Probabilistic Coastal Flood Forecasting

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44th Defra Flood and Coastal Management Conference, Telford, UK 30th June - 2nd July 2009

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PROBABILISTIC COASTAL FLOOD FORECASTING

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Key Words

Coastal, Forecasting, Probabilistic

Abstract

The project described in this paper included development of surge ensemble modelling for the UK, and demonstration of probabilistic coastal flood forecasting for an area in the Irish Sea. Its purpose was to develop, demonstrate and evaluate probabilistic methods for surge, nearshore wave, and coastal flood forecasting. The main features that distinguish these methods from existing UK practice are in the use of hydraulic models extending through to action at coastal defences, and the use of ensemble and other probabilistic approaches throughout. Estimation of high overtopping as an indicator of coastal flooding involves transformation of wave forecasts through the nearshore and surf zones, and the combined effects of waves and sea level in causing overtopping; with sufficient accuracy and reliability for acceptance, and sufficient lead-time for actions to be taken to reduce potential losses.

1 INTRODUCTION

1.1 Coastal flood forecasting

Coastal flood forecasting differs from weather and ocean forecasting in that it focuses on the coastline and on the likelihood of flooding. Flooding may occur through damage to sea defences or high wave overtopping of defences, both of which depend on astronomical tide, surge, waves, coastal bathymetry and the profile and state of the sea defences.

Figure 1 illustrates high overtopping when large waves coincide with a high sea level. This is sufficient to pose a severe threat to pedestrians, and require closure of the promenade area, but insufficient to cause widespread flooding landward of the promenade.

Although this paper concentrates on flood forecasting, this needs to be considered in the context of an overall flood forecasting and warning service. Unless all five elements below work together to achieve some reduction in potential losses due to flooding, there would be little purpose to flood forecasting.

- Monitoring of waves, water levels and wind.
- Forecasting of potential flood events.
- Warning of possible flood events.
- Dissemination of warnings.
- Response, to mitigate potential losses.

1.2 Existing offshore and coastal forecasts in the UK

Ocean forecasting is implemented nationally through the Met Office, with updates provided four times per day. Still water level comes from a deterministic surge prediction model, the predictions from which are combined locally with astronomic tide predictions to provide an overall still water level. Offshore wave forecasts come in the form of integrated

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parameters, i.e. significant wave height, mean wave period and mean wave direction, for each of the separate wind-sea and swell wave components.

Figure 1: Overtopping at Margate during Winter 2000/01 (photo by Peter Barker, RNLI)
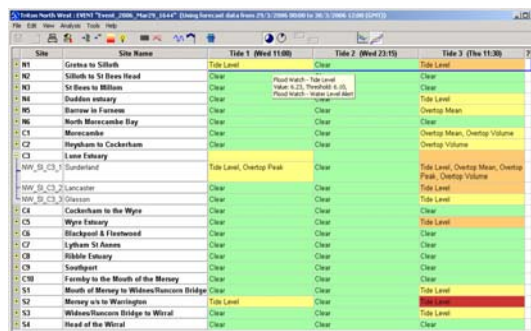

Figure 2: Example NW Region coastal flood forecast from 29 March 2006

The Environment Agency (EA) National Flood Forecasting System (NFFS) is implemented through the EA Regions of England and Wales. There is a wide range of coastal types including open sea coasts and estuaries, and a wide range of coastal defence types, both natural and man made. The prevailing nearshore wave and still water level conditions are influenced by a range of processes including, for example, the waves in many areas being depth limited by shallow sand bars and flats.

Nearshore wave predictions are based on look-up tables, relating nearshore to offshore wave conditions. Wave overtopping rates and volumes are also predicted using pre-computed look-up tables, which relate overtopping to incident wave and still water level conditions and a description of the structure. The operational coastal forecasting

system used in the NW Region includes alerts based on forecast exceedences of pre-defined site-specific still water level and overtopping thresholds. Figure 2 is a screenshot showing alerts at some NW Region locations.

1.3 Environment Agency R&D Project SC050069: Probabilistic coastal flood forecasting

Research & Development Project SC050069, *Probabilistic coastal flood forecasting*, March 2006 to December 2008, was funded by the EA, and undertaken by HR Wallingford, the Met Office and the Proudman Oceanographic Laboratory. The overall objective was to *Develop, demonstrate and evaluate improved probabilistic methods for surge, nearshore wave, and coastal flood forecasting in England and Wales.* This project followed on from the recommendations of the earlier UK Government Department for Environment, Food and Rural Affairs (Defra) R&D Project FD2206, *Best practice in coastal flood forecasting*, (Defra / EA, 2003).

The project investigated the relative value of different models and model linkages and refinements, and then built, demonstrated and evaluated forecasting models that could be taken up for operational use in coastal flood forecasting. The generic non-operational model review, classification, development and evaluation elements of the project are described in EA (2007). The near-operational forecast demonstration and evaluation elements are described in EA (2009).

2   SURGE ENSEMBLE AND PROBABILISTIC COASTAL FLOOD FORECASTING

2.1 Classification and evaluation of meteorological and hydraulic models

EA (2007) describes the forecasting and hydraulic models, information flow through the models, sources of uncertainty, and representation of uncertainty through ensemble and Monte Carlo modelling. It provides a classification and list of suitable hydraulic models, with information on their properties and performance.   Figure 3

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illustrates the four physical zones used in the classification: offshore, nearshore, shoreline and inundation (although the inundation zone is outside the scope of this project). EA (2007) describes development of a near-operational ensemble surge forecasting model. Offshore wave modelling was in the form of an area-specific method for wave ensemble forecasting. Nearshore wave modelling was also area-specific, introducing uncertainties through Monte Carlo sampling. Probabilistic overtopping prediction was site-specific, including sources of uncertainty. EA (2007) also describes the overall implementation and the types of offshore, nearshore and shoreline forecast information available.

2.2 Probabilistic methods in modelling

Storm surge predictions have an associated uncertainty, coming primarily through the driving atmospheric forecast of conditions at the sea surface, which can vary substantially depending on the meteorological situation. Ensemble prediction works by running several forecasts, using slightly different initial conditions, boundary conditions and/or model physics. These are chosen to sample the range of uncertainty in model inputs and formulation, so that the corresponding forecasts will sample the range of possible results consistent with those uncertainties. The Met Office Global and Regional

Ensemble Prediction System (MOGREPS; Bowler *et al*, 2008) provides 24 different predictions of meteorological evolution over a North Atlantic and European domain with a 24 km grid length.
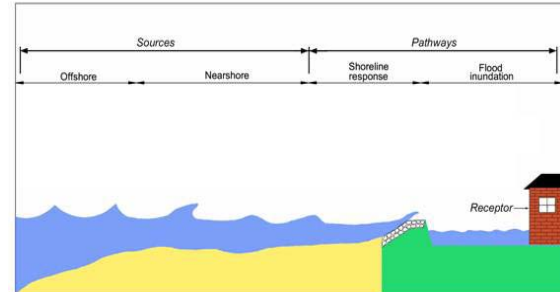

Figure 3: **Classification of offshore, nearshore, shoreline and inundation zones**

The Monte Carlo approach to handling uncertainty includes typical representations of uncertainties, but also assimilates and retains information from the ensemble modelling. It involves random simulation from probability distributions incorporating the ensemble information, and the various assumed uncertainties in the source variables (waves, still water level and wind), the overtopping formulae, the descriptors of sea defences and model parameters. Uncertainty is specified in terms of a distribution, e.g. Normal, and its associated parameters, e.g. mean and standard deviation.
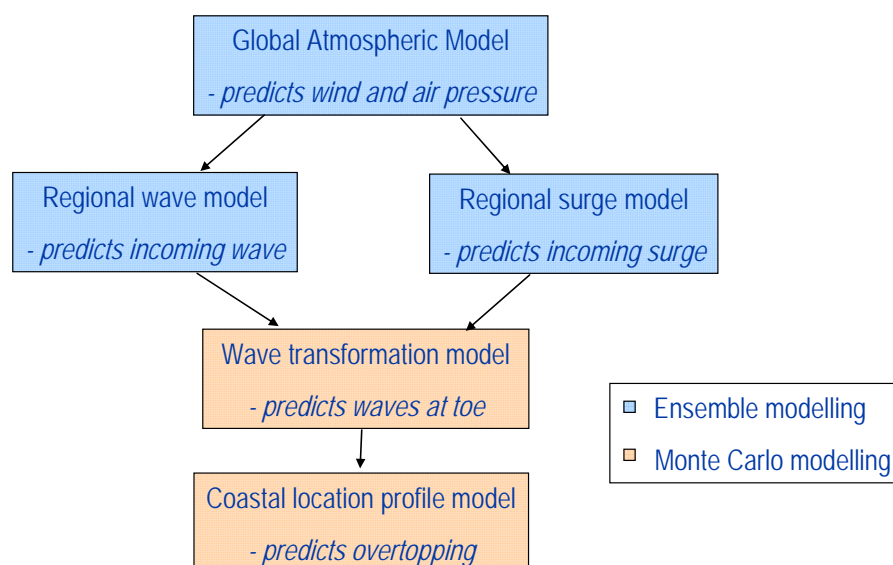

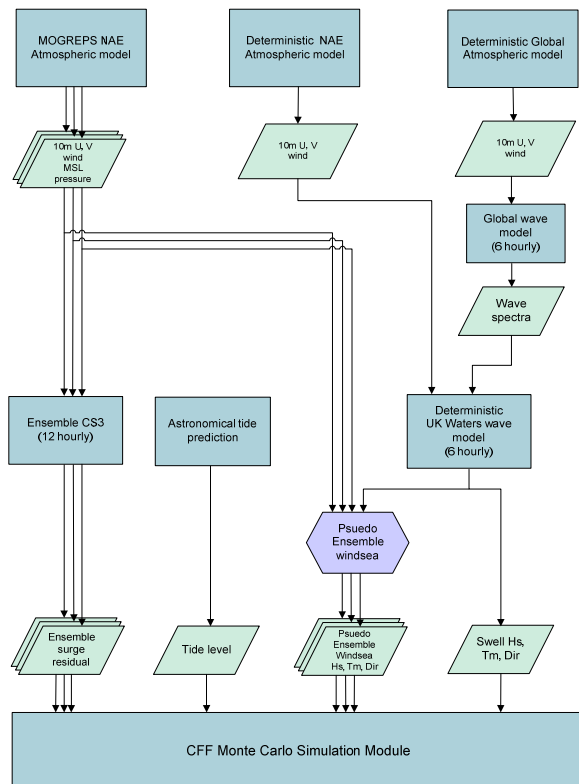**Figure 4: Grouping of models used in offshore and coastal flood forecasting**

Figure 5: Models and information flow through the coastal flood forecasting system (NAE meaning North Atlantic and European; CFF meaning coastal flood forecasting)

Figure 6: Process/data flow of the Monte Carlo simulations

The Monte Carlo simulations work by taking random draws from the parameter distributions, and following these selections through to the computation of mean wave overtopping rates and volumes. This process is repeated until a convergence criterion is achieved, e.g. consistency in the mean overtopping rate. This is then repeated for each ensemble member, to build up an overall distribution.

2.3 Overall modelling approaches and information flow

Some component uncertainties are handled through retention of ensemble members through the processes, and some are handled through Monte Carlo simulation. A conceptual flow diagram of this approach is given in Figure 4: ensemble still water level and offshore wave predictions, coupled with Monte Carlo simulation to account for further uncertainties and nearshore wave transformation and overtopping. Figures 5 and 6 provide more
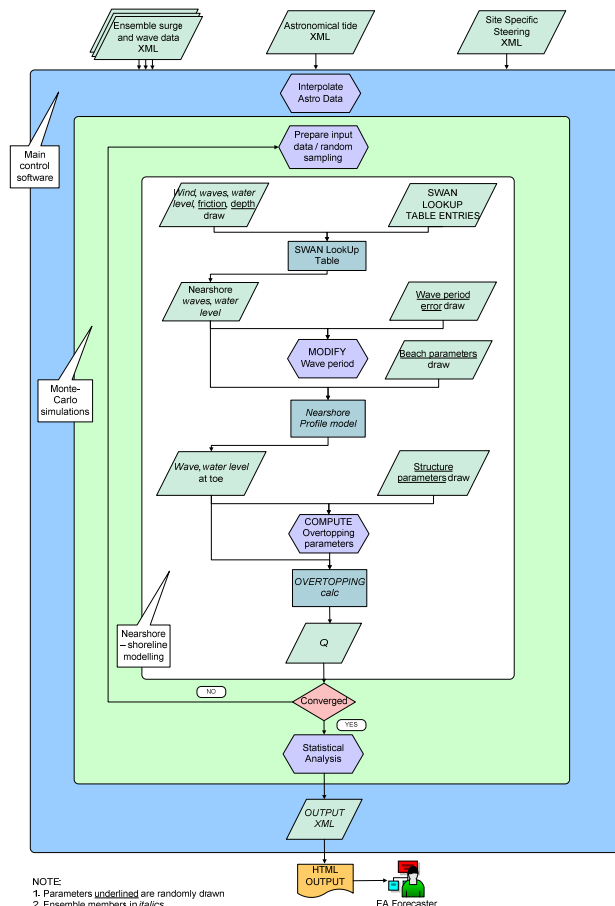
detail of the modelling process and flow of data. Figure 5 illustrates the modelling process required to generate the real-time ensemble wind and surge residual, and pseudo ensemble wave data to be used as input to the Monte Carlo simulations.

Figure 6 illustrates the modelling process, data feed and flow of data in the Monte Carlo simulations, including the nearshore and shoreline modelling. This includes all necessary site-specific data, including the parameters with uncertainties, and the thresholds for alerts. Figure 6 indicates three bands, an outer level main control used primarily to read in and write out data, a middle level which represents the Monte Carlo simulation control, and an inner level which represents the offshore to nearshore and shoreline modelling. Output incorporates a range of parameters, probabilities, graphical outputs and alerts, in a format that could later be assimilated into NFFS.

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2.4 Demonstration of surge ensemble forecasting

The surge ensemble forecast is run twice-daily at the Met Office, looking 54 hours ahead with output every 15 minutes. The demonstration began in December 2006, and continues at the time of writing as it may be adopted 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 7) running through the 54 hour forecast period display all the information contained within the ensemble. The forecast probability of exceeding successive thresholds at each port can be summarised in a stacked bar chart, as shown in Figure 8. The plot is constructed using the maximum value predicted by each ensemble member in the 12 hour period ending at the indicated verification time (VT).

Figure 9 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 0 hours ahead of the event. The oscillatory line represents astronomical tide (in reverse, so the low values indicate high tide) a crossing of which indicates crossing of a sea level alert threshold. Fortunately, the 2-3 m surge peaked close to low tide.

2.5 Demonstration of probabilistic coastal flood forecasting

There were two main purposes to the demonstration. One was to show that the models could work together consistently to deliver coastal flood forecasts at regular intervals, in time for them to be acted upon. The other was to check individual model elements and the modelling system as a whole against field measurements and other forecasting methods. The locations were chosen to correspond to sites where there is an existing forecast system and where there are coastal measurements.
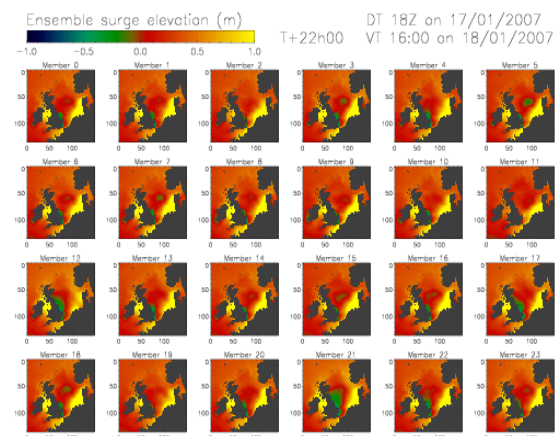

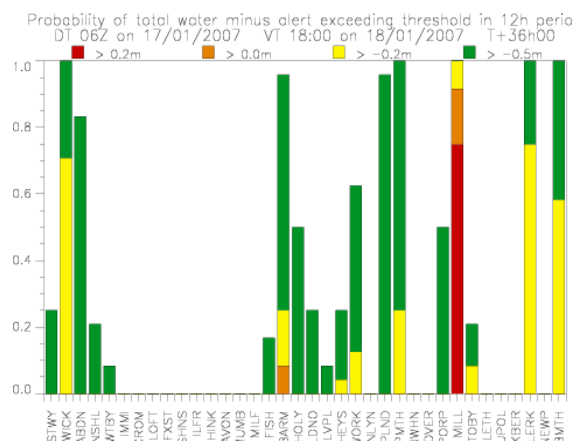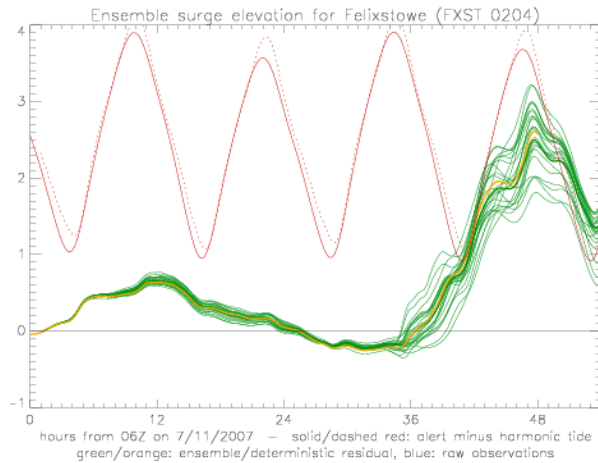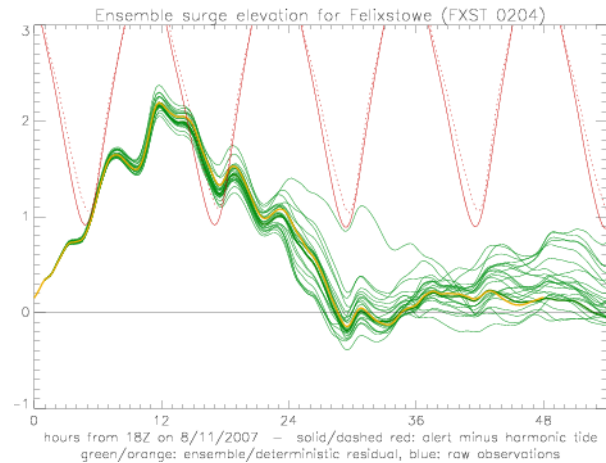**Figure 7:** **'Postage stamps' showing surge elevation for each of 24 ensemble members**


Figure 8: Stacked probability chart for total water level exceeding successive thresholds within a 12 hour period

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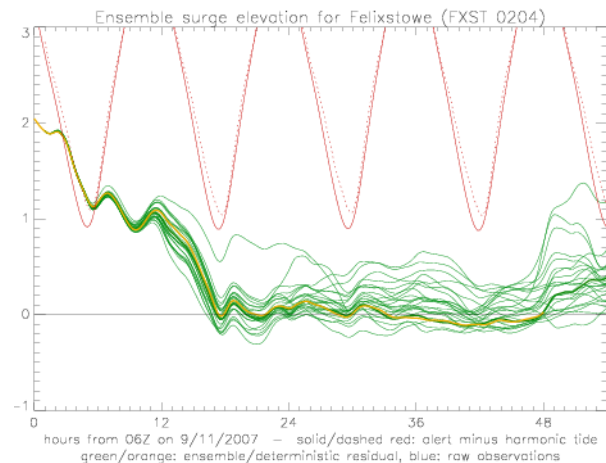
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Figure 9a: Morning forecast, November 2007 (surge 48 hours away)

Figure 9c: Afternoon forecast, 8 November 2007 (surge 12 hours away)
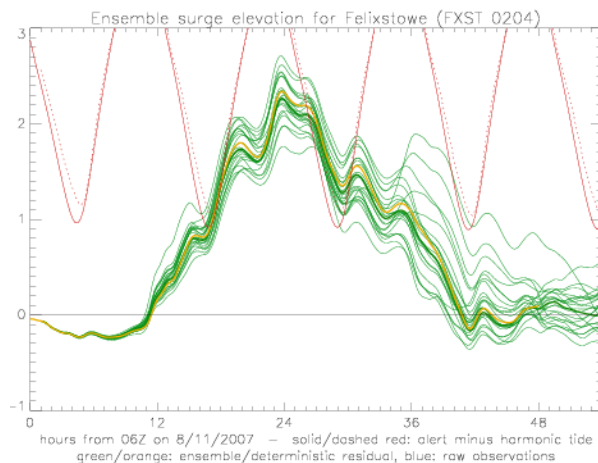
Figure 9b: Morning forecast,   November 2007 (surge 24 hours away)

Figure 9d: Morning forecast, November 2007 (surge 'nowcast')

The demonstration covered the area shown in Figure 10, to mimic an operational system, running over the Winter period of 2007/08. A SWAN wave model was used (rectangle in Figure 10) taking boundary conditions from several offshore wave prediction points, to produce look-up table transformations to required nearshore points. Overtopping prediction points were set up for two coastal structures at Anchorsholme, Blackpool (triangle in Figure 10). Met Office surge and offshore wave inputs were taken twice daily, to generate the corresponding coastal forecasts, with results made available in real-time to the project team through a project website.

Figures 11 and 12 are photographs of Anchorsholme: Figure 11 in calm conditions and Figure 12 showing overtopping during stormy conditions. Figure 13 is an example site-specific coastal flood forecast for 24-26 January 2008. Each diagram provides forecasts for the 7 hours prior to forecast delivery time, and the 47 hours after the forecast delivery time. Figures 13a-f show, respectively, ensemble wind speed, ensemble offshore significant wave height (H_s), ensemble water depth, probabilistic seawall toe H_s, and (e and f) probabilistic mean overtopping rate.

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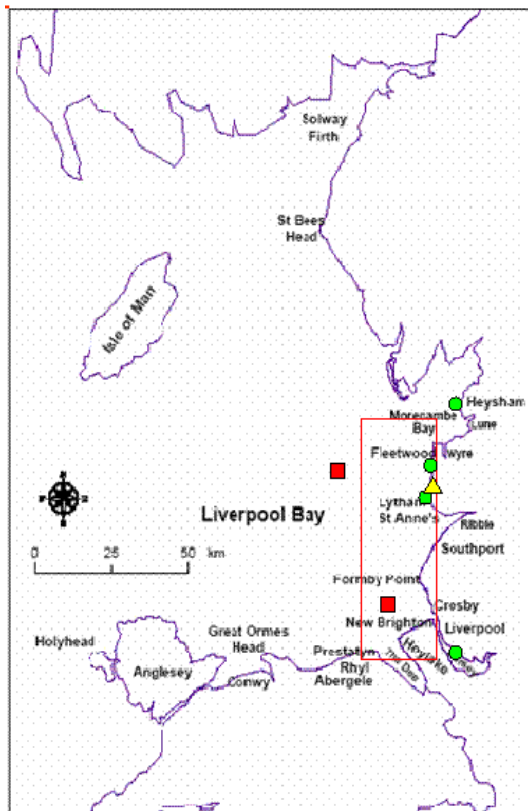
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Figure 10: Location map for the probabilistic coastal flood forecasting demonstration (rectangle, wave model; squares, wave measurements; triangle, overtopping measurements; circles, tide gauges)

Figure 11: The seawall at Anchorsholme, Blackpool (photo by Tim Pullen, HR Wallingford)

Figure 12: Overtopping at Anchorsholme on 07/12/06 (photo by Ian Davison, then of the EA)
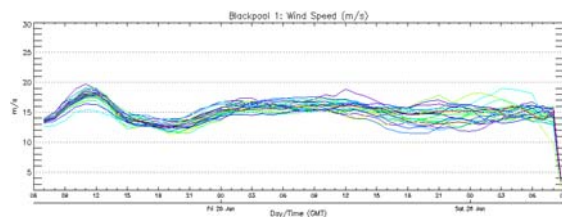

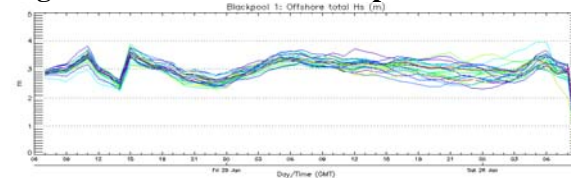**Figure 13a: Ensemble wind speed**

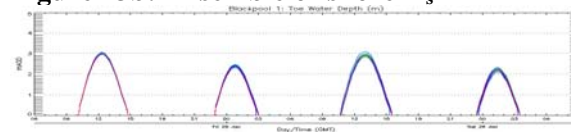**Figure 13b: Ensemble offshore H_s**

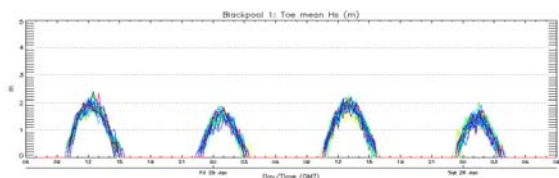
Figure 13c: Ensemble seawall toe water depth

Figure 13d: Probabilistic seawall toe H_s
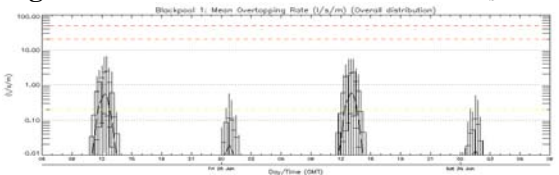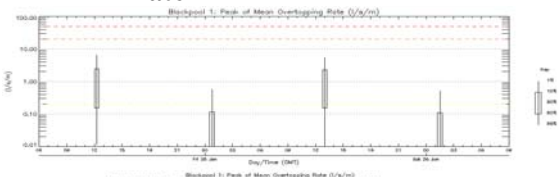

Figure 13e: Probabilistic mean overtopping rate

Figure 13f: Peak values (per tide) from Fig. 13e

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3 EVALUATION OF FORECASTS

3.1 Surge ensemble forecasts

Ensemble verification involves testing not only the ensemble mean, but also whether the spread accurately reflects variations in forecast skill, and whether the forecast probability of exceeding each threshold matches the frequency with which they are exceeded.

Figure 14 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 have been evaluated against a merged observation dataset, converted to an observed surge using the harmonic tide prediction.

Figures 14 and 15 show rms error binned as a function of spread (top), ensemble mean forecast (middle), and lead time (bottom), for spread and each forecast type using the symbols shown in the legend. The grey histograms show observation density according to the logarithmic scale on the right of each plot. Wider bins have been used for the more extreme cases to boost the number of contributions and so reduce the effects of statistical noise.
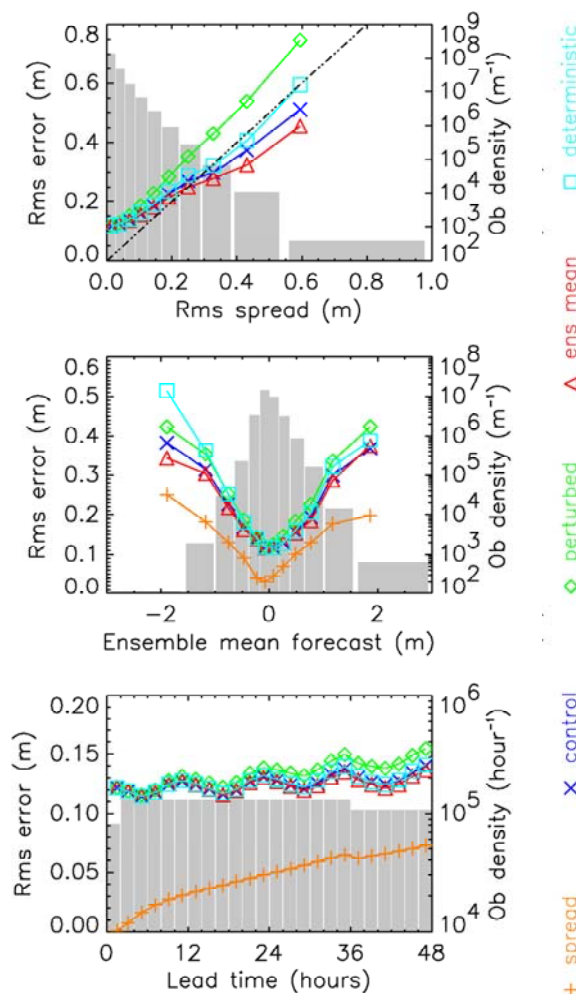

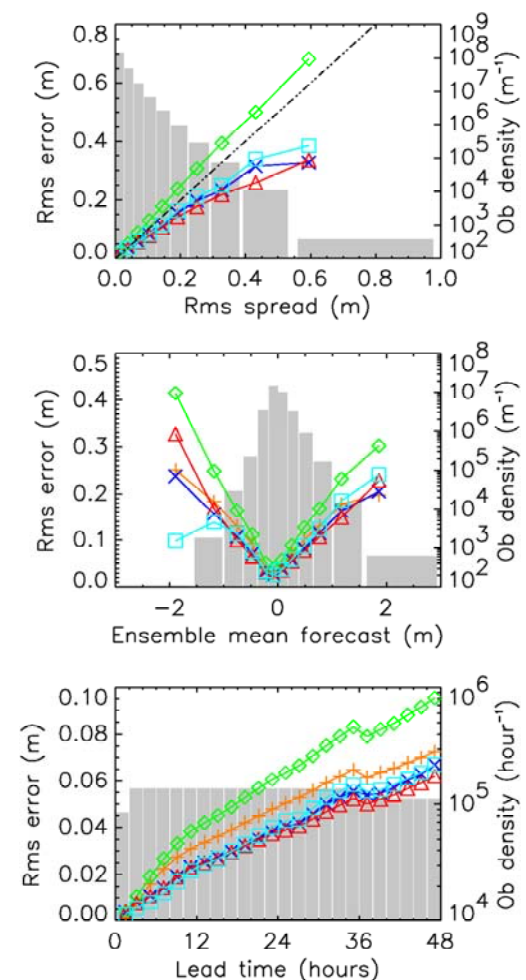**Figure 14: Variable statistics with respect to merged observations**

Figure 15: Variable statistics with respect to hindcasts

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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. 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.   Other evidence suggests that almost all of this discrepancy arises from errors in the harmonic tide prediction, which the ensemble does not sample.   This fixed error becomes progressively less important in the high surge situations that matter most for flood forecasting, compared to the meteorological uncertainty which the ensemble samples well.

As expected, the individual perturbed member forecasts have the largest error,

since they are perturbed away from the best estimate of the atmospheric state. However, the ensemble mean generally has the lowest error, so that as well as providing an estimate of uncertainty, the ensemble mean also produces a better central forecast beyond the first 18 hours.

Figure 15 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 that was detected with respect to observations is due to one of the other causes.
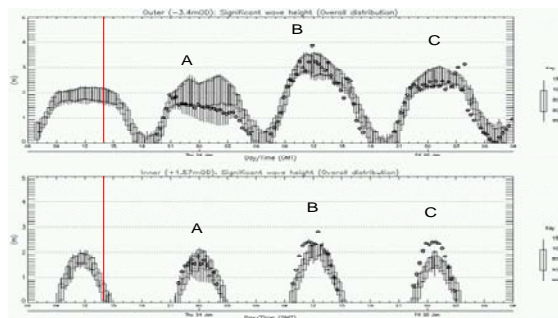
Figure 16: Nearshore H_s, 24-26 January 2008: forecast percentiles and measured (diamonds) over 54 hours, at 'outer' and 'inner' locations
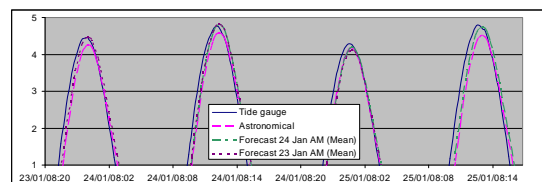

Figure 17:   Sea level (mOD), 24-25 January 2008: Blackpool tide gauge, astronomical, and a.m. forecasts on 23 and 24 January 2008

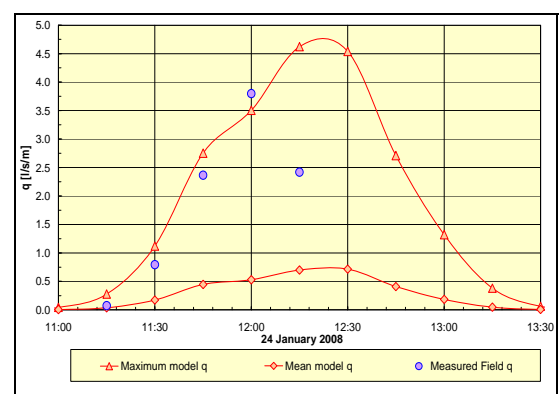**Figure 18:   Overtopping measurement tank at Anchorsholme**

Figure 19: Field overtopping discharges and probabilistic forecasts for 24 January 2008

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Ensemble performance can also be evaluated in terms of the reliability and sharpness of the probabilities which it forecasts for the surge or total water level to exceed specific thresholds. 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. EA (2009) examines a variety of statistics and thresholds, comparing ensemble performance to that which could be obtained by 'dressing' a single forecast. It is found that the ensemble generally provides the best performance, particularly at more extreme thresholds and longer lead times. There are also several indications that the surge ensemble could provide valuable forecast skill beyond the current 54 hour lead time limit, perhaps out to 5 or 6 days given suitable forcing data from a medium range atmospheric ensemble.

3.2 Coastline wave, sea level and overtopping forecasts

Waves, sea level and overtopping rate were measured over short stormy periods at the coast at Anchorsholme, Blackpool. The event for which there is the most information occurred on 24-26 January 2008; used in Figures 16-19 to provide an indication of coastline forecasting accuracy.

Figure 16 shows the wave conditions at 'outer' (-3.4 mOD) and 'inner' (+1.57 mOD) locations on the beach at Anchorsholme. The vertical lines represent forecast significant wave heights (H_s) from the a.m. 23 January 2008 forecast run. The black diamonds show the corresponding measured H_s. The long 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 to forecasters.

Figure 17 shows the Blackpool tide gauge water level measurements for the period

24-25 January 2008, together with the astronomical tide predictions used in the forecasting demonstration, and the forecast mean sea levels (astronomical tide prediction plus surge) for the a.m. forecasts issued on 23 and 24 January 2008. This shows that the forecast sea level, including surge, is generally in good agreement with the tide gauge data. There is a small lag of approximately 15 minutes in the astronomical tide prediction, leading to a similar lag in the forecast water levels.

Figure 18 is a photograph of the overtopping measurement tank, *in situ*, at Anchorsholme. A comparison between measured and predicted overtopping discharges is shown in Figure 19. The isolated circles show the measured mean overtopping rate. The continuous lines show the mean ensemble overtopping prediction and the maximum ensemble prediction. This shows that the field measurements of overtopping are closer to the *maximum* discharges predicted by the model. The field measured overtopping discharges are within the margins of the model prediction, and are in general between the maximum and mean predictions.

3.3 Probabilistic coastal forecasts

The project considered four evaluation criteria.

3.3.1 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 flood alert 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.

3.3.2 Timeliness of forecasts

Forecasts need to provide sufficient time for mobilisation, warning and mitigation of potential losses due to flooding, so the

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entire modelling package has to run in a reasonable time. The weather, wind ensemble and offshore wave forecast takes about 5.5 hours to run, and the surge ensemble a further half 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 hours, providing 15-minute 'nowcasts' from T+1 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.

3.3.3 Reliability of forecasts

Forecasters need to be able to rely on the 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%, with losses due to more fragile methods of computer communication and backup than would be used in an operational system.

3.3.4 Usefulness of forecasts

Does every aspect of a specific probabilistic coastal flood forecast add value (as compared to more general or offshore forecasts) in terms of anticipating flooding and being able to take action to mitigate potential losses? Initial reactions tended to be of polite interest but doubt about how the probabilistic information might be absorbed and used in an operational setting. As the project progressed, the general view changed to recognise that the additional information content is potentially useful, particularly in giving an earlier indication of low-probability potentially high-impact events, but that new ways of working may be needed to exploit it fully. For example,

thresholds on the probability at which to act could be derived from the ratio of the *cost* of false alarms relative to the *loss* associated with missed opportunities for mitigation.

4 POTENTIAL USE OF PROBABILISTIC INFORMATION IN COASTAL FLOOD FORECASTING

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.

4.1 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 the 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.

4.2 Sensitivity to uncertainty

An important element of the evaluation was to investigate the relative sensitivity of forecast parameters to the many different uncertainties involved in generation of the forecasts. As the end-product of the sequence of meteorological and hydraulic models, overtopping rate is influenced by all of the component uncertainties

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introduced at different points in the modelling sequence. Mean overtopping rate was used to assess the *relative importance* of the different component uncertainties. These uncertainties include 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.

Based on a fairly limited sample of overtopping rates forecast for Anchorsholme during the demonstration period, uncertainties introduced through ensemble modelling appear to contribute more to the overall uncertainty than uncertainties introduced through Monte Carlo modelling. 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. 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.

In a different type of uncertainty assessment, two areas within the Anglian Region were selected, each containing up to two years of offshore wave measurements, offshore wave forecasts and nearshore wave measurements. 'Events' were identified (retrospectively 'forecasted') in several different ways, as the ten storms with either the greatest wave height or the greatest predicted overtopping rate, based either on wave forecasts or on offshore or nearshore wave measurements. (Overtopping rate was for a nominal seawall at a nominal high sea level, so not directly related to flooding). With the exception of one storm, over two years at two sites, where wave period was influential, it appears that

increasing coastal relevance in wave data does little to improve skill in picking the most severe events. Improved wave transformation modelling and/or nearshore wave measurements would, therefore, appear to be a relatively low priority.

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 overtopping prediction points, more accurate seawall profiles (particularly crest levels), and choice of the most appropriate overtopping rate prediction method for each particular seawall.

4.3 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 EA. The potential benefit could only be realised through being able to use the additional information content in more efficient flood risk management.

Greater than 50% probability of a flood threshold being crossed is comparable with a deterministic forecast of its being crossed. 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.

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5 CONCLUSIONS AND RECOMMENDATIONS

The feasibility of surge ensemble forecasting and probabilistic coastal flood forecasting has been demonstrated. They were shown to be sufficiently accurate, timely and reliable for operational use.

Surge ensemble forecasting could be reconfigured for national operational use within the National Flood Forecasting System of England and Wales. Offshore wave ensemble modelling could also be implemented within NFFS, but would require substantial development work.

The probabilistic coastal flood forecasting models were coded in a way that is compatible with NFFS, but there would be considerable effort required to set up the necessary area-specific nearshore wave models and site-specific overtopping models. These models could be set up incrementally, prioritising the areas of England and Wales most vulnerable to coastal flooding.

If any form of probabilistic forecast is adopted, then the Environment Agency would need to decide how best to interpret such results, and which decisions they might help to inform; requiring discussion, documentation, training and implementation.

There would be value in improving the astronomical tidal predictions for use in shoreline sea level and overtopping predictions; also in refining the existing thresholds of sea level, overtopping rate and overtopping volume at which alerts are provided to forecasters. To make the most efficient use of the new probabilistic information, these thresholds would involve probabilities based on cost/loss ratio.

The main recommendations from the project, with relative priorities and approximate dates, are summarised in Figure 20, based on the draft implementation plan (Chapter 7 of EA, 2009) written in September 2008.

Description of recommendation to the Environment Agency Implementation Team (and priority, ***** highest)	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
Surge ensemble forecasting (*****)																				
Development, testing and verification (done)	■	■																		
Implementation, documentation, training					■	■	■	■												
Maintenance and delivery (cost per year)									■	■	■	■	■	■	■	■	■	■	■	■
Astronomical tide & threshold levels (***)																				
Astronomical tide					■	■	■	■												
Threshold levels and probabilistic thresholds					■	■	■	■												
.. implementation, maintenance and delivery									.	.	.	.								
EA use of probabilistic forecasts (***)																				
Review and discussion					■	■														
Procedures, documentation, implementation						■	■	■												
Ensemble wave forecasting pilot (**)																				
Methodology and scoping study							■	■												
Development									■	■	■	■								
Testing and verification													■	■	■	■				
.. implementation, maintenance and delivery																			.	.
Probabilistic coastal forecasting pilot (**)																				
Review of priority areas within EA					■	■														
Adoption of code and plots into NFFS						■	■	■												
Wave and overtopping model (cost per area)									■	■	■									
Testing and verification (cost per area)													■	■	■					
.. implementation, maintenance and delivery																			.	.

Figure 20: Summary of main recommendations of SC050069: Probabilistic coastal flood forecasting

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Acknowledgements

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