NATURAL ENVIRONMENT RESEARCH COUNCIL

Flood Risk from Extreme Events (FREE)

Progress Report October 2008

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A. Progress against Research Themes

Theme 1: *Improved modelling and forecasts through new data assimilation methods*	**Theme 2:** *New approaches to modelling uncertainty in an integrated modelling environment*	**Theme 3:** *The statistics of extremes and their use*	**Theme 4:** *The Impacts of a changing climate on the occurrence of flooding*
Illingworth – NWP and new remote sensing observations	**Zou** – linking meteorological, hydrological and coastal models using ensemble methods	**Svensson** – joint probability analysis of fluvial and estuarine floods	**Osborn** – changing occurrence of rainfall
Dance – initialisation of coastal sediment models	**Beven** – constraining uncertainty in hydrologic modelling	**McSharry** – quantifying flood risk using density forecasts based on a new digital archive and weather ensemble predictions	**Cloke** – changes in hydrological and hydraulic flows
TBC – reducing the risk of pluvial flooding	**Wheater** – groundwater modelling of rare events	**Toumi** – a hybrid model for predicting the probability of very extreme rainfall	**Reynard** – changes in fluvial flooding and inundation
	O’Connell – impact of land use on behaviour of floods		**Williams** – changes in characteristics of coastal floods

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Theme 1: Improved modelling and forecasts through new data assimilation methods

Considerable progress has been made in developing numerical weather prediction and new remote sensing observations (**Illingworth**). Five months of quasi-operational refractivity data has now been collected at Cobbacombe. In early April the Intermediate Frequency filters were optimised for refractivity work at Cobbacombe providing a significantly improved range pattern of the radar pulse. Comparisons with synoptic stations close to Cobbacombe over several months show that the refractivity inferred from the radar tracks well. The accuracy of the radar data continues to be assessed so that errors can be derived. Data is clearly degraded when the radar transmit frequency exhibits very large excursions. *Following the success of the trials at Cobbacombe, the code will be rolled-out to several other radars in the UK operational network in the coming months.*

On deriving insect winds, the comparison between the Thurnham and Chenies radar has been completed, pending modifications to improve the Thurnham radar's sensitivity. The insect season has begun and data are now being examined from all operational Doppler radars. This will give a better idea of data availability and coverage for insect wind measurements. The operational threshold for Doppler returns has been lowered, so during this summer changes to insect return utilisation for VADs in the Met Office's NWP are being monitored. Test assimilations of insect VADs have been conducted with the Met Office observation processing and assimilation systems. Experiments to assimilate VADs from all radars into a full quasi-operational assimilation-forecast cycle are under development. This will test the effect of the additional wind data on the forecast.
[***Relevance:*** Observing the two new parameters is crucial to the success of the project.]

Further analysis of the previously-performed 4km ensemble simulations for CSIP [Convective Storm Initiation Project funded by NERC] IOP18 is being carried out and is now near completion. The analysis aims to determine the direct effects of the perturbation on the model state, and based on this to build an understanding of the variations in cloud distribution and RMSE of precipitation. Preliminary results indicate that the sensitivity to the perturbation changes during the day, and is dependent on perturbation intensity with a modulating effect due to the typical scale length. Conclusions from this work will drive the choice of the perturbation strategy for the 1.5 km experiments. The Boscastle flood was chosen for several parts of this study as common event to test both the hydrological effects of the current version of the ensemble, and the data exchange with the Joint Centre for Mesoscale Meteorology (JCMM).
[***Relevance*****:** Knowledge of physical processes that lead to predictabilty and error growth is key for a meaningful design of the meteorological ensemble.]

Further results have been obtained using the distributed G2G hydrological model configured over an area of southwest England as part of the Boscastle case study. The model performance is being assessed in both simulation and forecast mode (assimilation of flow data) for a range of lead times.

[***Relevance:*** Progress on a convective storm case study using high resolution NWP rainfall forecasts in a distributed flood forecasting model and in ensemble mode.].

The project led by **Dance** has received tidal constituent data from Roger Proctor at POL. These will provide the tidal boundary conditions for the Morecambe Bay and Dee estuary hydrodynamic models. Discussions are underway with Kevin Horsburgh at POL (replaced Roger Proctor who has taken a new position in Hobart) to obtain surge input data for the hydrodynamic models. Surge input is necessary for assigning heights to the waterline data.

Various numerical schemes for solving the sediment conservation equation have been received, and it has been decided to use the Euler-WENO method of Long et al. (Long W, Kirby JT, Shao Z, 2008. A numerical scheme for morphological bed level calculations. Coastal Engineering 55, p167.). This has been implemented in the old Morecambe Bay model, for comparison against the old Lax-Wendroff scheme, which suffers from dispersion. The Euler-WENO scheme has some teething problems. The data assimilation/parameter estimation scheme has been further developed to estimate the parameters associated with the sediment flux in a simple nonlinear model. The results of this scheme are currently being analysed.

There has been significant involvement with other bodies including the Environment Agency, HR Wallingford and Lancaster City Council. Nigel Cross of Lancaster City Council arranged for Tania Scott and Polly Smith to visit Morecambe Bay and familiarise themselves with the site. This involved a quad-bike tour of the flats organised by NWNW Sea Fisheries Association). Nigel Cross visited ESSC to discuss the project and exchange data. He is interested in mapping changes in low-water channels in Morecambe Bay for flood management purposes, and to aid navigation across the flats. Nigel supplied the project with complete LiDAR coverage of Morecambe Bay flown at low-water in November 2005. This will be extremely useful for data assimilation and model validation. He also provided data from GPS surveys of the tidal flats. In return access to SAR images was provided.

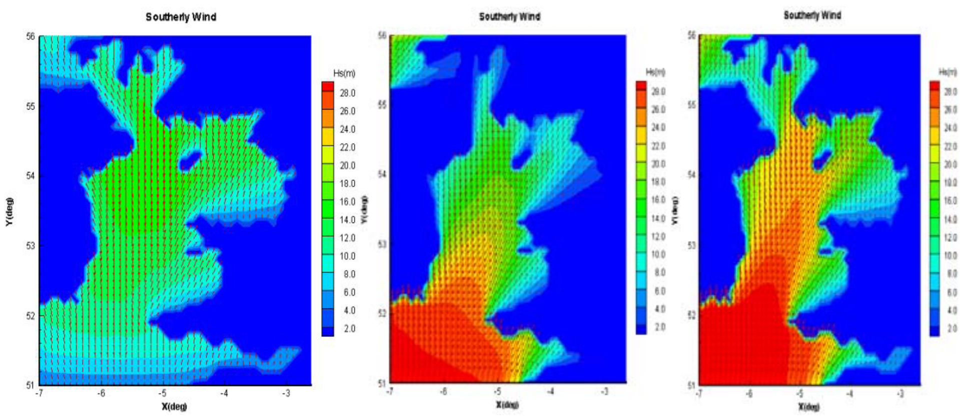
Theme 2: New approaches to modelling uncertainty in an integrated modelling environment

The project aimed at linking meteorological, hydrological and coastal models using ensemble methods (**Zou**) has set up the MM5 mesoscale model in two regions to simulate extreme events included in the ERA40 re-analysis data set such as the 1987 and 1990 storms. The MM5 has been setup using the four dimensional data assimilation option (fdda) in order to assimilate the re-analysis data when running the model for several days. The MM5 allows assimilating wind, temperature and mixing ratio. For every field to be assimilated, a nudging coefficient has to be defined allowing the model state to move towards the analysis. The nudging coefficient is very important because it may force the model state too much towards the re-analysis, decreasing the ability of the model to resolve mass-momentum imbalances. Different nudging factors have been tested and the results will be compared using hundred of wind and atmospheric pressure observations from ground surface stations within the UK. A study is also currently underway to develop a methodology to generate ensemble simulations using the re-analysis data.

The work on tide, surge & wave model has focused on the sensitivity tests of both POLCOMS and WAN models to gain further understanding of hydrodynamics produced by the model. Two sites have been used for these tests: the Irish Sea and English Channel, in order to get the model ready for specific sites to be identified in the project.

(a) Irish Sea

The quantitative assessment of wind and wave boundary forcing effects on wave climates has been carried out by running WAM model alone in the North Atlantic Sea (NAS) and in the Irish Sea (IRS). The model was first run in NAS domain, with 64 different wind forcing cases: combinations of 8 different wind directions (0º, 45º, 90º, 135º, 180º, 225 º, 270 º, 315 º, anti-clockwise to East) with 8 different wind speed (5m/s, 10m/s, 15m/s, 20m/s, 25m/s, 30m/s, 35m/s, 40m/s). The model was then run in IRS domain with three scenarios: (a) wind forcing only; (b) wave forcing only; and (c) both wind and wave forcing for all the wind speeds. The same wind conditions were used in these two domains and the wave forcing conditions for the IRS domain were obtained from the larger NAS domain by nesting techniques. Fig 1 shows the comparisons of the significant wave height and mean wave direction (vectors) between different forcing scenarios for cases with U=40m/s and Dir=90 º. It can be seen clearly that wave height responses to the wind forcing well, but is limited by the wind fetch (Fig 1a). As shown in Fig 1b, the wave forcing which represents the swell waves from far field affects significantly the wave field in the domain, but propagates to the limited area near the forcing boundaries, without the details of the waves affected by the local winds, in comparison with Fig 1c. The sensitivity of wind velocity and direction on different locations has been analysed and several look-up tables of the significant wave height at selected points have been created, although not shown here.

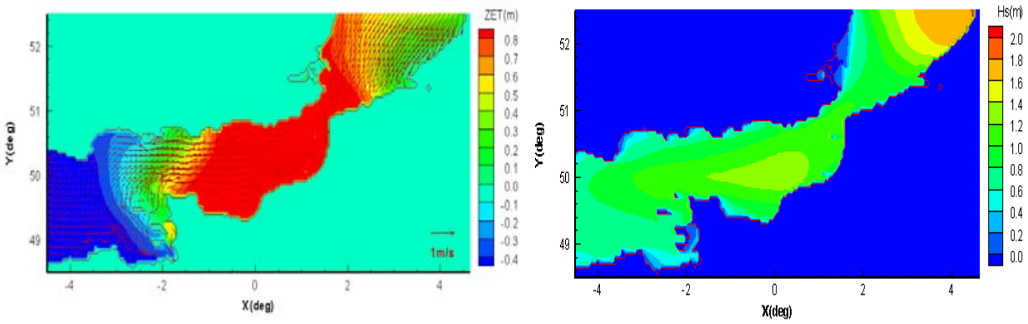


(a) wind forcing only **(b) wave forcing only** **(c) both wind and wave forcings**

Figure 1: Computed significant wave height (contours) and mean wave direction (vectors)

(b) English Channel

The POLCOMS and WAM models have also been successfully set up in the English Channel, with appropriate implementations of parameter settings for local bathymetry, tidal and wave boundary conditions required. The preliminary results on tidal currents and waves are shown in Fig 2. Further validations of models with the field measurement data is currently being carried out.



Computed surface elevation (m) and tidal currents (m/s) **Computed significant wave height (m)**

Figure 2: Computed tides and waves at 00:00:00 09/11/2008

Constraining uncertainty in hydrological modelling (**Beven**) has involved has involved assembling comprehensive data sets for model application and development for the specified test site from a variety of sources. In particular, topographic information (such as river cross sections, LiDAR and IfSAR data) were acquired and processed (see Fig. 3). Also, historic river flow and level data have been gained from the Environment Agency (EA) for the River Dee, River Alun and other major tributaries. Finally, two satellite images of the December 2006 flood event were acquired from the European Space Agency (ESA) and processed in order to derive flood extent maps (see Fig. 3).

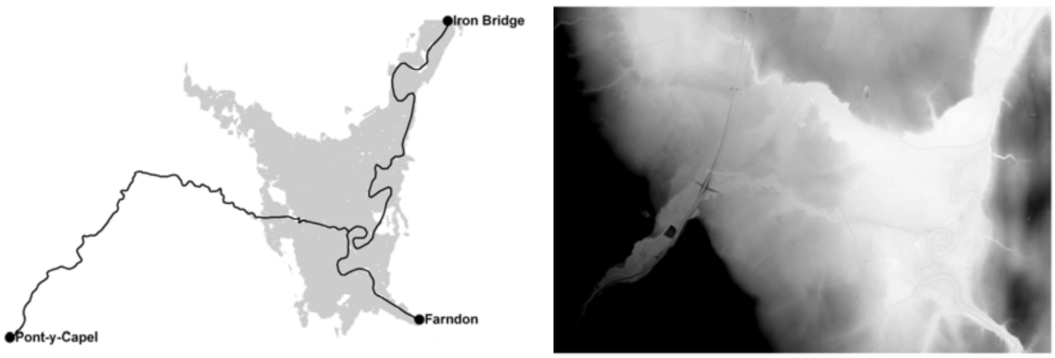


Figure 3: Test site: River Dee between Farndon and Iron Bridge and River Alyn between Pont-y-Capel and the confluence (black line); Environment Agency gauging stations (black circles); flood extent derived by using the ESA satellite image (ERS-2 SAR, grey area) [left panel]; DTM at 2 m resolution derived by using LiDAR and IfSAR data (grey scale) [right panel].

A variety of 1D and 2D hydrodynamic models were built for the test site (e.g. Fig. 4):

- 1D model (HEC-RAS);
- Low resolution 2D model (50m, LISFLOOD-FP, Fig. 2);
- High resolution 2D model (20m, LISFLOOD-FP).

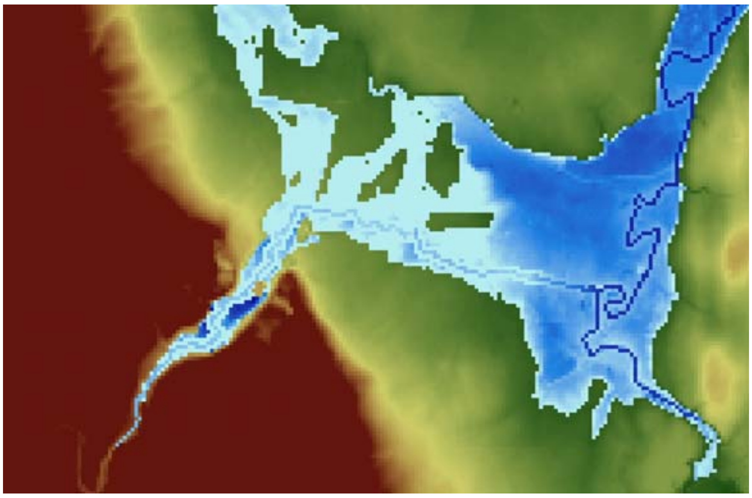


Figure 4: Low resolution 2D model (20m, LISFLOOD-FP): Results in terms of maximum water depth (blue scale) for the November 2000 flood event.

Working is ongoing in developing adaptive real time Transfer Function forecasting techniques applicable for the River Dee. Work has focused upon capturing the interaction of the tidal and river dynamics. Of particularly interest have been the tidal bore and any control placed on the drainage of the flood plain (after flooding). The nature of the transfer functions constructed for a prediction of a single location is inherently multiple input, single output (MISO). The ARMAX transfer function formulation formulation for MISO systems appears unable to reproduce the system dynamics so alternative transfer function formulations are being explored. These include the use of state dependant denominators and the use of a separate transfer function for each input the results of which are then summed (see Jakeman *et al.*, 1980, IEEE Transactions on systems, man and cybernetics, Vol 10 Pgs 593-602.)
An adaptable framework for incorporating heteroscedacicity into the error structure for the forecasting model has been formalised and incorporated within the simulation environment constructed for testing purposed.

Software and hardware infrastructure has been configured and deployed at the gateway site in the new River Dee deployment. This infrastructure, in combination with the previously reported software framework will allow the deployment of transfer function models developed by Lancaster's Environmental Science department to be hosted locally on the flood plain and integrated with the sensing hardware.

Deployment of the gateway node is complete and further deployment locations (Figure 5) have been refined based upon the results of the initial results from WP1, on-site range testing and surveying of specific locations for sensor deployment. Discussions are ongoing with local landowners and fishing clubs to ensure suitable access.

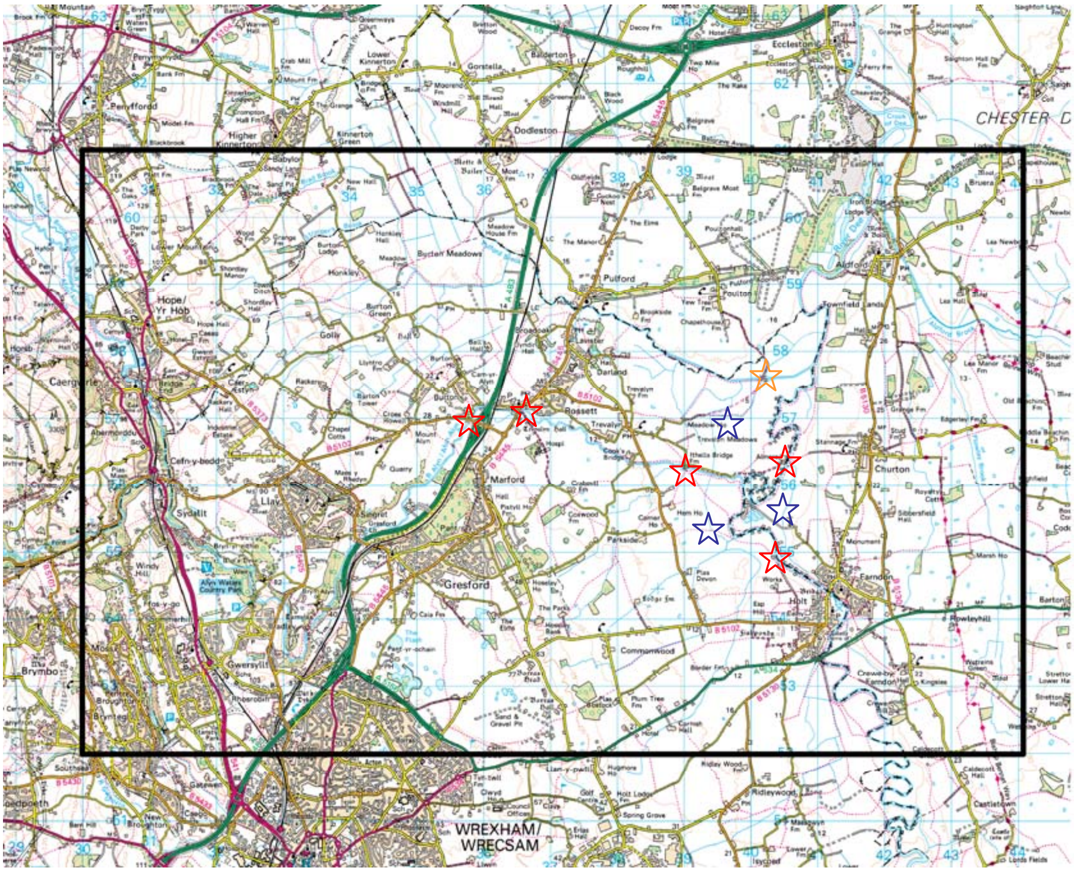


Figure 5: A detailed map of the proposed study area around the confluence of the River Dee and River Alun (Alyn). Red stars mark the proposed deployment locations of the GridStix hardware in river reaches, while blue stars denote deployment on the flood plain. The gold star marks the location of the EA Trevelyan pumping station which houses the gateway to GridStix network.

The previously reported Dust/Java wrapper has been extended significantly, allowing for fine-grained remote control of critical mote functionality such as scheduling sensor readings and modifying network structure. A new C-based Dust network driver has also been created allowing the Dust motes to be used as a network interface card by host systems with insufficient resources to support Java. Additionally, a graphical system has been developed for logging and retrieving sensor data over the GSM link to the flood site.

The campus-based test deployment of Dust sensor nodes has been successfully completed and factors such as battery life and range have been tested with extremely positive outcomes (e.g. high reliability and battery life of multiple years). Ongoing work in this area now focuses upon testing of the same hardware at the River Dee deployment site.

Work has continued on improving the understanding of the groundwater system to be able to better predict groundwater flooding (**Wheater**). Specifically, an understanding of the 2000/1 groundwater flooding event continues to be developed, including the collation of data which describes this event. The MaBSWeC model has been enhanced to simulate the 2000/1 event on a daily time step. Work has also been carried out to ensure that the ZOOMQ3D model can be run on the National Grid Service (www.ngs.ac.uk). Time series techniques have been developed and applied to simulate groundwater levels.

The 1D model has been applied to all field sites. Performed well except in 2006, where large gaps in rainfall data are thought to be the problem. Further insights will be made with 2D model. This has been applied to the hillslope around East Ilsley. Currently the simulated water table response is too attenuated, which is thought to be associated with the specific storage.

A meeting was held after the last quarterly report submission, in which a work plan was drawn up regarding how to proceed with modelling of the river Lambourn around the village of Boxford. Specific objectives were to determine the distance away from Boxford beyond which changes in aquifer parameters would not affect Boxford hydrology and to determine how adjusted aquifer parameters at Boxford would affect the time-variant boundary conditions supplied by the larger regional model, were that model to be run with those adjusted parameters. Additionally, it was agreed that the effect of layering would be examined. This work is ongoing.

A technical meeting of the staff from the project led by **O'Connell** was held at Lancaster (May 28/29th). The meeting included a field visit to the Hodder catchment, during which several sites undergoing land use/management changes were identified for small scale monitoring (by Newcastle University) to support the Imperial College metamodelling (WP1). Newcastle are in the process of obtaining permissions for the installation of weirs at the sites, which are required for the provision of accurate flow measurements. A technical meeting was also held at Gregynog (July 10th/11th). This included a field trip to the Pontbren catchment (Upper Severn), which has been the focus for the initial development of the IC metamodelling.

Soil properties data (including HOST) have been purchased from NSRI (Cranfield) for each of the three study catchments (Severn, Eden, Hodder). These data are being used to setup the small-scale physics-based models that underpin the metamodelling approach, and to support regionalisation.

A preliminary comparison of regionalisation approaches has been carried out for Pontbren. A new approach to regionalisation has been developed, using the Base Flow Index (from the HOST classification) as an uncertainty restriction for modelling current conditions. Land use effects for the Pontbren field-based model have been evaluated using a local precipitation scenario and an extreme event recorded near Carlisle.

A physics-based model of drained / undrained peat response has been developed and used for sensitivity studies. The development has utilised data from the Upper Eden (Gais Gill). Agreement has been reached with Joe Holden (University of Leeds) to access experimental data sets from peat plots/hillslopes to support model development and parameterisation. This will supplement the data being collected in the Hodder.

Software has been developed to generate river networks from high resolution DEMs). This will be used to couple the hydraulic models and the runoff generation metamodels for the test catchments. A field survey of channel cross sectional geometry has been performed in the Hodder. Using these data, scaling relationships have been developed (bankfull depths / widths / area relationships with upstream area) to fine-tune a DEM generated network of the Hodder. A grid representation of the Pontbren catchment has been prepared (100m x 100m scale). The grid representation and corresponding parameter sets have been provided for Information Tracking implementation. The Upper Severn (to Shrewsbury) boundaries have been obtained from Hannah Cloke (King's College London FREE project).

Significant advances have been made in the development of a new algorithm for Information Tracking.. An adjoint model has been created for the non inertia approximation to the Saint Venant equations, with special attention given to the accurate representation of flows at junctions and backwater effects. The algorithmic differentiation of the adjoint model provides a Jacobian, the elements of which relate the sensitivity of an impact (e.g. the catchment peak flows) to a change in a model parameter at a particular location. Using this approach it is possible to simultaneously calculate the impact sensitivities with respect to all possible perturbations in channel flow, resulting from a change in a model parameter, in a single simulation (i.e. the sensitivity is known for a change at any given landscape unit). This allows the creation of 2D vulnerability maps, showing where local scale changes will have the greatest impact on downstream flooding.

Current activities are focusing on the further development of the adjoint model to study the propagation of impacts during extreme events, initially focusing on the Hodder. To create physically realistic coupling, attention is being paid to the interaction between channel processes and the hydrological processes on adjacent land surface (i.e. flood inundation processes).

A space-time rainfall model has been developed for the Upper Eden (upstream of Temple Sowerby). In the first instance, the model has been calibrated using daily data. Hourly data have now been assembled to improve the calibration. Finally a literature review on peat hydrology has been completed. This includes information regarding the hydrological impacts of upland peat gripping and grip blocking.

Theme 3: The statistics of extremes and their use

Three more trial locations have been selected in Great Britain, and data have been retrieved for use by both CEH Wallingford (**Svensson**) and Lancaster. The trial locations now total five sites, with varying soils/geology and climatic characteristics. The CEH work focuses on an event-based joint probability approach, although continuous data series are used to appropriately define the event variables. The characteristics of rainfall events of different durations are being investigated, and some tentative series of monthly rainfall maxima have been derived. Monthly river flow maxima have also been retrieved and plotted together with the associated rainfalls. Convex hull plots have been derived for some of the data, to illustrate the seasonal variation in the dependence between the variables, and in the marginal distributions of the variables.

Lancaster have concentrated on developing covariate and random effects models for the rate of occurrence of flow events. Covariates used so far include baseflow and a moving average of (lagged) rainfall. The use of random effects was motivated by the observation that the number of events per year is over-dispersed for many UK catchments (even after accounting for covariates). Random effects are useful when there are missing covariates. Investigations of a more theoretical nature have also been made into the effect on the distribution of the annual maxima when different probability distributions are used for the number of events per year and, when included, the random effects. So far efforts have been concentrated on a single site, with considerable time being spent on identifying flow events and their properties. Some time has also been spent on getting acquainted with relevant hydrological literature.

The project led by **McSharry** has reached a milestone in reporting on a procedure for producing site-specific probability density rainfall forecasts which are needed to price insurance premiums, contracts, and other financial products based on precipitation.

The digitisation and GIS part of the project including British Rainfall (BR) data entry and map scanning; BR data entry checking and extreme event classification has been complete. A data preparation analysis including ECMWF data conversion and other data arching (Met Office MIDAS, NCEP GENS forecasts) has also been completed. In addition GLM ensemble calibration and quantile regression have been completed as has the model development.

The spatio-temporal correlations in UK daily rainfall amounts over the Thames Valley have been investigated, and a statistical, Markov chain generalised linear models (Markov GLM) of rainfall have been constructed. Point and density forecasts of total rainfall amounts have been produced, and compared with each other and with forecasts of probability of occurrence rain from other proposed density models, including persistence, statistical climatology, Markov chain, unconditional gamma and exponential mixture models, and density forecasts from GLM regression post-processed NCEP numerical ensembles, at up to 45 day forecast horizons.

The Markov GLMs and GLM processed ensembles produced skilful one-day ahead and short term point forecasts. Diagnostic checks show all models are well-calibrated, but GLMs perform best under the continuous-ranked probability score. For lead times of greater than one day, no models were better than the GLM processed ensembles at forecasting occurrence probability. Of all models, the ensembles are best able to account for the serial correlations in rainfall amounts. In conclusion, we recommend GLMs for future site-specific density forecasting. Investigations explain this conclusion in terms of the interaction between the autocorrelation properties of the data and the structure of the models tested.

Work on the development of a hybrid model for predicting the probability of very extreme rainfall (**Toumi**) continues. A numerical modelling case study of a very extreme rainfall event is underway. In order to fully understand the response of the model to changes in atmospheric moisture availability a simpler set of idealised experiments are underway. To date, most of the work has concentrated on these idealised experiments.

A suite of experiments using the WRF (Weather Research and Forecasting) model has been completed. This suite of experiments comprises both 2-D and 3-D simulations of an idealized squall line for a range of temperatures with relative humidity held constant. In this way, the precipitable water (i.e. the atmospheric moisture vailability) can be changed while the system remains in dynamic balance. A detailed analysis of the model response to the changes in moisture availability is currently being undertaken.

The WRF model (version 3) is a fully compressible, non-hydrostatic regional atmospheric model that is under constant development through the collaborative efforts of various research and operational institutions worldwide. One of the main advantages it has over other similar models is that it has been developed to enable simulations of a number of atmospheric situations within an idealised framework. This allows the user to fully isolate the effects of changes to any of the forcing mechanisms in the initial conditions or model physics.

For the experiments the model is run with a horizontal resolution of 1km on a domain that is 800km in the x-direction and 160km in the y-direction (for 3-D simulations). 80 vertical levels are used with a grid spacing of 250m with the model top at a height of 20km. Open lateral boundary conditions are used in at the x boundaries and periodic boundary conditions are applied at the y boundaries. For cloud microphysics parameterisation, a Kessler type scheme is used. This is a simple warm cloud scheme that includes water vapour, cloud water and rain. The effects of Coriolis force, surface physics and atmospheric radiative transfer are not included.

The model is initiated with vertical profiles of temperature and water vapour that are based on a typical condition for strong midlatitude convection. The vertical profile of wind includes strong shear in the lowest 2.5 km of the atmosphere. Squall lines are initiated by a line oriented thermal perturbation with a x-radius of 5km and vertical radius of 1.5 km placed at the domain centre 1.5km above the ground. For the 3-D experiments small random temperature perturbations are added to the thermal in order to accelerate the squall line towards a 3-dimensional structure.

For constant relative humidity, theory suggests that the amount of atmospheric precipitable water is constrained by the water vapour content of saturation, which is governed by the Clausius-Clapeyron relation. The Clausius-Clapeyron relation predicts that there will be a 7% increase in precipitable water per degree of warming. Fig. 1 shows the peak 1-hour rainfall accumulation from the simulated idealised squall line for a range of initial surface temperatures. It is clear that up to a temperature of about 25C the response of peak hourly precipitation to increased temperature (and therefore moisture as relative humidity is held constant) scales with the Clausius-Clapeyron relation. However, at higher temperatures this scaling diminishes. For the 8-hour accumulation period, the peak accumulation actually decreases with increasing temperature.

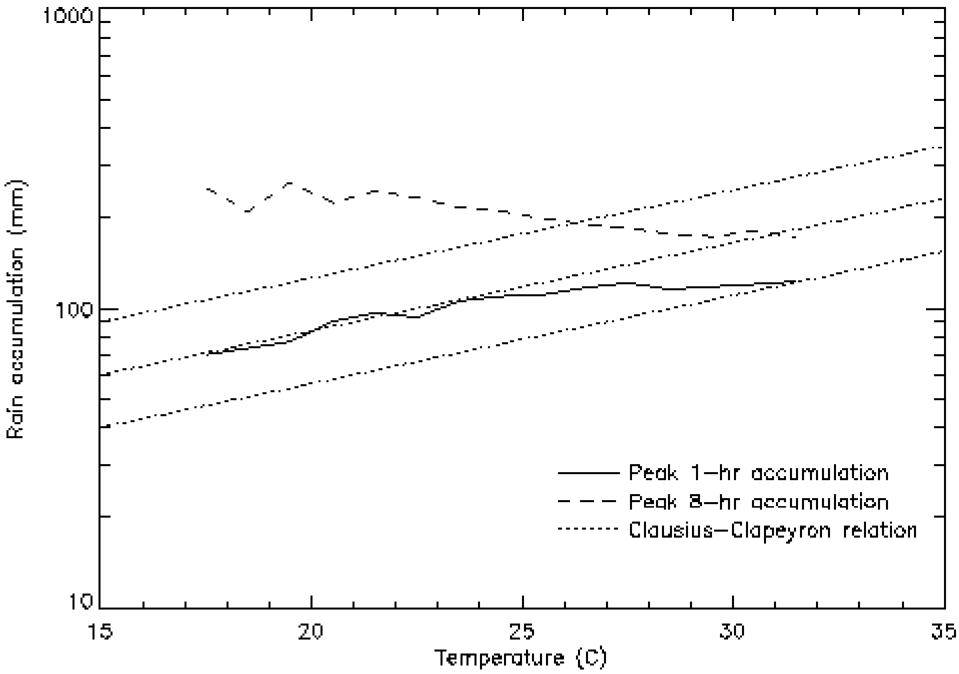


Figure 6: Peak precipitation accumulation on a logarithmic scale as a function of temperature.

The solid line in Figure 6 shows the peak 1-hour precipitation, the dashed line shows the peak 8-hour accumulation and the dotted lines show the Clausius-Clapeyron relation (7% increase per degree C). The decrease in peak 8-hour accumulation and diminishing increase for the 1-hour accumulation with increasing temperature is due to an increase in the speed at which the squall line moves. Fig. 7 shows Hovmöller diagrams for squall lines with initial surface temperatures of 22C, 25C and 28C. From Fig. 7 it is clear that as the temperature is increased, the heaviest rainfall moves more rapidly to the east. At this stage, the team believe that this is due to increased latent heat release as a result of a warmer moister atmosphere. This energy is converted to momentum that increases the strength of the rear-to-front flow in the squall line thus accelerating the system. A full momentum analysis is being undertaken in order to test this hypothesis. The results suggest that, at least for the case of an idealised squall line, increased moisture availability does not necessarily result in an increase in point rainfall accumulations, particularly for warmer temperatures and longer accumulation periods. This means that rainfall extremes, which are typically associated with convective rainfall, may not be governed by moisture availability alone. Further idealised experiments are planned that will help to clarify the role of other influences on extreme rainfall for squall lines such as vertical wind shear and topography.

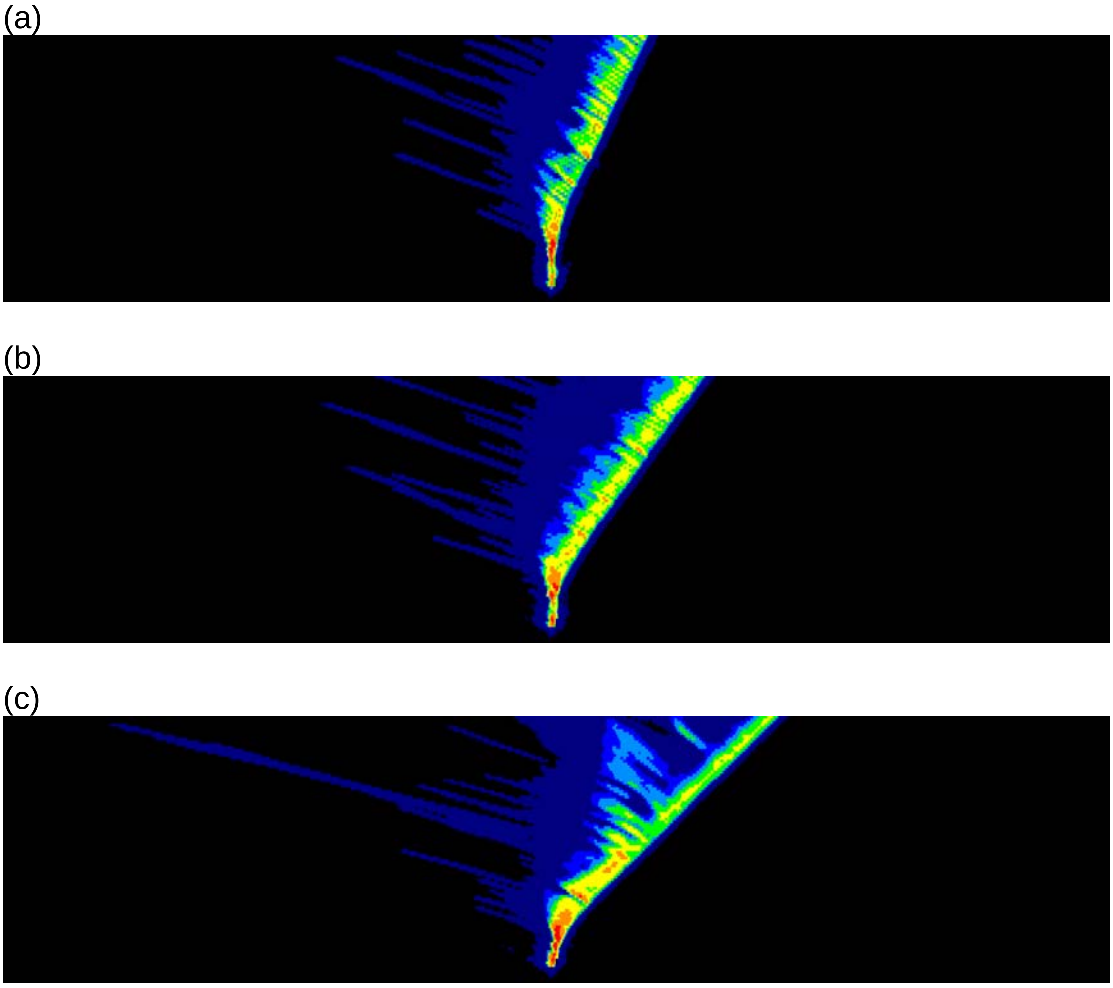


Figure 7: Hovmöller plots of 5-minute rainfall accumulations for different initial surface temperatures for 2-D squall line simulations: (a) 22C, (b) 25C, (c) 28C. The y-direction is time from 0 to 8 hours with a resolution of 5 minutes, and the x-direction is distance along the domain with a resolution of 1km.

Initially the plan was to use the Met Office Unified Model (UM) to study the July 2007 extreme rainfall event. However, for consistency with the idealised experiments, it was decided to use the WRF model. In addition, it was felt that the WRF model provides a much more user-friendly solution to performing the sorts of experiments of interest.

A control run to simulate the July 2007 event has been carried out using the WRF model with initial and boundary conditions provided by analyses from the Global Forecasting System. The model is run in nested configuration with the highest resolution nest having a grid length of 3km. At this grid length it is expected that the model will be able to explicitly resolve convective processes, so no cumulus parametrisation is employed. An initial examination of the model output suggests that WRF does a reasonable job in simulating the rainfall extremes observed in this event, although there are some small errors in the timing and location of the extreme rainfall. For this project interest is focused on the effects of increasing atmospheric moisture availability on the extreme amounts of rainfall rather than timing and location of these extremes, so it was felt that such errors would not affect the interpretation of the results. Modifications have been made to the WRF code to allow the temperature in the initial and boundary conditions to be increased whilst keeping the relative humidity fixed in a consistent manner. Simulations are ongoing.

Theme 4: The impacts of a changing climate on the occurrence of flooding

Work continued to study the relation between air flow indices and precipitation extremes in the UK (**Osborn**). VGAM (Vector Generalised Additive Models) statistical models have been developed that describe the relationships between airflow indices and the probability distribution of monthly precipitation maxima across the UK. The spatial and seasonal variations in the statistical model parameters have been visualized, and physical explanations for these variations, including elevation and exposure to prevailing winds, have been sought. These statistical models have been used to identify time-variations in UK precipitation extremes that can be explained by time-variations in the air flow characteristics over the UK, and also the residual variations that cannot be explained in this way by our models.

New work has been begun during this period to extend the analysis of the relationships between air flow and UK precipitation extremes to simulations with the HadRM3H regional climate model.

Knowledge about the covariates is important to identify physical drivers of extreme precipitation. These links are now being used to evaluate the performance of regional climate models. Knowledge about their future behaviour will also help to better predict changes in extreme precipitation.

Work continues (**Cloke**) on developing uncertainty assessments of flood inundation Impacts using spatial climate change scenarios to drive an ensemble of distributed models for extreme conditions. The aim is to improve estimates of flood inundation hazard by propagating uncertainties from Regional Climate Model precipitation projections into an ensemble of flood inundation predictions for large river catchment scales, based on the Upper Severn catchment, UK (in particular the reach Buildwas to Montford which includes the town of Shrewsbury). The initial simulation set is now almost complete with regards to generating the various input precipitation fields, routing these through part of the model cascade (LisfloodRR and FP) and analysing the sensitivities of the modelling components. All RCM data is now downloaded and processed along with new observed gridded meteorological data from the Met Office.

Overall the intention is to use a cascade of distributed climate, rainfall-runoff and flood inundation models to: (i) Quantify the top-end uncertainties by assessing extreme precipitation fields produced using two contrasting approaches. (ii) Assess the impact of these top-end uncertainties on flood inundation predictions. (iii) Quantify all inter- and intra- model uncertainties of the cascade framework for various climate, land use and soil moisture scenarios. (iv) Assess the impacts of using different existing rainfall-runoff and flood inundation models with a relatively low number of simulations using novel techniques. (v) Deliver a methodology for general use that is highly scaleable.

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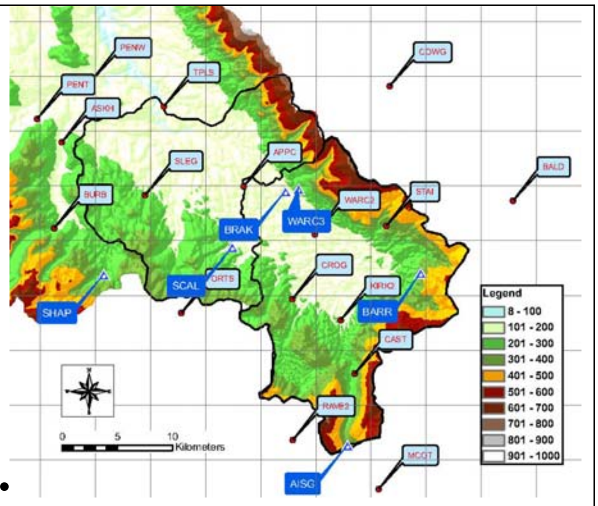
The major progress over the last 6 months in the project FRACAS: A next generation national Flood Risk Assessment under climate ChAnge Scenarios (**Reynard**) has been in applying the large basin NSRP model to simulate spatial rainfall for the Eden catchment (Cumbria) at the hourly level. All available hourly and daily rainfall data above Temple Sowerby (near Carlisle, 616 km^2 area) have been analysed and used in fitting the model (see Figure 8).

The model performs well for a range of daily and hourly properties, including cross-correlations (Figure 9) and extremes at high and low elevation sites (Figure 10).



•**Figure 8: The locations of the daily and hourly raingauge records for the Eden catchment above Temple Sowerby.**

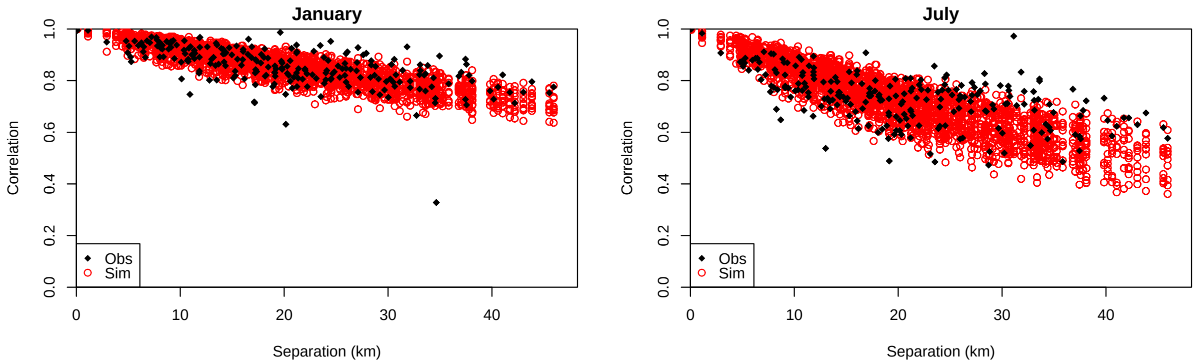


Figure 9: Daily cross-correlation against raingauge separation estimated for all observed sites for (Obs) for January and July compared with the corresponding estimate from a 10 member ensemble of 20y simulations sampled at all raingauges.

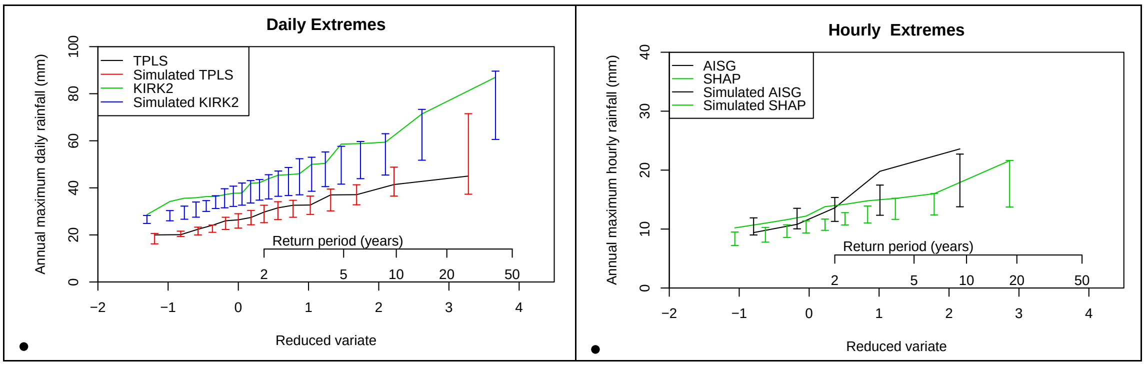


Figure 10. Gumbel plots comparing simulated daily and hourly annual extreme rainfall amounts. Estimates of the observed extremes are plotted as curves. Simulated extremes are plotted as confidence intervals displaying the 10th and 90th percentiles of the simulated extreme distribution.

This parameterisation has been obtained using detailed statistics from the observed rain gauge network, which is a time-consuming process and is not practical for repetition in other, larger basins. This model will therefore be used as a benchmark for comparison with more parsimonious fitting methods suitable for application in regional and national settings.

This approach will use 5km statistics derived from the UKMO 5km data sets used in the UKCIP08 weather generator, allowing the same methodology for perturbation for climate change to be applied. An extension of the UKCIP08 methodology to spatial application has now been outlined and work will commence soon on implementation.

Work has also progressed on the frequency curve mapping (Ledingham). The overall aim is to develop a technique to estimate flood frequency curves (ffc) from rainfall frequency curves (rfc), accounting for antecedent rainfall. A number of advances have been made in the last 6 months:

Data Discretisation. Since daily rainfall data are more widely available than hourly, analysis was carried out to allow the estimation of the fraction of the effective flood generating rainfall contained within the same or previous 24 hr period (09.00-09.00) as the flood peak. Discretisation factors in the region of 1.14 were found, this agrees broadly with the work undertaken by Dwyer and Reed (1995).

Rainfall and Flow Seasonality. The seasonality of annual maximum and POT5 rainfall and flow data have been investigated for around 500 UK catchments. Polar plots such as those shown in figure 11 provide an initial assessment of how well the rainfall and flow regimes correspond, therefore indicating those catchments where the Flood Curve Mapping (FCM) methodology is more likely to work.

Development of the Link between Rainfall and Flood Frequency. Work has centred on assessing the correlation of the r-largest events in the rainfall and flood peak series (where r=1 corresponds to an annual maximum analysis). Work has now moved on to investigation of dependence of matching on physical catchment descriptors such as area and PROPWET. Key findings so far include:

- With annual maximum data, patterns of matching are similar to the distribution of mean annual rainfall in the UK with better matches in the West and Northern Areas (Figure 12).
- Maximum matching values are around 60% for the annual maximum analysis, with most around the 40% mark.
- The POT analysis provided broadly similar results and with the top three rainfall events provided improved matching with around 90-95% maximum matching values.

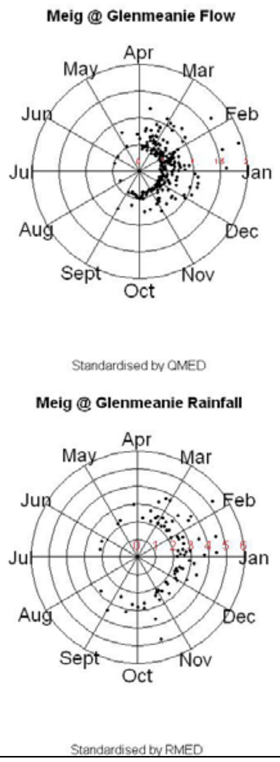


Figure 11: **Flow and Rainfall Polar plots of annual maximum events on the Meig, showing the time of year of these events as the Julian Day. Plots are standardised by qmed and rmed respectively.**

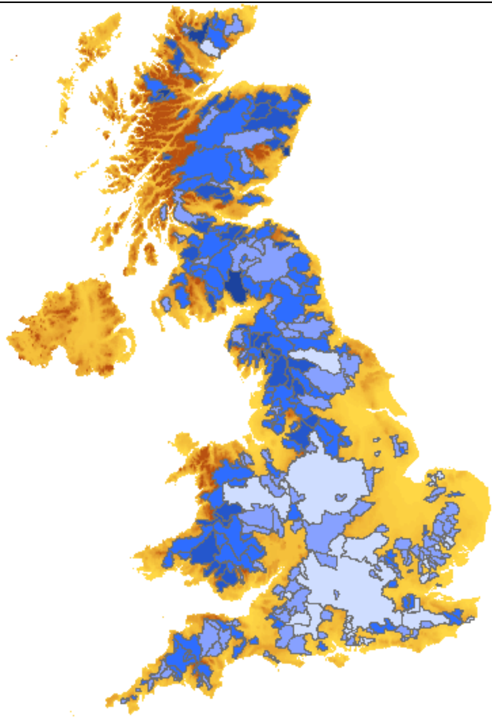


Figure 12: **Map of the UK showing the percentage of annual maximum flow events that can reasonably be attributed to the annual maximum rainfall events. Light colours show low matching and darker colours show higher matching (max. c. 60%). Background is a DEM.**

For the work to develop national rainfall datasets to derive the Grid-to-Grid (G2G) model Having sourced the RCM rainfall data sets have been sourced, and alternative sources are now being collated. These include the space-time rainfall for the study catchments from Newcastle University and the rainfall data from the Upper Severn catchment from the "Uncertainty Assessments of Flood Inundation Impacts: Using spatial climate change scenarios to drive ensembles of distributed models for extremes" FREE project led by Kings College, London.

The G2G Model has been configured for a range of UK catchments including the Thames region. The model, which has recently been reconfigured to use soil datasets, has been run at the national scale using the Hadley Centre RCM data from the HadRM3 ("acqqa" and "acqqb") runs. Figure 13 shows the estimated percentage change in modelled 20-year return period flow across the UK. G2G modelled river flows for the Eden catchment near Carlisle are being used by HR-Wallingford to drive the new methodologies being developed within RASP HLM*plus*.

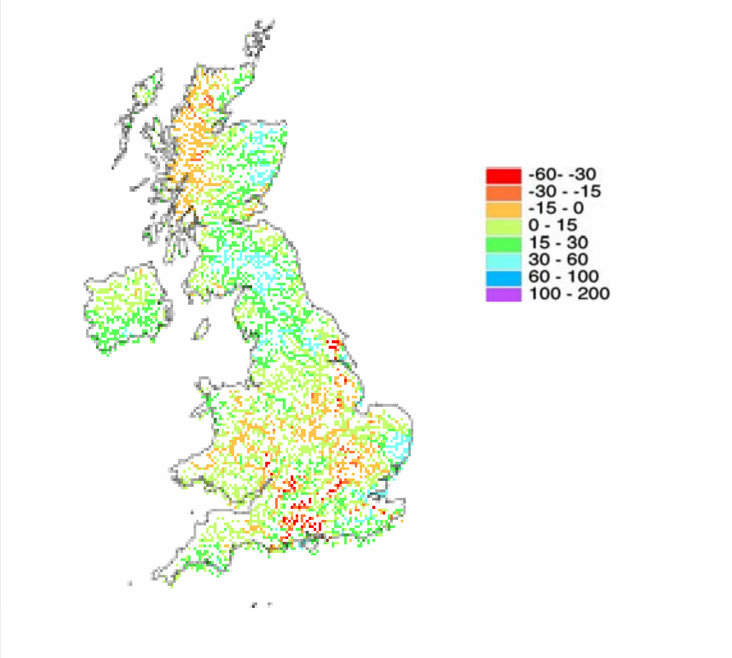


Figure 13: Estimated percentage change in modelled 20-year return period flow across the UK

Three options have been devised for incorporating continuous flow data, provided by the CEH G2G model, into the RASP HLM*plus* framework, where each approach offers differing advantages and disadvantages in terms of ease of implementation and benefits gained over the existing approach. The preferred option is outlined in Figure. 14 and offers the following enhancements over the existing RASP HLM*plus* model:

- The assumption of load dependence between different river reaches is relaxed through the use of continuous flow data to represent flood events.
- Consideration of continuity between the river and the floodplain is improved, allowing losses upstream to be better accounted for when estimating downstream flood risks.
- More advanced breach volume calculations, involving varying breach size with time, are enabled through the use of HR Breach within InfoWorks RS.

However, this option also necessitates significant modification of the existing flood risk analysis model, requiring the development of new software code to allow additional analyses to be undertaken and to enable linking/communication between new and existing model components, which hitherto have not been coupled. It is still unclear at this stage whether such modifications will be feasible; thus, it may be necessary to resort to alternative options for incorporating continuous flows into the flood risk analysis framework. These options would either involve a simplified defence system analysis (using expected values) or simplified floodplain volume calculations

Nevertheless, each of the three devised options requires the sampling/screening of flood events from the continuous flow series to allow efficient computation of flood risk. Work has progressed on the development of a flood event selection tool comprising a pre-processing method for extracting summary hydrograph information, a flow database for storing continuous flows and summary characteristics, and a flexible query/selection method based on peaks-over-threshold. This tool is being developed with the use of a test dataset provided by CEH consisting of 2 months of continuous flow data for the Carlisle area.

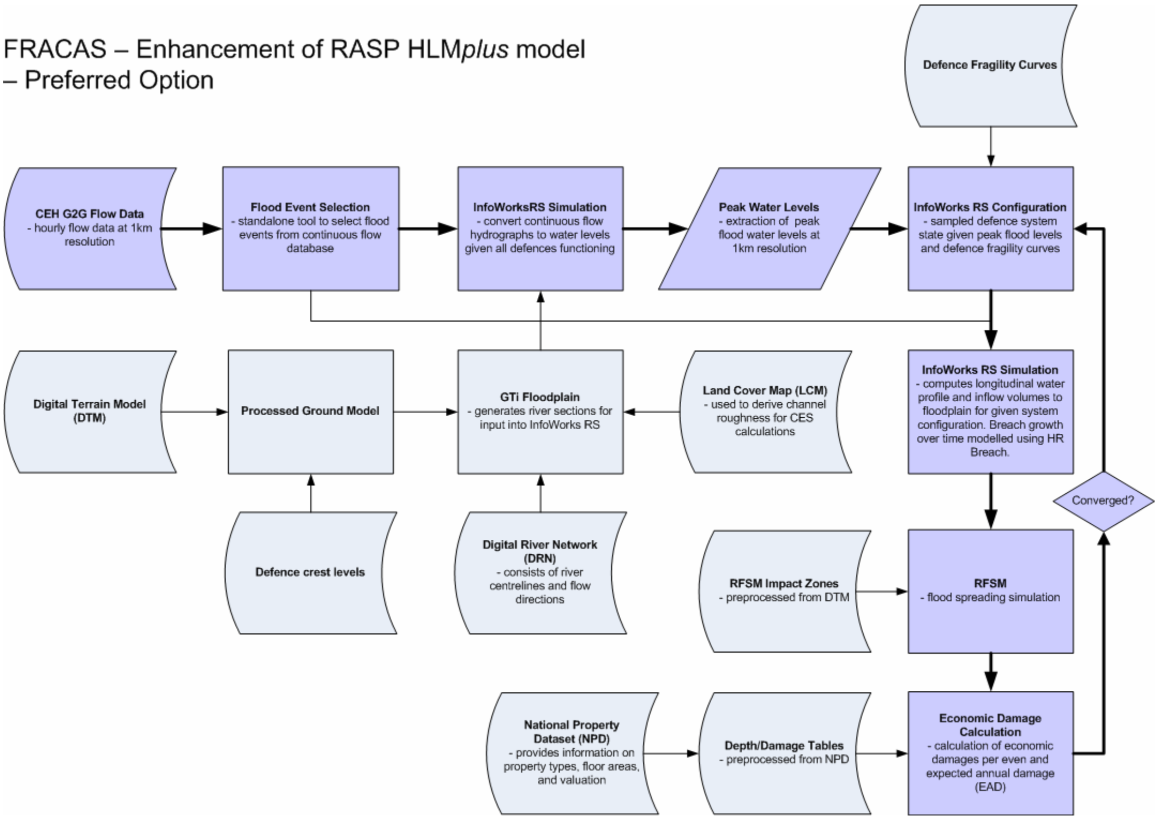


Figure 14: Preferred option.

Within the Coastal Flooding by Extreme Events (CoFEE) project (**Williams**) the University of Plymouth team have produced a review of state-of-the-art for the CoFEE study site (Sefton Coast) has been completed and will, be made available to all CoFEE Partners at the next Project meeting to be held in Plymouth on 20-21 October 2008. This includes: Introduction; Description of the Study Sites; General overview; Description of the UK study site: Dee estuary and Liverpool Bay; risk definition (for each site); existing hazards at each study site; existing management plans; shoreline management plans (SMPs); catchment flood management plans (CFMPs); Proposed methods to be used to assess each risk at the study area (on a probabilistic base approach); strategic approaches (e.g. vulnerability indexes, set-back lines – used for special planning on a decadal basis); operational approaches (e.g. real time models – used for civil protection plans); potential improvements; civil protection schemes; summary of datasets availability; final considerations; and works cited. In addition they have been: (a) analysing remote sensing data to assess rates of shoreline recession; (b) progressing coastal flooding modelling using ANUGA; (c) compiling and processing the Sefton GIS; and (d) analysing net shoreline movement using the USGS Digitial Shoreline Analysis System (DSAS) with ESRI ArcGIS to give statistics for 100 years and for the Dune Toe GPS surveys from 2001-2008. These will be cross-referenced to historical storms.

Data management (BODC): In collaboration with BADC, the period May to September has been spent identifying the main data types used by CoFEE project partners. With these data types identified, the feasibility of using different data management methods has been assessed. It is now becoming clear that the best approach to data management for CoFEE involves selective banking, concentrating on definitive model runs along with the boundary condition inputs, aerial photographs and verification data such as erosion monitoring data. Work to assemble a suitable data suite is currently underway.

POL has been working on improving the coupling between the wave model WAM and POLCOMS aimed primarily at the related surface stresses and looking at the effect that this modified stress has on the storm surge, hence its implication for flooding. This work has been submitted to Continental Shelf Research and presented in PECS 2008 and UK Marine Sciences. An abstract and paper have been submitted to Littoral'08. It should be noted that work during the last 6 months has been hampered at POL due to catastrophic failure of its disk system, which left us without reliable computers for 2 months. Nevertheless, a 10 hind cast of waves and currents have been carried out for the North Atlantic and work preparing simulations for the Irish see are almost in place. Setting the fine resolution Livepool Bay is almost ready, tidal barotropic runs have been successful in reproducing tidal elevation and currents (work presented at PECS, paper in preparation) and work is been carried out to properly couple wind and waves with the wetting and drying algorithms.

EHU have continued with the bi-monthly sedimentary monitoring along the north Sefton Coast. A small number of short [50cm] cores have been taken from across the Marshside marshes and north Southport beach, some of which have had preliminary work [particle size, magnetics and some chemistry]. EHU have met [with GL] with the RSPB warden from Hesketh Out Marsh and assessed the site with the aim of co-ordinating the placement of a series of sediment traps across the Marsh. Note: Hesketh Out Marsh was selected for returning to the sea by DEFRA and Natural England as part of their flood protection strategy for the Ribble Estuary. It is considered that the breaching of the [1980s] embankment may ultimately have significant effects upon the sediment deposition and accretion further south i.e. across our monitoring sites. This may be detected in the monitoring over the next couple of years.

UoL activity has undertaken: a review of published literature and reports on the evolution of the interface between the Mersey Estuary and the Irish Sea: the South Sefton Shore; a review of published literature and reports on the sediments of the Irish Sea and their interaction with the Sefton coast; and a collation of particle size data on the bed sediments of the Irish Sea, and laser granulometry of the sediment samples collected during Irish Sea Observatory cruises. These reports and data will be passed to Project Partners soon.

B. Papers

1. Contribution to paper on groundwater flooding for the Floodrisk 2008 conference (www.floodrisk2008.net) [Wheater project]. A paper at this conference was also presented on the FREE Project by the Science Coordinator.

2. A paper on the Carlisle Flood Case Study using high resolution NWP rainfalls for flood warning has been accepted for publication in Met. Apps.. This work was presented as a poster paper at EGU2008 in April along with a second oral paper on model initialisation and data assimilation for the distributed G2G hydrological model. [Illingworth project – CEH Wallingford].

3. Planet Earth magazine invited JJW to write a feature article. This was submitted on 8 May 2008 and will appear in the next edition.

4. A draft report on data assimilation for parameter estimation with a linear advection model has been written. Once a few details have been polished it will be published on the web as a Reading Mathematics Dept Report.

5. *Monthly Weather Review* paper (see below) has been accepted for publication.

6. *Weather* paper (see below) currently in revision.

7. Second paper for *Hydrology and Earth Systems Sciences* (see below) describing the automated classification technique has been accepted for publication.

8. Exploration for the use of HTML files for displaying data is in progress.

Peer-Reviewed Papers and Conference Presentations

9. "Site-Specific Density Forecasting of UK Daily Rainfall: Generalised Linear Models versus Ensembles", M. A. Little, P. E. McSharry, J. W. Taylor, Monthly Weather Review (in press)

10. "Extreme Rainfalls in the British Isles 1866-1968", H. J. E. Rodda, M. A. Little, R. G. Wood, N. MacDougal, P. E. McSharry, Weather (in revision)

11. "Parsimonious Modeling of UK Daily Rainfall for Density Forecasting", in Geophysical Research Abstracts, EGU General Assembly, Vienna 2008, Volume 10.

12. The UEA team received the reviews of their paper about the annual cycle of extreme UK precipitation (submitted to the *International Journal of Climatology*). It has been revised and returned to the Journal Editor.

13. A poster ("*Estimating climate change impacts on river flows across the UK: how uncertainties in model structure can affect predictions")* was presented at a workshop on Hydrological Monsters and Outliers, Cemagref and ENGREF-AgroParistech, Paris, 18-20 June 2008. A draft paper has been written describing and comparing the application of two alternative configurations, the "Slope-G2G" and the "Soil-G2G", at the national scale, as well as presenting change in peak

flows under a future climate scenarios and a method for assessing those areas of the country where the signal of change in peak flows is more “robust”.

14. A paper has been drafted by the Beven team for the forthcoming special issue of Meteorological Applications.

C. Web sites

1. Development of a website and wiki (http://www.groundwaterflooding.org) for the Wheater project.
2. Sefton's Dynamic Coast Landform, Ecology and Management Conference was held in Southport on 1st September 2008, (http://www.seftoncoast.org.uk/research_conf2008.html). The conference was attended by the majority of CoFEE Partners.

D. Deliverables

There follows a first attempt to assess the level to which the Programme Deliverables specified at the beginning of the Project have been achieved.

Objective 1

- *Joint research to be undertaken by an identifiable integration of science communities.*

Several of the projects are bringing together different communities. For example in the project led by Illingworth Hydrologists at CEH Wallingford are working with meteorologists from the JCMM at Reading. In the project led by Dance satellite remote sensing scientists are working with coastal oceanographic modellers, and in the project led by Zou hydrometeorologists are working with ocean wave modellers.

The UEA joint British Council/DAAD (German Academic Exchange Service) project was completed and a final report sent to the British Council (this project supported scientific exchanges between UEA and the University of Potsdam, with much knowledge shared and joint analysis done on the topic of climate/weather extremes).

The project led by O’Connell has collaborated King’s College London FREE project for the modelling of the Upper Severn (Hannah Cloke’s group: “Uncertainty Assessments of Flood Inundation Impacts”). This project has also agreed with Joe Holden (University of Leeds) for the provision of access to field data collected from upland peat sites. Collaboration with the FRACAS FREE project and the Newcastle-led project has also been arranged for the generation of rainfall fields under present and future climates.

The modelling work in the FRACAS Project will involve use of Met Office and UKCIP08 datasets.

- *Language integration across discipline boundaries leading to the training of a new generation of scientists having an integrated way of approaching environmental scientific research.*

Research students such as Polly Smith (Reading; Dance project), Josie Geris (Newcastle; O'Connell project|), Jamie Ledingham (Newcastle;Reynard project) and Kim Bartholomew (Reading, Illingworth project) are all working in projects involving cross-discipline activities.

- *Synergy between different models specifically demonstrated by a prototype complete integrated system or through its component parts.*

Particularly good examples of synergy between models are discussed in sections 1, 2 and 4 above.

Objective 2

- *Specifying techniques for data assimilation through coupled models between meteorological, hydrological, hydraulic, coastal and climate models.*

Work in the projects led by Illingworth, Dance, Wheater, Cloke, Williams, Zou and Reynard illustrate excellent progress towards this deliverable.

- *Transfer of data handling, quality control and assimilation techniques between disciplines.*

There is evidence that this is happening within projects, but not between projects, although the Data Management Plan is providing a framework for data archiving..

- *Demonstrated complimentarity with, but not duplication of, the FRMRC programme.*

Several of the FREE researchers are working on FRMRC projects for example Beven, Wheater, Reeve and O'Connell. At present overlaps do not seem to be occurring, but further analysis will be undertaken.

Objective 3

- *Quantification of forecast uncertainty across disciplines and within data and models.*

There is much activity in specifying and dealing with uncertainty, see for example the projects let by Toumi, McSharry and Svensson. Much more work in this area is planned.

NATURAL ENVIRONMENT RESEARCH COUNCIL

- *Specifying and managing the propagation of uncertainty across discipline and model boundaries.*

This is particularly well illustrated in the projects led by Beven, Cloke and Illingworth.

- *Estimating and utilising uncertainty in the physical processes represented in models.*

To some extent the derivation of refractivity and insect winds in the project led by Illingworth provide information which will reduce uncertainty in high resolution meteorological models. In addition the project led by Beven work is well advanced in the project led by Toumi using the WRF model.

- *Analysis of factors impacting changes in frequency and intensity of storms and extreme flood events.*

The projects led by Osborn and Reynard are investigating the impact of climate change upon extreme rainfall, and the projects led by Svensson and Toumi are examining frequency analysis and conditions leading to extreme storms..

- *Preparing a scientific approach to the development of risk assessment tools.*

New approaches are being developed in the projects led by Beven, McSharry, Svensson, Reynard and Toumi.

- *New approaches for forecasting extreme events in rapid response catchments.*

The CEH work in the Illingworth led project is particularly relevant to this deliverable.

- *New approaches for forecasting extreme pluvial events in urban and built up areas.*

Not being addressed yet.

- *Analysis of the relative contributions to flooding from natural variability and human forcing of climate change.*

The projects led by Williams, Reynard, O'Connell and Cloke are particularly relevant.

Objective 4

- *Achieve a better understanding of the sensitivity of fluvial, surge and total water levels to uncertainties in model inputs.*

Projects led by Zou, Williams, Dance, O'Connell, Wheater and Beven are all relevant to this deliverable.

- *Development of procedures for constraining and presenting risk and uncertainty to end users, and the impact of this uncertainty on the environment.*

The Beven led project aims to deliver appropriate procedures as do the projects led by Cloke, Zou, Williams and McSharry.

- *Consider the relationship of meteorological indices in global models to the likelihood of catchment flooding and coastal surges.*

To be analysed.

Objective 5

- *Identifying the implications of uncertainty across disciplines for policy development e.g. within the framework of the EU Water Framework Directive.*

To be analysed.

- *Identifying consequent changes in engineering design risk in both fluvial and coastal zones arising from the impact of sediment transport and geomorphologic change caused by extreme events.*

To be analysed.

- *Development of a national network of world class scientists and professionals in this multi-disciplinary field.*

Certainly the FREE Projects promise major outputs which will illustrate the excellence of UK research in the multi-disciplinary field represented by FREE.

Objective 6

- *To develop for this programme a methodology for gathering new data and collating existing data for extreme events shortly after they occur.*

The basis of a methodology has already been established through FLoAT.

- *Archiving within the Research Council Data Centres using the e-science Data Grid, data sets derived from research studies and extreme events occurring during FREE.*

The FREE Data Management Plan has been established.

Objective 7

- *Quarterly updates describing activity and new opportunities presented by research outputs.*

Updates are being produced as required by most projects, although some projects have to be pushed!

- *Identification of specific routes to user involvement and early adoption of science by operational agencies.*

The Met Office and the Environment Agency are both closely involed in some of the projects. The Met Office has already adopted the procedures for deriving refractivity and insect winds developed in the project led by Illingworth.

- *Demonstrations of outputs at appropriate events or workplaces.*

The radar products from the Illingworth project have been demonstrated at the Cobbacombe Met Office operational radar site. It is expected that other demonstrations from other projects will take place.

- *Transfer of research outcomes to policy makers.*

To be analysed.

Objective 8

- *Research degrees awarded from FREE supported research.*

To be analysed at the end of the programme.

- *Involvement of a mix of cross-disciplinary students in FREE and related international activities.*

To be analysed. A number of students are participating in national and international conferences.