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Probabilistic coastal flood forecasting

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& K. Horsburgh

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Probabilistic coastal flood forecasting

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ABSTRACT: The project described in this paper includes development of surge ensemble modelling for the UK, and demonstration of probabilistic coastal flood forecasting for an area in the Irish Sea. Its purpose is to develop, demonstrate and evaluate probabilistic methods for surge, nearshore wave, and coastal flood forecasting in England and Wales, but the concepts and models would be equally applicable elsewhere. The main features that distinguish these methods from existing 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. Use of offshore forecasts to estimate the likelihood of high overtopping as an indicator of coastal flooding is not trivial, involving transformation of wave forecasts through the nearshore and surf zones, and the combined effects of wind, 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. The Environment Agency has responsibility for fluvial and coastal flood forecasting for England and Wales. The Met Office has operational responsibility for offshore forecasting for the UK.

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 or high wave overtopping of sea 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 seen in the context of an overall flood forecasting and warning service. Only in this way can its potential value be realised. 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.

Figure 1. Overtopping at Margate, England during Winter 2000/2001 (photo by Peter Barker, RNLI).

- Monitoring of waves, water levels and wind.
- Forecasting of potential flood events.
- Warning of possible flood events.

Figure 2. Division of England and Wales into eight Environment Agency Regions.

- 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 from the UK Waters wave model in the form of integrated parameters, i.e. significant wave height, mean wave period and mean wave direction, for each of the separate wind-sea and swell components of waves.

The Environment Agency (EA) National Flood Forecasting System (NFFS) is implemented through the EA Regions (see Figure 2) of England and Wales. EA North West Region covers a large area from the River Dee on the border with Wales in the south, to the River Esk on the border with Scotland in the north. There is a wide range of coastal types including open sea coasts and estuaries and a wide range of coastal defence types, including both natural and man made defence types. 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 due to sand bars and flats.

Nearshore wave predictions are based on look-up tables, relating nearshore to offshore wave conditions.

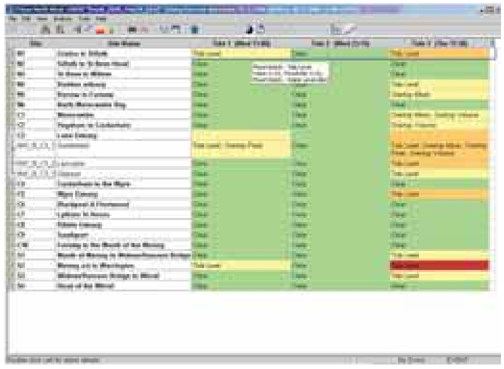

Figure 3. Example NW Region coastal flood forecast from 29 March 2006.

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 3 is a screenshot showing alerts at some NW Region locations.

1.3 *Environment agency research & development project SC050069: coastal flood forecasting*

Research & Development Project SC050069, *Coastal flood forecasting*, running March 2006 to December 2008, was funded by the Environment Agency (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 Defra R&D Project FD2206, *Best practice in coastal flood forecasting*, (Defra/Environment Agency, 2003; Hawkes *et al*, 2004).

The project investigated the relative value of different modelling 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 Environment Agency (2007). The near-operational forecast demonstration and evaluation elements will be described in a second Environment Agency project report later in 2008. The evaluation will include comparison with measured sea level, offshore and nearshore waves, wind and overtopping rate.

2 SURGE ENSEMBLE AND PROBABILISTIC COASTAL FLOOD FORECASTING

2.1 *Classification and evaluation of meteorological and hydraulic models*

The forecasting, modelling and information flow chapter of Environment Agency (2007) describes modelling, linking and forecasting concepts, requirements and benefits. The offshore/nearshore/shoreline model coupling chapter provides a description of the types of hydraulic model needed, and the sources and propagation of information and uncertainty between them. The chapter on classification and cataloguing of models provides a classification and list of suitable hydraulic models, together with tick-box information on their properties and performance. Figure 4 illustrates the four different physical zones considered: offshore, nearshore, shoreline and inundation. The hydraulic modelling developments chapter describes the separate surge, wave and overtopping modelling developments. The wave modelling chapter describes offshore and nearshore wave modelling issues, and a temporary method for wave ensemble forecasting. The probabilistic overtopping chapter describes measures of overtopping, the range of formulae and models used to estimate them, and the sources of uncertainty. The overall implementation chapter describes implementation of the overall modelling solution and what types of shoreline forecast information are produced.

2.2 *Probabilistic methods in modelling*

Like all forecasts, storm surge predictions have an associated uncertainty, but this is not directly predicted by current operational systems. The dominant source of this uncertainty is thought to be uncertainty in the driving atmospheric forecast of conditions at the sea surface, which can vary substantially depending

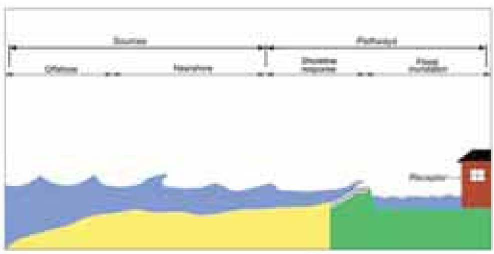

Figure 4. Classification of offshore, nearshore, shoreline and inundation zones.

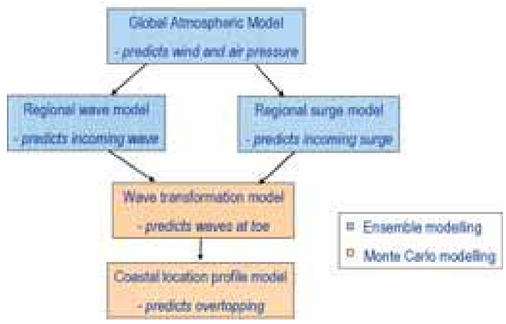

Figure 5. Grouping of models used in coastal flood forecasting.

on the meteorological situation. Ensemble prediction works by running not one but 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 that are consistent with those uncertainties. The Met Office Global and Regional Ensemble Prediction System (MOGREPS) provides 24 different predictions of meteorological evolution over a North Atlantic and European domain with a 24 km grid length.

The Monte Carlo approach to handling uncertainty includes typical representations of uncertainties, but is also capable of assimilating and retaining 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.

The Monte Carlo simulations work by taking a random draws from the range of offshore wave and still water level conditions, and from the parameter distributions, and following these selections through to the computation of wave overtopping rates and volumes. This process is repeated until a convergence criterion is achieved, e.g. consistency in the mean overtopping rate.

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 5: ensemble still

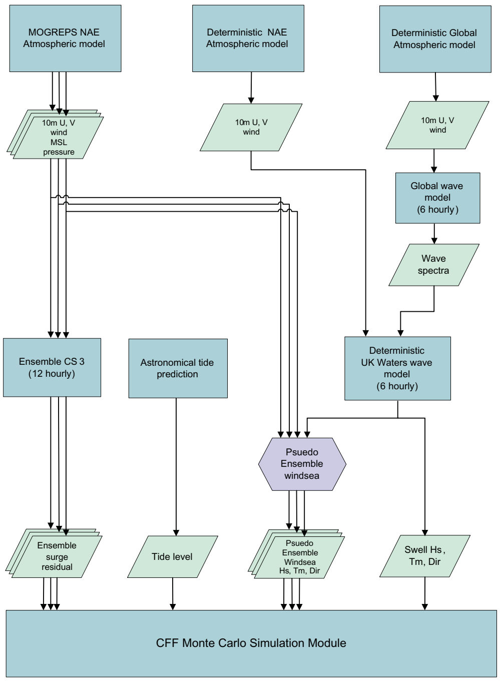

Figure 6. Models and information flow through the coastal flood forecasting system.

water level and offshore wave predictions, coupled with Monte Carlo simulation to account for further uncertainties and nearshore wave transformation and overtopping.

Figures 6 and 7 provide more detail of the modelling process and flow of data. Figure 6 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 7 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 7 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.

2.4 *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 the winter period of 2007/08, but continues at the time of writing as it may be adopted for operational use.

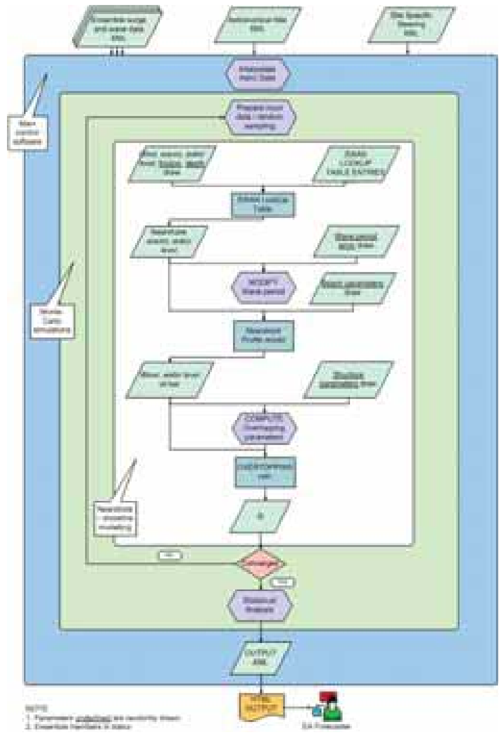

Figure 7. Process/data flow of the Monte Carlo simulations.

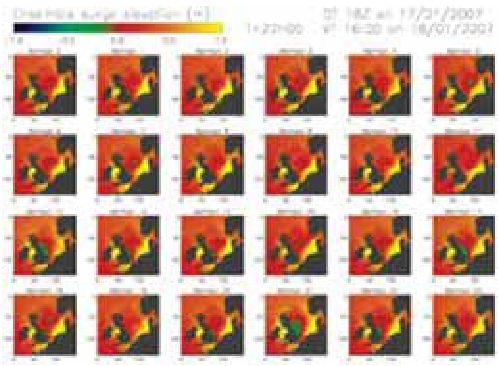

Figure 8. 'Postage stamps' showing surge elevation for each of 24 ensemble members.

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

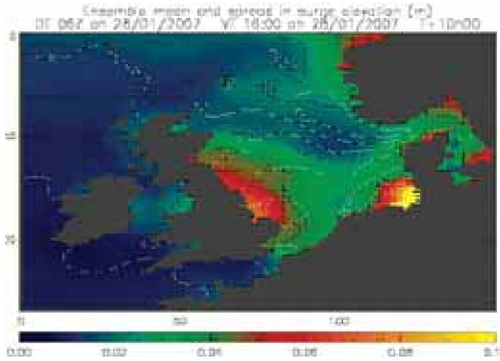

Figure 9. Mean (contours) and standard deviation (colours) of surge elevation.

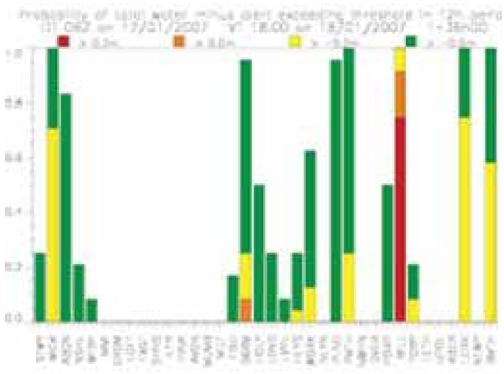

Figure 10. Stacked probability chart for total water level exceeding successive thresholds within a 12 hour period.

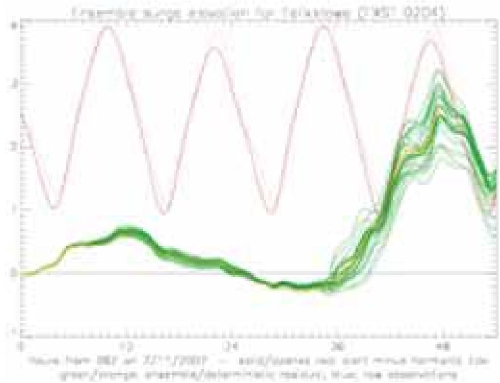

Figure 11a. Morning surge forecast on 7 November 2007.

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.

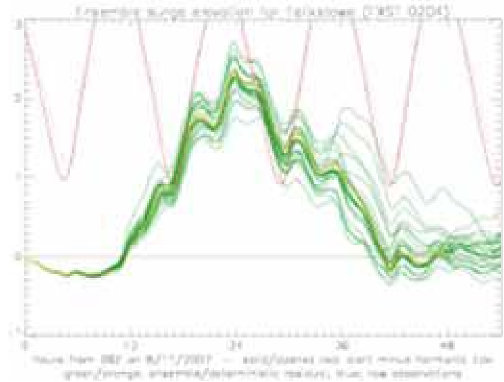

Figure 11b. Morning surge forecast on 8 November 2007.

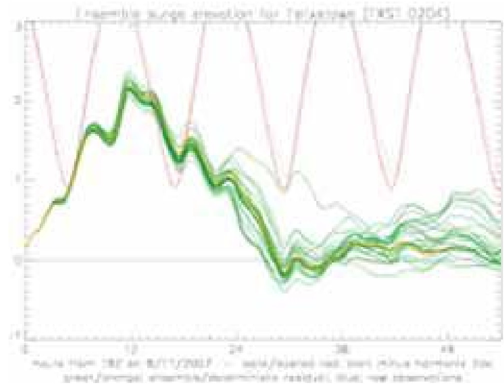

Figure 11c. Afternoon surge forecast on November 2007.

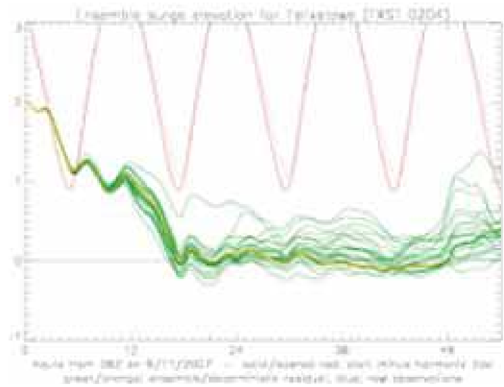

Figure 11d. Morning surge forecast on 9 November 2007
Figure 11a-d. Ensemble forecasts of the surge at Felixstowe, East England, on 9 November 2007 (the oscillatory line represents astronomical tide, a crossing of which indicates crossing of a sea level alert threshold).

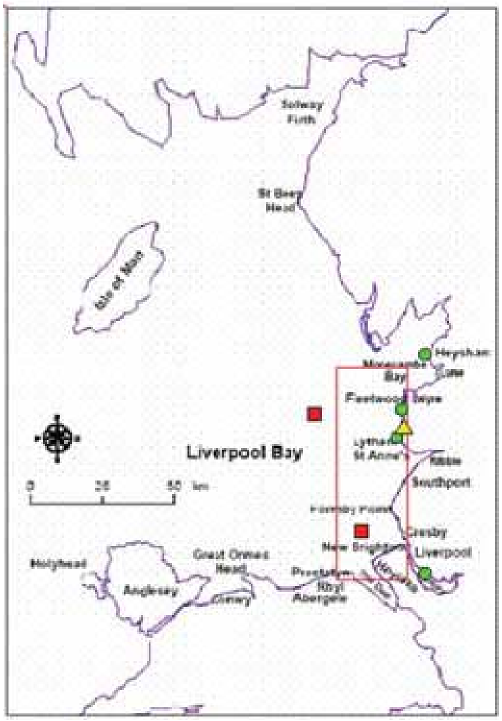

Figure 12. Location map for the probabilistic coastal flood forecasting demonstration (rectangle, wave model; squares, wave measurements; triangle, overtopping measurements; circles, tide gauges).

Figure 13. The seawall at Anchorsholme, Blackpool (photo by Tim Pullen, HR Wallingford).

Figure 14. Overtopping at Anchorsholme, Blackpool, England on 7 December 2006 (photo by Ian Davison, Environment Agency).

Postage stamp animations (a still example is given in Figure 8) running through the 54 hour forecast period display all the information contained within the ensemble.

Mean and spread charts such as Figure 9 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 northeast coast of England runs across the contours of mean surge prediction, perhaps indicating uncertainty in the timing of the surge wave along that coast.

The forecast probability of exceeding successive thresholds at each port can be summarised in a stacked bar chart, as shown in Figure 10. 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 11. 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.

2.5 *Demonstration of probabilistic coastal flood forecasting*

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

The demonstration was set up for the area shown in Figure 12, to mimic an operational system. A wave transformation model was set up (rectangle in Figure 12) taking boundary conditions from

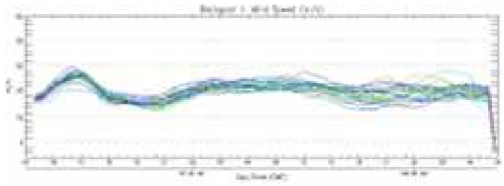

Figure 15a. Ensemble wind speed.

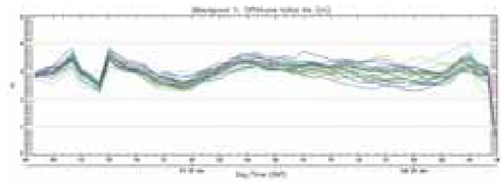

Figure 15b. Ensemble ofshore significant wave height.

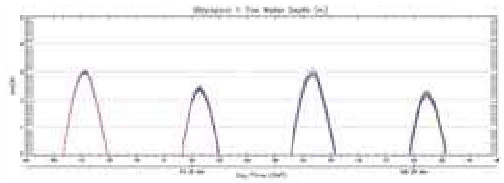

Figure 15c. Ensemble seawall toe water depth.

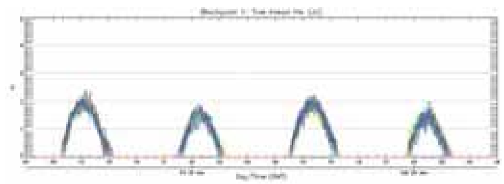

Figure 15d. Probabilistic seawall toe significant wave height.

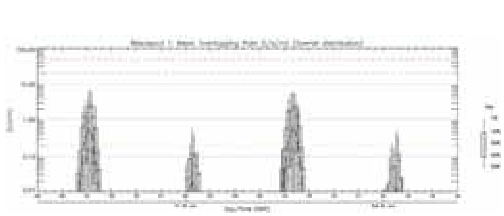

Figure 15e. Probabilistic mean overtopping rate.

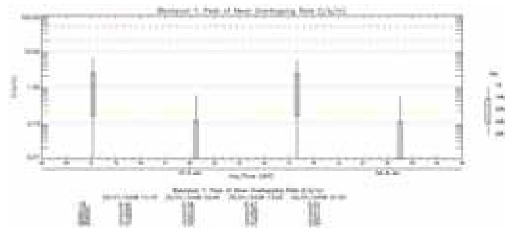

Figure 15f. Peak values (per tide) of probabilistic mean overtopping rate.

Figure 15a-f. Example site-specific wind, offshore wave and water depth ensemble forecasts, and probabilistic near-shore wave and overtopping forecasts, for Anchorsholme, Blackpool, for 24–26 January 2008.

several offshore wave prediction points. Two near-shore overtopping prediction points were set up at Anchorsholme, Blackpool (triangle in Figure 12). The system took Met Office inputs twice daily, and generated the corresponding coastal forecasts twice daily, with results made available in real-time to the project team through a project website. The demonstration ran over the winter period of 2007/08.

Figures 13 and 14 are photographs of Anchorsholme, Blackpool (triangle in Figure 12): Figure 13 in calm conditions and Figure 14 showing overtopping during stormy conditions. Figure 15 is an example coastal flood forecast for Anchorsholme during stormy conditions.

3 EVALUATION OF FORECASTS

This represents a preliminary evaluation, prior to completion of the project report later in 2008.

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.

Initial verification results (Flowerdew *et al*, 2007) are encouraging, although statistical evaluation suggests the ensemble spread is generally too small. Figure 16 provides an indication of the spread-skill relationship. This is based on approximately six months of data from 27 ports and lead times up to 36 hours, beginning in December 2006. Figure 16d confirms the overall tendency for spread to increase as a function of lead time. In all cases, the ensemble mean has the lowest error, followed by the unperturbed ensemble control, followed by the rms error of the perturbed ensemble

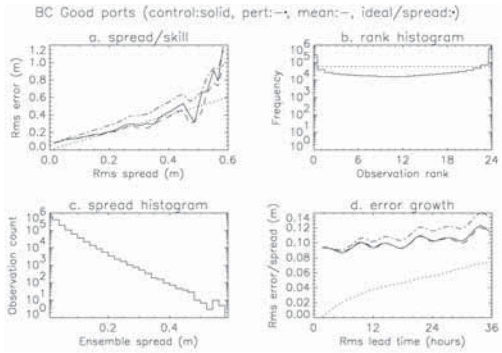

Figure 16. Preliminary verification of surge ensemble forecasts: a) error as a function of spread (ideal diagonal plotted); b) rank histogram (ideal line plotted); c) spread histogram; d) spread (dotted) and error as a function of lead time; panels a) and d) show rms errors for the unperturbed control model (solid), perturbed ensemble members (dash-dot) and ensemble mean forecast (dashed), after subtracting the bias (mean error) at each port.

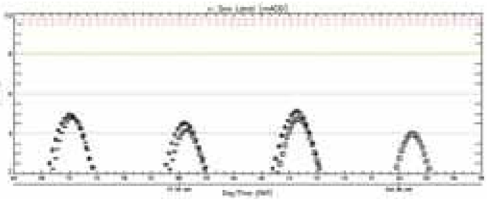

Figure 17a. Nearshore sea level

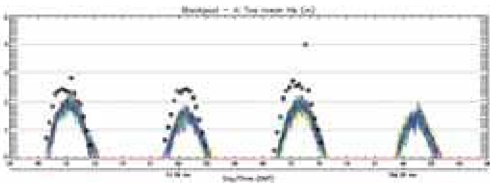

Figure 17b. Significant wave height at the seawall toe

Figure 17a-b. Forecast (rectangles) and measured (diamonds) sea levels and wave heights over 54 hours 24–26 January 2008

members. This indicates that, as well as providing an estimate of uncertainty, the ensemble also provides a superior central estimate to a single unperturbed forecast, as is common in ensemble systems.

3.2 *Coastline wave and sea level forecasts*

The event for which there is the most information on conditions at the coastline at Anchorsholme occurred on 24–26 January 2008. This event is used in Figure 17 to provide a preliminary indication of coastline forecasting accuracy and sensitivity.

The forecasts are in reasonable agreement with measurements. The forecast sea level is slightly lower than the measured sea level, which could be due either to the astronomical or the surge component of sea level. Similarly the forecast wave height at the toe of the seawall is slightly lower than the measured wave height at the toe. This small discrepancy in wave height could be attributed entirely to the discrepancy in sea level. If the measured sea levels at the toe were used in place of forecast values then the agreement between measured and forecast wave heights would be better.

3.3 *Probabilistic coastal forecasts*

There are 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. Initial 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. This will be explored further in the final project report.

3.3.2 *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 5 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 2 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? Might the forecasts be taken even further, to include inundation modelling?

The initial reaction to probabilistic information tended to be one of bafflement as to 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, but that new ways of working may be needed to exploit it fully. Chapter 4 expands on this topic.

4 POTENTIAL USE OF PROBABILISTIC INFORMATION IN COASTAL FLOOD FORECASTING

This represents a preliminary discussion, prior to completion of the project report later in 2008. 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 is to investigate the relative sensitivity of key forecast parameters to the many different uncertainties involved in generation of the forecasts. 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. This will be investigated in a systematic way.

A related investigation will focus on which of the different coastal models, if any, add value to correct identification of the most severe events at a coastal site. Starting from routinely available offshore wave forecasts, does it make any difference progressively to add offshore wave measurements, nearshore wave transformation, nearshore wave measurements, and overtopping prediction?

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 Environment Agency. The information presently available from deterministic forecasts, either offshore or at the coast, would also be available through probabilistic forecasting. Probabilistic forecasting does not seek to be more accurate or reliable than deterministic forecasts, and it is bound to be slightly less timely. The potential benefit can only come through being able to use the additional information content in more efficient flood risk management.

A high 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.

5 CONCLUSIONS

The feasibility of surge ensemble forecasting and probabilistic coastal flood forecasting has been demonstrated. It has been shown to be sufficiently accurate, timely and reliable for operational use. Whether it is sufficiently beneficial for operational use in forecasting, and the relative sensitivities to different uncertainties, are still being investigated.

The surge ensemble forecasting system could be reconfigured fairly easily 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.

ACKNOWLEDGEMENTS

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Today, HR Wallingford has a 50 year track record of achievement in applied research and consultancy, and a unique mix of know-how, assets and facilities, including state of the art physical modelling laboratories, a full range of computational modelling tools, and above all, expert staff with world-renowned skills and experience.

The Company has a pedigree of excellence and a tradition of innovation, which it sustains by re-investing profits from operations into programmes of strategic research and development designed to keep it – and its clients and partners – at the leading edge.

Headquartered in the UK, HR Wallingford reaches clients and partners globally through a network of offices, agents and alliances around the world.

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