coast	Poole	0.00	-0.1	1.74	0.17
	Rustington	-0.05	-3.2	1.53	0.15
	Hastings	0.10	6.0	1.73	0.17
	Bracklesham	-0.05	-4.3	1.26	0.13
	Hayling	-0.10	-8.6	1.12	0.11
UK East Coast	Moray Firth	0.00	-0.3	1.39	0.14
	Firth of Forth	-0.10	-7.6	1.33	0.13
	Tees	0.02	0.9	1.66	0.17
	Dowsing	-0.10	-6.4	1.53	0.15
	West Gabbard	0.04	2.3	1.59	0.16
Irish West Coast	M3	0.32	8.2	3.90	0.39
	M4	0.20	5.8	3.50	0.35
Offshore	K7	0.02	0.7	3.60	0.36
	M6	0.34	8.4	4.10	0.41
North Sea	FINO1	0.10	4.5	2.21	0.22
	FINO3	-0.05	-2.2	2.24	0.22
France	Gascogne	0.42	12.7	3.30	0.33
	Brittany	0.20	4.8	4.10	0.41
Spain	Penas	-0.24	-9.3	2.58	0.26
	Tarra	0.22	9.1	2.46	0.25

Table A2. Model calibration: Significant wave height, Hs, scatter and correlation

Area	Location	Scatter Index, SI	Correlation Coefficient, R	Regression Coefficient, β_0
Scottish West `Coast	West Hebrides	15.2	0.95	0.96
	Blackstones	17.3	0.95	0.93
Irish Sea	Liverpool Bay	27.4	0.88	0.82
	M2	21.2	0.93	1.03
Bristol Channel	Scarweather	13.4	0.89	0.83
	Hinkley	35.2	0.85	0.68
Celtic Sea	Seven Stones	27.4	0.94	0.91
	M5	18.4	0.96	1.08
English South Coast	Poole	20.1	0.93	0.89
	Rustington	18.8	0.93	0.86
	Hastings	19.1	0.96	1.12
	Bracklesham	26.6	0.91	0.70
	Hayling	23.4	0.93	0.72
UK East Coast	Moray Firth	23.0	0.85	0.85
	Firth of Forth	26.6	0.87	0.75
	Tees	21.8	0.90	0.91
	Dowsing	19.7	0.90	0.80
	West Gabbard	21.2	0.89	0.97
Irish West Coast	M3	16.8	0.95	1.01
	M4	17.8	0.93	1.05
Offshore	K7	14.4	0.91	1.02
	M6	17.7	0.94	1.08
North Sea	FINO1	16.2	0.93	0.95
	FINO3	13.5	0.94	0.99
France	Gascogne	22.0	0.91	0.97
	Brittany	15.9	0.93	0.97
Spain	Penas	23.8	0.86	0.71
	Tarra	23.6	0.89	0.83

Table A3. Model calibration: Wave period, Tz, bias

Area	Location	Bias (m)	Bias as a Percentage of the Mean Observed Tz\ (%)	Mean Observed Tz (s)	20% of Mean Observed Tz (Tz Bias Performance Target) (s)
Scottish West Coast	West Hebrides	-0.06	-0.80	7.23	1.45
	Blackstones	-0.22	-3.70	5.95	1.19
Irish Sea	Liverpool Bay	-0.39	-10.80	3.60	0.72
	M2	-0.73	-14.70	5.00	1.00
Bristol Channel	Scarweather	-0.48	-8.00	5.95	1.19
	Hinkley	-0.90	-24.20	3.72	0.74
Celtic Sea	Seven Stones	-1.74	-19.30	9.00	1.80
	M5	-0.14	-2.40	6.00	1.20
English South Coast	Poole	-0.57	-10.90	5.23	1.05
	Rustington	-0.21	-4.70	4.50	0.90
	Hastings	-0.11	-2.40	4.50	0.90
	Bracklesham	-0.62	-12.80	4.80	0.96
	Hayling	-0.69	-16.10	4.30	0.86
UK East Coast	Moray Firth	-0.57	-12.20	4.63	0.93
	Firth of Forth	-0.69	-14.90	4.63	0.93
	Tees	-0.37	-7.90	4.63	0.93
	Dowsing	-0.44	-10.30	4.29	0.86
	West Gabbard	-0.35	-7.80	4.46	0.89
Irish West Coast	M3	0.43	5.30	8.00	1.60
	M4	0.40	5.60	7.00	1.40
Offshore	K7	0.16	2.20	7.00	1.40
	M6	0.44	5.50	8.00	1.60
North Sea	FINO1	-0.22	-4.50	5.00	1.00
	FINO3	-0.19	-3.60	5.19	1.04
France	Gascogne	0.19	2.70	7.00	1.40
	Brittany	-0.11	-1.30	8.00	1.60
Spain	Penas	-1.37	-18.40	7.42	1.48
	Tarra	0.21	3.00	6.88	1.38

Table A4. Model calibration: Wave period, Tz, scatter and correlation

Area	Location	Scatter Index, SI	Correlation Coefficient, R	Regression Coefficient, β_0
Scottish West Coast	West Hebrides	15.2	0.84	1.19
	Blackstones	16.7	0.85	1.14
Irish Sea	Liverpool Bay	14.5	0.89	0.85
	M2	19.3	0.84	0.96
Bristol Channel	Scarweather	11.3	0.76	0.82
	Hinkley	31.0	0.58	0.37
Celtic Sea	Seven Stones	23.6	0.81	0.96
	M5	12.8	0.88	1.04
English South Coast	Poole	19.5	0.80	0.78
	Rustington	15.5	0.83	0.95
	Hastings	10.7	0.91	1.16
	Bracklesham	22.2	0.72	0.69
	Hayling	26.9	0.64	0.50
UK East Coast	Moray Firth	19.6	0.78	0.88
	Firth of Forth	20.6	0.80	0.85
	Tees	15.0	0.83	0.86
	Dowsing	13.9	0.83	0.76
	West Gabbard	13.9	0.79	0.74
Irish West Coast	M3	12.6	0.89	1.06
	M4	15.2	0.85	1.16
Offshore	K7	12.0	0.85	1.09
	M6	11.4	0.86	1.00
North Sea	FINO1	8.4	0.92	0.89
	FINO3	7.4	0.92	1.02
France	Gascogne	13.4	0.86	1.02
	Brittany	10.9	0.87	1.03
Spain	Penas	26.7	0.60	0.53
	Tarra	16.3	0.90	1.10

Table A5. Model calibration: Wave direction bias and scatter

Area	Location	Bias (º)	Scatter Index, SI
Scottish West Coast	West Hebrides	21.5	11.2
	Blackstones	25.0	13.8
Irish Sea	Liverpool Bay	24.8	14.6
Bristol Channel	Scarweather	14.8	7.6
	Hinkley	29.8	18.4
English South Coast	Poole	23.3	19.2
	Rustington	13.5	10.1
	Hastings	14.8	14.1
UK East Coast	Moray Firth	29.6	46.4
	Firth of Forth	30.1	46.4
	Tees	28.5	38.7
	Dowsing	25.4	20.8
	West Gabbard	16.8	16.5
North Sea	FINO1	25.8	14.1
	FINO3	20.3	16.3
France	Gascogne	15.9	12.4
	Brittany	14.0	13.4
Spain	Penas	37.9	27.2
	Tarra	14.0	8.2

Appendix B

SWHM Validation

Appendix B. SWHM Validation

Table B1. Model validation: Significant wave height, Hs, bias

Area	Location	Bias (m)	Bias as a Percentage of the Mean Observed Hs (%)	Mean Observed Hs (m)	10% of Mean Observed Hs (Hs Bias Performance Target) (m)
Irish Sea	Liverpool Bay	-0.07	-7.3	0.96	0.10
English South Coast	Poole	0.05	6.1	0.79	0.08
	Rustington	0.00	0.7	0.67	0.07
	Hastings	-0.03	-2.8	1.00	0.10
UK East Coast	Moray Firth	0.14	11.9	1.21	0.12
	Firth of Forth	0.06	6.5	0.99	0.10
	Dowsing	-0.03	-2.4	1.43	0.14
	West Gabbard	-0.01	-1.2	1.17	0.12
North Sea	FINO1	0.14	9.4	1.49	0.15
France	Gascogne	0.28	9.9	2.80	0.28
	Brittany	0.10	3.1	3.20	0.32
Spain	Penas	-0.12	-4.9	2.46	0.25

Table B2. Model validation: Significant wave height, Hs, scatter and correlation

Area	Location	Scatter Index, SI	Correlation Coefficient, R	Regression Coefficient, β_0
Irish Sea	Liverpool Bay	27.1	0.92	0.78
English South Coast	Poole	22.6	0.94	0.87
	Rustington	24.3	0.94	0.82
	Hastings	20.3	0.95	1.04
UK East Coast	Moray Firth	34.2	0.85	1.01
	Firth of Forth	35.7	0.78	0.73
	Dowsing	19.0	0.91	0.86
	West Gabbard	16.4	0.95	1.00
North Sea	FINO1	41.4	0.87	0.61
France	Gascogne	20.3	0.92	0.96
	Brittany	16.0	0.93	0.96
Spain	Penas	17.9	0.94	0.80

Table B3. Model validation: Wave period, Tz, bias

Area	Location	Bias (s)	Bias as a Percentage of the Mean Observed Tz (%)	Mean Observed Tz (s)	20% of Mean Observed Tz (Tz Bias Performance Target) (s)
Irish Sea	Liverpool Bay	-0.48	-13.0	3.7	0.74
English South Coast	Poole	0.10	2.5	4.1	0.82
	Rustington	-0.66	-18.4	3.6	0.72
	Hastings	-0.44	-11.7	3.8	0.76
UK East Coast	Moray Firth	-0.66	-16.0	4.1	0.82
	Firth of Forth	-0.51	-11.8	4.3	0.86
	Dowsing	-0.53	-11.9	4.5	0.90
	West Gabbard	-0.47	-11.7	4.0	0.80
North Sea	FINO1	0.20	4.5	4.5	0.90
France	Gascogne	0.03	0.4	7.0	1.40
	Brittany	-0.30	-3.7	8.0	1.60
Spain	Penas	-0.13	-1.9	6.9	1.38

Table B4. Model validation: Wave period, Tz, scatter and correlation

Area	Location	Scatter Index, SI	Correlation Coefficient, R	Regression Coefficient, β_0
Irish Sea	Liverpool Bay	16.89	0.89	0.89
English South Coast	Poole	25.45	0.63	0.77
	Rustington	27.40	0.64	0.64
	Hastings	16.77	0.84	1.06
UK East Coast	Moray Firth	25.32	0.60	0.61
	Firth of Forth	20.82	0.77	0.84
	Dowsing	16.76	0.75	0.68
	West Gabbard	17.10	0.74	0.74
North Sea	FINO1	43.50	0.58	0.26
France	Gascogne	13.20	0.88	1.07
	Brittany	12.03	0.84	0.98
Spain	Penas	16.17	0.83	1.06

Table B5. Model validation: Wave direction bias and scatter

Area	Location	Bias (°)	Scatter Index, SI	Correlation Coefficient, R	Regression Coefficient, β_0
Irish Sea	Liverpool Bay	23.0	13.6	0.54	0.64
English South Coast	Poole	35.5	24.9	0.65	0.94
	Rustington	30.2	22.3	0.75	1.03
	Hastings	27.6	26.4	0.57	0.64
UK East Coast	Moray Firth	39.5	47.2	0.64	0.67
	Firth of Forth	36.5	53.3	0.49	0.60
	Dowsing	25.6	18.1	0.56	0.51
	West Gabbard	27.4	30.2	0.39	0.43
North Sea	FINO1	30.7	20.1	0.84	0.71
France	Gascogne	44.8	31.7	0.36	0.28
	Brittany	49.3	33.6	0.49	0.39
Spain	Penas	21.9	10.8	0.34	0.51

ABP Marine Environmental Research Ltd (ABPmer)
Quayside Suite, Medina Chambers, Town Quay, Southampton SO14 2AQ

T +44 (0)23 80 711840
F +44 (0)23 80 711841
E enquiries@abpmer.co.uk

www.abpmer.co.uk

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