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Probabilistic Coastal Flood Forecasting: Forecast Demonstration and Evaluation

Science project SC050069/SR2

Flood and Coastal Erosion Risk Management Research and Development Programme

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Steve Killeen

Steve Killeen

Head of Science

Executive summary

This project on *Probabilistic coastal flood forecasting* ran from March 2006 to December 2008. The project was funded by the Environment Agency and was carried out by HR Wallingford, the Met Office and the Proudman Oceanographic Laboratory. The project will be of most use to Environment Agency flood forecasters, but its findings are also relevant to Scottish flood forecasters and Met Office forecasters, and to others involved in flood incident management.

The project set out to develop and evaluate probabilistic methods for surge, nearshore wave and coastal flood forecasting in England and Wales. The main features that distinguish these methods from existing practice are in the use of hydraulic models extending from offshore, through the nearshore and surf zones, to action at coastal defences, using ensemble and other probabilistic approaches throughout.

The Environment Agency is responsible for fluvial and coastal flood forecasting in England and Wales. The Met Office has operational responsibility for offshore forecasting for the UK. Use of offshore forecasts to estimate the likelihood of coastal flooding is not trivial, potentially involving nearshore transformation of wave and surge forecasts, transformation of waves in the surf zone, the effect of wind, waves and still water level in causing beach movement, overtopping and breaching, to a probability of damage to people and property. All this must be carried out with sufficient accuracy and lead time for actions to be taken to reduce potential losses due to flooding.

This project included several modelling elements in coastal flood forecasting. These are grouped under four headings below, any or all of which could be developed further:

- surge ensemble modelling for all of the UK, run in near operational manner;
- temporary wave ensemble modelling specific to the South-East Irish Sea, for demonstration use;
- wave transformation and overtopping models specific to the South-East Irish Sea, for demonstration use;
- generic handling of a large number of uncertainties associated with nearshore waves and overtopping.

A real-time demonstration of the probabilistic coastal flood forecasting system provided distributions of surge, sea level, offshore waves, nearshore waves and overtopping rate, at each prediction point, at 15-minute time steps, updated 12-hourly. The feasibility of surge ensemble forecasting and probabilistic coastal flood forecasting was demonstrated. Evaluation of the overall system showed sufficient accuracy, timeliness, reliability, intelligibility and usefulness for possible operational use.

Some elements were found to offer greater potential than others to flood forecasters. The main recommendations from this project are listed below, in order of priority:

- implementation of the surge ensemble forecasting developed here;
- improved astronomical tidal prediction and flood thresholds at coastal flood forecasting locations;
- training to standardise flood forecasters' use of probabilistic forecasts;
- pilot study of near-operational wave ensemble forecasting;
- pilot study of near-operational probabilistic coastal forecasting.

These recommendations are described in Chapter 7 of this report, and are broken down into action points, with approximate costs and timings, in the implementation programme outlined in Figure 7.1.

This report, the second of two, describes the forecast demonstration and forecast evaluation stages of the project, with brief reference to the earlier model development and model evaluation stages. It is intended to stand alone as a report on the entire project, outlining the overall conclusions and recommendations of the project. Anyone involved in implementing the recommendations, or interested in the detail of the modelling approaches, will find more information in the first project report, published November 2007, describing the model development and evaluation.

Acknowledgements

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The Proudman Oceanographic Laboratory Project Team comprised Kevin Horsburgh and Chris Wilson.

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1. Introduction

1.1 Background

The Met Office is responsible for weather and offshore forecasting for the UK, while the Environment Agency is responsible for fluvial and coastal flood forecasting and warning in England and Wales. Operational flood forecasting is carried out through the Environment Agency's National Flood Forecasting System (NFFS).

Use of offshore forecasts to estimate the likelihood of coastal flooding is not trivial, potentially involving nearshore transformation of wave and surge forecasts, transformation of waves in the surf zone, the effect of wind, waves and still water level in causing beach movement, overtopping and breaching, to a probability of damage to people and property. As overtopping rate prediction is quite uncertain, for example, it may be helpful to represent this uncertainty through probabilistic forecasting to provide an estimate of the likelihood of high overtopping and consequent flooding.

Coastal flood forecasting should be considered within the wider context of risk assessment and emergency response. For flood forecasting to be useful, the forecasts need to have sufficient accuracy and lead time for actions to be taken to reduce the potential losses due to flooding. This project uses the word 'coastal' to describe the range of applicability of the approach and the models developed and evaluated. In principle, the methods remain valid for use, for example in estuaries and in Morecambe Bay, up to the point where rainfall, river flow, urban water supply and/or urban drainage begin to have a significant impact upon water level at defences.

Related recent and ongoing projects include:

- *Best practice in coastal flood forecasting* (FD2206), undertaken by HR Wallingford, Atkins and Posford Haskoning for the Department for Environment, Food and Rural Affairs (Defra), reported by Defra and Environment Agency (2003a and 2003b).
- *Performance measures for flood forecasting* (SC020076), undertaken by HR Wallingford and Eden Vale Modelling Services for the Environment Agency, reported in Environment Agency/Defra (2004).
- *Probabilistic* (FD2901), undertaken by Atkins Water and Management for the Environment Agency, reported in Defra/Environment Agency (2007).
- *Use of probability forecasts*, undertaken by the Met Office for the Environment Agency, 2006-2009.
- *Ensemble prediction of inundation risk and uncertainty arising from scour*, undertaken by the University of Plymouth within the FREE programme, 2007-2010.
- *Ensemble wave forecasting*, to be undertaken by the Met Office for the Environment Agency, to start in 2008.
- Defra/CEFAS WaveNet and Channel Coastal Observatory.
- Developments within FLOOD*site*, 2005-2009.
- Developments within FRMRC, 2004-2008.

- *National Flood Forecasting System*, designed and coded by Delft Hydraulics for the Environment Agency, in operational use within the Environment Agency.
- Coastal flood forecasting developments within Environment Agency North West, North East, Anglian and possibly Southern Regions.

More detail on the background, motivation and related projects is given in the first project report (Environment Agency, 2007).

1.2 Objective and scope of work

Develop, demonstrate and evaluate probabilistic methods for surge, nearshore wave, and coastal flood forecasting in England and Wales.

The project aimed to investigate different types of modelling, ultimately producing and demonstrating surge ensemble and probabilistic coastal forecasting models. The Environment Agency will consider adopting some aspects of these developments for operational use in England and Wales.

The project ran from March 2006 to December 2008. Full details of the scope of work are given in the first project report (Environment Agency, 2007), including the main technical elements outlined below:

Model evaluation: Generic review and classification of possible surge, wave and coastal models, and methods for linking them and tracking uncertainties.

Model development: Generic development of coupled offshore, nearshore and coastal models, including ensemble surge modelling and probabilistic coastal modelling.

Forecast demonstration: The demonstration showed that it is practical to run a number of component models together, and to deliver a hierarchy of probabilistic information potentially useful to flood forecasters. The demonstration ran from September 2007 to April 2008, nationally for the surge ensemble forecasts and for part of NW Region for the wave and coastal forecasts.

Forecast evaluation: To determine whether the model developments had any real value in terms of forecasting accuracy and/or additional information provided to Environment Agency forecasters. The evaluation compared forecasting accuracy against measurements and existing forecasting methods, and explored potential benefits in terms of the accuracy and usefulness of the forecasts produced, without detriment to their timeliness and reliability.

1.3 Summary of first project report

The first project report (Environment Agency, 2007) covers the generic model development and evaluation stages of the project. Chapter 1 (Introduction) introduces the subject, the background, the scope of work, and related projects and developments. Chapter 2 (Forecasting, modelling and information flow concepts) describes generic modelling, linking and forecasting concepts, requirements and benefits. Chapter 3 (Hydraulic modelling developments) describes the separate surge, wave and overtopping modelling developments. Chapter 4 (Overall implementation) describes how the overall modelling solution will be implemented and what types of shoreline forecast information will be available. Chapter 5 (Conclusions) lists the conclusions and recommendations for further work.

Section 2.1 (Flood forecasting and modelling requirements) outlines the purpose and scope of coastal flood forecasting. Section 2.2 (Extent and evaluation of modelling) discusses how the overall benefit of the forecasting might be evaluated and how that might guide the appropriate extent of forecasting in a particular area. Section 2.3 (Offshore/nearshore/shoreline model coupling) provides a generic description of the types of hydraulic model needed, and the sources and propagation of information and uncertainty between them; it also explains the overall modelling concept developed in this project. Section 2.4 (Classification and cataloguing of models) introduces Appendix 2, which classifies hydraulic models suitable for use in coastal flood forecasting, together with tick-box information on model properties and performance.

Section 3.1 (Ensemble modelling of surge) describes the development, interpretation and preliminary verification of surge ensemble modelling. Section 3.2 (Wave modelling) describes offshore and nearshore wave modelling issues, and a temporary method for wave ensemble forecasting to be used in the later forecasting demonstration. Section 3.3 (Probabilistic overtopping model) describes measures of overtopping, the range of formulae used to estimate them, and the sources of uncertainty.

Section 4.1 (The overall modelling approach) discusses implementation of the overall modelling solution, and the range of information available to forecasters. Section 4.2 (The forecast demonstration) introduces the forecast demonstration and forecast evaluation stages covered in the present report.

1.4 Outline of this project report

Chapter 1 and Sections 2.1 and 2.2 briefly review coastal flood forecasting, this project and model development, all covered in more detail in the first project report (Environment Agency, 2007). The remainder of Chapter 2 describes the forecast demonstration and other data sources used for evaluation. Chapter 3 presents the evaluation of the surge ensemble forecasts and of the offshore wave ensemble forecasts. Chapter 4 presents the evaluation of the nearshore wave and overtopping forecasts. Chapter 5 provides an analysis of the probabilistic aspects of the coastal flood forecasts, and their potential value to forecasters. Chapters 6 and 7 summarise the conclusions and recommendations from the project.

This report is intended to stand alone, and to be sufficient for most readers. Further details of the generic concepts, model selection and model developments are given in Environment Agency (2007).

1.5 Papers and reports produced in this project

The science reports and conference papers produced in this project are listed below in chronological order. Full citations are given in the reference list at the end of the report.

Environment Agency, 2007. *Coastal flood forecasting: Model development and evaluation*. First report produced for this project.

Tozer *et al.*, 2007. *Coastal flood forecasting*. Paper presented at the Defra conference in York - Defra Flood and Coastal Management Conference, 3-5 July 2007..

Flowerdew *et al.*, 2007. *Ensemble forecasting of storm surges*. Poster presented at the EGU General Assembly, Vienna - European Geosciences Union General Assembly, Vienna, 15-20 April 2007

Flowerdew *et al.*, 2008. *Ensemble forecasting of storm surges*. Paper presented at the JCOMM Symposium, Korea.

Pullen *et al.*, 2008. *Use of field measurements to improve probabilistic wave overtopping forecasts*. Paper presented at the ICCE Conference, Hamburg - International Conference on Coastal Engineering. The conference period was 31 August to 5 September 2008, but the papers are written in November 2008 and probably not published in book form until 2009. I suggest we settle for "September 2008"..

Hawkes *et al.*, 2008. *Probabilistic coastal flood forecasting*. Paper presented at the FLOODrisk 2008 conference, Oxford.

2. Demonstration of surge ensemble and coastal flood forecasting

2.1 Context of coastal flood forecasting, warning and response

2.1.1 Forecasting, warning and response processes

For coastal flood forecasting to help reduce losses, it needs to be considered as part of an overall flood forecasting, warning and action scheme comprising:

Monitoring: Continuous observations and measurements of flood risk variables, such as wave height and still water level, and general alertness to the potential for flooding.

Forecasting: Continuous weather and ocean forecasting of flood risk variables such as wind, waves, still water level and possibly shoreline responses such as overtopping.

Detection: Typically, the monitored and/or forecast variables have threshold levels associated with them which, when reached, represent a potential flood threat. There may be different threshold levels, leading to heightened activity of flood forecasters, additional monitoring, mobilisation of additional staff, site visits and so on.

Flood warning: Decision making using the output of the flood forecasting process is the focus of this stage. The decisions relate to whether to issue a warning or not, and the level of the warning to be issued.

Dissemination: This process involves informing the public and/or emergency services of the expected flood event.

Response: The actions of the public and the emergency services, following dissemination of the flood warning.

2.1.2 Physical zones, variables and processes

Typically, the detection process focuses on the source variables; for the coastal environment these will include measurements and forecasts of waves and still water levels (tide and surge). Physical processes dominating the sources of coastal flooding vary from the large scale oceanic environment, through the regional scale coastal environment and into the shoreline. As the dominant physical processes change, so do the modelling methods that have been developed to simulate them. With these dominant physical processes in mind, it is useful to describe the physical system in terms of the interconnected zones illustrated in Figure 2.1.

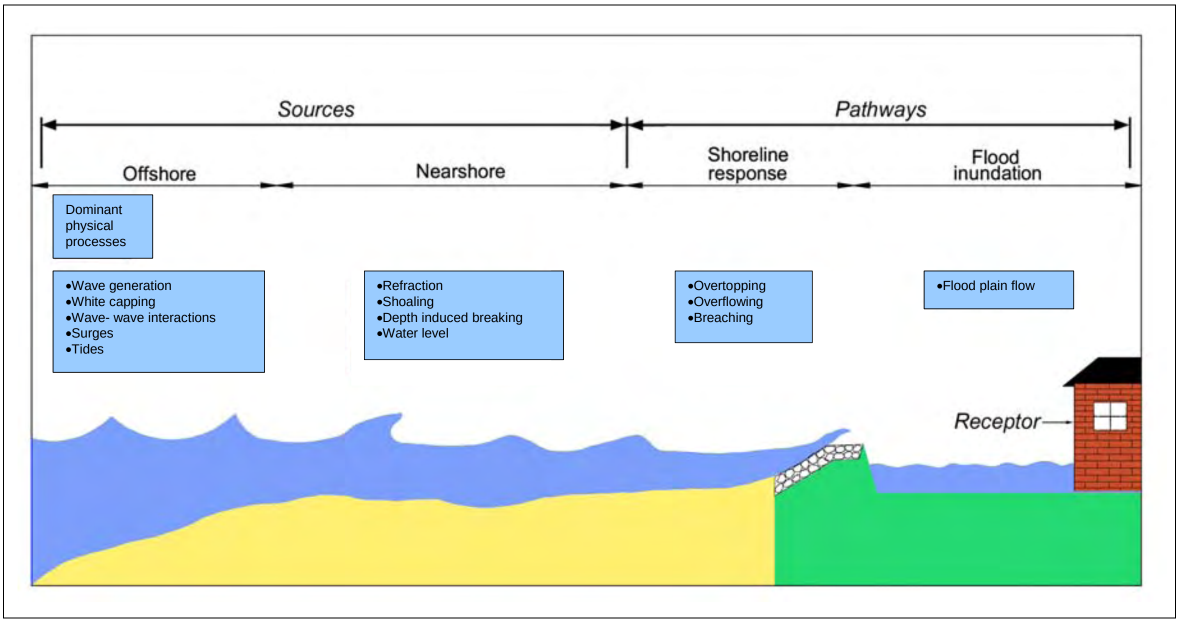

Figure 2.1 Physical zones of coastal flood forecasting

Offshore zone: waves and still water levels, including the processes of wave generation and the interaction of waves with each other.

Nearshore zone: waves and still water levels, loosely defined as the zone in which the seabed influences wave propagation and includes shallow water effects such as shoaling, depth refraction, interaction with currents and depth-induced wave breaking.

Shoreline response zone: including the responses of beaches and defences to waves, wave structure interaction, overtopping, overflowing and breaching.

2.1.3 Criteria for assessing the value of flood forecasting

Flood warnings and subsequent dissemination processes focus on the people and property at risk, whilst the response process aims to reduce the consequences. The purpose of flood forecasting is to inform and aid the flood warning process. The aims of flood warning are to increase the likelihood that action will be undertaken to reduce the effects of a flood (primarily to reduce loss of life and damage to property) and enable more successful action to be undertaken. Flood forecasting therefore needs to be:

Reliable: the input data, processes and models should remain valid and continue to work throughout potential flood risk events.

Accurate: the methods and models used should provide accurate predictions of flood risk variables, beyond what is otherwise available from weather forecasts.

Timely: flood forecasts should be available with sufficient lead time for forecasters, those sending out warnings, the emergency services and the public to take appropriate action to mitigate the impacts of flooding.

Useful in information content: forecasts should provide clear and appropriate information relevant to Environment Agency flood forecasters' needs.

Exceedence of initial threshold levels (in terms of still water level, wave height, wind speed and/or overtopping rate) may trigger heightened forecasting and monitoring activity. Exceedence of higher threshold levels will prompt forecasters to consider the preparation of warnings or mobilisation of emergency responses but, for the moment, human decision should override these prompts. The availability of ensemble or other probabilistic forecasts of each of these variables adds another dimension to the information available, offering the possibility to define thresholds in terms of probabilities of variables exceeding certain magnitudes.

2.2 Existing operational forecasts

The national forecasting system run from the Met Office includes surge and offshore wave modelling, both updated four times a day. During the forecast demonstration and evaluation phases of this project, the Met Office UK Waters Wave Model was used for operational forecasting. The UK Waters Model is a second generation phase averaged wave model, working with a wave energy spectrum, where the wave energy in each frequency and each direction is predicted by the model. From the wave spectrum, the integrated parameters of significant wave height, mean wave period and mean wave direction can be computed. In additional to providing total sea conditions (based on the integration of the complete wave spectrum) the model also provides equivalent separate wind-sea and swell components. During the last phase of this project, the Met Office switched to a third generation WaveWatch III model for wave forecasting.

Still water level (sea level in the absence of wave action) is based on the deterministic CS3 surge prediction model developed by POL which provides predictions of the surge residual. The surge residual predictions are combined with astronomic tide predictions derived by interpolating, in space and time, from the Environment Agency supplied harmonic predictions to provide an overall still water level prediction.

Nearshore and coastal forecasts are run by Environment Agency regions within the National Flood Forecasting System. The NW region TRITON system (an NFFS module), for example, provides flood forecasts based on still water level and overtopping predictions. Wave overtopping rates and volumes are predicted using look-up tables, which relate overtopping to incident wave and still water level conditions and a description of the sea defence structures. The nearshore wave predictions are also based on look-up tables, relating nearshore to offshore wave conditions from the Met Office UK Waters Wave Model. The present operational forecasts are deterministic, meaning a single best estimate prediction, at 15-minute intervals, updated four times daily. The existing TRITON forecaster interface includes a summary colour-coded list of sites indicating whether threshold levels have been exceeded in forecasts.

2.3 Summary of the probabilistic modelling approaches and information flow

The developments made in this project, described in more detail in Environment Agency (2007), include:

- ensemble surge forecasts, implemented nationwide;
- proxy-ensemble offshore wave forecasts, implemented for the SE Irish Sea;
- a Monte Carlo approach, to represent uncertainties in the model and structure parameters;
- probabilistic offshore to nearshore wave transformation, implemented for the SE Irish Sea;
- probabilistic overtopping forecasts, implemented for the SE Irish Sea.

2.3.1 Surge and offshore wave ensemble forecasts

A traditional deterministic forecast produces a single estimate of how each output will evolve as a function of time. An ensemble modelling approach produces not one but several forecasts. Each forecast uses slightly different initial conditions, boundary conditions and/or model physics, with the aim of sampling the range of forecast results consistent with the uncertainty in observations and the modelling system itself.

For storm surge forecasting, the uncertainty in meteorological forcing is expected to dominate over uncertainties in the surge model formulation and initial state (Section 3.1.4 presents test results supporting this assumption). In this project, the effect of this meteorological uncertainty were sampled by driving each surge ensemble member with surface wind and pressure forecasts taken from the corresponding member of the Met Office Global and Regional Ensemble Prediction System (MOGREPS, Bowler *et al.*, 2007). The data for this project come from the regional ensemble, which covers a North Atlantic and Europe domain at 24 km resolution, with two forecasts per day starting at 06:00 and 18:00 GMT. The boundary conditions for each regional integration are obtained from the corresponding member of the lower resolution global ensemble. Both ensembles contain 23 perturbed members, sampling the uncertainty in atmospheric initial conditions and model physics, together with one unperturbed ‘control’ member. During the course of this project, the length of the regional runs was extended from 36 to 54 hours, giving a full two days of useful forecast available five to six hours after data time.

The surge ensemble uses the same underlying CS3 storm surge model as the current operational deterministic surge forecasting system. During the course of this project, both systems were upgraded from CS3 to CS3X, which uses a larger domain to improve both tidal response and the far-field surge generation. All surge ensemble members start from the same initial state, copied from the deterministic system to take advantage of the latest atmospheric observations. As in the deterministic system, the tidal component of each CS3 forecast is replaced by a harmonic tide prediction based on local gauge data to give the final still water level prediction at each individual port.

Although not part of this project, the Met Office intends to develop an operational ensemble wave forecasting system. This will be compatible with the existing MOGREPS approach to surge ensemble forecasting, in the sense that the same number and meaning of ensemble members will be used, and that forecasting will be to T+54, updated twice daily. It was helpful, therefore, to develop coding during this project to accommodate use of ensemble forecasting of waves. A temporary method was developed to produce realistic offshore wind-sea ensemble forecasts for the South-East Irish Sea demonstration area.

2.3.2 Nearshore wave and overtopping probabilistic forecasts

Ideally, a single nearshore model would be used to predict wave and still water level conditions at the toe of the structure to be used as input to the overtopping calculations. However, because of the different physical processes and scales, together with current computational constraints, this is not presently viable. Wave transformation from offshore to the toe of the structure is modelled in two stages. The first stage represents the transformation from offshore to the surf zone.

The second stage represents the process of wave transformation along the beach profile to the toe of the structure. There may be significant uncertainty associated with the geometry, primarily the slope of the beach and the depth of the toe at the structure. This uncertainty exists partly because this region is often difficult to survey accurately, but may also be subject to short and medium timescale changes often caused by wave action. The beach profile/chainage represented in the profile model is expected to vary from site to site and will depend on the geometry of the approaches. In most cases, the profile model will represent wave propagation over the final few wavelengths up to the toe of the structure.

The sea defence toe wave conditions and the still water level (assumed unchanged through the nearshore zone) are used in overtopping rate prediction. The best overtopping rate predictors are inherently uncertain, but the methods developed here attempt to identify, quantify and model the various component uncertainties as they flow through the series of hydraulic models.

To accommodate possible future development of operational wave ensemble forecasts, the nearshore wave and overtopping models are coded to take as offshore boundary conditions ensemble wind-sea *and* swell forecasts (although the swell forecast is at present deterministic, with the same values used 24 times).

2.3.3 Overall concept

The overall probabilistic coastal flood forecasting concept is centred on surge ensemble modelling, offshore wave forecasting, and Monte Carlo simulations of the uncertainties involved in wave transformation and overtopping. Conceptual flow diagrams of this approach are given in Figures 2.2 and 2.3: Figure 2.2 shows the grouping of different types of model; Figure 2.3 focuses on the detail of the information flow through the different stages of modelling.

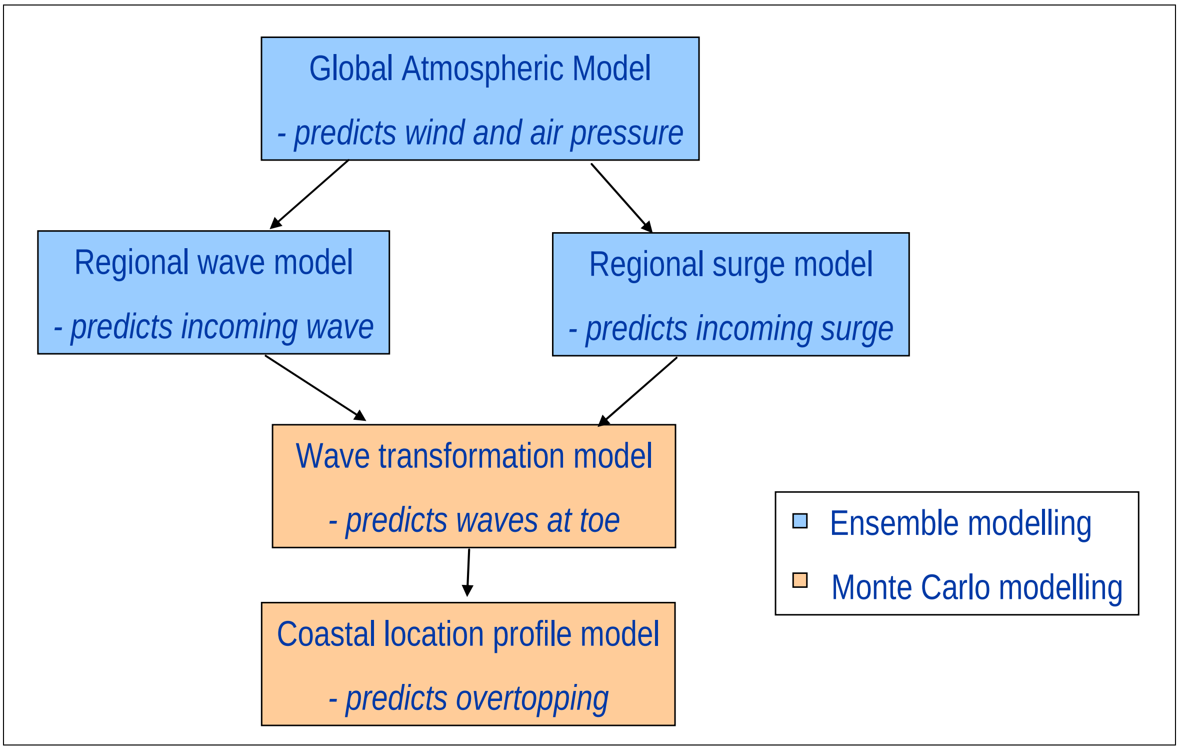

Figure 2.2 Grouping of models used in coastal flood forecasting

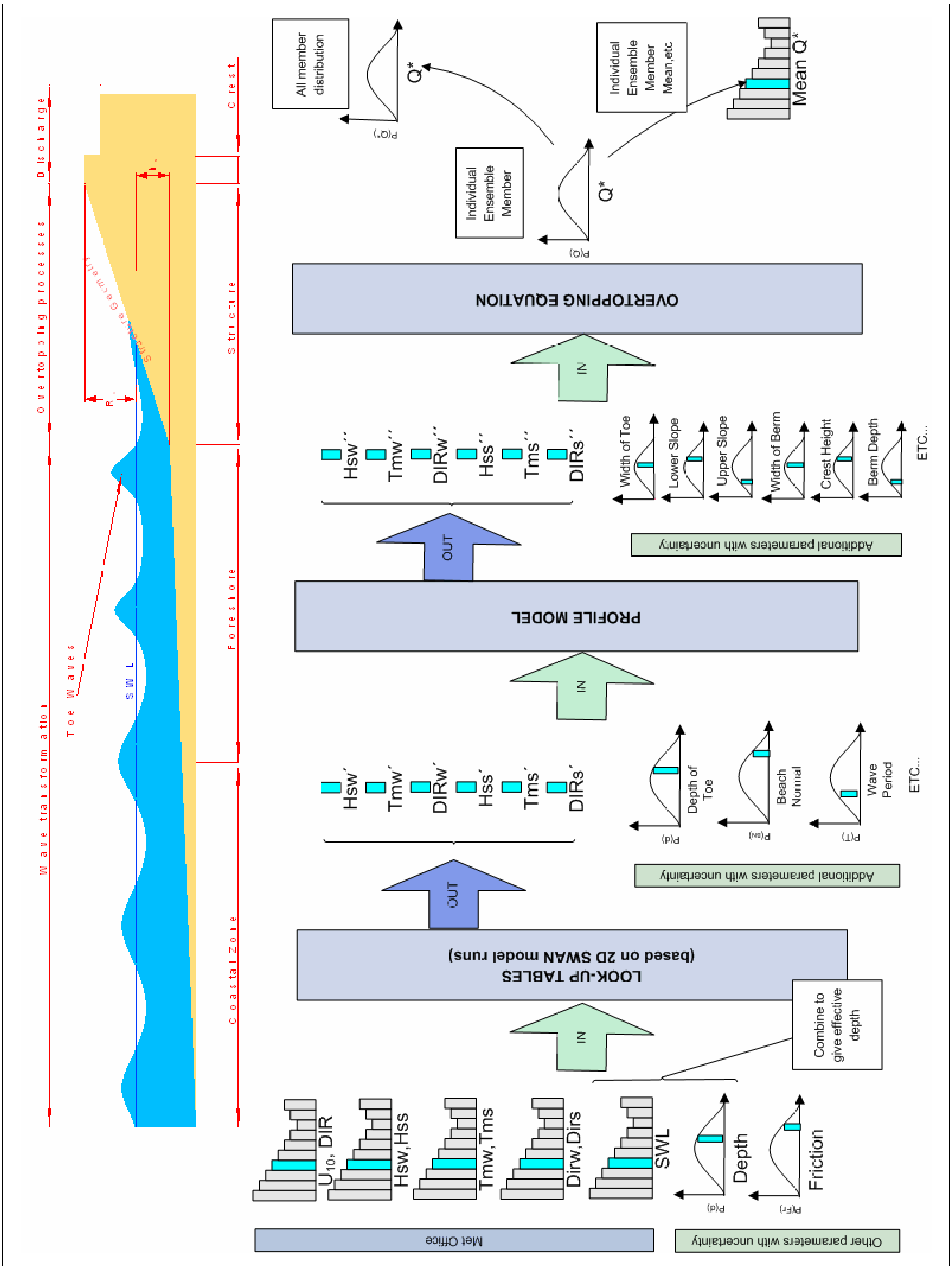

Figure 2.3 Overall probabilistic coastal flood forecasting concept

The upper panel in Figure 2.3 gives a breakdown of the physical domain from offshore to the area of land behind the coastal defence at risk of flooding. The lower panel in Figure 2.3 shows the overall flow of data from left to right starting from offshore wind, wave and still water level predictions. Astronomic tide predictions are provided by the Environment Agency, and these are incorporated into the still water levels reported at the coast and used in overtopping calculations.

The Met Office and Environment Agency offshore wave and still water level predictions form part of the inputs into the Monte Carlo simulations, shown in Figure 2.3 as a series of discrete members. The other inputs to the Monte Carlo simulations are a series of distributions that represent the uncertainties of a range of parameters affecting the transformation of waves from offshore to the toe of the structure and the calculation of wave overtopping.

Potentially, there is a vast amount of information available to forecasters from the probabilistic approach. The same flood risk variables presently available, over about the same forecast period presently available (albeit for a much reduced number of shoreline locations in the forecast demonstration) are available from the probabilistic approach. However, each variable, at each location and at each time step, are now available not only in the form of a central prediction, but also of alternative ensemble values and/or a probability distribution.

2.4 Outline of the demonstration

There were two main purposes to the forecast demonstration: to show that the various organisations and models can work together consistently (the reliability criterion); and to deliver coastal flood forecasts at regular intervals, in time for them to be acted upon (the timeliness criterion). Individual model elements and the modelling system as a whole were also compared against field measurements and against other forecasting methods (the accuracy criterion). Although rather outside the scope of this project, there was also the question of whether the probabilistic forecasts would allow Environment Agency forecasters to work more effectively (the usefulness criterion).

Models were run at the Met Office and at HR Wallingford. Results were disseminated within the Project Team and Project Board through a password-protected demonstration website operated by HR Wallingford. As far as possible, the file formats and protocols followed the requirements of the Delft FEWS system used within the National Flood Forecasting System. Details of the parameters, file formats and program code are given in Appendix 1. The demonstration was run over one winter period, from September 2007 to April 2008. The system took Met Office inputs twice daily, and generated the corresponding coastal forecasts twice daily. New forecasts were posted on the website at approximately 02:00 and 14:00 each day, about eight hours after commencement of weather model runs at 18:00 and 06:00 (and these timings would be about the same for an operational system).

Offshore wave modelling and surge ensemble modelling were run (and continue to run) on a national scale, and so model validation could be performed against field data anywhere around the UK. The offshore wave ensemble modelling, nearshore and shoreline modelling, and the interface to Environment Agency forecasters were run only in a limited area and for a limited time.

2.5 Demonstration of surge ensemble forecasting

The surge ensemble forecast is run twice daily at the Met Office, looking 54 hours ahead in 15-minute time steps. The demonstration ran over two winter periods, 2006/07 and 2007/08, but continues at the time of writing as it is likely to be implemented for operational use.

The surge ensemble forecasts are post-processed to produce a variety of graphical outputs. These plots focus on the surge residual, due to the lack of accurate gridded tide predictions, and to prevent the meteorologically-driven surge being lost in the much larger tidal signal. In most situations, the ensemble develops rather little spread, suggesting a fairly predictable situation and a high degree of confidence in the forecast. On some occasions, however, the spread is much larger, suggesting a greater degree of uncertainty.

Postage stamp animations (a still example is given in Figure 2.4) running through the 54-hour forecast period display all the information contained within the ensemble.

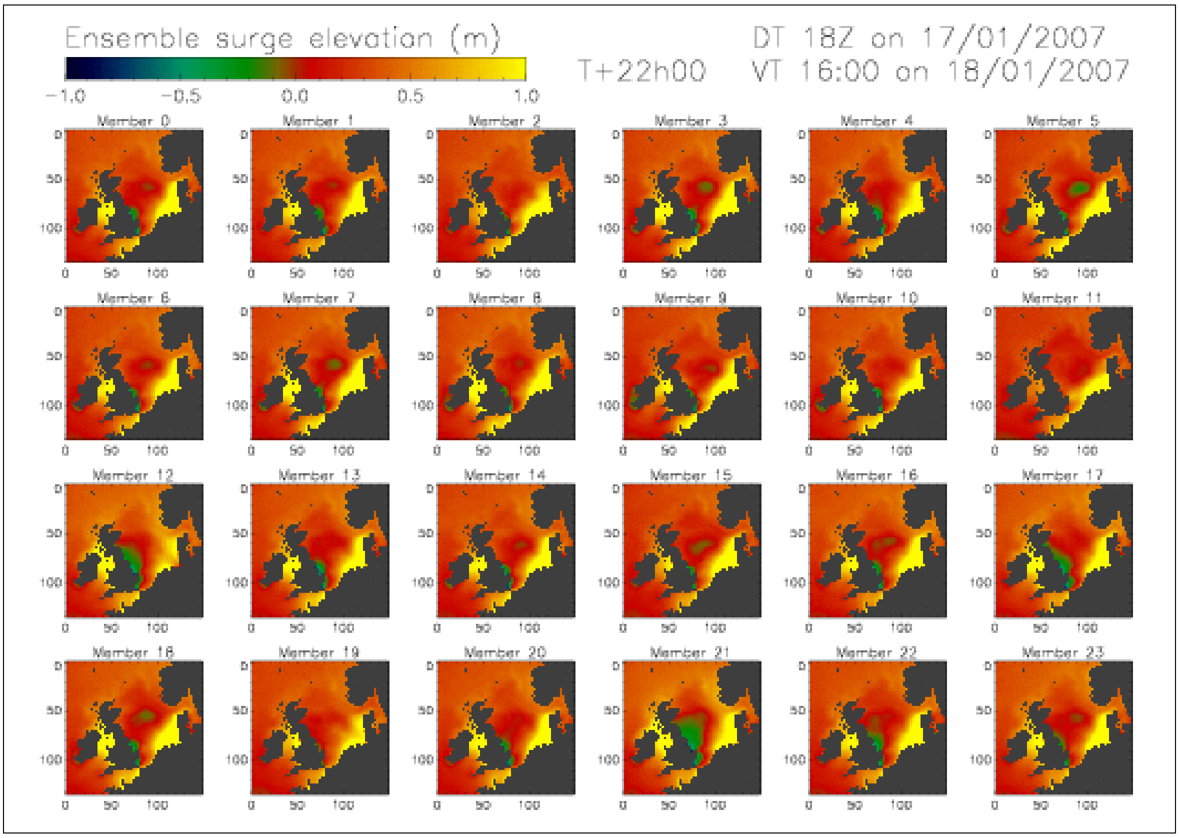

Figure 2.4 'Postage stamps' showing surge elevation for each of 24 ensemble members

Mean and spread charts such as Figure 2.5 more clearly indicate where the forecast is uncertain, and how this uncertainty relates to the mean surge prediction. In the example shown, the uncertainty along the German coast is directly related to the large mean at that location, whereas the band of uncertainty along the North-East coast of England runs across the contours of mean surge prediction, perhaps indicating uncertainty in the timing of the surge along that coast.

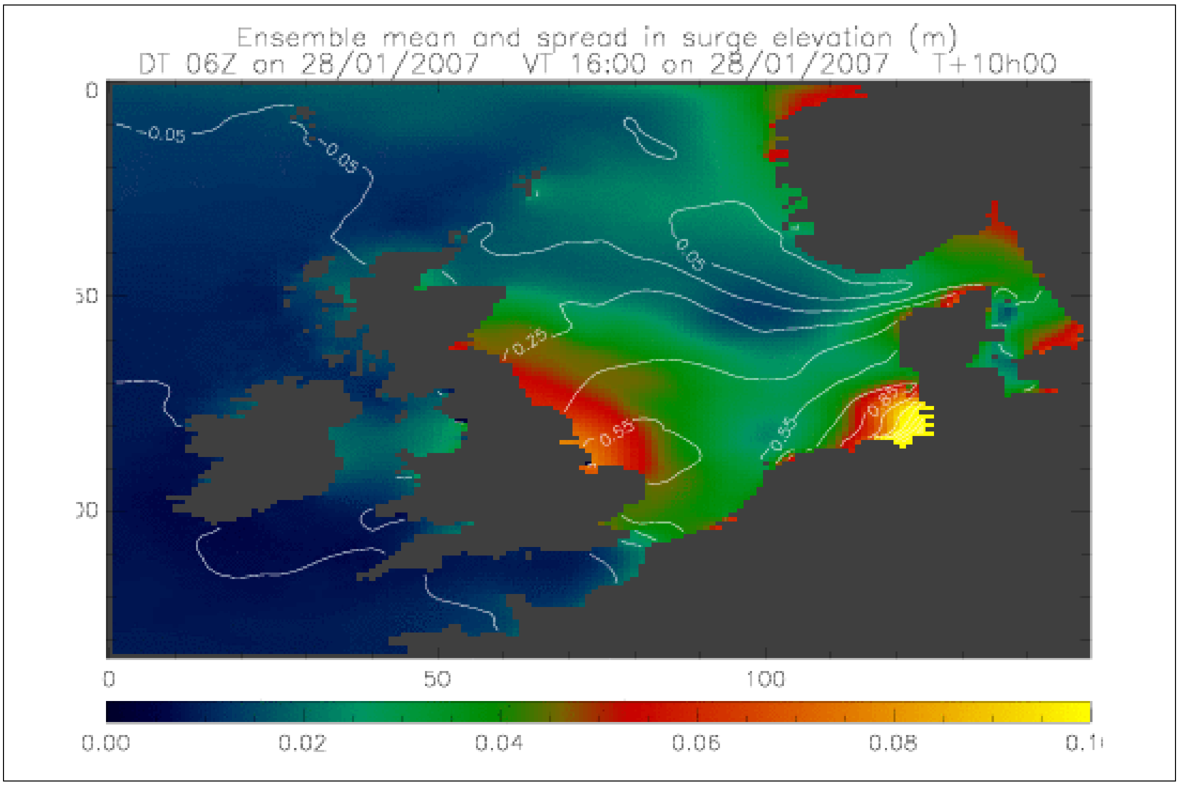

Figure 2.5 Mean (contours) and standard deviation (colours) of surge elevation

The forecast probability of exceeding successive thresholds at each port can be summarised in a stacked bar chart, as shown in Figure 2.6. The plot is constructed using the maximum value predicted by each ensemble member in the 12-hour period ending at the indicated verification time.

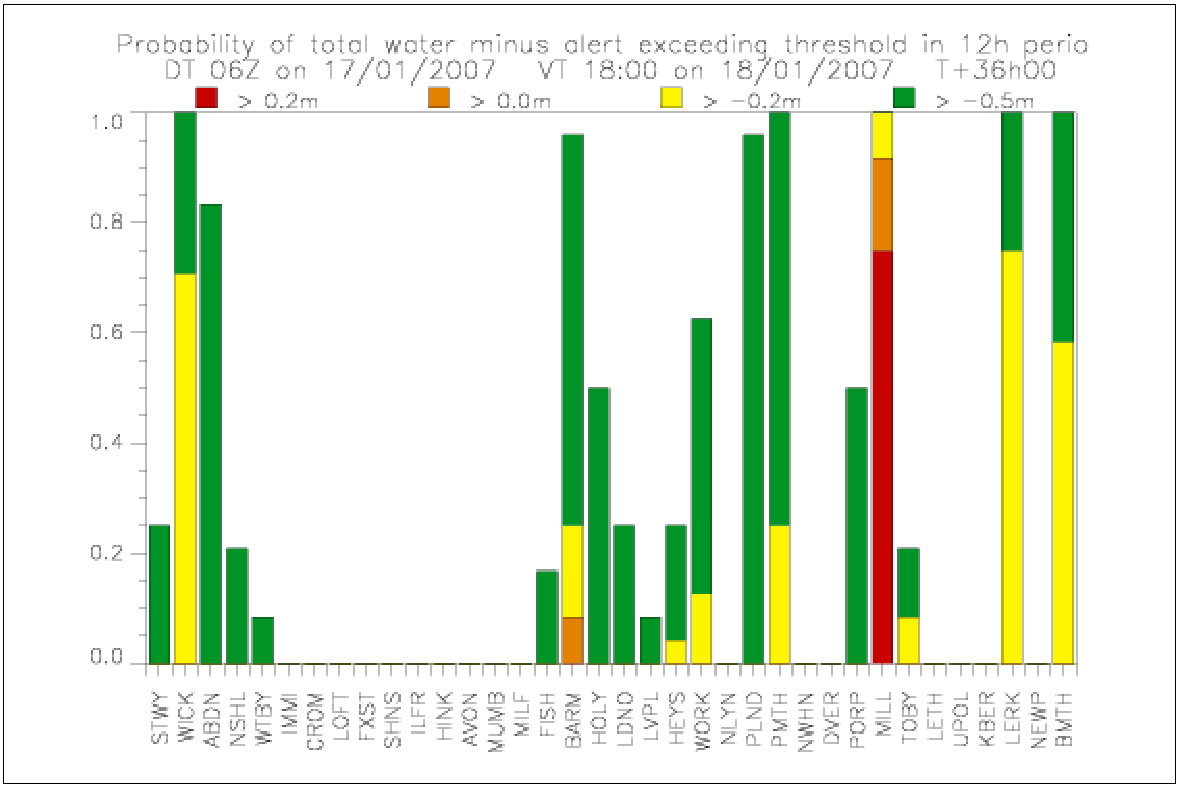

Figure 2.6 Stacked probability chart for total water level exceeding successive thresholds within a 12-hour period

Figure 2.7 illustrates development of a site-specific North Sea ensemble surge forecast over a period of two days. The diagrams show the surge forecast for Felixstowe on 9 November 2007, 48, 24, 12 and zero hours ahead of the event. The red oscillatory line represents astronomical tide, a crossing of which indicates crossing of a sea level threshold.

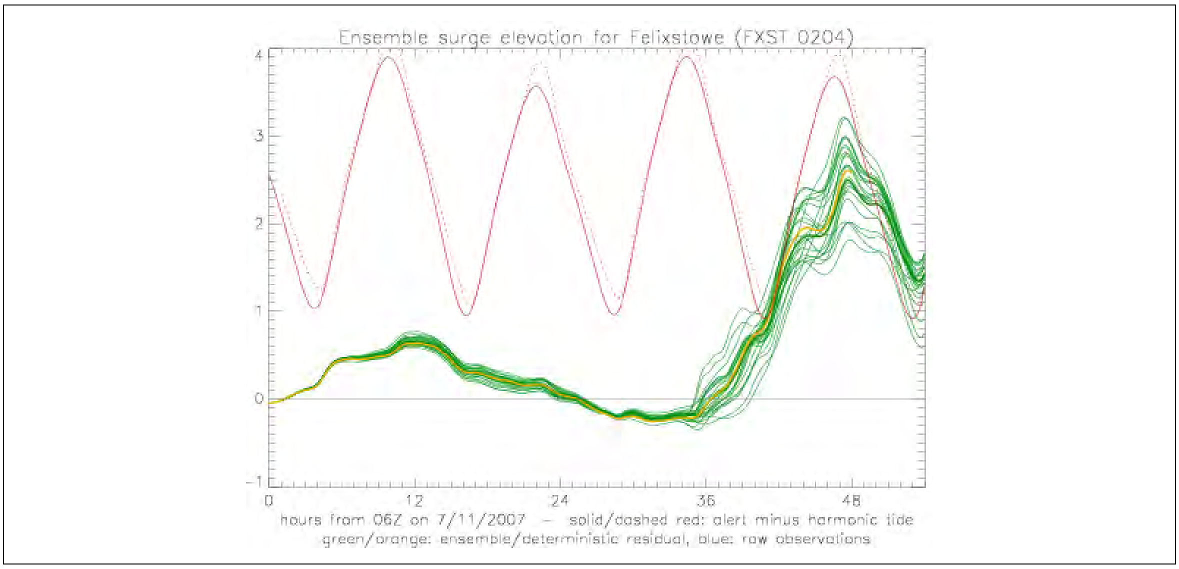

Figure 2.7a Morning surge forecast on 7 November 2007

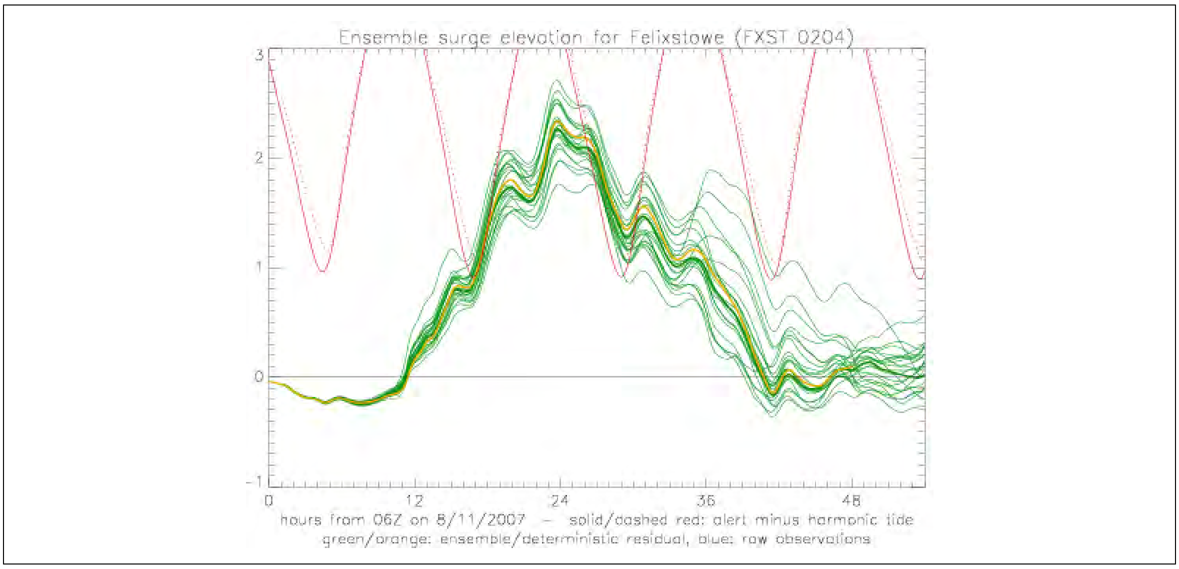

Figure 2.7b Morning surge forecast on 8 November 2007

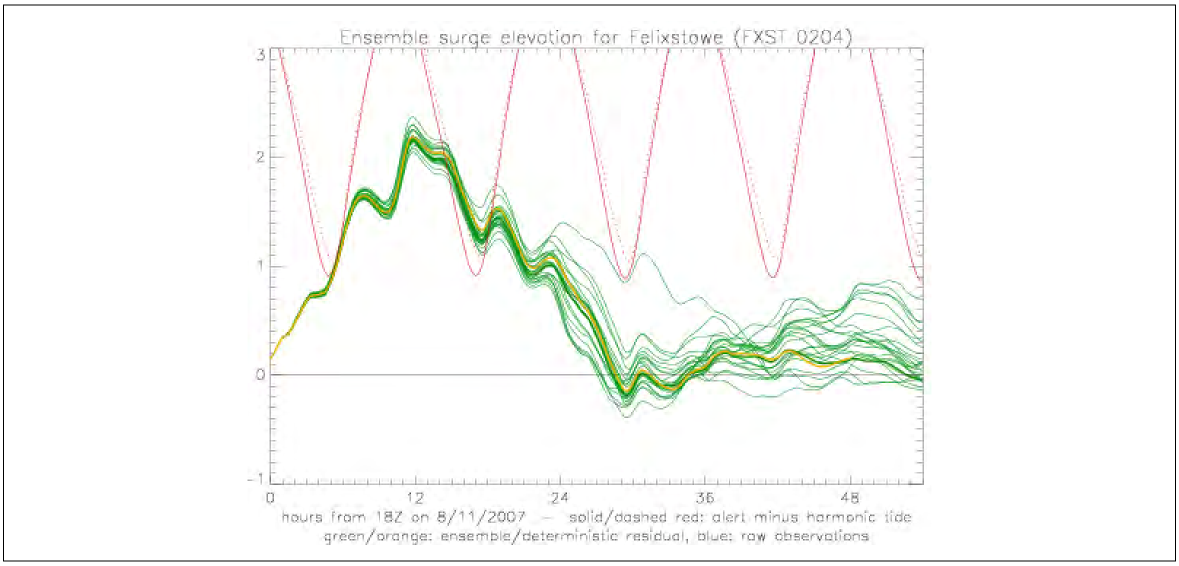

Figure 2.7c Afternoon surge forecast on 8 November 2007

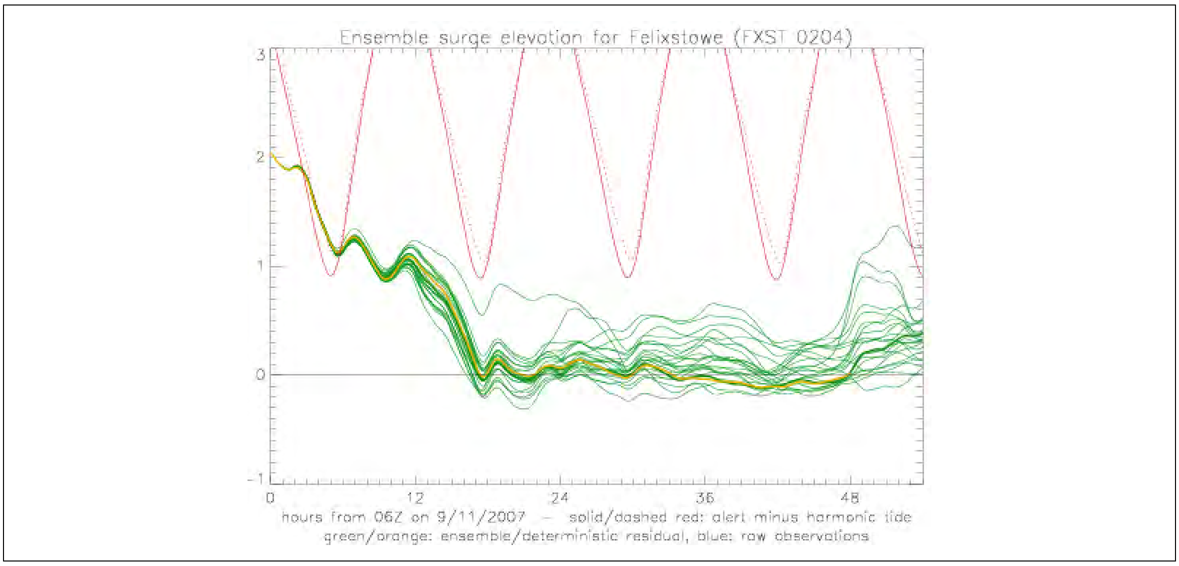

Figure 2.7d Morning surge forecast on 9 November 2007

2.6 Demonstration of probabilistic coastal flood forecasting

2.6.1 North West Region demonstration area

The demonstration was set up for the area shown in Figure 2.8, to mimic an operational system. A wave transformation model was set up (rectangle in Figure 2.8) to take boundary conditions from several offshore wave prediction points. Two nearshore overtopping prediction points were set up at Anchorsholme, Blackpool (triangle in Figure 2.8).

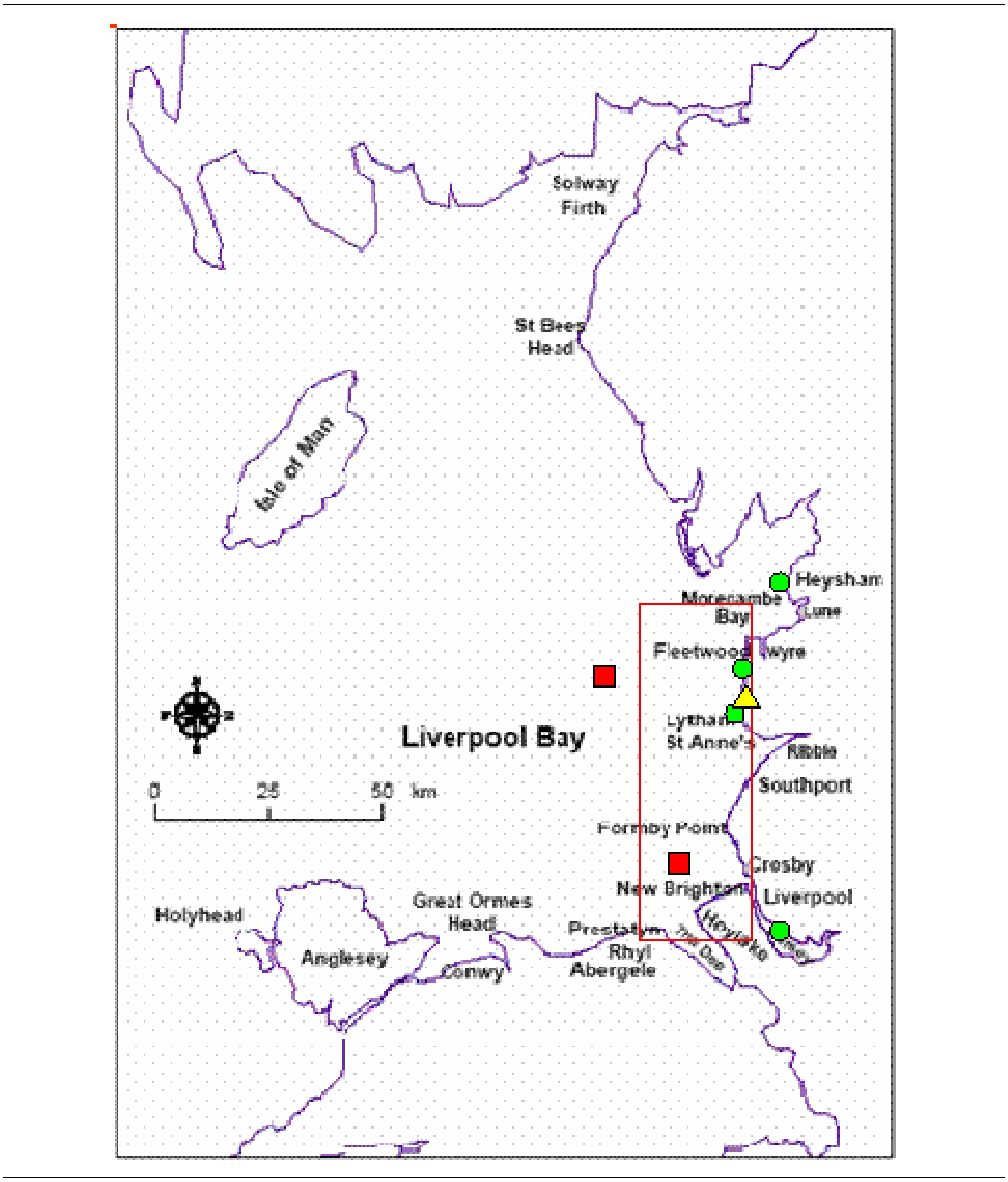

Figure 2.8 Location map for the probabilistic coastal flood forecasting demonstration (rectangle, wave model; squares, wave measurements; triangle, overtopping measurements; circles, tide gauges)

Figures 2.9 and 2.10 are photographs of Anchorsholme, Blackpool (triangle in Figure 2.8): Figure 2.9 in calm conditions and Figure 2.10 showing overtopping during stormy conditions.

Figure 2.9 Seawall at Anchorsholme, Blackpool (photo by Tim Pullen, HR Wallingford)

Figure 2.10 Overtopping at Anchorsholme on 7 December 2006 (photo by Ian Davison, Environment Agency)

2.6.2 Application of the SWAN model for the demonstration area

A SWAN model was set up to cover Liverpool Bay, extending northwards to the entrance to Morecombe Bay and westward to approximately the -30 mCD contour. The model bathymetry was taken from the C-Map database of digital Admiralty Chart data. The SWAN model consisted of a single rectangular grid aligned with North. Sensitivity tests were carried out to determine an optimum resolution for the bathymetric grid that would give efficient model run times while providing sufficiently accurate predictions of wave conditions in the nearshore zone.

Figure 2.11 shows the extent and bathymetry of the model area. Two alternative grid resolutions defined in Table 2.1 were selected for use in the forecasting demonstration. The fine resolution grid was primarily used for lower still water level runs and longer period swell runs, where it was found that the coarser gridded SWAN model failed to converge.

Table 2.1 SWAN model grid systems used for the demonstration area

Grid	Grid spacing (m)		Number of nodes		Grid origin (British national grid coordinates)	
	x direction	y direction	x direction	y direction	x direction	y direction
Course	1000.0	1000.0	39	105	298000	381000
Fine	250.0	250.0	153	417	298000	381000

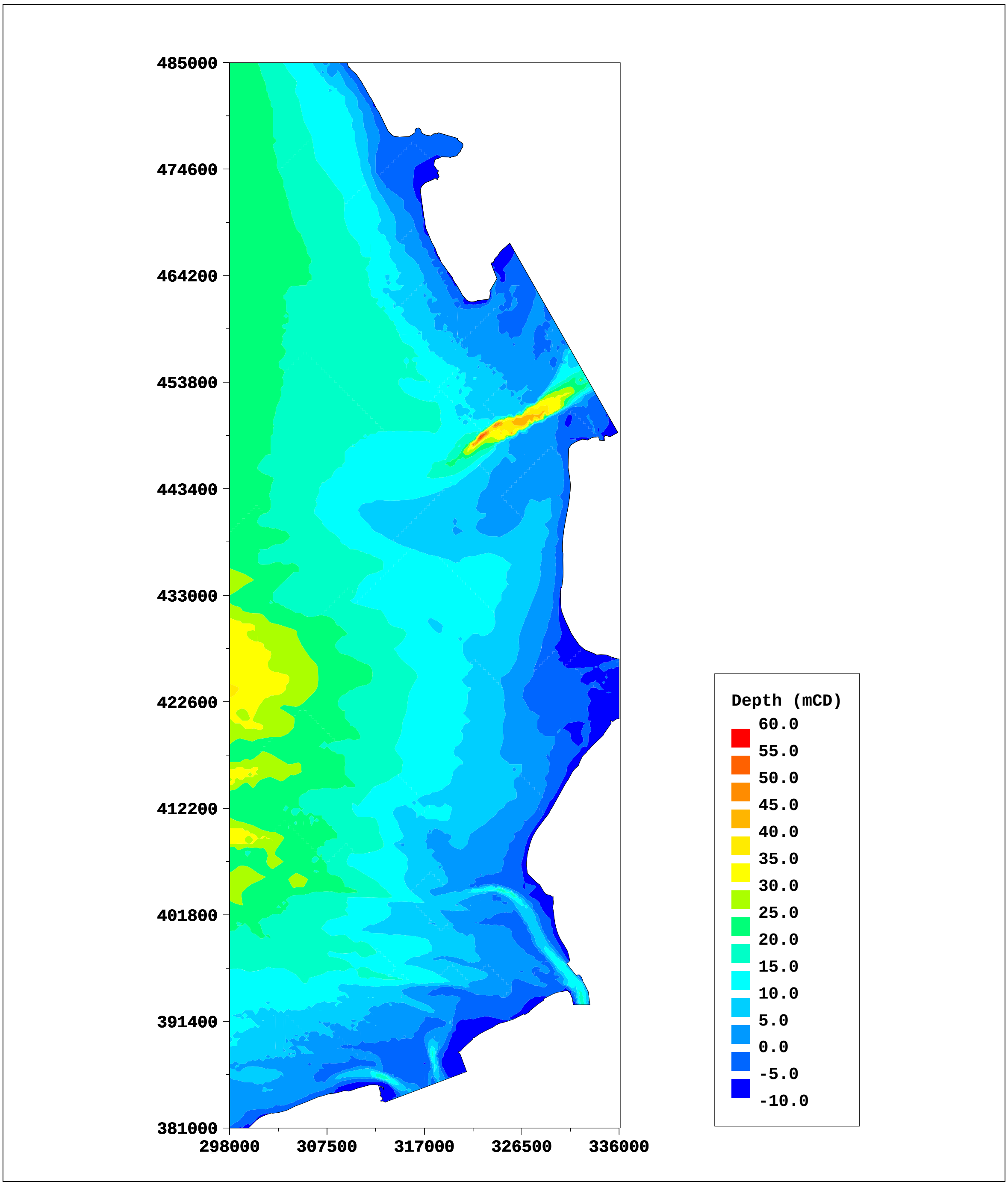

Figure 2.11 SWAN model area and bathymetry

A large number of SWAN model runs were carried out to cover the range of offshore wave conditions, wind conditions and tidal water levels that can occur in Liverpool Bay.

The model was run for wind-sea and swell components separately. For wind-sea events, wave growth over the model area due to winds was also included.

In addition, to allow for the uncertainty in seabed type, a range of friction factors was considered. The full set of SWAN input conditions is listed in Tables 2.2 and 2.3, for the wind-sea and swell components, respectively.

Table 2.2 SWAN wind-sea input conditions

Friction factors		
0.038	0.067	0.100

Still water levels (mCD)					
0.5	3.5	6.5	8.5	10.0	11.0

Wind conditions				
Wind speed (m/s)	5	15	25	35

Wind directions same as wave direction and ± 30°, limited to range of 180-360°N

Wind-sea conditions

Significant wave height (m)	Mean period range (s)						
0.5	3	4	5				
1.5	3	4	5	6			
2.5		4	5	6	7		
3.5			5	6	7	8	
4.5				6	7	8	9
5.5				6	7	8	9
6.5				6	7	8	9

Wave direction (ºN)	Significant wave height range (m)						
180	0.5	1.5	2.5	3.5	4.5	5.5	
210	0.5	1.5	2.5	3.5	4.5	5.5	6.5
240	0.5	1.5	2.5	3.5	4.5	5.5	6.5
270	0.5	1.5	2.5	3.5	4.5	5.5	
300	0.5	1.5	2.5	3.5	4.5	5.5	
330	0.5	1.5	2.5	3.5	4.5		
360	0.5	1.5	2.5	3.5			

Table 2.3 SWAN swell input conditions

Friction factors		
0.005	0.038	0.067

Still water levels (mCD)					
0.5	3.5	6.5	8.5	10.0	11.0

Swell conditions							
Wave direction (ºN)	180	210	240	270	300	330	360
Significant wave height (m)	Mean period range (s)						
0.5	4	6	8	10	12	14	16
1.5	4	6	8	10	12		
2.5	4	6	8	10	12		

Results from each of the model runs were stored as ascii files of water depth, significant wave height (H_s), three different measures of mean wave period (T_{m01}, T_{m10}, and T_{m02}), peak wave period (T_p) and mean wave direction at each node of the computational grid.

For the demonstration, the 2D files were analysed at a site of interest offshore of Anchorsholme (329790 mE, 442310 mN), on the -2 mCD contour, to create the required look-up tables for use as input to the Monte Carlo simulation code.

2.6.3 Surf zone wave transformation

The main element of the surf zone transformation from the nearshore (SWAN model) point to the toe of the seawall is the representation of wave breaking using a well established formulation due to Goda. The method depends on foreshore steepness, wave steepness and, of course, water depth. The equations are detailed in Box 4.9 of *the Rock Manual* (CIRIA/CUR/CETMEF, 2007).

2.6.4 Monte Carlo simulations

The Monte Carlo simulations to incorporate uncertainties in various input parameters into the forecasts for Anchorsholme used the parameter settings listed in Tables 2.4a to 2.4c.

Table 2.4a Monte Carlo settings (normal distributions)

Parameter	**Distribution type**	**Mean**	**Standard deviation**
Wind-sea friction	Normal	0.067	0.01
Swell friction	Normal	0.038	0.01
SWAN mean period error	Normal	0 s	0.1 s
Beach normal	Normal	270 °N	5 °N
Beach slope	Normal	1:500	5
Toe depth	Normal	1.8 m	0.5 m
Sea depth	Normal	0 m	0.5 m
Crest level	Normal	7.8 m	0.21 m

Table 2.4b Monte Carlo settings (triangular distributions)

Parameter	Distribution type	Lower limit	Central	Upper limit
Roughness	Triangular	1	0.95	0.9

Table 2.4c Monte Carlo settings (overtopping rate formulation factors)

Parameter	Factor 1	Factor 1	Factor 1
Structure 1 factors	0.04406	0.06416	0.11811
Structure 2 factors	-53.204	-61.667	-75.133

The flood forecasting thresholds used, summarised in Table 2.5, are the same as used in NW Region TRITON. A structure length of 900 m, also as used in TRITON, was assumed in the overtopping volume calculations.

Table 2.5 Flood forecasting thresholds for Anchorsholme

Threshold names	Flood Watch Level	Flood Warning A	Flood Warning B
Sea level thresholds	8.1 mOD	9.5 mOD	9.7 mOD
Mean overtopping rate thresholds	0.2 l/s/m	20 l/s/m	50 l/s/m
Peak overtopping rate thresholds	30 l/m	3,000 l/m	4,000 l/m
Overtopping volume thresholds	1,500 m^3	100,000 m^3	250,000 m^3

2.6.5 Example Monte Carlo model output

Figures 2.12a to 2.12f provide example site-specific wind, offshore wave and water depth ensemble forecast graphs, and probabilistic nearshore wave and overtopping forecast graphs, for Anchorsholme, Blackpool, for 24-26 January 2008.

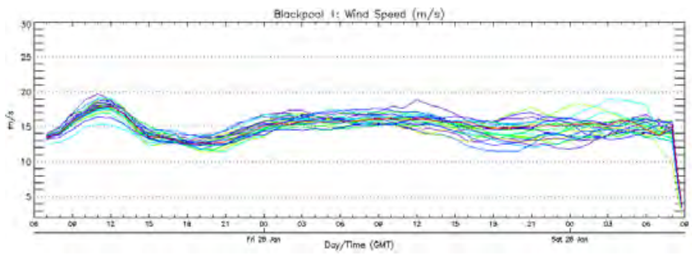

Figure 2.12a Ensemble wind speed

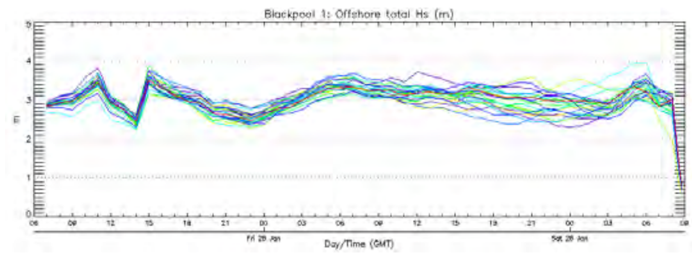

Figure 2.12b Ensemble offshore significant wave height

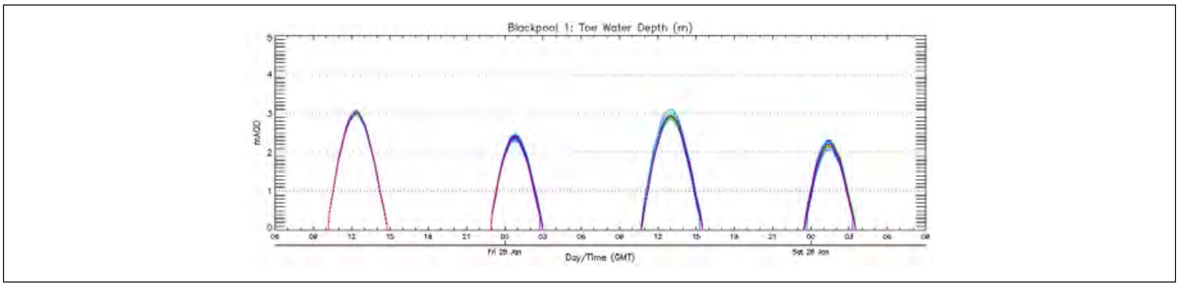

Figure 2.12c Ensemble seawall toe water depth

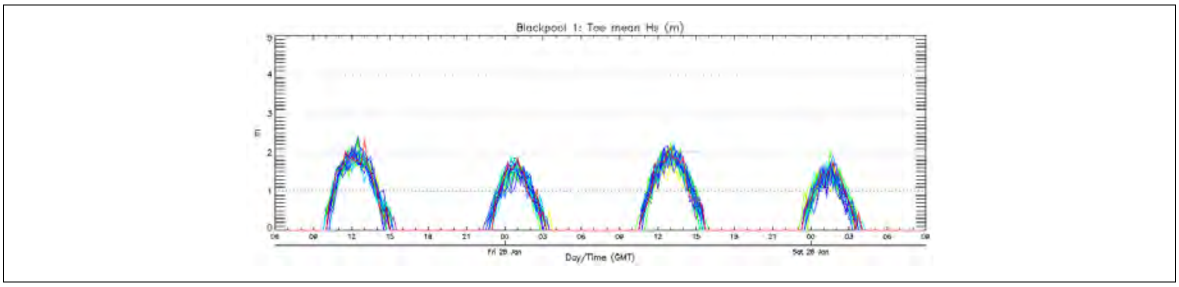

Figure 2.12d Probabilistic seawall toe significant wave height

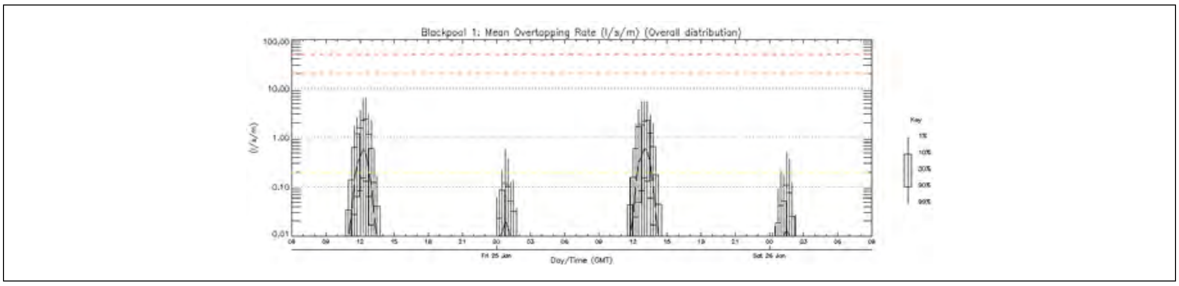

Figure 2.12e Probabilistic mean overtopping rate

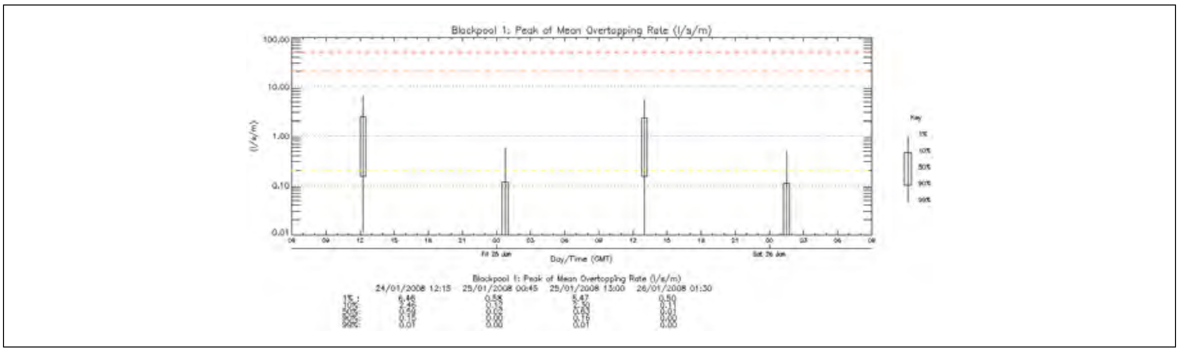

Figure 2.12f Peak values (per tide) of probabilistic mean overtopping rate

2.7 Field measurements

Overtopping and nearshore wave measurements were funded in this project, in support of verification of the coastal forecasts at Blackpool. Locations, photographs and results from the nearshore wave recording, at two locations off Anchorsholme, are given in Appendix 2. Photos and results from overtopping measurements at Anchorsholme are given in Appendix 3. Tide gauge measurements from Blackpool Pier are in Appendix 4. Other measurements obtained from existing sources, for use in verification, are sea level and surge data from other tide gauges, offshore wave data from Liverpool Bay, and observational data of winds and overtopping during stormy conditions.

3. Evaluation of surge and offshore wave ensemble forecasts

3.1 Surge ensemble verification

3.1.1 Introduction

This section evaluates the performance of the storm surge ensemble system, which predicts the difference between still water level and the harmonic tide prediction. The central aim is to quantify how well the forecast distribution of possible outcomes in each case matches the actual distribution of outcomes across many cases. An ideal ensemble system would be reliable (a match between the forecast and actual error distributions) and sharp (a narrow range of uncertainty in each situation). The error of any single forecast is not very informative, since it is only over many cases that the distribution of errors can be formed. Nonetheless, forecasters are presented with cases one at a time, and Section 3.1.2 provides examples from the East coast surge event of 9 November 2007. Section 3.1.3 describes a number of data issues affecting the statistical verification, and Section 3.1.4 demonstrates the dominance of meteorological uncertainty over other sources of error which the ensemble currently neglects. Section 3.1.5 examines the root mean square (rms) error of the surge forecast, and its variation with spread, lead time and forecast magnitude. The surge forecasting problem involves natural thresholds at which the potential damage due to an event increases sharply, and Section 3.1.6 evaluates the performance of the surge ensemble in predicting the probability of exceeding particular thresholds. Section 3.1.7 provides a more subjective evaluation of the usefulness of the system, based on feedback from forecasters. Section 3.1.8 examines the computational cost, timeliness and robustness of the system, whilst Section 3.1.9 summarises the steps which would be needed to make it operational. Conclusions and suggestions for future work are given in Section 3.1.10.

3.1.2 Case study: 9 November 2007

The potential for a storm surge on 8-9 November 2007, due to a deep low pressure system passing north of Scotland, was recognised several days in advance by long-range deterministic systems. Figure 3.1 shows the MOGREPS regional ensemble mean surface pressure and probability for winds over 50 knots for midnight on 9 November, at 42 hours lead. This led to high confidence of a significant event in the surge ensemble forecasts, with some members predicting surges of several metres at many locations along the East coast. The overall forecasting picture led to some evacuations, COBRA meetings, and significant media interest. The actual outcome involved some localised flooding, but in general a near miss without large-scale damage.

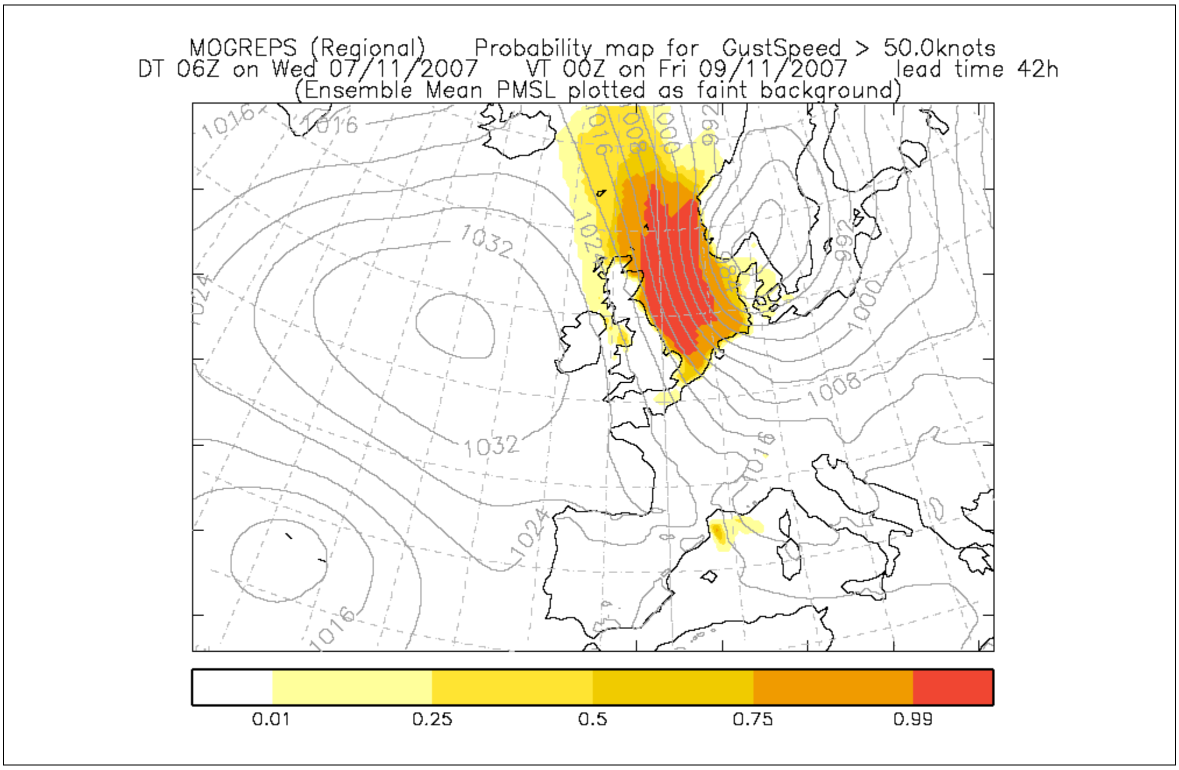

Figure 3.1 MOGREPS regional ensemble mean surface pressure and probability for winds over 50 knots for midnight 9 November 2007, from the 06Z forecast on 7 November

Figure 3.2 shows time series from the two earliest surge ensemble forecasts to include the East coast event. The ensemble forecast surges are shown in green, the deterministic forecast in orange, the alert level minus the harmonic tide prediction in red, and the observed surge (observations minus harmonic tide) in blue. In both cases, the observations lie within the range of the ensemble except for very short lead times, where the lack of allowance for initial condition uncertainty could start to be an issue. The strong signal of an abnormal event at the very end of the earlier forecast suggests there may be useful skill in longer forecasts if suitable driving data were available. The Immingham results show some significant departures from the deterministic forecast, where the observations rise more quickly and do not reproduce its final peak. The ensemble forecasts seem to fall into two subgroups, one rising early and staying high for longer, whilst the other rises later but to a higher single peak. This kind of bifurcation, if realistic, is exactly the sort of uncertainty that is much more readily predicted by an ensemble of fully dynamic forecasts than by climatological error statistics.

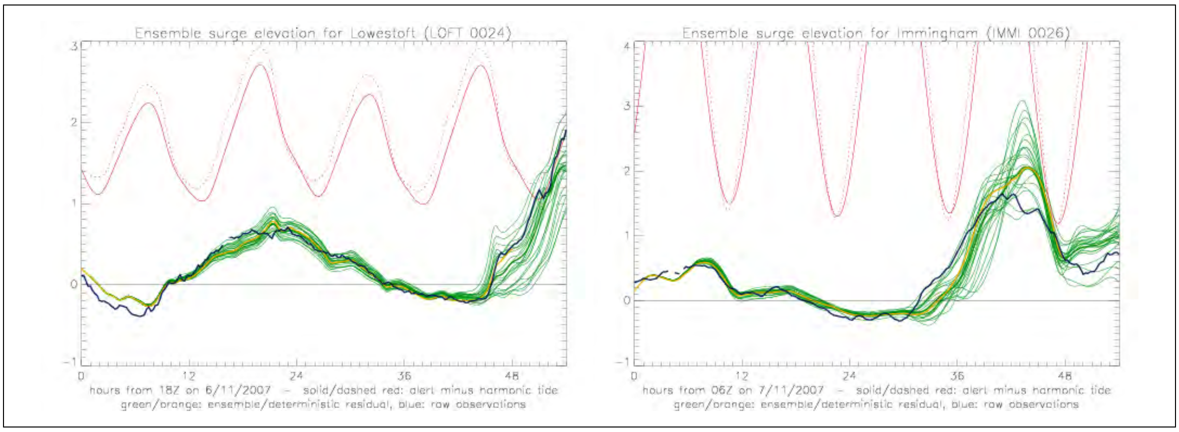

Figure 3.2 Surge ensemble forecasts for Lowestoft from 18Z on 6 November 2007 and Immingham from 06Z on 7 November 2007, with the deterministic forecast overlaid in orange and the observed surge in blue

3.1.3 Data issues

The primary data for evaluating the performance of the surge ensemble were tide gauge observations from 36 locations around the coast of the UK, as shown in Figure 3.3. Most of the results presented here combined results from all ports, to ensure maximum possible significance in the statistics and summarise behaviour across the range of local climatologies. The data period covered two winters, from the beginning of the surge ensemble forecast archive at 18Z on 4 December 2006 to the end of March 2008. During this time, there were regular updates to the driving MOGREPS atmospheric ensemble. There were also two significant changes to the surge ensemble system itself: the extension from 36 to 54-hour forecasts from 2 March 2007 and the move from CS3 to CS3X (which uses a larger domain to improve both tidal response and the far-field surge generation) on 16 March 2007.

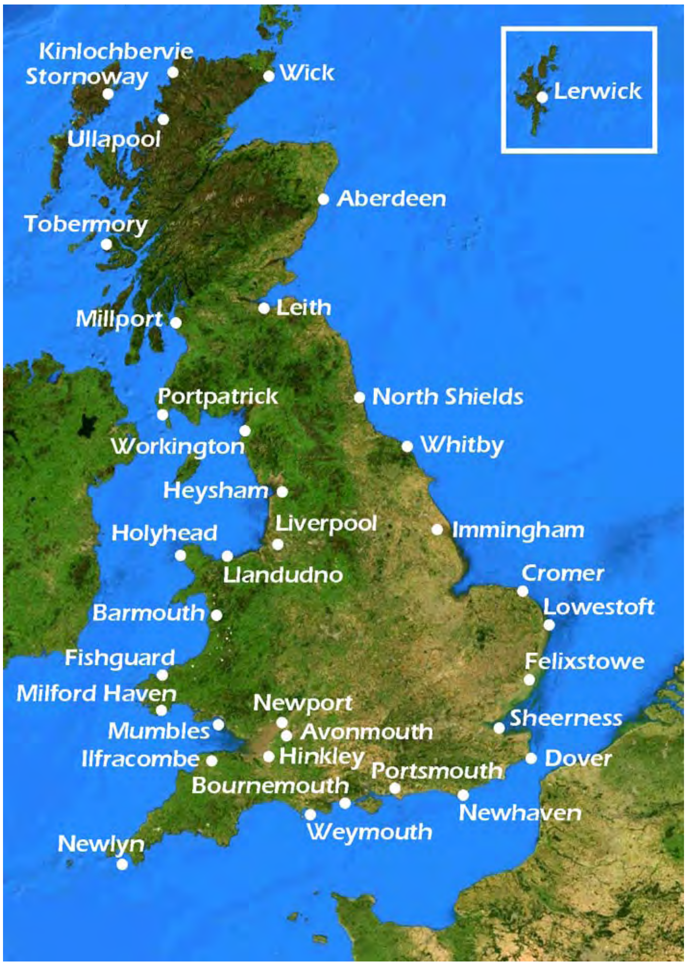

Figure 3.3 Locations of the 36 ports used for surge ensemble verification

There were two sources of tide gauge observations available to this project: raw observations downloaded monthly from the British Oceanographic Data Centre (BODC) website, and observations that were quality-controlled by BODC and provided by the Proudman Oceanographic Laboratory. Detailed examination uncovered problems with both datasets. The raw observations have occasional spurious values or exact zeroes. Each observation site actually has at least two independent sensors, and when one of these starts producing unrealistic values the raw observations have a tendency to report both results for a time, with no consistent order. The quality-controlled observations that were supplied, on the other hand, included several long periods of unrealistic values. Each observation set also contained a number of gaps where the other observation set appeared reasonable.

Subsequent analysis showed that whilst the underlying BODC quality control of each channel was performing effectively, the problems arose in the software that delivered a single quality-controlled time series for this project. The monthly validation of the deterministic model (see http://www.pol.ac.uk/ntslf/surgemonthlyplots.html) contains a manual step to choose the functional channel, if the primary channel is suspect. This step was not applied for the data supplied to validate the surge ensemble and as a consequence, some data from a bad channel were included. This validation exercise has highlighted the need to use data from both channels along with the corresponding quality control flags and merge them, but there has not been time to pursue this within this project.

To reduce the impact of all these issues on the verification statistics, a number of steps were taken. Some rudimentary quality control was implemented for the raw observations, including a filter that chooses from multiple observations for the same time step whichever surge most closely matches the preceding data. Remaining bad periods in each observation set were manually blacklisted. The final merged dataset was constructed using quality-controlled observations where available and not blacklisted, otherwise falling back to the raw observations where available and not rejected or blacklisted.

In order to relate the forecast surge to a total water level, it is necessary to add a harmonic tide prediction. This can involve significant error, particularly for the ports with the largest tidal range. Figure 3.4 shows surge forecasts and observations for Mumbles in the first half of June 2007. The forecasts and hindcast (in red) suggest a calm situation, but subtracting the harmonic tide prediction from the observations yields a significant residual oscillation (blue/cyan). The semi-diurnal pattern in the observed residual arises because of small errors in the predicted times of high and low waters (see Horsburgh and Wilson, 2007). The effect scales linearly with tidal range. A similar effect occurs on longer timescales as a month-to-month variation in bias between the forecast and observed residuals.

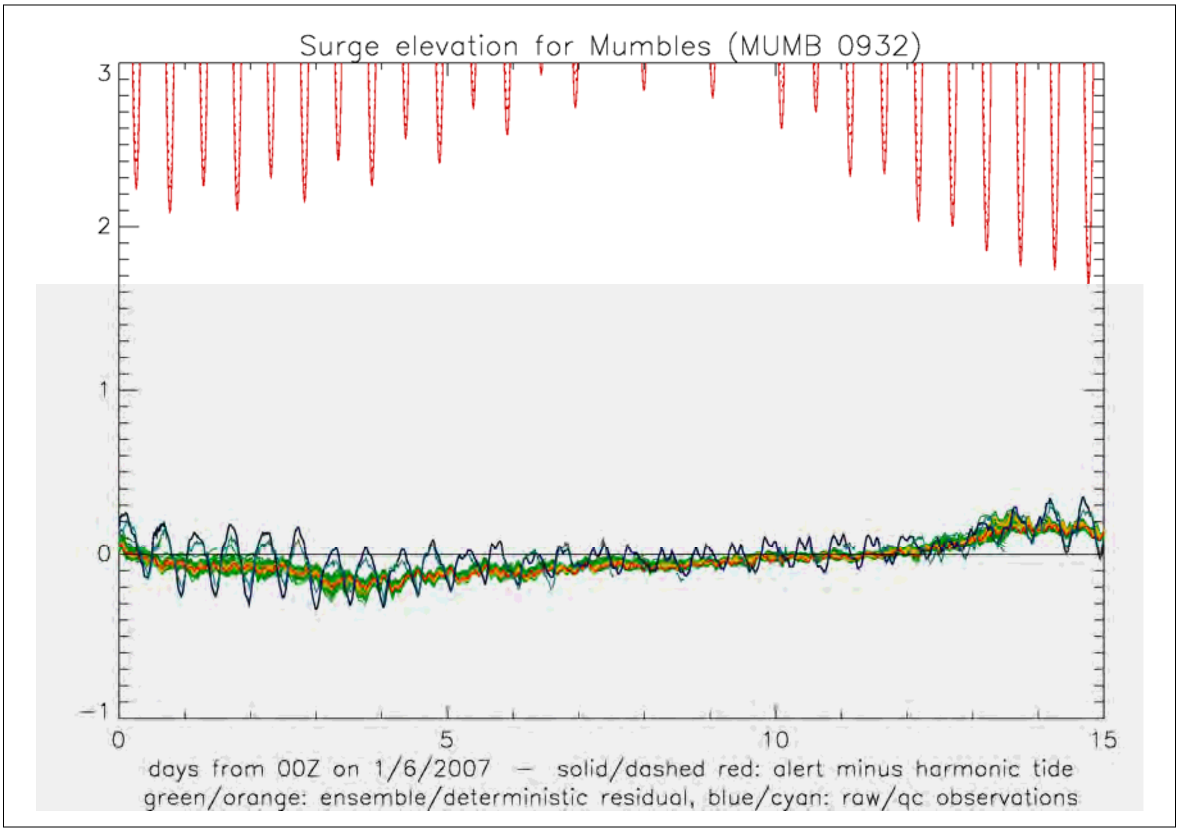

Figure 3.4 Observed (blue), forecast (green/orange) and hindcast (lower red) surges for the first half of June 2007. The hindcast surge comes from the surge model driven by analysed meteorology

With an observational time series, it is difficult to separate the error in the harmonic method from genuine surge (the effects of wind and atmospheric pressure on the sea surface). One can perform a harmonic analysis, and reconstruct the tide over that period, but the residual thus obtained combines surge, instrumental and harmonic errors. However, one can get some feel for the magnitude of the error in the harmonic analysis process by running a numerical model with no meteorological forcing. To quantify this, the CS3X model was run for the years 2004 and 2005 forced only by its tidal boundary conditions. On the basis of the 2004 output, a 50-constituent harmonic analysis was performed for all 44 port locations that make up the UK strategic tide gauge network. Using these constituents, the tide at every port was then predicted for 2005 and compared to the corresponding model output. The average rms error was seven cm, with a maximum value of 29 cm at Newport, in the Bristol Channel. This experiment is unrealistically noise free, and if one repeated the procedure adding some white noise to the 2004 output used for analysis (to represent the effect of weather on the basic process of harmonic analysis), harmonic prediction rms errors are of order 10 cm when averaged around the UK coastline. The fact that CS3X tide predictions are imperfect should not affect the validity of this conclusion, since it simply examines the ability of the harmonic method to reconstruct a tide-like time series.

The surge ensemble samples errors only from the driving meteorology. It cannot predict the component of rms difference from observations due to observation or harmonic tide error. From the point of view of surge, they are both observation errors, and the ensemble should not be penalised for not including them within its spread. For total water level predictions, the harmonic tide error is relevant, but will not be predicted by the surge ensemble. To the extent that surge forecast error increases with surge magnitude, whilst harmonic tide error remains the same, the latter will be more harmful to overall rms differences than to statistics that select only the large events.

As a further check on the impact of observation and harmonic tide issues, verification statistics were also calculated with respect to surge hindcasts (the output of the surge model forced by analysed meteorology). By comparing two model surge outputs, this method sidesteps the problems of observation quality control and harmonic analysis error. It provides complete data coverage for all ports, with much reduced noise, and should thus provide greater statistical significance and discrimination between systems. As with all verification against analyses, however, hindcasts lack the independence of true observations. In particular, they will fail to penalise systematic biases within the model, and will tend to underestimate the error at short lead times, because both forecast and hindcast start from the same state at the forecast data time.

3.1.4 Impact of neglected sources of uncertainty

The current surge ensemble system examined in this report assumes that the dominant source of error in storm surge forecasting is the driving meteorology. Each surge ensemble member is driven by a different atmospheric forecast, but they share the same initial state and surge model formulation. The neglect of initial condition error is likely to make the ensemble spread too small in the first few hours of the forecast, until the accumulated uncertainty from the driving meteorology becomes dominant.

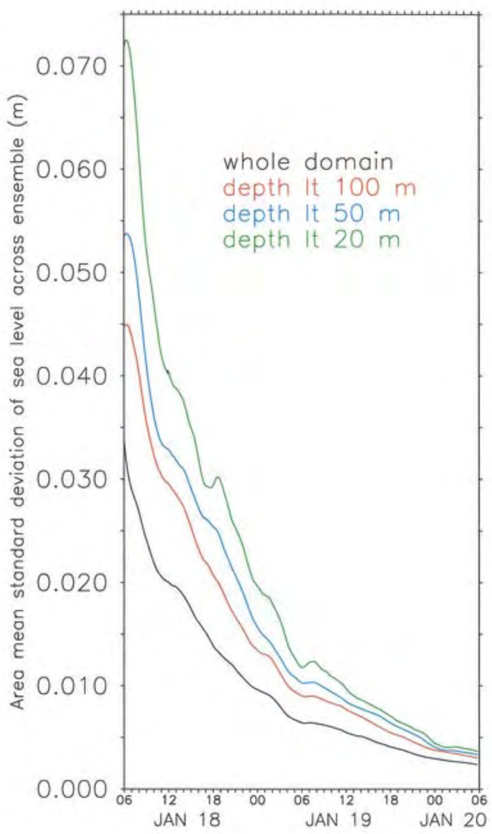

Figure 3.5 Decay of spread as a function of time from 06Z on 18 January 2007 when meteorological uncertainty is neglected, averaged over the whole CS3X domain (black line) or gridboxes with water depth less than 100 m (red), 50 m (blue) or 20 m (green)

A simple experiment was performed to demonstrate the sensitivity of the ensemble spread to the surge model initial condition. This focused on a large surge event in the Irish Sea, which was also significant in the North Sea. A 24-member run was performed with initial conditions taken from the surge ensemble members at 06Z on 18 January 2007, extracted from the run that began 12 hours before. The ensemble was integrated for 48 hours, using the meteorological forcing from just one atmospheric ensemble member for all of the surge ensemble members. This is the exact opposite of the standard surge ensemble, neglecting the uncertainty in meteorological forcing whilst sampling a range of initial conditions. The standard deviation of these runs decayed rapidly, halving within six hours. Even if one considers the effects in the model area where water depths are less than 20 m, the standard deviation dropped from seven cm to less than four cm in the first six hours. Although this experiment considered only a single event, it is very suggestive that model memory of surge initial conditions is rapidly lost during subsequent model runs, and that the variability of the subsequent meteorological forcing is far more significant. The effects of large changes in the frictional parameters of the surge model were also investigated and no significant impact found.

3.1.5 Spread/error statistics

Figure 3.6 presents statistics on the accuracy of different surge forecasts and the usefulness of the ensemble spread as a predictor of how that accuracy varies between different forecasting situations. Rms errors are shown for four types of forecast: the unperturbed ensemble control, the perturbed ensemble members, the mean of all ensemble members (including the control) and the existing deterministic surge forecast (which uses the same surge model driven by higher resolution meteorology). The forecasts were evaluated against the merged observation dataset described in the previous section, converted to an observed surge using the harmonic tide prediction. Each 15-minute time step was compared directly with the corresponding observation, and only time steps for which an observation and all forecasts were available were included. Results were aggregated across all ports, lead times and forecast magnitudes.

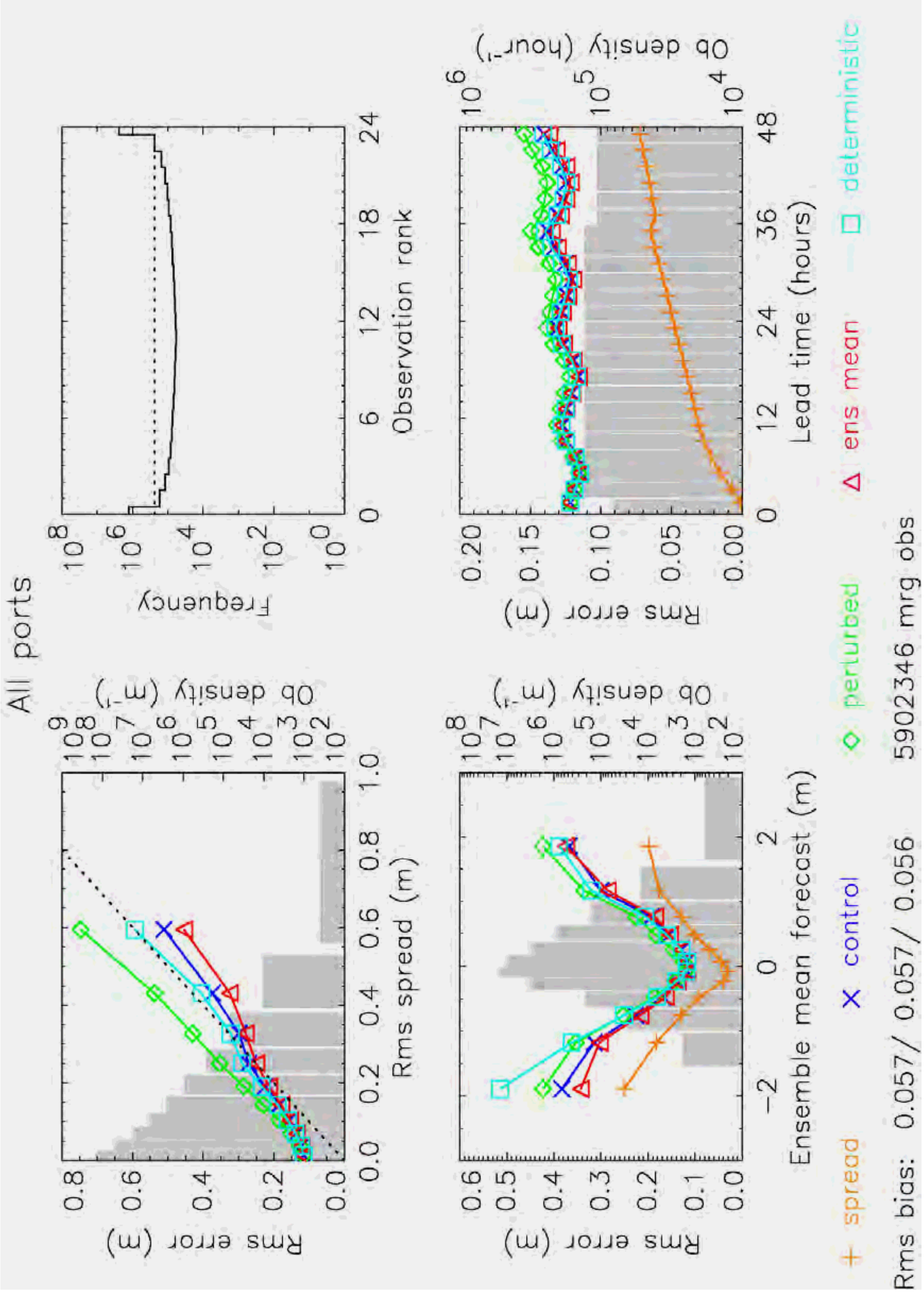

Figure 3.6 Variable statistics with respect to merged observations, showing rms error binned as a function of spread (top left), ensemble mean forecast (bottom left), and lead time (bottom right), for spread and each forecast type using the symbols shown in the legend. The grey histograms show observation density according to the scale on the right of each plot. The top right plot shows a histogram of the rank of each observation within the 24-member ensemble

The first plot shows the rms error of the four forecast types within bins defined by the ensemble spread. Throughout this document, spread is defined as the standard deviation of the ensemble forecasts, including the control. This divides the forecasts into groups for which the ensemble predicts different accuracies. If the ensemble members genuinely approximate random draws from the distribution of possible forecast errors, the two distributions should be identical. In particular, the rms spread should match the rms error on the ensemble mean (with a small correction arising from the rms difference between sample means from a finite ensemble and the true mean of the underlying distribution from which the ensemble members are drawn). The grey histogram shows the relative population of each bin, where a logarithmic vertical scale was used to better distinguish the smaller populations. Wider bins were used for the more extreme cases to boost the number of contributions and so reduce the effects of statistical noise.

The results show that spread is a fairly good predictor of the rms error across the cases where that spread is predicted, certainly a much better predictor than the overall rms error of 10-12 cm. A forecast 10 cm short of overtopping in such cases would have a much broader error distribution, and larger probability to overtop, than the 10 cm average error would suggest. In the most common situation of low spreads, there is an additional error of around 10 cm which the ensemble fails to predict. The lack of perturbations to the surge initial condition will contribute to this underestimate, but results restricted to lead times of 24-48 hours (not shown) show that this is not the main cause. Indeed, the value is consistent with the expected limits of accuracy of harmonic predictions described in Section 3.1.3.

As expected, the individual perturbed member forecasts have the largest error, since they are perturbed away from the best estimate of atmospheric state. Mathematically, their error is the sum in quadrature of the spread and ensemble mean error, so will always be greater than either of those quantities. The ensemble mean consistently has the lowest error, indicating that the sampling of uncertainty provided by the perturbed members allows it to produce a more accurate forecast on average than either unperturbed forecast. More surprisingly, the ensemble control exhibits a lower rms error than the deterministic forecast, even though the latter is based on higher resolution meteorology.

The top right plot shows a histogram of the rank of each observation within the forecast ensemble (including the control) for the corresponding time step. If the forecast and observed error distributions were identical, the result would be the dotted horizontal line. The ‘U’ shape, with almost an order of magnitude too many outliers, is a classic indication of insufficient spread. This is, again, largely the result of the unpredicted 10 cm error in the most common case of low ensemble spread and no significant surge.

The bottom left plot shows spread and error binned by ensemble mean forecast. This confirms the subjective impression that the spread and error are larger in cases where a larger surge is forecast. The partition shown in this plot is not identical to that provided by spread in the top left plot, since the range of spread values is smaller and they always significantly underestimate the error. The variation in rms error between bins shows that forecast magnitude is almost (but not quite) as discriminating a predictor of variations in error as the ensemble spread. This suggests that a deterministic forecast dressed with an error distribution that increases with forecast magnitude may provide almost as good an estimate of the probability of reaching a given threshold as the full ensemble. However, this plot has been conditioned on the ensemble mean, which is a better estimate of the most likely outcome than a single deterministic forecast.

The bottom right plot shows spread and error binned by forecast lead time. This is dominated by the normal cases of low ensemble spread and no significant surge. The ensemble variance (square of spread) increases approximately linearly with lead time, as would be expected for a random walk process. The forecast error increases much more slowly with lead time, being dominated by the initial 12 cm error. At least part of this error is due to the short and long-term harmonic tide artefacts identified in the previous section. If the five ports with the largest tidal range (and most evident observed surge oscillations) are excluded, the initial rms error drops to 10 cm (not shown). Removing port-specific biases further reduces it to 7-8 cm. The disparity in gradient between the spread and error curves is partly an artefact of plotting rms results rather than variances; the overall change in error variance is approximately equal to the square of the change in spread.

The oscillations in error as a function of lead time are seen much more strongly at individual ports (not shown) mostly with periods of about 12 hours. These reflect small errors in the primary harmonic tide coefficients, which cause a semi-diurnal residual. They are absent or greatly diminished when results are calculated with respect to hindcasts (Figure 3.7 below), where there is no need for a harmonic tide prediction.

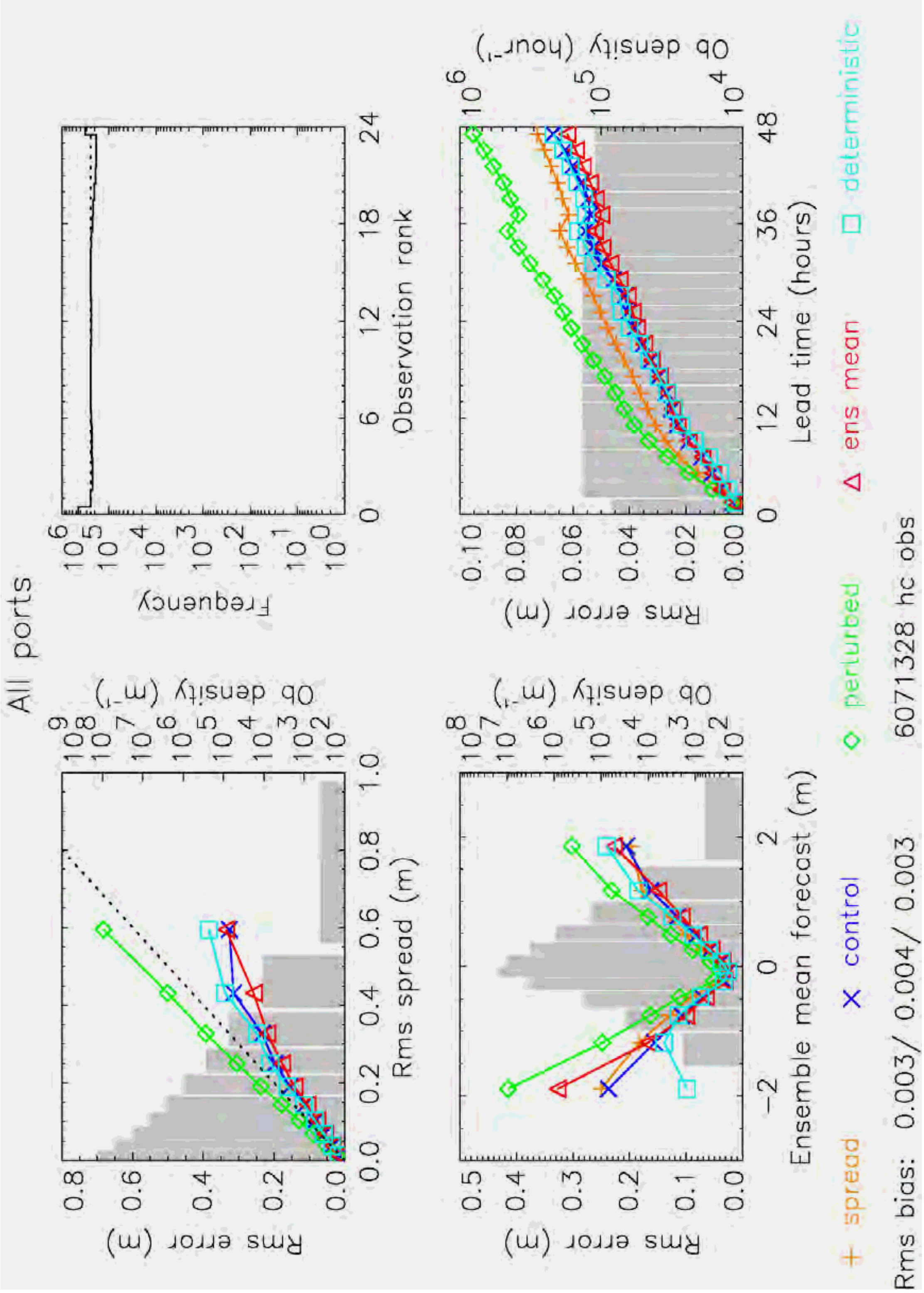

Figure 3.7 Variable statistics with respect to hindcasts, using the same format as Figure 3.6

Figure 3.7 shows the same statistics calculated using surge model hindcasts as the reference instead of observations. This eliminates errors in the harmonic tide, observations and surge model, focussing on the meteorological uncertainty (although systematic errors common to the meteorological analyses and forecasts will also be ignored). The residual error at low spread is largely eliminated, showing that situations in which the ensemble forecasts low spread genuinely have low meteorological uncertainty, and the error detected with respect to observations is due to one of the other causes. This result remains when lead times are restricted to 24-48 hours (not shown), suggesting it is not simply the result of the correlation between analysis and forecast errors at short lead time. The rank histogram is much flatter, though a few outliers remain. The rms spread tends to slightly over predict the error with respect to hindcasts, but this may simply reflect some of the genuine forecast errors which verification against hindcasts ignores. The error growth with time looks reasonable, the kink at 36 hours being due to the fact that forecasts before 2 March 2007 ran to only T+36 hours.

Figure 3.8 plots the overall rms error for each port and forecast type against the rms spread for that port. The results for any one port lie in a vertical stack with the port abbreviation attached to the topmost symbol. This highlights the geographical variation in error, and the extent to which the ensemble correctly samples that variation. As before, the perfect result would have rms spread equal to the rms error of the ensemble mean, so that the red triangles would lie on the dotted diagonal line. Against merged observations, there is just the suggestion of a relationship for the bulk of ports. The prominent outliers fall into two groups. Ports such as Whitby and Milford Haven have significant bias, which can be effectively removed by subtracting the average difference between forecast and observations over the previous 12 hours (not shown). The other ports, such as Avonmouth and Newport have the least accurate tidal predictions in absolute terms due to the large tidal range of the Severn Estuary. Against hindcasts, there is a much stronger relationship with near-zero intercept and gradient much closer to unity, showing that the ensemble has a much better understanding of this subset of errors.

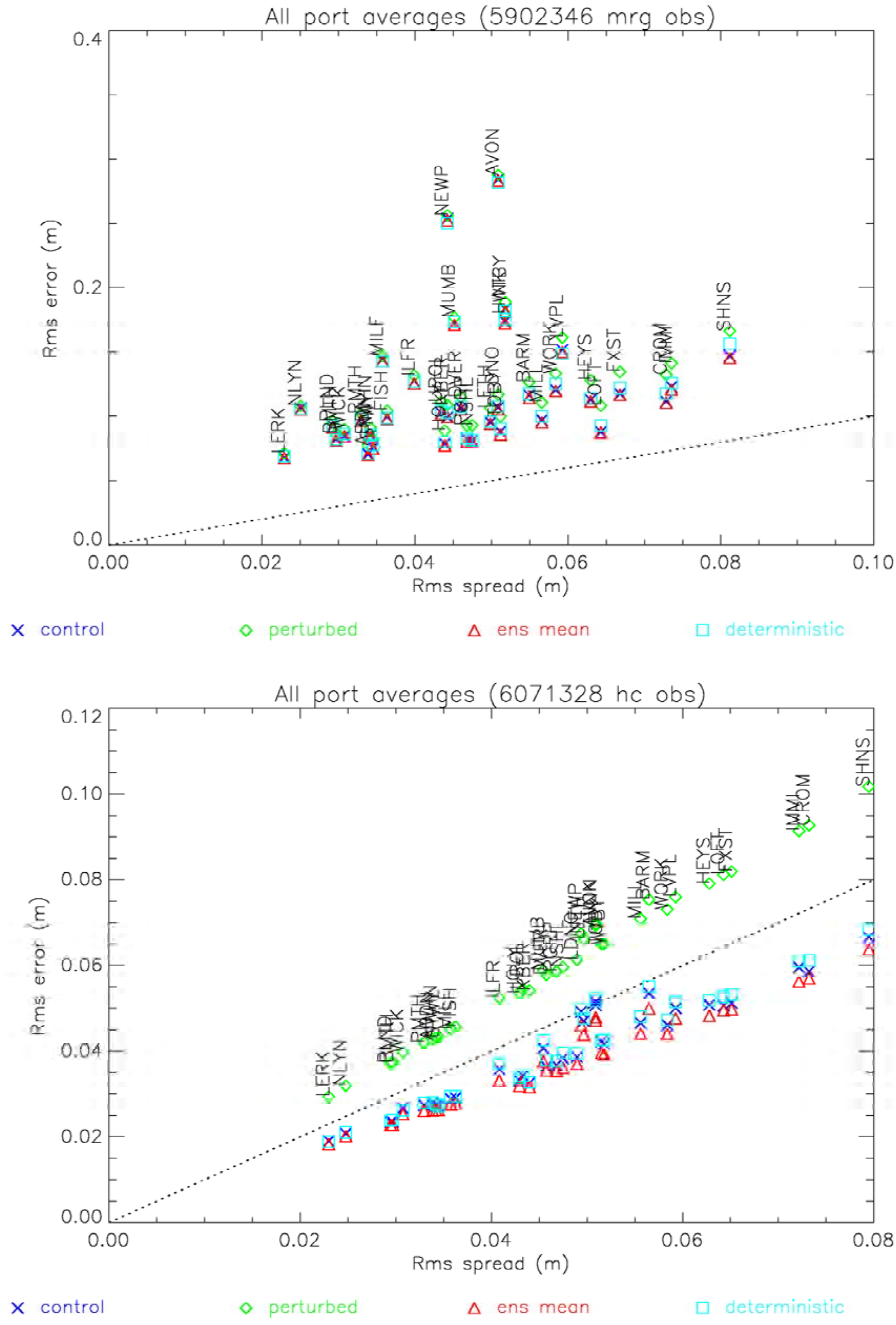

Figure 3.8 Scatter plot of rms error against rms spread for each port (denoted by four-letter abbreviations within the plot) and forecast type (denoted by plot symbol as indicated in the legend), compared against merged observations (top) and hindcasts (bottom)

3.1.6 Verification of threshold exceedence probabilities

Forecasting problems often end in the need to make yes/no decisions, and a large number of scores have been devised to compare different methods of making those decisions. An ensemble forecast for a single location and time period can be transformed into a yes/no answer by defining two thresholds: one on the underlying variable to specify the water level whose actual exceedence would justify protective action, and a second on the forecast probability of exceeding the first threshold, quantifying how certain one needs to be that this event will occur before action is cost-effective. For the simplest possible problem of a single binary decision based upon a reliable forecasting system, where action has a cost C and prevents a loss L if the event actually occurs, the long-term economically optimal probability threshold is equal to C/L, the cost-loss ratio (Richardson, 2000).

The verification presented here focuses on the events used to define the surge ensemble port risk bar charts. These events fall into three groups: surge above a threshold, surge below a threshold, and total water level minus alert level above a threshold. In each case, the events are defined over a series of 12-hour time windows, at six-hour intervals throughout the forecast. The event is defined to occur if the actual water level exceeds the threshold in at least one 15-minute time step within the 12-hour window. The ensemble forecast probability for the event is calculated as the fraction of members that exceed the threshold for at least one 15-minute time step within the 12-hour window. The use of a time window allows for some discrepancy between the forecast and observed timing of the maximum water level, allowing two ensemble members that forecast peaks at slightly different times to be recognised as giving a higher total probability for the threshold to be exceeded at some point within a given tidal cycle. It also means that thresholds on surge and total water level must be considered separately, because their maxima do not necessarily coincide.

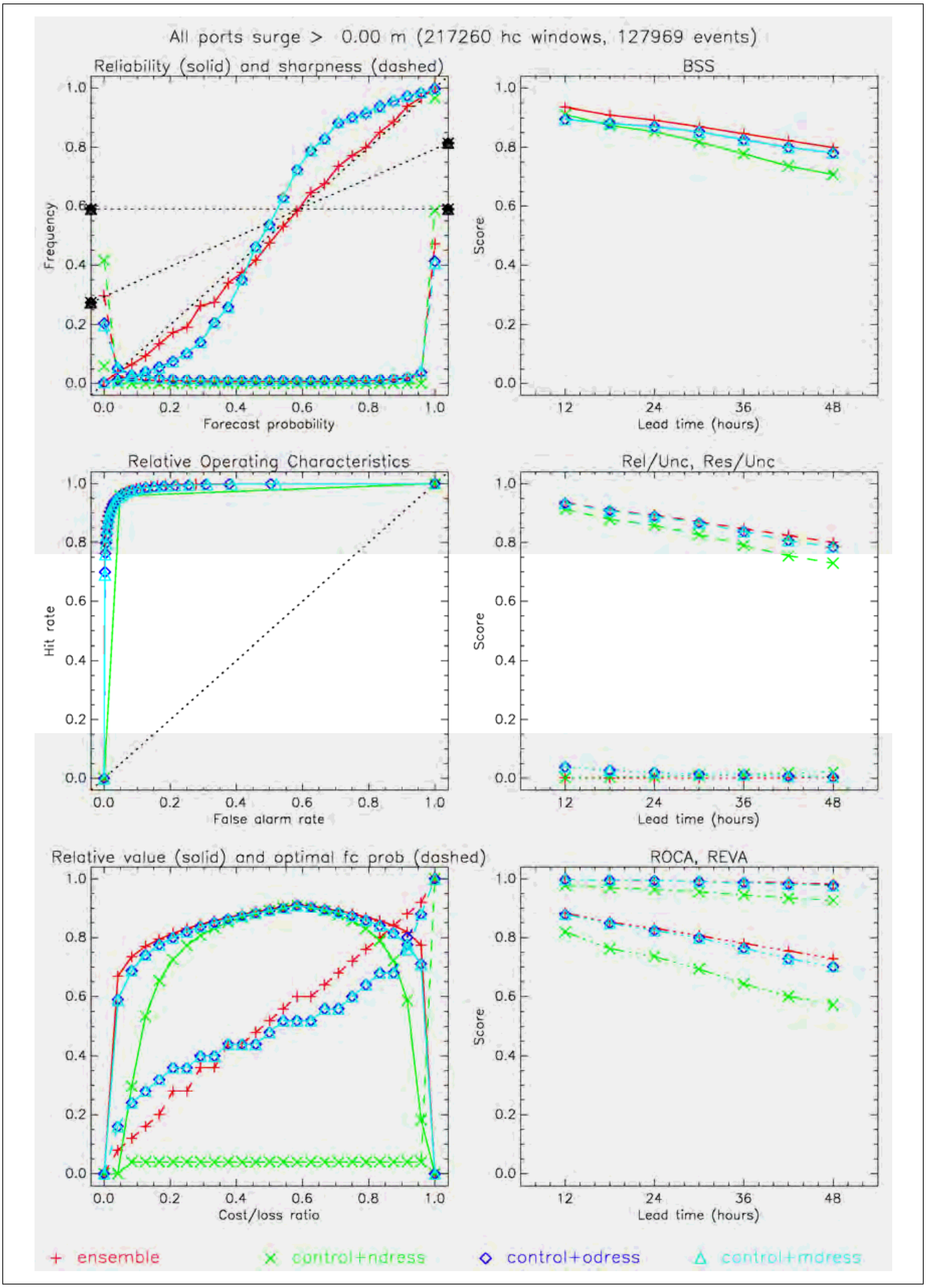

Figure 3.9 Probabilistic verification measures with respect to hindcasts for surge exceeding zero metres, for the ensemble (red plus signs), undressed control (green crosses), control dressed with fixed error distribution (blue diamonds) and control dressed with magnitude-related error distribution (cyan triangles). The right hand plots show Brier Skill Score (solid), normalised reliability penalty (dotted), normalised resolution (dashed), area beneath ROC curve (dot-dash) and area beneath REV curve (dot-dot-dot-dash) as a function of lead time window

Figure 3.9 presents a number of probabilistic verification measures for surge exceeding zero metres. This is generally irrelevant for civil protection, but it does illustrate the performance of the system under normal conditions and provides better statistical sampling than the more interesting rare events. These results have been calculated against hindcasts rather than observations because of the greatly reduced statistical noise. Corresponding results for observations will be briefly discussed at the end of this section and shown in Appendix 5. The plot title indicates the total number of time windows used (seven for each 54-hour forecast), and the number of windows in which the event occurred according to the reference dataset (hindcasts in this case). In verification against observations, only observed time steps are considered and windows with observations at fewer than 80 per cent of the time steps are excluded.

To put the ensemble performance in context, each plot shows four sets of results, distinguished by the symbols shown in the legend. The three comparison traces are all based on the ensemble control. Corresponding results can be calculated from the deterministic model, but as in the previous section, these tend to be very similar or slightly inferior to those from the control forecast, so have been omitted for clarity. The three comparison traces result from three basic ways to convert (dress) a deterministic forecast into a probabilistic one. The simplest of all (ndress) treats the deterministic forecast as having no error, giving a probability of one if the forecast is above the threshold and zero otherwise. The next (odress) assumes a constant Gaussian error distribution with standard deviation equal to the overall rms error of the forecasts (taken as four cm when verifying against hindcasts, 10 cm when verifying against observations). The forecast probability is then the fraction of this assumed distribution that lies above the threshold. As shown in the previous section, the actual error is strongly related to the magnitude of the forecast. The final method (mdress) consequently uses a Gaussian error distribution with standard deviation equal to sum in quadrature of the overall rms error and a percentage of the forecast magnitude derived from the results of the previous section (12.5 per cent when verifying against hindcasts, 20 per cent against observations). Comparison between these results and those of the ensemble should then demonstrate the degree of benefit obtained from the ensemble's dynamically forecast error distribution over a climatological relationship between error and forecast magnitude (mdress) over a simple constant error distribution (odress) over no error distribution at all (ndress). Note that none of the dressing parameters is port-specific, and each is applied only to the most extreme value forecast within each time window (the equivalent of assuming that ensemble members do not cross within a time window).

All of the plots show standard probabilistic verification measures, described in texts such as Wilks (2006). Those in the left-hand column decompose performance at each probability threshold, and use results aggregated from all observed time windows within each forecast. The right-hand column shows five scalar scores, related to the plots in the left-hand column, plotted as a function of lead time.

The reliability plot (top left) shows, for each forecast probability, how often the event actually occurred when that probability was forecast. Results for a perfectly reliable system (and an infinite number of forecast-observation pairs) would lie along the dashed diagonal from [0,0] to [1,1], indicating that when the system forecasts that the event will occur with probability p, it actually does occur on a fraction p of those occasions. For this event, the ensemble has excellent reliability, whilst the two nontrivial dressing methods both exhibit an 'S' shaped curve characteristic of overspread, indicating that forecasts for this threshold have errors below the overall rms error used in the dressing.

Reliability indicates how well the system understands its own uncertainty in each situation. This is clearly important for any use of the system, but can in principle be fixed by post-processing so long as the statistics do not change over time. A more fundamental attribute of system performance is the degree of its actual uncertainty – how well it distinguishes events from non-events. For a reliable system, this can be measured by sharpness (how often each probability value is issued), shown by the dotted lines towards the bottom of this plot. For two reliable systems, the one which issues more forecast probabilities near zero or one is preferable to one which issues more intermediate probabilities. A climatological forecast has perfect reliability but no sharpness, since it always issues the same probability equal to the climatological frequency of the event (marked by the dashed horizontal line across these plots). Sharpness without reliability, however, is misleading, since the forecast appears to have high confidence in its predictions, but they do not match up to reality. The appropriate measure of the underlying ability of an unreliable forecast to distinguish different classes of event is resolution, one of the scores plotted in the middle right plot, measuring the distance of each reliability point from the dashed horizontal line which represents the observed frequency. The perfect case, with points only at [0,0] and [1,1], has maximum resolution, whilst zero resolution arises if all points lie on the horizontal dashed line, indicating that the event frequency is completely independent of the forecast probability.

The middle left plot shows the relative operating characteristics that result from decisions made when the forecast probability exceeds each possible threshold, supplemented with the points at [1,1] and [0,0], representing always and never acting, respectively. For each decision threshold, the hit rate is the number of times action would be correctly taken divided by the number of actual events, whilst the false alarm rate is the number of times action would be needlessly taken divided by the number of non-events. A perfect system would have a hit rate of one (every event correctly forecast) and a false alarm rate of zero (no positive forecasts when the event does not occur). Adopting a low probability threshold (high willingness to act) will give a large number of hits at the expense of a large number of false alarms, but would be appropriate for users with a low cost/loss ratio, since false alarms cost them much less than misses. Conversely, a high probability threshold (low willingness to act) will give a lower number of false alarms at the expense of an increased number of misses, which would be appropriate if the cost of action were only slightly less than the scale of loss which it is able to prevent. The overall area under the ROC curve provides a second resolution-like measure, indicating how well the system is able to produce hits without also producing false alarms (in other words, to discriminate between events and non-events). In this case, all of the systems have strong discriminating capability, able to achieve high hit rates without very many false alarms, although the undressed control performs noticeably worse than the other methods.

The bottom left plot shows ROC information in an alternative form, indicating the long-term economic benefit of each forecasting system according to the simple cost/loss model introduced at the start of this section. Results are presented as a function of cost/loss ratio, so users with large potential losses (who should generally act at small forecast probabilities) fall to the left of the graph, whilst users for whom protective action costs almost as much as the loss it would prevent (who should only act at high forecast probabilities) fall towards the right. For each cost/loss ratio, the profit that would have resulted from acting at each probability threshold is calculated, based on forecast performance during the trial period. The probability threshold giving the largest profit is determined and plotted as the dotted line (from never acting as zero, through acting when one member forecasts the event, up to all members, and then always acting as one). For a reliable system, the optimal probability threshold would be equal to the user's cost/loss ratio, but for an unreliable system, this method identifies the maximum possible value that could be achieved with optimal post-processing. The solid line shows the corresponding profit, scaled so that zero represents the value of acting according to the climatological probability and one represents the profit that would result for perfect forecasts. In this case, the undressed control forecast performs worst, the two nontrivial dressings next best and the ensemble slightly better again, the differences being largest at low and high cost/loss ratios and smallest near the climatological frequency. The outermost points will always show no value, since C/L = 0 represents infinite loss (in which case you should always act) whilst C/L = 1 represents cost equal to loss (in which case there is no point acting).

The right-hand column collates scalar scores related to the other graphs, and plots them for each lead time window separately. The top right plot shows the Brier Skill Score, which is one measure of the overall accuracy of the forecast probabilities. It is a normalised version of the Brier Score, which simply measures the mean square difference between the forecast probability and the ‘observed probability’ (one if the event occurred, zero if it did not). The normalisation inverts the sense of this score and scales it so that the climatological probability has a BSS of zero and a perfect forecast (equal to the observed probability in each case) has a BSS of one. In this case, the skill decreases slightly with lead time, as would be expected. Once again, the ensemble scores slightly but consistently better than the two climatological dressings, which are in turn better than the undressed control.

The Brier Skill Score can be decomposed into reliability and resolution components, shown in the middle right plot. These are related to the mean square distance of the reliability curve in the top left plot from the diagonal and horizontal dashed lines respectively, weighted by the number of times each probability is forecast. As discussed above, this separates the intrinsic discriminating power of the system (resolution, dashed lines) from the numerical correctness of the forecast probabilities (reliability, dotted lines). Larger resolutions and lower reliability scores represent better systems. In this case, the ensemble has slightly better resolution than the nontrivial dressings towards the end of the forecast, and slightly better reliability towards the start, whilst the undressed control has lower resolution throughout.

The bottom right plot shows the area beneath the ROC and relative economic value curves. These highlight the poor performance of the undressed control, and the economic advantage of the ensemble over the dressed control forecasts at longer lead times.

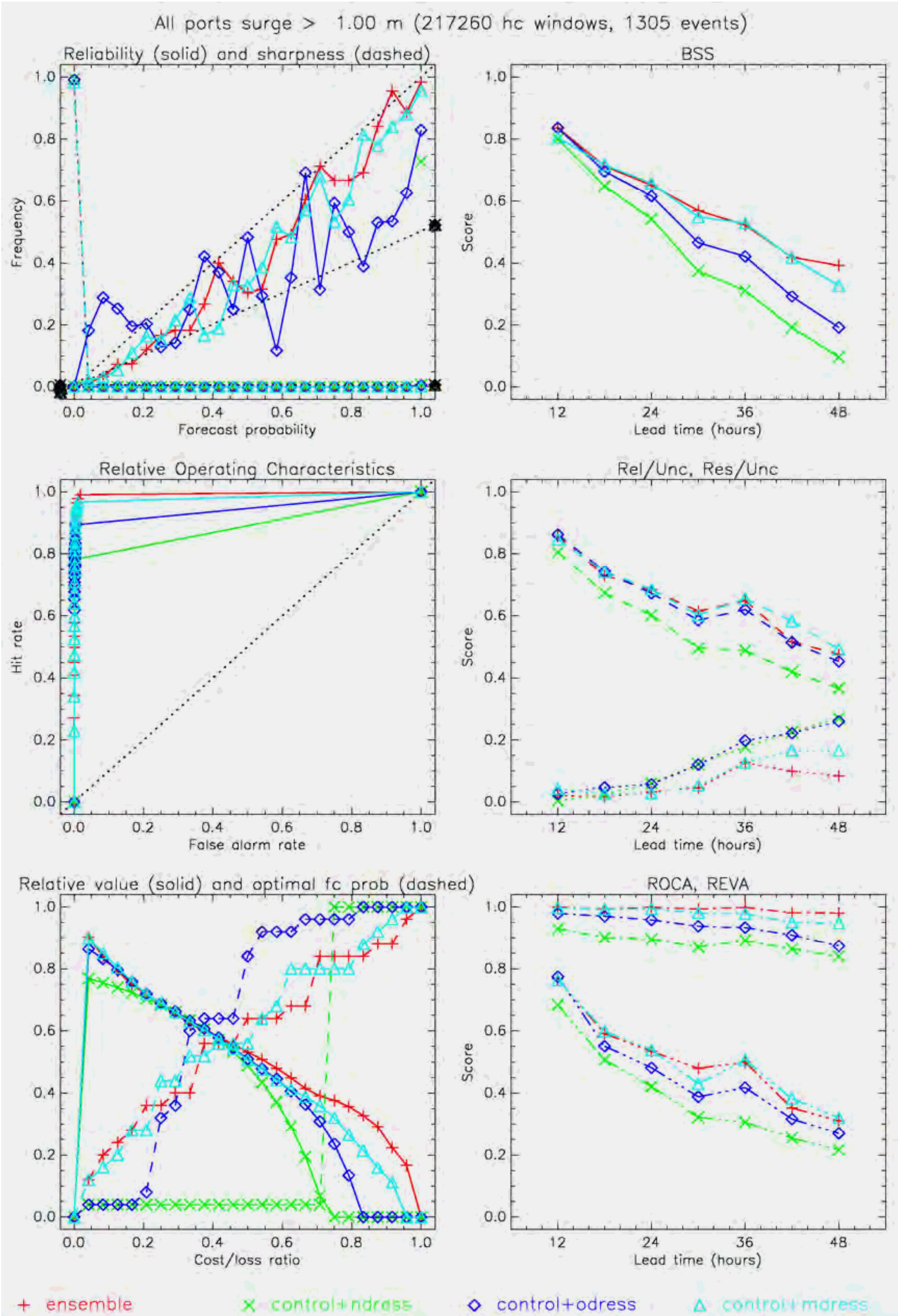

Figure 3.10 Probabilistic verification measures with respect to hindcasts for surge exceeding one metre, in the same format as Figure 3.9

Figure 3.10 shows the same verification measures for the much rarer event that surge exceeds one metre. The greatly reduced sample size is evident in the noise on the reliability diagram, but the ensemble remains the most reliable at long lead times. The magnitude-dressed control (mdress) is now more reliable than the climatological dressing (odress), since the event is sufficiently strong that the relevant error distribution is significantly wider than the climatological rms error. The ROC area has a clear preference for ensemble over mdress over odress over ndress, particularly at longer lead times. This difference comes from the lowest probability threshold, where a sufficiently wide forecast error distribution significantly improves the hit rate, benefiting users at low cost/loss ratio. The false alarm rate remains low because the event is rare, even when the climatological distribution is broadened by the forecast error distribution. By contrast, the most visible economic benefit of the better forecasts is to users with high cost/loss ratios, presumably due to a reduction in false alarms which does not show up on the ROC curve due to the very large number of non-events.

The overall Brier skill of the forecasts decreases much more rapidly with lead time than was the case for surge exceeding zero metres, but remains positive, indicating a better forecast than the climatological probability. The trend in skill is mostly due to a drop in the ability to distinguish events from non-events (resolution), although reliability also worsens in the second forecast day. On this measure, the ensemble and mdress have jointly the best skill, ahead of odress which is in turn ahead of the undressed control. Extrapolating the Brier skill for the best forecasts suggests they would beat climatology for about one further day if the forecast length were extended.

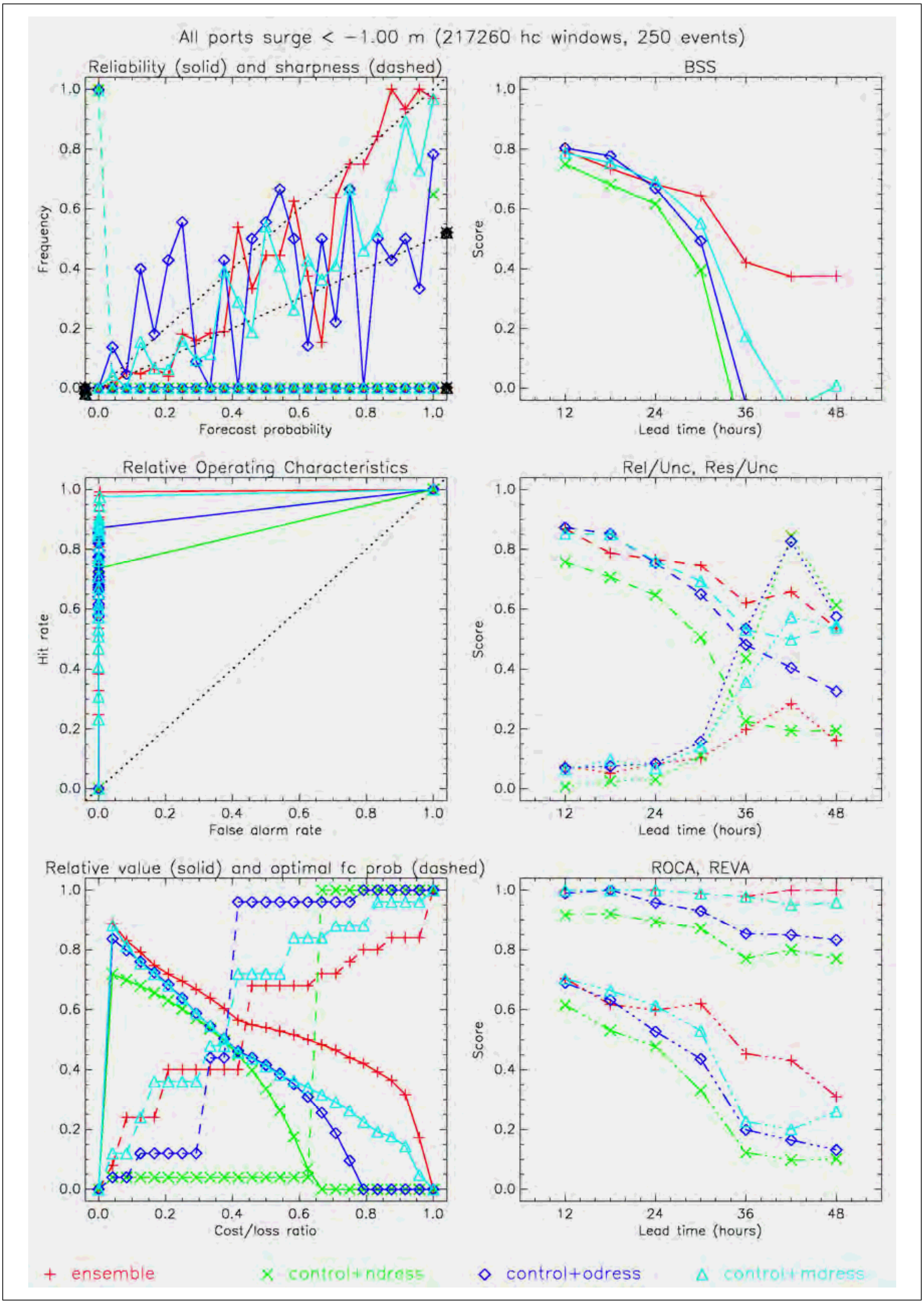

Figure 3.11 Probabilistic verification measures with respect to hindcasts for surge below -1.00 metres, in the same format as Figure 3.9

Figure 3.11 shows the same verification measures for the still rarer event of a one metre negative surge. This event is relevant for shipping, and also explores forecast performance in a different physical regime. The advantage of the ensemble's dynamic prediction of uncertainty over the statistical methods is particularly clear, with larger economic value at almost all cost/loss ratios. The drop in the Brier score of the statistical methods in day two is particularly noticeable, with the two simpler methods producing a worse forecast than climatology from T+36 hours. The decline in Brier score of the ensemble is much less pronounced, thanks to a slower decline in both reliability and resolution. As before, the order of preference between the statistical methods is generally magnitude-based dressing better than climatological dressing better than no dressing, as expected.

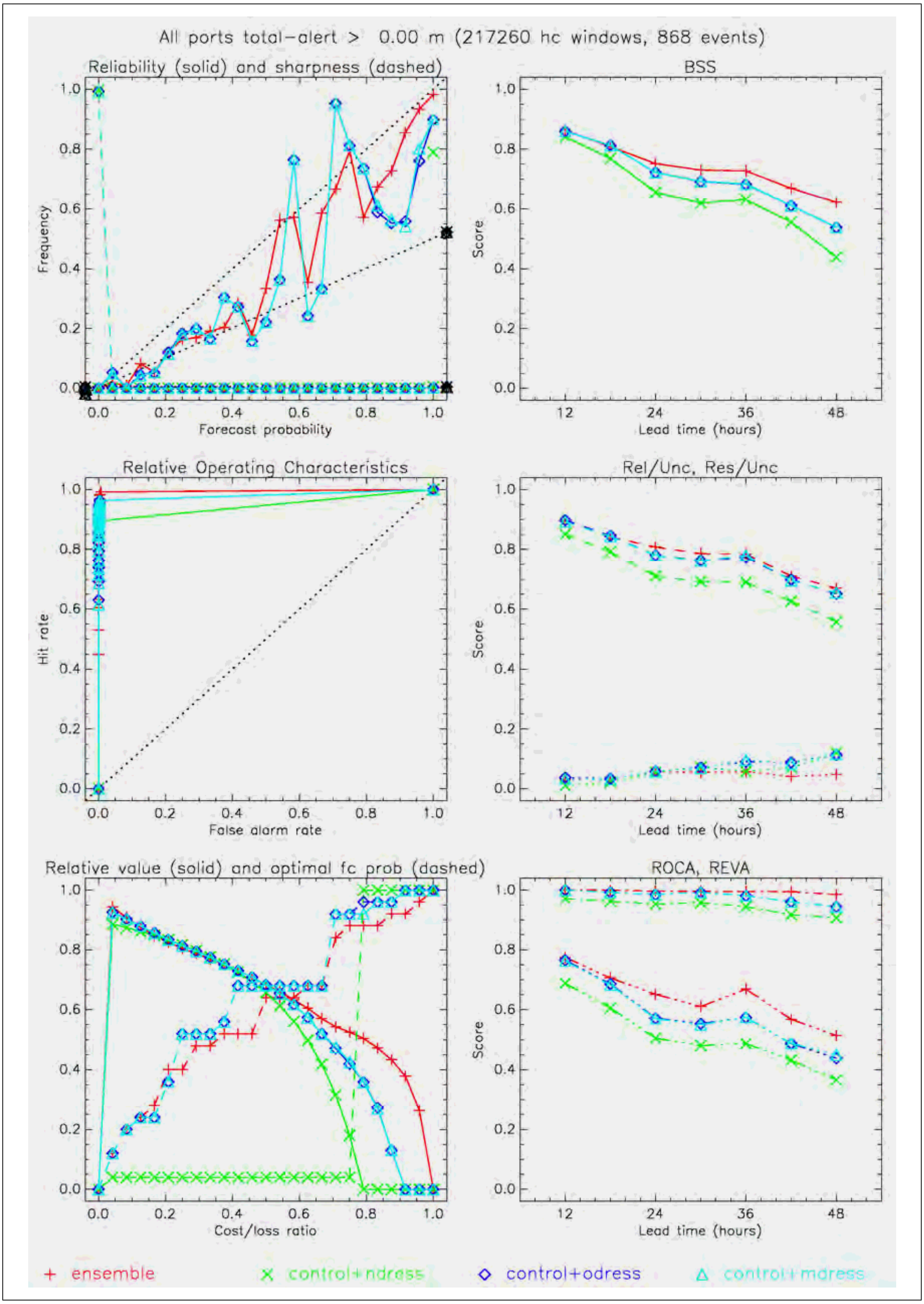

Figure 3.12 Probabilistic verification measures with respect to hindcasts for total water exceeding alert level, in the same format as Figure 3.9

Finally, Figure 3.12 presents the probabilistic verification for total water level (adding the harmonic tide to both the forecasts and verifying hindcasts) to exceed the port-specific alert level. In this case, there is little to choose between the two dressing methods, perhaps due to the lower surge magnitude required at times of high tide. At high cost/loss ratio, there is a clear advantage from the ensemble over the dressed control over the undressed control. The same ordering is just discernable at low cost/loss ratio. The ensemble consistently possesses the highest ROC area and Brier score, particularly at longer lead times. The skill of all methods declines rather slowly with lead time, somewhere between the gradient for zero and one metre surges. Linear extrapolation suggests the ensemble may have skill over the climatological forecast out to about six days if the lead time range were extended.

In summary, verified against hindcasts, the dynamic uncertainty forecast provided by the ensemble is almost uniformly superior to the dressed control forecasts, particularly for larger thresholds, longer lead times and high cost/loss ratios. The contribution of increased errors on larger surges is shown by the slight advantage of magnitude-based dressing over climatological dressing in these cases. In all situations, the undressed control forecast (where the forecast probability jumps from zero to one as the control forecast crosses the threshold) performs worst of the four methods considered.

The same verification results can be calculated with respect to observations, but the comparison is much less clear cut. Results for the four thresholds considered above are shown in Appendix 5. To reduce the effects of low-frequency bias, the average difference between hindcasts and observations over the 12 hours prior to data time has been subtracted from each forecast. As discussed in Section 3.1.3, this bias is thought to be mostly due to low-frequency errors in the harmonic tide prediction, rather than a problem with the forecasts themselves. Nevertheless, the use of forward extrapolation only (rather than taking advantage of observations after data time) means this correction scheme could in principle be used in forecast mode to achieve the levels of skill demonstrated here. The evolving bias estimate is also able to remove somewhat more low-frequency error than simply subtracting the average bias over the whole trial period.

The probabilistic performance of the raw ensemble against observations (not shown) is sometimes inferior to the dressed control forecasts, particularly for thresholds involving little or no surge, or low probabilities of stronger surges. These situations correspond to the insufficient spread at short lead times, small surges and low spreads, identified in Section 3.1.5 and thought to arise from issues such as the error of the harmonic tide prediction, which the ensemble does not sample. To allow for these unsimulated errors, the ‘odress’ method described above for the control forecast was also applied to each ensemble member to produce the results shown in Appendix 5. This allows the ensemble to give a dynamic prediction of the errors it can simulate, whilst the dressing provides a climatological addition to cover the errors which the ensemble does not sample (and which are not removed by the online bias correction). This dressing could also be applied in forecast mode when producing probability products such as the port risk bar charts. The resulting ensemble performance is generally comparable with the dressing methods, and retains an advantage in some cases. In all cases, the undressed control performs significantly worse than all other methods, since it makes no allowance for forecast error. All of the scores are worse than those calculated with respect to hindcasts, although the forecasts do still beat the overall climatology.

3.1.7 User feedback

To complement the statistical verification, and provide a view on forecasting process and presentation aspects, an email-based survey was sent to users of the surge ensemble system. The questions covered the user’s responsibilities, time spent using the system, usefulness of the various outputs, the decision-making process, and suggestions for improvement. Responses were received from two Met Office forecasters and five Environment Agency regions.

All of the respondents indicated that they looked at the surge forecasts only when some external factor (high tides, strong low-pressure system, warning or query from another agency) suggested that an event might be likely. Environment Agency forecasters focused on a particular region, and several requested the ability to zoom animations or filter plots to focus on their region of interest. One Environment Agency forecaster seemed to be unaware that the surge ensemble demonstration covered sites all round the UK coast, not just the Liverpool site used for the nearshore and overtopping demonstration. One of the Met Office forecasters noted that putting almost all the output of a run on a single page made it slow to load, particularly over dial-up connections when sited in an emergency control centre.

Most forecasters made greatest use and were most confident with the port time series charts, exploring the range of uncertainty at a particular location in a familiar format. One Environment Agency region requested that the time series show total water level rather than surge and tide separately. Another had difficulty reading precise water levels from the axes, and suggested the numerical values could be displayed as the mouse was moved over the graph. Most users were less clear about the meaning of the port risk bar charts, which is unfortunate given that in theory they encapsulate precisely the probability which the user is trying to evaluate. Several users requested the ability to step, pause and rewind the animations. Almost all users found the postage stamps of very little use, and too small to see any significant detail.

Almost all respondents highlighted the need for further help pages. A few requested information on the accuracy of the system. Environment Agency forecasters highlighted the different terminology used by the two organisations and the need to provide a translation between them. The main Met Office respondent suggested that a short training course might help the Public Weather Service advisors to get further benefit out of the system.

Some responses showed a marked difference between Met Office and Environment Agency forecasters. There were several suggestions that the Met Office should do the main assessment of uncertainty, although one Environment Agency region did suggest that ensembles gave more opportunity than the deterministic forecast for the duty officer to add value. The main Met Office respondent said the system was a “fantastic tool” for assessing uncertainty, that it appeared to represent the uncertainty “very well”, that they had “a lot of confidence” in the system, and that it provided a valuable reference when briefing others. Several Environment Agency respondents made reference to the importance of uncertainty in proximity to warning levels, and to provide worst case scenarios, but there were also comments such as “I want the forecast to be accurate, not the uncertainty” and a suggestion that uncertainty information only made the decision-making process more difficult. Several also highlighted alternative methods of assessing uncertainty, such as past performance of the model at high water or when conditions were similar. These methods bear some similarity to the magnitude-based dressing considered in Section 3.1.6, which the ensemble tended to outperform at longer lead times. It is possible that some of these differences in perception reflect the Met Office forecasters’ greater familiarity with ensemble weather products, in which case the Environment Agency forecasters may benefit from a suitable training module.

The respondents indicated that greatest forecasting focus was placed on the next one or two tidal cycles, extending out to a couple of days before weekends. Warnings were issued only in the 12-36 hour range. Apart from some pressured cases focussing on the current tidal cycle, the delayed availability of the ensemble products compared to the deterministic forecast was not seen as a major problem, provided the deterministic forecast also remained available. Environment Agency forecasters saw some possible value in a five-day outlook, particularly during periods of high tide, but nothing beyond that. The main Met Office respondent, on the other hand, saw significant potential in

6-10 day forecasts, following experience with the oil industry. He suggested that advance notice to appropriate authorities, even at low confidence, could provide an opportunity to review contingency plans, staff availability, and check stocks of materials such as sandbags.

3.1.8 Cost, timeliness and robustness

The storm surge ensemble forecasts for this demonstration project were run across four processors on one SX-6 node under a non-operational account. Table 3.1 shows the mean and standard deviation of the cpu time, elapsed time, and completion time (hours from data time) for the three configurations used during the trial period.

Table 3.1 Summary of cpu time, elapsed time and completion time for the surge ensemble forecasts

	36h CS3	**54h CS3**	**54h CS3X**
Number of runs	152	28	750
Cpu time (mins)	9.5 ± 0.5	13.7 ± 0.6	24.6 ± 2.4
Elapsed time (mins)	11.8 ± 7.9	14.8 ± 3.0	20.2 ± 10.0
Completion time (hours from data time)	5.6 ± 0.8	6.3 ± 1.0	5.9 ± 0.9

The extension from 36 to 54 hours increased costs by somewhat less than the 50 per cent increase in forecast length. The extended domain of CS3X increased cpu cost by 80 per cent but added only 36 per cent to elapsed time. Elapsed time is much more variable than cpu time, due to variations in the load on the rest of the node, network and disks. About two-thirds of the elapsed time of the forecasts is spent in the 'residual calculation program' rather than the surge model itself. This converts the surge model output into fieldsfile format, which is required for downstream wave and overtopping models, but not the current surge ensemble graphics generation. Following on from the MOGREPS regional atmospheric ensemble, the supercomputer component of the surge ensemble system completed about six hours after data time, with a standard deviation of one hour arising from operational problems, parallel suites, maintenance work and so on. Following this, data copying and graphics generation on a 2.66 MHz Intel Xeon took an average of 14 minutes, with a standard deviation of four minutes arising from variable load on the system and network.

The output data from the surge ensemble currently consume 4.6 GB per run, dominated by 3.3 GB of raw output files and 1.2 GB of equivalent fieldsfiles produced by the residual calculation program. The raw output files are copied to the graphics generation machine, along with 1.2 GB of equivalent output from the four most recent deterministic runs. The graphics output directory for each run consumes about 9 MB, dominated by the postage stamp animation (2.3 MB) and spread animation (1.9 MB). The probability animations each consume about 0.5 MB under normal conditions, rising slightly in nontrivial situations where they have significant evolving detail. The size of the animation files could be reduced by increasing the frame interval from one to three hours, although if this were done the plot should be changed to show the probability of reaching the threshold at any point within each three-hour period to avoid missing the peak water level.

The final archive of forecasts is missing 27 out of 967 runs between 18Z on 4 December 2006 and the end of March 2008. This 2.8 per cent loss rate is very low considering that the demonstration was running on non-operational systems without full time support. Causes of failure included missing input data from the deterministic surge model, failure of the atmospheric ensemble, planned supercomputer maintenance, resilience tests or parallel suites, problems with the batch queuing and hook job systems, operator error, disk space exhaustion, and the need for a new set of harmonic tide files at the start of each year. In most cases where input data were still available, the surge ensemble forecasts and/or graphics generation were rerun as appropriate. A fully operational service, running in a protected environment with 24 hour support would experience fewer failures and quicker resolution of those which did occur.

3.1.9 Steps to make the system operational

A separate quote has been supplied to the Environment Agency for operational implementation of the surge ensemble, and it is not the place of this document to provide detailed estimates or costings. The simplest implementation would translate the current demonstration system into a fully supported and resilient operational environment, providing the current set of images through a Met Office-hosted website. Further work may be required to re-engineer the system to fit Met Office IT Architecture requirements or provide new or improved graphics. Intellectual property rights, licensing and fees would need to be clarified early in the process. Any implementation would also need to provide for ongoing system monitoring and verification, as well as appropriate training for Met Office and Environment Agency forecasters.

Beyond images, the Environment Agency would wish to receive some of the underlying data for ingestion into NFFS, to be integrated into their standard display systems and used by downstream models. Port time series might be provided in XML format, such as was sent to HR Wallingford during this project. Further work would be needed if the Environment Agency wanted to receive full two-dimensional fields, providing at each point either the forecast from each ensemble member or summary statistics such as the mean and spread. GRIB2 format would be particularly suited to transfer of full ensemble fields, although support for this format is not yet well developed. Data volume would be a significant concern with this latter proposal, noting the above total of 3.3 GB per run for uncompressed full field output from all ensemble members at 15-minute intervals. It would also be important to design the data interchange format in such a way that changes to the Met Office production process, model resolution, number of ensemble members and so on would not automatically require corresponding work to be undertaken on Environment Agency systems.

The Met Office currently provides a tidal outlook guidance product based solely on the deterministic surge forecast. To take full advantage of Met Office forecaster expertise, it may be beneficial to consider whether this could be supplemented or replaced by a product that also took account of ensemble information and output from other models.

3.1.10 Summary and conclusions

An ensemble forecast aims to improve decision making by providing an explicit estimate of the probability distribution function (PDF) of possible outcomes, given the uncertainties specific to each particular forecast. Ensemble verification requires comparison of these PDFs with the actual distribution of forecast errors across a large number of cases.

Section 3.1.2 examined surge ensemble forecasts of the 9 November 2007 event. The ensemble provided an unambiguous signal of an abnormal event at the full extent of its 54-hour lead time range. The predicted range of uncertainty gave forecasters more confidence in the spread of possible outcomes, and encompassed the observations even though these sometimes differed significantly from the deterministic forecast.

Statistical comparison with observations is complicated by any deficiencies in observation quality control, and also by errors inherent to the method of harmonic analysis. This project has highlighted the need for careful quality control on the data used to validate ensemble forecasting systems. Section 3.1.3 described the steps taken to clean up and merge the raw and quality-controlled datasets to optimise data coverage and accuracy. Verification against hindcasts (surge model output for analysed meteorology) was also used to provide a complementary view of forecast accuracy, free of observational issues though not as independent from the forecasts themselves.

Section 3.1.4 examined the impact of errors which the surge ensemble currently neglects. Large changes to frictional parameters within the surge model were found to have no significant effect. Initial condition uncertainty, even starting within a significant surge event, was rapidly damped with a half-life of six to 12 hours. Methods to allow for initial condition uncertainty would need to estimate, implicitly or explicitly, the reduction in uncertainty due to the extra twelve hours of data incorporated into the meteorological analyses used to drive the hindcasts, which produce the new initial state for each successive surge ensemble forecast. Whilst this should improve the spread/skill relationship at short lead times, the impact may be negligible by the time forecast outputs are actually available.

Section 3.1.5 examined the rms error of the different forecasts, and the accuracy of ensemble spread as a predictor of that error. The higher resolution meteorology of the deterministic forecast gives it the lowest rms error with respect to hindcasts for about the first 18 hours, but the ensemble mean has the advantage at longer lead times due to its sampling of the full range of uncertainty. For reasons that are not entirely clear, the deterministic forecast is also beaten by the ensemble control at longer lead times, despite the fact that this forecast is based on lower resolution (though still unperturbed) meteorology.

The ensemble spread is a good predictor of the rms error of the ensemble mean across cases where that spread is predicted. Much of the variation in error can also be related to the magnitude of the forecast surge, although this requires suitable data for calibration and lacks the generality of an explicit ensemble forecast. All of the forecasts have a residual error of about 12 cm with respect to observations in situations where the ensemble predicts low spread. There are strong suggestions that this is largely due to problems with the harmonic tide prediction, since the error can be reduced by low-frequency bias correction and exclusion of ports with the largest tidal range, whilst verification against hindcasts eliminates it entirely.

Threshold exceedence probabilities provide an alternative way to evaluate the PDFs produced by an ensemble system, focusing on behaviour in the vicinity of the chosen threshold. This is particularly appropriate for the storm surge problem, where the ultimate aim is to estimate the likelihood of water level exceeding the limit of the defences. Section 3.1.6 presented a variety of verification measures for forecasts of positive surges exceeding zero and one metre, negative surge exceeding one metre, and total water level with harmonic tide included exceeding the port-specific alert level. Most of the results were presented with respect to hindcasts, since the verification against observations (shown in Appendix 5) was much less clear due to the noise arising from problems with the harmonic tide. Ensemble results were compared with probabilities calculated from the control forecast using no dressing, a single climatological error dressing, and a dressing whose width varies with forecast magnitude. Against hindcasts, the ensemble consistently produced the best results, and the undressed control forecast the worst, particularly for larger thresholds, higher cost/loss ratios, and longer lead times (where dynamic evolution is more significant). The magnitude-based dressing does somewhat better than the climatological dressing in similar conditions. Linear extrapolation of the decline in the Brier Skill Score of the ensemble with lead time suggests that extended forecasts from the same system would have skill over climatology until roughly three days when forecasting surge above one metre, and six days forecasting total water above alert level. Actual skill would probably be lower in the more likely situation where longer range forecasts are based on lower resolution meteorology in order to limit the computational cost.

Section 3.1.7 presented the results of a small user survey. Met Office forecasters in particular found the surge ensemble to be a valuable tool for assessing uncertainty and a useful reference to confidently brief others on the range of possible outcomes. The port time series plots were the most useful and readily understood output, whilst the postage stamps were found to be of very little use. There is a need for more training and online help to allow forecasters to get best value out of the products, including more complicated plots such as the port risk bar charts. Animation controls, zoom capability, numerical values, and splitting of different plot types onto separate web pages were also requested.

The total elapsed time for the 54-hour CS3X surge ensemble forecasts and graphics generation is about 35 minutes, delivering products about six and a quarter hours after data time. For a demonstration system it is fairly reliable, producing 97 per cent of the expected forecasts, with failures mostly due to external causes. A transitional website is planned to give the Environment Agency continued access to the demonstration forecasts until funds are available for a fully resilient and supported operational service. If the Environment Agency ultimately wishes to receive surge ensemble data as well as plots, it will be important to design the interface formats to allow for changes such as increased surge model resolution without adversely affecting Environment Agency systems.

Beyond operational implementation, there are at least two areas in which the surge ensemble itself might be improved. Allowing for initial condition uncertainty may provide some benefit at short lead times, particularly for forecasts starting within active surge events. This report has also highlighted the large residual error with respect to observations which arises from inaccuracies in the harmonic tide prediction. Improved tidal predictions that use artificial intelligence techniques to combine harmonic methods with recent real-time data, or alternative approaches such as the response method (Munk and Cartwright, 1966), could benefit both total water forecasts and the power of verification to highlight differences between modelling systems.

3.2 Wave ensemble verification

3.2.1 Substitute wave ensemble

Offshore forcing for the wave component of the forecasting system was provided by way of a ‘proxy ensemble’ based on regional scale forecast model data.

The Met Office currently runs short-range numerical weather prediction atmospheric and storm surge models using ensemble techniques, but, due to run-time constraints, does not run wave models in this manner. This section presents a substitute method for the ensemble approach, based on the standard deterministic forecast and assumptions specific to the site of interest in Liverpool Bay, and analyses the results.

3.2.2 Wind-sea correction

The technique makes use of the ensemble wind data compared with the deterministic wind and wave forecast, assuming that in this location the wave field will generally be unimodal (comprising either a dominant locally forced wind-sea or swell, but rarely both). This assumption should avoid complications in scenarios where wind direction varies through the ensemble members. A check from approximately six years of UK Waters model data at the location of NDBC station 62125 appeared to support this, by indicating that for over 80 per cent of the time a wind-sea or swell component made up over 70 per cent of the wave field energy; and that within the remaining 20 per cent of the time only 10 per cent of occasions saw the swell acting obliquely to the wind-sea.

At a given forecast lead time, the deterministic forecast provides values for wind speed and direction, and for wind-sea height (the component of the wave field acting under local wind forcing). Based upon this information, empirical equations derived by Carter (1982) can be used to derive a theoretical 'fetch' over which the wind must have blown. The fetch value (subject to consistency checks) can then be applied to ,ensemble wind values to generate a related wind-sea value for each ensemble member.

The advantage of this technique is that wave values generated are directly related to the wind/surge ensemble members. The science used, however, is not generically applicable since it expects a wind-sea dominated environment. In addition the forecast output retains any model biases introduced through either the Met Office model or Carter's equations.

Although the method is expected to be reliable, the assumption of a generally unimodal wave spectrum is essential, and means that the technique is not generically applicable (for example to North Sea coasts, or coastlines bordering the Western Approaches, where significant bimodal sea-states are expected). For bimodal seas, a full wave ensemble is necessary to produce meaningful results.

3.2.3 Data provided to the coastal flood forecasting system

The system was provided with ensemble winds, ensemble wind-sea parameters, deterministic swell parameters and ensemble parameters for resultant wind-sea plus swell (such as the overall significant wave height). An example of the data provided is shown in Figure 3.13.

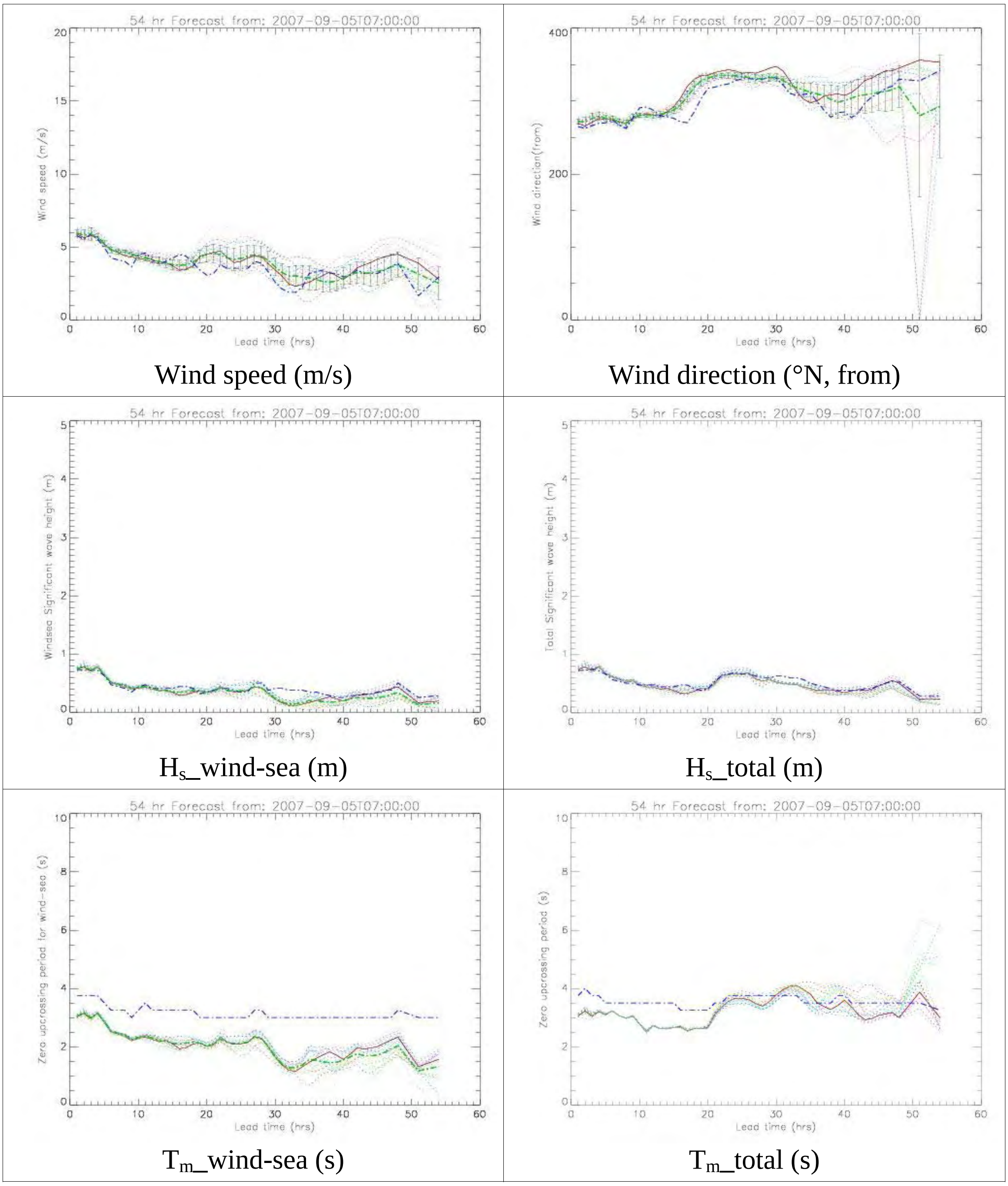

Figure 3.13 Typical set of data provided to the coastal flood forecasting system for 53.39N 3.58W

3.2.4 Validation results

Wave buoy measurements were not available for the four offshore wave points in the South-East Irish Sea used in the model setup. Figure 3.14 shows two offshore wave recording locations operating in the Irish Sea during the period of demonstration (there is also the WaveNet Liverpool Bay buoy not shown in Figure 3.14). Platform recorder Station 62125 appeared to be the most suitable for verification, as it was close to the point at which forecasts were passed on to the nearshore wave model. However, information reported from Station 62125 lacked continuity and consistency.
Buoy 62091 appeared to be more reliable, and was used instead. Statistics are

presented for Buoy 62091, located at 53.47N 5.42W, see Figure 3.14. For the purposes of comparison and verification, the substitute ensemble approach was applied to UK Waters wave model forecasts for the grid point closest to Station 62091.

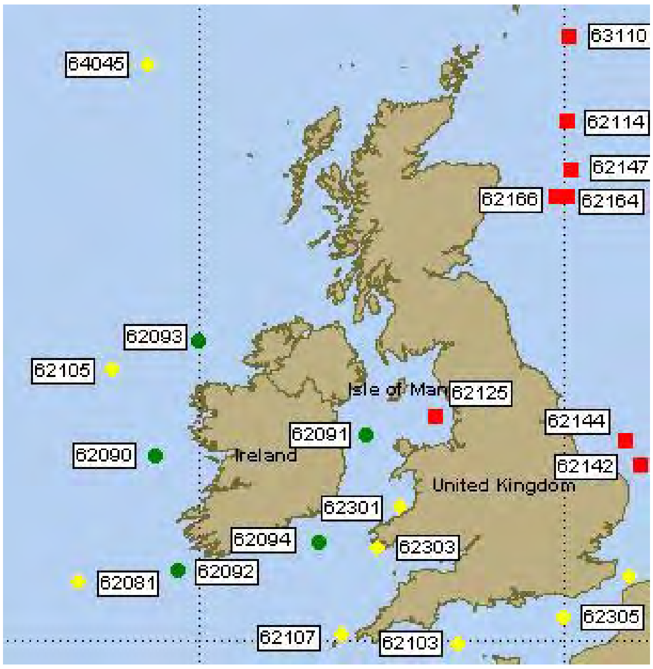

Figure 3.14 Location of wave recording Buoy 62091

The verification focused on significant wave height as no observational data were available for wave period. There were also no data available from this buoy to differentiate the wind-sea and swell components. Four periods of interest for the project were analysed, corresponding to storms in the Irish Sea having led to overtopping. The periods concerned were 5-7 December 2007, 8-11 January 2008, 14-16 January 2008 and finally 23-26 June 2008.

Figures 3.15 to 3.18 show forecasts from the ensemble members compared with deterministic forecasts and the observed values of H_s. The spread of the ensemble generally grows with lead time as expected. For much of the time both the observations and the deterministic forecast lie within the spread of the ensemble, but there are significant periods in several of the forecasts where this is not the case, for example in the lower graphs of Figure 3.16. A good-performing ensemble system should produce a few outliers but not as many as this. This shows some of the inadequacy of the proxy-ensemble approach employed here to perturb all the sources of uncertainty, and supports the need for a full wave ensemble in the future.

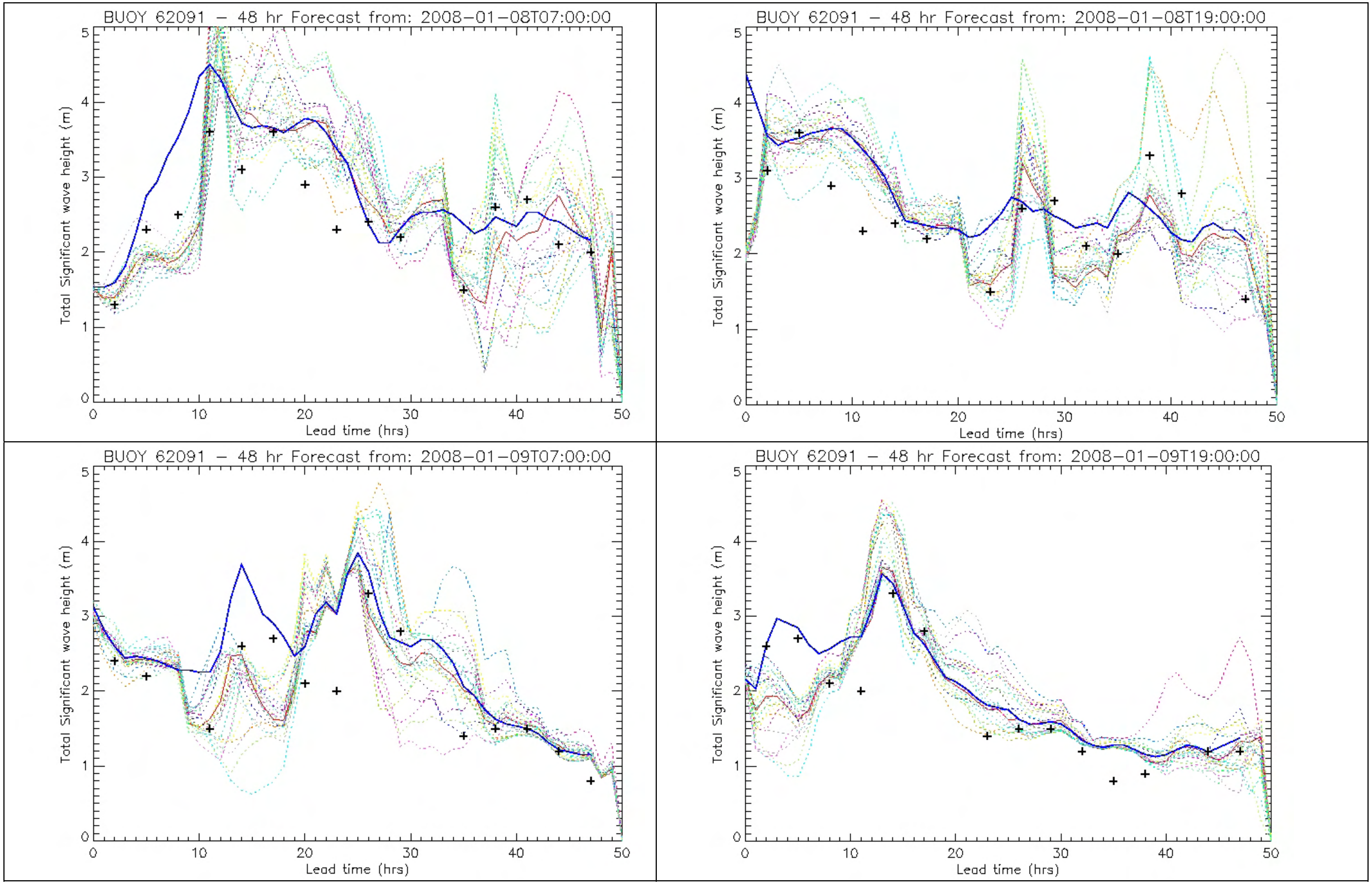

Figure 3.15 H_s as a function of lead time for 8 and 9 January 2008: deterministic model (solid blue line), observations (crosses), ensemble members (dotted lines), ensemble mean (red solid line)

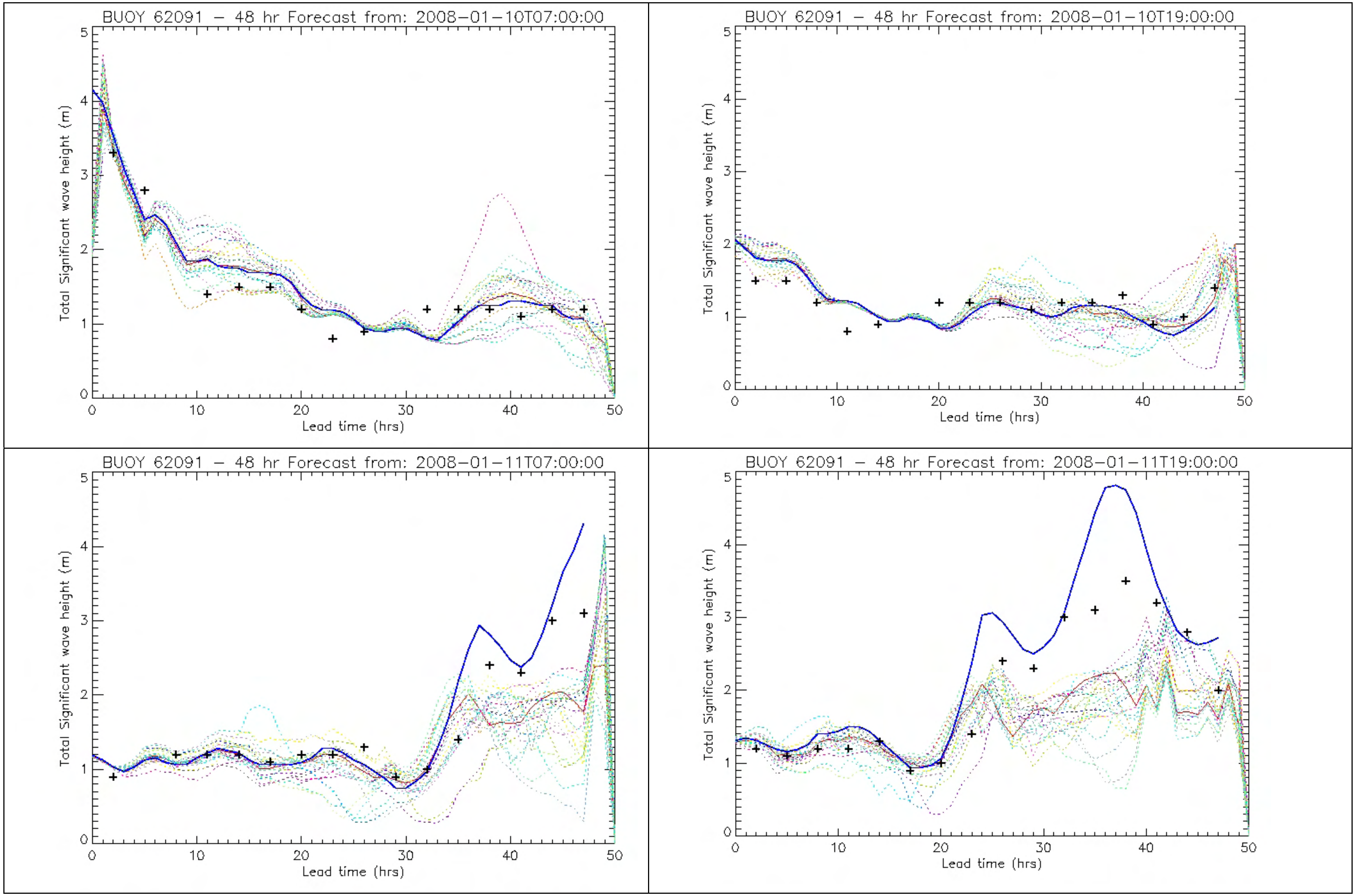

Figure 3.16 H_s as a function of lead time for 10 and 11 January 2008: deterministic model (solid blue line), observations (crosses), ensemble members (dotted lines), ensemble mean (red solid line)

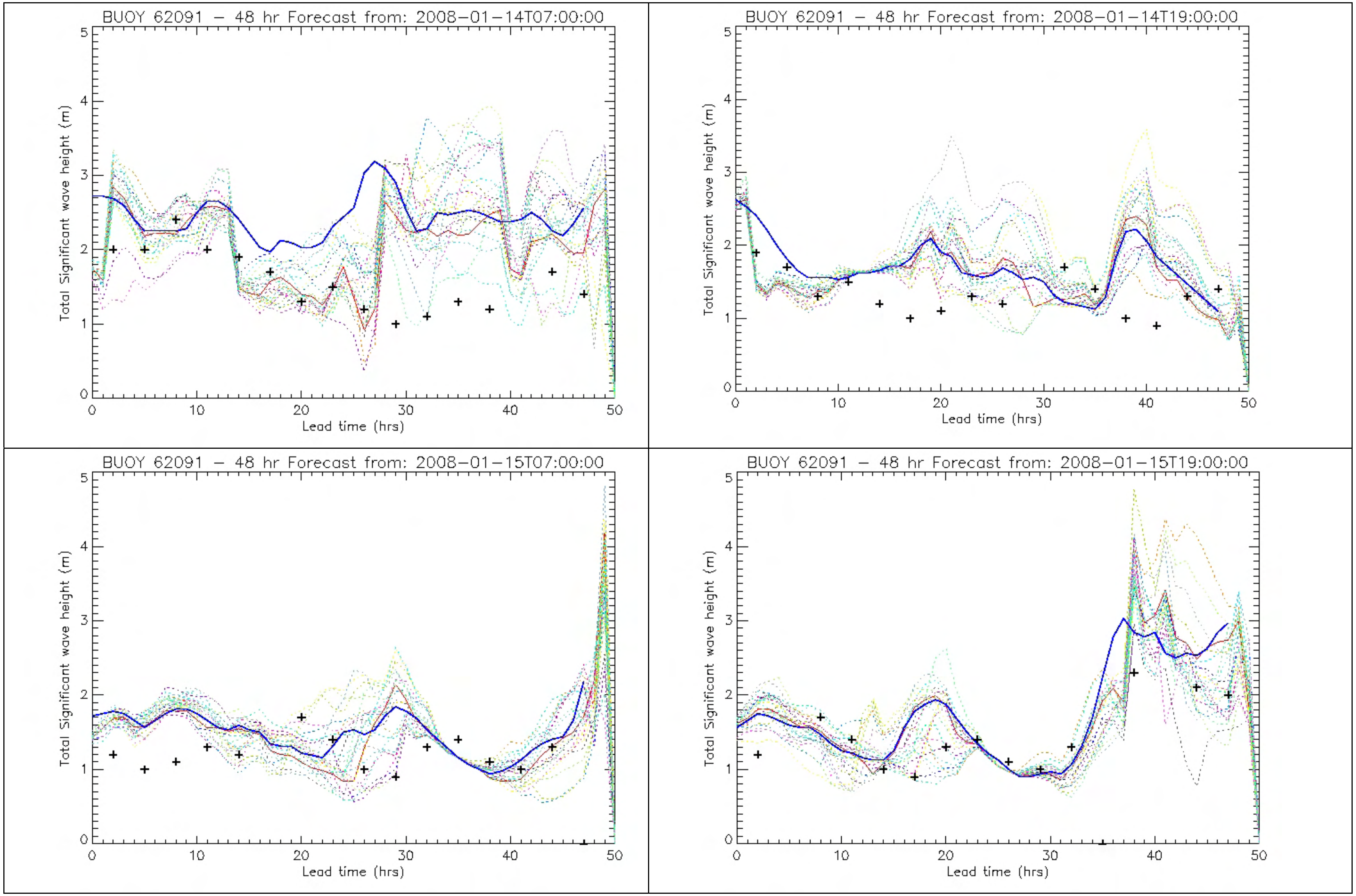

Figure 3.17 H_s as a function of lead time for 14 and 15 January 2008: deterministic model (solid blue line), observations (crosses), ensemble members (dotted lines), ensemble mean (red solid line)

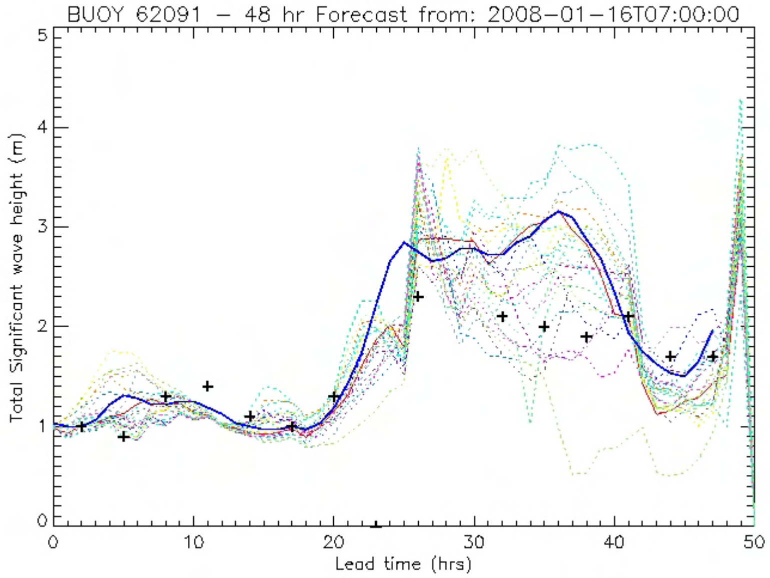

Figure 3.18 H_s as a function of lead time for 16 January 2008: deterministic model (solid blue line), observations (crosses), ensemble members (dotted lines), ensemble mean (red solid line)

Bias and RMSE/spread are presented in Figure 3.19: the plots show the RMSE error of the deterministic wave model versus the spread of the wave-ensemble proxy, averaged over all of the forecasts in the periods of interest, as a function of lead time. Both the deterministic model and the proxy ensemble exhibit a positive bias of less than 0.5 m. In the ideal case where the wave ensemble would capture all the uncertainty of the deterministic system, the spread in H_s for the ensemble members should be equal to the RMSE of the model. Here the ensemble system seems to be roughly equal to 80 per cent of the RMSE, and indicates that the proxy ensemble technique does at least capture the main uncertainties.

There is the hint of a 12-hour cycle in the bias plot in the upper part of Figure 3.19. Over a short period of forecasts, this might be attributed to the approximately 12-hourly tidal cycle effects upon the measurements not being reproduced by the model. Although this graph averages over several cases, it is quite a small sample and the effect may be a residual aliasing of the tidal cycle, and possibly also the 12-hourly cycle of model runs. Another possibility is that it is due to diurnal variations in the bias of the forcing MOGREPS wind forecasts.

Discrepancies between model/ensemble values and the observations can be explained in part by the fact the uncertainties in the swell are not accounted for, and in part by biases introduced as a result of the way in which the waves are grown in the Met Office second generation wave model.

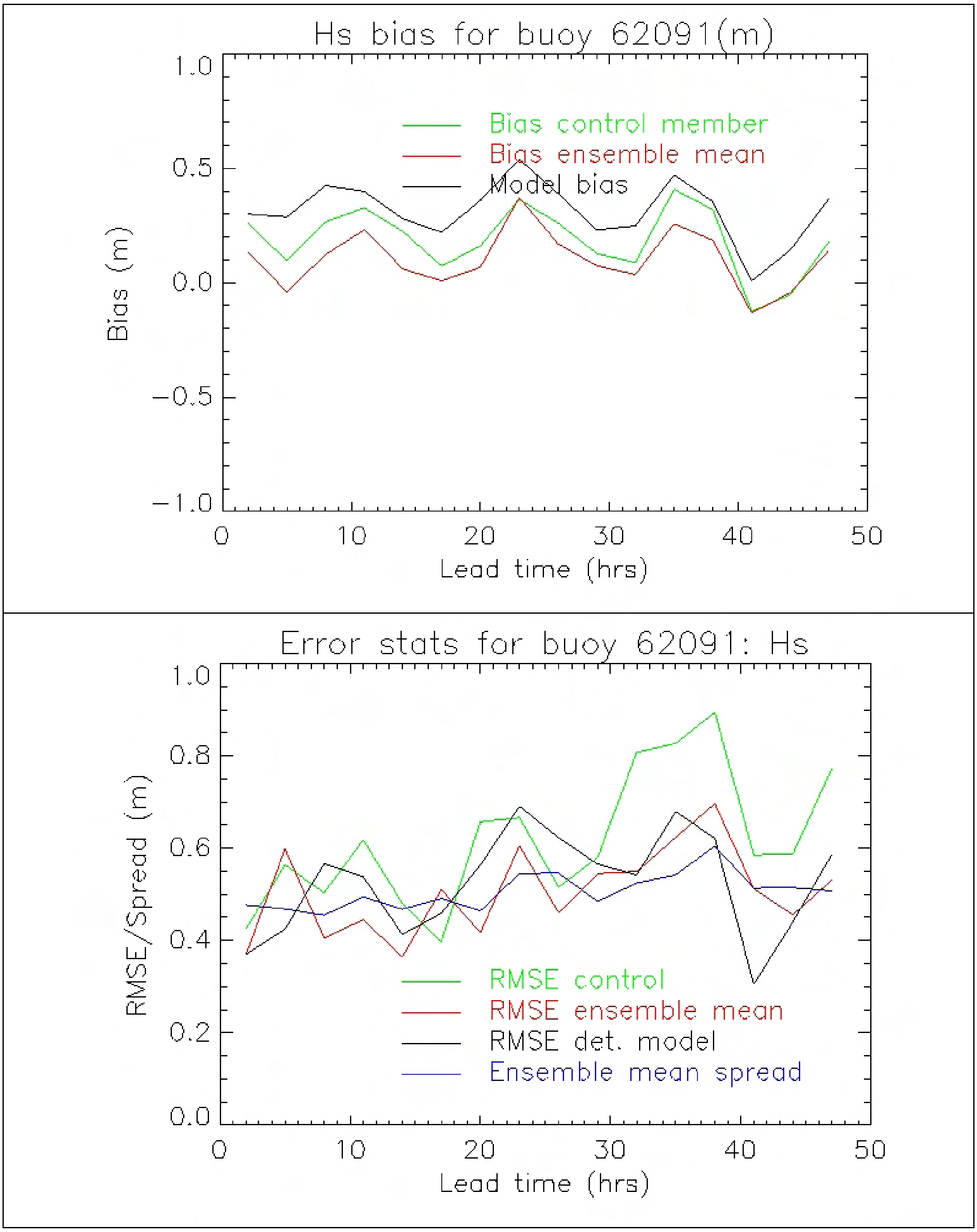

Figure 3.19 Bias plot and RMSE versus spread plot for the validation period

3.2.5 Conclusions

The demonstration shows that it is feasible to produce realistic wind-sea ensemble forecasts consistent with the Met Office MOGREPS approach to ensemble forecasting. The validation results show that the proxy method can provide a spread of wave parameters capable of capturing the observations on average, but that it may fail to account for important uncertainties in some situations, resulting in rather more outliers than expected. The development of a full wave ensemble would be highly desirable to capture better the true range of uncertainty in the wave forecast.

It is likely that much larger errors would occur in other areas around the UK coast where stronger swells occur on a frequent basis. This issue can only be resolved by using a full wave ensemble forecasting system, which was not technically feasible for this demonstration due to the computational time involved. A further feasibility study for a wave ensemble system has been commissioned and pending the results, the system might be implemented at the Met Office on their new supercomputer.

With the additional computer power recently installed at the Met Office, operational offshore wave ensemble forecasting for the whole of the UK may now be feasible. The recommendation carried forward to Chapter 7 of this report is based on the assumption that most of the operational developments would be funded from elsewhere. The recommendation from this project is for a pilot study over a large open coast area into the use of ensemble wave forecasting in coastal flood forecasting. This would mean near operational forecasting runs, coupled to wave transformation and possible overtopping modelling, for several coastal sites, with the involvement of Environment Agency forecasters.

4. Evaluation of nearshore wave and overtopping forecasts

Chapter 4 focuses on verification of nearshore waves and overtopping rates. Probabilistic aspects and their potential usefulness in coastal flood forecasting are considered in Chapter 5.

4.1 Nearshore wave verification

4.1.1 Comparison with measurements

Wave conditions and water levels were measured at two nearshore sites, along a profile perpendicular to the seawall at Anchorsholme, during the period 24-26 January 2008 when wave overtopping was also measured. Details of the wave measurements, undertaken by Wallingford Environmental Surveys (WES) are provided in Appendix 2. Figure 4.1 shows the seabed levels at the two nearshore measurement locations (labelled WES offshore and WES inshore) in relation to the SWAN model (nearshore) point, the toe depth, chart datum (CD) and mean sea level (MSL).

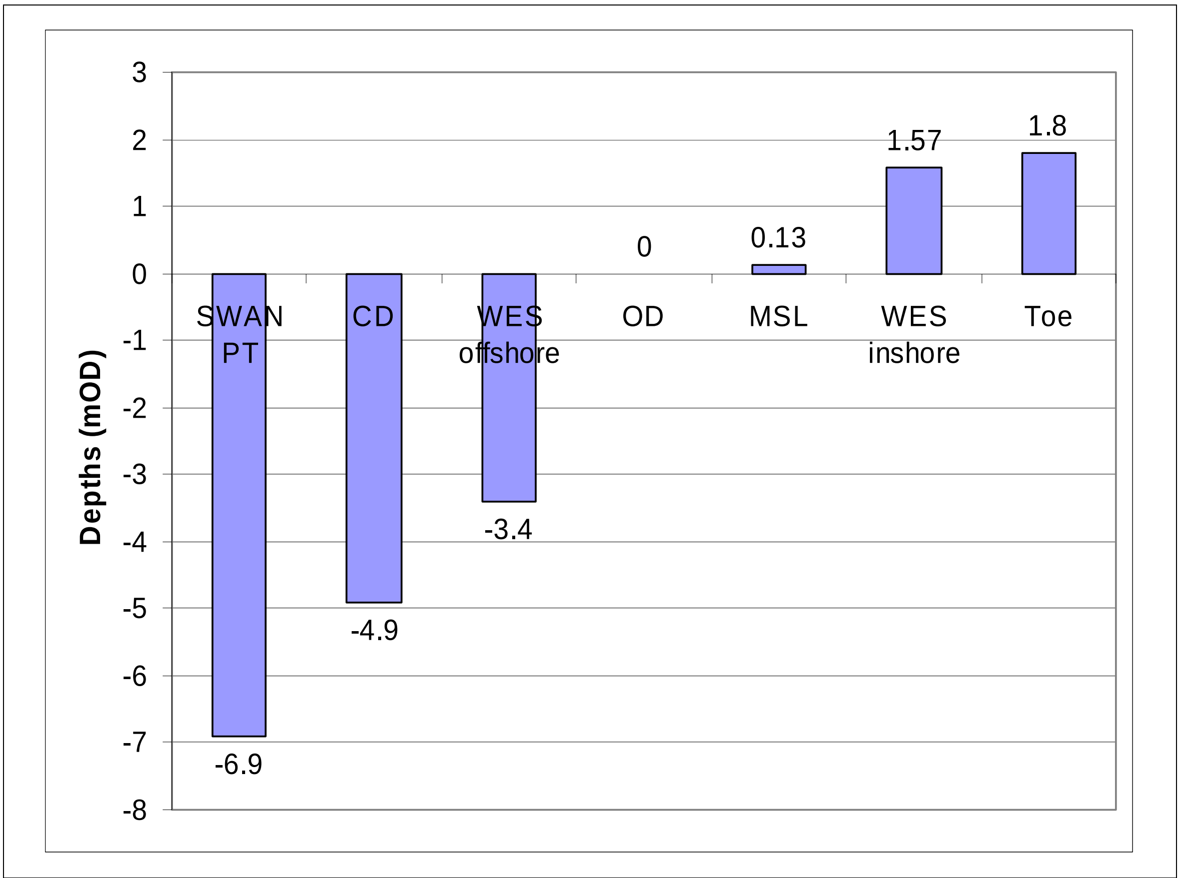

Figure 4.1 Seabed levels of model and measurement locations relative to Ordnance Datum

Figure 4.2 shows the Blackpool tide gauge water level measurements for the period 23-26 January 2008. It provides an indication of coastline forecasting accuracy and sensitivity. Also plotted are: the astronomical predictions as used in the forecasting demonstration, the nearshore WES measurements and the forecast mean levels (astronomical tide prediction plus surge) for the forecasts issued as part of the demonstration on 23rd and 24th of January 2008.

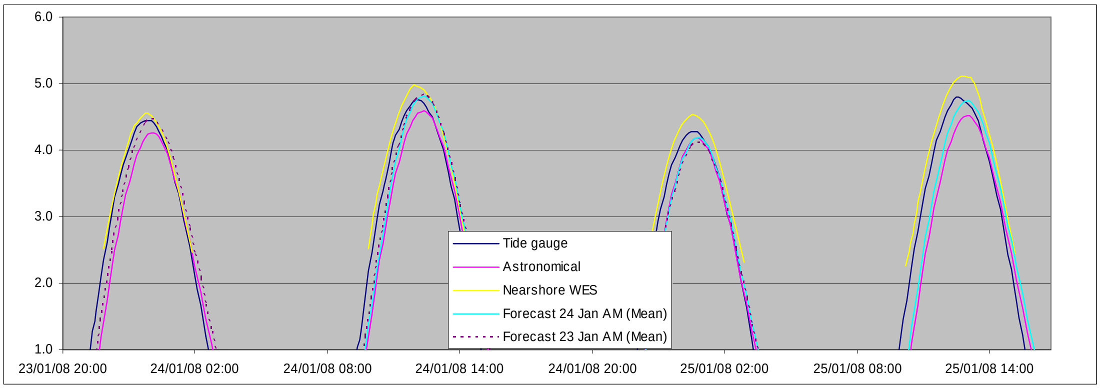

Figure 4.2 Nearshore sea level relative to OD over 54 hours, 24-26 January 2008: Blackpool tide gauge, astronomical, nearshore WES measurements, forecast 23 January AM, forecast 24 January AM

Figure 4.2 shows that the forecast sea level, including surge, is generally in good agreement with the tide gauge data, but also that the WES measurements are noticeably higher than the tide gauge data. This could possibly be due to wave setup affecting the WES measurements, but which is not expected to be appreciable at the tide gauge. There is also evidence of a small lag of approximately 15 minutes in the astronomical tide prediction, leading to a similar lag in the forecast water levels.

Appendix 4 compares time series traces of water level measured by the Blackpool tide gauge with astronomical tidal predictions for Blackpool used in flood forecasting, from 29 September 2007 to 30 April 2008. This is not a precise comparison, as the gauge does not record below -2.5 mOD and will include surge as well as astronomical tide.

Some conclusions can be drawn from this comparison. Astronomical tide is consistently 15 minutes out of phase with the measurements, peak water levels being predicted to occur 15 minutes after measured peak levels. The tidal amplitudes are not systematically different between the two traces, and where differences do occur they may be attributable to surge. Throughout, and particularly during October and November 2008 where there appear to be significant spring neap phase differences, forecasting could benefit from improved astronomical tidal predictions.

Although there remains a degree of uncertainty regarding actual water levels, the tide gauge data is expected to be more reliable than the WES measurements, due to the nature of measurements and the reliability of the levelling in such field measurements.

Figures 4.3 to 4.6 are a sequence of graphs presenting the forecast wave conditions at the WES offshore (labelled outer, -3.4 mOD) and inshore (labelled inner, +1.57 mOD) locations. Please note, the mean toe depth for the forecasts of overtopping used in the demonstration was +1.8 mOD. The sequence shown is based on forecasts model runs issued as part of the demonstration, namely:

- Figure 4.3 – Based on the Tuesday 22 January AM run
- Figure 4.4 – Based on the Tuesday 22 January PM run

- Figure 4.5 – Based on the Wednesday 23 January AM run
- Figure 4.6 – Based on the Thursday 24 January AM run

Each high tide is labelled uniquely A, B, C and so on to help identify each particular high tide within each forecast displayed. Also, each figure presents box and whisker graphs of significant wave height at 15-minute intervals, representing the first, 10, 50, 90 and 99th percentiles of the overall distribution comprising 24 ensemble members and Monte Carlo simulations.

The black diamonds show measured significant wave height (H_s). The figures show that there are occasional outliers with much greater H_s than at neighbouring times. There remains a higher degree of uncertainty in these observations.

The vertical red line shown on each figure indicates time T+14, where T is the model initial time. During the demonstration, forecasts were issued at about T+8. Therefore, events earlier than approximately T+8 would already have occurred, and events earlier than T+14 would be too close for effective response. Typically events between T+14 and T+27 are of most interest. The forecast of events beyond T+27 will provide advance warning of potential events, but with twice daily (as per the demonstration) or more frequent updates these are expected to be updated in later forecasts before a decision on response needs to be taken.

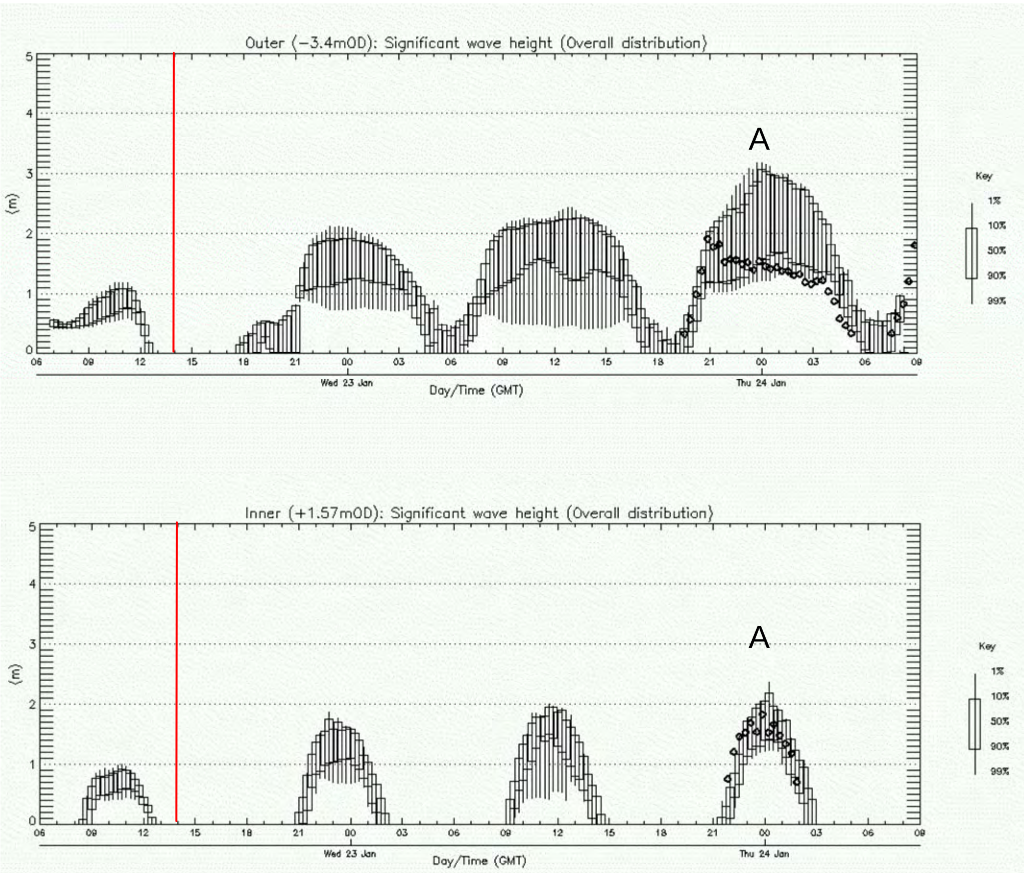

Figure 4.3 Nearshore significant wave heights: Forecast percentiles and measured (diamonds) over 54 hours, 24-26 January 2008 (a) WES offshore location (b) WES inshore location

Figure 4.3 shows that, in general, the forecast significant wave heights agree reasonably well with the measurements for Tide A (24 January 00:00) over 24 hours in advance of this high tide occurring. Forecast wave heights at the inshore location appear to agree better with measurements than those predicted at the offshore location. Waves at the inshore location may be more strongly depth limited.

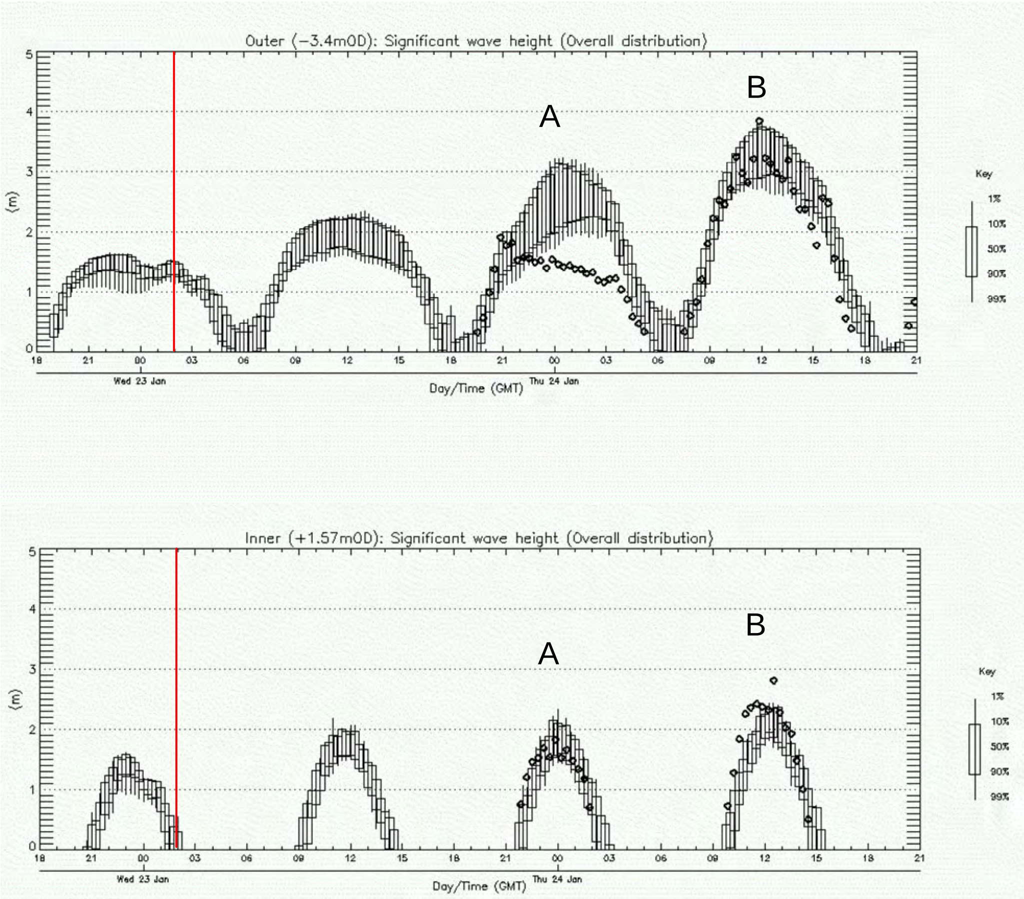

Figure 4.4 Nearshore significant wave heights: Forecast ensemble means and measured (diamonds) over 54 hours, 24-26 January 2008 (a) WES offshore location (b) WES inshore location

Figure 4.4 shows the forecasts for the following update, issued approximately 12 hours later than that presented in Figure 4.3. This figure shows slightly improved and less uncertain forecasts at the offshore location for Tide A. For Tide B, the forecasts of wave heights agree well at the offshore location, although they are noticeably low at the inshore location. This may partly be due to the model neglecting reflected wave energy from the seawall; any discrepancy between the predicted and actual water levels will influence the depth limiting process.

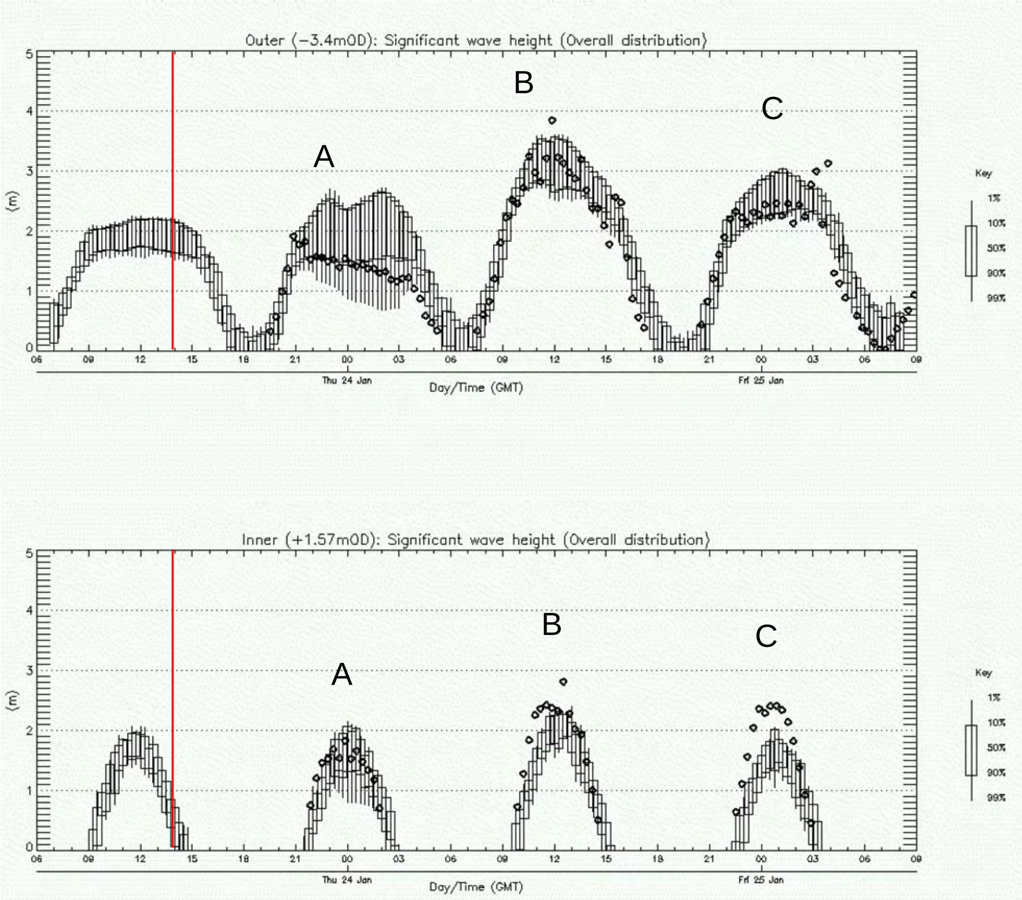

Figure 4.5 Nearshore significant wave heights: Forecast percentiles and measured (diamonds) over 54 hours, 24-26 January 2008 (a) WES offshore location (b) WES inshore location

Figure 4.5 shows the forecasts for the following update, issued approximately 12 hours later than the forecast presented in Figure 4.4. This figure shows a noticeable improvement to the forecast at the offshore location for Tide A, illustrating for this case the benefit of frequent updates. Little change to the forecast for Tide B can be observed, compared with the previous forecast (Figure 4.4). Similarly, the predicted waves at the inshore location remain low compared with the measurements.

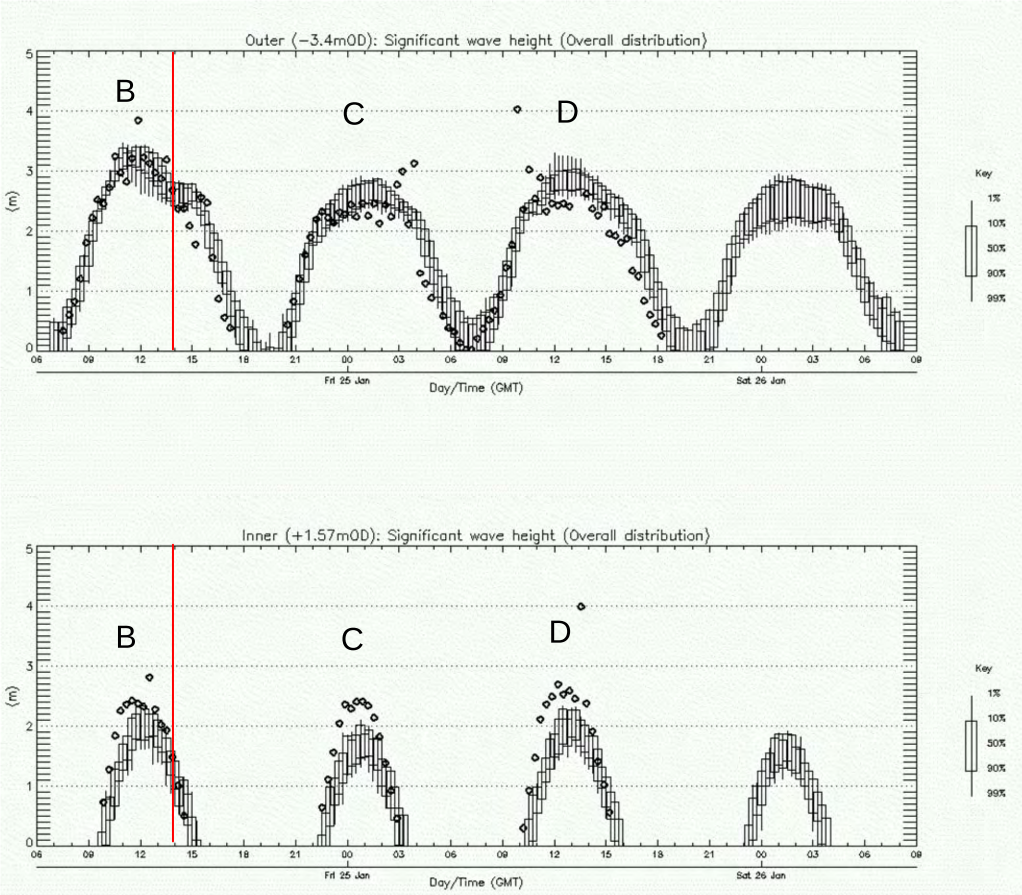

Figure 4.6 Nearshore significant wave heights: Forecast percentiles and measured (diamonds) over 54 hours, 24 26 January 2008 (a) WES offshore location (b) WES inshore location

The forecast significant wave heights presented in Figure 4.6 show the forecast for the following update, issued approximately 12 hours later than the forecast presented in Figure 4.5. This figure shows that the significant wave heights at the inshore location are consistency low compared with the measurements.

In general, the figures show that there is no significant phasing error; if anything, the forecast wave conditions lag the measurements slightly. It is concluded that a phase lag, to account for the time it takes for waves to travel across the model area as used in the NW Region TRITON system, is not required in this case or for offshore to inshore model areas of similar size.

Based on this comparison, it is likely that use of the *forecast* nearshore wave height for this period would lead to under-prediction in subsequent associated calculations of overtopping rate. The availability of measured data for this site, although only for a relatively short period, offers the possibility of calibrating wave models for future use.

4.1.2 Sensitivity to the choice of offshore wave model grid point

For the forecasting demonstration, only one of the four offshore model data points provided by the Met Office was used as boundary conditions to the Monte Carlo simulations. The point used was 3.58W, 53.72N, selected on the basis of the exposure of this point to waves generated within the Irish Sea and its location relative to Anchorsholme. The nearest other most suitable point was 3.58W, 53.94N. To illustrate the difference between the forecasts based on these two offshore points, model runs were carried out using this offshore point for the forecast of 24 January 2008 (AM).

Figures 4.7 and 4.8 show the forecast mean overtopping rates based on the two offshore points. These figures show relatively small differences in the forecast mean overtopping rates, with marginally higher rates forecast for the 3.58W, 53.94N data.

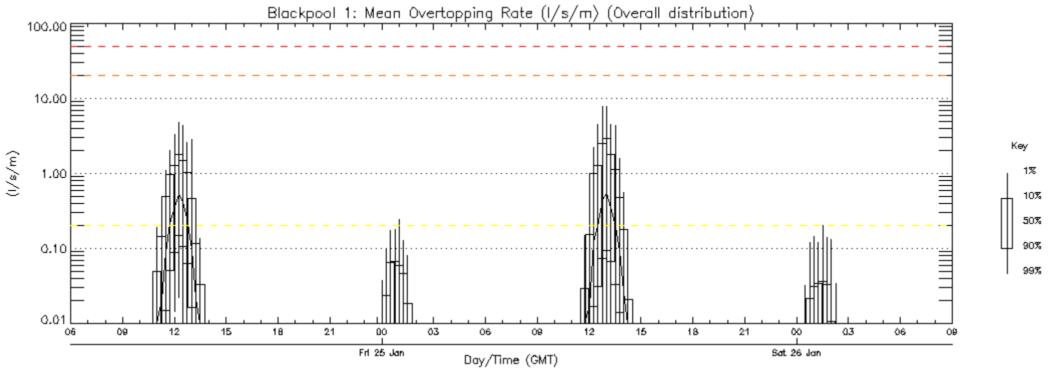

Figure 4.7 Forecast mean overtopping rates for 24-26 January 2008, based on offshore model point (3.58W, 53.72N)

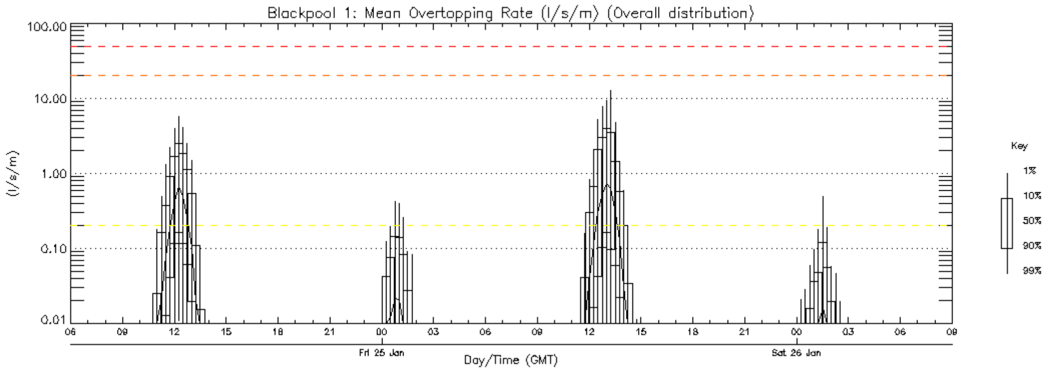

Figure 4.8 Forecast mean overtopping rates for 24-26 January 2008, based on offshore model point (3.58W, 53.94N)

Figures 4.9 to 4.12 show the corresponding forecast of significant wave height at the two WES measurement locations, labelled offshore (or Outer) and inshore (or Inner). These figures show that there is only marginal difference in the forecast significant wave heights.

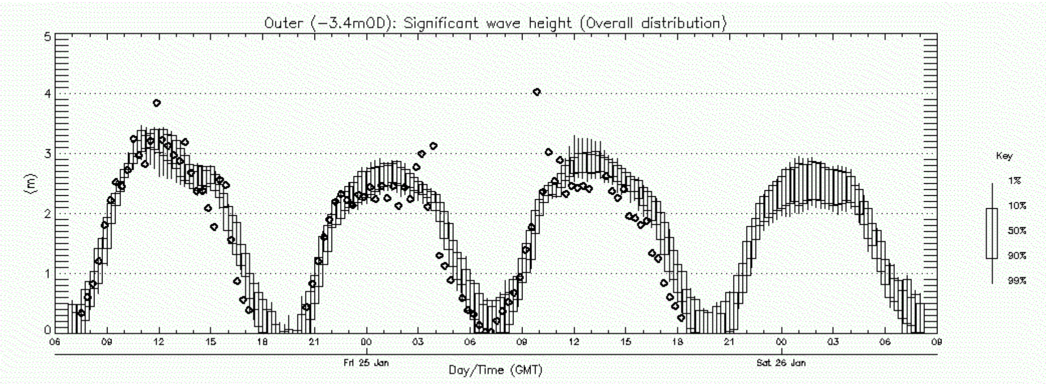

Figure 4.9 Forecast significant wave heights at the WES outer location for 24-26 January 2008, based on offshore model point (3.58W, 53.72N)

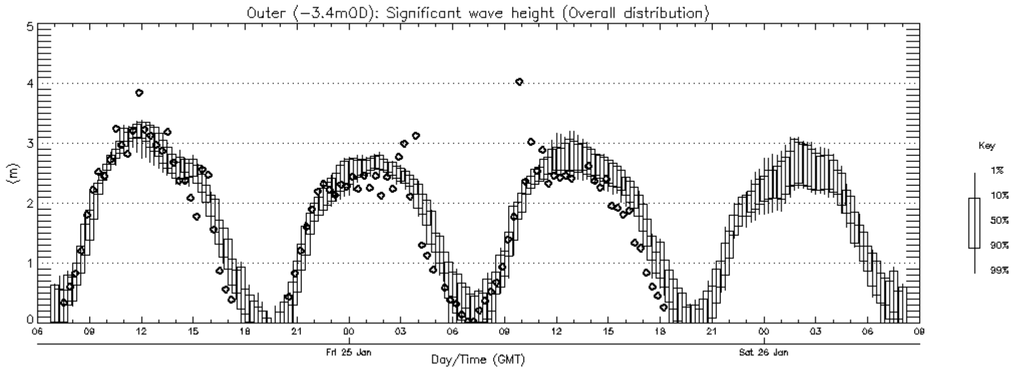

Figure 4.10 Forecast significant wave heights at the WES outer location for 24-26 January 2008, based on offshore model point (3.58W, 53.94N)

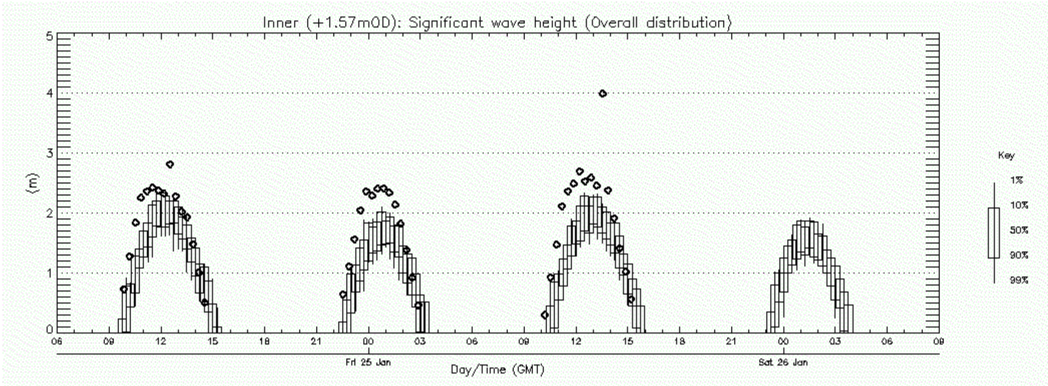

Figure 4.11 Forecast significant wave heights at the WES inner location for 24-26 January 2008, based on offshore model point (3.58W, 53.72N)

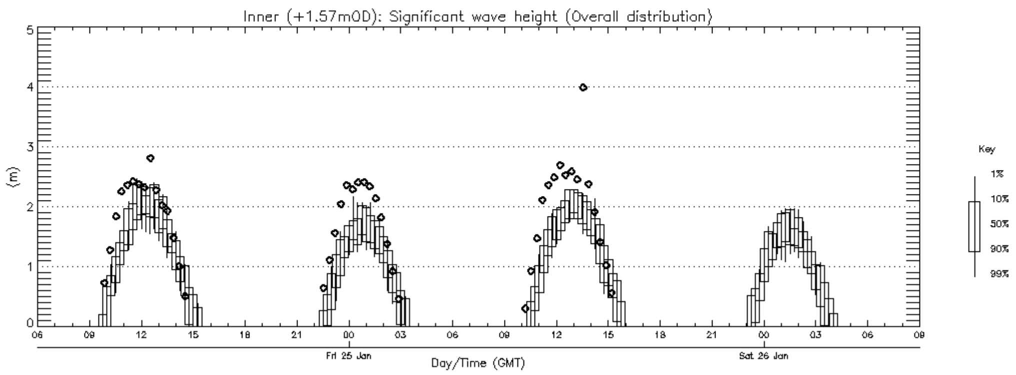

Figure 4.12 Forecast significant wave heights at the WES inner location for 24-26 January 2008, based on offshore model point (3.58W, 53.94N)

Although not necessarily true for all sites covered by the SWAN model used in the demonstration service, for Anchorsholme these figures suggest that at these times the wave and mean overtopping rates predicted were relatively insensitive to the difference between the two offshore model points.

4.2 Overtopping verification

This section compares the probabilistic forecasts of mean overtopping rate with field data for the NW Region. The comparisons focus on Blackpool and on stormy periods. There are four evaluation criteria for the forecasts: accuracy, timeliness, reliability and usefulness.

4.2.1 Accuracy of forecasts

Forecasts need to provide a good indication of what is soon to occur, in terms of sea levels, nearshore wave conditions, overtopping rates and exceedences of thresholds. Comparisons indicate that the central estimates from the probabilistic forecasts are in good agreement with the operational deterministic forecasts. Also, low overtopping forecasts correspond, correctly, with low overtopping at the site.

A total of three events were recorded at the field overtopping measurement site; further details are given in Appendix 3. Of these events, one recorded no overtopping when a very low probability of overtopping was predicted. For the remaining events there was a high probability of overtopping predicted, and these are discussed in detail here.

The events of 9 January and 24 January 2008, both spring tides, were successfully captured and recorded in overtopping discharges in the tank at Anchorsholme shown in Figure 4.13. The tank recorded all discharges as a continuous time series, and the total volumes recorded during each 15-minute period were derived. These volumes were then used to establish the total discharge in litres per second per metre (l/s/m) for each 15-minute period, to correspond with the predictions made by the probabilistic model. The time series comparison between recorded and predicted overtopping discharges can be seen in Figures 4.14 and 4.15.

Figure 4.13 Field overtopping tank *in situ* at Anchorsholme, Blackpool

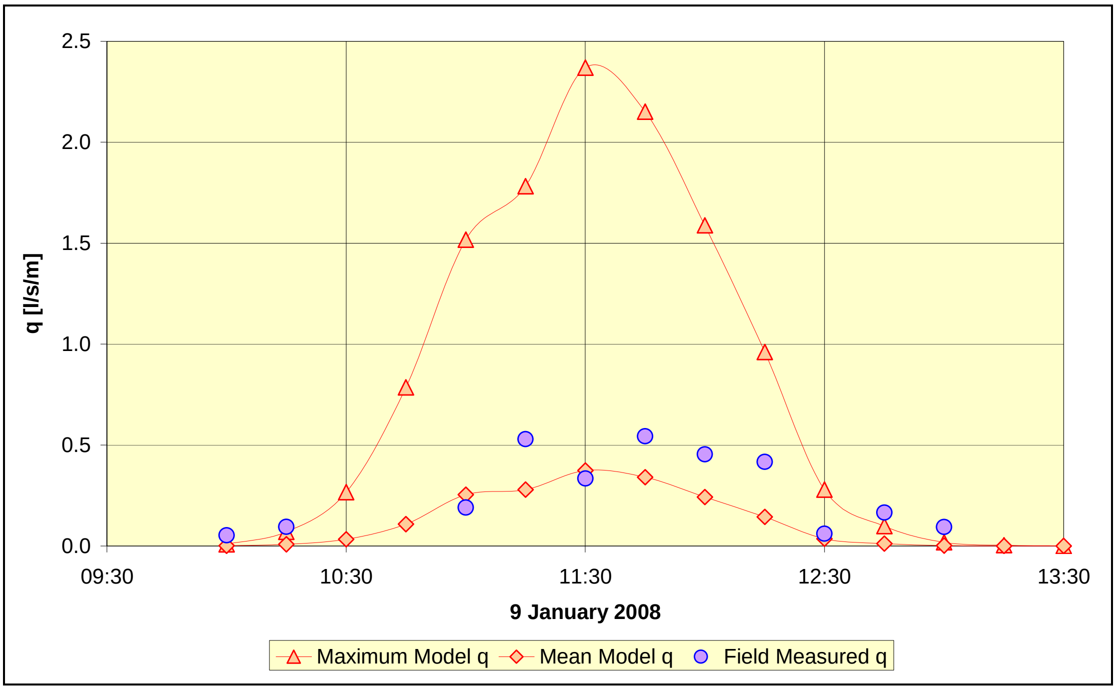

Figure 4.14 Field overtopping discharges and probabilistic forecasts for 9 January 2008

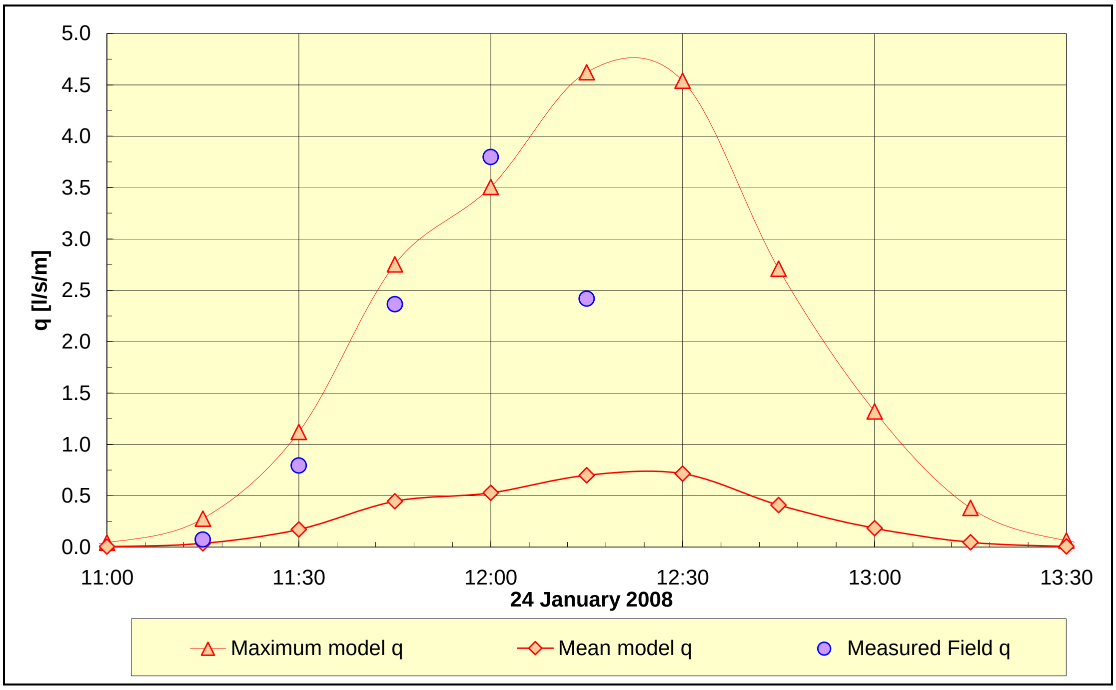

Figure 4.15 Field overtopping discharges and probabilistic forecasts for 24 January 2008

Three sets of data are shown in each of Figures 4.14 and 4.15. These are the field data, the mean ensemble overtopping prediction and the maximum ensemble prediction. The event of 9 January 2008, shown in Figure 4.14, demonstrates close agreement between the field overtopping measurements and the mean ensemble prediction. Typical recommendations for overtopping allow for differences of up to a magnitude of three, in certain cases up to ten, between predicted and measured overtopping discharges. In this instance, there is clearly no difference in certain cases and little more than a difference of approximately a factor of two in the most extreme case. In general overtopping terms, this would be considered to be an excellent fit of the model to the data. The measured overtopping is closer to the maximum predicted discharge at the start and end of the event.

The event of 24 January 2008, shown in Figure 4.15, shows that field measurements of overtopping are closer to the *maximum* discharges predicted by the model. The discharges for this event are higher than those for the previous event and so greater absolute differences between predicted and measured discharges should be expected. In this case two observations can be made. The field measured overtopping discharges are within the margins of the model prediction, and are in general between the maximum and mean predictions.

Further examination of the event of 24 January 2008 is shown in Figure 4.16. This figure replicates the measured and model results presented in Figure 4.15, but also includes model results using the WES inshore wave and water level measurements, described in Section 4.1, as input. Time series wave heights, wave periods and water levels were entered into the empirical prediction method described in Section 3.3 of Environment Agency (2007). This model assumes that all the uncertainties take their mean or central values for the purpose of this comparison. The field maximum, mean and minimum overtopping (q) values shown in Figure 4.16 represent the upper, middle and lower bounds of the empirical model, respectively. In this instance there is better agreement between the field measurement of overtopping and the *mean* prediction of the model. This shows that the model expressions used for overtopping rate prediction are sensitive to nearshore wave and water level conditions, but that the upper and lower limits of the forecast tend to encompass the true rate.

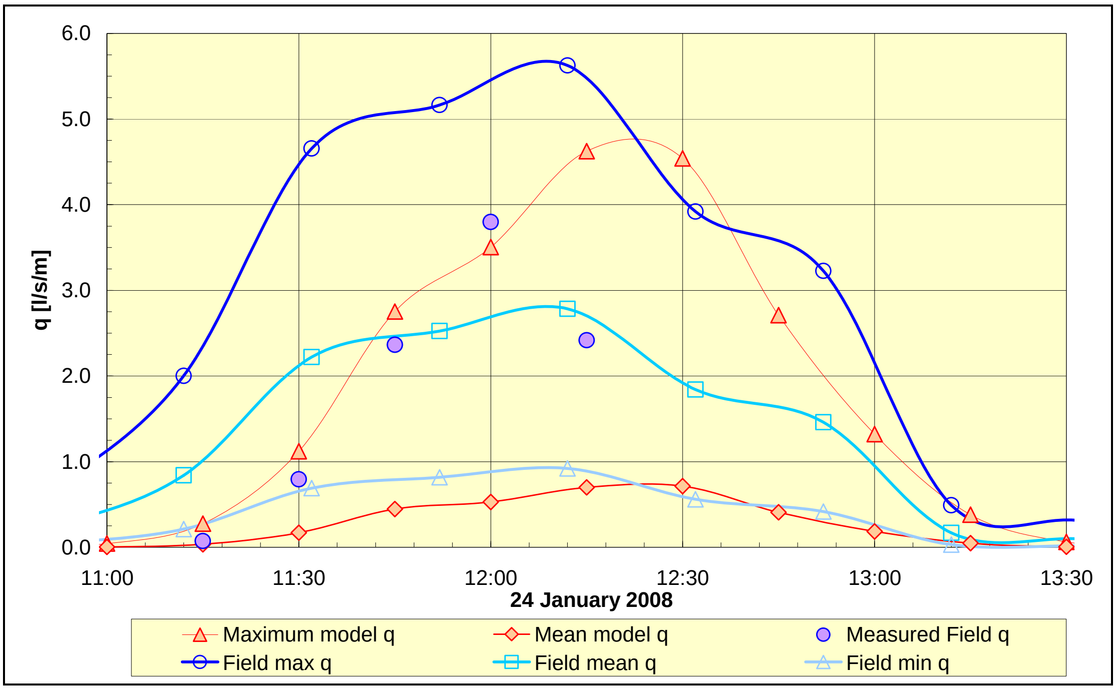

Figure 4.16 Field overtopping discharges and probabilistic forecasts for 24 January 2008, and equivalent predictions based on measurements of nearshore sea level and waves

4.2.2 Timeliness of forecasts

Forecasts need to provide sufficient time for mobilisation, warning and mitigation against flooding, so the entire modelling package has to run in a reasonable time. The weather, wind ensemble and offshore wave forecast takes about five hours to run, and the surge ensemble a further hour. The nearshore wave and shoreline models add a few minutes per shoreline prediction point (and in an operational system there may be a great many of these). For the demonstration, based on just two coastal points, the total time was manageable at seven or eight hours, providing 15 minute ‘nowcasts’ from T+0 to T+7, and ‘forecasts’ from T+8 to T+54 (three or four high tides). Delivery time is about two hours longer than the present operational system, but fast enough to be useful.

At present, the Environment Agency lead time of greatest interest is about 12 hours. This refers to the time difference between receipt of a forecast and the time to which the forecast applies. Coastal flood forecasts could be delivered about eight hours (T+8) from initiation (T+0) of a weather model forecast run. In the demonstration, the forecasts were updated every twelve hours. Therefore, high tides occurring between about T+14 and T+27 correspond to the lead time of greatest interest.

4.2.3 Reliability of forecasts

Forecasters need consistent availability, accuracy, timeliness and format of forecasts, especially during severe weather conditions. Those aspects of the demonstration system that would be taken forward into an operational system were reliable, with only a handful of forecasts lost during a seven-month period. However, the proportion of coastal forecasts actually delivered during the demonstration was lower, at about 80 per cent, with losses due to more fragile methods of computer communication and backup than would be used in an operational system.

4.2.4 Usefulness of overtopping rate forecasts

Two types of location where overtopping rate forecasting would be of benefit are:

(a) flood-prone areas where the main contribution to the threat derives from wave overtopping;

(b) areas close to heavily wave-attacked defences where direct overtopping can cause hazards close behind the defence.

Many areas in England and Wales falling into the first category may be identifiable from data already held by or available to the Environment Agency. Some areas may, however, require supplementary interrogation, perhaps using additional databases.

Some areas prone to overtopping, particularly in the second category, may not be identified in current Environment Agency databases and may require additional research or supplementary interrogation of other databases.

The remainder of this section suggests ways of categorising wave overtopping receptors, and then wave overtopping hazards. This can be done by initially categorising potential receptors in ways that may assist their identification using current (or near future) data held by or for the Environment Agency.

Most places around the coastline of England and Wales that are vulnerable to flooding by direct wave action could be identified by interrogating results of National Flood Risk Assessments (NaFRA) to identify defences where overtopping may contribute significantly to flood risk. Potentially vulnerable *residential* or *commercial* receptors within flood-prone areas should also be identifiable from the Receptor Database, within which the National Property Database will give property location, size and so on.

These databases should in theory (but may not yet in practice) identify other flood recipients under *transport infrastructure, major services* and *utilities*. If necessary, all of these should be identifiable from the Ordnance Survey Master Map.

Given their focus on flood-prone areas, these searches may miss recipients of direct wave overtopping which have not previously been categorised as at risk of flood. The most likely examples will be coastal promenades or footpaths, coastal roads, railways, and/or buildings or coastal attractions along the base of cliffs, or generally higher land where local land is well above sea levels, say +7 mODN, but could still be reached by wave action. This might be most likely for small coastal conurbations on or close to exposed shorelines, say where a three-metre significant wave height is exceeded in ten spells per year.

For the transport links it may be useful to identify levels of consequence, perhaps as: coastal footpath (low use); coastal promenade (high use); minor road (little consequence of tidal closure); moderately trafficked road; important road (where closure could substantially affect traffic flow and/or user safety).

If the defence and the receptor are on approximately the same level, direct overtopping hazards might be expected to decrease by a factor inversely proportional to the distance of the receptor back from the defence. This simplification is vulnerable to misuse, and would not be safe to apply to overtopping flows down the back of an elevated embankment seawall. Close to such a seawall, the hazard may be at least as great as at the seawall crest, indeed the hazard might increase if the land level behind the defence is particularly low. Such areas should, however, have already been captured by the NaFRA sifting outlined above.

Another approach to identify potential recipients of overtopping hazards would be to estimate the 200-year return period mean overtopping rate for locations of interest, and then compare these values with the thresholds listed in Table 4.1 to see where overtopping forecasts might be of greatest value.

Table 4.1 Threshold vulnerabilities to overtopping

The 200-year mean overtopping rate at defence line (l/s/m)	Potential hazards
< 0.01	Little direct hazard; mainly spray; may be unpleasant.
< 0.05	Spray will affect vehicles at moderate to high speed within 20 m of defence; danger for pedestrians if not aware and well protected.
< 0.1	Heavy spray and splash possible at steep and vertical walls: danger to vehicles within 10-20 m of defence; danger for pedestrians even if aware and well protected.
< 1.0	Unsafe for untrained people unless back from defence; danger for lightly engineered/protected defences; danger to buildings close to defence (< 10 m).
< 10	Damage to engineered defences; danger to slow traffic aware of overtopping; damage to buildings within 10-20 m of defence.
< 100	Unsafe for all except the best engineered defences; unsafe for any traffic.
> 100	Considerable danger for the defence structure unless very heavily engineered, and well detailed.

4.2.5 Conclusions

The demonstration shows that it is feasible to produce probabilistic forecasts of nearshore waves and overtopping rates in a timely and reliable way. The validation results show that the forecasts are sensible for the demonstration area.

At present, it seems impractical to set up nearshore wave and overtopping models on a national basis, although the generic parts of the probabilistic forecasting code could be adopted into NFFS, to be available for use as the need arises. Wave transformation models would be set up area by area, as necessary. Overtopping rate models would be set up point by point, as necessary within an area.

Probabilistic nearshore wave and overtopping forecasting is feasible. On the PC used during the demonstration, computer run-time would limit the number of overtopping locations that could be used to tens, when hundreds might be preferred. However, if run on the central computer resource at the Environment Agency, the nearshore wave and overtopping modelling would add only of the order of two hours to the delivery time for offshore forecasts. The recommendation carried forward to Chapter 7 of this report is for a pilot study over a large open coast area. This would mean near operational forecasting runs, including wave transformation and overtopping modelling, preferable within NFFS, for several coastal sites, with the involvement of Environment Agency forecasters.

5. Evaluation of probabilistic information for coastal flood forecasting

5.1 Scope of the evaluation

Any value from coastal flood forecasting would come through optimising use of flood management resources, and minimising damage and loss caused by flooding. Any improvement would come through more efficient prompts to action, usually in the form of prediction of threshold crossings of sea level, wave height, overtopping or flood probability. It is, therefore, the accurate, reliable and timely prediction of these potential threshold crossings that is important for coastal flood forecasting.

Verification of nearshore waves and overtopping rates was described in Chapter 4. The evaluation here in Chapter 5 focuses on the probabilistic aspects of nearshore wave and overtopping forecasts and their potential usefulness in coastal flood forecasting.

As the end-product of the sequence of meteorological and hydraulic models, overtopping rate will be influenced by all of the component uncertainties introduced at different points in the modelling sequence. There is insufficient information to *verify* the uncertainty in mean overtopping rate predicted by the models. However, the way that the different uncertainties are introduced can be controlled to allow a series of experiments to be carried out to test the *relative importance* of the different component uncertainties.

To assist with the assessment of uncertainty, a set of ‘stormy’ forecasts was selected for use in the analysis, based on the following sequentially applied criteria:

1. Identify forecasts on the demonstration website showing over 50% chance of exceeding the Flood Watch mean overtopping rate threshold (0.2 l/s/m) on any high tide at Anchorsholme, but ignoring ‘nowcasts’ in the range T+0 to T+8.
2. For each of these identified forecasts, identify one or more high tides for which the 50% criterion is exceeded.
3. For each of these identified forecasts and high tides, select the 15-minute forecast time step closest to high tide.
4. For each of these selections, where forecast mean overtopping rate exceeds 0.5 l/s/m two time steps (half an hour) before and/or after the selection time, also select the one or two additional forecast time steps.

The 57 ‘stormy’ forecasts chosen in this way are listed in the first two columns of each of the calculation sheets reproduced in Appendix 6. The first column gives the forecast run time where, for example, 0600/09/03/08 refers to the 06:00 forecast on 9 March 2008, which would have been posted to the website about 14:00 the same day. The second column gives the time for which a particular forecast time step applies, where, for example, 11/03/2008 01.15 refers to the forecast for 01:15 on 11 March 2008. The third column gives the forecast mean overtopping rate for that forecast run time and time step (note that this may be different to the value given on the website, as these ‘stormy’ forecasts were re-run with greater precision for the purposes of this uncertainty tracking analysis).

Three sub-categories were selected from within the 'stormy' forecasts:

- **All**: all 57 'stormy' forecasts.
- **About 12-hour lead time**: The 19 forecasts where the difference between run time and time step (T) is in the range T+14 to T+27, representing the lead time of around twelve hours of greatest interest to forecasters.
- **Low overtopping**: The 17 forecasts where the forecast mean overtopping rate is less than 0.35 l/s/m.
- **High overtopping**: The 15 forecasts where the forecast mean overtopping rate is greater than 1.5 l/s/m.

In the calculations reproduced in Appendix 6, and in the results in Tables 5.1 and 5.2 in this chapter, these categories are identified by labels All, 12hr, Low and High.

5.2 Evaluation and use of probabilistic threshold crossing forecasts

During the demonstration forecasting at Blackpool, there were many instances of overtopping, some of them severe. Both the operational and probabilistic systems were reasonably accurate in forecasting the occasions of severe overtopping, when action needed to be taken to protect the public.

Often, the probabilistic forecasts would predict a low probability of exceeding a threshold overtopping value, which usually turned out, correctly, to correspond to overtopping, but not severe overtopping.

Appendix 7 shows some comparisons between operational NFFS forecasts for Anchorsholme and the probabilistic forecasts. The forecasts chosen for this purpose are broadly the same as the 'stormy' forecasts described in Section 5.1, but excluding spells where NFFS forecasts were not available, and including a few additional forecasts for continuity during a stormy spell.

For the four stormy periods chosen in this way, maximum (per tide) overtopping rate predictions are given for several different forecast times and for several different high tides. As the probabilistic forecasts are twelve-hourly, commencing at 06:00 and 18:00, the additional six-hourly NFFS forecasts commencing at midnight and midday are excluded from the comparisons. Central (best) estimates are given for both systems, but for the probabilistic forecasts a median (50th percentile) value is also given. Cells are shaded yellow in Appendix 7 where the overtopping rate exceeds the Flood Watch threshold of 0.2 l/s/m. The columns headed "NFFS" and "Mean" provide the closest comparison between the two systems. However, even though both are for the same location, the assumed seawall profile and crest level may be different between the two, which could introduce a systematic difference between the two sets of forecasts.

The forecast overtopping rate changes with lead time. The NFFS forecast rate is usually much higher than the probabilistic mean rate. The median probabilistic rate is consistently a little lower than the probabilistic mean rate, as one would expect from the asymmetric distribution of overtopping rate from the probabilistic model. It is reassuring to note that, in most instances, both systems agree on whether or not the first overtopping rate threshold is expected to be exceeded. The probability of exceeding a threshold (%>0.2 in Appendix 7) could be passed on to professional partners or to the public to give an idea of the likelihood that a flood might occur.

5.3 Sensitivity of forecasts to different uncertainties

An important element of the evaluation was to investigate the relative sensitivity of key forecast parameters to the many different uncertainties involved in generation of the forecasts. These uncertainties included the ensemble spread of surge, the ensemble spread of waves, SWAN model parameters, seawall profile parameters, and the beach elevation at the toe of the seawall. This was investigated in a systematic way, using the three different approaches described in Sections 5.3.1 to 5.3.3. Each approach focuses on stormy conditions as this is the only situation of interest for coastal flood forecasting.

5.3.1 Relative contributions to uncertainty of the ensemble and the Monte Carlo elements

The probabilistic forecasts contain an objective indicator of the relative contributions to uncertainty in overtopping rate, from the ensemble modelling, and from the Monte Carlo simulation of additional coastal uncertainties. In the absence of the Monte Carlo modelling, each ensemble member would produce an overtopping rate forecast close to its median value. The variation of the ensemble median values therefore indicates the contribution to overall uncertainty of the ensemble modelling of surge and waves. For any particular ensemble member, the variation about the median value indicates the contribution to overall uncertainty of the additional nearshore and coastal uncertainties introduced through the Monte Carlo modelling.

Small and zero overtopping rates would be of little practical interest and so the analysis was limited to the 'stormy' forecasts described in Section 5.1. Exactly how the uncertainties should be compared and collated is not obvious, and so some preliminary calculations were made using a range of approaches. The variability of ensemble median overtopping rate forecasts tended to be approximately symmetrical about a median value approximately equal to the mean value (of the ensemble medians). Conversely, the Monte Carlo uncertainties tended to be skewed towards the upper tail, with a mean value consistently higher than the median value.

The large size of the uncertainties (often greater than the central estimate) meant that use of a plus/minus expression of uncertainty would be unrepresentative. For the Monte Carlo uncertainties a multiply/divide (logarithmic) expression of uncertainty would be more representative, but this would not suit the ensemble uncertainties. It would have been convenient to use a single summary calculation of uncertainty, whether plus or minus, but the asymmetrical nature of the uncertainties meant that too much information would be lost on the upper tail uncertainty of greatest interest.

After trying several approaches to summarise and normalise uncertainty, the method adopted here and in Section 5.3.2 is as follows.

1. Take the median overtopping rate (OT50) as the central estimate. For the Monte Carlo-based distributions, this is the 50th percentile value. For the 24 ensemble medians ranked in order of magnitude, this is the average of the 12th and 13th largest values.
2. Take the overtopping rate exceeded by 10 % of the probabilistic estimates (OT90) as representative of higher values in the distribution. For the Monte Carlo-based distributions, this is the 90th percentile value. For the 24 ensemble medians ranked in order of magnitude, this lies between the second and third largest values, weighting the third value nine to one relative to the second one.
3. Take the overtopping rate exceeded by 90 % of the probabilistic estimates (OT10) as representative of the lower values in the distribution. For the Monte

Carlo based distributions, this is the 10th percentile value. For the 24 ensemble medians ranked in order of magnitude, this lies between the 22nd and 23rd largest values, weighting the 22nd value nine to one relative to the 23rd value.

4. Characterise and normalise the uncertainties, taking OT90/OT50 for the upper values and OT50/OT10 for the lower values.

5. Where relevant, average the OT90/OT50 and OT50/OT10 values over all ensemble members, to produce values representative of a single forecast.

6. Where relevant, summarise (average or median) the OT90/OT50 and OT50/OT10 over all 'stormy' forecasts selected for inclusion in the analysis, to provide overall representative values for a particular type of uncertainty.

Details of the results for the 'stormy' forecasts are given in Appendix 6. For each forecast time step, four ratios are given: Med90/Med50 and Med50/Med10 to represent the uncertainty introduced through ensemble modelling, and OT90/OT50 and OT50/OT10 to represent the uncertainty introduced through Monte Carlo modelling.

The *average* values of OT90/OT50 for the ensemble medians and for the Monte Carlo distributions are 5.5 and 2.5 respectively, indicating that the ensemble modelling contributes significantly more to the high-end uncertainty in forecast overtopping rate. The *median* (not average as some of the values are very high) values of OT50/OT10 for the ensemble medians and for the Monte Carlo distributions are 4.7 and 3.3, respectively, suggesting that the ensemble modelling contributes more to the low-end uncertainty in forecast overtopping rate.

These and equivalent figures for the sub-categories of the 'stormy' forecasts are summarised in Table 5.1. Note that the minimum possible ratio of OT90 to OT50 is one (meaning that the two values are equal) and, for example, that a ratio of three would indicate a 10 per cent chance of overtopping rate being at least three times greater than the median value.

Table 5.1 Relative contributions of the ensemble and Monte Carlo approaches to the overall uncertainty in mean overtopping rate prediction

General category of uncertainty	Low value uncertainty (Median OT50/OT10)				High value uncertainty (Average OT90/OT50)			
	All	12hr	Low	High	All	12hr	Low	High
Introduced through ensemble modelling	4.7	3.1	4.6	5.1	5.5	2.9	9.7	3.7
Introduced through Monte Carlo modelling	3.3	3.2	3.6	2.4	2.5	2.5	3.6	2.1

The results suggest, as one would hope, that ensemble uncertainty reduces as an event comes closer in time, but that uncertainties introduced through Monte Carlo modelling do not change with lead time. For All, Low and High, the ensemble modelling appears to contribute greater uncertainty than the Monte Carlo modelling, but for the 12hr sub-category, the two are approximately equal. This reflects a lower spread in the ensemble forecasts at lower lead times.

5.3.2 Relative contributions to uncertainty of the different Monte Carlo elements

The same selection of 'stormy' forecasts and a similar approach were used here, as for the comparisons in Section 5.3.1, and again some evidence of the calculations performed is given in Appendix 6. In this case, to remove the ensemble uncertainty (and because the collation and calculations are manually intensive) only the central Ensemble Member 0 was used. A series of runs were carried out for the 'stormy' forecasts with all of the Monte Carlo uncertainties switched on (as on the demonstration website), with all switched off or set to minimum values, and with all but one uncertainty switched off (for each uncertainty in turn).

The second of the two calculation sheets in Appendix 6 lists the individual 'stormy' forecasts, and the ratios OT90/OT50 and OT50/OT10 (based on Ensemble Member 0 only) for each forecast and for each separate uncertainty. The results are summarised in Table 5.2, in the form of values of the two ratios averaged over all 'stormy' forecasts and averaged over each of the three sub-categories defined in Section 5.1. In Table 5.2, a higher number indicates a greater contribution to overall uncertainty (and note, as in Table 5.1, that the minimum possible value of these ratios is one).

Table 5.2 Relative contributions to uncertainty in mean overtopping rate prediction of the different Monte Carlo uncertainty components

General category of uncertainty	Specific single category of uncertainty	Low value uncertainty (OT50/OT10)				High value uncertainty (OT90/OT50)			
		All	12hr	Low	High	All	12hr	Low	High
All uncertainties		3.11	3.13	3.70	2.33	2.47	2.49	2.84	1.98
Wave transformation model	Wind-sea friction	1.07	1.07	1.09	1.06	1.10	1.10	1.11	1.07
	Swell friction	1.07	1.08	1.09	1.06	1.10	1.10	1.11	1.07
	Wave period	1.18	1.18	1.22	1.13	1.18	1.18	1.22	1.12
Nearshore bathymetry	Beach normal	1.07	1.07	1.09	1.06	1.10	1.10	1.11	1.07
	Beach slope	1.07	1.07	1.09	1.06	1.10	1.10	1.11	1.07
	Sea depth	1.07	1.08	1.09	1.06	1.10	1.10	1.11	1.07
Seawall profile	Toe depth	1.08	1.08	1.09	1.06	1.10	1.10	1.11	1.07
	Roughness	1.32	1.32	1.37	1.25	1.30	1.30	1.35	1.24
	Crest level	1.75	1.75	1.85	1.58	1.75	1.74	1.85	1.56
O/T rate formula	Structure factors	2.48	2.49	2.81	2.00	2.12	2.11	2.44	1.70

The figures in Table 5.2 for all 'stormy' forecasts are very close to those for 'stormy' forecasts in the range T+14 to T+27 (the 12hr sub-category). Although based on only a small sample of results, this is consistent with the expectation that the Monte Carlo-based uncertainties are not dependent on forecast lead time (any lead time dependence should be filtered out through use of only Ensemble Member 0).

The figures in Table 5.2 are consistently higher for Low than for All, and consistently lower for High than for All. Although based on only a small sample of results, this appears to be a genuine effect and intuitively correct. If the central prediction of overtopping rate is high anyway, it is likely still to be high even when uncertainties are introduced. If the central prediction is low, introduction of uncertainties could lead to more variability in predictions, some being near zero and some being high.

The greatest contributions to overall uncertainty come from the assumed uncertainties in the overtopping rate calculation formula, followed by seawall crest level, followed by wall roughness, followed by wave period. The other components of uncertainty appear to contribute very little.

Flood forecasting can do little to address the inherent uncertainty in overtopping rate prediction methods. The results suggest that wave transformation model uncertainties have little impact on the final overtopping rate predictions. The figures in Table 5.2

suggest that structure-related parameters contribute the greatest *avoidable* uncertainty and that getting these right is critical. The practical ways in which this contribution to uncertainty could be reduced are through use of more seawall profiles, more accurate seawall crest elevations, more accurate seawall profiles, and choice of the most appropriate overtopping rate prediction method for each particular seawall.

5.3.3 Sensitivity of forecasts to site-specificity of wave and overtopping information

A different way of looking at uncertainties is to consider whether the complete removal of apparently key parameters or processes from the forecasting system would make any difference to the capacity to identify potential coastal flood events. In this context, the actual wave heights and actual overtopping rates matter less than the ability to spot the most severe events. One might consider the range of approaches below to identify occasions when it would be worth taking action to mitigate the potential impacts of coastal flooding, and ask whether each increase in sophistication and cost really adds anything to the forecasting of such events.

from 'do nothing'
or 'just look out of the window'
- through use of only weather (not ocean) forecasts
- through use of only existing offshore wave and sea level forecasts
  - through addition of probabilistic information
  - through addition of measurements
  - through addition of nearshore modelling
  - through addition of overtopping forecasts
    - to 'perfect prediction with hindsight' (although maybe not timely!)

East Anglia is well served with a network of active wave recorders. Most of the nearshore wave recording is funded by the Environment Agency Anglian Region. These data provided an additional opportunity to consider the importance of waves to coastal flood forecasting. An investigation based on Anglian Region measured wave data looked to establish which of the different ways of handling wave information, if any, would add value to identification of the most severe events at a coastal site. Starting from routinely available offshore wave forecasts, would it make any difference progressively to add offshore wave measurements, nearshore wave transformation, nearshore wave measurements, and overtopping prediction?

Two small areas were selected, each containing simultaneous offshore and nearshore wave measurements over the winters of 2006/07 and 2007/08. 'Events' were identified (retrospectively 'forecasted') in several different ways: based on the highest wave heights measured offshore, measured nearshore, or forecast by the UK Waters forecasting model; and also based on overtopping rate predictions from the same three sources of wave height and period data.

Details of the data sets and analysis are given in Appendix 8, testing whether apparently enhanced 'relevance' in wave data adds value to the ability of forecasts to identify events. With the exception of one storm, over two years at two sites, where wave period is influential, it appears that increasing coastal relevance in wave data does little to improve skill in picking the most severe events.

It seems obvious that reliable *nearshore* wave conditions are necessary for prediction of the *absolute* value of mean overtopping rate (for example, 2.0 l/s/m). *Absolute* values would be needed to distinguish between the levels of risk at different locations, and might be needed to determine the appropriate types of warning and response. However, the analysis above for two areas within the Anglian Region suggests that reliable *nearshore* wave conditions are not necessary for prediction of the *rank* of mean overtopping rate (for example, typically fourth highest rate seen in one year). If the purpose of flood forecasting were only to identify a pre-determined number of events per year when mobilisation for potential flooding would be of most value, then *rank* would probably be sufficient.

In conclusion, improved wave transformation modelling and/or nearshore wave measurements would appear to be a relatively low priority.

5.4 Use of probabilistic information in coastal flood forecasting

The potential for use of probabilistic information in coastal flood forecasting is a matter for continued discussion within the Environment Agency. The information presently available from deterministic forecasts, either offshore or at the coast, would also be available through probabilistic forecasting (either directly, or noting that a 50 per cent probability of a threshold being crossed is comparable with a deterministic forecast of its being crossed). Probabilistic forecasting would be slightly less timely, although this would be somewhat offset by the fact that, because an ensemble forecast gives a distribution of forecast values, the forecast generally changes less from run to run than an equivalent deterministic forecast. The main benefit would come through being able to use the additional information content in more efficient flood risk management.

5.4.1 Forecasters' views and desirable improvements to the probabilistic forecasts

The initial reaction to probabilistic information tended to be one of surprise as to why it might be needed in an operational setting. Some thought that uncertainty information would only make the decision-making process more difficult. As the project progressed, the general view changed to recognition that the additional information content would potentially be useful, but that new ways of working might be needed to exploit it fully.

Operationally, forecasting focuses mainly on the coming one or two tidal cycles, extending out to a couple of days before weekends. Deterministic forecasts would continue to play an important role close to an event, but the ensemble would provide important supplementary information on risk. Warnings are issued in the 12-36 hour range. The graph in Figure 2.7b shows that for a major event, there was considerable uncertainty remaining in the 24-hour forecast which would need to be taken into account when issuing warnings and considering appropriate responses. It might at times be important to express some uncertainty in the wording of warnings. Apart from some pressured cases focussing on the current tidal cycle, the slightly delayed availability of the ensemble products compared to the deterministic forecast was not seen as a major problem, provided the deterministic forecast also remained available. However, the particular delivery times for probabilistic forecasts, about 02:00 and 14:00 during the demonstration, fitted poorly with Environment Agency working patterns. Forecasters saw some possible value in a five-day outlook, particularly during periods of high astronomical tides, but nothing beyond that.

Several specific comments could be addressed if and when the developments were implemented for pilot studies or operational use. Too much forecasting output on a single webpage could make it slow to load, particularly over dial-up connections from an emergency control centre. Almost all users found the postage stamps of surge of little use, being too small and running too fast to see any significant detail. Forecasters requested the ability to zoom in or filter plots to focus on their region of interest. Most users would like further help pages and a short training course in how to make best use of probabilistic information. Most users thought there was too much information, including some variables that would not be used in real time. More information in terms of guidance and detail would be needed only when thresholds were crossed. One solution might be for the tables to focus on ‘best estimate’, ‘higher possibility’ and ‘lower possibility’ with the box and whisker format used as the main tool for display of the probabilistic overtopping rate forecasts for overtopping.

5.4.2 New opportunities for forecasters

Probabilistic forecasting offers a broader picture of the forecast. Use of this method might change the way decisions are made to issue flood warnings, and ways of working internally and externally during an incident, particularly in terms of what information is passed on to professional partners. Longer lead time on low probability events gives confidence in subsequent forecasts as the event time comes closer. Ensembles give more opportunity than the deterministic forecast for the duty officer to evaluate the different risk associated with different forecasts. Several Environment Agency respondents made reference to the importance of uncertainty in proximity to warning levels, and in considering worst (and best) case scenarios.

Lower probability information offers the possibility of different levels of preparation, and early warning of the possibility of flooding. For example, a low probability of flooding three tides ahead might prompt closer monitoring and earlier contact with people who may need to take action to mitigate the potential flood losses.

Ensemble forecasts may be the only practical method of receiving early warning of an exceptionally severe event, for example if it requires a number of low probability weather developments to coincide in a particular way. One or two ensemble members might indicate this whilst a deterministic (central estimate) forecast would not.

5.4.3 Involvement of forecasters’ professional partners

Forecasters and those who send warnings work in different ways, in the sense that their responsibilities can vary. Probabilistic flood forecasting could bring benefits through better ways of working. The introduction of new techniques would force change, with the potential to make incident management more efficient.

If probabilistic forecasting were used to improve the accuracy of flood warnings, then the methods used to decide on whether to issue a warning would need to be reviewed. Currently in Southern Region, for example, if the forecast predicts a certain combination of factors, a warning is issued. The additional information content of probabilistic forecasting may lead to several possibilities of conditions, so using this information to decide on a warning could be tricky. The user might continue to issue on the deterministic forecast, but use the probabilistic forecast to provide confidence in decision making. Or the method used to decide on whether to issue a warning might need to vary according to risk, giving rise to a combination of approaches based on the level of risk. Currently in Southern Region, the method used to disseminate a warning to communities is based on the level of risk.

If probabilistic forecasting were used in Environment Agency internal communications during an incident, then training at all incident management levels would be necessary to ensure full understanding of the information. To ensure a nationally consistent approach, an assessment of how forecasters, warning-issuers and incident responders communicate should be made, to understand where to direct appropriate training.

If probabilistic forecasting were used to improve information to professional partners during an incident, then they would need clear advice about the technique of forecasting and appropriate use of its results. This would in turn require a clear picture of the current and future purpose of coastal flood warning. Might the service be extended to include warning partners of stormy conditions that may not cause flooding but may pose a danger to the public? Also, what do partners require from forecasters and warning-issuers, and would provision of probabilistic forecast information assist them with decisions on the actions needed in an incident?

Environment Agency forecasters might benefit from a training module provided by Met Office forecasters already familiar with the interpretation and dissemination of probabilistic forecasts.

Longer lead time forecasts, even up to six to ten days ahead, could be used to provide advance notice to authorities, even at low confidence, to review contingency plans and staff availability, and check stocks of materials such as sandbags.

5.4.4 Conclusions

Our study shows that it is feasible to produce probabilistic forecasts in a realistic, timely and reliable way. The generic parts of the probabilistic forecasting code could be adopted into NFFS, to be used as the need arises. Wave transformation models would be set up area by area, and overtopping rate models point by point, as necessary.

As the end-product of the sequence of meteorological and hydraulic models, overtopping rate will be influenced by all of the component uncertainties introduced at different points in the modelling sequence. Overtopping rate was used to assess the *relative importance* of the different component uncertainties.

The variability of ensemble median overtopping rate forecasts tended to be roughly symmetrical about a median value approximately equal to the mean value (of the ensemble medians). Conversely, the Monte Carlo uncertainties tended to be skewed towards the upper tail, with a mean value consistently higher than the median value.

Based on a fairly limited sample of results analysed in Section 5.3.1, uncertainties introduced through ensemble modelling appear to contribute more than uncertainties introduced through Monte Carlo modelling to the overall uncertainty in forecast overtopping rate. The ensemble-induced uncertainty is lower at shorter lead times, but on major events can remain large less than 24 hours ahead. The Monte Carlo-based uncertainties are not dependent on forecast lead time. The uncertainty, as a ratio of the central value, is less for higher overtopping rates than for lower overtopping rates.

In a different type of uncertainty assessment, two areas within the Anglian Region were selected, each containing simultaneous offshore and nearshore wave measurements. ‘Events’ were identified (retrospectively ‘forecasted’) in several different ways. With the exception of one storm, over two years at two sites, where wave period is influential, it appears that increasing coastal relevance in wave data does little to improve skill in picking the most severe events. Improving wave transformation modelling and/or nearshore wave measurements would appear to be a relatively low priority.

The greatest contributions to nearshore and coastal uncertainty come from the assumed uncertainties in the overtopping rate calculation formula, followed by seawall crest level, followed by wall roughness, followed by wave period. Flood forecasting can do little to address the inherent uncertainty in overtopping rate prediction methods. The results suggest that wave transformation model uncertainties have little impact on the final overtopping rate predictions. Structure-related parameters appear to contribute the greatest *avoidable* uncertainty and getting these right is important. The practical ways in which these structure parameters could be improved include use of more seawall profiles, more accurate seawall profiles (particularly crest levels), and choice of the most appropriate overtopping rate prediction method for each particular seawall.

The additional information content of probabilistic forecasts is potentially useful, but new ways of working may be needed to exploit it fully to make incident management more efficient. Probabilistic forecasting provides a broader picture of the forecast. Lower probability information offers the possibility of different levels of preparation, and early warning of the possibility of flooding. Ensemble forecasts may be the only practical method of receiving early warning of an exceptionally severe event. This might change the way decisions are made to issue flood warnings, the ways of working internally in an incident, and the information passed on to professional partners.

The recommendation (already made in Section 4.2.5) carried forward to Chapter 7 of this report is for a pilot study over a large open coast area. This would mean near operational forecasting runs, including wave transformation and overtopping modelling, preferably within NFFS, for several coastal sites, with the involvement of Environment Agency forecasters.

6. Conclusions

6.1 Overall comments and evaluation

This project included development, demonstration and evaluation of several modelling elements for use in coastal flood forecasting. These elements are grouped under the four headings below, any or all of which could be developed further for operational use:

- surge ensemble modelling, continuing operationally for the whole of the UK, in a way consistent with the MOGREPS ensemble approach used for wind forecasting;
- temporary wave ensemble modelling, specific to the South-East Irish Sea, for demonstration use;
- wave transformation and overtopping models, specific to the South-East Irish Sea, for use in the demonstration area;
- a generic approach to the handling of a large number of uncertainties, including uncertainties in what might appear to be fixed values such as toe depth and crest elevation.

A real-time demonstration of the overall probabilistic coastal flood forecasting system provided, through the offshore, nearshore and shoreline zones, a distribution of each forecast parameter, at each prediction point, at 15-minute timesteps. The feasibility of surge ensemble forecasting and probabilistic coastal flood forecasting was thus demonstrated. Evaluation of the overall system showed sufficient accuracy, timeliness, reliability, intelligibility and usefulness for operational use.

6.2 Surge ensemble forecasts

The storm surge ensemble extends the existing surge forecast system with an explicit high quality prediction of the probability of reaching a given water level. This permits more quantitative management of flood risk, and is highly valued by Met Office forecasters for the range of scenarios which it provides. The ensemble also produces a more accurate central estimate of water level beyond the first day of the forecast. The surge ensemble should be made operational to provide a fully supported and resilient ongoing service. Appropriate documentation and training should be provided to both Met Office and Environment Agency forecasters to maximise the benefit obtained from the new system. The potential value of forecasts to five days or beyond should be investigated, alongside the identification of preparatory actions appropriate to the inevitably lower confidence associated with longer range forecasts.

The development of the surge ensemble has highlighted the relatively large error of the harmonic tide predictions which are added to the surge forecasts. This reinforces the importance of existing work to improve tide predictions based on data from the days or weeks immediately before each forecast. For optimal performance, the ensemble should be extended to allow for any remaining error from the harmonic tide prediction or other sources. To produce accurate probability distributions in the 6-12 hour range of the forecast, the ensemble would also need to sample the error in the surge initial state.

The surge ensemble forecasting system could be reconfigured fairly easily for national operational use within the National Flood Forecasting System of England and Wales. The specific recommendations carried forward to Chapter 7 are to:

- implement the surge ensemble forecasting system for operational use;
- produce documentation and training for Environment Agency and Met Office forecasters;
- refine tide predictions based on data from days immediately before a forecast;
- investigate the benefits of extending the surge ensemble to five days, and of introducing perturbations to the surge initial state.

6.3 Wave ensemble forecasts

Within the project, it was impractical to develop and demonstrate a near operational wave ensemble forecasting system to cover the whole of the UK, mainly because run times would have been incompatible with the timeliness required of flood forecasts. However, the possibility of generating and using ensemble wave forecasts in coastal flood forecasting was demonstrated successfully.

The method used to demonstrate wind-sea wave ensemble forecasts is consistent with the MOGREPS approach used for wind and surge, but was specific to the South-East Irish Sea area shown in Figure 2.8 where swell wave energy is low. Ensemble modelling was not applied to swell waves, but instead the same forecast was used 24 times so that the information and file formats associated with ensemble modelling could be coded and demonstrated.

The evaluation presented in Section 3.2 shows that the method generally provides a sensible offshore wave forecast for the demonstration area, and that it generates a spread of wave parameters close to that which would be expected from a true wave ensemble. A separate feasibility study for nationwide implementation of a wave ensemble forecasting system, including both wind-sea and swell, is in progress. Depending on the results, the offshore wave ensemble forecasting system might be implemented at the Met Office on the new supercomputer commissioned during 2008. If this is done, then a pilot study on the value of extending ensemble wave forecasting to coastal flood forecasting would be useful. This would mean near-operational forecasting runs, coupled to wave transformation and possible overtopping modelling, preferably within NFFS. The recommendations carried forward to Chapter 7 are for:

- a scoping and methodology study into how the wave ensemble forecasting would be used in coastal flood forecasting;
- development of a near-operational pilot forecasting system in one region;
- testing, verification and recommendations for implementation of an operational system.

6.4 Wave transformation and overtopping forecasts

The coastal flood forecasting concepts developed in this project assume that wave transformation will be carried out on a regional (say 50-200 km length of coastline) basis, using wave transformation models appropriate to the technical challenges of each area. The capability to accept and process offshore ensemble wave forecasts was demonstrated successfully for the South-East Irish Sea area shown in Figure 2.8.

Similarly, it is assumed that overtopping rate forecasts will be carried out on a site-specific basis, for as many locations as needed to cover the range of seawall types and flood risks existing within a region of interest. For each site of interest, appropriate surge and nearshore wave forecast grid points are chosen, together with information on the seawall profile and crest level. The capability to accept ensemble surge forecasts, transformed ensemble wave forecasts and seawall profile information was demonstrated for two seawalls within the demonstration area.

The evaluation presented in Chapter 4 shows that the models generally provide sensible and timely nearshore wave and coastline overtopping rate forecasts for the demonstration sites. Whether they provide sufficient additional value (relative to using only offshore forecasts) in terms of forecasting potential flooding events is unclear. Considerable effort would be required to set up the necessary area-specific nearshore wave models and site-specific overtopping models for other areas. These models could be set up incrementally, prioritising the areas of England and Wales most vulnerable to coastal flooding. Implementation of wave transformation and overtopping modelling should be considered on an area-by-area basis, and perhaps be limited to areas where there is a need for it, for example, where existing methods appear poor at identifying potential flood events.

The recommendation carried forward to Chapter 7 is as follows: if a pilot study of nearshore wave ensemble (Section 6.3) and/or probabilistic coastal flood forecasting (Section 6.5) is undertaken, it should include nearshore wave and overtopping prediction, involving site-specific wave and overtopping model development, testing and verification.

6.5 Probabilistic coastal forecasts

This study demonstrated the capability to propagate probabilistic information through the forecasting system to site-specific nearshore wave conditions and coastline overtopping rates. The source uncertainties introduced through Monte Carlo simulation can be tailored to individual sites, using as many or as few uncertainties as required.

Probabilistic models generally provided sensible and timely nearshore wave and overtopping rate forecasts for the demonstration sites. The forecasts showed a plausible spread of values and the capability to forecast probabilities of exceeding the different thresholds of interest. Whether they provide sufficient additional value (relative to deterministic or ensemble offshore forecasts) in terms of forecasting potential flooding events and actions to mitigate losses is unclear. One could imagine Environment Agency forecasters seeing the benefit of identifying low-probability high-impact events with a longer lead time than would otherwise be available.

The contributions to uncertainty were assessed in terms of impact upon forecast mean overtopping rate. Contributions to uncertainty from ensemble surge and wave modelling are higher than those from Monte Carlo simulation of nearshore and coastal uncertainties. The greatest contributions to nearshore and coastal uncertainty come from assumed uncertainties in the overtopping rate calculation formula, followed by seawall crest level, followed by wall roughness. Improving wave transformation modelling would appear to be a relatively low priority.

The probabilistic coastal flood forecasting models were coded to be compatible with NFFS, but significant effort would be required to extend them to other areas of England and Wales and to make them operational. Although the hydraulic models needed for the nearshore and coastal zones would be site-specific, the probabilistic coding and display formats are largely generic. If the probabilistic methods are taken up for operational use, perhaps after a further period of forecaster evaluation, there would be efficiency savings in implementing them nationwide, rather than area by area. A pilot study of near-operational probabilistic coastal flood forecasting could then be undertaken within NFFS, followed by further verification and evaluation. The specific recommendations carried forward to Chapter 7 are for:

- a review of areas of England and Wales that might benefit from probabilistic coastal forecasts;
- adoption of probabilistic code and display formats into NFFS;
- development of a near-operational pilot forecasting system in one region;
- testing, verification and recommendations for implementation of an operational system.

7. Recommendations

The main recommendations, based on the conclusions and developments from this project, are given in approximate order of priority (***** maximum) in Sections 7.1 to 7.5. They are collated into an outline implementation plan in Section 7.6.

Section 5.2 of the first project report (Environment Agency, 2007) outlined several ideas for new work. These were not the primary recommendations of the project, which could not be made until completion of the project, but loosely related ideas that might assist take-up of the developments in this project, or extension of their use to other flood-risk applications.

- Decision support tool (to assist assimilation and effective use of probabilistic forecast information).
- Potential for adoption of the new probabilistic methods into fluvial or urban flood forecasting.
- Appropriate trigger levels based on overtopping forecasts.
- Extension of coastal flood forecasting to include inundation modelling.
- Extension of coastal flood forecasting to include morphological changes.

Of these five ideas, only ‘decision support tool’ and ‘appropriate trigger levels’ are relevant to the recommendations of this project, and those ideas are assimilated into Sections 7.3 and 7.2 respectively.

7.1 Surge ensemble forecasting (*****)

Nationwide surge ensemble forecasting has been developed, demonstrated in near operational conditions, and evaluated. Additionally, it has been viewed with interest by Environment Agency forecasters outside the Project Team and Project Board.

The Met Office is continuing to run the surge ensemble forecasting beyond the demonstration period, to allow for the possibility of its becoming a permanent service. As the surge ensemble forecasting clearly works, and is accepted as potentially useful by Environment Agency forecasters, it is recommended to continue the surge ensemble forecasting, moving to operational form as soon as convenient.

This recommendation is already accepted, with operational implementation proposed during 2009/2010. The specific action points to implement this recommendation are:

- national implementation of surge ensemble forecasting;
- documentation and training;
- maintenance and continued delivery of surge ensemble forecasting.

7.2 Astronomical tide and flood forecasting thresholds (***)

Refinement of astronomical tidal predictions and review of thresholds are two separate topics but are linked here as both would complement the adoption of surge ensemble forecasting.

The natural time to undertake these refinements would be calendar year 2009, to be ready for operational use of surge ensemble forecasts. The specific action points to implement this recommendation are:

- refinement of tidal predictions (Section 7.2.1);
- refinement of thresholds (Section 7.2.2);
- implementation within NFFS.

7.2.1 Refinement of astronomical tidal predictions

The subtleties of interpretation and evaluation of surge ensemble forecasting can be confused by a lack of accuracy in astronomical tidal prediction. The difference (residual) between measured sea level and predicted astronomical tide, at any instant, is usually taken as representing surge, and this value is used for comparison with surge forecasts. However, a phase error in astronomical tidal prediction of as little as ten minutes can introduce a significant residual component which is not a surge. This effect is more relevant in evaluation than in practical use of forecasts. Current research is directed towards the best way of correcting such phase errors, with reference to sea level data measured locally over the preceding few days.

7.2.2 Refinement of thresholds

Refined surge and sea level forecasts with probabilistic content deserve refined thresholds of interest to flood forecasters. Some existing thresholds are nominal and would only rarely occur, and the existence of probabilistic thresholds offers new possibilities for defining thresholds.

Flood risk depends not only on meteorological conditions, but also on land use, number of people, animals, vehicles, and/or buildings in the area, and the potential to move people or assets to safer places or to close promenades or highways. The EurOtop project has recommendations for tolerable discharges, but it would be of value to collate experience of Environment Agency, Maritime Districts, and other owners with overtopping rate forecasts and warnings. Overtopping rate thresholds could be refined to improve guidelines for potential responses to high overtopping rate forecasts.

7.3 Environment Agency use of probabilistic forecasts (***)

Probabilistic forecast information would be of little (possibly even negative) value to Environment Agency forecasters and warning-issuers, if they were unwilling or unable to use it. The initial reaction to probabilistic information tended to be one of polite curiosity, but with growing experience most forecasters begin to see some potential value to flood forecasting and warning.

The natural time for this internal development would be calendar year 2009, to be ready for operational use of surge ensemble forecasts. The specific action points to implement this recommendation are:

- review and discussion of probabilistic forecasts within the Environment Agency;

- development of procedures (e.g. Sections 7.3.1 and/or 7.3.2) for ways of working with probabilistic forecasts;
- documentation and training.

7.3.1 Standard operating procedures

Even if the only modelling element taken forward for operational use was the surge ensemble forecasting, it would be useful to have a consistent approach to its use by flood forecasters and warning-issuers. This could be developed entirely within the Environment Agency, but might benefit from Met Office experience in the interpretation and use of ensemble forecasts.

Probably the best way forward here would be to gather the experience of forecasters in the form of new procedures or work instructions for the use of probabilistic flood forecasts.

7.3.2 Decision support

When Environment Agency forecasters gain experience in when and how best to use probabilistic information, a support tool could be developed to assist decisions to be made as a result of forecasting. Forecasters, warning-issuers and emergency services take a series of decisions about warnings and actions in response to flooding prompted initially by crossing of thresholds of wave height, still water level and/or overtopping rate and volume. With probabilistic forecasting, there would be different probabilities of exceeding different thresholds at different locations and for different variables – potentially an order of magnitude more information than at present. A decision support tool could assist in assimilating all of the available information in a consistent way, for training and/or operational use.

7.4 Ensemble wave forecasting (**)

Ensemble wave forecasting is a lower priority, with less clear benefits to flood forecasting, than surge ensemble forecasting. However, it is complementary to ensemble forecasting of other weather and metocean variables, and seems a natural development at some stage in the future. The present project used ensemble wave forecasts from a temporary system specific to the South-East Irish Sea.

Development of a nationwide operational wave ensemble forecasting system would involve significant research and development, requiring different wave modelling techniques to those used for the South-East Irish Sea forecasting demonstration. Prior to that, further pilot studies are recommended, building on the work of this project. Development of offshore ensemble wave forecasting is being partially funded by the Met Office Public Weather Service budget. An outline project description and budget has been prepared for a pilot study covering extension of wave ensemble modelling through to the coast. This would involve a suitable offshore wave model configuration, nearshore wave transformation and overtopping rate prediction, evaluation of the system for use in coastal flood forecasting, and an implementation plan.

As a lower priority than surge ensemble forecasting, funding for this pilot study, if taken up, could follow the implementation of surge ensemble forecasting, with development in 2010/11 and demonstration and evaluation the following financial year. The specific action points to implement this recommendation are:

- methodology and scoping study for generic wave ensemble forecasting system;
- development of the wave ensemble forecasting system;
- testing and verification in a pilot study in one region, and recommendations for national implementation if appropriate.

7.5 Probabilistic coastal flood forecasting (**)

As with ensemble wave forecasting this is a lower priority, with less clear benefits to forecasting, than surge ensemble forecasting, and it would not be part of the Met Office ensemble suite of forecasting models. It would be inappropriate to commit to nationwide adoption of the methods developed within this project without further discussion and evaluation within the Environment Agency (e.g. Section 7.3 above).

It seems natural to move forward with this discussion to assess which areas would benefit from probabilistic wave transformation and overtopping predictions, based on the findings of this project. This is best done soon after completion of this project, but, as with wave ensemble forecasting, any serious development and implementation work would not begin before 2010/11.

A pilot study is suggested. This would require adoption of the code developed in this project into NFFS, and additional probabilistic display formats in NFFS, similar to those used in the present project. Probabilistic nearshore wave and overtopping rate forecasting would be run in near-operational fashion over a winter period in one large area with several overtopping rate prediction locations. This could be run as a single project with the wave ensemble pilot study, but otherwise either or both could be run as individual studies. The specific action points to implement this recommendation are:

- a review of priority areas for probabilistic forecasting;
- adoption of probabilistic code and plots into NFFS;
- development of site-specific nearshore wave and overtopping models;
- testing and verification in a pilot study in one region, and recommendations for national implementation if appropriate.

7.6 Implementation plan

This section gathers the recommendations and action points made in Sections 7.1 to 7.5 as an outline implementation plan in Figure 7.1. Each item is accompanied by a budget price and an indication of when it might be undertaken. This programme will be considered by the Environment Agency Implementation Team.

Section reference and description of recommendation to the Environment Agency Implementation Team	Priority	Scope cost	2008/09 quarters				2009/10 quarters				2010/11 quarters				2011/12 quarters				2012/13 quarters			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
7.1 Surge ensemble forecasting	*****																					
Development, testing and verification		Done																				
Implementation, documentation, training		£150,000																				
Maintenance and delivery (cost per year)		£110,000																				
7.2 Astronomical tide and threshold levels	***																					
Astronomical tide		£50,000																				
Threshold levels and probabilistic thresholds		£50,000																				
... implementation, maintenance and delivery											..	..										
7.3 EA use of probabilistic forecasts	***																					
Review and discussion		£20,000																				
Procedures, documentation, implementation		£20,000																				
7.4 Ensemble wave forecasting pilot	**																					
Methodology and scoping study		£20,000																				
Development		£100,000																				
Testing and verification		£75,000																				
... implementation, maintenance and delivery																					..	..
7.5 Probabilistic coastal forecasting pilot	**																					
Review of priority areas within EA		£20,000																				
Adoption of code and plots into NFFS		£30,000																				
Wave and overtopping model (cost per area)		£50,000																				
Testing and verification (cost per area)		£40,000																				
... implementation, maintenance and delivery																					..	..

Figure 7.1 Implementation programme

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List of abbreviations

AWAC	Automatic Wave And Current recording device
BODC	British Oceanographic Data Centre
BSS	Brier Skill Score
CD	Chart Datum
CS3, CS3X	POL operational surge prediction model
ECMWF	European Centre for Medium-range Weather Forecasting
FEWS	Flood Early Warning System (Delft Hydraulics software)
FREE	Flood Risk from Extreme Events (a research programme)
FRMRC	Flood Risk Management Consortium
GRIB, GRIB2	GRIdded Binary (meteorological data format)
H_s	Significant wave height
MOGREPS	Met Office Global and Regional Ensemble Prediction System
MSL	Mean Sea Level
NaFRA	National Flood Risk Assessment
NDBC	National Data Buoy Center (USA)
NFFS	National Flood Forecasting System
NPD2	National Property Database
OD, ODN	Ordnance Datum (Newlyn)
OT10, OT50, OT90	Percentiles of the distribution of forecast overtopping rate
PDF	Probability Distribution Function
POL	Proudman Oceanographic Laboratory
q	Overtopping rate
REV	Relative Economic Value
RMSE	Root Mean Square Error
ROC	Relative Operating Characteristics
T_m, T_{m01}, T_{m10}, T_{m02}	Mean wave period
T_p	Peak wave period
TRITON	NW Region NFFS module for coastal flood forecasting
WES	Wallingford Environmental Surveys
XML	eXtensible Markup Language (data format)

Appendix 1 Demonstration website, forecast formats and list of forecast parameters

A secure website was set up to disseminate the forecasts and threshold crossing alerts. The website was set up to roughly replicate the output style of NW Region TRITON and/or Delft FEWS so that Environment Agency users would be relatively familiar with the types of output, whilst being able to see the probabilistic output.

The main page (Figure A1.1) provides a summary of threshold crossing status at all coastal structures (for the demonstration there are two simulated structures) for the forthcoming high tides. As well as displaying the appropriate threshold crossing status colour, the percentage likelihood of exceedence is also quoted.

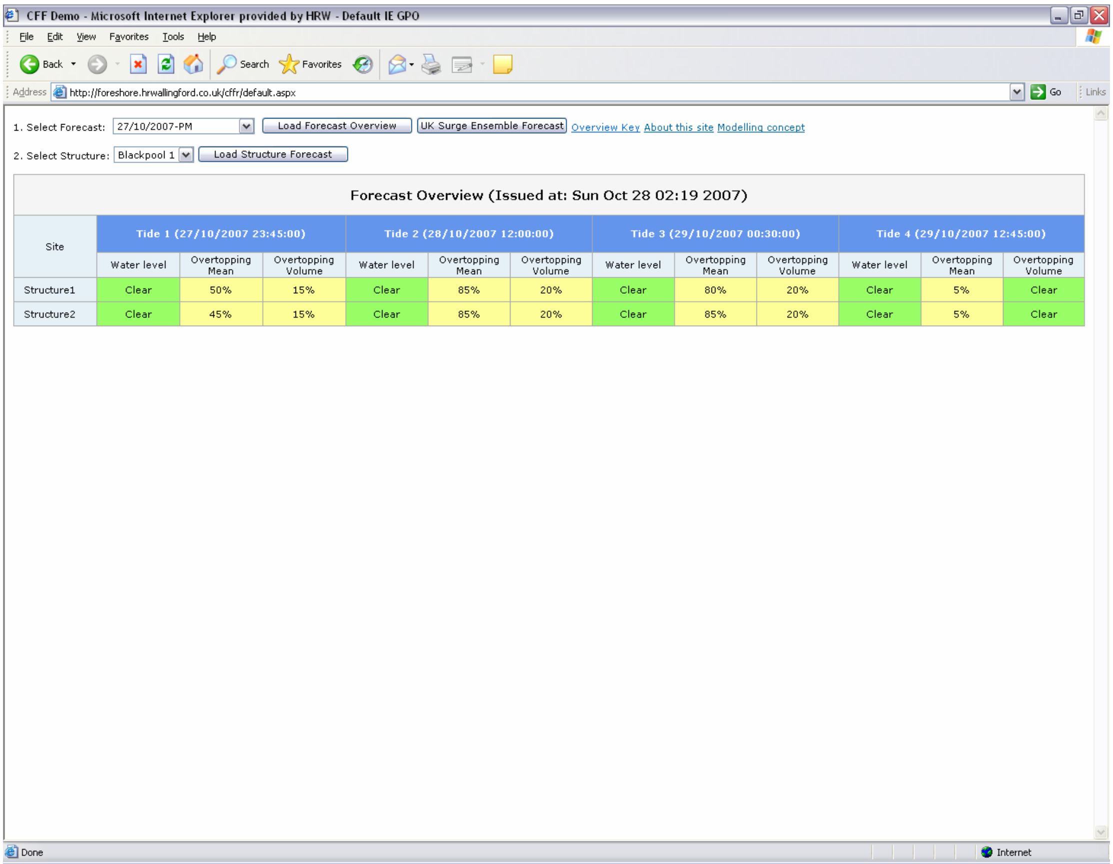
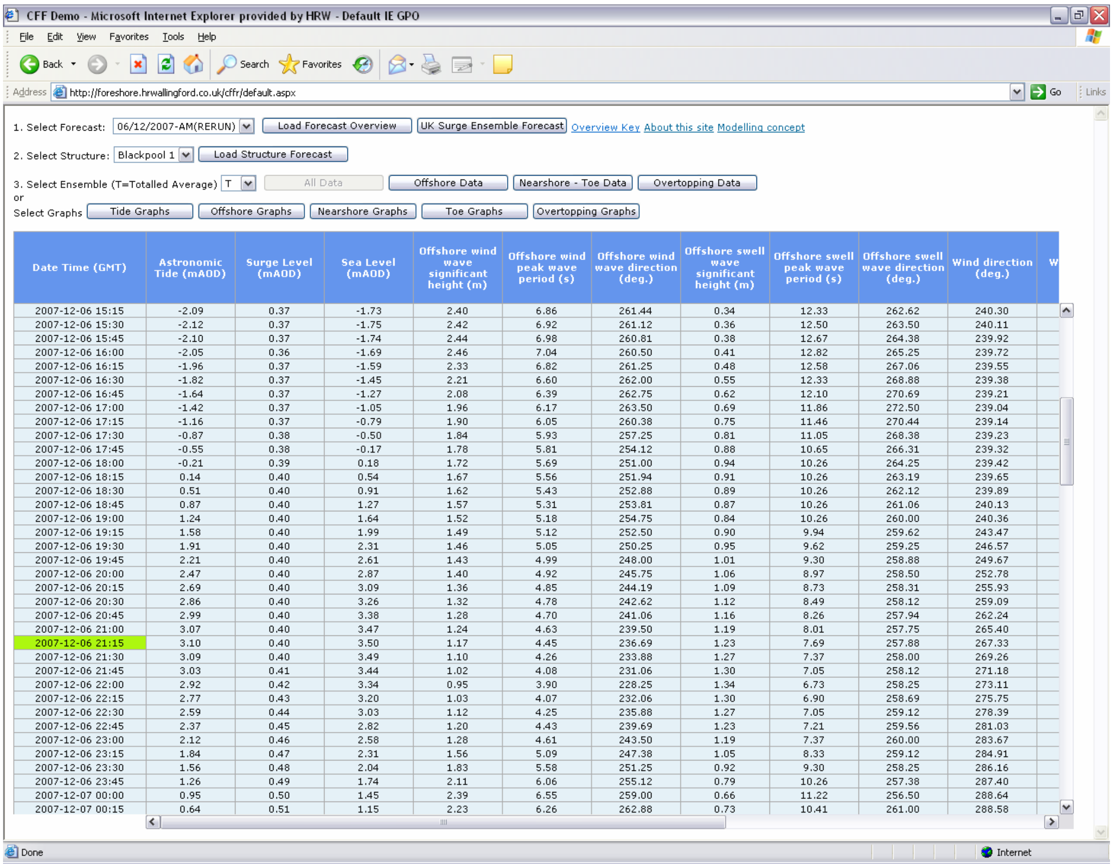


Figure A1.1 Coastal flood forecasting demonstration website main page

Surge ensemble model forecasts are provided under the UK Surge Ensemble Forecast tab. This includes surge forecasts for sites throughout the UK in the graphical formats illustrated in Section 2.5.

All forecasts produced were made available throughout the duration of the forecast demonstration and evaluation stages of the project. This was so that post-event analysis could be carried out at the convenience of the Environment Agency and Project Team.

Tables of ensemble and averaged variables, as illustrated in Figure A1.2, are sorted into similar groups: offshore, nearshore and overtopping. Times of high water are highlighted in the tables.



Date Time (GMT)	Astronomic Tide (mAOD)	Surge Level (mAOD)	Sea Level (mAOD)	Offshore wind wave significant height (m)	Offshore wind peak wave period (s)	Offshore wind wave direction (deg.)	Offshore swell wave significant height (m)	Offshore swell peak wave period (s)	Offshore swell wave direction (deg.)	Wind direction (deg.)	W
2007-12-06 15:15	-2.09	0.37	-1.73	2.40	6.86	261.44	0.34	12.33	262.62	240.30	
2007-12-06 15:30	-2.12	0.37	-1.75	2.42	6.92	261.12	0.36	12.50	263.50	240.11	
2007-12-06 15:45	-2.10	0.37	-1.74	2.44	6.98	260.81	0.38	12.67	264.38	239.92	
2007-12-06 16:00	-2.05	0.36	-1.69	2.46	7.04	260.50	0.41	12.82	265.25	239.72	
2007-12-06 16:15	-1.96	0.37	-1.59	2.33	6.82	261.25	0.48	12.58	267.06	239.55	
2007-12-06 16:30	-1.82	0.37	-1.45	2.21	6.60	262.00	0.55	12.33	268.88	239.38	
2007-12-06 16:45	-1.64	0.37	-1.27	2.08	6.39	262.75	0.62	12.10	270.69	239.21	
2007-12-06 17:00	-1.42	0.37	-1.05	1.96	6.17	263.50	0.69	11.86	272.50	239.04	
2007-12-06 17:15	-1.16	0.37	-0.79	1.90	6.05	260.38	0.75	11.46	270.44	239.14	
2007-12-06 17:30	-0.87	0.38	-0.50	1.84	5.93	257.25	0.81	11.05	268.38	239.23	
2007-12-06 17:45	-0.55	0.38	-0.17	1.78	5.81	254.12	0.88	10.65	266.31	239.32	
2007-12-06 18:00	-0.21	0.39	0.18	1.72	5.69	251.00	0.94	10.26	264.25	239.42	
2007-12-06 18:15	0.14	0.40	0.54	1.67	5.56	251.94	0.91	10.26	263.19	239.65	
2007-12-06 18:30	0.51	0.40	0.91	1.62	5.43	252.88	0.89	10.26	262.12	239.89	
2007-12-06 18:45	0.87	0.40	1.27	1.57	5.31	253.81	0.87	10.26	261.06	240.13	
2007-12-06 19:00	1.24	0.40	1.64	1.52	5.18	254.75	0.84	10.26	260.00	240.36	
2007-12-06 19:15	1.58	0.40	1.99	1.49	5.12	252.50	0.90	9.94	259.62	243.47	
2007-12-06 19:30	1.91	0.40	2.31	1.46	5.05	250.25	0.95	9.62	259.25	246.57	
2007-12-06 19:45	2.21	0.40	2.61	1.43	4.99	248.00	1.01	9.30	258.88	249.67	
2007-12-06 20:00	2.47	0.40	2.87	1.40	4.92	245.75	1.06	8.97	258.50	252.78	
2007-12-06 20:15	2.69	0.40	3.09	1.36	4.85	244.19	1.09	8.73	258.31	255.93	
2007-12-06 20:30	2.86	0.40	3.26	1.32	4.78	242.62	1.12	8.49	258.12	259.09	
2007-12-06 20:45	2.99	0.40	3.38	1.28	4.70	241.06	1.16	8.26	257.94	262.24	
2007-12-06 21:00	3.07	0.40	3.47	1.24	4.63	239.50	1.19	8.01	257.75	265.40	
2007-12-06 21:15	3.10	0.40	3.50	1.17	4.45	236.69	1.23	7.69	257.88	267.33	
2007-12-06 21:30	3.09	0.40	3.49	1.10	4.26	233.88	1.27	7.37	258.00	269.26	
2007-12-06 21:45	3.03	0.41	3.44	1.02	4.08	231.06	1.30	7.05	258.12	271.18	
2007-12-06 22:00	2.92	0.42	3.34	0.95	3.90	228.25	1.34	6.73	258.25	273.11	
2007-12-06 22:15	2.77	0.43	3.20	1.03	4.07	232.06	1.30	6.90	258.69	275.75	
2007-12-06 22:30	2.59	0.44	3.03	1.12	4.25	235.88	1.27	7.05	259.12	278.39	
2007-12-06 22:45	2.37	0.45	2.82	1.20	4.43	239.69	1.23	7.21	259.56	281.03	
2007-12-06 23:00	2.12	0.46	2.58	1.28	4.61	243.50	1.19	7.37	260.00	283.67	
2007-12-06 23:15	1.84	0.47	2.31	1.56	5.09	247.38	1.05	8.33	259.12	284.91	
2007-12-06 23:30	1.56	0.48	2.04	1.83	5.58	251.25	0.92	9.30	258.25	286.16	
2007-12-06 23:45	1.26	0.49	1.74	2.11	6.06	255.12	0.79	10.26	257.38	287.40	
2007-12-07 00:00	0.95	0.50	1.45	2.39	6.55	259.00	0.66	11.22	256.50	288.64	
2007-12-07 00:15	0.64	0.51	1.15	2.23	6.26	262.88	0.73	10.41	261.00	288.58	

Figure A1.2 Website example table

Time series graphs of ensemble and averaged variables, as illustrated in Figure A1.3 (and as illustrated in Section 2.6.5) were also made available. Where appropriate the thresholds are displayed on the graphs. Similarly, these are sorted into groups: sea level, offshore, nearshore, toe and overtopping. A complete set of diagrams, illustrating the 32 different graphs used on the demonstration website, is given in Figures A1.4 to A1.35 at the end of this appendix. Note that the rapidly varying nearshore peak wave period seen in Figure A1.20 is a realistic representation of the bi-modal sea conditions, made up of approximately equal wind-sea and swell components, in which dominance between the two components alternates frequently.

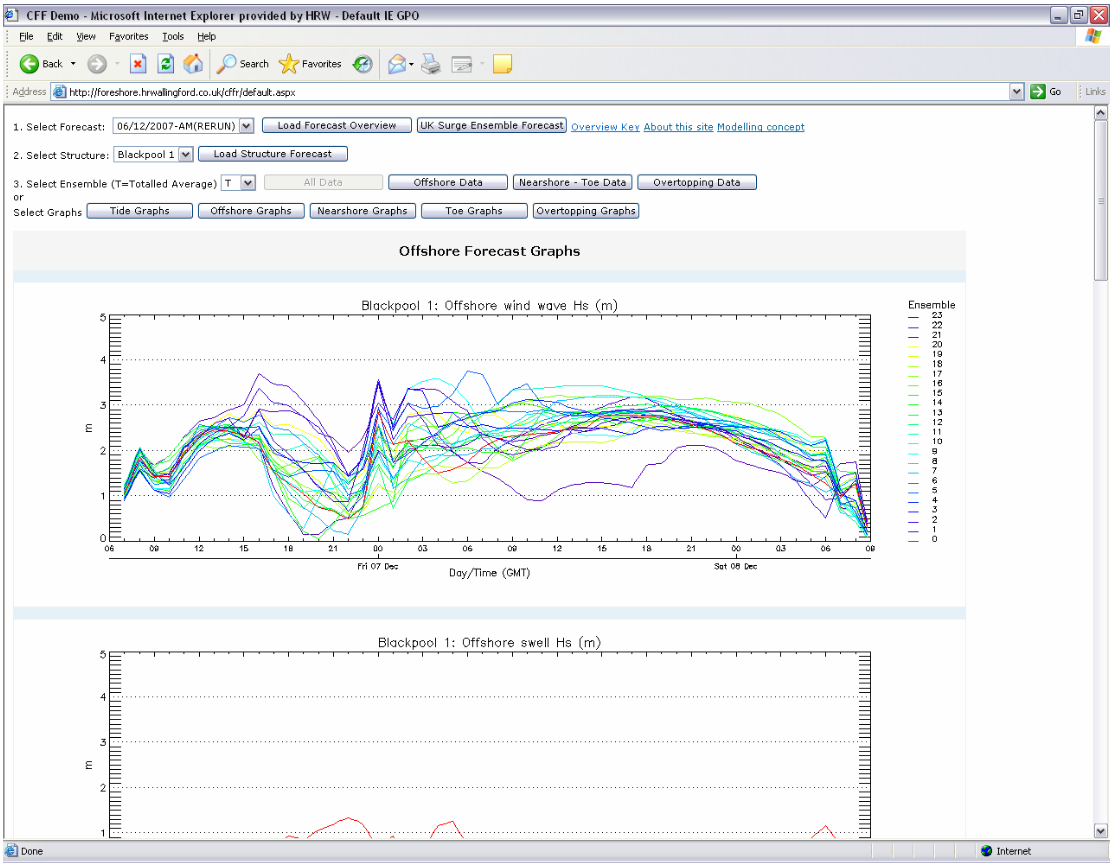


Figure A1.3 Website example graphs

Tables A1.1 and A1.2 list all the parameters available from the forecasting software, for each 15-minute time step, for each coastal location and, where relevant, for each ensemble member. These include several different variables and, where relevant, several different percentiles within the probabilistic distribution of that variable. All of these parameters are retained in an XML file, consistent with guidelines for producing output compatible with Delft FEWS. Only a sample of these parameters are displayed on the demonstration website, but the larger number available in the XML output is intended to give greater flexibility in tailoring forecast output formats in the future.

The particular graphical formats used on the demonstration website would need to be re-coded for adoption within Delft FEWS, which, when the demonstration began, had little scope to display probabilistic forecasts. Apart from that, the products of the probabilistic coastal flood forecasting system are as near ready for adoption into NFFS as is practical within the present project.

All new program code developed by HR Wallingford during this project is available to the Environment Agency. Details will be provided in separate code documentation.

Table A1.1 XML output parameters for each ensemble member and each forecast time step

Astronomic tide
Surge level
Sea level
Offshore wind wave significant height
Offshore wind peak wave period
Offshore wind wave direction
Offshore swell wave significant height
Offshore swell peak wave period
Offshore swell wave direction
Nearshore wind wave significant height
Nearshore wind peak wave period
Nearshore wind wave direction
Nearshore swell wave height
Nearshore swell peak wave period
Nearshore swell wave direction
Nearshore combined wave significant height
Nearshore combined wave peak period
Nearshore combined wave direction
Toe wave significant height
Toe wave mean period Tm-10
Toe wave direction
Wind direction
Wind speed
Mean of the mean overtopping rate
Maximum of the mean overtopping rate
Standard deviation of the mean overtopping rate
Mean of the maximum (per wave) overtopping volume
Maximum of the maximum (per wave) overtopping volume
Standard deviation of the maximum (per wave) overtopping volume
Median overtopping volume
Total overtopping volume (cumulative median overtopping volume)
Overtopping mean rate 1 percentile
Overtopping mean rate 5 percentile
Overtopping mean rate 10 percentile
Overtopping mean rate 15 percentile
Overtopping mean rate 20 percentile
Overtopping mean rate 25 percentile
Overtopping mean rate 30 percentile
Overtopping mean rate 35 percentile
Overtopping mean rate 40 percentile
Overtopping mean rate 45 percentile
Overtopping mean rate 50 percentile
Overtopping mean rate 55 percentile
Overtopping mean rate 60 percentile
Overtopping mean rate 65 percentile
Overtopping mean rate 70 percentile
Overtopping mean rate 75 percentile
Overtopping mean rate 80 percentile
Overtopping mean rate 85 percentile
Overtopping mean rate 90 percentile
Overtopping mean rate 95 percentile

Overtopping mean rate 99 percentile
Maximum (per wave) overtopping volume 1 percentile
Maximum (per wave) overtopping volume 5 percentile
Maximum (per wave) overtopping volume 10 percentile
Maximum (per wave) overtopping volume 15 percentile
Maximum (per wave) overtopping volume 20 percentile
Maximum (per wave) overtopping volume 25 percentile
Maximum (per wave) overtopping volume 30 percentile
Maximum (per wave) overtopping volume 35 percentile
Maximum (per wave) overtopping volume 40 percentile
Maximum (per wave) overtopping volume 45 percentile
Maximum (per wave) overtopping volume 50 percentile
Maximum (per wave) overtopping volume 55 percentile
Maximum (per wave) overtopping volume 60 percentile
Maximum (per wave) overtopping volume 65 percentile
Maximum (per wave) overtopping volume 70 percentile
Maximum (per wave) overtopping volume 75 percentile
Maximum (per wave) overtopping volume 80 percentile
Maximum (per wave) overtopping volume 85 percentile
Maximum (per wave) overtopping volume 90 percentile
Maximum (per wave) overtopping volume 95 percentile
Maximum (per wave) overtopping volume 99 percentile
Number of Monte Carlo runs
Convergence ratio

Table A1.2 XML output parameters for the overall forecast

Astronomic tide
Surge level
Sea level
Offshore wind wave significant height
Offshore wind peak wave period
Offshore wind wave direction
Offshore swell wave significant height
Offshore swell peak wave period
Offshore swell wave direction
Nearshore wind wave significant height
Nearshore wind peak wave period
Nearshore wind wave direction
Nearshore swell wave height
Nearshore swell peak wave period
Nearshore swell wave direction
Nearshore combined wave significant height
Nearshore combined wave peak period
Nearshore combined wave direction
Toe wave significant height
Toe wave mean period Tm-10
Toe wave direction
Wind direction
Wind speed
Mean of the mean overtopping rate
Maximum of the mean overtopping rate
Standard deviation of the mean overtopping rate
Mean of the maximum (per wave) overtopping volume
Maximum of the maximum (per wave) overtopping volume
Standard deviation of the maximum (per wave) overtopping volume
Median overtopping volume
Total overtopping volume (cumulative median overtopping volume)
Overtopping mean rate 1 percentile
Overtopping mean rate 5 percentile
Overtopping mean rate 10 percentile
Overtopping mean rate 15 percentile
Overtopping mean rate 20 percentile
Overtopping mean rate 25 percentile
Overtopping mean rate 30 percentile
Overtopping mean rate 35 percentile
Overtopping mean rate 40 percentile
Overtopping mean rate 45 percentile
Overtopping mean rate 50 percentile
Overtopping mean rate 55 percentile
Overtopping mean rate 60 percentile
Overtopping mean rate 65 percentile
Overtopping mean rate 70 percentile
Overtopping mean rate 75 percentile
Overtopping mean rate 80 percentile
Overtopping mean rate 85 percentile
Overtopping mean rate 90 percentile
Overtopping mean rate 95 percentile
Overtopping mean rate 99 percentile

Maximum (per wave) overtopping volume 1 percentile
Maximum (per wave) overtopping volume 5 percentile
Maximum (per wave) overtopping volume 10 percentile
Maximum (per wave) overtopping volume 15 percentile
Maximum (per wave) overtopping volume 20 percentile
Maximum (per wave) overtopping volume 25 percentile
Maximum (per wave) overtopping volume 30 percentile
Maximum (per wave) overtopping volume 35 percentile
Maximum (per wave) overtopping volume 40 percentile
Maximum (per wave) overtopping volume 45 percentile
Maximum (per wave) overtopping volume 50 percentile
Maximum (per wave) overtopping volume 55 percentile
Maximum (per wave) overtopping volume 60 percentile
Maximum (per wave) overtopping volume 65 percentile
Maximum (per wave) overtopping volume 70 percentile
Maximum (per wave) overtopping volume 75 percentile
Maximum (per wave) overtopping volume 80 percentile
Maximum (per wave) overtopping volume 85 percentile
Maximum (per wave) overtopping volume 90 percentile
Maximum (per wave) overtopping volume 95 percentile
Maximum (per wave) overtopping volume 99 percentile
Number of Monte Carlo runs
Convergence ratio
Water level 1 percentile
Water level 5 percentile
Water level 10 percentile
Water level 15 percentile
Water level 20 percentile
Water level 25 percentile
Water level 30 percentile
Water level 35 percentile
Water level 40 percentile
Water level 45 percentile
Water level 50 percentile
Water level 55 percentile
Water level 60 percentile
Water level 65 percentile
Water level 70 percentile
Water level 75 percentile
Water level 80 percentile
Water level 85 percentile
Water level 90 percentile
Water level 95 percentile
Water level 99 percentile
Total water level in the tide peak 1 percentile
Overtopping mean rate in the tide peak 1 percentile
Overtopping volume in the tide peak 1 percentile
Maximum (per wave) overtopping volume 1 percentile
Total water level in the tide peak 5 percentile
Overtopping mean rate in the tide peak 5 percentile
Overtopping volume in the tide peak 5 percentile
Maximum (per wave) overtopping volume 5 percentile
Total water level in the tide peak 10 percentile

Overtopping mean rate in the tide peak 10 percentile
Overtopping volume in the tide peak 10 percentile
Maximum (per wave) overtopping volume 10 percentile
Total water level in the tide peak 15 percentile
Overtopping mean rate in the tide peak 15 percentile
Overtopping volume in the tide peak 15 percentile
Maximum (per wave) overtopping volume 15 percentile
Total water level in the tide peak 20 percentile
Overtopping mean rate in the tide peak 20 percentile
Overtopping volume in the tide peak 20 percentile
Maximum (per wave) overtopping volume 20 percentile
Total water level in the tide peak 25 percentile
Overtopping mean rate in the tide peak 25 percentile
Overtopping volume in the tide peak 25 percentile
Maximum (per wave) overtopping volume 25 percentile
Total water level in the tide peak 30 percentile
Overtopping mean rate in the tide peak 30 percentile
Overtopping volume in the tide peak 30 percentile
Maximum (per wave) overtopping volume 30 percentile
Total water level in the tide peak 35 percentile
Overtopping mean rate in the tide peak 35 percentile
Overtopping volume in the tide peak 35 percentile
Maximum (per wave) overtopping volume 35 percentile
Total water level in the tide peak 40 percentile
Overtopping mean rate in the tide peak 40 percentile
Overtopping volume in the tide peak 40 percentile
Maximum (per wave) overtopping volume 40 percentile
Total water level in the tide peak 45 percentile
Overtopping mean rate in the tide peak 45 percentile
Overtopping volume in the tide peak 45 percentile
Maximum (per wave) overtopping volume 45 percentile
Total water level in the tide peak 50 percentile
Overtopping mean rate in the tide peak 50 percentile
Overtopping volume in the tide peak 50 percentile
Maximum (per wave) overtopping volume 50 percentile
Total water level in the tide peak 55 percentile
Overtopping mean rate in the tide peak 55 percentile
Overtopping volume in the tide peak 55 percentile
Maximum (per wave) overtopping volume 55 percentile
Total water level in the tide peak 60 percentile
Overtopping mean rate in the tide peak 60 percentile
Overtopping volume in the tide peak 60 percentile
Maximum (per wave) overtopping volume 60 percentile
Total water level in the tide peak 65 percentile
Overtopping mean rate in the tide peak 65 percentile
Overtopping volume in the tide peak 65 percentile
Maximum (per wave) overtopping volume 65 percentile
Total water level in the tide peak 70 percentile
Overtopping mean rate in the tide peak 70 percentile
Overtopping volume in the tide peak 70 percentile
Maximum (per wave) overtopping volume 70 percentile
Total water level in the tide peak 75 percentile
Overtopping mean rate in the tide peak 75 percentile

Overtopping volume in the tide peak 75 percentile
Maximum (per wave) overtopping volume 75 percentile
Total water level in the tide peak 80 percentile
Overtopping mean rate in the tide peak 80 percentile
Overtopping volume in the tide peak 80 percentile
Maximum (per wave) overtopping volume 80 percentile
Total water level in the tide peak 85 percentile
Overtopping mean rate in the tide peak 85 percentile
Overtopping volume in the tide peak 85 percentile
Maximum (per wave) overtopping volume 85 percentile
Total water level in the tide peak 90 percentile
Overtopping mean rate in the tide peak 90 percentile
Overtopping volume in the tide peak 90 percentile
Maximum (per wave) overtopping volume 90 percentile
Total water level in the tide peak 95 percentile
Overtopping mean rate in the tide peak 95 percentile
Overtopping volume in the tide peak 95 percentile
Maximum (per wave) overtopping volume 95 percentile
Total water level in the tide peak 99 percentile
Overtopping mean rate in the tide peak 99 percentile
Overtopping volume in the tide peak 99 percentile
Maximum (per wave) overtopping volume 99 percentile

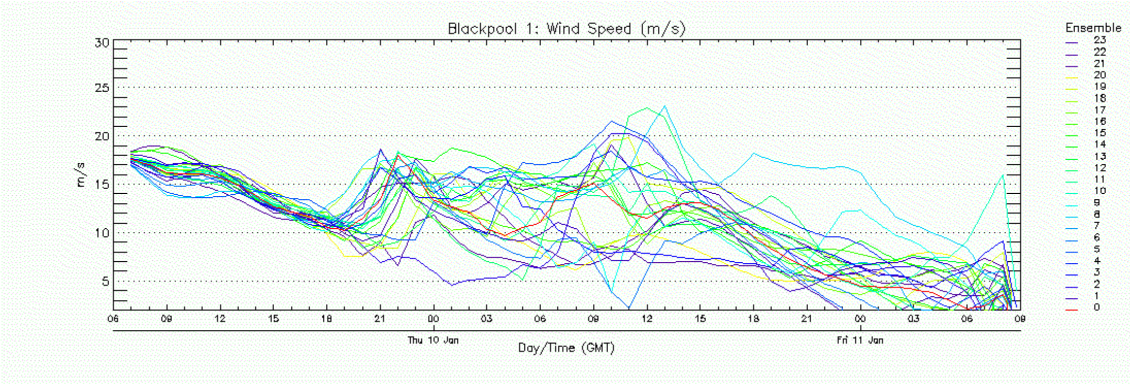


Figure A1.4 Wind speed (ensemble members)

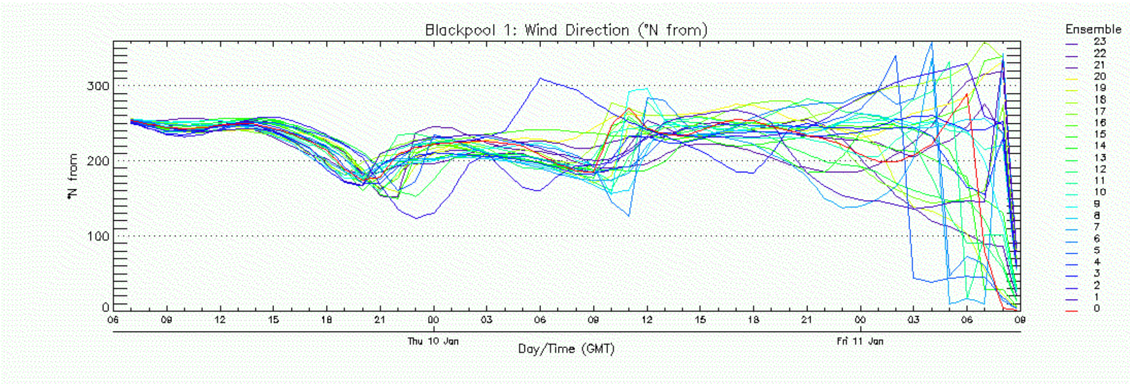


Figure A1.5 Wind direction (ensemble members)

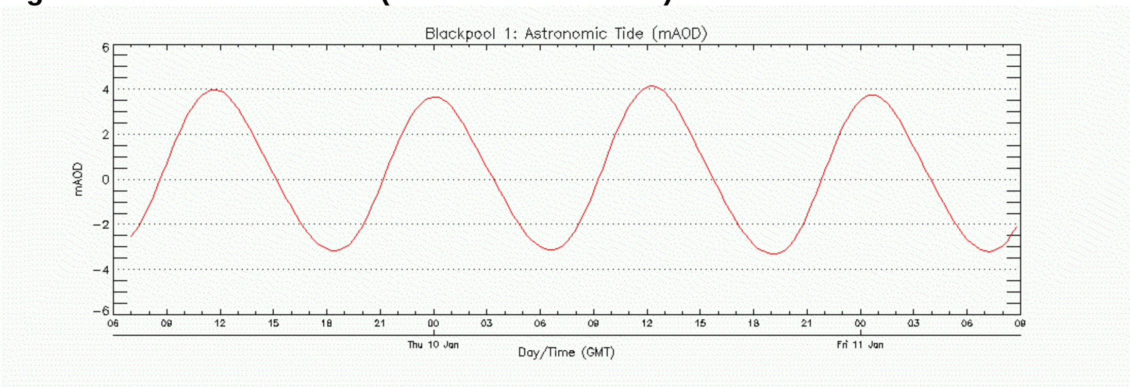


Figure A1.6 Predicted tide level (source Environment Agency)

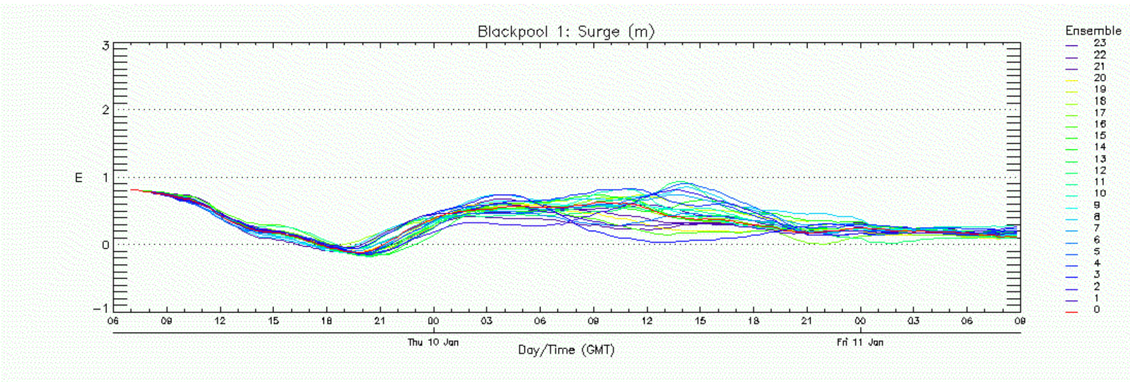


Figure A1.7 Surge level (ensemble members)

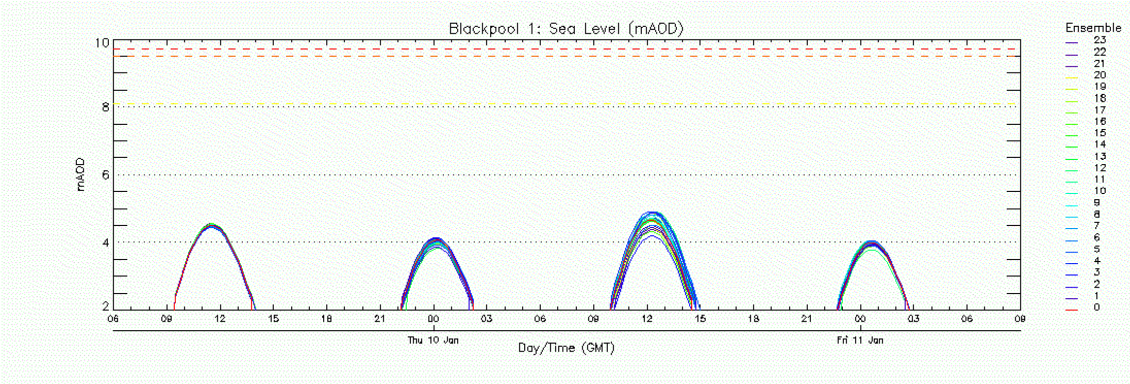


Figure A1.8 Sea level (ensemble members)

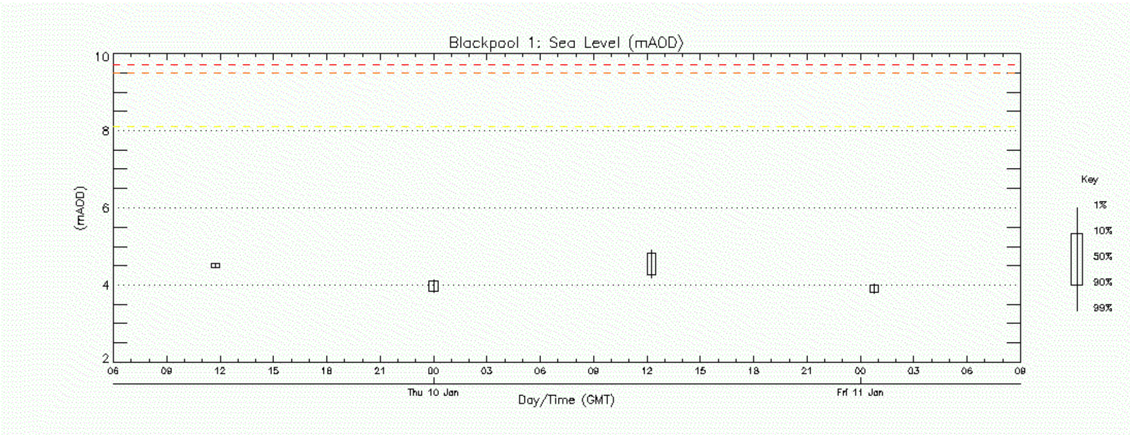


Figure A1.9 Sea level (percentiles)

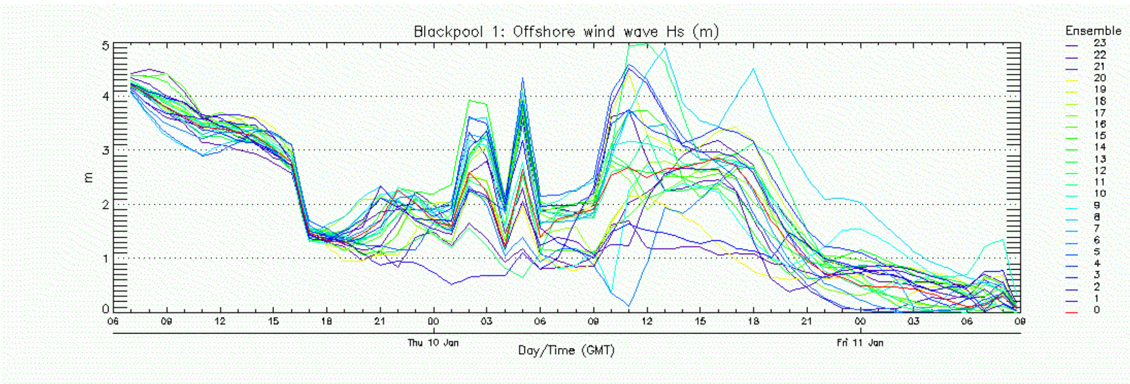


Figure A1.10 Offshore wind wave significant wave height (ensemble members)

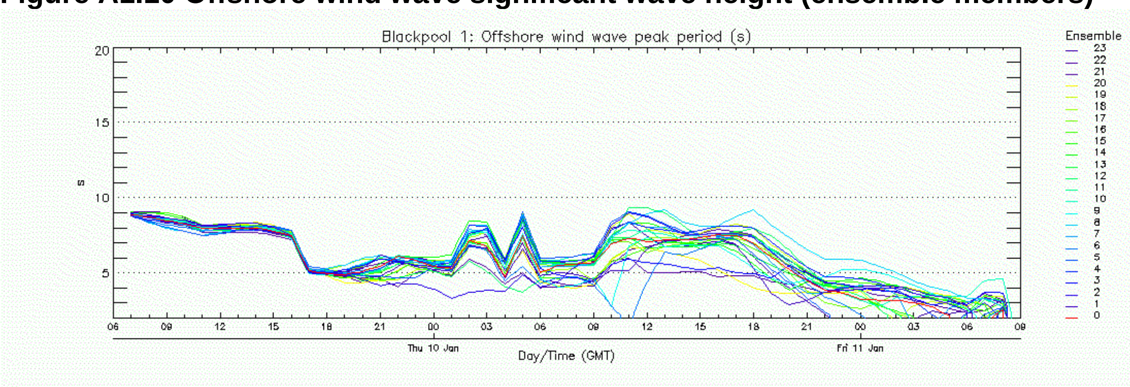


Figure A1.11 Offshore wind wave peak period (ensemble members)

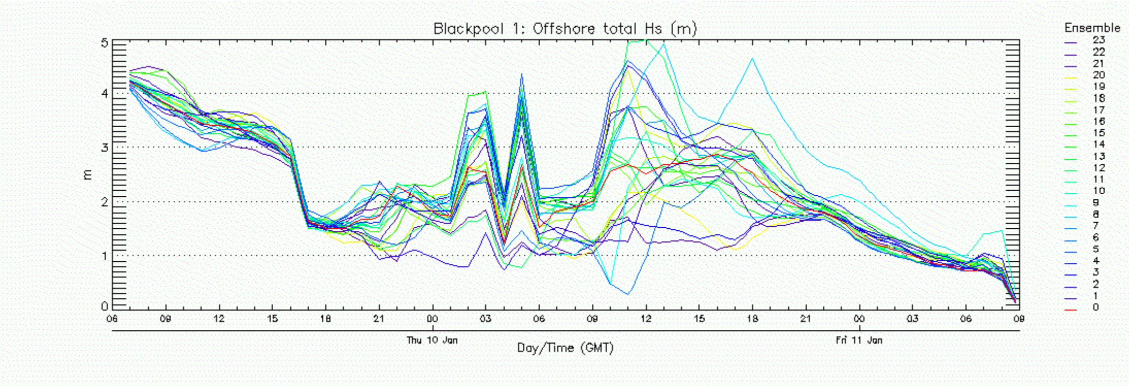


Figure A1.12 Offshore total wave significant height (ensemble members)

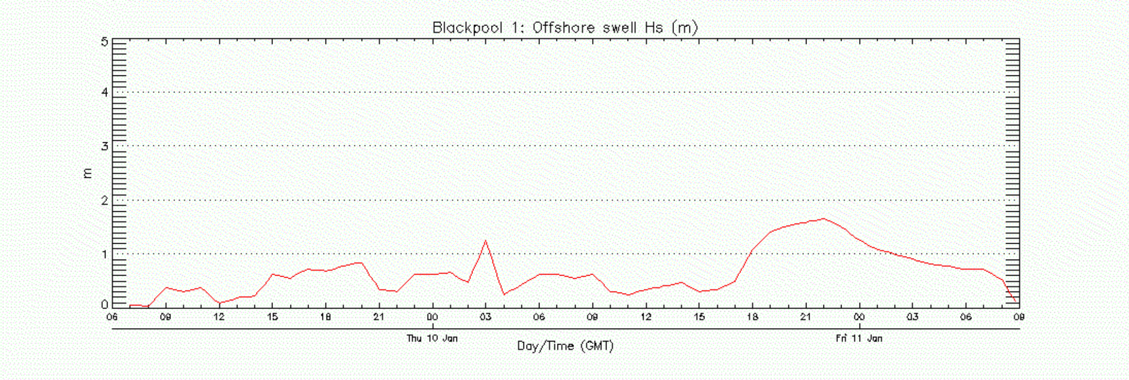


Figure A1.13 Offshore swell wave significant height (ensemble members)

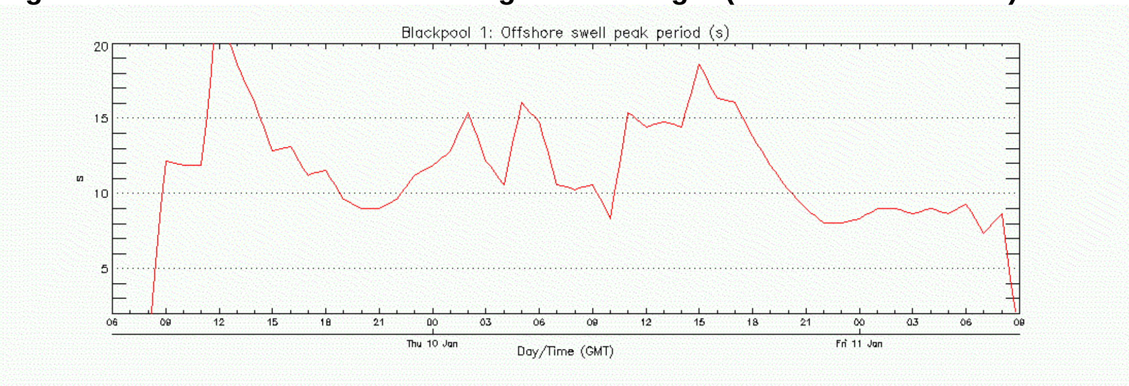


Figure A1.14 Offshore swell wave peak period (ensemble members)

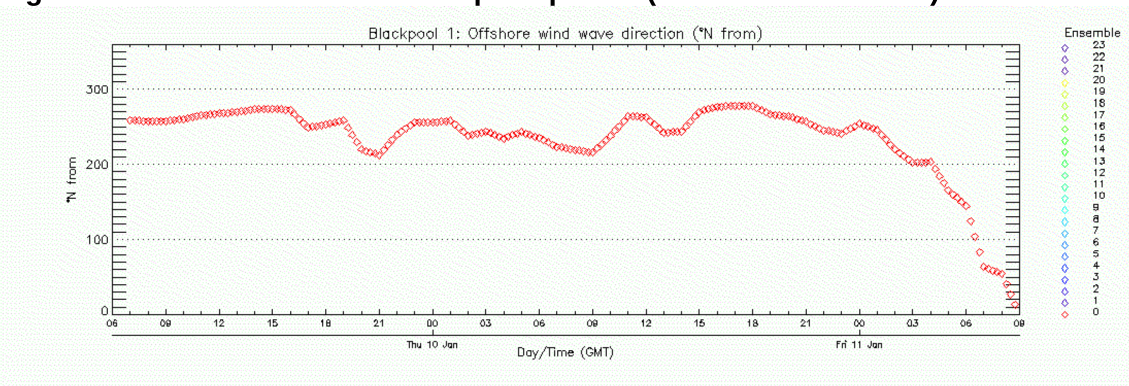


Figure A1.15 Offshore wind wave mean direction (ensemble members)

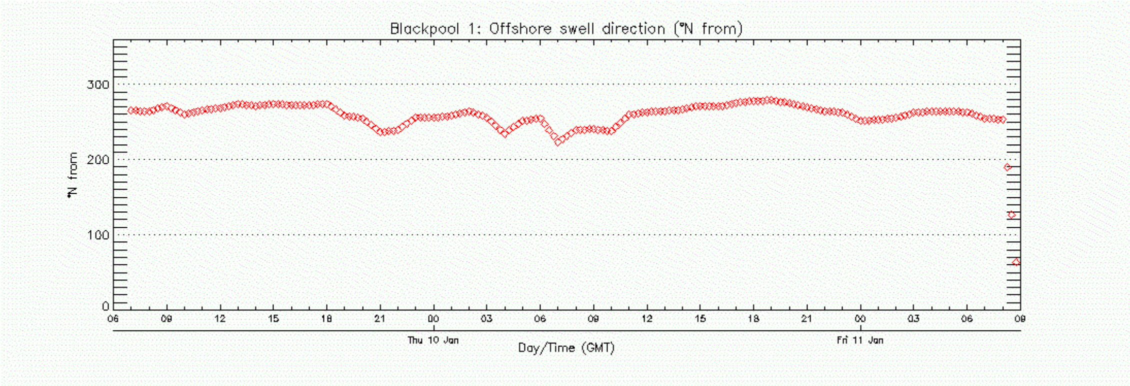


Figure A1.16 Offshore swell mean direction (ensemble members)

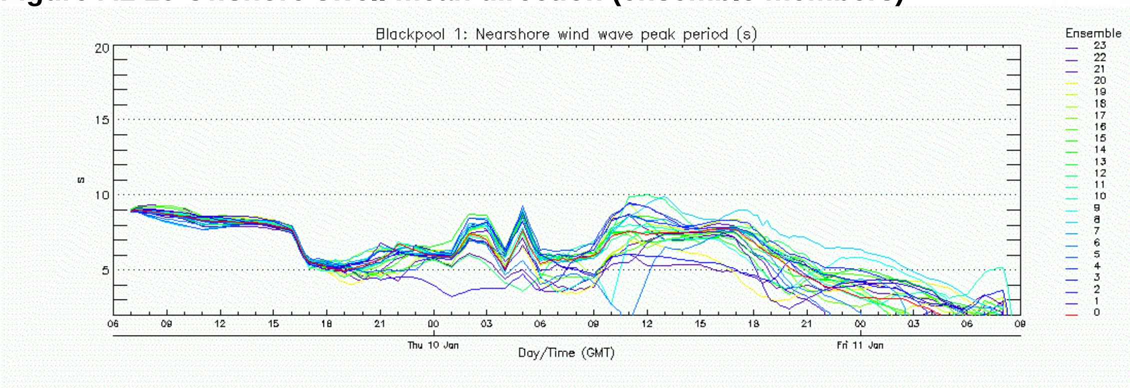


Figure A1.17 Nearshore wind wave peak period (ensemble members)

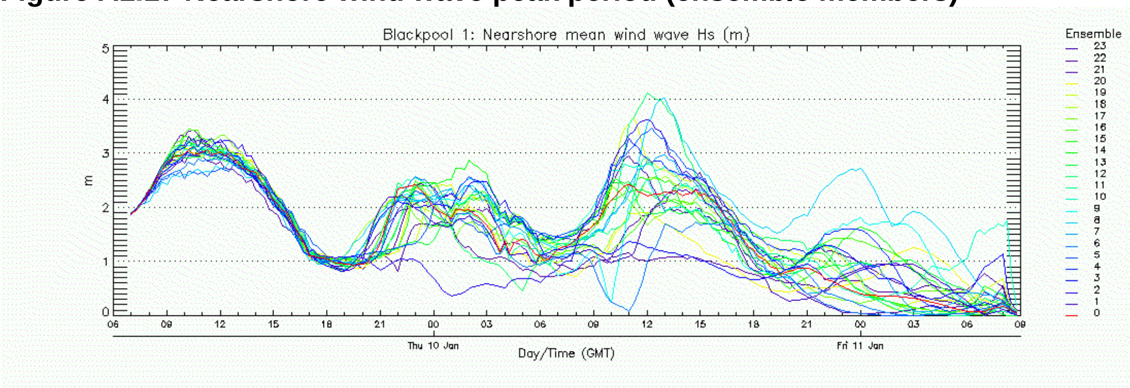


Figure A1.18 Nearshore wind wave significant wave height (ensemble members)

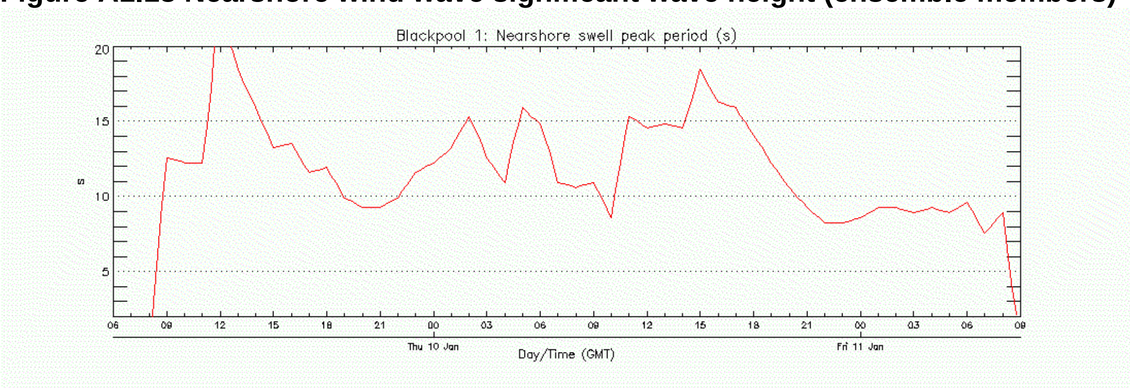


Figure A1.19 Nearshore swell wave peak period (ensemble members)

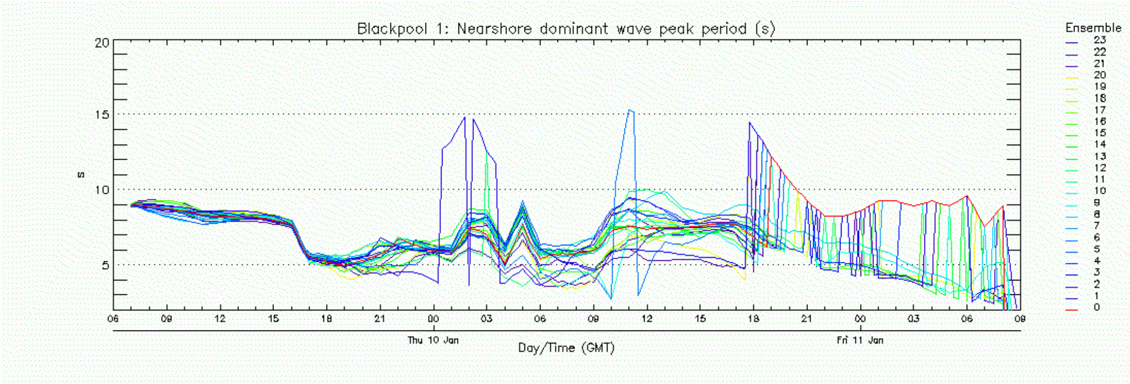


Figure A1.20 Nearshore dominant peak period (ensemble members)

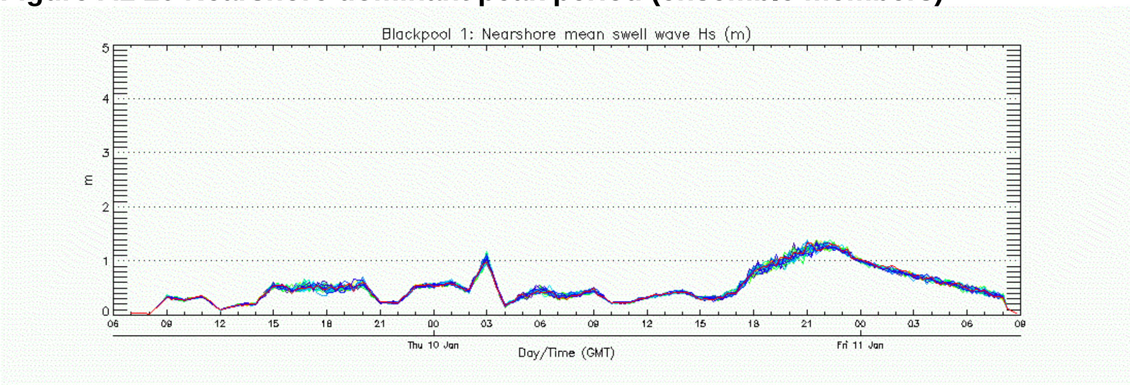


Figure A1.21 Nearshore swell wave significant height (ensemble members)

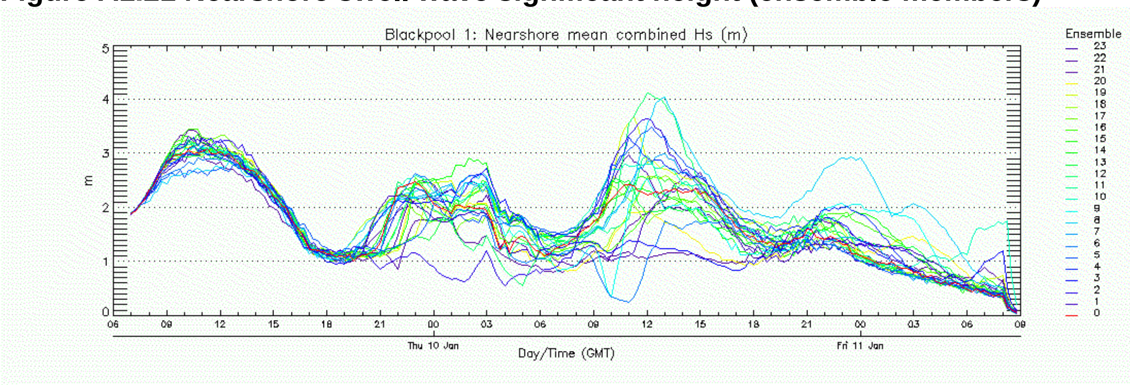


Figure A1.22 Nearshore combined wave significant height (ensemble members)

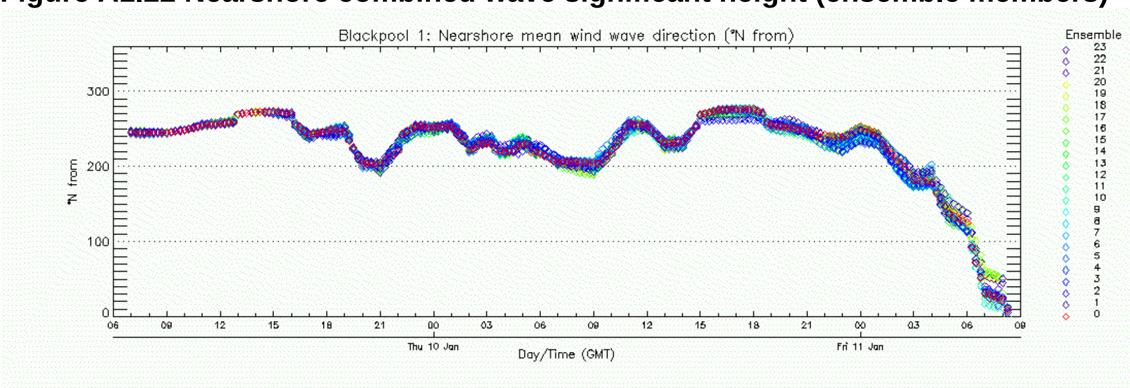


Figure A1.23 Nearshore wind wave mean direction (ensemble members)

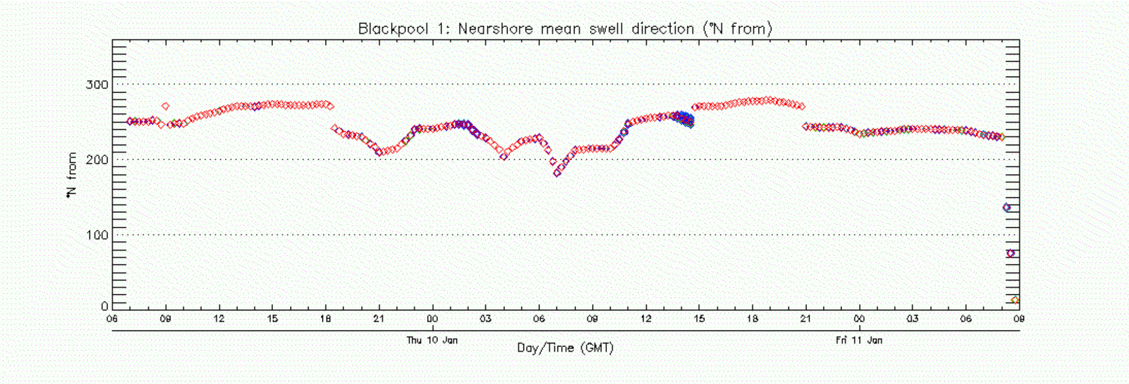


Figure A1.24 Nearshore swell mean direction (ensemble members)

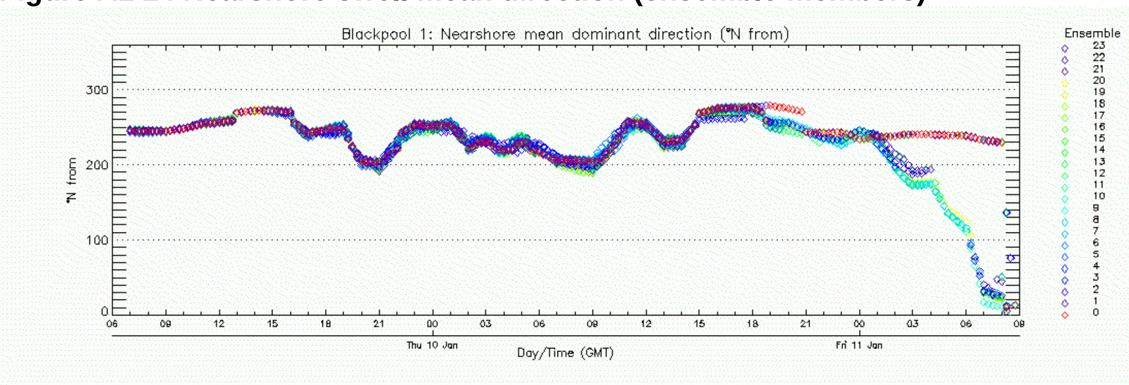


Figure A1.25 Nearshore mean dominant direction (ensemble members)

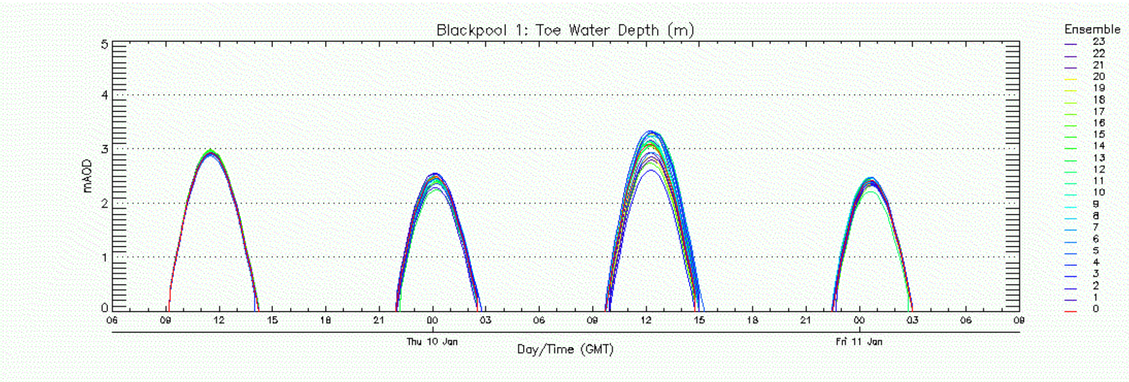


Figure A1.26 Toe water depth (ensemble members)

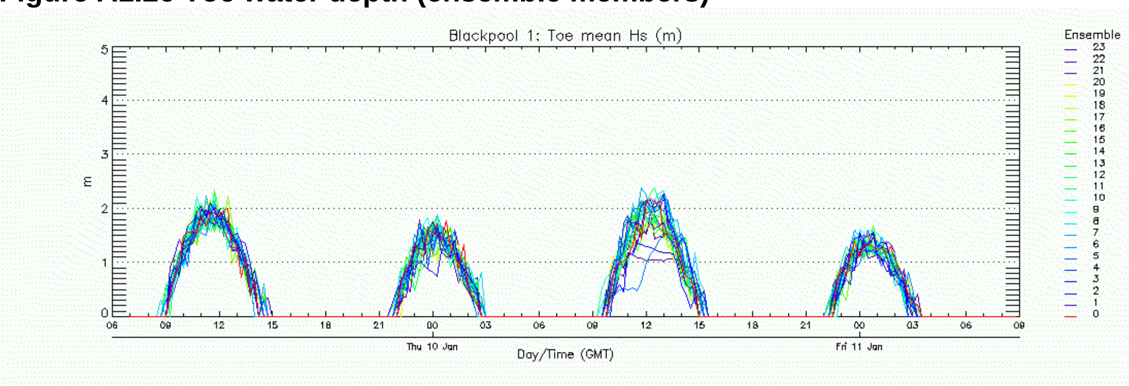


Figure A1.27 Toe mean significant wave height (ensemble members)

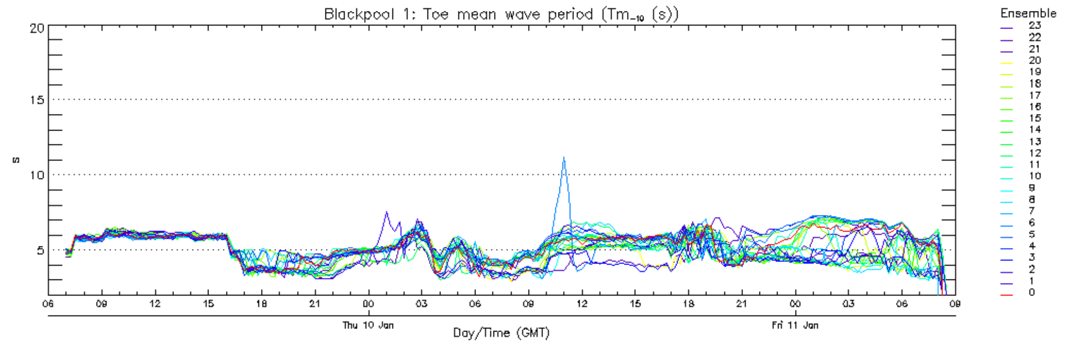


Figure A1.28 Toe mean wave period (Tm-10) (ensemble members)

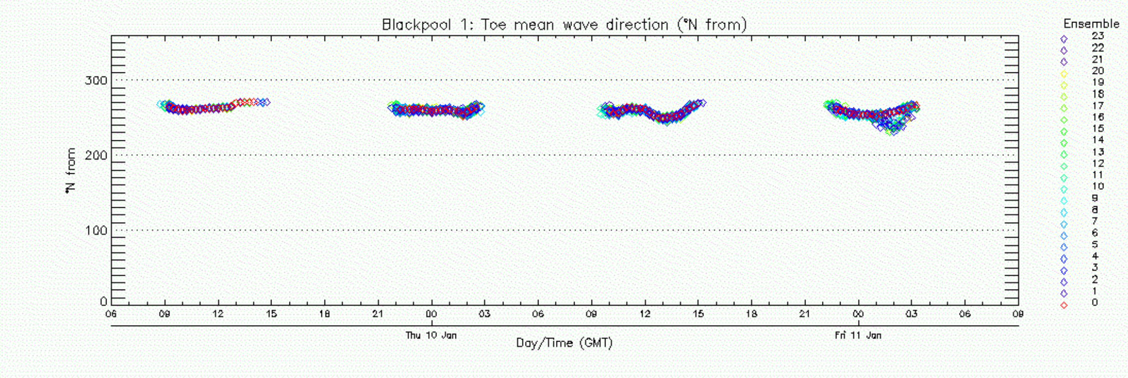


Figure A1.29 Toe mean wave direction (ensemble members)

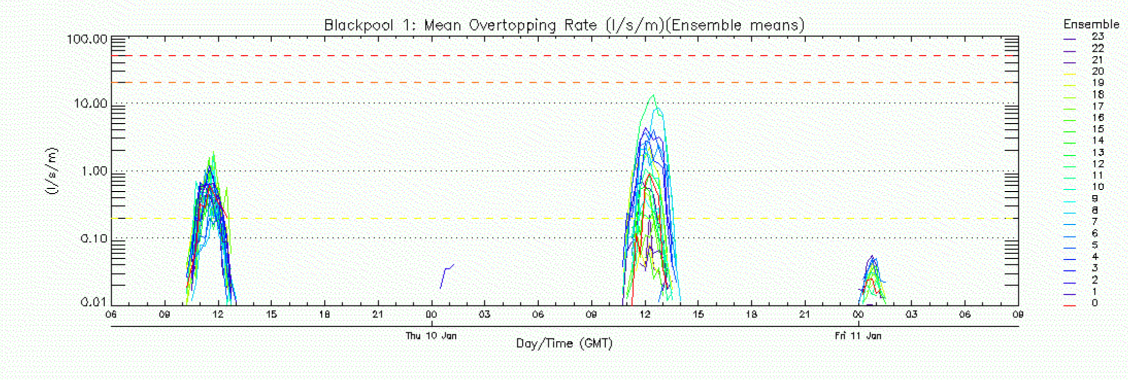
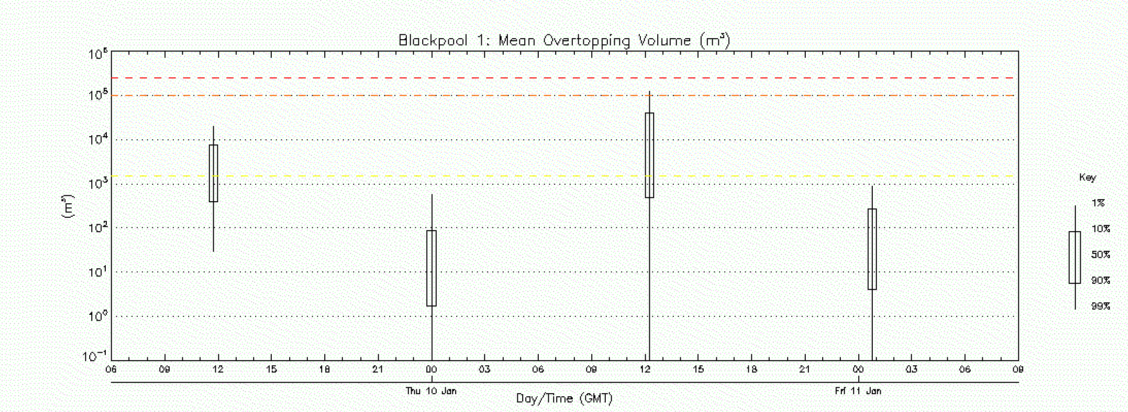


Figure A1.30 Mean overtopping rate (ensemble members)



Blackpool 1: Mean Overtopping Volume (m^3)

	09/01/2008 11:45	10/01/2008 00:00	10/01/2008 12:15	11/01/2008 00:45
1% :	20163.76	580.43	124156.97	872.59
10%:	7370.05	87.66	39742.69	272.69
50%:	1709.61	9.97	3062.06	29.06
90%:	389.02	1.72	492.42	4.09
99%:	30.40	0.00	0.00	0.00

Figure A1.31 Mean overtopping volume (percentiles)

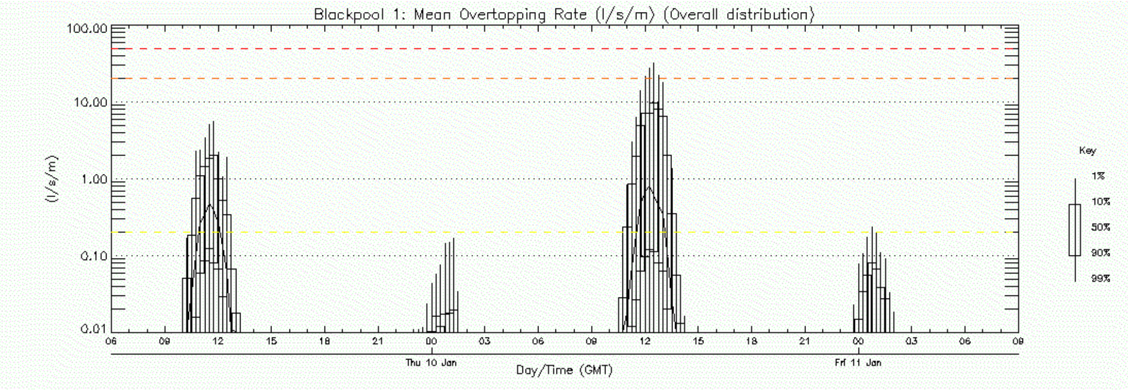
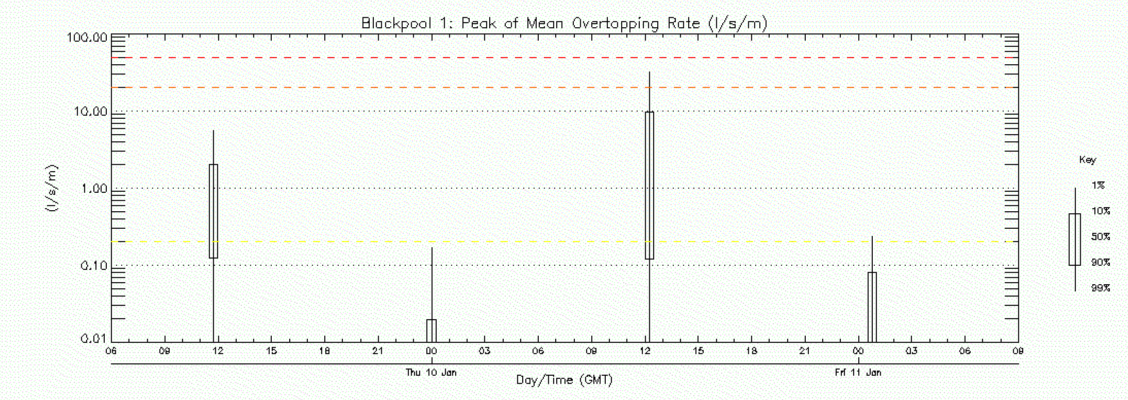


Figure A1.32 Mean overtopping rate (percentiles)



Blackpool 1: Peak of Mean Overtopping Rate (l/s/m)

	09/01/2008 11:45	10/01/2008 00:00	10/01/2008 12:15	11/01/2008 00:45
1% :	5.53	0.17	32.15	0.23
10%:	2.00	0.02	9.65	0.08
50%:	0.48	0.00	0.81	0.01
90%:	0.12	0.00	0.12	0.00
99%:	0.01	0.00	0.00	0.00

Figure A1.33 Per tide peak of mean overtopping rate (percentiles)

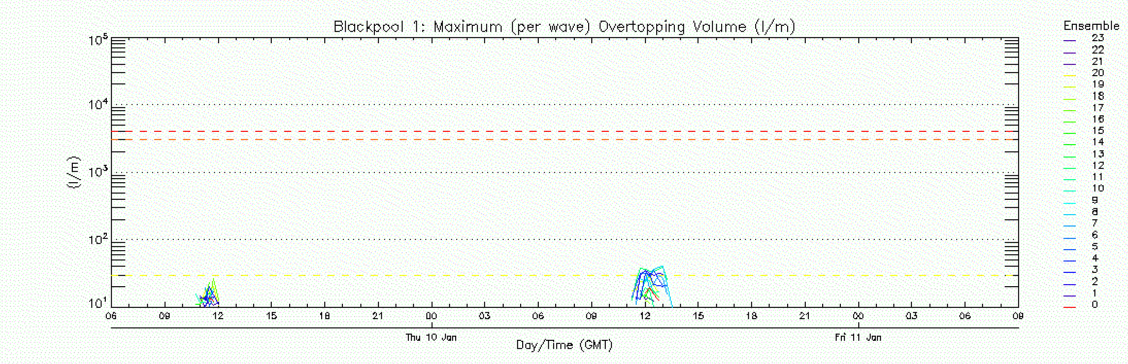
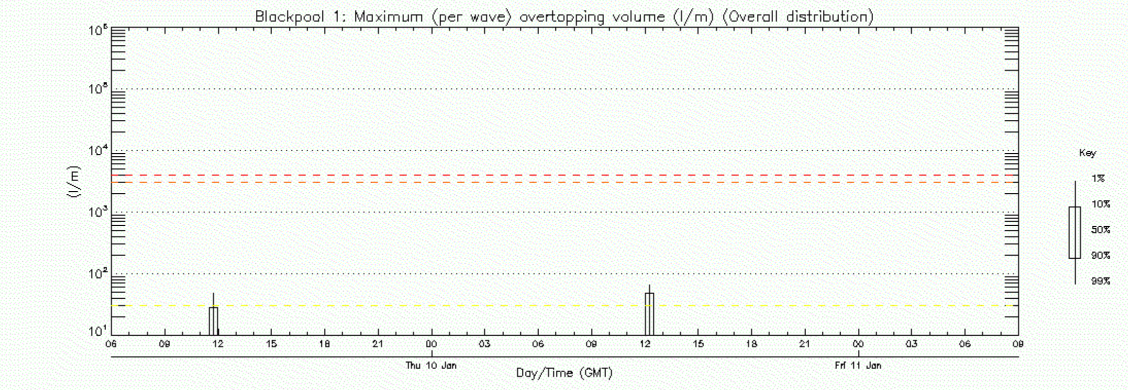


Figure A1.34 Maximum (per wave) overtopping volume (ensemble members)



Blackpool 1: Maximum (per wave) overtopping volume (l/m) (Overall distribution)

	09/01/2008 11:45	10/01/2008 12:15		
1% :	47.54	5.38	64.61	8.41
10%:	28.16	2.11	47.81	4.54
50%:	13.11	0.40	14.57	1.07
90%:	6.49	0.04	2.50	0.10
99%:	1.40	0.00	0.00	0.00

Figure A1.35 Maximum (per wave) overtopping volume (percentiles)

Appendix 2 Blackpool nearshore wave measurements

Two AWAC sea level, wave and current recording devices were deployed by Wallingford Environmental Surveys over four tides from 23 to 25 January 2008. They were placed immediately seaward of the overtopping tank at Anchorsholme, Blackpool, as shown in Figure A2.1.

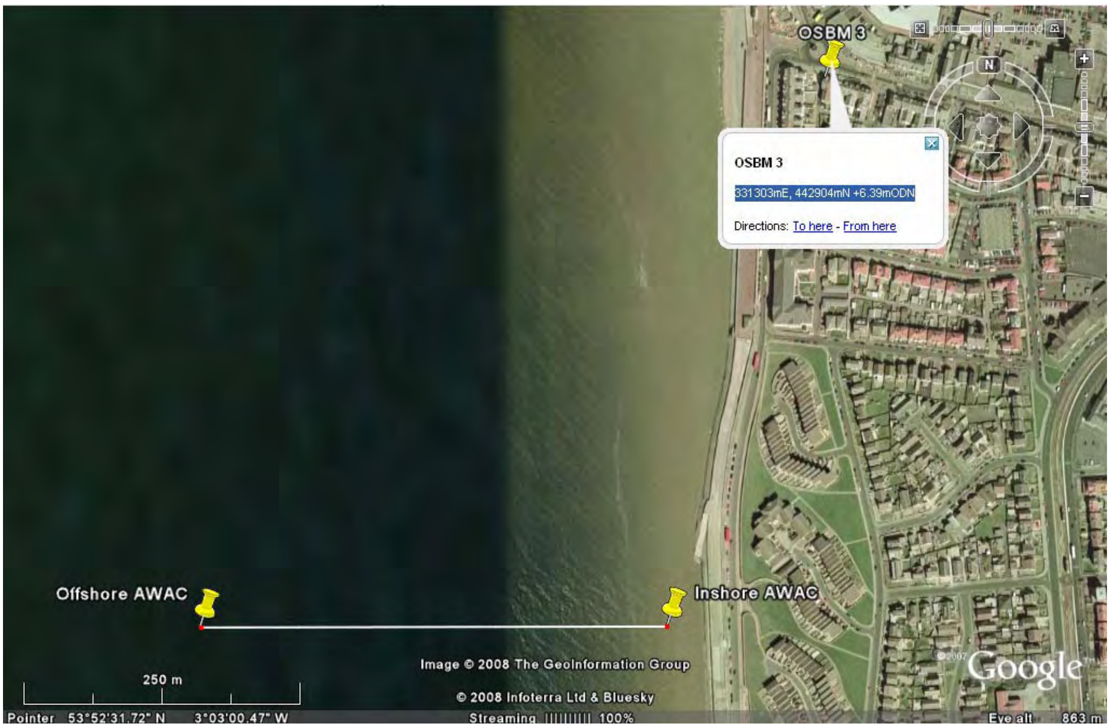


Figure A2.1 Locations of two AWAC wave recorders off Anchorsholme, Blackpool

The offshore AWAC was placed nearly 500 m from the seawall, at 330732 mE 442424 mN. A precise level for this site was not obtained as it was uncovered only at low water, which occurred in the dark, but the level was approximately -3.40 mODN.

The inshore AWAC was placed about 30 m from the seawall, at 331155 mE 442410 mN. An accurate level of +1.57 mODN was obtained by closed loop levelling traverse from OSBM #2 Victoria Road +6.38 mODN.

Figures A2.2-A2.5 are photographs of the devices on the beach. The wave measurements are plotted in Figures A2.6 and A2.7. All photographs and plots are by Wallingford Environmental Surveys.

Offshore (water depth about eight metres) significant wave height (H_s) reached four metres near to the daylight high tides on 24 and 25 January 2008. The accompanying mean wave period (T_m) was about five seconds. The very high wave steepness ($2\pi H_s/gT_m^2$) of about 0.1 suggests that the waves were breaking strongly at the measurement point, and that they might have been even higher further offshore. Inshore H_s was further limited by wave breaking, reaching three metres on each of the daylight high tides in a still water depth (excluding wave effects) of about three metres.

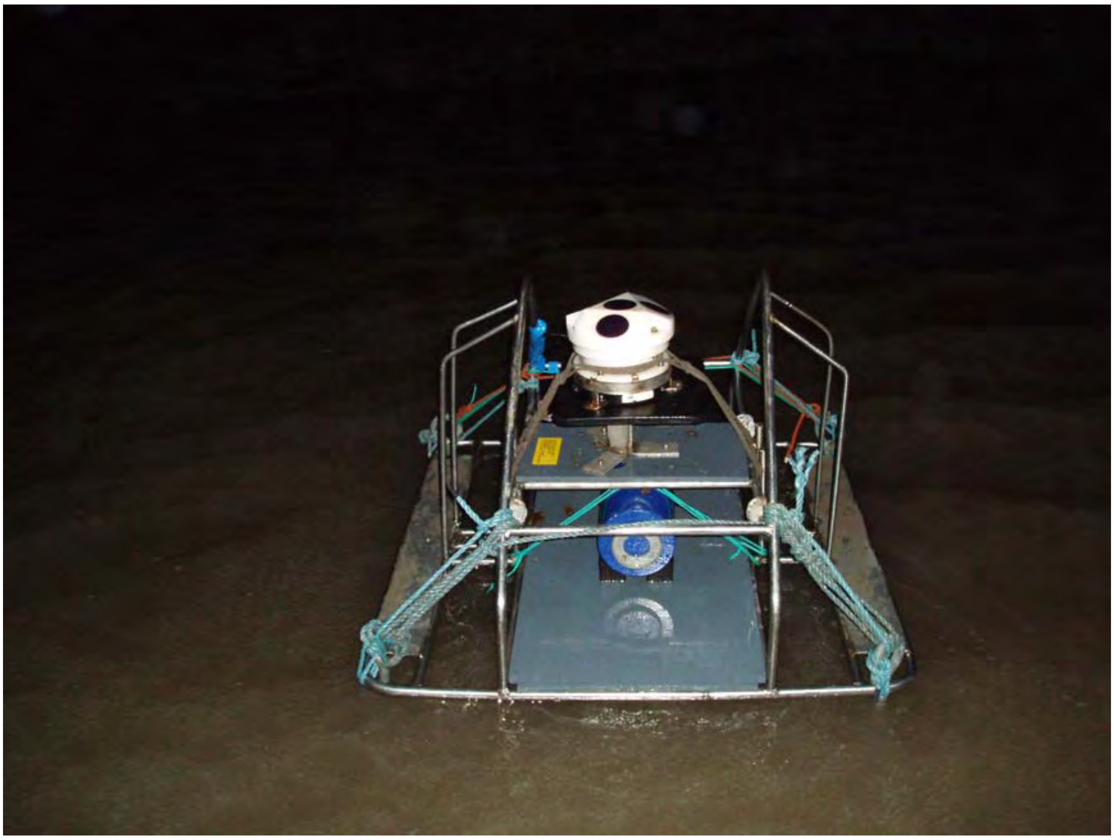


Figure A2.2 Offshore AWAC

Figure A2.3 Inshore AWAC

Figure A2.4 Inshore AWAC

Figure A2.5 Inshore AWAC

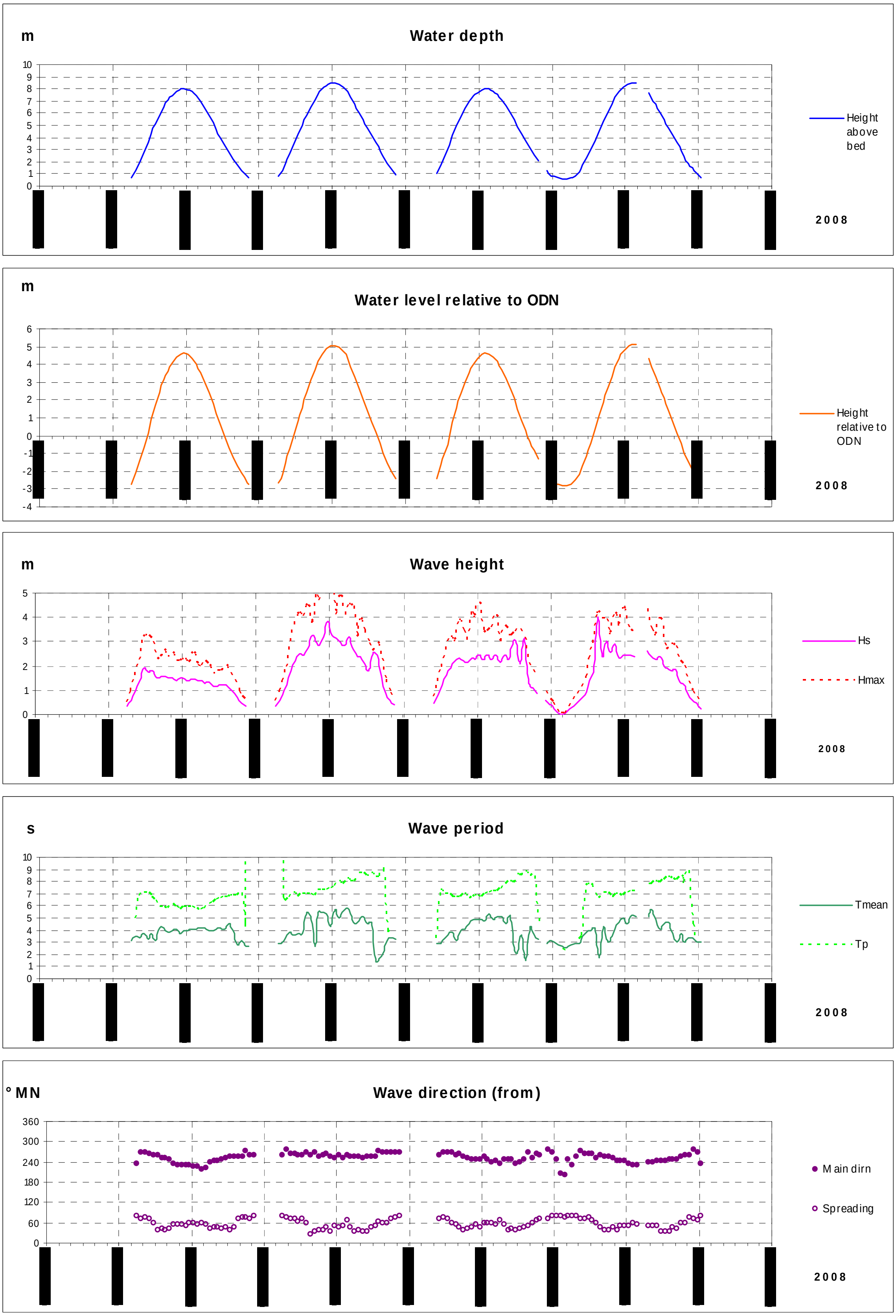


Figure A2.6 Offshore sea level and wave measurements 23-25 January 2008

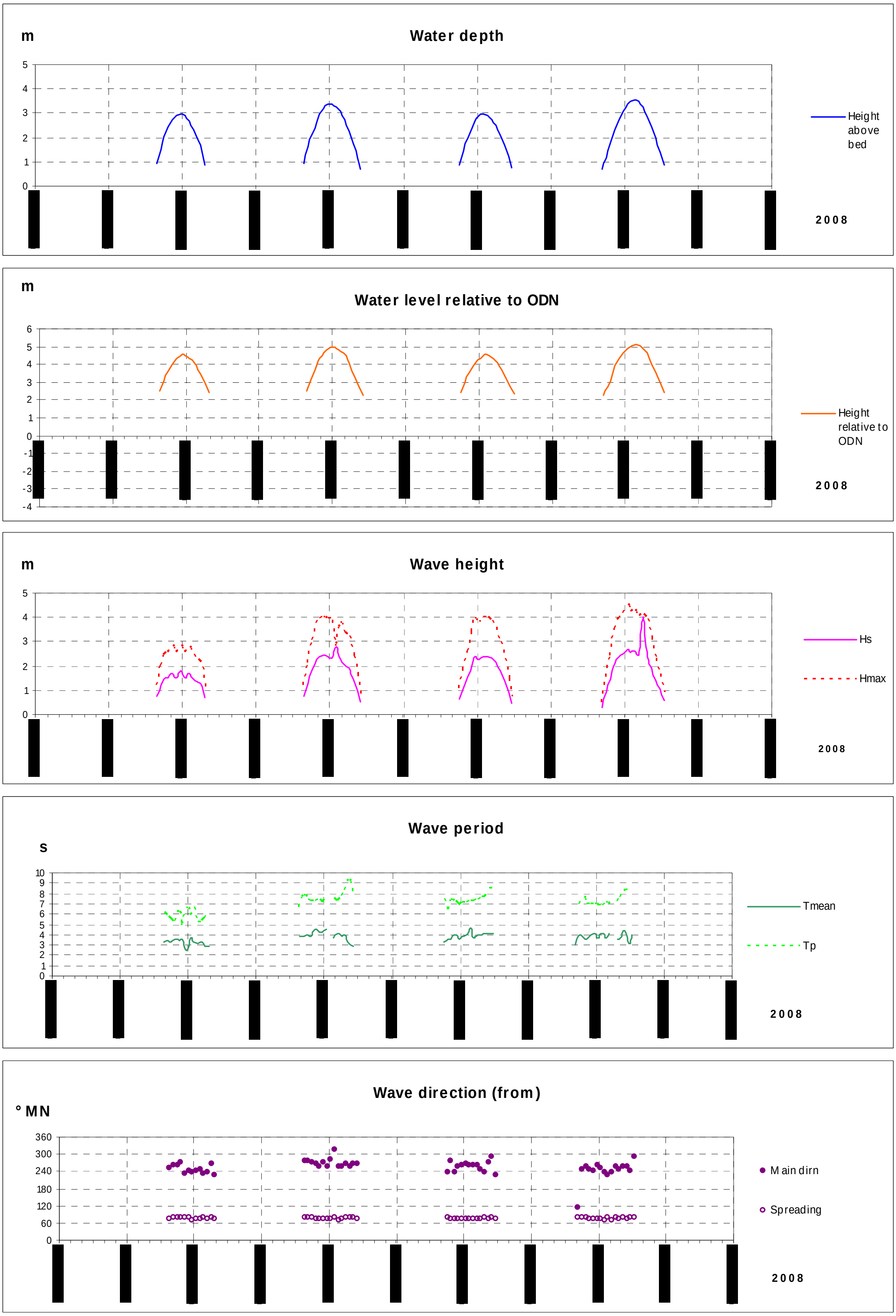


Figure A2.7 Inshore sea level and wave measurements 23-25 January 2008

Appendix 3 Blackpool wave overtopping measurements

Saturday 30 October 2007

Tank deployed: Yes

Overtopping measured: No

HR Wallingford staff went to Blackpool to set up for the storm and record overtopping. Operational problems with the data logger and water ingress into the box meant that the data were corrupted.

Friday 7 December 2007

Tank deployed: No

Overtopping measured: No

The coastal flood forecasting demonstration did not predict overtopping within sufficient time to deploy the team. Ian Davison was able to get to Blackpool and witnessed the event. See Figure A3.1.

Figure A3.1 Wave overtopping on 7 December 2007 (photograph by Ian Davison)

Wednesday 9 January 2008

Tank deployed: Yes

Overtopping measured: Yes

The tank was deployed and overtopping was measured at around 0.6 litres per second per metre run. Initial analysis indicated predicted and measured overtopping discharges in good agreement.

Thursday 10 January 2008

Tank deployed: Yes

Overtopping measured: No

The tank was deployed on the morning of the storm. No readings were detected on the card. It is thought failure to engage the logger correctly in its mount may have contributed to lack of data as it is known that overtopping did occur.

Tuesday 15 January 2008

Tank deployed: Yes

Overtopping measured: No

The tank was deployed and operated successfully. No overtopping entered the tank and the data show mostly noise. The predictions that day were for very low overtopping discharges, and this was recorded.

Wednesday 23 January 2008

Tank deployed: No

Overtopping measured: No

Overtopping was predicted, but a bigger storm was expected the following day. An operational decision was taken to abandon recording on 23rd January and concentrate on getting good results the following day, when waves would also be measured.

Thursday 24 January 2008

Tank deployed: Yes

Overtopping measured: Yes

The tank was deployed and overtopping was measured at up to 3.6 litres per second per metre run. Initial analysis showed predicted and measured overtopping discharges not in good agreement. Waves were measured for this storm and show that the coastal flood forecasting model under predicted wave heights and water levels. This should explain the difference between the predicted and measured overtopping. The team recording the waves took the photograph shown in Figure A3.2 during the storm.

Figure A3.2 Wave overtopping at the tank during the 24 January event (photograph by Wallingford Environmental Surveys)

Friday 25 January 2008

Tank deployed: Yes

Overtopping measured: No

The tank was deployed, but wave overtopping was so high that the tank was torn from its mountings. The damaged tank was returned to HR Wallingford the following week. Shortly after the damage to the tank, a ferry beached itself just offshore of the measurement site, Figure A3.3, confirming the severity of the sea conditions.

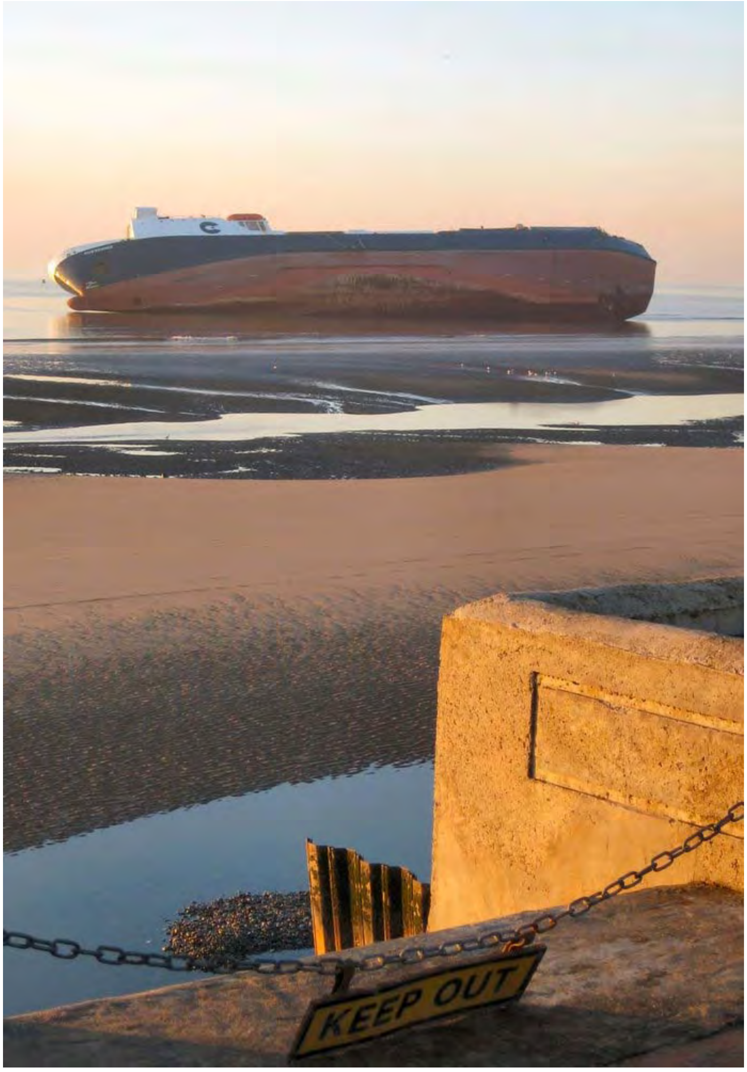


Figure A3.3 Ferry beached at the overtopping measurement site after the 25 January 2008 storm

Appendix 4 Blackpool sea level measurements

This appendix contains time series traces (metres above Ordnance Datum) of sea level for Blackpool, from the:

- tide gauge at Blackpool Pier, 29 September 2007 to 30 April 2008 (but with a few days missing);
- astronomical tidal predictions for Blackpool used in coastal flood forecasting, 29 September 2007 to 30 April 2008 (with the few days missing from the measurements also removed);
- nearshore AWAC, 23-25 January 2008.

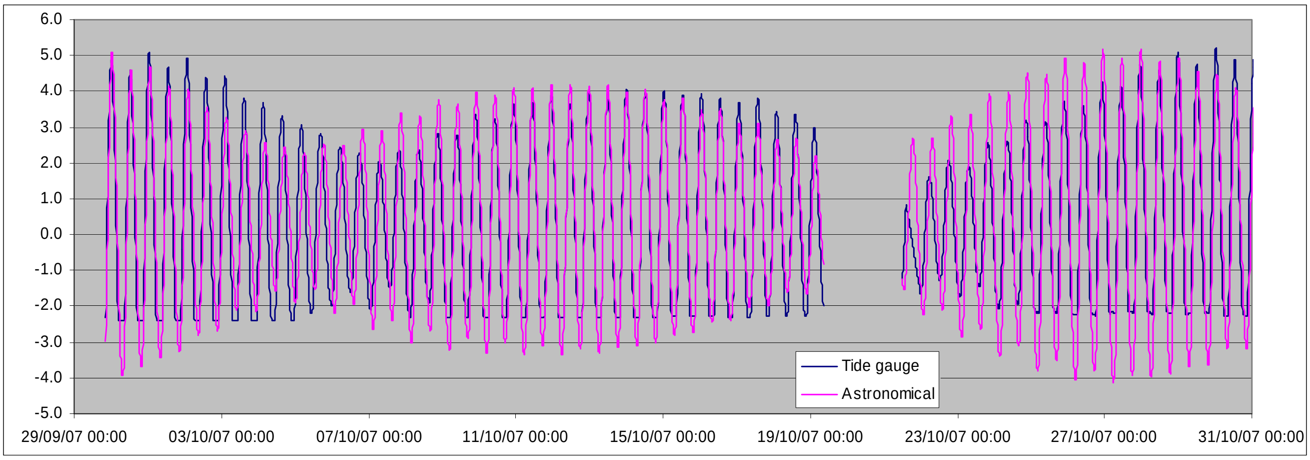


Figure A4.1 Blackpool sea level 29 September to 31 October 2007

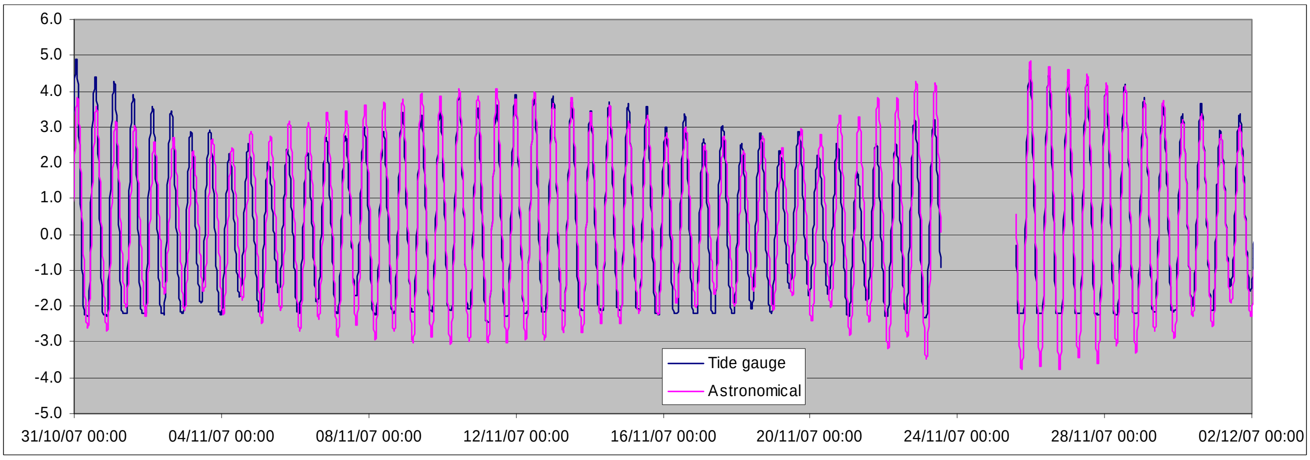


Figure A4.2 Blackpool sea level 31 October to 2 December 2007

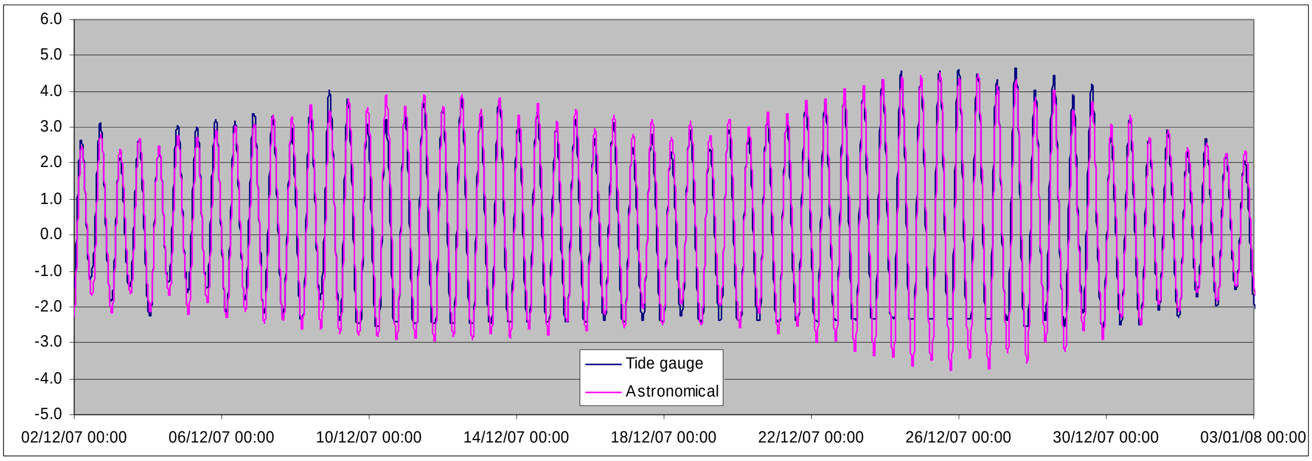


Figure A4.3 Blackpool sea level 2 December 2007 to 3 January 2008

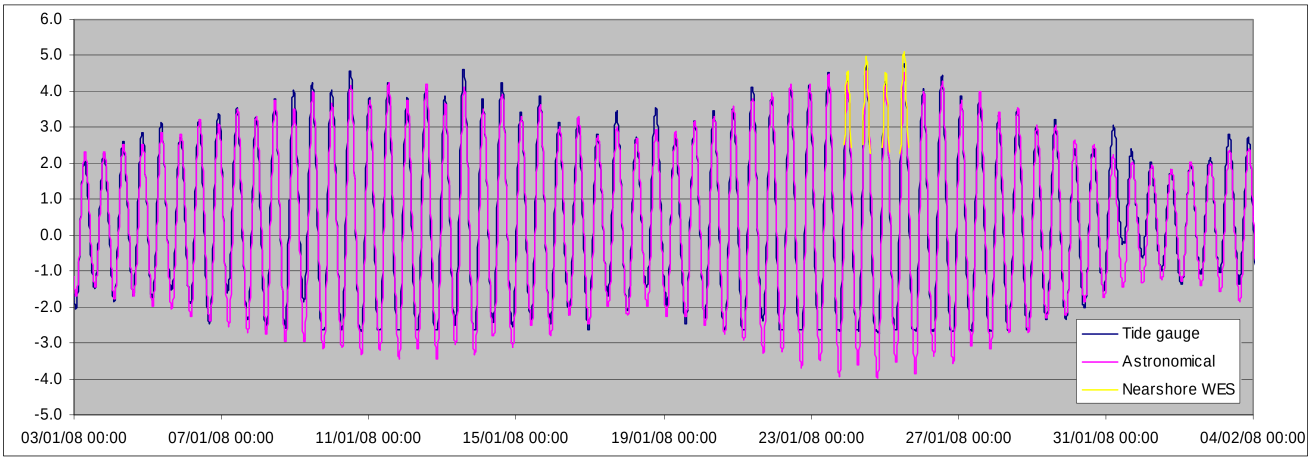


Figure A4.4 Blackpool sea level 3 January to 4 February 2008

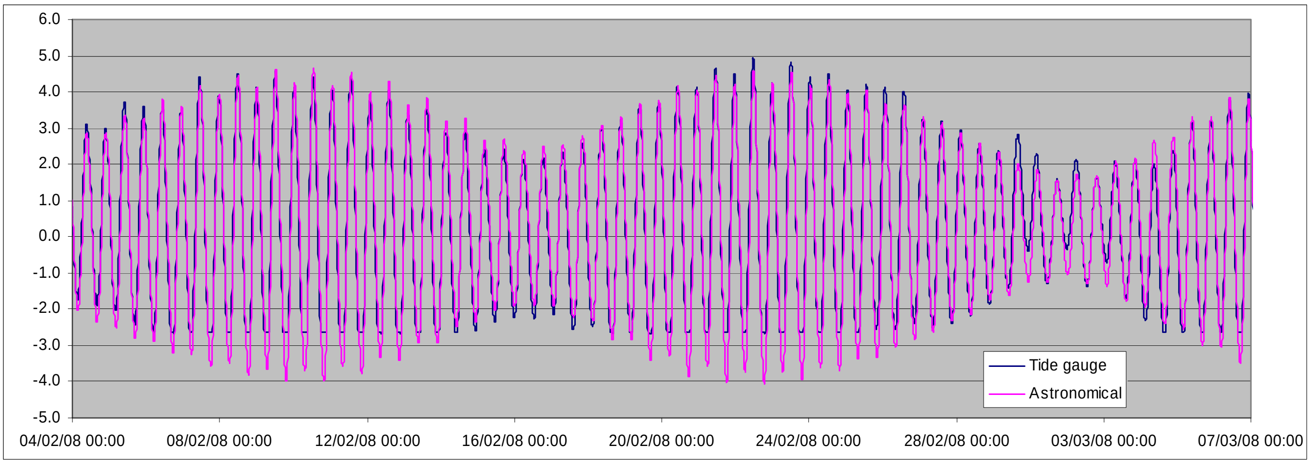


Figure A4.5 Blackpool sea level 4 February to 7 March 2008

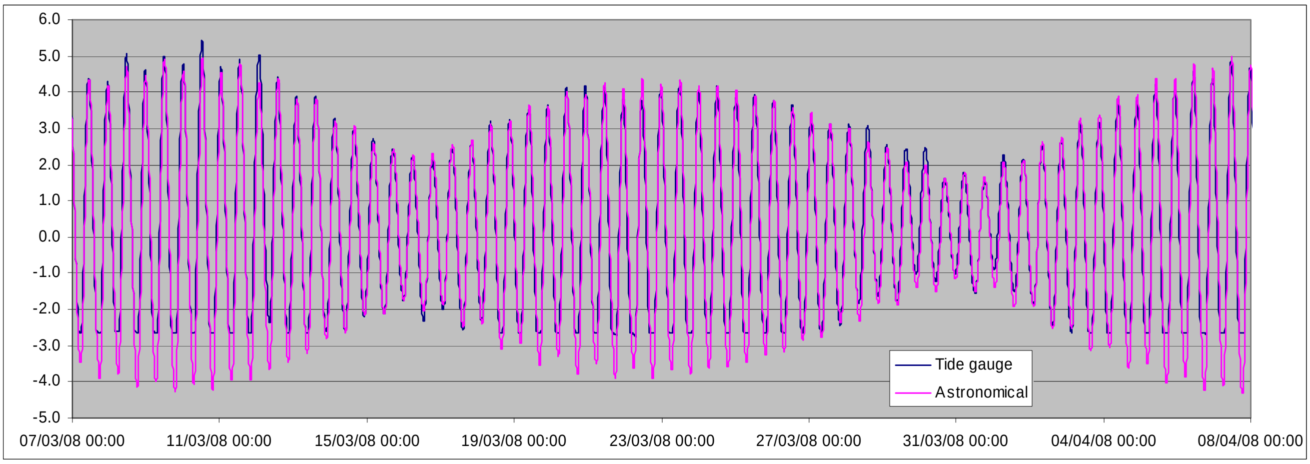


Figure A4.6 Blackpool sea level 7 March to 8 April 2008

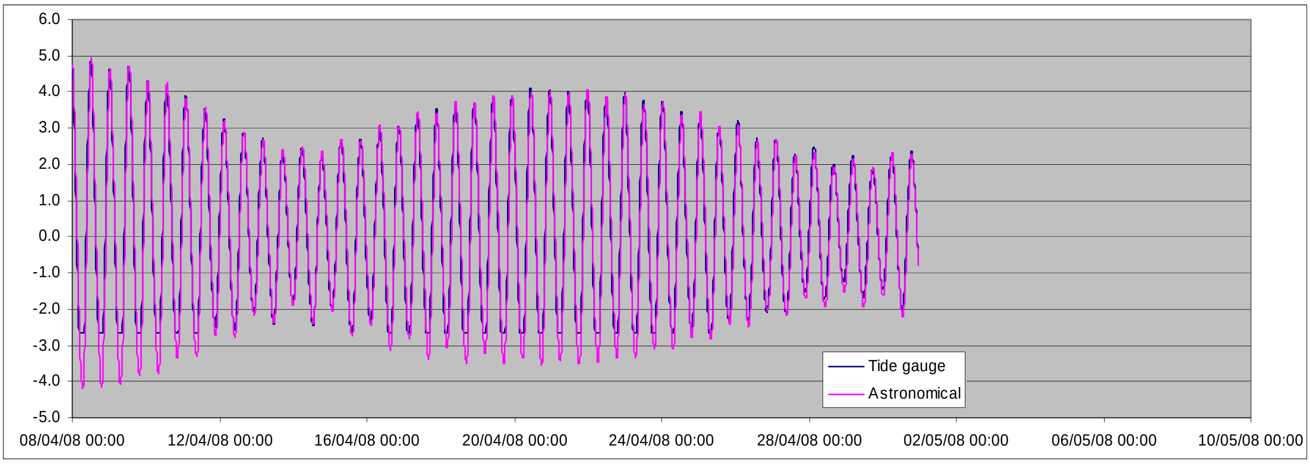


Figure A4.7 Blackpool sea level 8 to 30 April 2008

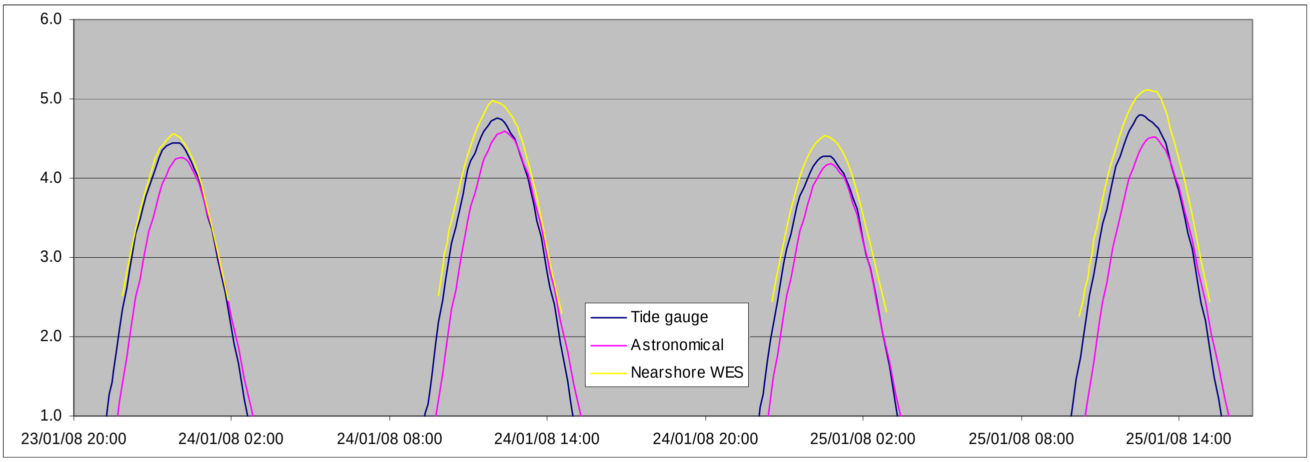


Figure A4.8 Blackpool sea level: Detail of the stormy period 23-25 January 2008

Appendix 5 Surge ensemble verification against surge measurements

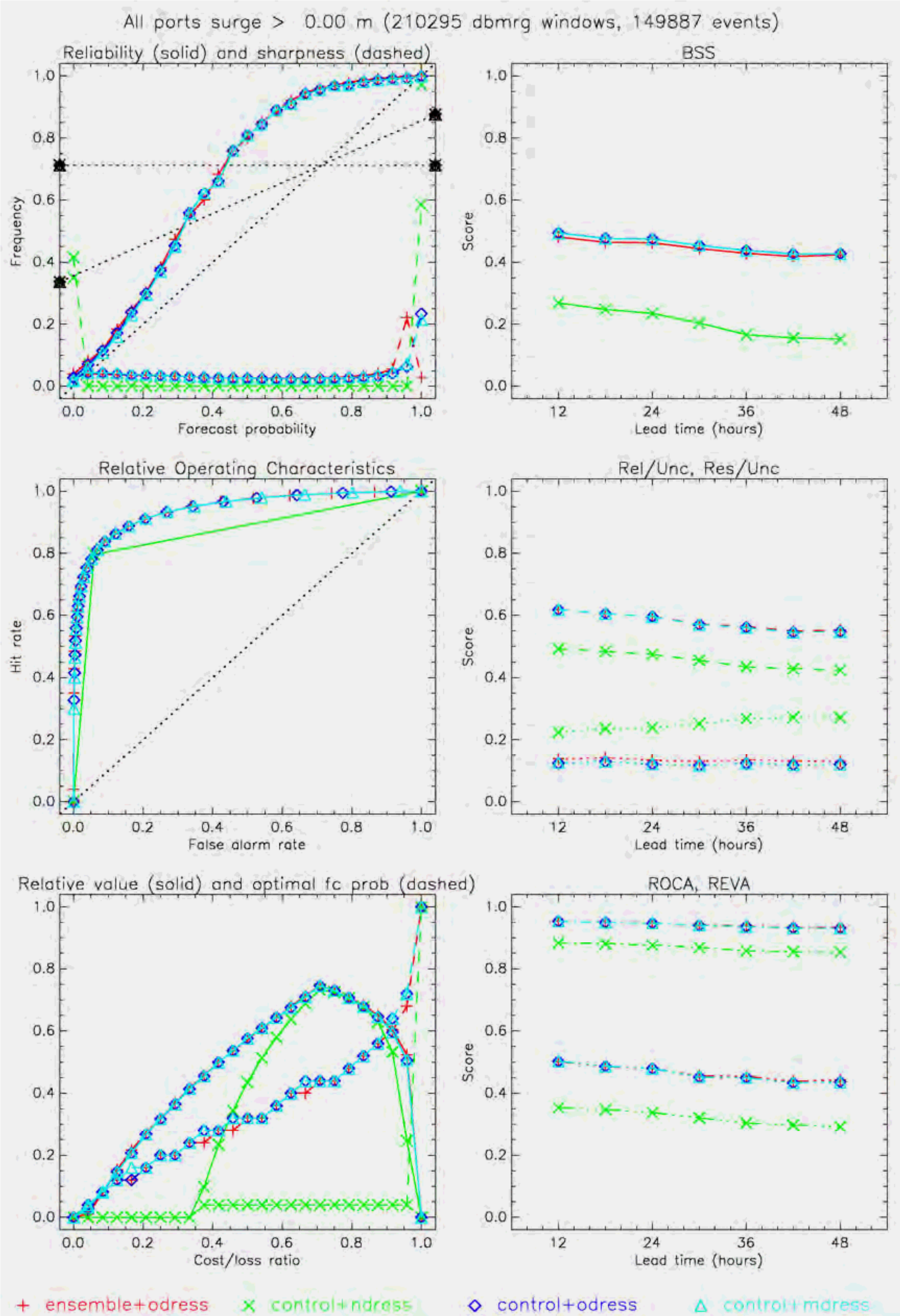


Figure A5.1: Probabilistic verification measures with respect to merged observations for surge exceeding 0.00 metres, using the same format as Figure 9. Low-frequency biases have been removed by subtracting the mean difference between observations and hindcasts from the 12 hours prior to data time, and a 10 cm Gaussian dressing has been applied to each ensemble member to cover unsimulated errors such as those in the harmonic tide prediction.

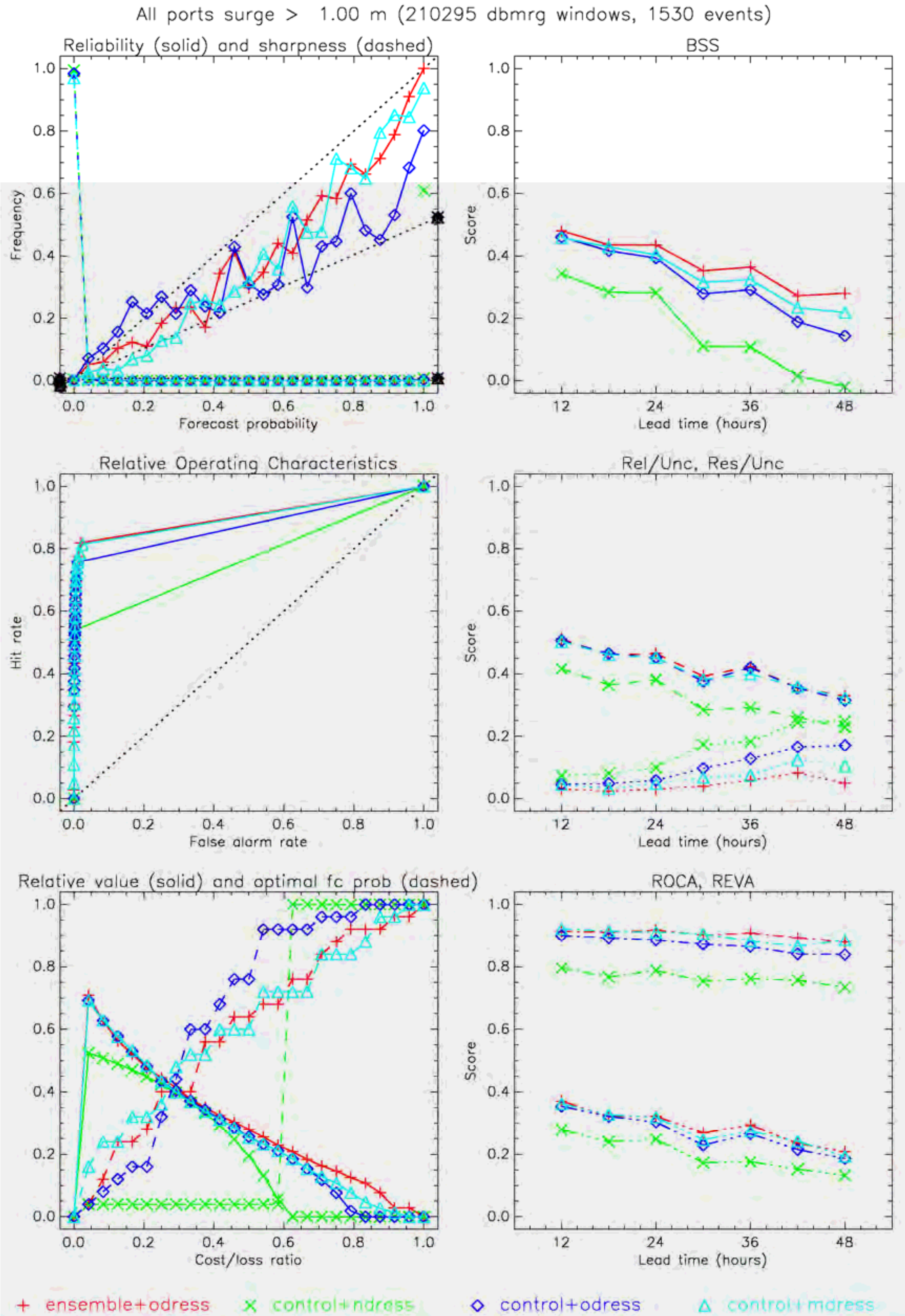


Figure A5.2: Probabilistic verification measures with respect to merged observations for debiased surge exceeding 1.00 metres, using the same format as Figure 9.

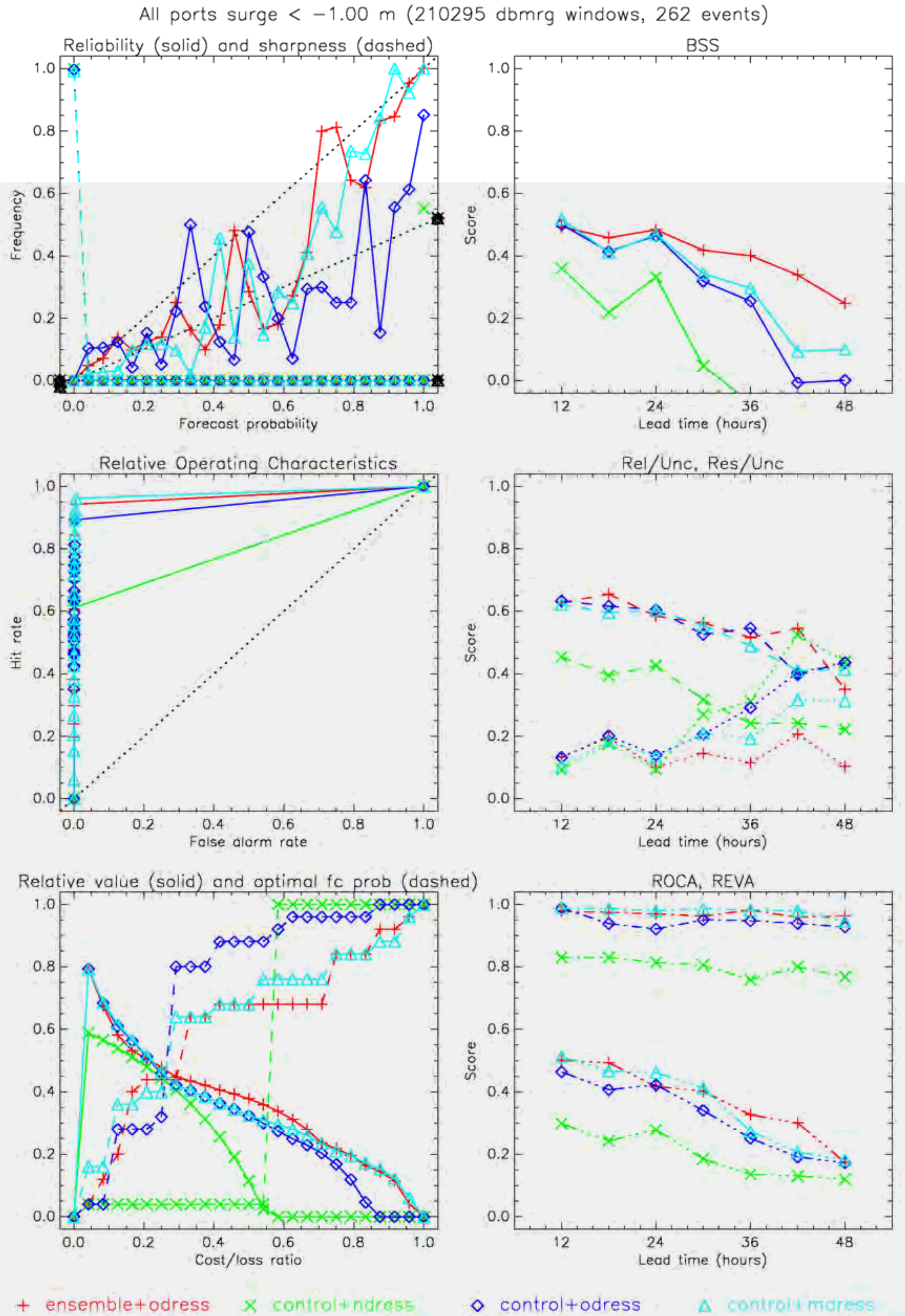


Figure A5.3: Probabilistic verification measures with respect to merged observations for debiased surge below -1.00 metres, using the same format as Figure 9.

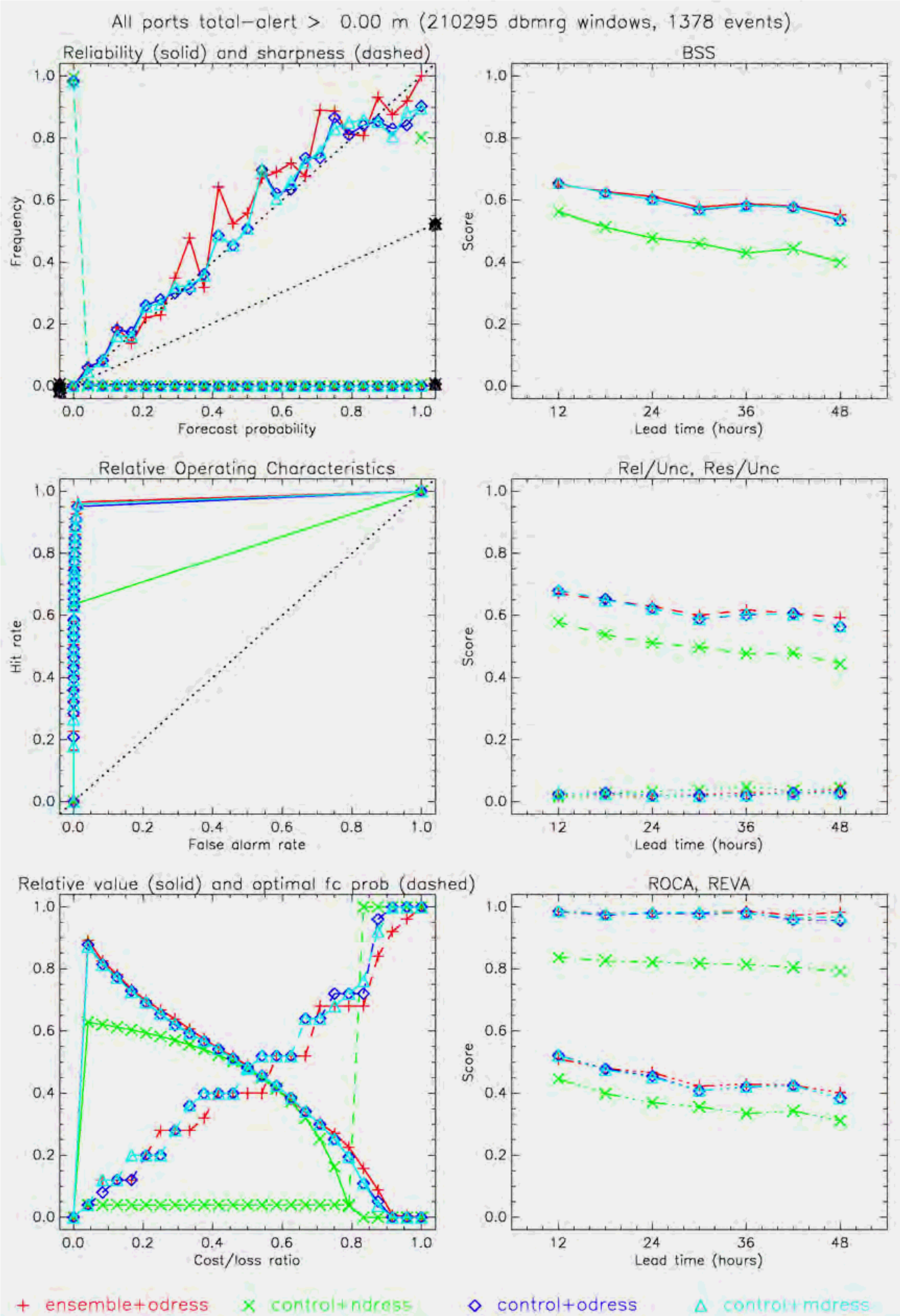


Figure A5.4: Probabilistic verification measures with respect to merged observations for debiased total water exceeding alert level, using the same format as Figure 9.

Appendix 6 Analysis of the relative importance of different uncertainty components

Forecast run time and sub-categories	Forecast timestep	Ensembles Med50/10	Med90/50	Monte Carlo OT50/OT10	OT90/OT50
1800/26/10/07	Time				
Low >	28/10/2007 12:00	,	4.13	3.73	2.87
0600/27/10/07	Time				
	28/10/2007 12:00	5.21	2.38	2.99	2.42
	28/10/2007 12:30	4.08	4.08	3.28	2.58
1800/27/10/07	Time				
12hr >	28/10/2007 12:00	2.20	2.25	3.18	2.58
	29/10/2007 00:00	4.17	6.07	3.38	2.68
	29/10/2007 00:30	4.22	3.25	3.26	2.63
0600/23/11/07	Time				
	24/11/2007 10:15	1.87	1.77	3.01	2.39
	24/11/2007 10:45	1.65	2.44	3.19	2.52
1800/23/11/07	Time				
12hr >	24/11/2007 10:15	2.43	1.53	2.97	2.37
12hr, Low >	24/11/2007 10:45	,	1.86	3.16	2.51
0600/08/01/08	Time				
	09/01/2008 11:15	4.83	7.00	3.11	2.45
Low >	09/01/2008 11:45	,	6.34	3.51	2.73
1800/08/01/08	Time				
12hr, Low >	09/01/2008 11:15	2.63	3.28	3.35	2.62
12hr, Low >	09/01/2008 11:45	4.06	3.79	3.40	2.66
0600/09/01/08	Time				
Low >	10/01/2008 11:45	344.82	14.52	4.01	3.08
Low >	10/01/2008 12:15	194.16	32.77	3.95	3.05
Low >	10/01/2008 12:45	15.26	27.10	4.08	3.08
0600/23/01/08	Time				
	24/01/2008 12:15	3.28	3.30	3.63	2.81
1800/23/01/08	Time				
12hr >	24/01/2008 12:15	3.03	2.25	3.22	2.60
Low >	25/01/2008 12:30	4.63	3.47	3.63	2.81
0600/24/01/08	Time				
Low >	25/01/2008 13:00	2.32	2.41	3.28	2.60
1800/24/01/08	Time				
12hr >	25/01/2008 13:00	1.93	2.17	3.29	2.58
1800/21/02/08	Time				
12hr >	22/02/2008 12:00	3.65	2.31	3.30	2.61
1800/07/03/08	Time				
12hr, Low >	08/03/2008 11:30	2.51	3.26	3.87	3.01
Low >	09/03/2008 00:00	2.32	4.74	3.50	2.78
	09/03/2008 11:45	3.38	2.85	3.26	2.58
	09/03/2008 12:15	3.27	2.13	3.12	2.51
1800/08/03/08	Time				
Low >	10/03/2008 12:15	368.14	16.34	4.07	3.11
	10/03/2008 12:45	30.06	5.33	3.03	2.50
	10/03/2008 13:15	22.80	4.07	2.78	2.33
0600/09/03/08	Time				
Low >	10/03/2008 12:45		1.98	3.52	2.81
	11/03/2008 00:45	7.22	9.13	3.40	2.73
	11/03/2008 01:15	16.17	5.14	3.12	2.52
	11/03/2008 01:45	15.37	2.78	3.58	2.77
1800/09/03/08	Time				
12hr, High >	10/03/2008 12:15	3.11	1.92	3.10	2.66
12hr >	10/03/2008 12:45	3.23	1.70	3.20	2.56
12hr >	10/03/2008 13:15	18.39	6.29	3.50	2.78
	11/03/2008 00:45	23.94	5.49	3.61	2.93
	11/03/2008 01:15	24.27	3.38	3.53	2.74
0600/10/03/08	Time				
12hr, Low >	11/03/2008 01:15	3.86	2.96	3.65	2.84
High >	12/03/2008 01:15	5.08	6.36	2.38	1.99
High >	12/03/2008 01:45	9.06	7.32	2.21	1.89
High >	12/03/2008 02:15	6.14	6.50	2.34	1.98
1800/10/03/08	Time				
High >	12/03/2008 01:15	5.13	2.47	2.25	1.91
High >	12/03/2008 01:45	5.13	2.36	2.09	1.81
High >	12/03/2008 02:15	17.22	2.58	2.16	1.87
Low >	12/03/2008 13:45	6.94	20.67	3.51	2.77
Low >	12/03/2008 14:15	9.93	15.94	3.66	2.83
0600/11/03/08	Time				
12hr, High >	12/03/2008 01:15	5.61	3.87	2.58	2.12
12hr, High >	12/03/2008 01:45	9.22	3.28	2.32	1.99
12hr, High >	12/03/2008 02:15	3.74	2.72	2.42	2.04
High >	12/03/2008 13:45	4.72	3.16	2.52	2.09
High >	12/03/2008 14:15	5.40	2.08	2.53	2.08
High >	12/03/2008 14:45	5.18	4.43	2.97	2.34
1800/11/03/08	Time				
12hr, High >	12/03/2008 13:45	2.35	3.55	2.91	2.33
12hr, High >	12/03/2008 14:15	1.69	3.19	2.92	2.32
12hr >	12/03/2008 14:45	3.03	2.26	3.31	2.58

	All	12hr	Low	High
Median Med50/10	4.72	3.07	4.63	5.13
Mean Med90/50	5.49	2.86	9.74	3.72
Median OT50/OT10	3.26	3.20	3.63	2.42
Mean OT90/OT50	2.53	2.51	3.64	2.09

Calculation Sheet A6.1 Relative importance of uncertainties introduced through ensemble and through Monte Carlo modelling

Calculation Sheet A6.2 Relative importance of different uncertainties introduced through Monte Carlo modelling

Forecast run time		All uncertainties on		Wind-sea friction only		Swell friction only		Wave period only		Beach normal only		Beach slope only		Toe depth only		Sea depth only		Roughness only		Crest level only		Structure factor only	
and sub-categories	Forecast timestep	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10
1800/26/10/07	Time																								
Low >	28/10/2007 12:00	2.89	3.84	1.12	1.09	1.12	1.09	1.23	1.24	1.12	1.09	1.12	1.09	1.12	1.09	1.13	1.11	1.35	1.40	2.00	1.99	2.54	2.82
0600/27/10/07	Time																								
	28/10/2007 12:00	2.49	2.99	1.09	1.07	1.09	1.08	1.19	1.19	1.09	1.07	1.10	1.07	1.10	1.07	1.11	1.10	1.29	1.31	1.77	1.81	2.08	2.40
	28/10/2007 12:30	2.53	3.51	1.10	1.08	1.10	1.07	1.19	1.18	1.10	1.08	1.10	1.08	1.10	1.08	1.12	1.11	1.31	1.34	1.77	1.76	2.20	2.64
1800/27/10/07	Time																								
12hr >	28/10/2007 12:00	2.49	3.09	1.10	1.08	1.10	1.07	1.19	1.20	1.10	1.08	1.09	1.08	1.10	1.08	1.11	1.10	1.30	1.35	1.86	1.84	2.20	2.57
	29/10/2007 00:00	2.52	3.20	1.10	1.08	1.10	1.08	1.21	1.21	1.10	1.08	1.10	1.08	1.10	1.08	1.11	1.11	1.32	1.34	1.80	1.82	2.23	2.61
	29/10/2007 00:30	2.55	3.05	1.09	1.07	1.09	1.07	1.20	1.20	1.10	1.07	1.09	1.08	1.10	1.07	1.11	1.10	1.31	1.32	1.80	1.79	2.10	2.46
0600/23/11/07	Time																								
	24/11/2007 10:15	2.33	3.01	1.10	1.07	1.09	1.07	1.17	1.17	1.09	1.07	1.09	1.07	1.09	1.07	1.09	1.08	1.29	1.32	1.69	1.69	2.00	2.48
	24/11/2007 10:45	2.50	3.02	1.10	1.08	1.10	1.08	1.18	1.18	1.10	1.08	1.10	1.08	1.10	1.08	1.10	1.08	1.31	1.33	1.75	1.73	2.19	2.65
1800/23/11/07	Time																								
12hr >	24/11/2007 10:15	2.37	3.02	1.10	1.07	1.10	1.07	1.18	1.18	1.10	1.07	1.09	1.07	1.09	1.08	1.09	1.08	1.29	1.31	1.73	1.74	2.06	2.42
12hr, Low >	24/11/2007 10:45	2.64	3.35	1.10	1.08	1.10	1.08	1.18	1.19	1.10	1.08	1.10	1.08	1.10	1.08	1.10	1.08	1.32	1.33	1.73	1.70	2.23	2.52
0600/08/01/08	Time																								
	09/01/2008 11:15	2.41	3.18	1.11	1.09	1.11	1.09	1.19	1.19	1.11	1.09	1.11	1.09	1.11	1.08	1.11	1.09	1.34	1.37	1.72	1.72	2.37	2.83
Low >	09/01/2008 11:45	2.73	3.77	1.12	1.09	1.12	1.09	1.22	1.23	1.12	1.10	1.12	1.10	1.13	1.09	1.12	1.09	1.37	1.40	1.80	1.76	2.63	2.94
1800/08/01/08	Time																								
12hr, Low >	09/01/2008 11:15	2.78	3.53	1.11	1.09	1.11	1.09	1.19	1.19	1.11	1.09	1.11	1.08	1.11	1.08	1.11	1.08	1.33	1.34	1.72	1.70	2.35	2.79
12hr, Low >	09/01/2008 11:45	2.76	3.42	1.11	1.09	1.11	1.08	1.19	1.20	1.11	1.08	1.11	1.08	1.10	1.08	1.11	1.09	1.34	1.34	1.70	1.71	2.34	2.67
0600/09/01/08	Time																								
Low >	10/01/2008 11:45	2.85	3.78	1.13	1.09	1.13	1.10	1.22	1.23	1.12	1.10	1.12	1.10	1.12	1.09	1.13	1.10	1.37	1.40	1.79	1.86	2.73	2.90
Low >	10/01/2008 12:15	3.13	3.86	1.12	1.09	1.12	1.09	1.22	1.22	1.12	1.09	1.11	1.09	1.11	1.09	1.12	1.09	1.34	1.39	1.78	1.81	2.46	2.95
Low >	10/01/2008 12:45	2.83	3.63	1.13	1.10	1.13	1.10	1.25	1.25	1.13	1.10	1.13	1.10	1.12	1.09	1.13	1.10	1.38	1.39	1.85	1.85	2.75	3.09
0600/23/01/08	Time																								
	24/01/2008 12:15	2.68	3.31	1.10	1.08	1.10	1.08	1.20	1.19	1.11	1.08	1.10	1.08	1.11	1.08	1.10	1.08	1.32	1.34	1.75	1.80	2.19	2.57
1800/23/01/08	Time																								
12hr >	24/01/2008 12:15	2.60	3.49	1.10	1.08	1.10	1.08	1.20	1.19	1.10	1.08	1.10	1.08	1.11	1.07	1.10	1.08	1.31	1.33	1.73	1.74	2.18	2.62
Low >	25/01/2008 12:30	2.64	3.42	1.11	1.09	1.11	1.09	1.20	1.21	1.11	1.09	1.11	1.08	1.12	1.09	1.11	1.09	1.35	1.34	1.75	1.74	2.45	2.82
0600/24/01/08	Time																								
Low >	25/01/2008 13:00	2.68	3.48	1.10	1.08	1.10	1.08	1.19	1.19	1.10	1.08	1.10	1.08	1.10	1.08	1.10	1.08	1.32	1.35	1.75	1.76	2.23	2.57
1800/24/01/08	Time																								
12hr >	25/01/2008 13:00	2.50	3.38	1.10	1.08	1.10	1.08	1.19	1.20	1.11	1.08	1.11	1.08	1.11	1.08	1.11	1.08	1.33	1.35	1.74	1.75	2.27	2.63
1800/21/02/08	Time																								
12hr >	22/02/2008 12:00	2.62	3.21	1.11	1.08	1.10	1.08	1.20	1.20	1.10	1.08	1.10	1.08	1.11	1.09	1.10	1.08	1.32	1.34	1.93	1.93	2.22	2.68
1800/07/03/08	Time																								
12hr, Low >	08/03/2008 11:30	3.31	4.67	1.12	1.09	1.12	1.09	1.27	1.27	1.13	1.09	1.12	1.09	1.13	1.11	1.12	1.09	1.36	1.40	1.97	1.99	2.54	2.96
Low >	09/03/2008 00:00	2.75	3.76	1.11	1.08	1.11	1.08	1.20	1.22	1.11	1.08	1.11	1.08	1.10	1.08	1.11	1.08	1.34	1.37	1.82	1.82	2.27	2.79
	09/03/2008 11:45	2.41	3.03	1.10	1.08	1.10	1.08	1.20	1.20	1.10	1.08	1.10	1.08	1.10	1.08	1.10	1.08	1.32	1.34	1.78	1.79	2.19	2.55
	09/03/2008 12:15	2.36	3.00	1.09	1.07	1.09	1.07	1.18	1.19	1.09	1.07	1.09	1.07	1.09	1.07	1.09	1.07	1.29	1.31	1.75	1.81	2.05	2.41
1800/08/03/08	Time																								
Low >	10/03/2008 12:15	2.90	3.89	1.10	1.08	1.10	1.09	1.23	1.24	1.11	1.08	1.10	1.08	1.11	1.08	1.11	1.10	1.33	1.34	2.15	2.14	2.32	2.70
	10/03/2008 12:45	2.52	3.04	1.08	1.07	1.09	1.07	1.19	1.20	1.09	1.07	1.09	1.07	1.08	1.07	1.09	1.08	1.28	1.30	2.08	2.03	1.96	2.28
	10/03/2008 13:15	2.53	3.27	1.09	1.07	1.10	1.07	1.19	1.18	1.09	1.07	1.09	1.07	1.09	1.07	1.10	1.10	1.29	1.30	1.98	1.98	2.11	2.36
0600/09/03/08	Time																								
Low >	10/03/2008 12:45	2.87	3.56	1.11	1.08	1.10	1.08	1.21	1.21	1.11	1.09	1.11	1.08	1.11	1.08	1.11	1.09	1.33	1.35	2.15	2.14	2.33	2.61
	11/03/2008 00:45	2.46	3.24	1.10	1.08	1.10	1.08	1.20	1.19	1.10	1.08	1.10	1.08	1.09	1.07	1.10	1.08	1.32	1.33	1.72	1.73	2.22	2.53
	11/03/2008 01:15	2.44	3.01	1.09	1.07	1.10	1.07	1.18	1.18	1.09	1.07	1.09	1.07	1.10	1.08	1.09	1.07	1.28	1.31	1.70	1.73	1.99	2.38
	11/03/2008 01:45	2.51	3.06	1.11	1.08	1.10	1.08	1.19	1.20	1.11	1.08	1.11	1.08	1.10	1.08	1.10	1.08	1.33	1.34	1.72	1.73	2.30	2.64
1800/09/03/08	Time																								
12hr, High >	10/03/2008 12:15	2.30	2.76	1.09	1.07	1.09	1.07	1.16	1.16	1.08	1.07	1.09	1.07	1.09	1.07	1.10	1.09	1.28	1.28	1.81	1.84	1.90	2.34
12hr >	10/03/2008 12:45	2.43	2.91	1.09	1.07	1.09	1.07	1.16	1.17	1.09	1.07	1.08	1.07	1.09	1.07	1.10	1.09	1.29	1.30	1.83	1.90	1.96	2.32
12hr >	10/03/2008 13:15	2.63	3.20	1.10	1.08	1.10	1.08	1.18	1.19	1.09	1.08	1.10	1.07	1.10	1.07	1.11	1.11	1.31	1.32	1.86	1.90	2.14	2.56
	11/03/2008 00:45	2.56	3.34	1.11	1.09	1.11	1.08	1.20	1.21	1.11	1.08	1.11	1.08	1.11	1.09	1.11	1.09	1.32	1.36	1.79	1.79	2.38	2.73
	11/03/2008 01:15	2.66	3.34	1.10	1.08	1.10	1.08	1.18	1.19	1.10	1.08	1.10	1.08	1.10	1.07	1.10	1.08	1.32	1.33	1.76	1.77	2.17	2.55
0600/10/03/08	Time																								
12hr, Low >	11/03/2008 01:15	2.85	3.63	1.12	1.09	1.11	1.09	1.22	1.22	1.12	1.08	1.12	1.08	1.11	1.08	1.11	1.09	1.34	1.36	1.81	1.81	2.36	2.82
High >	12/03/2008 01:15	1.99	2.28	1.06	1.05	1.06	1.05	1.11	1.12	1.06	1.05	1.06	1.05	1.06	1.05	1.06	1.05	1.22	1.23	1.52	1.52	1.57	1.88
High >	12/03/2008 01:45	1.69	1.91	1.05	1.04	1.05	1.04	1.10	1.10	1.05	1.04	1.05	1.04	1.06	1.04	1.05	1.04	1.20	1.20	1.50	1.52	1.46	1.72
High >	12/03/2008 02:15	1.82	2.02	1.06	1.05	1.06	1.05	1.11	1.11	1.06	1.05	1.06	1.05	1.06	1.05	1.06	1.05	1.20	1.22	1.52	1.52	1.54	1.82
1800/10/03/08	Time																								
High >	12/03/2008 01:15	1.77	2.06	1.06	1.05	1.06	1.05	1.11	1.11	1.06	1.05	1.06	1.05	1.06	1.05	1.06	1.05	1.21	1.23	1.54	1.50	1.54	1.83
High >	12/03/2008 01:45	1.72	1.95	1.05	1.04	1.05	1.04	1.10	1.10	1.05	1.04	1.05	1.04	1.05	1.04	1.05	1.04	1.19	1.20	1.49	1.51	1.47	1.69
High >	12/03/2008 02:15	1.71	2.02	1.05	1.05	1.06	1.04	1.10	1.11	1.06	1.05	1.05	1.05	1.06	1.05	1.06	1.05	1.20	1.21	1.49	1.50	1.50	1.76
Low >	12/03/2008 13:45	2.80	3.63	1.11	1.09	1.12	1.09	1.22	1.23	1.12	1.09	1.12	1.09	1.11	1.09	1.12	1.09	1.36	1.36	1.82	1.84	2.44	2.89
Low >	12/03/2008 14:15	2.90	3.70	1.11	1.09	1.12	1.09	1.23	1.22	1.11	1.09	1.12	1.09	1.11	1.08	1.12	1.09	1.36	1.37	1.84	1.76	2.47	2.86
0600/11/03/08	Time																								
12hr, High >	12/03/2008 01:15	2.09	2.41	1.07	1.06	1.07	1.06	1.13	1.13	1.07	1.06	1.07	1.06	1.07	1.05	1.07	1.06	1.25	1.27	1.56	1.58	1.77	2.08
12hr, High >	12/03/2008 01:45	1.98	2.23	1.06	1.05	1.07	1.05	1.12	1.11	1.06	1.05	1.06	1.05	1.06	1.05	1.07	1.05	1.22	1.23	1.56	1.57	1.63	1.92
12hr, High >	12/03/2008 02:15	1.93	2.45	1.07	1.05	1.07	1.05	1.13	1.13	1.07	1.06	1.07	1.05	1.08	1.07	1.07	1.06	1.23	1.24	1.56	1.57	1.66	1.98
High >	12/03/2008 13:45	1.95	2.46	1.07	1.06	1.07	1.06	1.12	1.13	1.07	1.06	1.07	1.06	1.07	1.06	1.07	1.06	1.24	1.26	1.56	1.56	1.75	2.03
High >	12/03/2008 14:15	2.04	2.45	1.07	1.05	1.07	1.06	1.12	1.13	1.07	1.05	1.07	1.06	1.07	1.06	1.07	1.06	1.24	1.25	1.52	1.57	1.72	2.00
High >	12/03/2008 14:45	2.27	2.58	1.09	1.07	1.09	1.07	1.15	1.15	1.09	1.07	1.09	1.07	1.09	1.07	1.09	1.07	1.28	1.29	1.59	1.60	1.99	2.25
1800/11/03/08	Time																								
12hr, High >	12/03/2008 13:45	2.26	2.81	1.09	1.07	1.10	1.07	1.16	1.16	1.09	1.08	1.09	1.08	1.09	1.07	1.10	1.08	1.30	1.33	1.62	1.66	2.06	2.36
12hr, High >	12/03/2008 14:15	2.21	2.59	1.09	1.07	1.09	1.07	1.15	1.16	1.09	1.07	1.09	1.07	1.09	1.07	1.09	1.07	1.28	1.32	1.62	1.63	1.97	2.39
12hr >	12/03/2008 14:45	2.64	3.35	1.11	1.09	1.11	1.09	1.19	1.19	1.11	1.08	1.11	1.08	1.12	1.09	1.11	1.08	1.33	1.36	1.67	1.65	2.29	2.73

Average ratios

All 'stormy'		**12hr**		**Low**		**High**	
OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10	OT90/50	OT50/10
2.47	**3.11**	**2.49**	**3.13**	**2.84**	**3.70**	**1.98**	**2.33**
1.10	1.07	1.10	1.07	1.11	1.09	1.07	1.06
1.10	1.07	1.10	1.08	1.11	1.09	1.07	1.06
1.18	1.18	1.18	1.18	1.22	1.22	1.12	1.13
1.10	1.07	1.10	1.07	1.11	1.09	1.07	1.06
1.10	1.07	1.10	1.07	1.11	1.09	1.07	1.06
1.10	1.07	1.10	1.08	1.11	1.09	1.07	1.06
1.10	1.08	1.10	1.08	1.11	1.09	1.07	1.06
1.30	1.32	1.30	1.32	1.35	1.37	1.24	1.25
1.75	1.75	1.74	1.75	1.85	1.85	1.56	1.58
2.12	2.48	2.11	2.49	2.44	2.81	1.70	2.00

Appendix 7 Comparison between NFFS and probabilistic overtopping forecasts

Time of high tide >	earlier	26/10/2007 23:00				a.m. 27th	27/10/2007 23:45				28/10/2007 12:00				29/10/2007 00:15				later
Time of forecast		NFFS	Median	Mean	%>0.2		NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	
26/10/2007 06:00	~0	0.35	<0.2	<0.2	0%	~0	<0.2	0.20	0.70	50%									
26/10/2007 18:00	~0	0.32	<0.2	<0.2	19%	~0	2.40	0.58	0.68	82%	<0.2	0.45	0.73	70%					
27/10/2007 06:00						~0	1.87	0.58	0.73	85%	0.63	1.24	1.56	90%	<0.2	0.23	0.34	54%	~0
27/10/2007 18:00							1.43	0.54	0.62	85%	0.71	0.64	0.79	84%	0.66	0.60	0.86	79%	~0
28/10/2007 06:00											0.48	0.40	0.50	55%	0.54	<0.2	<0.2	20%	~0
28/10/2007 18:00															0.58	0.3	0.42	65%	~0

The figures noted are the maxima of forecast mean overtopping rate at Anchorsholme, Blackpool over a high tide, in litres per second per metre run of seawall: greyed out cells are either missing or outside the time range of the forecasts; yellow shading indicates above the 0.2 alert level; "~0" indicates no overtopping on that high tide. The Median and Mean values are the 50 percentile and mean values from the probabilistic forecasts. The %>0.2 values indicate probability of exceeding 0.2 units, from the probabilistic forecasts. Columns headed NFFS show deterministic forecasts from the operational forecasting system.

Figure A7.1 Comparison for 26-29 October 2007

Time of high tide >	earlier	23/11/2007 22:00				24/11/2007 10:15				24/11/2007 22:45				later
Time of forecast		NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	
22/11/2007 18:00	~0	<0.2	<0.2	<0.2	0%		0.60	0.77	90%					
23/11/2007 06:00	~0	<0.2	<0.2	<0.2	0%	4.69	0.91	1.08	92%		<0.2	0.21	42%	~0
23/11/2007 18:00	~0	<0.2	<0.2	<0.2	0%	4.03	0.98	1.10	96%	1.88	<0.2	0.22	43%	~0
24/11/2007 06:00	~0					4.91	1.00	1.20	95%		0.6	0.2	45%	~0
24/11/2007 18:00	~0										0.2	0.3	50%	~0

Figure A7.2 Comparison for 23-24 November 2007

Time of high tide >	earlier	08/01/2008 23:30				09/01/2008 12:00				10/01/2008 00:00				10/01/2008 12:15				11/01/2008 00:45				later
Time of forecast		NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	NFFS	Median	Mean	%>0.2	
07/01/2008 06:00	~0		0.21	0.33	40%																	
07/01/2008 18:00	~0	0.84	<0.2	0.27	30%		2.30	2.80	91%													
08/01/2008 06:00	~0	1.03	<0.2	<0.2	13%	<0.2	<0.2	0.32	40%	<0.2	<0.2	<0.2	1%									
08/01/2008 18:00	~0	0.84	<0.2	<0.2	20%	1.46	0.20	0.26	50%	<0.2	<0.2	<0.2	0%	<0.2	<0.2	<0.2	13%					
09/01/2008 06:00						1.30	<0.2	0.24	47%	<0.2	<0.2	<0.2	1%	1.5	0.48	1.3	79%	<0.2	<0.2	<0.2	0%	~0
10/01/2008 06:00														<0.2	<0.2	0.2	35%	<0.2	<0.2	<0.2	5%	~0

Figure A7.3 Comparison for 8-11 January 2008

Time of high tide >	earlier	24/01/2008 00:00				24/01/2008 12:30				25/01/2008 00:45				25/01/2008 13:00				26/01/2008 01:30				later
Time of forecast		NFFS	Median	Mean	>0.2	NFFS	Median	Mean	>0.2	NFFS	Median	Mean	>0.2	NFFS	Median	Mean	>0.2	NFFS	Median	Mean	>0.2	
22/01/2008 06:00	~0		<0.2	<0.2	25%																	
22/01/2008 18:00	~0	<0.2	<0.2	<0.2	25%		1.34	1.90	90%													
23/01/2008 06:00	~0	<0.2	<0.2	<0.2	12%	4.57	0.37	0.51	70%		<0.2	<0.2	1%									
23/01/2008 18:00	~0	<0.2	<0.2	<0.2	4%	13.20	0.50	0.63	80%	<0.2	<0.2	<0.2	5%		0.50	0.70	77%					
24/01/2008 06:00						9.05	0.5	0.65	80%	<0.2	<0.2	<0.2	1%	2.80	0.43	0.54	76%		<0.2	<0.2	0%	~0
24/01/2008 18:00										<0.2	<0.2	<0.2	3%	1.91	0.45	0.58	77%	<0.2	<0.2	<0.2	0%	~0
25/01/2008 06:00														1.44	0.33	0.48	65%	<0.2	<0.2	<0.2	5%	~0
25/01/2008 18:00																		<0.2	<0.2	<0.2	5%	~0

Figure A7.4 Comparison for 24-26 January 2008

Appendix 8 Parallel evaluation using Anglian Region wave measurements

There is little direct evaluation of wave transformation modelling elsewhere in this report. The intention here is to carry out a different style of evaluation, using ongoing wave recording funded by the Environment Agency Anglian Region, focusing on its relevance to coastal flood forecasting.

Sea level and surge are obviously important in coastal flood forecasting, and there is no attempt to prove that again here. Waves would appear to be relevant, but is it worth the effort of transforming existing offshore wave forecasts, firstly inshore to the coast, and secondly into overtopping rate? Does wave transformation improve skill, not in terms of the absolute accuracy of wave height predictions, but in terms of identifying the potential flood events where action may be necessary? Does overtopping prediction improve skill in identifying events? Essentially the approach is to identify (retrospectively ‘forecast’) the dates of potential flood risk events and which will be the most severe, but in terms of the relative ranking of wave heights and overtopping rates, rather than their actual values.

Two areas were chosen from the ongoing Anglian Region wave measurement programme, using data from October 2006 to March 2008, summarised in Tables A8.1 and A8.2.

Table A8.1 North Norfolk wave data series

North Norfolk		
1 December 2006 to 31 March 2008 (Blakeney to only 8 January 2008)		
Offshore forecast	Met Office UK Waters Model: 53°10’N 1°15’E	Seven storms over 3.25m H_s; highest 3.6m
Offshore measured	Blakeney Overfalls Waverider: 18m depth; 53°3.39’N 1°6.56’E	Six storms over 3.5m H_s; highest 4.5m
Nearshore measured	Cley AWAC: 5m plus tide depth; 52°57.8’N 1°4.8’E	Five storms over 3.0m H_s; highest 3.7m

Table A8.2 North Suffolk wave data series

North Suffolk		
12 October 2006 to 31 March 2008		
Offshore forecast	Met Office UK Waters Model: 52°17’N 1°45’E	Five storms over 3.0m H_s; highest 3.7m
Offshore measured	Southwold Approach Waverider: 20m depth; 52°19.28’N 1°46.67’E	Five storms over 3.25m H_s; highest 4.5m
Nearshore measured	Dunwich Bay AWAC: 5m plus tide depth; 52°17.19’N 1°38.57’E	Five storms over 2.5m H_s; highest 3.0m
Nearshore measured	North Southwold AWAC: 5m plus tide depth; 52°22.14’N 1°42.75’E	Seven storms over 2.5m H_s; highest 3.5m

The approach was to rank the ten highest events based on time series data of apparently increasing relevance to coastal flood forecasting, in an attempt to see if additional ‘relevance’ adds further model skill in picking the ‘right’ dates. As there is no information on actual overtopping rate, this can be done without reference to sea level or seawall profile, as these will not affect relative (between source series) rankings, instead using wave information only. The criteria used in each ranking are:

1. H_s from offshore forecasts (Met Office UK Waters Model).
2. H_s from offshore measured (Blakeney Overfalls and Southwold Approach).
3. H_s from nearshore measured (Cley, Dunwich Bay and North Southwold).
4. Overtopping rate based on offshore measured H_s and T_m.
5. Overtopping rate based on nearshore measured H_s and T_m.

The ‘overtopping rate’ is nominal, based on a simple sloping sea wall, with deep water at the toe, and a fixed ‘freeboard’ (difference between wall crest level and still water level) chosen to obtain a good number of non-zero overtopping rates. The formula, freeboard and overtopping rates are deliberately not given here, as only the relative ranking of the values between different storms is relevant.

Results from the ranking are shown in Tables A8.3 for North Norfolk and A8.4 for North Suffolk. Each row of each table contains the numbers one to ten, ranking the ten highest storms either in terms of wave height or overtopping rate. The top three storms in each row are highlighted in red. A blank box in a row indicates a storm identified by one of the other criteria, but not by the criterion of that row. An X indicates data missing for that storm.

The different criteria tend to pick out the same storms, particular the highest storms, suggesting that additional coastal relevance in wave data makes little practical difference to identification of events. However, an interesting feature of Table A8.4 is that the storm on 1 November 2006 is picked out strongly by the two sets of nearshore wave measurements when converted to overtopping rate, but not by any of the other criteria. This is traceable to unusually large wave periods in the nearshore measurements. Although the offshore measurements show slightly increased wave periods during that storm, they are not quite high enough to record a top-ten storm.

Comparisons of offshore measured waves versus offshore forecast waves, and of offshore measured waves versus nearshore measured waves, for North Norfolk and for North Suffolk are shown in Figures A8.1 to A8.6. In all four diagrams, there is good agreement between offshore measured (purple) and offshore forecast (dark blue) wave heights. The nearshore measured (light blue and yellow) wave heights follow the same general pattern as the offshore data, but with a distinctly lower wave heights. This is all as expected, again suggesting that added sophistication in nearshore wave transformation does not add a great deal of value to the coastal forecast, provided that the offshore forecast wave height is representative of the area.

Table A8.3 Rankings of ten highest events (dd/mm/yy), North Norfolk, 1 December 2006 – 31 March 2008

	Storm date	18/01/07	20/03/07	28/05/07	26/06/07	20/07/07	22/08/07	26-28/09/07	09/11/07	23-25/11/07	10/12/07	03/01/08	01/02/08	16/03/08	21-22/03/08
Offshore forecast	Met Office UK Waters Model: (ranked by wave height)	**9**	**2**	**8**	**4**		**6**	**7**	**3**		**10**		**5**		**1**
Offshore measured	Blakeney Overfalls Waverider: (ranked by wave height)	**3**	**2**	**6**	**4**	**10**	**7**	**5**	**1**	**8**	**9**		**X**	**X**	**X**
Nearshore measured	Cley AWAC: (ranked by wave height)		**3**	**6**	**5**		**7**	**4**	**2**	**10**	**9**			**8**	**1**
Offshore measured	Blakeney Overfalls Waverider: (ranked by overtopping rate)	**7**	**2**	**5**	**4**		**6**	**3**	**1**	**8**	**9**	**10**	**X**	**X**	**X**
Nearshore measured	Cley AWAC: (ranked by overtopping rate)		**2**	**7**	**10**		**6**	**3**	**1**	**8**	**9**			**4**	**5**

Table A8.4 Rankings of ten highest events (dd/mm/yy), North Suffolk, 12 October 2006 – March 2008

	Storm date	25/10/06	01/11/06	17/11/06	03/12/06	11/12/06	30/12/06	03-06/03/07	20/07/07	28/09/07	09/11/07	18-19/11/07	17/12/07	29/12/07	02-03/01/08	13-15/01/08	31/1-1/2/08	03-05/02/08	10/03/08	16/03/08	22/03/08
Offshore forecast	Met Office UK Waters Model: (ranked by wave height)				**2**		**6**	**8**		**9**	**10**					**3**	**5**	**7**	**1**		**4**
Offshore measured	Southwold Approach Waverider: (ranked by wave height)			**6**	**2**	**9**	**10**					**3**				**5**		**7**	**1**	**8**	**4**
Nearshore measured	Dunwich Bay AWAC: (ranked by wave height)	**6**			**1**			**8**	**10**			**4**	**7**		**5**				**2**	**9**	**3**
Nearshore measured	North Southwold AWAC: (ranked by wave height)	**9**		**10**	**3**		**7**					**2**			**5**	**6**		**8**	**1**		**4**
Offshore measured	Southwold Approach Waverider: (ranked by overtopping rate)			**6**	**3**	**10**	**8**	**9**				**4**				**5**		**7**	**1**		**2**
Nearshore measured	Dunwich Bay AWAC: (ranked by overtopping rate)		**2**		**6**					**7**	**4**	**9**	**8**		**5**		**10**		**3**		**1**
Nearshore measured	North Southwold AWAC: (ranked by overtopping rate)		**2**	**8**	**3**					**10**		**1**		**9**		**6**		**7**	**5**		**4**

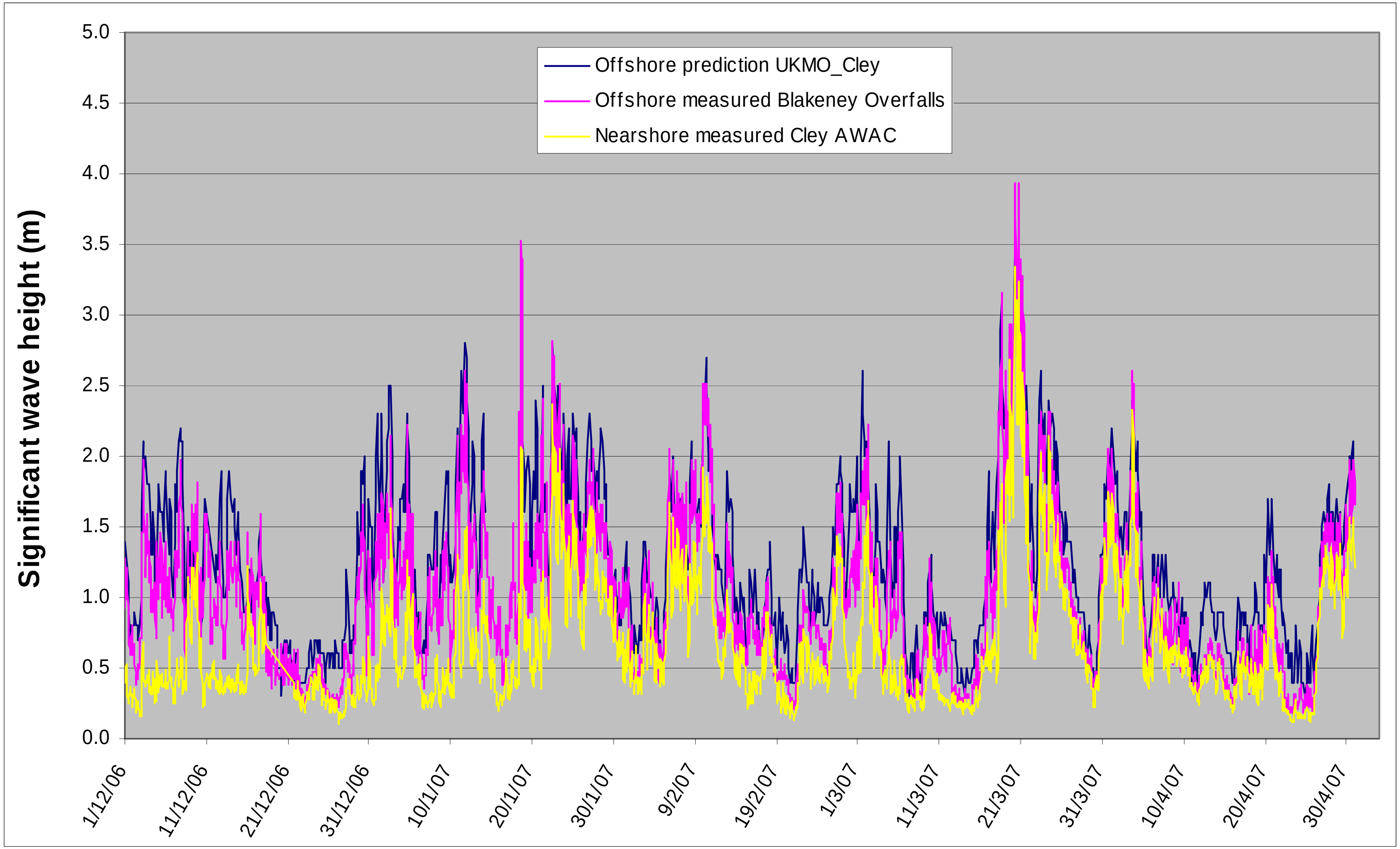


Figure A8.1 North Norfolk wave data series (1 December 2006 – 30 April 2007)

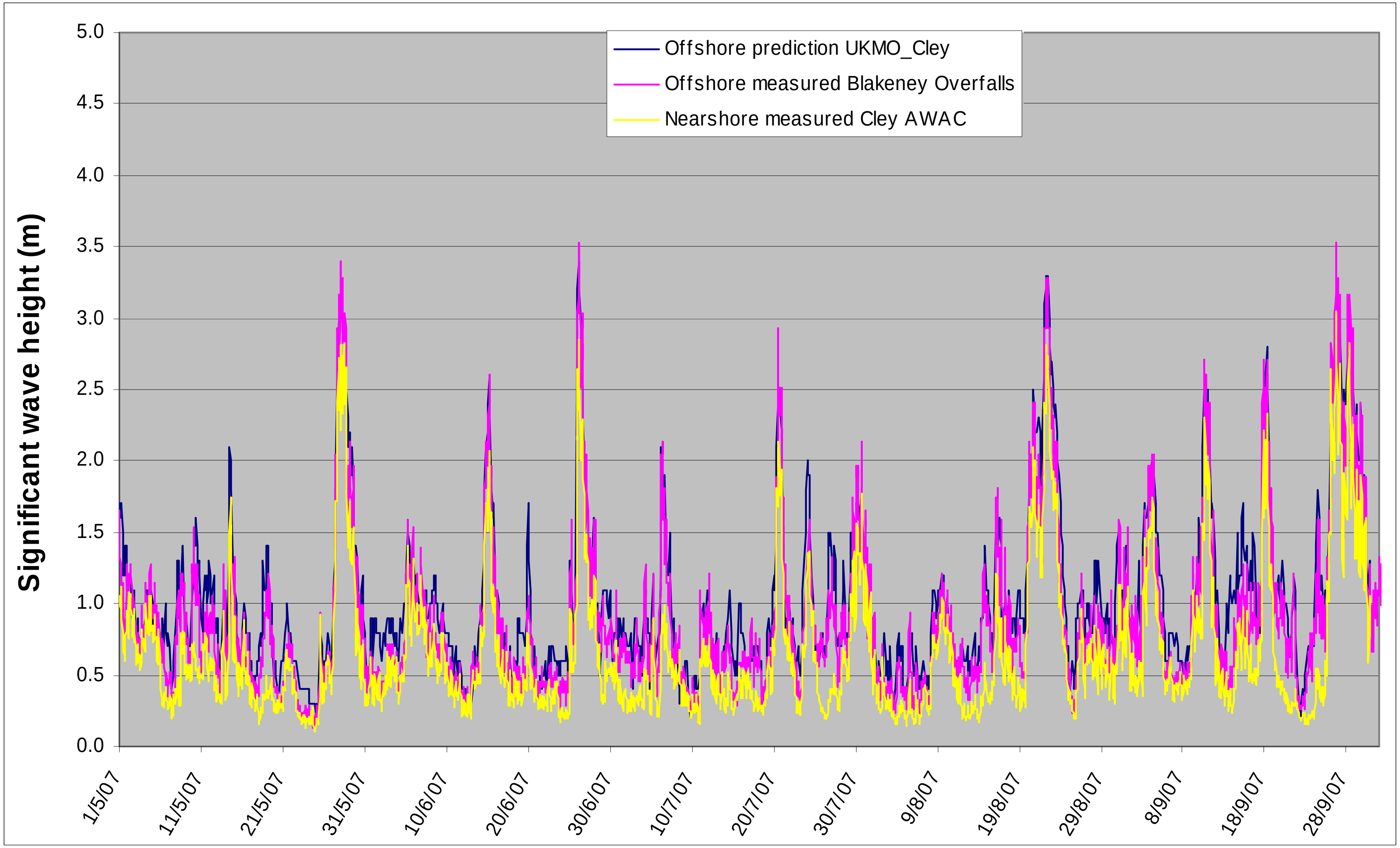


Figure A8.2 North Norfolk wave data series (1 May 2007 – 30 September 2007)

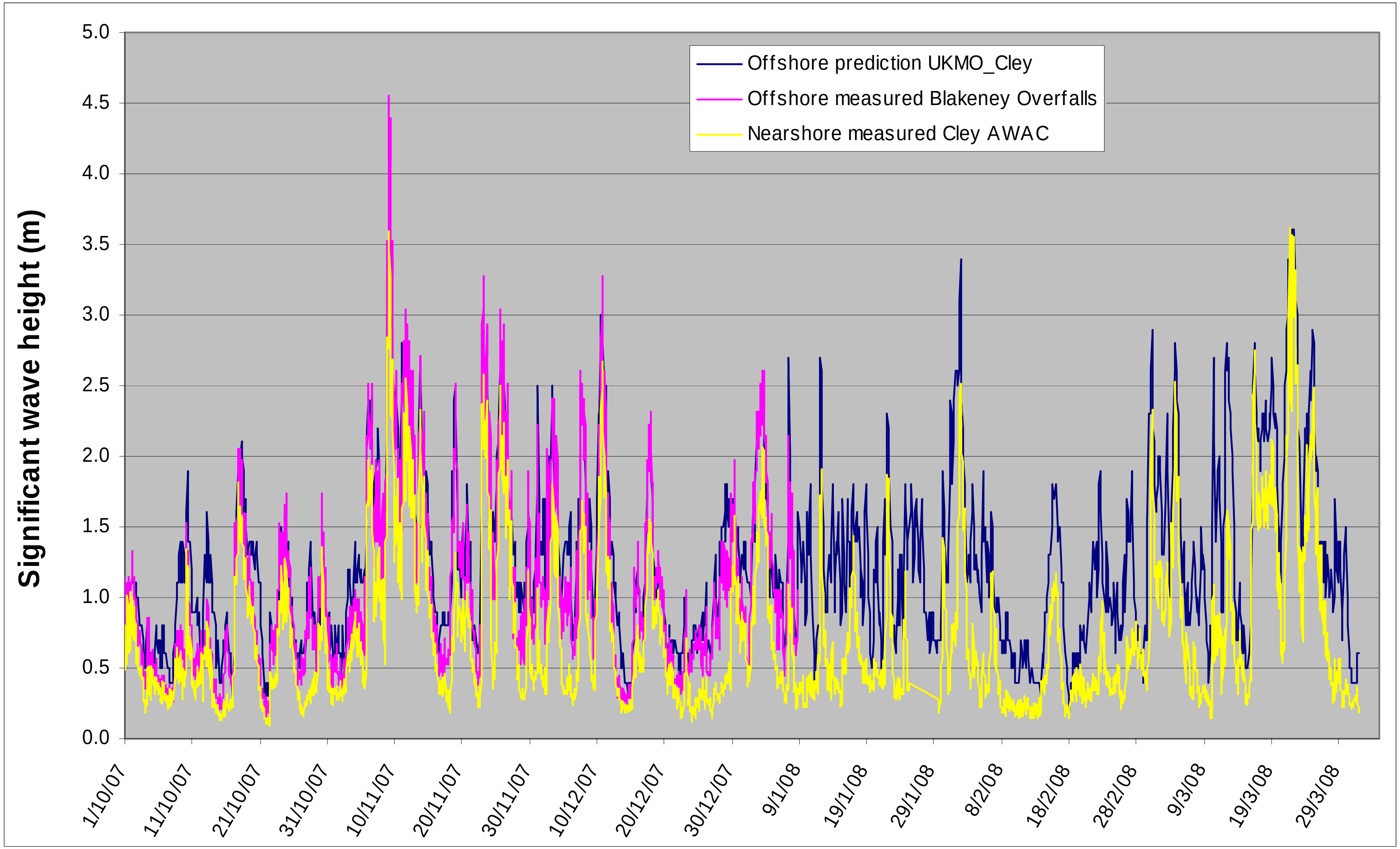


Figure A8.3 North Norfolk wave data series (1 October 2007 – 31 March 2008)

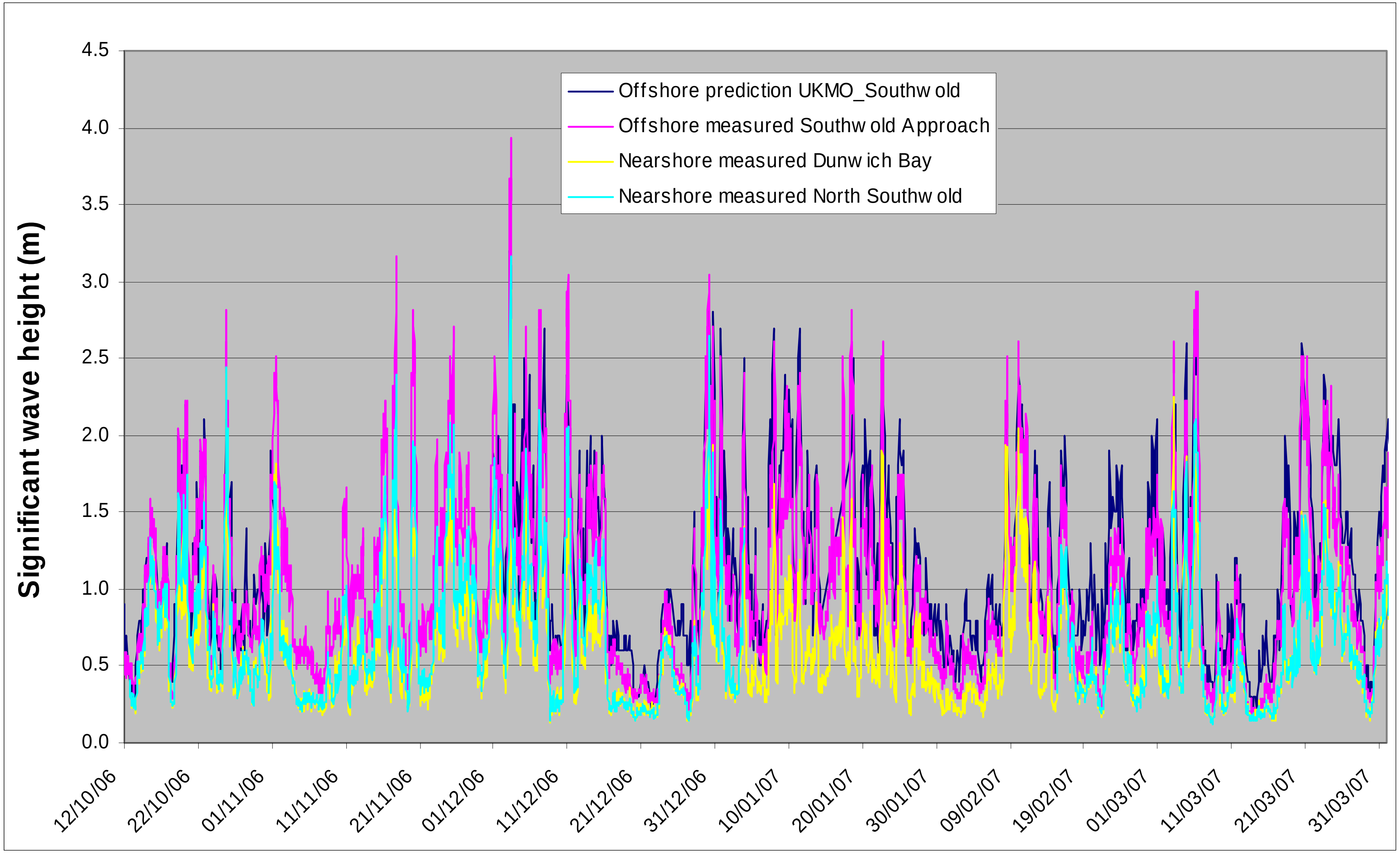


Figure A8.4 North Suffolk wave data series (12 October 2006 – 31 March 2007)

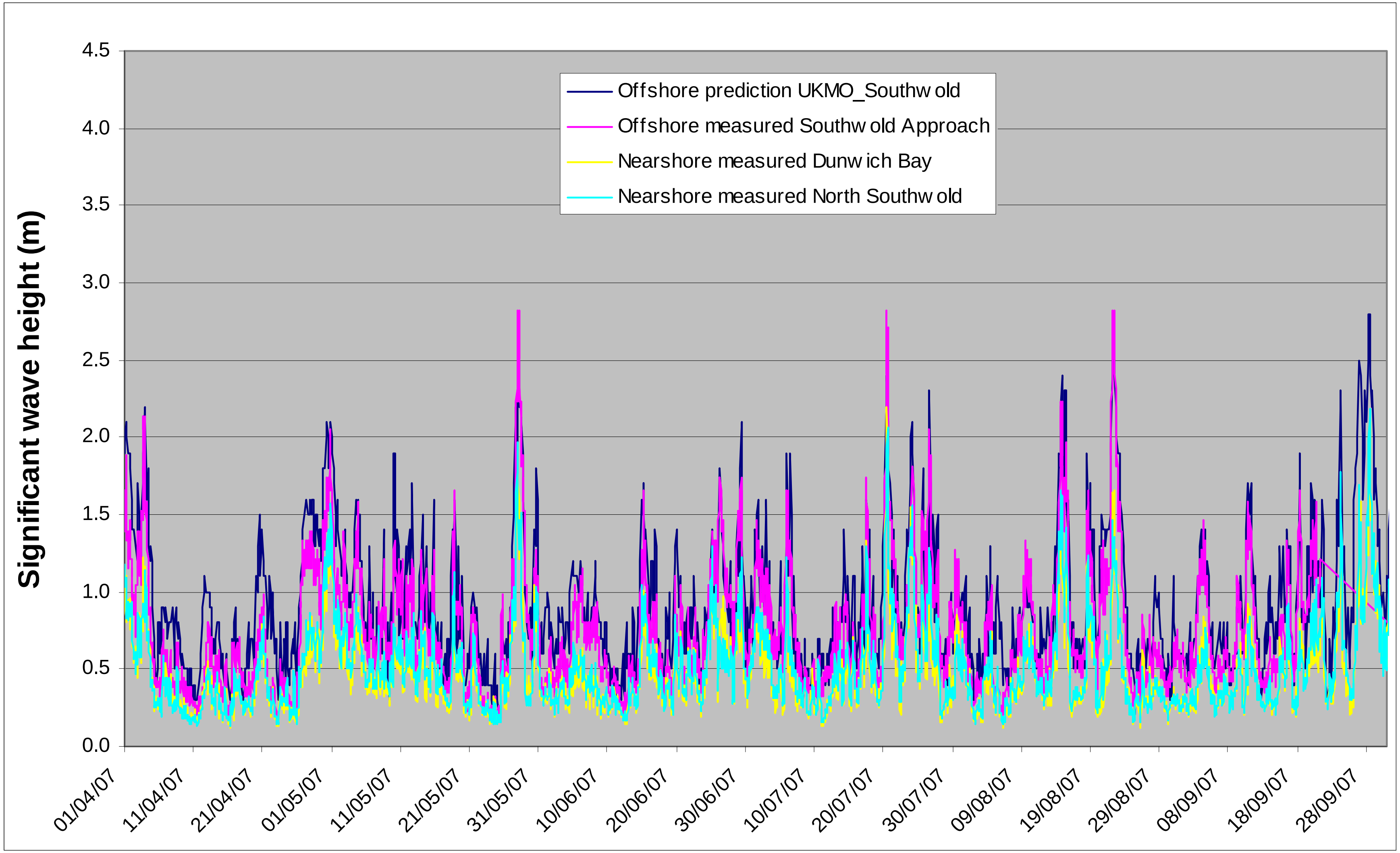


Figure A8.5 North Suffolk wave data series (1 April 2007 – 30 September 2007)

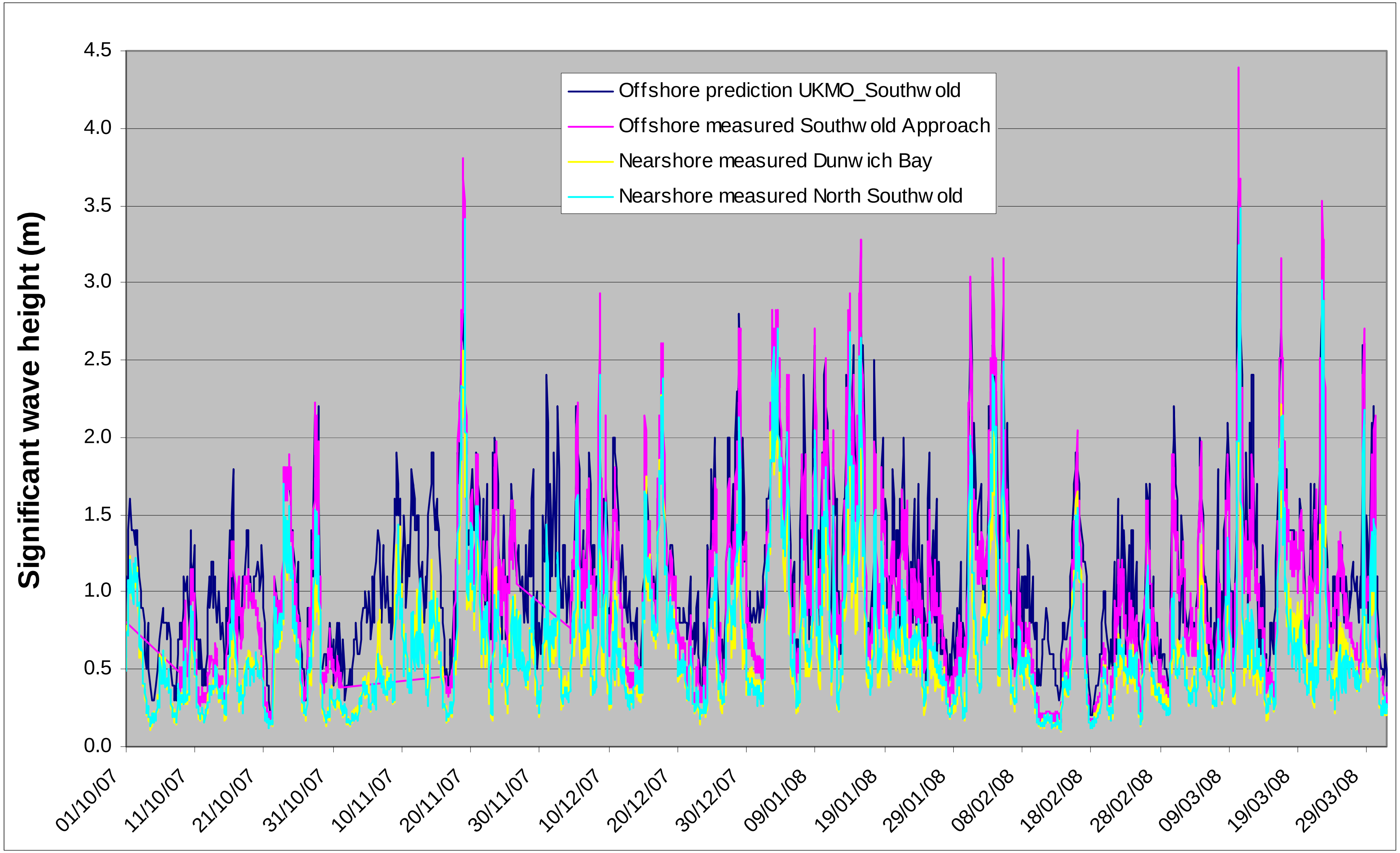


Figure A8.6 North Suffolk wave data series (1 October 2007 – 31 March 2008)

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