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Coupled hydro-meteorological modelling on HPC platform for high resolution extreme weather impact study

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Abstract: High performance computing (HPC) has long been used in the disciplines of atmospheric and oceanic sciences, and remains the main tool of choice to extract numerical solutions to complex geophysical problems on the global scale, often accompanied with very large numbers of degrees of freedoms. However, with the growing recognition that the spatially distributed feedback from the land surface is important to weather and the climate system, representation of the land surface is established with increasingly complex (and physically complete) models, which often leads to the coupling of heterogeneous models such as numerical weather prediction (NWP) models and hydrological models. As a result, the spatial grids and the temporal resolutions have become finer and thereby computers with far greater computational and storage capacity are in great demand than those used in the past. Additionally, impact-focused studies that require coupling of accurate simulations of weather/climate systems as well as impact-measuring hydrological models that demand larger computer resources in its own right.

In this paper, we present a preliminary analysis of an HPC-based hydrological modelling approach, which is aimed at utilising and maximising HPC power resource, to support the study on extreme weather impact due to climate change. Here, two case studies are presented through implementation on the HPC Wales platform of the UK mesoscale meteorological Unified Model (UM) UKV, alongside a Linux-based hydrological model, HYdrological Predictions for the Environment (HYPE). The results of this study suggest that high resolution rainfall estimation produced by the UKV has similar performance to that of NIMROD radar rainfall products as input in a hydrological model, but with the added-value of much extended forecast lead-time.

Key words: HPC, extreme weather impact, Unified Model, UKV, HYPE, coupled hydro-meteorological modelling

1. Introduction

Extreme precipitation with great intensity and the subsequent flash flooding events arising from rivers and mountainous watersheds often lead to considerable economic damage and casualty, because water levels can react extremely quickly within rather limited warning lead-time (flash flooding). Therefore, the evaluation of potential flooding risks in extreme weather conditions, and the corresponding protection measures required, demand accurate short-term flood forecasting, and more often very short lead-time forecasting – termed 'nowcasting' (Cloke and Pappenberger, 2009).

Understandably, hydrological models together with hydraulic models play a key role in predicting runoff, river flow as well as possible inundations. However, the lead time, which is crucial for hazard mitigation and evacuation, is often highly limited in such a classic model chain configuration, since basically then, the lead-time is the travelling time of flood water. It is therefore, other means of providing rainfall estimates with extra lead-time (e.g., weather radar observations), have become increasingly essential in flood forecasting under extreme weather conditions (Zhu et al. 2014). However, it has also been recognised, e.g., by Golding (1998) and Smith and Austin (2000), that the performance of radar-based rainfall nowcasting deteriorates rapidly when the lead-time goes beyond 0.5 hr. Then, the combination of radar nowcasting and hydrological forecasting is reduced to a normal model, or even worse. In fact, early attempts, whilst using the NIMROD radar rainfall product, already introduced a rainfall forecast from numerical weather prediction models to compensate for this shortcoming.

The fast development of HPC, as well as that of NWP (Numerical Weather prediction) models, has since given rise to the use of NWP, either directly or indirectly in hydrological simulations, in an effort to push hydrological forecasting beyond the limit of the rainfall-observation time-horizon. This link between two different modelling disciplines is often referred to as model coupling. The resulting coupled meteorological-hydrological models appeared from the beginning of the 21st century, being initially focused on flash flood forecasting, and later extended to handle climatic-hydrological coupling. This has facilitated many climate-change impact studies on water resources that rely heavily on the use of climate projections or simulations. Nevertheless, the linkage between the meteorological and hydrological models is scientifically challenging due to differences in model structures and issues of incompatible units (use of different scales in time and space). This is encapsulated, in particular, in the task of how best to transform and regionalise global climate scenarios, with spatial resolutions of 1,000-10,000 km^2, to hydrological mesoscale catchments of (10 – 1,000 km^2).

Simulation with meteorological–hydrological coupling in high spatial and temporal resolution is a comparatively new field of hydrological research, yet some pioneering work has recently appeared. In order to analyse the prediction of selected events characterized by peak flows, Westrick et al. (2002) proposed a hydrometeorological forecasting system for mountainous watersheds by coupling the Penn State–NCAR

Mesoscale Meteorological Model (also known as MM5 for brevity; Dudhia, 1993; Grell et al., 1995) in 4*4 km^2 resolution and the distributed hydrological model DHVSM (Wigmosta et al., 1994). Jasper et al. (2002) compared the hydrological performance of radar and gauge measurements, with five different high-resolution numerical weather prediction (NWP) models and grid-cell sizes between 2 and 14 km. This work covered the prediction of peak-flows on the alpine Ticino-Toce watershed, using the distributed hydrological model WaSiM (Schulla and Jasper, 2000). The results suggest that, the accuracy and consistence of NWP rainfall in hydrological applications heavily depend on their process modelling at all scales of model nesting. Particularly so, as inaccuracies introduced by downscaling of precipitation from NWP models can lead to large differences in the predicted hydrological results, especially during extreme convective storm periods. Kunstmann and Stadler (2005) coupled (in 1-way manner) the mesoscale meteorological model MM5 with the distributed hydrological model WaSiM. The meteorological re-analysis data were dynamically downscaled with MM5 grid cell sizes from 100 km to 2 km using four nests. Findings show that the MM5-based interpolation of precipitation yielded 21% less total yearly precipitation in the catchment area, compared to the station-based interpolation. Yarnal et al. (2000) linked a high-resolution meteorological model (MM5 at 4 km resolution) and a suite of coupled hydrological models (HMS) in the Susquehanna River Basin Experiment (SRBEX). This work points out that the coupled model has to confront several issues, such as, physics and parameterizations for a mesoscale atmospheric model to match the time-scales of climate coupled to the hydrological process models, meteorological and climatological process models with different scales; and the immense computational needs accordingly. Xuan et al (2009) also indicted that the inaccuracies and uncertainties in NWP could propagate to the downstream hydrological models, and they proposed to use an ensemble-based approach, together with effective bias correction, to mitigate this problem.

The majority of the studies cited above have been relying on the use of the so-called downscaling of large-scale NWP results using regional meteorological model such as MM5. These studies are often conducted in an off-line manner where hydrological modellers have hardly any control of NWP except the meso-scale one used for downscaling. However, the work presented in this paper, not only focuses on the performance of coupled high-resolution meteorological–hydrological simulations for extreme storm events on a HPC platform, it is also aimed at exploring the potential of building and running fully-coupled NWP-hydrological forecasts on a single computer platform; and therefore is able to obtain first-hand knowledge on fully integrated hydro-meteorological modelling. As such, we did not apply the meteorological model in forecasting mode, but used hindcasting mode instead, to test the model performance and benchmarking over several selected historical events.

2. Materials and Methods

In this study, the principal goal of the experiment has been to simulate the river basin response to extreme storm events, by linking a semi-distributed hydrological HYPE model to the UK Met Office Unified Model (UM) at a much finer spatial scale (1.5km). The combined high-resolution one-way driven model experiments generate runoff hydrographs for three extreme flood events, which occurred in the Upper Medway catchment (220 km^2) located to south of London in the UK (see Figure 1). The properties of this catchment regarding the topography, vegetation and soil types, as well as the availability of a hydrological data set, have been detailed in Zhu and Cluckie (2012) and Zhu et al. (2014).

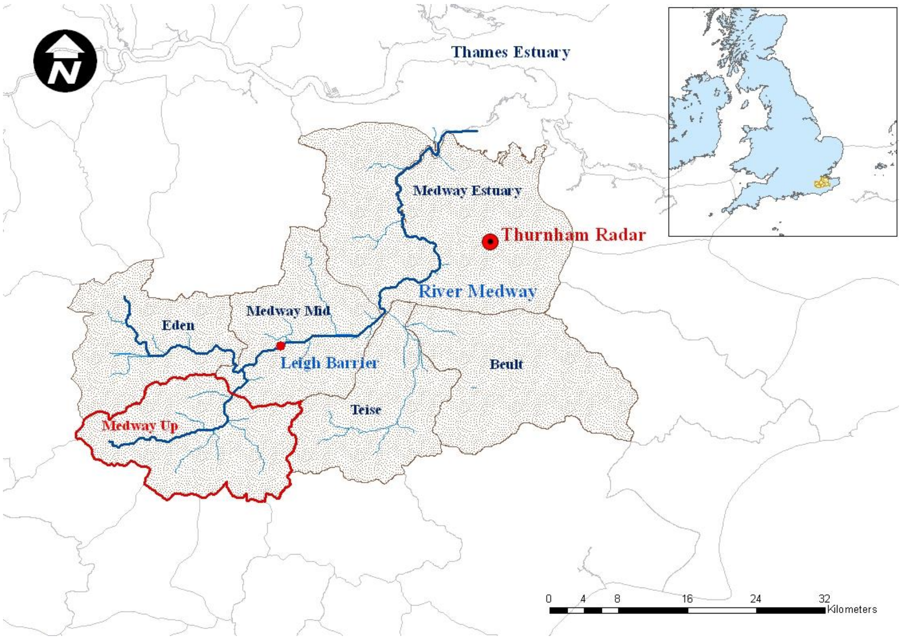

Figure 1. Location of UpperMedway Catchment in the UK

The catchment elevation varies between 30 m and 220 m above mean sea-level and the majority of slope ranges from 2 degrees to 8 degrees, which makes up around 70% of the whole catchment. This suggests that the main scenery of the Upper Medway Catchment is small hills surrounding the flat, little relief low-lying area without much variation of elevation. The land use in the catchment can be simplified and described as permanent grass (over 95%). The catchment is characterized by a mixture of permeable (chalk) and impermeable (clay) geologies and the dominant aquifers consist of the Ashdown Formation and the Tunbridge Wells Formation of the Hastings Group. The saturation-excess mechanism is the major runoff generation process in the catchment.

In such model experiments, two different sets of meteorological input data were used: (1) surface observation data from station measurements and from weather radar estimation, and (2) forecast rainfall data UKV from high-resolution numerical weather prediction (NWP) models with grid-cell sizes 1.5 km. The experiments were designed as: (1) selecting representative storms and hydrographs for simulation; (2) simulating these storms using the high-resolution UM-UKV model, and (3) modelling the river-basin response to the simulated storm events using the HYPE hydrological model. Moreover, it is worth noting that this experiment of a fully-coupled NWP-hydrological forecast is preliminarily designed to be a one-way coupling system, which will form the basis for extension into a two-way coupling system, which will be developed further in the future.

One notes that Met Office has used the operational high-resolution UK 1.5 km model (UKV) under the New Dynamics algorithm specification. This introduces nested operations, through parallel suites PS30 and the time periods of interest. As such, this consists of a Global 25km simulation, followed by a North Atlantic European 12 km simulation, and finally, a UKV 1.5 km simulation. Each such simulation stage provides the necessary lateral (spatial-temporal) boundary conditions for the regionally-refined subsequent stage.

2.1 UKV model configuration and implementation

The unified model (UM) is an atmospheric predictive numerical modelling software, offered by the UK Met Office and written in FORTRAN. Here, its output is coupled with a hydrological model for the purpose of accurate flood and extreme storm prediction. The UM was built on Archer hardware, with specification as a Cray XC30 MPP supercomputer, with up to 4920 compute nodes, each having a two 12-core Intel Ivy Bridge series processor, providing a total of 118,080 processing cores. Each node has 64GB memory, with a subset of large memory nodes possessing 128 GB.

The high-resolution simulation was achieved using the UKV suite which is a regional configuration of the UM, derived from operations through Parallel Suites (PS30), which consist of three nested domain simulations: Global 25 km simulation, North Atlantic European (NAE) 12km simulation, and UKV 1.5 km simulation. The Global N512L70 problem suite is discretized into approximately 25 km mid-latitudes, upon a 1024x769 grid. There are 70 model levels vertically and a time-step of 10 mins is used. The regional NAE problem suite has a resolution of 12km, across a 600x360 grid. The NAE suit also has 70 vertical levels but the time-step choice is 5 mins. Finally, the regional UKV is set at 1.5 km resolution over a 622x810 grid with a time-step of 50sec.

UKV model implementation requires a few events for model run. This includes an initialisation date and a number of subsequent time-duration periods i.e. 3 days, 6 Days, 8 Days and 12 days. Each event is specified to run at different lead times. A selection of start dumps for the different lead times are requested from ECMWF or the Met. Office. The Met. Office holds start dumps to a back-date of up to five years only; prior to that, start dumps would need to be obtained from other sources.

The UKV model outputs were also on a rotated lon-lat grid, whose resolution is not constant, with small deviation from 1.5 km depending on the locations. The data was further projected onto the National Grid Reference Grid to become comparable with other sources of data, such as the weather radar rainfall observation from the NIMROD system. A nearest-neighbour interpolation was used to produce the evenly distributed grid data after projecting.

2.2 The configuration and calibration of hydrological model - HYPE

Whilst many hydrological models could have been selected, e.g., see Zhu et al (2014), an open source model – HYPE (HYdrological Predictions for the Environment) has been selected in this study to avoid reliance on commercial modelling packages. HYPE is developed at Swedish Meteorological and Hydrological Institute (SMHI) with a focus on integrating water and water quality throughout the model compartments, predictions in ungauged catchments with large model set-ups, e.g. across Europe. It is a dynamical model forced with time series of precipitation and air temperature, typically on a daily time-step. Forcing in the form of nutrient loads is not dynamical. Examples of HYPE applications include atmospheric deposition, fertilizers and waste water.

The HYPE model is able to predict water and nutrient concentrations in the landscape at the catchment scale. Its spatial division is related to sub-catchments and corresponding characteristics, including land use, vegetation, soil type and elevation. Within a particular catchment, the model will simulate water content in different compartments, including soil moisture, shallow groundwater, rivers and lakes.

The default time-step in HYPE is daily, but it can be reduced to hourly, which is normally specified in the input dataset, such as precipitation. Since there is no 2-D surface runoff algorithm built in the HYPE model, it is in principle a lumped model. However, spatial variations can be accounted for by portioning the catchment into smaller sub-catchments. In this respect, the simulated precipitation was processed as the catchment average before being fed to the HYPE model.

The winter flood event started from 06/12/2003 to 28/02/2004 was used for model calibration, carried out using 1-hour time step rain-gauge measurements and parameterised with the streamflow observation at the catchment outlet. In order to achieve the best fit between observed and modelled flow, the model parameters were calibrated in simulation mode using a mixture of manual and automatic parameter adjustment, according to their functionalities in the model. First, all the parameters went through an initial manual sensitivity analysis, to decide those worthy of further automatic parameterisation. This then involved progressive Monte Carlo simulation, with parameter space reduced in stages.

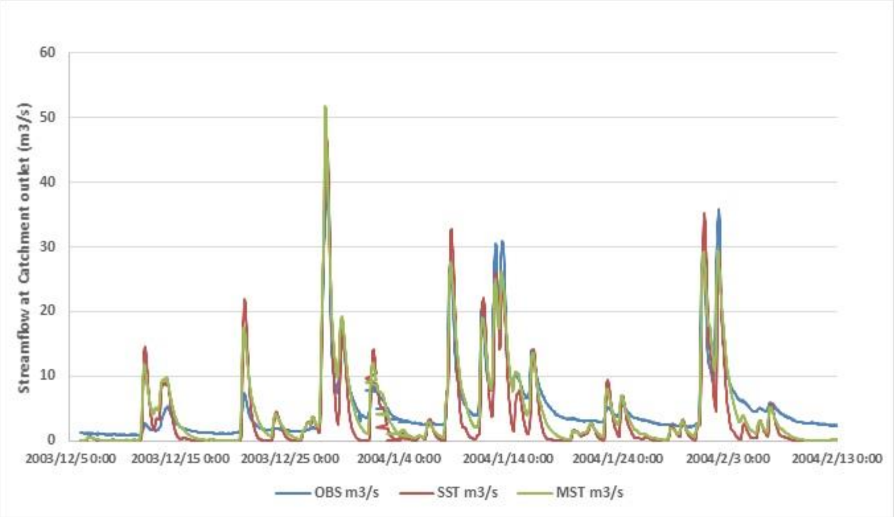

Figure 2. The comparison of model calibration with different soil settings

The soil properties setting is critical in HYPE model. Figure 2 shows the model calibration performance with single soil type (SST) and multiple soil type (MST) settings. This data clearly indicates that the recessions period with SST setting was much faster than the observation, possibly due to the less resilience from a single soil type setting and the shallow depth of soil layer in the model. Consequently, multiple soil types and the increment depth of the soil layer were introduced to the model while the recession of flood was improved. Additionally, the most critical performance criteria for the model, as in the Nash-Sutcliffe Efficiency (NSE), increases from 0.68(SST) to 0.82(MST).

2.3 The settings of a coupled UKV-HYPE case study

The UKV model is set to make 36-hr forecast with a high resolution inner domain (1.5 km grid boxes) over the area of forecast interest, separated from a coarser grid (4 km) near the boundaries by a variable resolution transition zone. This variable resolution approach allows the boundaries to be moved further away from the region of interest, reducing unwanted boundary effects on the forecasts.

Part of the motivation of using such resolution is to improve forecasts of convective rainfall. The variable resolution model with 1.5 km grid length over the UK, but increasing to 4km at the edges of the domain, enables the boundaries of the model to be pushed further away from the area of interest at lower cost, and also to reduce the resolution mismatch with the driving (12 km) model. The UKV rainfall estimation produced by the Unified Model is used as the input for the HYPE model, which provides the cornerstone to the coupled UKV-HYPE model.

As the HYPE model is currently in a lumped formation, the gridded UKV rainfall data was averaged over the catchment area and interpolated into 1-hour time-steps. Two selected historical flood event is simulated as a case study, with the coupled UKV-HYPE model. The first event, started from 2007/01/05 to 2007/01/13, was a relatively small flood event, considering the precipitation depth over the catchment is less than 25mm in nine days and producing the highest peak flow of around 10 m3/s. The second event was a flash flood with sudden high peak flow and short period, started from 2007/07/15 to 2007/07/23, especially during the period from 2007/07/20/ 08:00 to 11:00 when over 30mm precipitation fell on the catchment in three hours, detected from the raingauge network.

3. Results and Discussions

Rainfall observations from weather radars were also introduced in this study to check the UKV output, since rain-gauges are point-based and the radar rainfall can provide well represented rainfall distribution. Moreover, the comparison with UKV input through a hydrological model can be drawn, in terms of lead-time difference.

The radar rainfall estimates used in this study is extracted from the UK NIMROD composite dataset. This has been provided and quality controlled by the UK Met Office using the lowest available scan. It has been adjusted against available rain-gauge measurement and undergone extensive processing to correct for various sources of radar error. Such radar error would include noise, clutter, anomalous propagation, attenuation, occultation, “bright band” and orographic enhancement. Therefore, these high-resolution radar composite rainfall estimates incorporate the latest UK Met Office processing algorithms to account for the different sources of errors in the estimation of precipitation using weather radars (Harrison et al., 2000). This implies that this data-set is the best possible estimate of rainfall available at the ground-level in the UK (most error-free).

The processed UKV rainfall data was compared with other rainfall data from rain-gauge and NIMROD radar. All types of rainfall data are interpolated and processed, sharing the same spatial and temporal resolution, which is 1km and 1 hour, for comparison purpose.

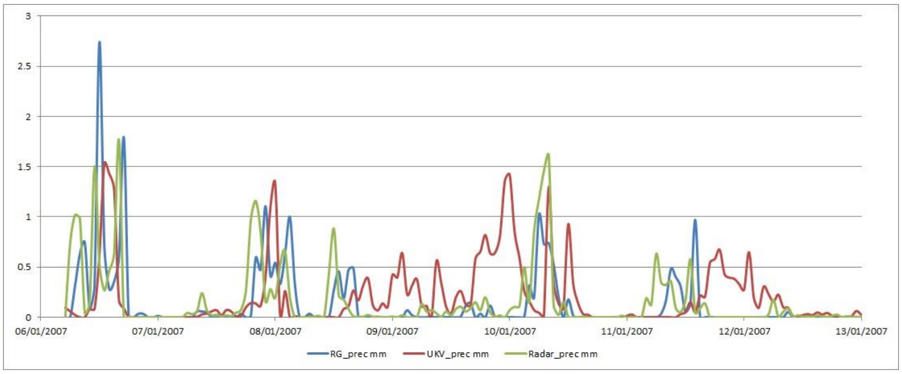

Figure 3 The comparison of rainfall data (mm) at each time step

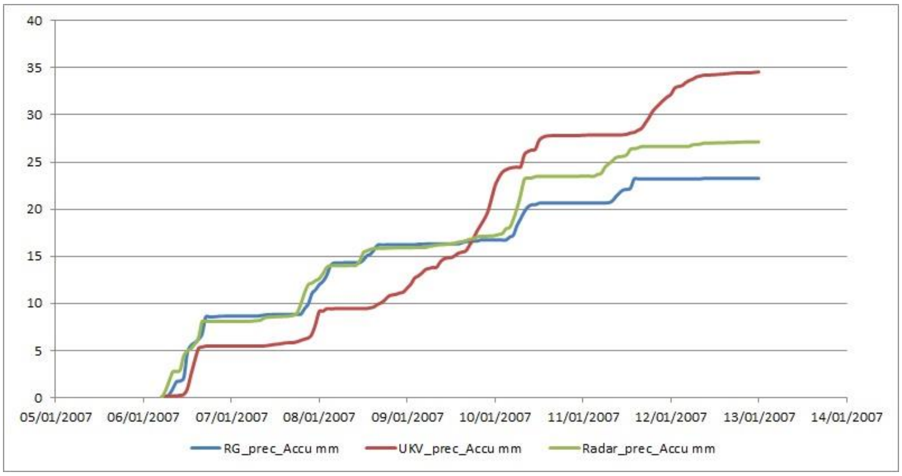

Figure 4. The comparison of accumulative catchment average rainfall (mm)

Figure 3 and Figure 4 show the rainfall comparison on each hourly step and the accumulation of catchment average rainfall over the flood period, respectively. Trends on the rainfall data at each time step of Figure 3 are reasonably good across all three data-sets, with capture of the main data-peaks. The UKV rainfall data does however pick up some exaggerated noisy peaks over the period between days 09/01/2007 to 10/01/2007 (see below to cumulative rainfall data).

Figure 4 shows that the NIMROD radar data produced more rainfall depth over the catchment than rain-gauge measurements, but less than the UKV rainfall. In addition, it shows similar rising cumulative rainfall for this event between all three data-sets, and particularly between rain-gauge measurements and radar rainfall estimation up to 10 Jan. In contrast, on cumulative rainfall of Figure 4, one notes that the UKV rainfall underestimates rain-gauge and radar data-sets before 10 Jan, but with a similar rising trend. Departure arises subsequently between all three data sets, with UKV rainfall providing the most extreme outcome.

Figure 5 shows the rainfall distribution from 1km radar NIMROD rainfall estimation over the study catchment on the midday of 6th Jan (06/01/2007 13:50) and the first half day of 10th Jan (10/01/2007 07:10)

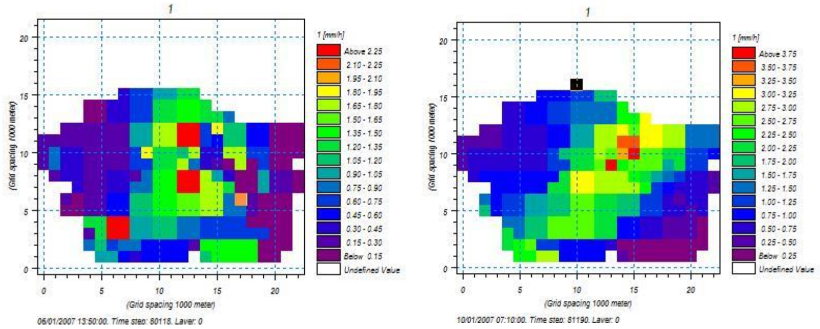

Figure 5. The snapshots of rainfall distribution extracted from radar images over the catchment (left was stamped on 13:50 06/01/2007, right was stamped on 07:10 10/01/2007)

The simulation of HYPE model with rain-gauge measurement, radar rainfall estimation and UKV rainfall is illustrated in Figures 6 and 7, for two events occurred in Jan 2007 and July 2007, respectively.

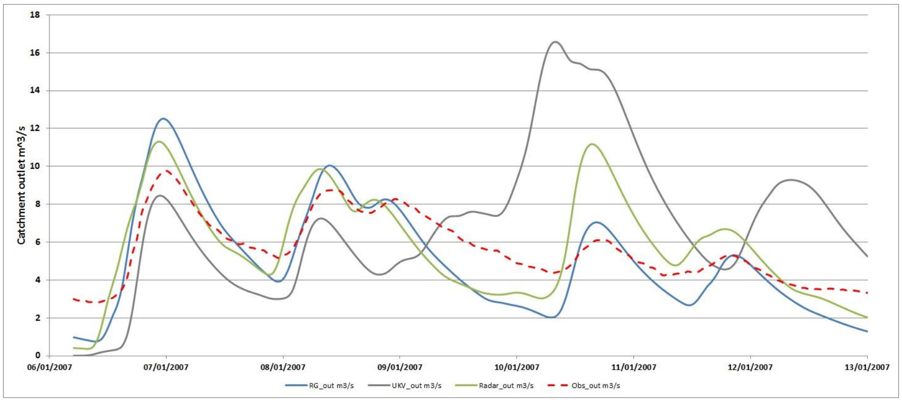

Figure 6. The comparison of flow simulation in HYPE (Event January 2007)

The performance of UKV rainfall in HYPE model simulation for this January 2007 flood event of Figure 6 shows that the peaks and troughs are reasonably well represented against the observed data up to 10 Jan, after which the fourth peak is overestimated, and thus so is the final peak. The radar data suffers likewise, over the final two peaks, which are better captured by the rain-gauge data. The rain-gauge data does however underestimate the observed data output over this period.

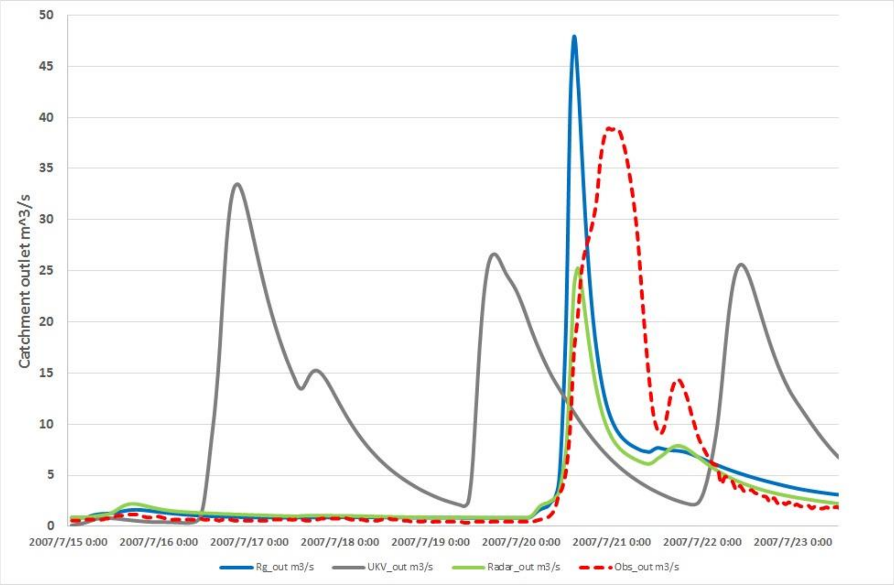

Figure 7. The comparison of flow simulation in HYPE (Event July 2007)

The second event of July 2007, in Figure 7, would appear to pick up an exaggerated peak in the UKV rainfall through HYPE model simulation after the first day (16/07/2007), which is not reflected in the other data-sets. This early disturbance influences the early undershoot of the observed-data first-peak (at 21/07/2007), and the overshoot of the observed-data second-peak (before 22/07/2007). Notably, rain-gauge data output overshoots the observed-data first-peak, whilst NIMROD radar data output provides an undershoot; both undershoot the observed-data second-peak. This is rather a testing event with only one single main flood event to sharply capture. Clearly, one would need to investigate further in this event instance as to why the early disturbance has arisen for UKV output in this case, and provide more data evidence to prove or refute this particular finding. Further case study events would help clarify this issue, as the Jan 2007 event did not show this up.

4. Conclusions

This paper describes a recent effort of integrating both the driver NWP models and the impact analyser – hydrological model on a single HPC platform to support better and refined studies on extreme weather impacts. What distinguishes this study from others is it is first time that modellers are able to simulate the entire system, ranging from the global circulation down to a target catchment for impact study. This study also explores the feasibility of building weather/climate services together with the impact oriented analysis on a single platform; and what can be done if otherwise, for example, how computing resources can be re-arranged for that matter.

The study finds that when running the entire system on a reasonably powerful HPC platform, the overall time frame does not yet allow for a real-time simulation even without the most complex and demanding data simulation part. It is therefore suggested that the components responsible for large scale simulation, such as global and the European area should remain at national weather service centre where dedicated HPC resources can well deal with the demand as they already have been doing. However, it is still possible to have a high resolution version with less geographical coverage running on a general purpose HPC platform together with the impact analysing model such as a hydrological model and further inundation models. This configuration also allows for finer control and/or tune the models to fit various purposes.

The other main purpose of this study is to gain the sight of how a common hydrological model can utilise the high resolution precipitation (among others) forecast and simulation in an impact study of extreme weather events. It is encouraging to find that event without fine-tuning, such as using various parameterisation schemes, the coupled hydro-meteorological was still able to capture the major flood peaks with much longer lead time compared with the conventional gauge- or radar-driving forecast (2-3 days vs 2-3 hours). The high resolution UKV rainfall shows some promising agreement with rain-gauge measurements and radar estimation in the first 2-3 days in this flood event, both in the catchment average rainfall amount and hydrological simulation in HYPE.

The study also identified uncertainties associated with precipitation forecast, particularly will increase as the forecast horizon goes beyond 3 days. For example, the latter part of the flood event was not represented well by the HYPE model simulation using the UKV rainfall, compared with those using other sources of rainfall, e.g., radar and raingauges. This is, however, understandable and consistent with our previous studies using other model, see, e.g., Seyoum et al (2013). Apparently, other more complicated uncertainty-aware technique needs to be applied in this model coupling configuration, which, in fact, is the key research topic for further studies.

Consequently, the following recommendations for future work are made:
1. The study needs to be repeated and extended, as more data-sets become available from UKV.
2. The impact of the high resolution new radar data needs to be explored in the context of distributed hydrological modelling.
3. The UKV rainfall needs to be fully assessed by various lead-times and ensemble simulations, that encapsulate uncertainty generation and propagation through complex 'cloud to catchment' or 'Whole Systems Modelling' concepts.

Acknowledgements and declaration

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