Met Office

Developing, trialling and demonstrating the benefits of a wave ensemble prediction system for coastal flood forecasting

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Summary

This report documents work undertaken by the Met Office to develop, trial and demonstrate the benefits of a wave ensemble forecasting system for coastal flood forecasting applications. The research was conducted in partnership with the Flood and Coastal Erosion Risk Management R and D Programme (project *SC120007)*.

The project was driven by the need for more robust forecasts of the risk of (tide plus surge) water level and sea state that can lead to coastal flooding in the UK. This has led to the development of probabilistic forecast methodologies, including an operational surge Ensemble Prediction System (EPS). Whilst water levels at the coastal boundary are critical in identifying high risk scenarios at a regional level, localised flooding events and/or damage to coastal defences are also frequently influenced by wave conditions. As a result, probabilistic wave forecasts are needed to complement tide and surge data.

The project ran in parallel with the development of an operational wave Ensemble Prediction System (wave-EPS) as part of the European Union FP7 sponsored 'MyWave' project (www.mywave.eu). Key activities and findings are as follows:

- Verification was undertaken that evaluated the performance and utility of short-range wave ensemble prediction systems (wave-EPS) for coastal flood prediction. The verification results demonstrated that: the wave-EPS developed by the Met Office is appropriate for use as an open waters boundary condition to coastal forecasting systems; the EPS can generate skilful probabilistic forecasts; and identified that further improvements can be made to the wave-EPS's performance by introducing a revised wave physics scheme or alternative methods to reduce bias in the short range forecast.

- The project provided preliminary demonstrations of wave-EPS products for use by flood forecasters. The engagement with forecasters highlighted the importance of developing a monitoring product that combines the wave-EPS with real-time in-situ observation data and has kick-started an ongoing process of dialogue and feedback between Flood Forecasting Centre forecasters and the Met Office science team responsible for the wave and surge models.

- The project made an initial assessment and proposal of methods by which wave-EPS information can be incorporated with surge-EPS data in order to improve coastal flood warning decision making processes. Findings are only preliminary, but highlight the importance of considering processes that will transform waves between offshore locations, forecast by a regional wave model, and the coastal zone. For example, forecasters should be aware of, or use systems that account

for, offshore wave direction relative to the angle of the coastline, since this has an important local influence on which communities are most exposed to wave action during an event.

- The project has identified follow-up tasks required to enable the operational use of wave-EPS data and products by UK Coastal Monitoring and Forecasting (UKCMF) stakeholders. Operational product development needs include: setting up a robust, supported system for data provision to UKCMF stakeholders at the Met Office; continuing to develop and maintain EPS monitoring and verification systems specific to the coastal flood forecasting task; and further engagement with UKCMF stakeholders and other practitioners on best practise methods to utilise wave-EPS data as an offshore boundary condition to coastal flooding prediction systems (alongside surge data). These activities are captured in a recently proposed FFC mandate ‘7-Day Wave Ensembles and Probabilistic Coastal Impact Forecasting’ (submitted to FFC, management board February 2015).

Crucially, the project has demonstrated the validity and case for further wave-EPS forecasting and development activities. At the end of the project, the Met Office have committed to continue to run and develop an operational wave-EPS based on an Atlantic-UK domain refined grid wave model, with forecast perturbations provided by wind forcing data from the Met Office Global and Regional EPS Global atmospheric ensemble (MOGREPS-G). The model will deliver forecasts out to 7 days ahead and uses the same atmospheric driving data as the Met Office surge-EPS, thus maintaining physical consistency between the wave and surge forecasts. Following results of the evaluation process, the wave model has been updated to use a variant of WAM Cycle-4 physics, with the aim of reducing systematic biases in regions such as the Irish Sea and North Sea, where short-moderate fetch waves are likely during storm events.

In addition, the Met Office science team will continue to support and develop combined wave-EPS and observation based monitoring and verification products, plus more experimental simplified “additional wave risk” products, where the wave forecasts are combined with tide and surge-EPS forecast data. These products will be co-developed with the Flood Forecast Centre (FFC) and other UKCMF stakeholders.

Contents

1. Project Purpose and Objectives

This report documents work undertaken by the Met Office in partnership with the Flood and Coastal Erosion Risk Management Research and Development Programme as part of project SC120007: 'Develop, trial and demonstrate the benefits of a wave ensemble forecasting system'.

The project was driven by the need for more robust forecasts of the risk of (tide plus surge) water level and sea state that can lead to coastal flooding in the UK. This has led to development of probabilistic forecast methodologies, including an operational surge Ensemble Prediction System (EPS). However, whilst water levels at the coastal boundary are critical in identifying high risk scenarios at a regional level, localised flooding events and/or damage to coastal defences are also frequently influenced by wave conditions. As a result, probabilistic wave forecasts are needed to complement tide and surge data. The Met Office's method to provide these forecasts at the boundary to the coastal zone, which importantly has been designed to maintain a physical consistency between surge and wave forecasts, is to develop and run a wave-EPS forced by the same Met Office Global and Regional EPS (MOGREPS) atmospheric model data that are used to force the surge-EPS.

The wave-EPS was developed during the period 2012-2014 as part of the EU FP7 funded project 'MyWave' (www.mywave.eu). With the wave-EPS established, this project ran in parallel, achieving the following objectives (a more detailed discussion of the project objectives is given in Appendix B):

- The potential benefits of the wave-EPS for flood forecasting applications were demonstrated through long term verification of the system in two UK regions (the North Sea and Western Approaches); see Section 2.
- Development of a demonstration product set, targeted at UK-wide guidance provided from the joint Met Office – EA Flood Forecasting Centre (FFC); see Section 3.
- Options and requirements for integration of probabilistic wave and surge data for coastal flood forecasting have been reviewed. In particular the study concentrated on integration of offshore data via coastal hydrodynamic modelling and illustrating the 'additional risk' to coastal flooding associated with waves, via a simplified method of wave transformation in the coastal zone. See Section 4.
- Requirement and recommendations for ongoing system development and support are discussed in Section 5.

2. Evaluation of wave-EPS for the UK

2.1 Configurations overview

Within the MyWave project, the Met Office set up and evaluated two regional wave models, both with application for wave forecasting in UK waters (Table 1, Figure 1). The Atlantic-UK wave model covers the whole Atlantic ocean and uses a refined grid method (the Spherical Multi-Cell Grid, Li, 2012) to "zoom" from a computationally efficient offshore resolution in the open ocean to higher resolution around the UK coast (Li and Saulter, 2014). The advantage of this configuration is that generation of high energy storm waves in the open waters of the Atlantic are simulated in the same model that is used for forecasting at the coast. At present the model grid steps from 25-12-6km. The model is forced by wind data derived from the Met Office Global-Regional Ensemble Prediction System (MOGREPS, Bowler et al., 2008) global model (MOGREPS-G). MOGREPS-G has an approximately 30km horizontal resolution and generates forecasts as far ahead as 7 days. This system is used to provide atmospheric boundary conditions to the Met Office surge-EPS (Flowerdew et al., 2010). Since surface ocean waves can be considered as a "forced-dissipative" system, responding to variations in the wind field, the atmospheric EPS provides the perturbations in the wave-EPS.

Table 1. MyWave trial wave-EPS configurations

EPS configuration name	Forecast lead time	Coastal cell size	Wind data horizontal scale	Source term physics	Wave boundary condition
Atlantic-UK	3 days*	6km	30km	TC96**	Global – Cape Horn only
UK	1.5 days	8km	2.2km	WAM-C4	Atlantic-UK

* forecast lead time was increased to 7 days post the project

** Tolman and Chalikov (1996), a variant of WAM-C4 physics (TS3M) was adopted based on project findings

A UK wave-EPS was also set-up. This model used a rotated grid model with horizontal resolution of approximately 8km. This scale was limited to keep down computational costs. The model was driven by wind from the convection permitting atmospheric EPS, MOGREPS-UK (approximately 2.2km horizontal resolution) and took lateral wave boundary conditions from the Atlantic-UK wave-EPS. The purpose of setting up this system was to contrast the variability introduced into the wave field by using atmospheric data that attempted to simulate convective scale variability with the “smoother” wind fields provided to the Atlantic-UK model by MOGREPS-G.

Both wave-EPS use a method of “member tracking” over subsequent forecast cycles, in which a short range wave forecast from each member is used as the restart condition for that same member in the next forecast. This is made possible due to the degree of memory between members in the atmospheric system (see Bowler et al., 2008) and enables a degree of spread to be retained in the wave model initial conditions. It is believed that this quality is particularly important to quantify uncertainty in swell event timing, although further work is needed to fully demonstrate this.

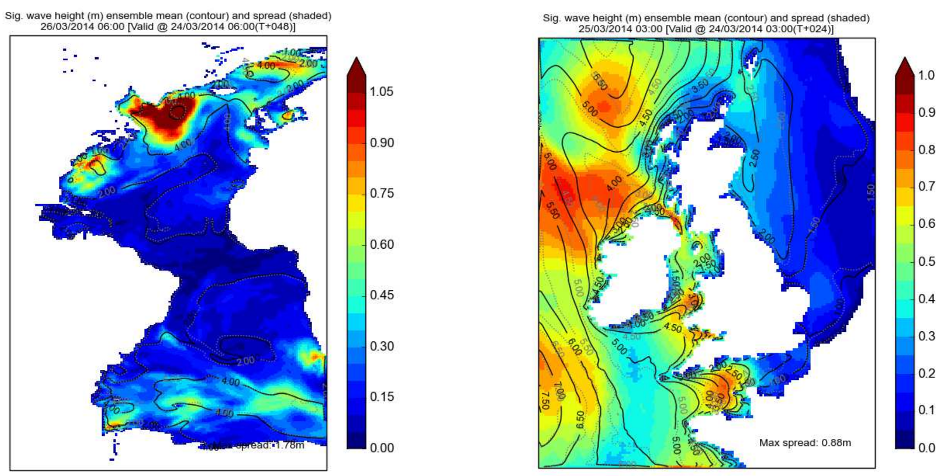

Figure 1. Regional domains for the Met Office wave ensemble forecast system.

2.2 Evaluation

A detailed overall verification of the two wave-EPS is presented in “*Performance and verification of the Met Office “Atlantic-Euro Zone” ensemble wave model. MyWave Report D3.5*” (Bunney, 2014). Key results and conclusions were that:

- Deterministically, both systems verified with expected skill for a wave model at this scale; i.e. with bias and root mean square error values on the order of 10s of cm, similar to the present generation of deterministic wave models run at the Met Office and used by UKCMF forecasters.

- The atmospheric EPS is able to generate dynamically varying spread in the wave-EPS members; the levels and variability in spread are such that the wave-EPS data provide value over and above that of a deterministic wave forecast.
- At the short ranges evaluated (out to 3 days ahead) spread was generally limited and such that systematic biases in the models significantly affect the skill of the EPS forecasts.
- In general, the EPS wind and wave forecasts were found to be under-spread. The levels of under-spread are emphasised when the EPS data are compared directly with observations, since the scale of observation errors (due to contributions from systematic biases, sampling variability, data truncation) is also significant compared to short range EPS spread. It is notable in the results that spread in the wave ensemble initially reduces over the first 6 hours, suggesting that a limited spread in the MOGREPS initial condition wind field constrains the development of spread in the wave model at each restart.
- Once bias and observation error contributions were accounted for, both Atlantic-UK and UK wave-EPS verified very well against probabilistic prediction performance metrics.
- For predictions of significant wave height, there is strong evidence that variations in spread have a correlation with background conditions, i.e. more spread should generally be expected for high wave conditions. This may have an implication for coastal flood forecasting, which is generally concerned with moderate to high energy events.

The main outcome from this research, in terms of future systems development, was that the Atlantic-UK system performed well at all lead times and that differences between this system and the UK wave-EPS were mainly attributed to choice of wave physics source terms rather than differences in the atmospheric perturbations. This enables the Met Office to consider the Atlantic-UK as the principal wave-EPS for coastal flood forecast applications, with the advantage that, at all lead times, data from the wave model will have been forced in a manner that is consistent with the surge-EPS (i.e. via MOGREPS-G).

2.3 Further evaluation of the Atlantic-UK wave-EPS

Verification specific to potential application of the Atlantic-UK wave-EPS for coastal flood forecasting was undertaken and reported by Bunney and Saulter (2014, 2015). A particular focus was an examination of regional differences in behaviours of the ensemble. The North Sea, where wave climate is predominantly affected by local wind conditions, was contrasted with exposed “Western Approaches” (WA) locations, where the wave climate includes significant contributions from mature wind-seas and swells developed by large storm systems in the Atlantic. The verification “truth” used observations from in-situ platforms and wave buoys available on WaveNet plus remote sensed wave observations from the JASON-2 satellite altimeter.

The main findings and recommendations from the report by Bunney and Saulter (2014) were as follows:

- The Atlantic-UK wave EPS is appropriate for wave forecasting in UK waters and should be extended to 7 days for consistency with the ensemble surge model.
- The wave model component should be updated to use a variant of WAM Cycle-4 physics (for example the TS3M tuning settings from Saulter, 2015), in order to resolve North Sea and Irish Sea bias issues.
- The verification undertaken was relevant for ‘offshore’ wave conditions. The report noted that inshore water levels are a strong control on wave variability and further exploration on the effect on the wave ensemble spread in the nearshore should be undertaken within the demonstration project (see Section 4 of this report).
- Whilst recognising EA constraints and forecasting procedures, the results from the wave verification supported the Met Office position (established for other ensemble models) that use of probabilities over multiple thresholds is the ‘best practise’ method for decision making from the ensemble.
- Further work to explore the operational feasibility of bias correction when creating probability products is recommended.

On the last point, Figures 2 and 3 illustrate the potential issues associated with model bias in a short range ensemble forecast. Figure 2 shows the binned errors in significant wave heights (Hs, top panels) and wind speeds (bottom panels) on forecast Day 3. The assignment of data into bins is governed by the forecast parameter, i.e. the errors shown are the average value for forecasts of a given Hs or wind speed. Wind speed errors and biases are reasonably similar between the two regions. Whilst the Hs RMS errors also follow the same trend in the two regions, the biases show an opposite behaviour. In the WA, bias increases for higher Hs and wind speeds. However, the North Sea Hs biases are neutral up to approximately 4 metres then become increasingly negatively biased.

This effect was attributed to the use of the Tolman and Chalikov (1996) physics scheme in this version of the wave model; the scheme is known to under-predict short fetch moderate-strong wind sea development. Although not verified in this report, performance of the Met Office deterministic models suggests that a similar issue would be encountered for a model using Tolman and Chalikov (1996) physics in the Irish Sea.

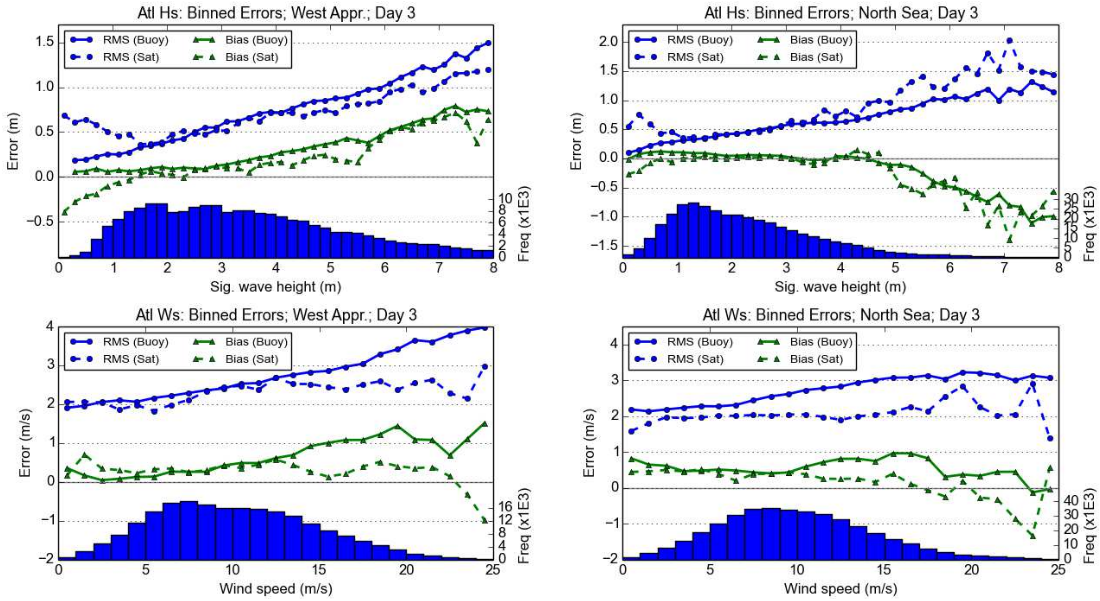

Figure 2. Bias (green triangles) and RMS (blue bullets) errors for binned significant wave heights (top) and wind speed (bottom) for forecasts on Day 3. Left panels: Western Approaches; right panels: North Sea. Errors derived from buoy (solid lines) and satellite (dashed lines) observations versus model ensemble mean.

At Day 3 (and shorter) forecast range(s) the biases are significant with respect to the RMS errors and, therefore, also with respect to EPS spread. In such circumstances the model biases will have a strong effect on the probabilistic skill of the model. Figure 3 shows reliability diagrams for significant wave height prediction of 4m and 6m thresholds. This verification tests whether event probabilities given by the model are then observed, e.g. if an event is predicted with 20% likelihood then it should subsequently occur 20% of the time. Good performance is indicated when the verification data lie along the 1:1 line in the diagram. In each diagram the solid gray line shows verification of the raw EPS data. The raw EPS tends to have skill, but often only marginally. However, once systematic bias is accounted for (using the binned statistics in Figure 2, correction values are given in each diagram) then reliability is massively improved, as shown by the red lines in Figure 3. A contrasting result can be seen in the reliability diagram from Hs greater than 4m predictions in the North Sea (top right panel, Figure 3), where the model bias is negligible and both raw EPS and bias corrected EPS reliability are similar and both very good. The existence of regional and situational differences in model bias imply that any bias correction scheme requires careful selection of verification sites in order to provide statistics that are robust, but also appropriate to the forecast location and associated wave conditions.

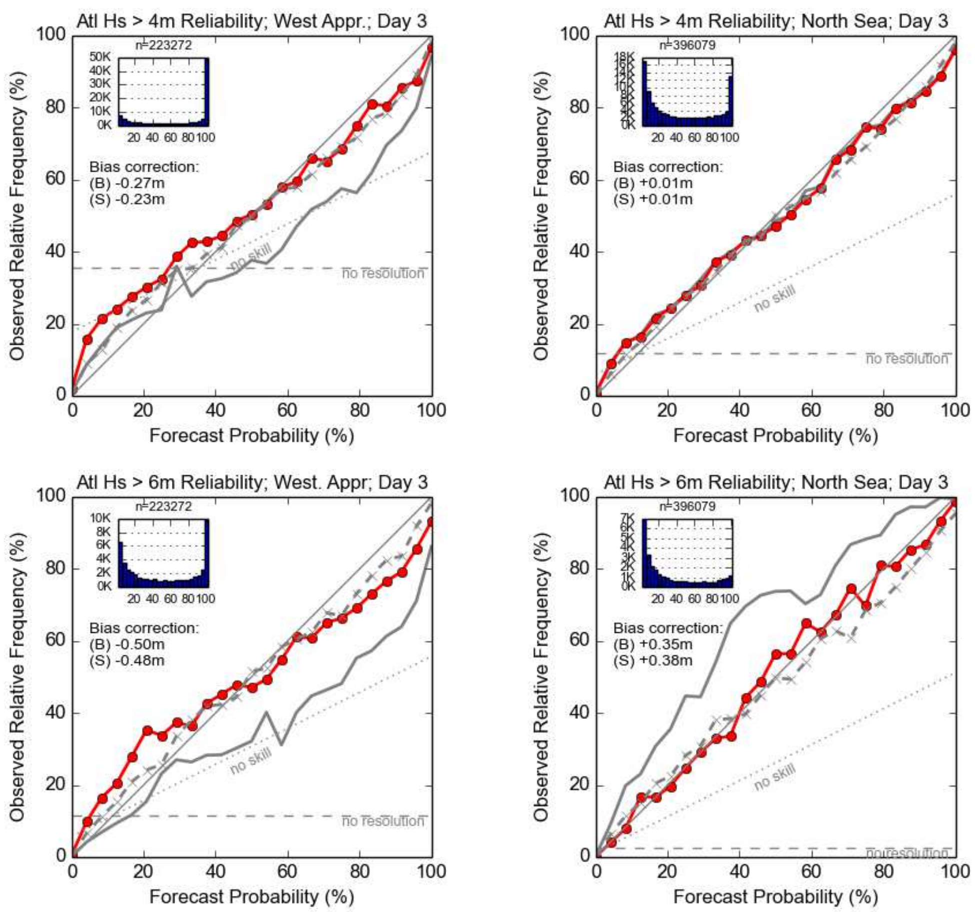

Figure 3. Significant wave height exceedance reliability plots (red lines+bullets) for H_s*>4m* (top) and H_s*>6m* (bottom). Left panels: Western Approches; right panels: North Sea. Reliability derived from bias corrected combined buoy and satellite data. Solid gray line: reliabiltiy of uncorrected forecast data. Dashed gray line: idealised perfromance verification against pseudo observations.

Subsequent to release of this report, both the extension to 7 day forecasting and implementation of WAM physics (using the TS3M tuning in Saulter, 2015) have been applied to the system. The revised physics package will change, and is expected to generally improve, the nature of systematic biases in the model. At forecasts beyond

Day 3, predictability associated with synoptic scale atmospheric features tends to break down. These features are key sources of variability for the wave forecast, so at lead times beyond Day 3 a step change increase in general EPS spread might be expected. Where spread generally increases, the relative influence of systematic bias should decrease, so it is anticipated that the longer lead time forecasts will be less susceptible to bias effects. Both these features of the revised EPS will need to be confirmed through ongoing verification.

3. Demonstration products

A major component of the project involved generation of data and graphical products from the wave-EPS, the utility of which was planned to be assessed by UKCMF flood forecasters. The work undertaken within this project has had the effect of commencing a dialogue on the most appropriate products, rather than defining a finalised set. This has been partly due to the availability of resources within UKCMF during the project but has also been because wave data are difficult to visualise in a probabilistic manner that can be readily appreciated by forecasters.

For example, significant wave height is readily visualized, but it can be argued that for coastal forecasting it is also critical to understand other characteristics of the "wave vector" by associating period and direction with the wave heights. Furthermore, it remains to be established whether flood forecasters are best served by wave data issued distinct from surge data, or combined at a nearshore location (see Section 4).

3.1. Data products

Presently the standard format for wave data from the ensemble uses CF compliant netCDF files. NetCDF provides a standardised framework for self-describing data (i.e. metadata about the parameters in a file are included in the file's content) and is supported by a number of open source utilities. Within the project, these data were worked with by graphical utilities written for and run on the Met Office research desktop platform. Outputs from the wave models include:

- Zonal and meridional wind speeds at 10m above sea level.
- Significant wave height, peak period, mean zero-upcrossing, mean and energy periods, mean direction and directional spreading, derived from the full wave spectrum.
- Significant wave height, peak period, mean direction and directional spreading, for a wind-sea and a combined swell component.
- Significant wave height, peak period, mean direction and directional spreading for primary, secondary and tertiary and quaternary wave field components (derived using a topographic partitioning method).

In the preliminary stages of the project a short tranche of work established an XML testing format, in order to provide EA with site specific wind, tide, surge and wave data for input to visualization and ingestion into their coastal downscaling systems. Due to resource issues, plans for data processing and assessment were delayed and this work is presently on hold.

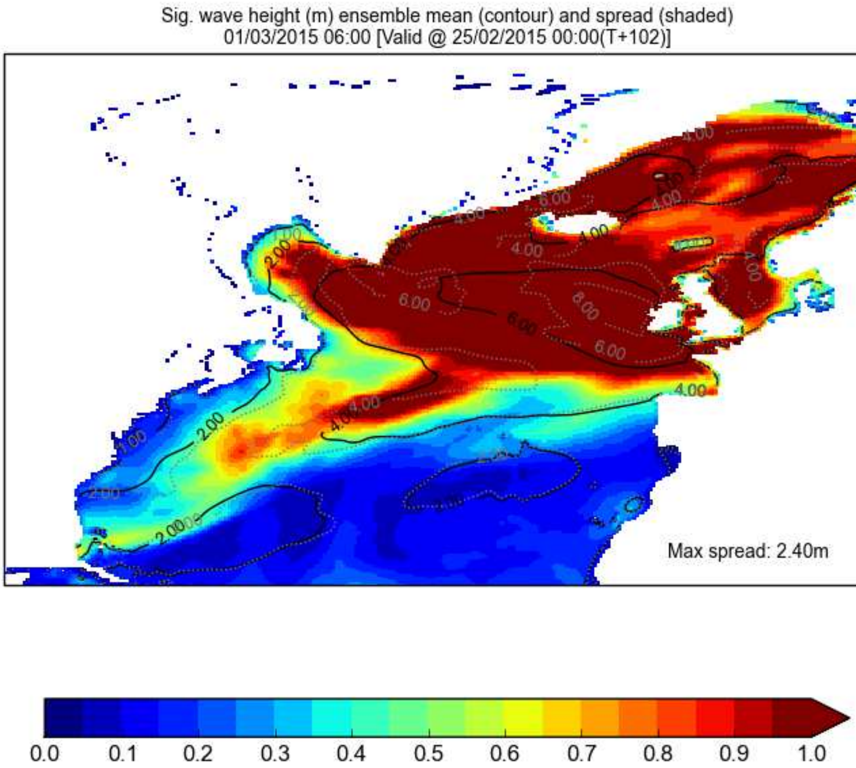

Figure 4. Mean significant wave height (in metres, contour) and associated spread (in metres, coloured field) forecast for the North Atlantic domain.

3.2. Graphical products

Within the project, graphical products largely concentrated on methods for visualising significant wave height, as a primary indicator of the background wave forecast and levels of variability. In the case of high energy storms this parameter is closely correlated with wave period (i.e. increases and decreases in period can be inferred from behaviour of Hs), although a requirement to identify moderate wave energy conditions dominated by long period (greater than 12-15 seconds) swell is also noted. The products were developed and hosted in-house at the Met Office, with use, review and feedback provided by forecasters from the Flood Forecast Centre (FFC).

Activities were focused around two summer development periods, leading to products that were used and reviewed by forecasters during the following autumn/winter season. During the first development period, mapped and station based products were developed:

1. Maps of mean forecast parameter plus spread (for wind speed, significant wave height and mean period, e.g. Figure 4). The maps give a spatial view of a deterministic forecast (the ensemble mean) and associated uncertainty.
2. "Postage stamp" maps of parameters (for wind speed, significant wave height and mean period, e.g. Figure 5). These plots enable a forecaster to examine the spatial variability introduced by different members of the EPS in more detail and are useful for spotting when forecast outcomes bifurcate significantly.
3. Time-series of significant wave height, mean period and wind speed at UK wave observation sites.
4. Time-series of significant wave height and surge at standard port locations (e.g. Figure 6). These plots enable the forecaster to take a view of co-located surge and wave conditions in the offshore zone.

Following review of these products, the second development period concentrated on integrating the wave forecasts with observed data, in order that the forecasters can monitor the forecast during an event and develop a better understanding on the likely behaviour of the wave model versus measured baselines. Figure 7 shows a typical example from the webpage that was developed. Coloured symbols on the map view indicate the level of error between prior model short range (T+1-6) forecasts and the observed Hs. Clicking on an individual symbol brings up observed monitoring data and forecast time-series plumes for Hs and, as appropriate, wind speed. Use and feedback on model performance via this view has been successful over the winter of 2014-15. This has led to further developments (e.g. addition of threshold values) being requested by FFC as follow on work items.

Additional to forecast visualizations, the Met Office science team created a set of rolling verification graphics that could be used to quantify the model's longer term performance. Verification is differentiated from monitoring as it evaluates an aggregated set of error data and views the EPS performance over many events rather than the "in the moment" evaluation at individual stations offered through the monitoring pages. To fully understand system limitations, it is important that a forecaster is aware of the verification as background to opinions formed when assessing monitoring data during an event. To improve use by forecasters it is proposed that the verification webpages are developed further to better meet coastal forecasting requirements.

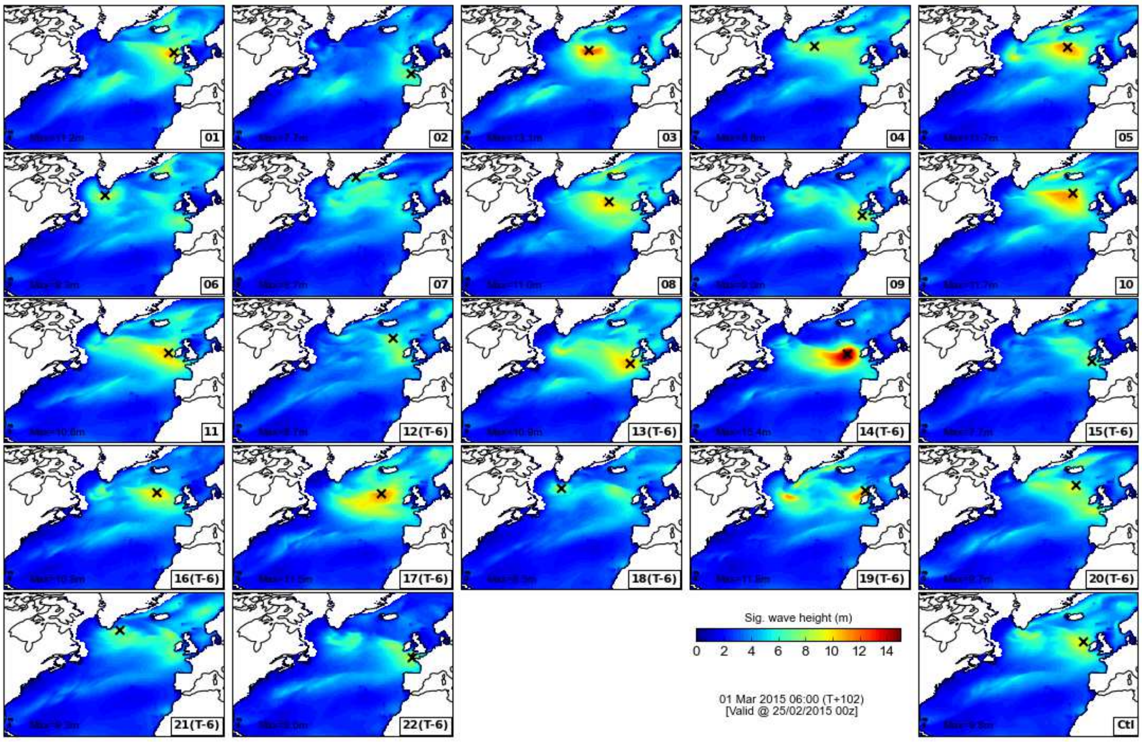

Figure 5. Significant wave height postage stamp plots for the forecast shown in Figure 4.

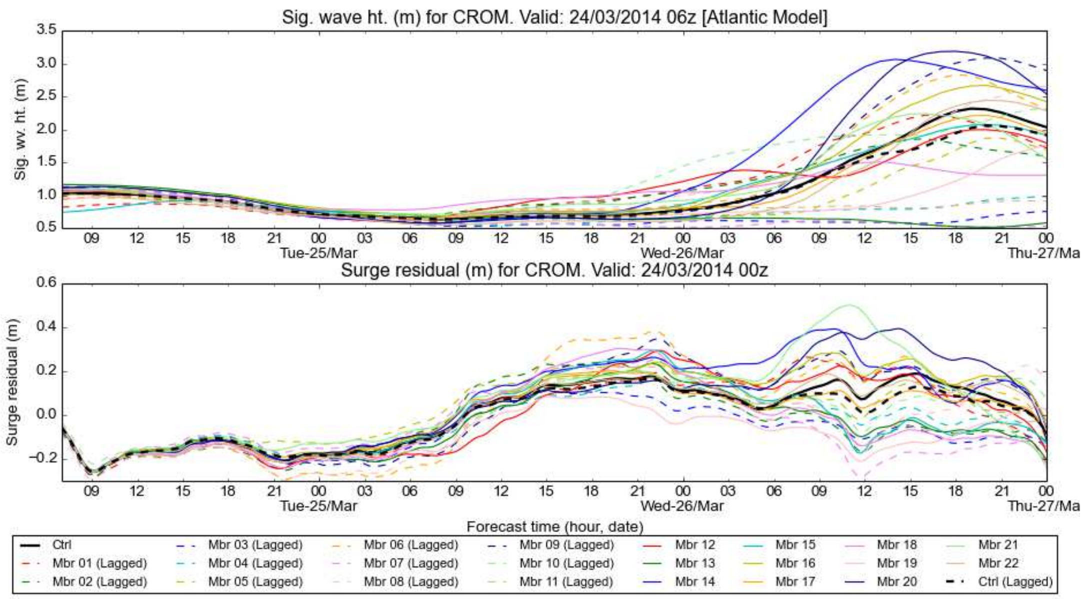

Figure 6. Significant wave height (top panel) and surge elevation (lower panel) time-series. EPS forecast members are coloured using the same scheme for physical consistency, e.g. member 14 (royal blue) indicates an outcome where the peak in the surge is coincident with high waves and is therefore likely to represent a worst case scenario.

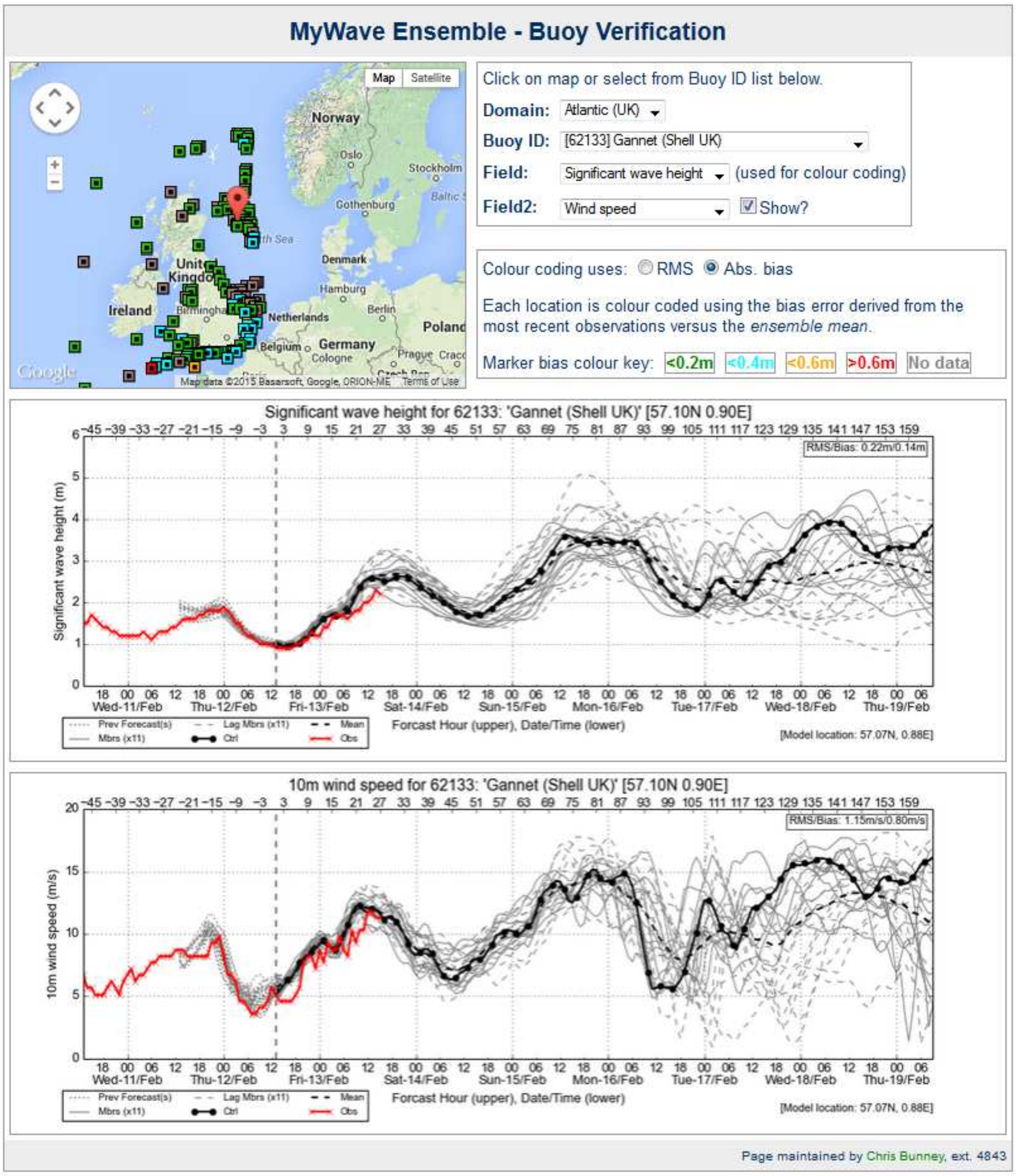

Figure 7. Example site specific monitoring page. Sites in the graphic correspond to locations of observation sites around the UK; each location is coloured according to the error between ensemble mean and observations of significant wave height. The monitoring trace (red) updates hourly and shows at least the last 48 hours of observations against short range (T+1-6) forecast data. The forecast time-series shows the 7 day ahead outlook for wave height on site, with the control member marked by the solid black line and the ensemble mean forecast marked by the dashed black line.

4. Methods for combination of tide, surge and wave forecasts

Issues with visualising the wave-EPS forecasts effectively have highlighted the fact that the model generates data that are appropriate to offshore areas but, in terms of impact, coastal flooding is a function of volumes of water associated with combined tide, surge and wave action at the shoreline. In comparison to tide and surge, wave parameters are often more likely to be significantly altered in the transition from offshore to shoreline. In addition, the process of wave breaking in the nearshore can serve to further enhance water levels on beaches, via wave set-up (Dean and Walton, 2008). The principle processes influencing changes to the wave field are briefly highlighted in Appendix A and it is important to note that any changes will be a function of the offshore wave characteristics (energy, direction and period), water depth and bathymetry (particularly close to the shoreline).

The implication is that the best way to understand the coastal risks posed by wave action is by properly combining tide, surge and wave data, via high resolution nearshore modelling, in order to quantify water levels and wave characteristics at the land-sea boundary and estimate coastal defence overtopping rates. In such a system, the Met Office wave ensemble would provide a boundary condition, crucially with each member of the ensemble physically consistent with the same member of the surge-EPS. The location of the wave boundary condition point would be determined by assessing where, in the offshore region, the scales of bathymetry changes that significantly influence the wave field are similar to the regional wave model scale.

In practise, running downscaling models using ensemble inputs for large areas of the UK coastline has major computing capacity implications, both for running the models and communicating the results across UKCMF partners. In lieu of this type of solution being resourced, it is important to understand if other, more scalable, methodologies for forecasting might be available in the interim.

4.1 Options for tide, surge and wave combination

A proper exploration of the benefits of forecasting using full dynamical downscaling of tide, surge and wave criteria versus simpler methodologies was beyond the scope of this project. However, work that has been completed has identified options and provided a limited demonstration of simple methods. Options that could be reviewed in future are as follows:

Full dynamical downscaling for land-sea boundary forecasting

Applying tide, surge and wave boundary inputs to high resolution coastal wave and ocean models that are run operationally, provides the most technically correct procedure available for predicting conditions at the land-sea boundary. This approach has the added advantage that new survey data can be incorporated relatively readily in order to update the models in response to major changes in approaches bathymetry and beach profile. However, this is a highly computationally expensive option that might only be practical to implement for a few key areas or locations with critical infrastructure.

Look up tables for land-sea boundary forecasting

An alternative use of high resolution coastal modelling is to run these systems offline, based on a set of discrete combinations of input boundary conditions (e.g. derived from a climate frequency analysis). Operationally this has the advantage that the conditions at the land-sea boundary are quantified, but at significantly less computational expense than for an operational downscaling model. However, significant effort is required to set up and make the runs needed to populate the look-up table; also to provide a suitable method to deal with problem of accessing data from a discretely binned table using a continuous set of input boundary conditions. Where variability in tide, surge, wind, wave and bathymetry are all needed to be accounted for, the dimensionality of the problem, and therefore number of offline runs required can be very large (order of 10,000s conditions). The offline studies may be needed to be rerun every few years in order to account for changes in boundary condition calibration or specification (e.g. due to substantial change in the bathymetry or the offshore model).

Derived offshore look up tables

This method is also based on a series of offline high resolution coastal model runs, but works backwards from an established set of land-sea boundary warning thresholds in order to establish the range of offshore boundary conditions that should trigger the warning. In principle, by focusing on warning criteria, the overhead in terms of the number of offline runs can be reduced significantly although a substantial number of runs may still be required. However, the method may be difficult to implement for large areas with a multiplicity of local thresholds. Forecast outputs are more qualitative, i.e. the forecast indicates risk but cannot be used to quantify impacts. A model of this type may also present a challenge for forecasters attempting to assess model uncertainty since the offshore thresholds will be multi-dimensional (i.e. comprising at least tide, surge and wave parameters). The offline studies may be needed to be rerun every few years in order to account for changes in boundary condition calibration or specification (e.g. due to substantial change in the bathymetry or the offshore model).

Simplified dynamical downscaling for land-sea boundary assessment of "additional wave risk"

The concept of additional wave risk is based on the principle that "still" water level (i.e. a combination of tide and surge) provides the primary indication of coastal flood risk, which is then enhanced by the presence of large waves. Since waves have a directional property, the level of risk on coasts with different aspects will vary. In addition, the period of the waves and variations in local water depths will act as primary influences on the nature of waves reaching the shoreline. Parameterising these effects should enable a forecaster to qualitatively differentiate between events and sections of coast in terms of the extra risk that the presence of waves may have. Due to the level of parameterisation, it is unlikely that the forecasts could be used to quantify the land-sea boundary condition. An example of this approach is given in Subsection 4.2.

Offshore assessment of "additional wave risk"

The approach is simply to provide the forecaster with appropriate offshore wave information in addition to tide and surge data, such that the forecaster can then make a judgement as to whether (and for where) waves may present an additional risk. A number of levels of sophistication are available; at the simplest level the forecaster is simply presented with offshore significant wave height data, however the known dependencies of the coastal conditions on wave direction and period imply that this information should also be available; one step on from the standard offshore data (and which offers simpler visualization) is to calculate an "equivalent offshore wave height", (i.e. an estimate of wave energy that will influence the coastal zone by accounting for wave direction and period effects) – an example of this approach is given in Subsection 4.2; further sophistication can be added by including wave threshold information, although these data should arguably be applied over a range or with a dependency on still water level. A higher degree of expertise is required from the forecaster in this instance than for the other approaches.

4.2 Demonstration of additional wave risk

Work within this project has been undertaken to demonstrate the feasibility of products that present additional wave risk. The presentation of wave time-series alongside surge (Figure 6) provides the simplest illustration of offshore risk. The aim was also to establish scalable (i.e. computationally simple) methods by which coastally focused offshore and land-sea boundary predictions could also be made.

At the offshore point, the method tested has been to generate an equivalent offshore wave height from the forecast values of Hs, period and direction, plus estimates of coastline direction and distance of travel from the offshore to nearshore location. The principle is that the revised wave height indicates the levels of energy that will impact the coast and gives the forecaster a scalar (rather than vector) parameter to work with. Revisions in wave height from the offshore Hs condition are based on parameterisations of three processes:

1. The proportion of offshore wave energy propagating shoreward. The most simple case would be one in which waves are being driven offshore by strong winds, so that none of the wave energy forecasted offshore would be shoreward directed and therefore the equivalent offshore wave height reduces to zero. In flood forecasting scenarios, the more likely case is one where waves are driven obliquely to the coastline, in which case (due to directional spreading of wave energy) a proportion of wave energy will refract shoreward and the remaining energy will continue to propagate offshore.

2. Dissipation due to sea bed friction. Once wave orbital motions penetrate as far as the sea bed, wave energy will be lost. For longer period waves this effect will commence in deeper water than for short period waves. In model parameterizations, some of the effect is offset by the faster speed of longer period waves since the dissipation effects are applied for a shorter length of time over a given distance. The effect can only be estimated when using a simplified model, but may achieve a reduction of wave energy of the order 10-40% dependent on the case.

3. A secondary process relates to the degree to which along-crest density of wave energy will be decreased as a result of obliquely propagating waves turning toward the shore normal direction due to refraction in shallow water (see Tucker and Pitt, 2001, p293-300, for a more detailed explanation).

Key known/forecast parameters affecting the equivalent wave height calculation are offshore significant wave height, period and direction, offshore (model) water depth and a shoreline alignment (shore normal) angle. Assumed/estimated parameters are the distance from the offshore location to the shoreline and a nominal water depth close to the shore for the refraction calculation. For a given instance, the principle differentiation applied to the offshore waves results from the wave period and direction and the shoreline alignment. Figures 8 and 9 show the reduction in offshore wave height estimated at two southern North Sea coastal locations (Cromer and Lowestoft), for days around the major surge event in early December 2013. Offshore waves during the event were moderate to high for the region, peaking at 3m offshore of Cromer and 2-2.5m offshore of Lowestoft, as shown by the green plume in the figures' lower panel. However, the general direction of the wave field was toward the south, so oblique to the coastline. This angle of approach, plus estimated sea bed friction dissipation, reduces peak equivalent wave height (yellow plume in the figures' lower panel) to 2m at Cromer and, because the angular differential is larger due to changes in coastline orientation (a shore normal of 20 degrees has been used for Cromer, 75 degrees at Lowestoft), the Lowestoft equivalent wave height is reduced to 0.5-1m. In the Cromer plumes it can be seen that the reduction is less marked after T+36 hours; this is associated with a change in the direction of the offshore waves such that more energy comes from the east.

Estimation of wave effects at the land-sea boundary are based on representation of two processes. The most important is that wave heights will be constrained by water depth. As an example, water of depth 1m can be assumed to only be able to support a significant wave height of 0.4-0.8m meaning that, if this were the water depth at the toe of a sea defence, then the waves interacting with the defence would be independent of whether the unbroken wave height further offshore were 1m, 2m or 5m. Where these situations differ however, is that for the larger offshore wave heights a wider surf zone is created, which leads to an increased level of wave set-up (an increase in the mean water level at the shoreline due to wave breaking), adding extra water level varying with periodicity of 10s to 100s of seconds. A useful summary of this process is provided by Dean and Walton (2008). Both processes can be parameterised using the equivalent wave height and wave period plus tide and surge levels as inputs, with assumed/estimated parameters set for beach slope and beach level at the land-sea boundary.

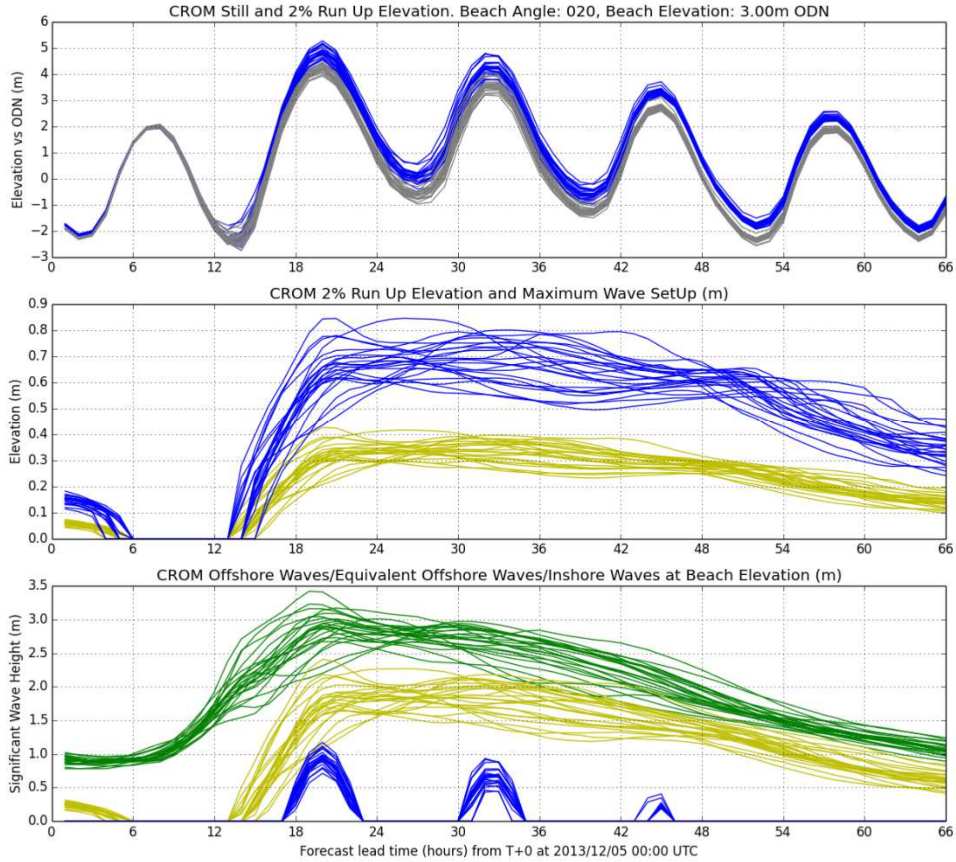

Figure 8. Illustration of additional wave risk products – forecasts for Cromer, assumed shoreline normal angle 20°, beach elevation 3m AOD. Lower panel shows EPS offshore wave height (green plume), equivalent offshore wave height (yellow) and wave height at the 3m AOD level (blue). Middle panel shows estimated wave set-up (yellow) and 2% run-up elevation (blue). Top panel shows tide+surge still water level (gray) and additional level due to (2%) wave run-up (blue)

Figures 8 and 9 show three different parameters predicting wave effects at the land-sea boundary. The blue plumes on the lower panels indicate the wave height forecast at the land-sea boundary, which is defined by the input beach level. For Cromer this has been set at 3m Above Ordnance Datum (AOD), whilst for Lowestoft this is set at 1m AOD. The position of the shoreline relative to this level is governed by the tide and surge components (with a further contribution from wave set-up), so that for large periods of the tidal cycle the land-sea boundary point will be dry and the wave height is set to zero. Once the point “wets” the wave height is governed by water depth and incoming wave height; in the examples here, although Cromer has larger offshore and equivalent wave heights, the maximum water depth relative to the beach level is similar to that at Lowestoft, so the inshore wave heights are similar or smaller.

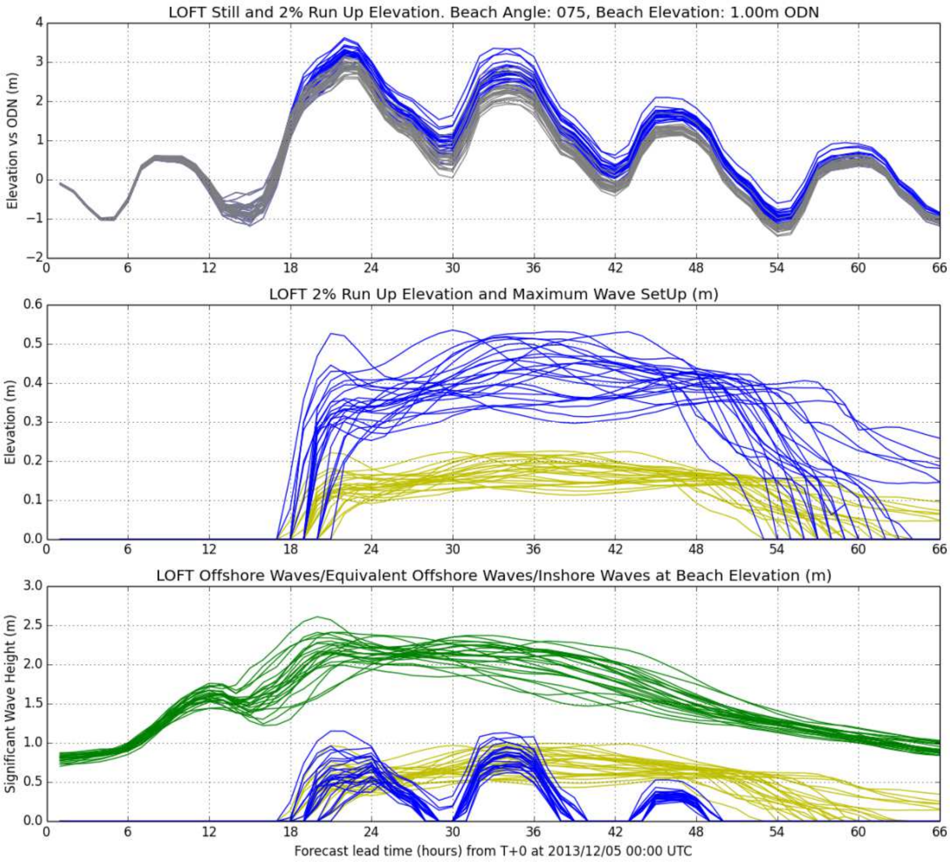

Figure 9. Illustration of additional wave risk products – forecasts for Lowestoft, assumed shoreline normal angle 75°, beach elevation 1m AOD. Lower panel shows EPS offshore wave height (green plume), equivalent offshore wave height (yellow) and wave height at the 3m AOD level. Middle panel shows estimated wave set-up (yellow) and 2% run-up elevation (blue). Top panel shows tide+surge still water level (gray) and additional level due to (2%) wave run-up.

A second parameter, mean wave set-up, is illustrated using the yellow plume in the central panel on the figures. In these cases the set-up is different at the two sites due to differences in the equivalent offshore wave height, so the values at Cromer are higher than at Lowestoft. It is worth noting that in this case the estimates of wave set-up are approximately 20-40% of the forecast surge for this event. The 2% Run-Up value (blue plume in central panel) is an alternative parameterisation to set-up that incorporates both the mean set-up value and a dynamic component resulting from variations in individual wave heights (Dean and Walton Jr., 2008). In this case, the parameter estimates the level on a beach that would be reached by 2 in 100 waves. To contextualise the additional effect of nearshore wave processes, the 2% Run-Up values have been added to a tide+surge time-series (the gray plume in the figures' top panels) to give an overall 2% water elevation value (blue plume).

It is emphasised that the values in these plots are heavily parameterised estimates and, in this context, are used to illustrate the significance of nearshore processes to the coastal flooding problem rather than accurately quantify them. As such, the data are not verified; however the empirical algorithms used have been derived from series of field and laboratory experiments (see Dean and Walton Jr., 2008 for an overview) so are similar, in terms of available background evidence, to a number of overtopping algorithms in use within coastal flood prediction systems. Some limited confidence can therefore be placed in the results, which show that, at the peak of the forecast time-series, the run up values add an extra 20-50% above the maximum mean water level (above ordnance datum) that is forecast due tide plus surge processes. The examples also demonstrate that cases where little or no additional wave risk can be detected are also a property of the forecast. In the figures, at lead times less than T+12, little or no wave energy is calculated propagating shoreward, and the additional effect of waves at the shoreline is therefore negligible.

5. Follow on development program

Work in this project has demonstrated and verified the feasibility of a wave-EPS for application in coastal flood forecasting. The next stage of work will need to progress the system toward providing a set of operational products that meet UKCMF needs. The following subsections identify and describe tasks required to be undertaken within this next stage.

Subsequent to this project, activities to further demonstrate and develop use of the wave ensemble, both using the relatively direct route between the Met Office science team and FFC and via wider dissemination of data to other EA stakeholders, aim to be continued through the mandate "7-Day Wave Ensembles and Probabilistic Coastal Impact Forecasting" (FFC, February 2015). The overall objectives of this project are provided in Appendix C. From a wave-EPS perspective, work under this mandate is expected to deliver the following ongoing infrastructure and application improvements:

- Establish a more robust data and graphics production system within the Met Office.
- Continued development of graphical products appropriate to the coastal flood forecasting task.
- Establish a wider understanding of the potential use of wave-EPS data in coastal flood forecast warning production amongst UKCMF stakeholders.
- Establish best practise for using wave-EPS data in coastal flood forecast warning production and identify work required to standardise this approach.

5.1. Operational status of Atlantic-UK wave-EPS

At completion of the project the Atlantic-UK wave-EPS is running as a fully supported operational model suite. The EPS runs four times daily, following the production cycle for MOGREPS-G atmospheric data, and alternately updates the medium range forecast component of 12 of the 24 members of the wave ensemble at each cycle. The full 24 member lagged-ensemble comprises 12 members from the current cycle and the overlapping 12 members from the previous cycle. Forecasts are available out to 7 days ahead, in line with production runs for the surge-EPS. Following results of the model evaluation, the model physics have been update to run using a WAM based formulation. Further physics upgrades are expected as part of the general model development process, based on the results of ongoing system verification.

For purposes of computational efficiency, the model uses a refined (SMC) grid mesh, which scales from (approximately) 25km in open waters offshore to 6km at the coastal boundary. An illustration of the mesh around the UK coastline is shown in Figure 10. At present, the majority of standard visualization and product suites expect regularly gridded data, so included in the wave-EPS run cycle are a series of jobs which reformat the SMC model data to a set of regularly gridded netCDF files covering Atlantic (interpolated to approximately 48km to reduce file sizes), North Atlantic (resolved at approximately 24km) and UK (interpolated to approximately 6km) domains.

Beyond "business as usual" scientific upgrades to the MOGREPS-G and Atlantic-UK wave models, no further major work is likely to be required at this stage in the production process.

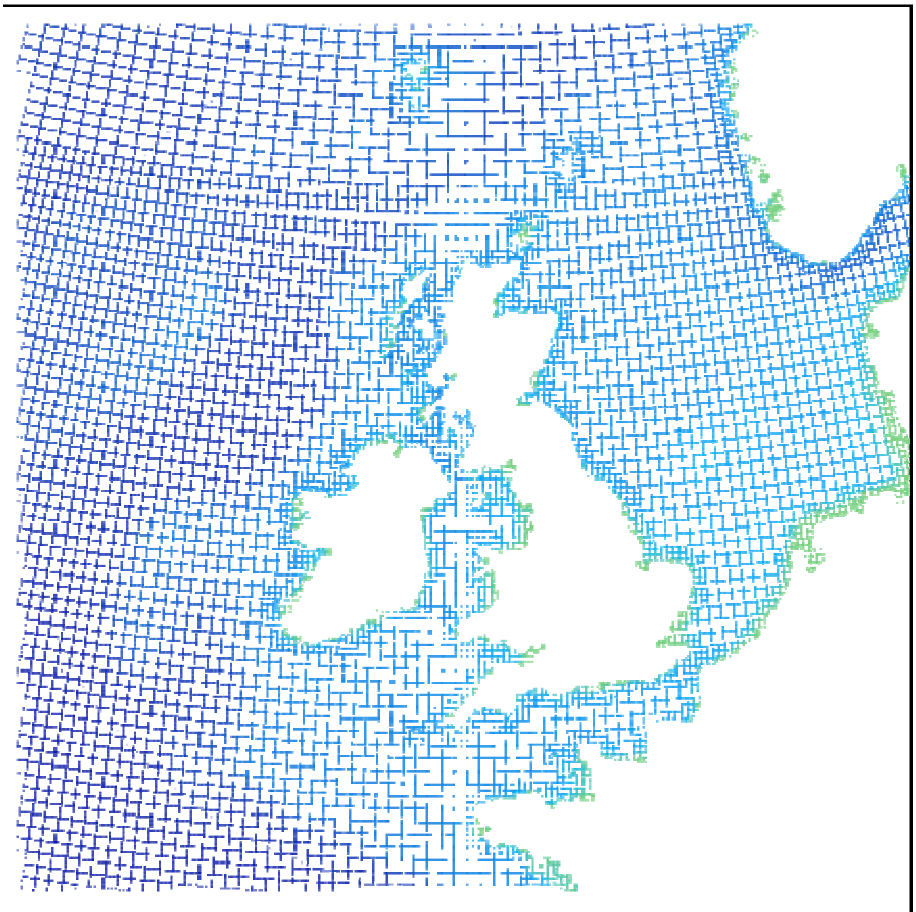

Figure 10. Atlantic-UK model grid mesh for UK. The smallest (coastal) cells are resolved at approximately 6km, the largest cells at approximately 25km.

5.2. Product development: data products for UKCMF

Whilst data are operationally generated on the Met Office's supercomputer, no similar operational infrastructure has been put in place for provision of data products. It is anticipated that the data production route should initially mirror that in place for the surge-EPS. This presently comprises transfer of model standard format files to an operationally supported Met Office Virtual Machine (VM) platform, which then deals with subsequent data (e.g. GRIB conversion) and graphical product post processing (e.g. for internal Met Office MOGREPS surge pages). This process should be a consistent interim step toward longer term plans to create products from a "gridded data store" of Met Office model outputs. It is noted that transition of wave-EPS data and product generating services onto the VMs will require passing a "TechGate" process within the Met Office.

Dependent on UKCMF requirements, it is anticipated that the volumes of wave data supplied will be 2-5 times larger than for the surge ensemble. This is due to the number of parameters required to describe the wave field, particularly if users were to require component wave systems.

In lieu of UKCMF stakeholders using gridded data from the ensemble, it may be worth exploring the option of providing point based data files (e.g. for the primary ports used by FFC forecasters) comprising aggregated tide, wind, surge and wave data. Volumes would be significantly smaller than for the gridded product and would have the advantage of ensuring consistent production links between wind, wave and surge ensemble member data. Through work in this project, the Met Office science team already have some experience in generation of netCDF and XML versions of this type of data file.

5.3. Product development: graphical and post processed products for the FFC

The graphics demonstrators provided in this project are run on the research desktop environment at the Met office and are not operationally supported. It is anticipated that a final version of graphical products will run on the operationally supported VMs at the Met Office and be hosted on similarly robust webpages (similar to the present surge products).

There will be an interim period where the utility of these products will need to be more fully assessed and developed. In particular any products associated with combination of wave-EPS forecasts with existing tide and surge-EPS data. One further item of research work, which may be necessary based on the results of verification in this project, is to assess the need and benefits of applying post processing methods to bias correct the wave-EPS and revise probability data provided by the system, based on representation scale differences between the model and observations. This latter form of post processing acknowledges the effects of sampling variability introduced in observations that "burst sample" for 20-30 minutes, versus a 1-3 hour average value that is more in line with atmospheric model representation scales. Bitner-Gregersen and Hagen (1990) suggest that such sampling variability introduces a 3-6% random error to the observations, which would be additional to the forecast perturbations in the wave-EPS.

5.4 Verification

In addition to graphics and monitoring, it is important that the wave-EPS is subject to an ongoing verification programme, with forecasters and scientists developing the model as the target audience. This work will be mostly dealt with under a wider support and development programme for the system but, as a critical user, it is anticipated that schemes to select verification data and metrics specific to the coastal flood forecasting problem will need to be developed. For example, ensuring that local and directional systematic biases in the model are well understood, or that predictability at particular thresholds is assessed. Some work will be required to select verification regions that strike an effective balance between generating verification that is robust, based on a sufficient number of observations, and localising results such that quantitative use of bias corrections or other statistics is appropriate.

5.5 Forecaster support and feedback process

Dialogue and feedback within the project has highlighted the need for ongoing support and feedback processes to be set-up between Met Office scientists and UKCMF stakeholders. These processes have been established with the FFC, for example dialogue between forecasters and the surge/wave team in the lead up to events, establishment of a Wiki page to capture post event feedback and queries.

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Appendix A: Principle processes affecting waves in the nearshore

Principle processes causing changes in wave height and direction in the nearshore versus the offshore region are:

1. Directional aspect of the affected shoreline and topographic sheltering; only wave energy propagating in a shoreward direction will reach the coast and, for waves arriving at an oblique angle, headlands will shelter given areas.
2. Refraction; this is caused when wave speed slows in shallow water, leading to the waves to become directed more toward the depth normal. Over features such as sand bars this may lead to patterns of higher and lower waves as “along-crest” wave energy becomes condensed or stretched. Equally common, for waves that are initially oblique to the coast, will be a stretching effect that means along-crest wave energy density will be decreased (such that wave heights will be lowered slightly) as the waves propagate toward shore and turn toward shore normal (see Tucker and Pitt, 2001, p293-300).
3. Shoaling; as waves slow in shallow water, the wave energy density is increased, leading to an increase in wave height. The wave speed change required to cause substantial shoaling is, for all but the longest period waves, generally restricted to water depths less than 4m
4. Dissipation due to bottom friction and depth limited wave breaking: both processes are related to the interaction between waves and the sea bed. The first process takes effect once wave orbital motions are constrained by the bed as a boundary layer – the depth at which is occurs is a function of wave period and is of order 10s of metres. This means that the bottom friction process can be in effect over a wide area if gradients in the bathymetry are low. Depth induced breaking occurs when the water depth can no longer support waves of a given height – this process causes a more violent dissipation of wave energy but, in all but the largest storms, is generally constrained to a zone within a few hundred metres of the shoreline.

Refraction and shoaling may also occur in the presence of strong currents. Other secondary effects to the waves will include diffraction and forward shifting of wave frequencies due to so-called triad interactions.

Appendix B: Project SC120007: 'Develop, trial and demonstrate the benefits of a wave ensemble forecasting system'; original and revised project objectives

The project ran from June 2013 to March 2015, with the following original objectives:

1. To evaluate available approaches for developing wave and joint wave and surge ensemble products building on experience with UK surge ensembles and elsewhere and confirm specific user requirements.
2. To create outputs and benefits from a prototype wave ensemble system for UK coastal waters that will be built as part of the EU funded MyWave project and match the requirements from Objective 1.
3. To specify and demonstrate long term and real time verification of the system specific to flood forecasting, through a long term trial and for specific events.
4. To demonstrate through case studies how wave ensembles can benefit and contribute to improved local flood forecasting and warning.
5. To investigate and produce initial guidance for how to assess the overall risk coastal flooding by considering both storm surge and wave ensemble forecasts.
6. To make recommendations and provide a plan for operational implementation and future proofing to benefit from ongoing improvements in weather and wave modelling.

The project ran in parallel with a wider programme of wave-EPS research and development undertaken by the Met Office as part of the EU FP7 funded project 'MyWave' (www.mywave.eu). Originally the project had been conceived assuming that some EA resource would be available to assist the evaluation of the benefits of applying combined wind, surge and wave EPS data to EA regional coastal flood forecasting systems. A process of reorganisation at the EA meant that these resources did not become available within the project lifetime, leading to some deviations in project scope:

- Objective 2 concentrated on the product development and feedback process targeted at the joint Met Office – EA Flood Forecasting Centre (FFC); i.e. more time was given to products to assist UK wide guidance forecasts rather than assessing the benefits to local flood warning systems.
- Objective 3 concentrated on developing long term verification and monitoring of the operational wave forecast in the offshore area, rather than undertaking case studies. Objective 4 is identified as a follow on activity.
- Preliminary steps towards objectives 1 and 5 were undertaken by reviewing options for modelling coastal hydrodynamics and demonstrating a simplified method of wave transformation in the coastal zone. This latter method has been

targeted at improving FFC forecaster appreciation of the relative impacts of offshore wave conditions at the coast and in combination with (combined tide plus surge) water levels.

Overall this has led to the project being more focused toward performance of the wider area guidance product and engagement of FFC, than demonstration of localised forecast performance in specific cases. However, in terms of delivery and utilisation of products by UK Coastal Monitoring and Forecasting (UKCMF) stakeholders, the FFC are expected to have been the most likely early adopters of wave-EPS data so the project revisions are expected to be appropriate in terms of long term development. Continued operational research and development work at the Met Office, plus the set-up of centralised coastal teams at the EA, should also enable follow on demonstrations of local forecast benefits to be achieved more efficiently than would have been possible within this project.

Appendix C: Wave-EPS coastal flood forecasting development mandate

Subsequent to this project, activities to further demonstrate and develop use of the wave ensemble, both using the relatively direct route between the Met Office science team and FFC and via wider dissemination of data to other EA stakeholders, aim to be continued through the mandate “7-Day Wave Ensembles and Probabilistic Coastal Impact Forecasting” (FFC, February 2015). Specifically the project will seek to:

1. Identify quick wins to develop non operational visualization web pages (on internal Met Office web pages) and products used to communicate uncertainty and scenarios in the wave (and overall coastal) conditions for UK coastal waters through updating approaches to FFC guidance. This will be of benefit to all UKCMF partners.
2. Scope options and identify a preferred approach for providing combined surge/wave data for use in the Coastal Decision Support Tool (CDST) by linking in with a concurrently running EA project to develop the CDST. The outcomes of both these work areas will provide improved strategic assessment and scenario planning of coastal flood risk.

The project will build on the working relationship established between FFC and the Met Office surge and waves team and will include inputs from a small group of EA coastal experts and the EA Flood Detection and Forecasting coastal lead. Work will be split into two phases:

- Phase 1 will indentify quick wins to develop non operationally supported visualization web pages (internal to Met Office) for use by FFC to provide enhanced operational guidance in time for winter 2015/16. In addition, a wiki page is will be developed as a means of sharing data captured by FFC OPs and analysis/feedback from the surge and waves team. Ongoing findings, observations and any conclusions will be shared back to FFC OPs at monthly OPs meetings creating a cycle of continuous learning. These findings will also help to shape guidance on understanding and communicating wave ensembles. It is anticipated that the wave ensembles will initially be used to improve communication of uncertainty and inform scenarios communicated through the Hydromet Guidance for winter 2015/16.
- Phase 2 will focus on the development of a combined surge/wave system and approaches to using wave ensembles in combination with surge forecasts to

provide a complete understanding of coastal flood risk. To achieve this, the following steps will be taken:

- A scoping workshop, facilitated by FFC, will be held to discuss and agree options for providing data suitable for the CDST. This project will focus on determining the most viable and technically appropriate approach for use of the ensembles in flood forecasting to determine the probability of certain coastal conditions occurring. The CDST project will focus on determining impacts of those conditions and how best to visualise the outputs - both likelihood and impact - in order to communicate throughout the responder and risk management community.
- The Met Office surge and waves team will review methods by which the interaction between water elevation, waves (height and direction) and beach levels can be dealt with in a scalable manner (i.e. stretch of coast, port or at a specific flood defence).
- As part of the CDST project, offline testing will be undertaken on a limited number of potential approaches to using and combining wave/surge ensembles with impacts to identify technical and communication issues. A review of approaches by comparing with recent events will be undertaken to determine how these new approaches compare in terms of user understanding, robustness of approach and communication clarity with what occurred.
- A preferred approach and format of data to be enable a scalable and consistent approach to operational implementation of ensemble wave and surge data in coastal flood forecast systems will be agreed and the technical details of the approach documented.

From a wave-EPS perspective, work under this mandate is expected to deliver the following ongoing infrastructure and application improvements:

- Establish a more robust data and graphics production system within the Met Office.
- Continued development of graphical products appropriate to the coastal flood forecasting task.
- Establish a wider understanding of the potential use of wave-EPS data in coastal flood forecast warning production amongst UKCMF stakeholders.

- Establish best practise for using wave-EPS data in coastal flood forecast warning production and identify work required to standardise this approach.

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