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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: FD2210
2. Project title: Modelling Extreme Rainfall Events
3. Contractor organisation(s): Met Office
4. Total Defra project costs (agreed fixed price): £ 91,981
5. Project: start date .... 01 November 2005

   end date .... 31 March 2008

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Background

The objective was to investigate the ability of a storm scale configuration of the Met Office Numerical Weather Prediction (NWP) model (the Unified Model (UM)) to predict extreme rainfall events up to 18-24 hours ahead and to determine what it is about the meteorology of these situations that the model must capture in order to produce useful predictions for flood warning.

The project follows on from the Storm Scale Modelling project in which it was found that the UM with a grid spacing of ~1 km has the potential to deliver significantly improved forecasts of convective rainfall events.

Operational implementation of a 'storm-resolving' version of the UM is now considered to be of paramount importance for the future delivery of improved weather forecasts (including heavy rain) in the UK. The UM is currently run operationally with a grid-spacing of 4 km over the UK. A 1-1.5 km version is planned for 2009/10 when computer resources are enhanced.

The project was split into three stages:

Stage 1: To identify five extreme rainfall events and assess the ability of a storm-resolving NWP model to predict these events. The report from stage 1 was completed in March 2006.

Stage 2: To study two of the cases chosen in stage 1 in considerably more depth. This was done to gain a better understanding of (1) the relevant meteorological processes, (2) the performance of the model in representing those processes, and (3) the predictability of these types of events. The report from stage 2 was completed in March 2007.

Stage 3: To perform an in-depth analysis on another extreme case that differed meteorologically from those previously examined. To perform model sensitivity studies on both the new case and the two cases from stage 2. To investigate whether the storm-resolving model was capable of giving better forecasts of any new extreme events identified during the course of the project.

Key Findings

1. There are no differences between the physical and dynamical processes that lead to ‘extreme’ events compared to other heavy rainfall events. It is the coincidence and interaction of those processes that leads to extreme events and the difficulty in their prediction.
2. A storm-resolving NWP model is capable of providing useful forecasts of ‘extreme’ rainfall events. The use of a storm-resolving model has the potential to greatly improve on our current ability to predict such events provided that it is understood that the output must include information about forecast uncertainty (e.g. probabilities).
3. The accuracy of the forecasts may vary considerably from case to case and depends crucially on getting all the necessary meteorological components correct.
4. For many events it is vital to represent accurately the larger-scale disturbances in the flow that may originate from outside the high-resolution domain; as well as any local effects.
5. A high-resolution grid (~1 km grid spacing) is absolutely essential to be able to represent the dynamics of more localised thunderstorms and many of the important local pre-cursors to the triggering of storms.
6. Some convective situations are inherently more predictable than others, and that predictability is strongly linked to the meteorology of the situation. A classification into three types of storm has been made. Knowledge of the likely type of storm can provide information about its predictability.
7. This work has lead to a greater understanding of both the meteorological processes that lead to extreme rainfall events and the strengths and weaknesses in the model in predicting them.

Recommendations

The development and operational implementation of a storm-resolving model (grid spacing ~ 1 - 2 km) should continue. It is likely to be the best route towards a significant improvement in our ability to provide warnings of severe convective storms.

There will always be uncertainty in forecasts of extreme rainfall events and the more precision we expect the more uncertainty there will be. It is essential that probabilistic outputs for users are developed and that users understand what they mean.

The model is capable of representing extreme storms, but getting the positioning correct presents a big challenge. Research and development into new data assimilation methods (for improving the initial state of forecasts) on the high resolution grid, including the use of new types of observations, must continue to play a vital role in the development of a storm-resolving model.

The uncertainty in a single ‘deterministic’ forecast is difficult to quantify and this can limit the usefulness of probabilistic outputs based on one forecast. We should now move towards developing a storm-resolving ensemble prediction system and ensemble-based probabilistic products. Initially, such a system would embed the storm-resolving model in a coarser-resolution ensemble to account for uncertainty in the larger-scale dynamics.

Further research is required to determine whether an estimate of the predictability can be deduced in advance from the meteorological conditions. Research into the use of ‘time-lag’ ensembles (combining the most recent forecast with older forecasts) as a possible means of determining predictability should also be undertaken.

High-resolution model output should be used in hydrological models for flood warning, particularly for orographically enhanced rainfall situations such as the Carlisle floods in 2005. For convective situations, a more probabilistic approach is necessary and needs to be developed.

There are still some outstanding issues to do with the way a storm-resolving model represents convective cells. Further work is needed in the areas of cloud microphysics and sub-grid-scale turbulence.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

Background

Numerical Weather Prediction (NWP) models are continually being updated with ever finer grids in the hope that this will bring improved weather forecasts. A major step forward in model development at the Met Office came in 2002 with the implementation of a new formulation of the Unified Model (UM) (the so called 'new dynamics' – Davies et al 2005). This improvement provided the capability for future operational forecasts to be run at much higher resolution; high enough to begin to resolve individual showers or thunderstorms. The expectation was that a 'storm resolving' model would be able to provide improved weather forecasts, but also, crucially, an improvement in the ability to predict extreme rainfall events that lead to flooding.

The objective of this project was to investigate the ability of a storm scale configuration (grid spacing ~ 1 km) of the Met Office Unified Model to predict extreme rainfall events up to 18-24 hours ahead and to determine what it is about the meteorology of these situations that the model must capture in order to produce useful predictions for flood warning. The project follows on from the Storm Scale Modelling project in which it was found that the UM with a grid spacing of ~1 km has the potential to deliver significantly improved forecasts of convective rainfall events.

Operational implementation of a 'storm-resolving' version of the UM is now considered to be of paramount importance for the future delivery of improved weather forecasts (including heavy rain) in the UK. The UM is currently run operationally with a grid-spacing of 4 km over the UK. A 1-1.5 km version is planned for 2009/10 when computer resources are enhanced.

The context of the project can be seen in Figure 1. It shows where this project sits chronologically in relation to the research and development programme at the Met Office - including high resolution model development, defra / EA funded projects – including those examining the nature of extreme events, other UK projects – including field programmes and European-wide interest in the same areas. A description of each of these projects is given in the final technical report.

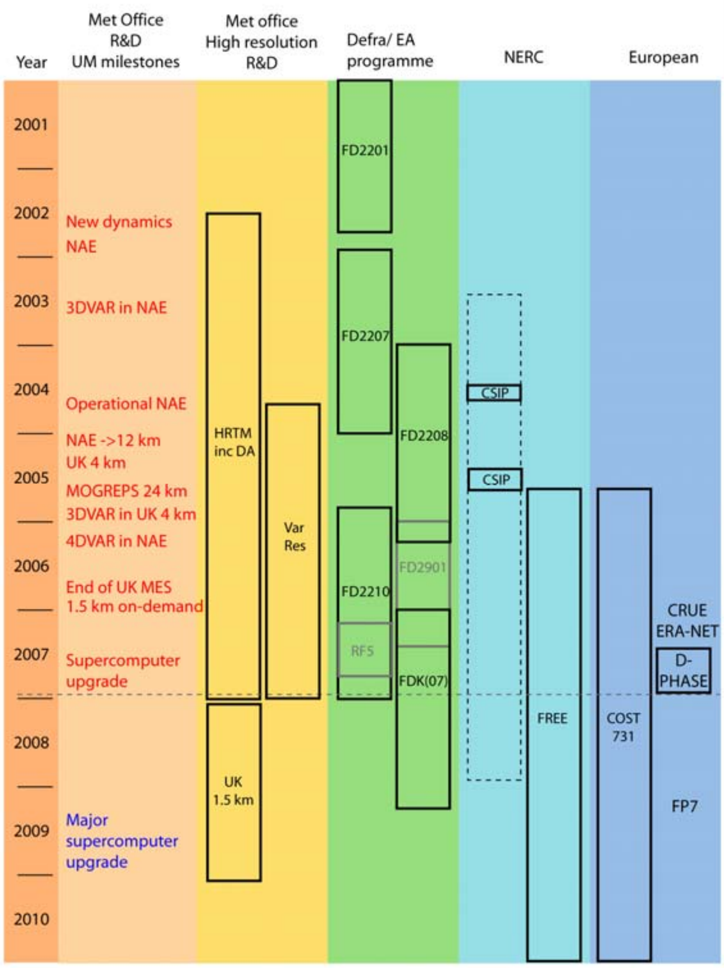


Figure 1. Projects related to extreme rainfall events and high resolution NWP modelling 2001 to 2010.
Terms and acronyms used in Figure 1:

- 1.5 km ‘on-demand’ – A version of the Met Office Unified Model that has a grid spacing of 1.5 km on a possible 9 different domains (each 300x300 km) that can be run on the most appropriate domain for the meteorological conditions once per day.
- 3DVAR – 3-dimensional Variational data assimilation. This is the primary methodology used to update the start of the UK 4km model forecasts with new observational information to give each forecast the most accurate start.
- 4DVAR – This is a more advanced version of 3DVAR in which both the spatial and temporal fit between the model and observations is used to create the most accurate starting point for each forecast. It is used in the global and NAE models.
- MOGREPS – The Met Office Global and Regional Ensemble Prediction System. The Met Office runs a global model ensemble and a regional model ensemble (NAE at 24 km) every day. Each ensemble has 24 members.
- New Dynamics – The new dynamical formulation of the Met Office Unified Model that allows the possibility of running on very high resolution grids and resolving individual storms.
- NAE – The North Atlantic European version of the Met Office Unified Model. The domain covers the north Atlantic and much of Europe with a current grid spacing of 12 km. Forecasts are run for 48 hours from 00, 06, 12 and 18 UTC each day.
- UK 4km – The version of the Met Office Unified Model that has a grid spacing of 4 km and a domain covering the UK. It is run four times a day at 03, 09, 15 and 21 UTC.

Project acronyms and numbers used in Figure 1.

- HRTM – High Resolution Trial Model project.
- UK 1.5 km – UK 1.5 km model project.
- Var Res – The Variable Resolution model project.

- FD2201 – The Extreme Event Recognition project – phase 1.
- FD2207 – The Storm Scale Numerical Modelling project.
- FD2208 – The Extreme Event Recognition project – phase 2.
- FD2210 – The project Modelling Extreme Rainfall Events.
- FD2901 - Probabilistic Flood Forecasting Scoping Study.
- RF5 - Feasibility study into expanding flood warning to cover other flood risks such as groundwater
- FDK(07)01 - Probabilistic Fluvial Forecast Modelling project
- FDK(07)06 - Blending convective scale NWP with ensemble nowcasting project.
- CSIP – Convective Storms Initiation Project.
- FREE – Flood Risk from Extreme Events programme.
- COST-731 – European Cooperation in the field of Scientific and Technical research. Action 731: Propagation of Uncertainty in Advanced Meteo-Hydrological Forecast Systems.
- CRUE ERA-NET - European Flood Research co-ordination programmes.
- D-PHASE - Demonstration of Probabilistic Hydrological and Atmospheric Simulation of flood Events in the Alpine region.
- FP7 – European Framework Programme 7.

Scientific Objectives

The following objectives were set out in the project contract.

1. Simulate a selection of extreme (~1:100yr) rainfall events using the convective scale NWP model.

2. Identify the causes of shortcomings in each simulation and investigate possible improvements.

3. Assess the ability of the model to reproduce features identified in the Extreme Event Recognition project (Hand *et al* 2004) as having contributed to the extreme nature of each storm.

4. Assess the ability of the model to reproduce the observed precipitation in each case.

5. Synthesise the results, draw conclusions on the predictability of extreme rainfall events using a convective scale model, and make recommendations on further work that could increase their predictability.

In order to meet the objectives above the project was split into three stages:

Stage 1: To identify five extreme rainfall events and assess the ability of a storm-resolving NWP model to predict these events. The report from stage 1 was completed in March 2006.

Stage 2: To study two of the cases chosen in stage 1 in considerably more depth. The objectives were (1) to achieve the best possible high-resolution forecasts and in doing so gain an understanding of the meteorological mechanisms involved; (2) to determine what a storm-resolving model needs to get correct and where there are deficiencies in the model, and (3) to gain insight into the predictability of these types of events. The report from stage 2 was completed in March 2007.

Stage 3: To perform an in-depth analysis on another extreme case that differed meteorologically from those previously examined. To perform model sensitivity studies on both the new case and the two cases from stage 2. To investigate whether the storm-resolving model was capable of giving better forecasts of any new extreme events identified during the course of the project.

Case Studies

The project was case-study based. Ten cases were documented and of these three were studied in considerably more detail. This meant that the project provided the framework for both an in depth analysis of the mechanisms that lead to the extreme rainfall in the three selected cases and a more general overview of the model capability on the basis of findings from the larger sample of ten cases.

The first five cases were examined in stage 1. They were:

1. Case A. 8th July 2004. Very high rainfall totals at the village of Wittering, Cambridgeshire from a localised thunderstorm that followed a large amount of frontal rain the previous night.

2. Case B. 3rd August 2004. Flash flooding in parts of northwest London as a result of intense thunderstorms during the afternoon.

3. Case C.16th August 2004. Very destructive flash flood at the village of Boscastle, North Cornwall from persistent localised thunderstorms during the afternoon.

4. Case D. 7-8th January 2005. Flooding in the city of Carlisle, following more than a day of persistent rain over the Lake District and northwest Pennines.

5. Case E.19th June 2005. Flash floods at the villages of Hawnby and Helmsley in North Yorkshire because of torrential rain from a very intense thunderstorm.

The findings from stage 1 were presented in the stage 1 report (Roberts 2006).

In stage 2 cases B and E were studied in considerably more depth. The findings from stage 2 were presented in the stage 2 report (Roberts 2007).

In stage 3 a new case was examined in detail. The choice of the new case was important as it had to be different in nature from those already studied (but still extreme) to provide a new perspective on the model capability and the predictability of extreme events.

6. Case F: The case chosen was a flash flood in the village of Albrighton in the West Midlands on the 4th July 2006 that occurred because of a localised and very intense thunderstorm.

Also in stage 3, another four cases were examined in less detail. These included the two major flooding events from the summer of 2007.

7. Case G: Large thunderstorm complex on the 10th May 2006 over Southern England that brought flooding to South Wales later in the evening.

8. Case H: Flash flooding from thunderstorms in Surry (west of London) 13th August 2006.

9. Case I: Severe flooding over northern England, particularly Hull and Sheffield, from a quasi-stationary frontal system on the 25th June 2007.

10. Case J: Severe flooding over the West Midlands and Southern England from widespread heavy convective rain on the 20th July 2007

Brief overviews of some the case studies

This section gives a flavour of the findings from seven of the cases. Considerably more information is provided in the final technical/scientific report.

Case B - 3rd August 2004 London

Heavy thunderstorms developed across southern England during the afternoon. These storms organised into a band and progressed north into the Midlands. More than 80mm of rain was measured by radar in parts of northwest London. This was enough to lead to flash flooding and major disruption to commuter traffic.

The frames in Figure 2 show the rainfall accumulations from several forecasts from the model with a 1-km grid spacing (but averaged to a 5km grid for comparison with radar). The forecast that began from the evening the previous day (LN1km18-02) did not predict the storms in the correct place or produce enough rain. This was because the larger scale flow pattern was poorly represented and this affected all resolutions. However, the later 1 km forecasts from 00, 03, 06 and 09 UTC on the day of the storms did manage to predict the band of thunderstorms and some of the forecasts produced very similar totals to those measured by radar in the London area. The forecast from 09 UTC was particularly good (but note that there are still differences from radar).

This was an occasion in which the 1 km model was able to produce significantly better forecasts than the 12 km and 4 km models. It was able to do so because it could represent the local dynamics that led to the initial formation of the storms and then the subsequent storm dynamics that led to the storms regenerating in the same locations.

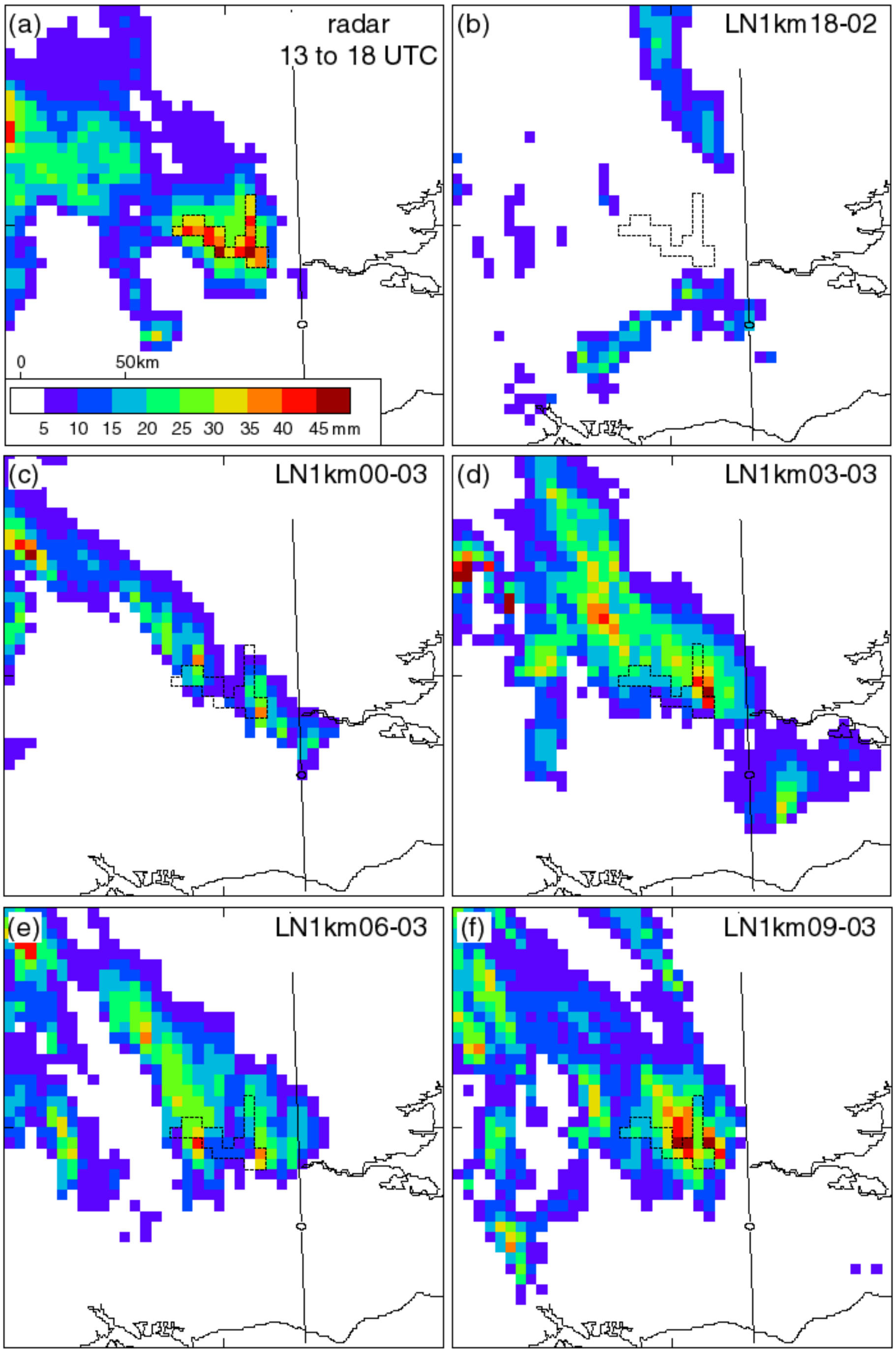


Figure 2. (a) Rainfall accumulations for the period 13 to 18 UTC 3rd August 2004 projected on to a 5-km grid from (a) radar, (b-f) 1-km model forecasts starting from 18 UTC 2nd, 00 UTC 3rd, 03 UTC 3rd, 06 UTC 3rd, 09 UTC 3rd.

Case C - 16th August 2004 Boscastle

During the afternoon a severe flash flood in the village of Boscastle inundated around 60 homes and washed 30 cars into the harbour. The storms responsible for the rain appeared to have developed along a line close to the north coast of Cornwall. The individual storm cells kept re-generating at the same location to the southwest of Boscastle before tracking northeast and producing large amounts of rain over the small river catchment just inland from Boscastle. It was the succession of small but torrential storms propagating over the same location that produced the very high rainfall totals. The highest recorded daily rainfall amount was 200.4mm at Otterham. For more information refer to Golding et al (2005).

The radar pictures in Figure 3 show how the storms repeatedly formed at the same location and formed a southwest-northeast oriented line.

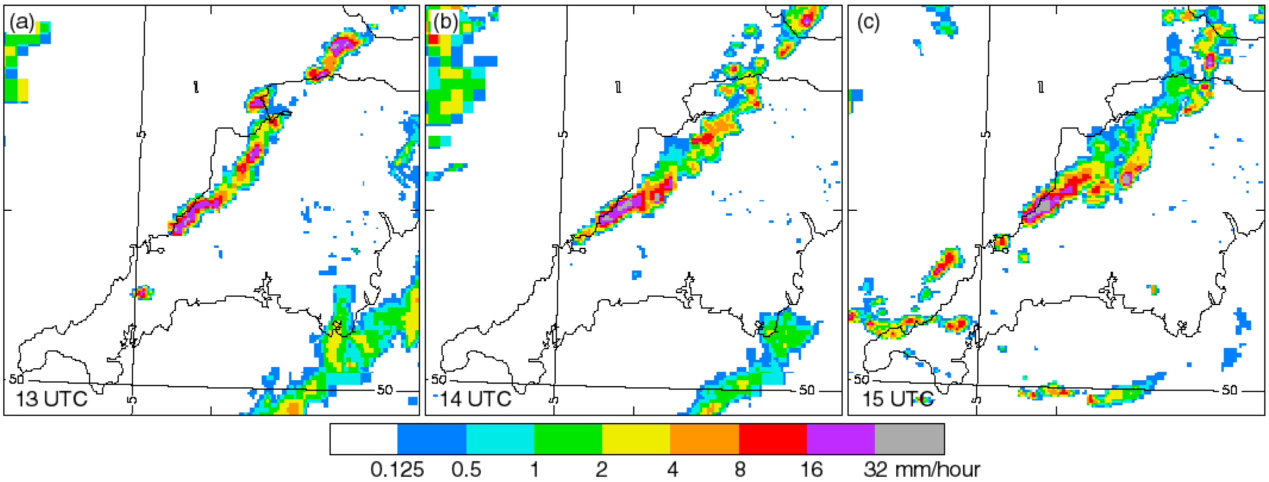


Figure 3. Rainfall rates from radar at 13, 14 and 15 UTC 16th August 2004

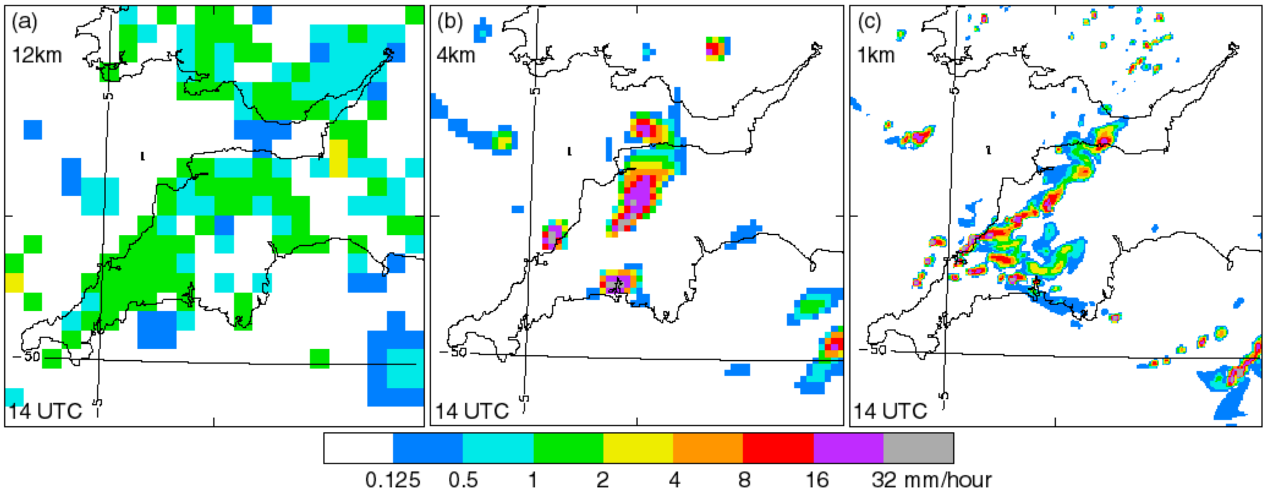


Figure 4. Rainfall rates at 14 UTC 16th August 2004 from (a) 12 km (b) 4km (c) 1 km forecasts starting from 00 UTC.

A comparison of forecasts at 12, 4 and 1 km at 14 UTC (Figure 4) shows that the 1 km forecast was the only one able to reproduce a line of storms that looked like the radar picture at that time. It shows the benefit of high resolution for this type of situation in which both the local topography and the storm dynamics played a major role in the organisation of the rainfall. Over the whole afternoon, the highest accumulations produced by the 1 km forecast were located in the correct area but were somewhat too low. In contrast, the 4 km model produced higher totals but too far to the northeast and the 12 km model produced rainfall totals that were far too low and over too wide an area.

Case D - 7-8th January 2005 Carlisle flood

During the 7th and through into the early hours of the 8th January 2005 a period of almost continuous rain affected Cumbria in northwest England. In the 36 hours from 00UTC 7th until 12UTC 8th more than 160mm of rain was measured in places over the Cumbrian mountains and this led to severe flooding in the city of Carlisle over the following days as rivers overtopped their banks.

The 36-hour accumulations from several combined 12-hour forecasts are shown in Figure 5 alongside the gauge and radar measurements for the same period. The 12 km forecasts did not produce anything like enough rain and the area of rain was misplaced to the southwest. In comparison, the 1 km and 4 km forecasts were much more accurate. The 1 km was the best spatially (although may have overdone the amounts).

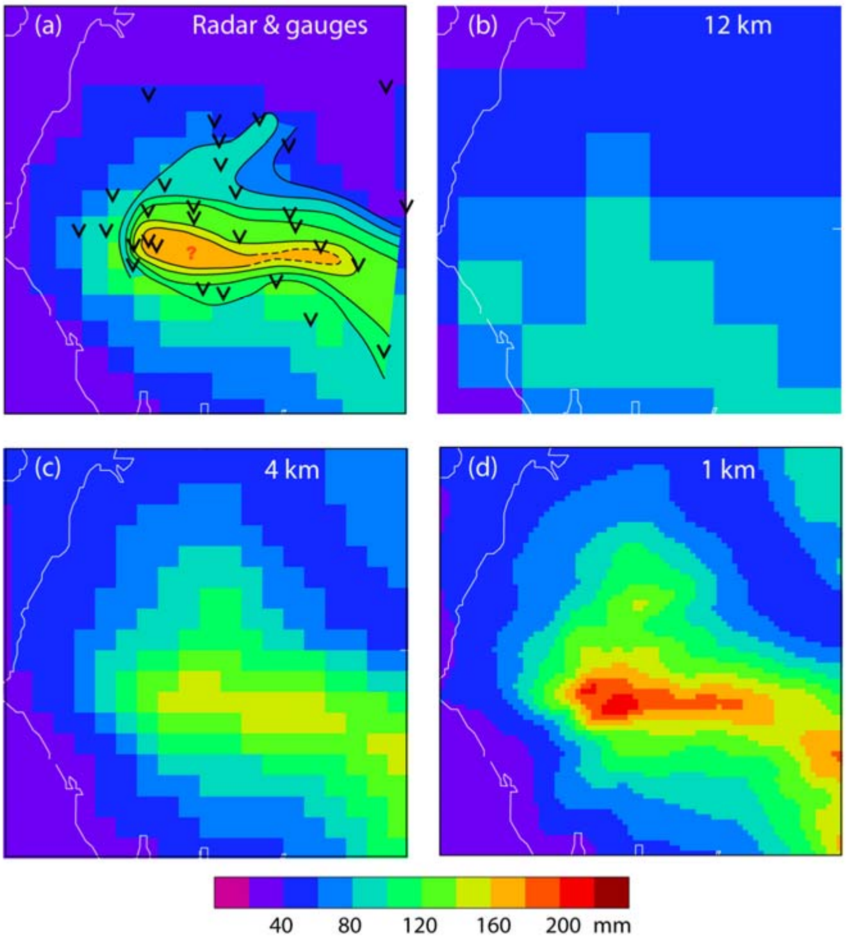


Figure 5. Rainfall accumulations for the period 00 UTC 7th to 00 UTC 8th January 2005. (a) Hand analysis from gauges (locations at bottom of 'V') contoured with shading on top of radar (block colours). (b, c, d) From a combined sequence of 12-hour forecasts at 12, 4 and 1km.

The 4 km and 1 km forecasts were more accurate primarily because they had a more detailed representation of the orography of the area. It is thought that in this type of situation when the rain area is reasonably broad and not convective (therefore more predictable) a 4 km or 1 km model would bring a major improvement compared to the 12 km model (that was the best resolution available at the time) and coupling to hydrological models should provide more timely and accurate flood warnings.

Case E - 19th June 2005 North Yorkshire

Intense thunderstorms developed during the afternoon in northern England. The heaviest rainfall was concentrated in a small region to the northwest of the village of Hawnby in the North Yorkshire Moors. The rain gauge at Hawnby (information provided by the Environment Agency) recorded 69.4mm in three hours, of which 59.8mm fell in one hour and 50.6mm in just half an hour (all have 200 year return period). As a result there was flash flooding at Hawnby, the larger nearby village of Helmsley and the surrounding area.

Forecasts were run at 12, 4 and 1 km from starting times ranging from ~18 hours to ~3 hours before the onset of the storms. None of the forecasts managed to produce the high rainfall totals in the area of interest (or further away) although the 4 and 1 km models did produce heavy showers. The reason all the forecasts failed in this instance is because the larger-scale flow pattern was wrong throughout and this was inherited at all the resolutions. The problem can be seen in Figure 6. The curved pattern seen in the water vapour imagery (white line) is very different to the equivalent pseudo imagery that can be generated from model forecast temperatures and humidities. It indicates that there was rotation in the upper troposphere in reality that was missing in the forecasts and this played a key part in the storm development. This case demonstrates that unless the larger-scale flow is reasonably correct, higher resolution is not likely to give a better forecast (even if as was the case here local effects are better represented). The impact of improving the coarser-resolution forecasts that provide the information at the boundaries of the high-resolution model should not be underestimated. The meteorological conditions need to be well represented at all scales from a few hundred kilometres down to the storm scale for a sufficiently accurate forecast.

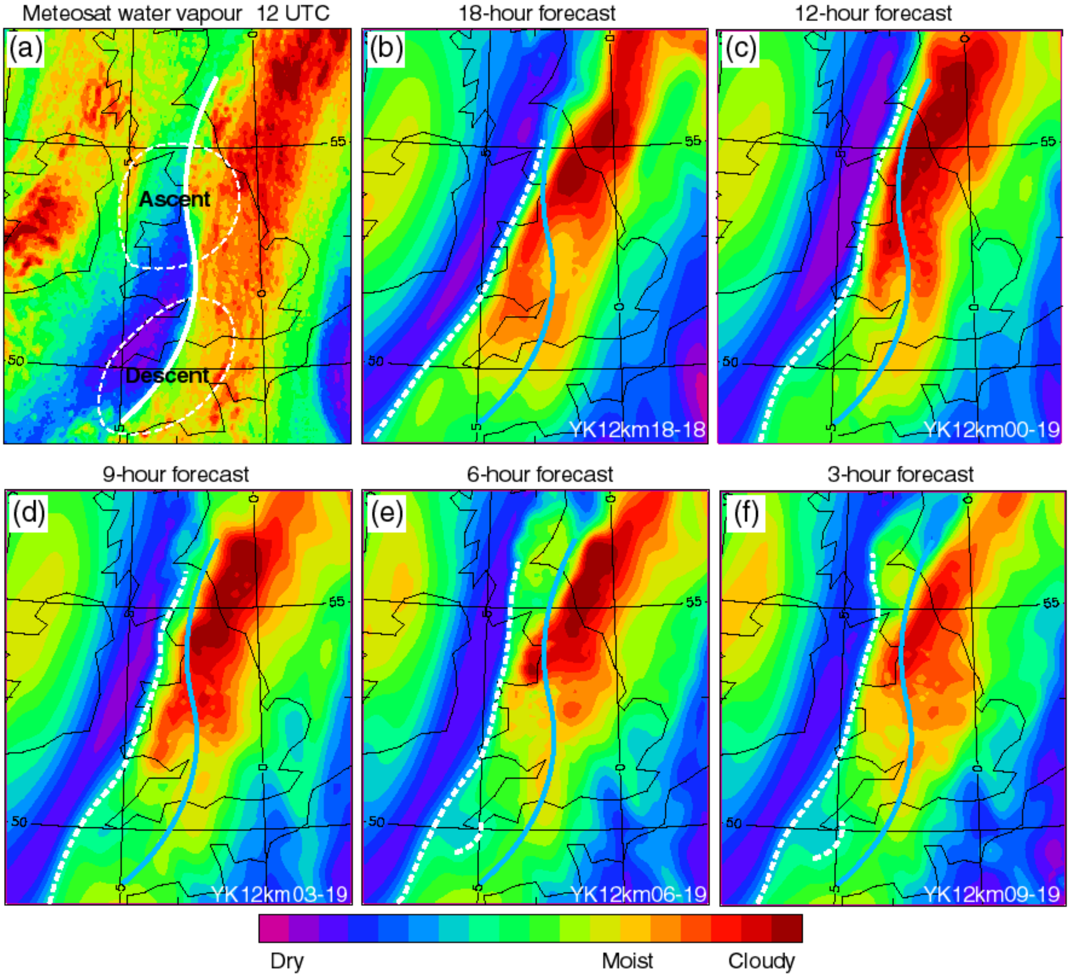


Figure 6. Meteosat Water Vapour image for 12 UTC 19/06/05. Areas with warmer brightness temperatures (dry regions) are blue, areas with cooler brightness temperatures (moist/cloudy regions) are orange/red. The white line marks the sharp transition between the drier and moister air (typically the axis of the jet stream). General regions of possible ascent and descent within the troposphere are depicted by the dashed circles. (b-f) pseudo Water Vapour imagery extracted from relative humidity fields at 300 to 600 hPa from the 12-km forecasts starting at 18 UTC 18th, 00, 03, 06 and 09 UTC 19th June as comparison against the imagery. The blue line is the same as the white line in (a). The dashed white lines mark the moist/dry air transition in the pseudo imagery.

Case F - 4th July 2006 Albrighton, West Midlands

An intense localised thunderstorm caused flooding of homes in the village of Albrighton in the west Midlands on the evening of the 4th July 2006. The storm began at around 17.30 UTC (6.30 pm local time) and was most intense over the area of interest between 18.10 and 18.40 UTC and then again between 18.50 and 19.15 UTC. A private raingauge within the catchment recorded 90mm in ~2 hours and a 1km radar pixel showed a rainfall total of 171mm.

This was a particularly difficult situation to predict. The meteorological conditions on that day meant that small variations in temperature and humidity could dictate whether there would be an intense thunderstorm or no storm at all at any particular location. Added to that, the extremely high rainfall totals at Albrighton were the result of secondary storm cells forming in the same place as the previous storm cell (a back-building storm). An NWP model must to be able to represent this dynamical process if it is going to reproduce that behaviour and to do that it needs to have sufficiently fine resolution.

The best representation of the storms did come from 1 km and 1.5 km simulations. They were able to produce back-building storms with high rainfall totals, although the positioning of the storms was not quite correct and a little delayed. The 4 km model did eventually develop a storm complex but too far south and several hours too late. The 12 km model was unable to produce the high rainfall rates and totals in this situation (it would not be expected to). Figure 7 demonstrates the differences between the 12, 4 and 1.5 km forecasts. The 1.5 km forecast is clearly the closest to radar in terms of the storm structure and intensity, but has a positional error that needs to be taken account of by a probabilistic interpretation of the storm location. Methods for doing this have been explored and need to be developed further.

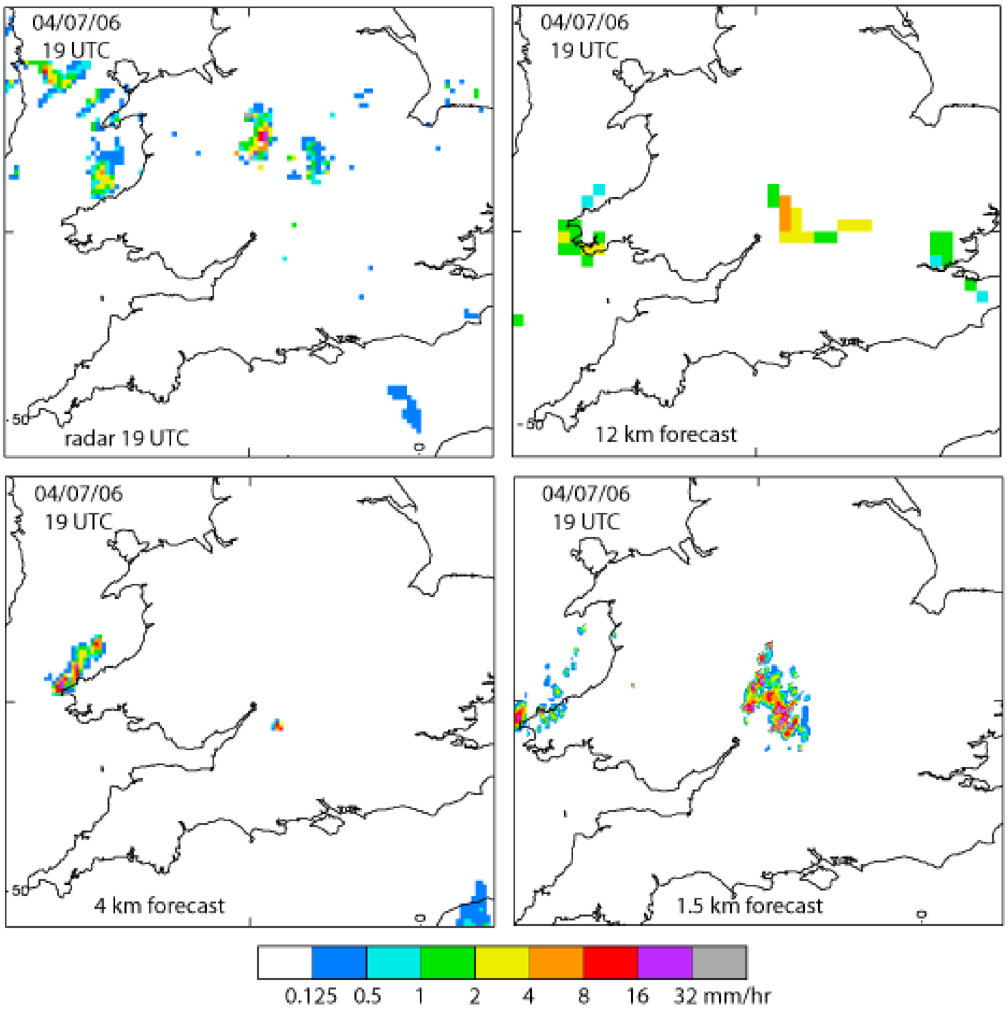


Figure 7. Rainfall rates at 19 UTC 4th July 2006 from (a) radar, (b to d) forecasts starting at 06 UTC with 12, 4 and 1.5 km grid spacing.

Case I – 25th June 2007 Hull & Sheffield floods

This was one of the major flood events in 2007. Very high rainfall totals occurred as an active frontal system became almost stationary over Yorkshire for the whole day. More than 100 mm of rain was measured in the Hull and Sheffield areas (most of that on the 25th). Severe surface-water flooding and river flooding occurred in parts of Hull and Sheffield and it became a major news item.

On this occasion the operational North Atlantic and European (NAE) model (12 km grid spacing) provided very good forecasts even two days before, hence the Met Office was able to issue early severe weather warnings. The NAE was able to perform well because the rain was frontal rather than convective. It is therefore difficult for a 'storm-resolving' model to improve on what was already a good forecast. Nevertheless, the 1.5 and 4 km models were able to simulate some important local effects in addition to the signal produced by the NAE. Figure 8 shows that both the 4 km and 1.5 km models produced an area of higher rainfall totals to the northwest of Sheffield that was observed. Higher totals were missing from the NAE forecasts. The additional rainfall occurred because of enhancement of the rain over the hills (like Case C), and is thought to have played a significant role in the Sheffield floods. The NAE does not have a detailed enough representation of the hills to produce this effect. Notice also that the 1.5 km forecast produced more rain just inland up the east coast for the same reason and again it is closest to observations.

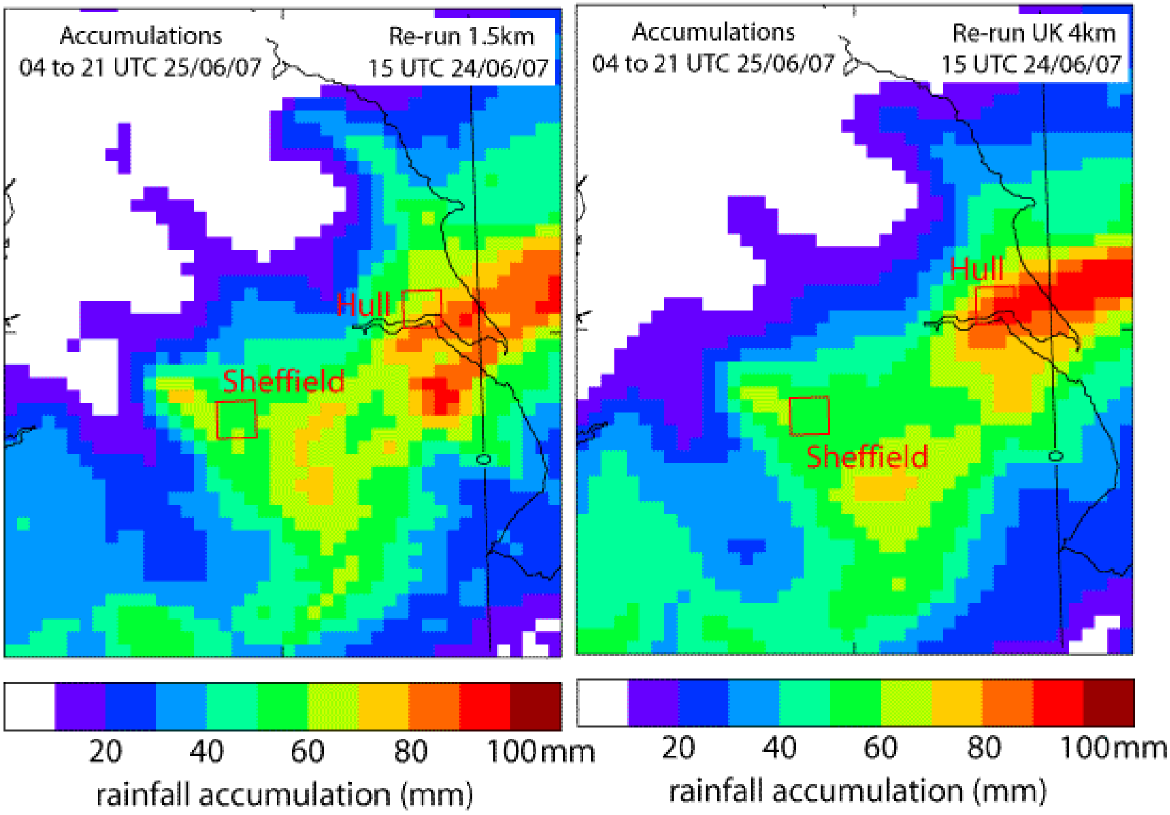


Figure 8. Rainfall accumulations from 04 to 21 UTC 25th June 2007 from Met Office Unified Model forecasts run at 1.5 km (run post event) and 4 km (operational) starting from 15 UTC on the 24th.

Case J – 20th July 2007 Central Southern England and West Midlands

This was another of the major flood events in 2007. A band of heavy and thundery rain moved slowly north across Central Southern England and the West Midlands during the day. In excess of 100 mm of rain was measured over a large area. The rainfall caused serious surface-water flooding over a very wide area during the day and this turned into serious river flooding over subsequent days. In addition to the main band of thundery rain, there were also thunderstorms further east (to the west of London) early in the morning that also caused surface-water flooding.

The Met Office forecasts of this event were excellent. Even a few days in advance there was a good signal. The 4 km model forecasts were particularly useful.

The 1.5 km model was run after the event. Rainfall accumulations from one of those forecasts are shown in Figure 9. The rain was so heavy over such a wide area that the radars are thought to have underestimated the amounts because of attenuation of the beams. Given that the radar was probably underestimating, the 1.5 km simulations are extremely good and if that model had been run operationally, it would, like the 4 km model, have given a very good indication of what was to come.

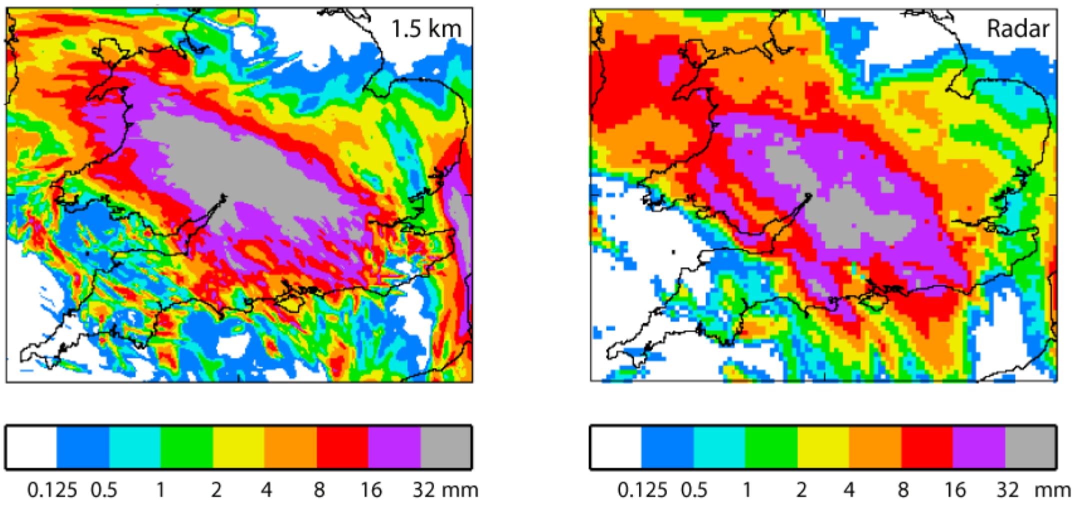


Figure 9. Rainfall accumulations over the period 03 to 15 UTC 20th July 2007 from (a) radar, and (b) a 1.5 km forecast starting at 03 UTC on the 20th. Courtesy of Humphrey Lean, Joint Centre for Mesoscale Meteorology (JCMM), Met Office.

Model sensitivity studies

A major requirement of this project was to gain an understanding of why the 1 / 1.5 km model behaves as it does when it is required to forecast extreme events. This included both an understanding of the aspects of the meteorology the model had to get right and an assessment of the impact of reasonable changes to model parameters (i.e. within known uncertainties) would have on the forecasts.

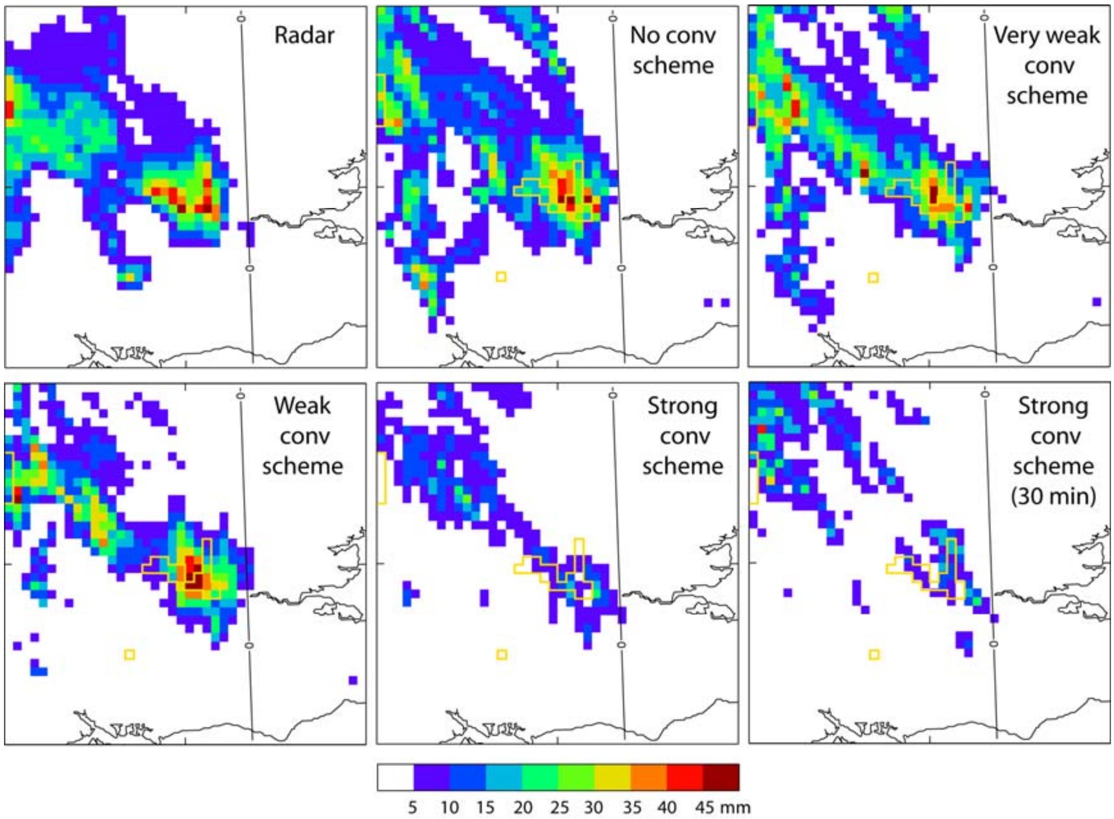


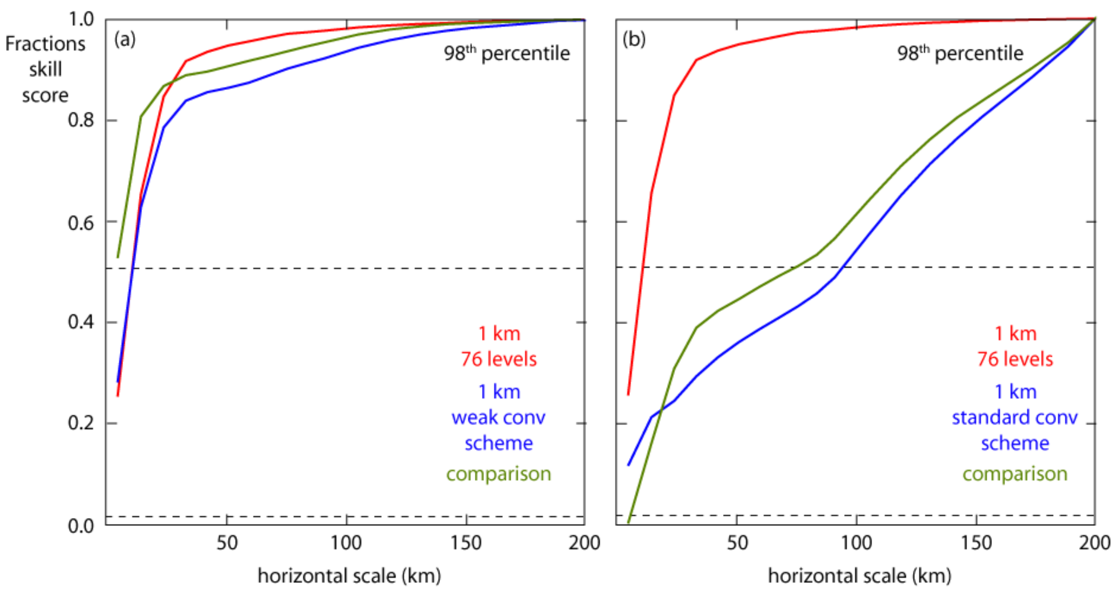
Figure 10. Rainfall accumulations over the period 13 to 18 UTC, 3rd August 2004 from (top left) radar, and a collection of 1 km forecasts from 06 UTC with different uses of the convection parametrization scheme (refer to text). The orange line in all but the top left panel encloses the totals above 30 mm from radar (over and to the west of London).

To help answer these questions a large number of model sensitivity experiments were performed on the three cases studied in more detail (cases B, E and F). An example of one of these experiments on case B is displayed in Figure 10. It shows that differing restrictions on the use of the convection parametrization scheme in the model can have a significant impact on the results.

The convection parametrization scheme is normally used in the 12 km NAE model to represent the effect of shower clouds that can not be represented on the grid. It is also used in the 4 km model, but is very restricted. It has been thought that it would not be needed at all in a 1 / 1.5 km model and has generally not been included in testing. However it was also known that there is a need for something to represent the turbulence within and on the fringes of convective clouds that can not be resolved on the grid. The purpose of this experiment was twofold, (1) to see if some kind of sub-grid mixing can be beneficial (even if perhaps a convection scheme is not the best way of doing it), and (2) to simply see what the use of the convection scheme does. The results (Figure 10) show that the use of the convection scheme 'very weak' (as used at 4km) or a little less restricted 'weak' is not detrimental and is perhaps even beneficial to the model performance. The use of the convection scheme as applied in the 12 km NAE model (Strong conv scheme 30 min) has a very detrimental impact and should not be used. Similar conclusions could be drawn from cases E and F.

Quantitative assessment of model performance

The impact of the sensitivity experiments was assessed quantitatively as well as by eye. A new measure called the Fractions Skill Score (FSS) (Roberts & Lean 2008) was used to measure the variation of forecast skill over different spatial scales. The same measure was also be used to identify the scales that affected most by changes to the model.



Graph of forecast skill using the Fractions skill Score (FSS) against spatial scale for the rainfall accumulation period shown in Figures 4-1 and 4-2 for (a) the 1 km forecast from 06 UTC compared with radar (red line), the 1 km forecast with weak convection scheme (blue line) compared with radar and the comparison between the two forecasts (green line). (b) the 1 km forecast from 06 UTC compared with radar (red line), the 1 km forecast with an unrestricted convection scheme (blue line) compared with radar and the comparison between the two forecasts (green line). The better the fit between forecast and radar or two forecasts the higher the value of FSS. The upper dashed line shows the minimum FSS value for a reasonable fit. The lower dashed line shows the FSS for a comparison with a randomly generated forecast.

Figure 11 gives an example of the use of the FSS and relates to the model-sensitivity experiment shown in Figure 10. The red curve is a comparison of the reference 1 km forecast with radar (panels 1 and 2 in Figure 10 above). The FSS increases rapidly with increasing horizontal scale then flattens off, showing that the 1 km forecast was not very skilful at the smallest scales but became reasonable skilful (past the dashed line) after ~15km and very skilful at larger scales. The blue lines show that the 'weak conv scheme' forecast (left) had very similar skill at smaller scales but is a little less skilful at larger scales and the 'standard conv scheme' forecast was much less skilful at all but the very largest scales.

The green lines show a comparison between different forecasts (rather than forecast and radar). The green line in the left panel has much higher values of FSS than the green line in the right panel because the 'weak conv scheme' forecast was much closer to the reference than the 'standard conv scheme' forecast. The 'weak conv scheme' forecast only had big differences at small scales compared to the reference – showing that that was where the changes had an impact, whereas the 'standard conv scheme' forecast was different at all scales.

Probabilistic Products

One of the findings and main themes of this work has been that a 'storm-resolving' model (~1/1.5 km) is able to produce more accurate forecasts of extreme events (convective in particular) than the 12 km or 4 km models on scales that are useful for flood warning. Such a model should be (and is being) developed for operational use because it is the best route towards improved forecasts of high-impact weather.

Once we have such a model though, we need to know how to use it. We need to recognise that there will always be uncertainty in the forecasts and this may become more apparent as we continue to expect more precision. Some forecasts will naturally be more skilful than others because some situations are inherently more predictable than others. The output should be therefore be presented in ways that are useful for specific applications, but also take account of and give an indication of the forecast uncertainty. The best way to assess forecast uncertainty is to use an ensemble forecast system and make the assumption that the more each of the forecasts in the ensemble differ from one another, the more uncertain the forecast will be. The problem we face in the near future is that we will not have an ensemble of storm-resolving forecasts until computer resources allow that possibility. In the meantime another approach is needed.

This section shows an examples of probabilistic outputs that could have been generated from 1 / 1.5 km forecasts of Case J (20th July 2007) using a fuzzy neighbourhood approach rather than requiring an ensemble. The method to generate the probabilistic forecasts this way has been described in the Storm Scale Modelling Project (Roberts 2004, 2005) and is similar to Theis *et al* 2005. It also forms the basis of the Fractions Skill Score verification method (Roberts and Lean 2008) mentioned earlier.

The purpose here is simply to give an idea of a subset of what can be done rather than go into the methodology in detail, but a very brief outline is given below.

The probability generation assumes that a rainfall pixel in the forecast is equally likely to occur at any other nearby pixel within a distance defined by some spatial scale below which we think the model is not skilful. In other words, the forecast of a shower over a town in an 18-hour forecast should be equally as skilful as the forecast of a shower over a town say 10 km away because we don't believe the model is accurate enough to pinpoint individual showers at specific places with that lead time. Probabilities are generated by examining the neighbourhood around each model pixel and computing the fraction of pixels that exceed some threshold we are interested in (e.g. > 40 mm of rain in 3 hours). Some additional filtering is also then done using a recursive filter. The size of the neighbourhood will be determined by the spatial scale we believe is the smallest that has useful skill for a particular model, application and forecast time. This scale can be determined by use of the Fraction skill Score verification method.

Probability examples

An example of probabilities of rainfall accumulations exceeding 75 mm using a neighbourhood of 60 km from two different 1.5 km forecasts 3-hours apart is shown in Figure 12. Both of the individual forecasts were good, but neither gave a probability distribution that was centred where the totals >75 mm were observed (using the 60 km neighbourhood). However, when they are combined the new probability picture, although broader, gives a better fit to what was observed. This combining of the latest forecast with previous forecasts is called a time-lag ensemble. Work by Mittermaier (2007) at the Met Office has shown that there is greater skill in using a time-lag ensemble with the UK 4km model than taking the latest forecast. The combination of a time-lag ensemble with this probabilistic approach could prove very useful for warnings of high rainfall amounts.

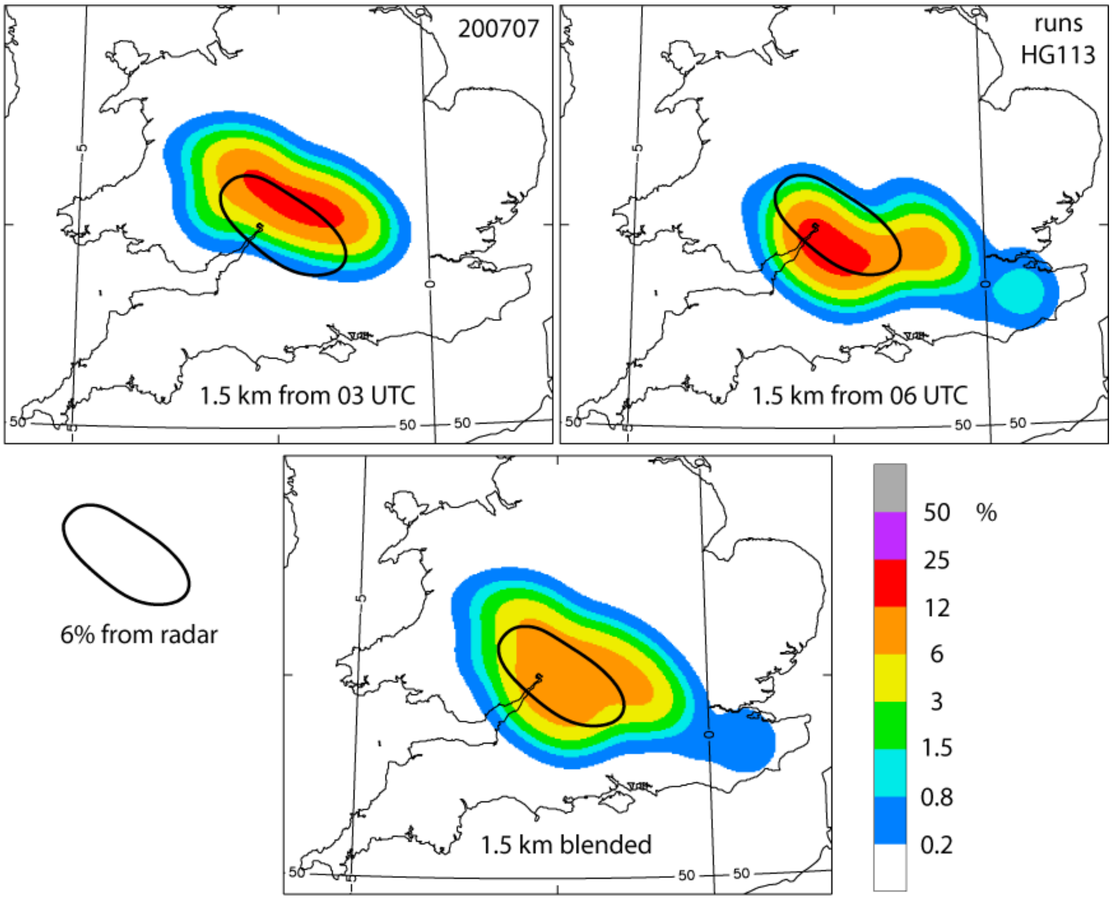


Figure 12. Probability that rainfall accumulations will exceed 75mm, using a 60 km neighbourhood, in the period 06 to 15 UTC 20th July 2007 from 1.5 km forecasts starting from (a) 03 UTC, (b) 06 UTC, and (c) the two forecasts combined with equal weighting. Black contour encloses the probabilities >6% when the same processing was applied to radar data.

Products can also be produced for specific areas. In Figure 13, Environment Agency warning areas are used, but, for example, a tiling of square areas could be used instead.

Figure 13(a) is designed to give an indication of the highest mean rainfall totals that could occur over a small area/catchment (24km^2) somewhere within each of the warning areas given that the positioning of the rainfall could be in error by up to 30 km in any direction.

Figure 13(b) shows the probabilities that an area of 24km^2 somewhere within each warning area will have an average accumulation of more than 50 mm. The probabilities are higher for this type of product than for the pixel-based probabilities shown earlier because there is more likelihood of exceeding a threshold somewhere within an area than at a specific pixel. E.g. it is easier to get any score on a dartboard than to land on the treble 20 (even when trying to!).

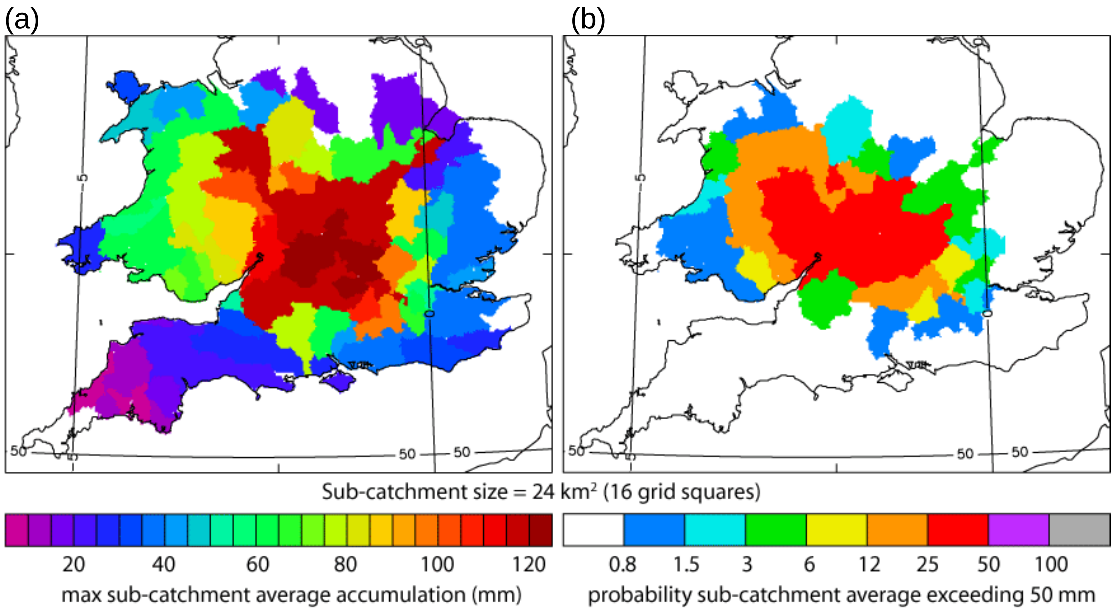


Figure 13. Diagnostics from the 1.5 km model forecast starting from 03 UTC 20th July 2007 for the period 06 to 15 UTC. (a) The maximum possible mean rainfall amount over a 24km^2 area within each EA warning area given a forecast uncertainty of 60 km. (b) The probability of exceeding a mean accumulation of more than 50 mm over a 24km^2 area within each EA warning area given a forecast uncertainty of 60 km.

Key Findings from the project

The key findings from the project are listed below.

1. There are no differences between the physical and dynamical processes that lead to 'extreme' events compared to other heavy rainfall events. It is the coincidence and interaction of those processes that leads to extreme events and the difficulty in their prediction.

2. A storm-resolving NWP model is capable of providing useful forecasts of 'extreme' rainfall events. The use of a storm-resolving model has the potential to improve greatly our current ability to predict such events provided that it is understood that the output must include information about forecast uncertainty (e.g. probabilities).

3. The accuracy of the forecasts may vary considerably from case to case and depends crucially on getting all the necessary meteorological components correct.

4. For many events is vital to accurately represent larger-scale disturbances in the flow that may originate from outside the high-resolution domain; as well as any local effects.

5. A high-resolution grid (~1 km grid spacing) is absolutely essential to be able to represent the dynamics of more localised thunderstorms and many of the important local pre-cursors to the triggering of storms.

6. Some convective situations are inherently more predictable than others, and that predictability is strongly linked to the meteorology of the situation. A classification into three types of storm has been made that is an extension of the classification made by the Extreme Events Recognition Project (FD2208). Knowledge of the likely type of storm can provide information about its predictability.

7. This work has lead to a greater understanding of both the meteorological processes that lead to extreme rainfall events and the strengths and weaknesses in the model in predicting them.

Recommendations for future work

On the basis of the results from this project the following recommendations for future work have been made.

1. The development and operational implementation of a storm-resolving model (grid spacing ~ 1 - 2 km) should continue. It is likely to be the best route towards a significant improvement in our ability to provide warnings of severe convective storms.

2. There will always be uncertainty in forecasts of extreme rainfall events and the more precision we expect the more uncertainty there will be. It is essential that probabilistic outputs for users are developed and that users understand what they mean.

3. The model is capable of representing extreme storms, but getting the positioning correct presents a big challenge. Research and development into new data assimilation methods (for improving the initial state of forecasts) on the high resolution grid and the use of new types of observations in data assimilation is, and must continue to, play a vital role in the development of a storm-resolving model.

4. The uncertainty in a single 'deterministic' forecast is difficult to quantify and this can limit the usefulness of probabilistic outputs based on one forecast. We should now move towards developing a storm-resolving ensemble prediction system and ensemble-based probabilistic products. Initially, such a system would embed the storm-resolving model in a coarser-resolution ensemble. The reason for taking this approach is that, over Western Europe, the dominant source of spatial uncertainty will often come from misplaced larger-scale dynamical features.

5. Further research is required to determine whether an estimate of the predictability can be deduced in advance from the meteorological conditions. Research into the use of 'time-lag' ensembles (combining the most recent forecast with older forecasts) as a possible means of determining predictability should also be undertaken.

6. High-resolution model output should be used in hydrological models for flood warning, particularly for orographically enhanced rainfall situations such as the Carlisle floods in 2005. For convective situations, a more probabilistic approach is necessary and needs to be developed.

7. There are still some outstanding issues to do with the way a storm-resolving model represents convective cells. Further work is needed in the areas of cloud microphysics and sub-grid-scale turbulence.

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Roberts, N. M. (2006). Simulations of extreme rainfall events using the Unified Model with a grid spacing of 12, 4 and 1 km. Met Office NWP technical report 486.

Roberts, N. M. (2007) Meteorological components in forecasts of extreme convective rainfall using 12-km and 1-km NWP models: A tale of two storms. Met Office NWP technical report 500.

Roberts, N. M. and H. W. Lean (2008). Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. *Monthly Weather Review*, 136, 78-97.

Met Office technical reports can be obtained online by going to:
http://www.metoffice.gov.uk/research/nwp/publications/papers/technical_reports/

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Stage 1 scientific report: Roberts, N. M. (April 2006). Simulations of extreme rainfall events using the Unified Model with a grid spacing of 12, 4 and 1 km. Available as Met Office NWP technical report 486.

Sid4, Interim report April 2006

Stage 2 scientific report: Roberts, N. M. (April 2007) Meteorological components in forecasts of extreme convective rainfall using 12-km and 1-km NWP models: A tale of two storms. Available as Met Office NWP technical report 500.

Final scientific report: Roberts, N. M. (2008) Investigation of forecasts of extreme rainfall events using a 'storm-resolving' (~1 km) version of the Met Office Unified Model. Available under the Joint Defra/EA Flood and coastal erosion risk management R&D programme under this project FD2210.

A paper entitled 'Use of high-resolution NWP rainfall and river flow forecasts for advance warning of the Carlisle flood, northwest England' by Nigel M. Roberts, Steven J. Cole, Richard Forbes, Robert J. Moore and Daniel Boswell has been accepted for publication in Meteorological Applications.