Inter-Agency Committee on the Hydrological Use of Weather Radar

Sixth Report

2005 to 2007

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Preface

I am pleased to present this report of the Committee's activities for the period 2005-07. This has been an exciting period for weather radar both in the operational and research fields and good progress has been made to improve operational implementation, coverage and data accuracy.

Weather radar has been a vital asset in managing the operational response to severe floods across the UK during the period. The forecasting of severe rainfall and flooding events, which is never easy, has been enhanced through the use of weather radar. The report provides examples of this, including very localised convective storms, such as that which affected Boscastle in Devon in August 2004 and the tornado that affected North West London in December 2006; through to frontal rain that affected parts of Scotland in December 2006, Northern England in June 2007 and Central England in July 2007. Weather radar is now widely embraced as an essential tool for both the meteorologist and the hydrologist in detecting and forecasting the impacts of these diverse and damaging rainfall events.

The period under review has seen the delivery of a number of enhancements to radar coverage. The South East Weather Radar Programme has successfully delivered two new installations into the UK network: the Thurnham radar in north Kent, that is a state-of-the-art dual-polarisation radar, and the Dean Hill radar in Wiltshire which is a conventional Doppler radar. Thurnham will allow us to fully evaluate the anticipated benefits of dual-polarisation in rainfall estimation and to the flood forecasting process. Both Thurnham and Dean Hill provide improved coverage, quality and resolution for important river catchments across Southern and South-Eastern England. There are also positive moves towards installing new radars in East Anglia and Northumbria. It is pleasing to see the coverage requirements articulated in strategies in the late 1990s coming to fruition.

In the research field, there has also been much activity with significant research programmes and projects in progress or being planned. A number of these have initiatives concerned with improving the use of radar for hydrological applications. The Committee has taken a keen interest in this work and has tried to provide guidance in this report on how the operational application of research programme outputs can be improved. It is hoped that this will be of value to the relevant managers and researchers.

I would like to thank all members of the Committee for their continuing support and enthusiasm during the past two years and for all their efforts in compiling this report. I will be stepping down as Chair in July 2007 and relinquishing my place on the Committee after 12 years service. I would like to wish those who remain, and in particular the new chairman Mr Mike Cranston from SEPA, every success in taking the work of the Committee forward.

Dr Chris Haggett
Chairman (2003-2007)
Inter-Agency Committee on the Hydrological Use of Weather Radar

Contents

1. Introduction

The weather radar network is going through an exciting period of change with new radars being added and new data being collected and used. The assimilation of radar data in numerical weather prediction models is another important development that gives the prospect of such models eventually replacing traditional radar nowcasting.

A more immediate benefit for quantitative precipitation estimation and data quality identification should be provided by the new data types being collected. This should in turn have positive effects on hydrological modelling. New technology is being embraced with a much better quality of data being provided to users. In future there will not only be improved accuracy of rainfall measurement, but also improved discrimination between rainfall and other targets and between rainfall and hail.

In hydrological applications, area-wide models in particular have been shown to be especially well suited to using radar data and can fully exploit the spatial information contained in such data. Area-wide models have the potential to provide real benefits when extreme and/or unusual storms are detected or forecast e.g. convective storms.

The uncertainty in all types of radar data must be taken into account and propagated through the derived radar products and ultimately through to the hydrological applications. On the hydrological side there is still some uncertainties on using data quantitatively and these concerns need to be addressed head on by researchers and practitioners alike. The roll-out of new flood forecasting systems (NFFS/FEWS) in the Environment Agency and SEPA places the operating agencies in an excellent position to routinely use and assess radar-based products for flood warning. But there is still work to do to convince operational forecasters of the merit of using radar data quantitatively in real-time flood forecasting.

Despite the obvious role of weather radar in detecting and forecasting the recent summer 2007 flood events (see Figure 1), its full potential to support other functions such as urban drainage and design, water supply and water resources is still to be fully realised by the water industry. The Government's new strategy for Flood Risk Management, Making Space for Water, is looking to extend the Environment Agency's strategic role to cover other sources of flooding other than from rivers and the sea. This may herald a change of emphasis in relation to the wider uses of weather radar.

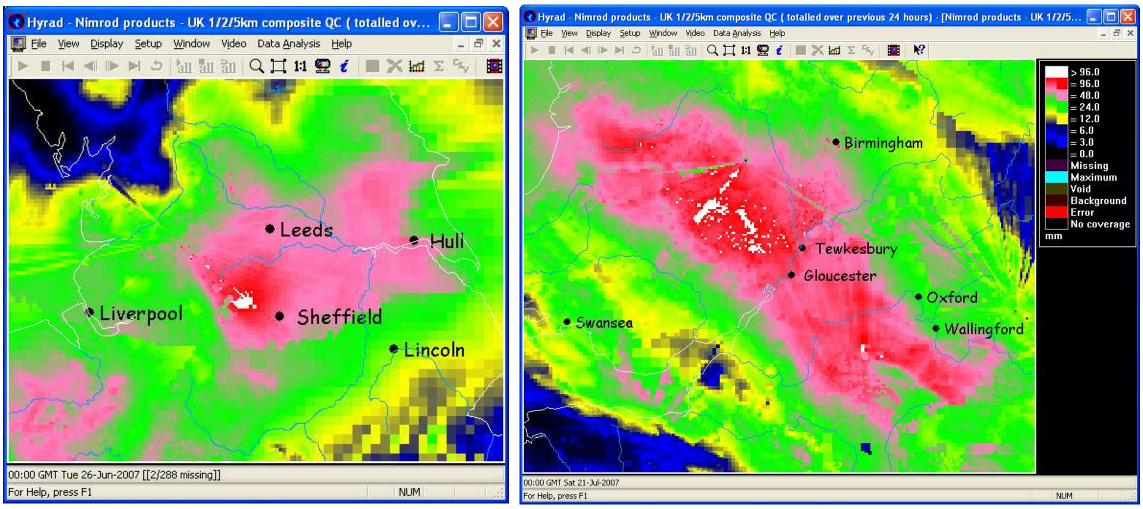


Figure 1 Daily radar rainfall accumulations using Nimrod 1/2/5 km composite radar data for 25 June 2007 (left) and 20 July 2007 (right).

2. Community Plan

2.1 Background and Aims

In the previous session the Committee addressed the following activities:

- Bringing research findings into operational use
- Identifying and addressing service delivery needs of operating agencies
- Raising awareness of weather radar in the wider community

In this session, the Committee continued to focus on ways to influence the greater use of weather radar by operating agencies to meet their service delivery requirements. In particular, it concentrated its efforts on monitoring and critically reviewing the significant research programmes and projects that are (or shortly will be) in progress, including FREE (Flood Risk from Extreme Events), FRMRC (Flood Risk Management Research Consortium), South East Weather Radar Project, CSIP (Convective Storm Initiation Project), etc. Through this work, the Committee is seeking to guide the operational application of outputs and influence future research directions. Raising awareness of the work with radar and the benefits that can be obtained continues to be a challenge and this was chosen as the subject of the second strategic area in the session.

2.2 Strategic Overview

Presented in Table 1 below is a broad strategic outline of the activities that have been pursued under the 2005-2007 Programme.

Table 1 Strategic Areas for the 2005-2007 Programme

Strategic Area 1	**Strategic Area 2**
Monitor and critically review ongoing research programmes and projects with the view to guiding the operational application of their outputs and influencing future research directions	Raising awareness of hydrological applications of weather radar in the wider community

This strategy has helped address the following terms of reference of the Committee:

1. To recommend priorities for future research and to coordinate research activities.
2. To identify research needs and opportunities.
3. To recommend priorities for future research and to coordinate research activities.
4. To publicise and promote hydrological uses of weather radar.
5. To report on its work to the nominating bodies and the water industry generally.

2.3 Milestones and Deliverables

Within each Strategic Area the Committee set out a number of deliverables against which it will be measured. These are outlined in Table 2 below, together with the responsible lead member(s) of the Committee. Reports on the two Strategic Areas are presented in Sections 3 and 4. Reports from the UK Research Groups and Agencies are given in Appendix C whilst the Committee's constitution, terms of reference and membership are set down in Appendices A and B.

Table 2 Milestones and deliverables for the 2005-2007 Programme

Strategic Area 1: Monitor and critically review ongoing research programmes and projects with the view to guiding the operational application of their outputs and influencing future research directions.
FREE (Flood Risk from Extreme Events) – Chris Collier (lead)/Bob Moore/Noel Higginson **FRMRC** (Flood Risk Management Research Consortium) - Miguel Rico-Ramirez (lead) /Mike Cranston **South East Weather Radar project** – Malcolm Kitchen (lead) /Chris Haggett **CSIP** (Convective Storm Initiation Project) – Anthony Illingworth (lead)/Graham Squibbs **Other relevant programmes and projects:** Extreme Event Recognition Project - Bob Moore, FLOODSITE - Chris Collier, Assimilation of radar data into NWP models in the UK - Anthony Illingworth, Assessment of radar data quality in a steep upland catchment – Chris Haggett, Weather radar and bathing water quality signage project – Michael Cranston Factors to be considered by each team for each programme/project: • Identify and critically review the deliverables and their relevance to hydrological applications of weather radar • Determine the timescales for delivery • Identify and critically review the pull-through mechanisms to operational application and how these will be implemented • Identify and critically review the training plans that have been put in place • Determine how the programme/project deliverables will be disseminated and to whom • Identify the scientific risks • Identify the operational risks • What further developments are required and what are the funding opportunities

Strategic Area 2: Raising awareness of hydrological applications of weather radar in the wider community
Further development of the Committee website - John Goddard/Chris Walden Identify opportunities for raising awareness of radar e.g. linking into public awareness and other campaigns - Linda Aucott Exploit opportunities for publicising the role of weather radar in detecting and forecasting of severe weather/flooding events - Chris Haggett/all members Identify opportunities for the funding of training e.g. European Union - Chris Collier Determine the need for a workshop to bring together the research community and operating agencies - Bob Moore

3. Report on Strategic Area 1

3.1 The NERC Flood Risk from Extreme Events (FREE) Programme

What are the deliverables and are they relevant to hydrological applications of weather radar?

So far only one project within FREE is concerned with the use of radar data for hydrological applications. The Principal Investigator of this project is Professor A. J. Illingworth, University of Reading with Mr R. J. Moore at CEH as Co-Investigator. The Collaborators are the Met Office and the Environment Agency. The project began on 1 January 2007. The title of the project is 'Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting'. The proposed work is outlined below.

Floods in the UK are often caused by extreme rainfall events. At present, weather forecasts can give an indication of a threat of severe storms which might cause flash floods, but are unable to say precisely when and where the downpours will occur, due to the complex range of processes and space-time scales involved. The first stage is to predict the air motions leading to convergence and ascent at a certain location where the precipitation will be initiated. Then the development of the precipitation needs to be forecast, and hydrological models used to produce accurate, quantitative, probabilistic flood predictions.

Data assimilation is a sophisticated mathematical technique that combines observation with model prediction to give an analysis of the current state of the atmosphere. This analysis may be used to initialise a weather forecast. Although precipitation is well observed by weather radar, attempts to assimilate radar data have had little success; by the time the rain develops the forecast model state is too far from the truth and the air motions are inconsistent with the position of the first radar precipitation echo. We propose to overcome this problem by assimilating new types of data from weather radars. These provide information on the evolving humidity fields and air motions in the lower atmosphere so that the model can accurately track the developing storm before precipitation appears. The model used will be a new Met Office model that can be run with a resolution (i.e., grid spacing) of order 1-4 km. This enables storm-cloud motions to be explicitly calculated, rather than treated as a sub-grid-scale effect. Furthermore, current operational forecast models are only updated with observations every few hours; in the new approach the model will be updated much more frequently. This should yield weather forecasts with improved locations (in space-time) for rainfall events.

Initialisation errors are not the only cause of inaccuracies in storm-sale weather forecasts. Models are often run only for a small region of the world, and the data on the boundaries of this area provided from a larger-scale model. These data are known as lateral boundary conditions. Errors in these lateral boundary conditions and modelling errors also contribute to the errors in the forecast. Even if these errors were reduced, the nonlinear nature of the storm dynamics ensures that there is a limit, beyond which the value of deterministic forecasts become questionable. After that point it becomes important to determine the uncertainties in the forecast precipitation, so an ensemble approach is required. (An ensemble is a collection of perturbed forecasts that may be considered as a statistical sample of the forecast probability distribution.) The appropriate construction of a storm-scale ensemble is an open question. A structured approach is proposed where perturbations will be designed on the basis of physical insight of the convective forcing mechanisms.

The resulting probabilistic rainfall forecasts can be interfaced to hydrological models used for flood forecasting. For the first time, this project will allow different scales of application of these methods to be supported: ranging from localised flash flooding of small catchments, through to indicative first-alert forecasting with UK-coverage and forecasting of river discharges to the sea. The project will also assess the impacts of improvements in numerical weather prediction on flood forecast performance.

In this project it is anticipated that there will be fruitful interactions between different disciplines of observations and measurement, meteorology and hydrology. Radar assimilation software development and ensemble forecasts will take place using Met Office models, so improvements can be implemented operationally very easily. The use of operational radars makes this project well placed to take advantage of data from any extreme events occurring during the period of the study.

Other FREE projects involve the use of numerical ensemble weather forecasts, the investigation of the uncertainties associated with them and the patterns of rainfall causing extreme floods using advanced statistical methods with the output from numerical forecast models. The linkages between atmospheric circulation variability, atmospheric humidity and resulting precipitation in model simulations will be investigated. However these projects do not involve the use of radar data. A second call for projects has been launched which may result in other projects involving radar data being funded.

What are the timescales for delivery?

- Whilst the FREE Programme has been running for over a year, individual projects will begin between January and the autumn 2007. Most projects have durations of 3-4 years. However projects are expected to report every quarter and undoubtedly results will be published after the first year.

How will the pull-through mechanisms to operational application be implemented?

- The work on the assimilation of new radar products will involve the use of the Met Office data assimilation framework. Should the impact of these products upon forecasts be positive, then the mechanism to transfer the results of the project to the Met Office operational data assimilation system will be easily implemented.
- As for the hydrological modelling aspects of the project, this will involve further negotiation with the Environment Agency. It should be noted that FREE does have a Knowledge Transfer element in its programme. However the research is regarded as environmental science and therefore direct implementation of operational systems is not necessarily a programme aim.

What training plans have been put in place?

- The project will involve the appointment of postdoctoral researchers, who will have to learn about Met Office data assimilation systems and the nature of radar data. There will be considerable technology transfer to the Met Office and the Environment Agency.

How will the programme/project deliverables be disseminated and to whom?

- Results will be communicated to the scientific community through conference and journal papers. Specific systems will be presented to the Met Office and the Environment Agency for possible operational implementation.

What are the scientific risks?

- The Met Office have now installed five operational Doppler radars at Clee Hill, Dean Hill, Chenies, Cobbacombe and Thurnam. The basic data needed for the Reading work will therefore be available. An approach to the derivation of humidity from the radar data has already been tested using Chilbolton data, although its viability for C-band radars requires further work.
- The major risk probably comes from the need to develop robust and reliable procedures for assimilating the data into the variational analysis scheme of the Met Office which will require the implementation of Observing System Experiments to ensure that the radar products do not conflict with other more conventional data.
- The hydrological modelling work will build upon previous work carried out at CEH. The risk here involves how best to use input from a high resolution numerical weather prediction model.

What are the operational risks?

- The outputs from the project are principally scientific. Operational implementation may take place depending upon the research outcomes, but it is not work specifically identified.
- FREE has an Implementation Plan that includes consideration of market application. Funding has also been set aside to support knowledge transfer including engagement with users. However, the Committee sees a role in monitoring and reinforcing application of successful research through its links with the user community.

What further developments are required and what are the funding opportunities

- The Reading-led work represents the major research activity in the UK for assimilating Doppler radial wind data and radar-derived humidity information into the Met Office high resolution numerical forecast model. However FREE does not include explicit research on ways in which the uncertainty in radar products, which is introduced into hydrological models through the high resolution numerical weather forecasts, could be handled.

3.2 The EPSRC Flood Risk Management Research Consortium (FRMRC) Programme

What are the deliverables and are they relevant to hydrological applications of weather radar?

The FRMRC Programme has several work packages which have a significant hydrological application of weather radar component. The relevant deliverables are detailed below.

- *Performance of attenuation correction algorithms using differential phase measurements*. C-band weather radars suffer from attenuation, particularly in heavy precipitation. It is important to correct for attenuation and differential attenuation before any estimation of precipitation is performed. There is an important overlapping area between the Chenies and the Thurnham radar coverage allowing testing of attenuation corrections to be carried out in the latter radar at long ranges. In this case, it is assumed that the Chenies radar is accurately calibrated and its attenuation is negligible at short ranges. Attenuation correction algorithms using differential phase measurements with intercomparison studies between attenuation-corrected reflectivity measurements further away from the

Thurnham radar and non-attenuated reflectivity measurements closer to the Chenies radar will be carried out.

- *Classification of hydrometeors and VPR correction*. Polarimetric radar measurements offer the possibility to classify hydrometeors, providing the possibility of applying different rainfall estimators within the rain region and minimising the effects of the vertical reflectivity profile within and above the bright band. The current research work done in this area is with an S-band system with a very narrow beam.
- *Performance of dual-polarisation algorithms for rainfall estimation*. The performance of the different dual-polarisation rainfall estimation algorithms based on physical and statistical/engineering models will be compared and improved with raingauge measurements from the Medway catchment (Environment Agency Southern Region).
- The dual-polarisation algorithms for rainfall estimation developed under the FRMRC programme will be evaluated in conjunction with those algorithms developed by the University of Reading under the South East Weather Radar project. The best algorithms will be implemented operationally.
- Detailed recommendations on versatility, accuracy, suitability and applicability of radar processing algorithms will be made available. Results will be communicated to the scientific and user community through national meetings, publications and workshops.
- *Distributed Hydrological Modelling over the Upper Medway catchment.* A fully distributed hydrological model is being constructed using the Mike11 and MikeShe modelling tools to further assess the impact of the dual-polarisation rainfall estimation into hydrological modelling. The testing site is the Upper Medway catchment and the Environment Agency has provided some of the calibration and validation datasets. It is hoped that the outputs of the distributed model will be compared with the operational ISIS model in the Medway region.
- A PhD student has been working on developing a 'realistic' radar data error model for hydrological applications. This is a contribution to a wider body of work and, in particular, the COST 731 action is looking at the same problem. It is well known that radar data errors have three important features: changing bias by rainfall intensity, variable variance and temporal autocorrelation. All of these features are very important to hydrologists. However, none of the existing radar data error models are realistic enough for hydrological usage. It is important that a realistic radar data error model should be built as a matter of urgency since uncertainty assessment in hydrological modelling is playing a more active role in modern flood management practice.
- It has been found by numerous research activities that physics-based distributed hydrological models cannot compete with lumped models in real-time flood forecasting. This is because the large number of model parameters could not be fully calibrated and more importantly, could not be updated in real-time when the predicted flows are different to the measured flows. On the other hand, lumped models can overcome these problems in a relatively easy manner. However, lumped models tend to ignore the spatial information provided by the weather radar and GIS data. This research is trying to explore the middle ground where a lumped model is expanded with an ability to absorb the spatial rainfall and catchment information. It is expected that this new model should outperform both the lumped and fully distributed models in real-time flood forecasting. This research work is focused on the Brue catchment using the HYREX dataset. Intercomparison studies will be carried out with the runoff forecasting model known as WRIP, which will be replaced by NFFS (National Flood Forecasting System). This model is being used by the Environment Agency Southwest Region.

What are the timescales for delivery?

- The FRMRC programme started in early 2004 and it will end by mid 2007/08. By mid 2007 it is expected to fulfil the first five deliverables. Preliminary work on the classification of hydrometeors, VPR correction and performance assessment of dual-polarisation algorithms is being carried at S-band frequencies. The distributed hydrological modelling over the Upper Medway catchment is due to be completed by mid 2008. The final two deliverables are closely allied with FRMRC but not directly funded by the FRMRC grant. However, this work is highly relevant to the objectives of the Consortium. It is expected that that the first phase of the FRMRC project will end in 2007.

How will the pull-through mechanisms to operational application be implemented?

- The dual-polarisation algorithms for rainfall estimation developed will be evaluated in conjunction with those algorithms developed by the University of Reading. The best algorithms will be implemented operationally. This will be carried out with the help of the Met Office in collaboration with the Environment Agency.
- The distributed modelling developed over the Upper Medway will be carried out in collaboration with the Environment Agency Southern region.
- Items will be applied in the Environment Agency, South West region in their flood modelling practice.

What training plans have been put in place?

- Three PhD students and one Research Assistant are working on this project (albeit not all are funded by FRMRC). The students will present their PhD's in 2007/08 and the Research Assistant will get the experience in teaching and research.
- The training of practitioners should be on the agenda at some point in the future.
- Helping the Met Office implement the dual-polarisation algorithms in an operational test environment.

How will the programme/project deliverables be disseminated and to whom?

- Results will be communicated to the scientific and user community through reports, national meetings, publications and workshops.
- It is hoped that the dual-polarisation algorithms for rainfall estimation will be implemented operationally into the Met Office system.

What are the scientific risks?

- The Thurnham radar is now operational and has been providing data since August 2006. However, some sub-optimal features have been identified such as the sinusoidal error in the differential reflectivity (Z_{dr}) as a function of azimuth at low elevation angles. This has been shown with vertical pointing measurements of Z_{dr}. Because large raindrops can be approximated by oblate spheroids, vertical pointing measurements of Z_{dr} should in theory be close to 0 dB. However, Z_{dr} measurements from the Thurnham radar at 90-degree elevation show a sinusoidal variation with peak-to-peak values of about 0.6 dB. This variation can have a large effect on the rainfall estimation with any polarimetric algorithm that uses Z_{dr}.

What are the operational risks?

- There are no plans to implement the distributed hydrological model of the Upper Medway operationally as its sole purpose was to help further assess the benefits of using dual-polarisation.
- There is a risk that the dual-polarisation algorithms will not yield the promised improvement in performance.

What further developments are required and what are the funding opportunities?

- The Thurnham radar is a multi-parameter radar and offers the first opportunity to develop and test new quantitative radar processing algorithms and assess whether this technology should be extended to the rest of the network.
- The tangible financial benefits of the dual-polarisation algorithms giving improved flood warning need to be assessed.
- A second phase has been proposed and is currently under consideration.

3.3 South East Weather Radar Project

What are the deliverables and are they relevant to hydrological applications of weather radar?

- The deliverables are two new radars in the UK operational network. The Thurnham radar (Kent) is a state-of-the-art dual-polarisation radar; the Dean Hill (Wilts) radar is a conventional Doppler radar which is identical to several existing network radars.
- The deliverables from the Dean Hill radar are improved coverage quality/resolution for critical catchments in Southern England and the Isle of Wight, without compromising coverage over catchments in Dorset closer to Wardon Hill.
- Also an evaluation of the benefits of dual-polarisation in rainfall estimation and to the flood forecasting process. The anticipated benefits include improved accuracy estimates of surface rainfall, improved discrimination between rainfall and other targets and between rainfall and hail. The evaluation is required to determine the future technical strategy for the UK weather radar network.
- Two candidate sets of dual-polarisation algorithms will be evaluated. Those developed by Reading University under the auspices of the South East Weather Radar Project, and those from Bristol University developed as part of the EPSRC FRMRC programme.
- The Met Office and Meteo-France obtained a joint contract to report on implementation of dual-polarisation radar to EUMETNET – the consortium of European National Met Services. The deliverable was a report delivered in November 2006
- A new test environment is being constructed at Exeter to be able to test these rainfall algorithms in parallel with the operational processing and in identical operational conditions. Whist the test environment will not enable open access to the processing, it is hoped that the facility will promote academic research into radar data quality control and correction and increase the take-up of such research into operational practice.
- Polar format dual-polarisation parameters will be forwarded to BADC for use in NERC/EPSRC research projects.

What are the timescales for delivery?

- Both radars were officially opened in October 2005.
- Dean Hill data started to be used operationally shortly afterwards.
- The standard reflectivity product from the Thurnham radar became operational from August 2006.
- The timescale for incorporating dual-polarisation radar parameters in the rainfall estimation algorithms is unknown at this time, since it will have to be first demonstrated that their quality is superior.
- A project evaluation stage commenced in August 2006 and is planned to run for about a year.

How will the pull-through mechanisms to operational application be implemented?

- See above, but in general, operational pull-through is to a large extent assured because the project has an operational element and the operating agencies are directly involved at all stages.
- The evaluation of the candidate dual-polarisation algorithms will demonstrate if they are superior to existing reflectivity-only processing. In that case, they will replace existing algorithms on the operational system.

What training plans have been put in place?

- Met Office radar technicians have received preliminary training on the maintenance of the new radar.
- Advice has been provided to academic groups on the operational processing system to help them design the interface to the dual-polarisation algorithms. The academic groups developing the algorithms will advise on the processing architecture required.
- Any new products derived from dual-polarisation parameters (such as an improved precipitation type, hail size/intensity) may generate a requirement for user training.

How will the programme/project deliverables be disseminated and to whom?

- Project reporting conforms to standard Environment Agency practice.
- Report for EUMETNET has been delivered to representatives of European Met Services.
- Dissemination of reports on algorithm comparisons has yet to be decided, but publication in the open literature would be preferred.

What are the scientific risks?

- Risk that the Thurnham radar will not perform to its design specification.
- Risk that benefits of dual-polarisation technology will not be assessed correctly due to problems such as unrepresentative conditions in the evaluation, radar design faults and errors in algorithms. For example, there is currently a concern that the design of the radome may be compromising quality of the dual-polarisation measurements.
- Risk that there will not be a scientific consensus about the evaluation methods.

What are the operational risks?

- Risk that an attempt to evaluate dual-polarisation technology on an operational radar will compromise the operational status of the radar. The risk has been mitigated through a radar design that can revert to conventional reflectivity-only operation.
- There has been some difficulty with the funding for the evaluation. The Environment Agency has been unable to providing funding in 2006/7 and so the costs are being borne by FRMRC, EUMETNET and the Met Office for this financial year, on the understanding that the Environment Agency will give the project higher priority in budgets for 2007/8. However, there can be no guarantees concerning continuation of funding into next financial year.
- Normal risks associated with weather radars, including data imperfections due to unforeseen problems with the site, radar reliability, damage due to lightning strike, vandalism etc.
- Risk that there is an unbridgeable gap between the current evaluation deliverables and a business case for network roll-out of dual-polarisation.

What further developments are required and what are the funding opportunities.

- Following the evaluation of dual-polarisation data, a decision will be needed on the cost/benefits of rolling this out across the whole of the UK network. The full project benefits will not be realised if this decision is not correctly made.
- Data from the Thurnham radar will be made freely available for *bona-fide* academic research through the British Atmospheric Research Centre. Hence other projects should be able to readily access and exploit the data.
- The project brings opportunities for leading-edge near-market weather radar research in the UK. Combined with the established RAL research facilities at Chilbolton and the Environment Agency's dense raingauge network in the London area, the UK now has excellent facilities for research into the hydrological application of radar.
- The new radar at Dean Hill is a Doppler radar located a few 10's of km from the RAL Chilbolton facility. The possibility of high resolution dual-Doppler winds, combined with radar reflectivity and humidity measurements, may offer improved opportunities for fundamental research into small scale atmospheric structure, convective initiation, etc.

3.4 The Convective Storm Initiation Programme (CSIP)

What are the deliverables and are they relevant to hydrological applications of weather radar?

- The goal of the Convective Storm Initiation Project (CSIP) is to understand the mechanisms responsible for the initiation of precipitating convection in southern England.
- To compare the results of the Met Office high resolution model with detailed observations of the early stages of convective clouds made with radars and associated ground-based instruments and use the newly gained understanding to improve the predictions of the model.
- The Met office is increasing the resolution of its operational model and should be able to better represent convection and provide better forecasts of its development in the following 6 hours. If this is successful then it would constitute a major advance in the use of radar to provide short-range predictions of heavy rain.
- The impact of new observations such as GPS humidity, lidars, sodars and specialised radar techniques on improved predictions will be assessed.
- More accurate predictions of rainfall over a six hour period will be of benefit to hydrologists.

What are the timescales for delivery?

- The pilot project for CSIP was in July 2004 and the main project was successfully completed in June, July and August 2005.
- The CSIP project will com to an end in August 2007 but the analysis will continue.
- The Met Office has been running a 4 km version of their operational model since early 2005, and is planning to have an improved 1.5 km version operational by the end of the decade. The 1.5 km version is available 'on demand' for various selected areas of the UK.

How will the pull-through mechanisms to operational application be implemented?

- The Met Office are centrally involved in the analysis of the CSIP data and are responsible for the implementation of any improvements into future versions of the high resolution mesoscale operational model.

- A decision to Dopplerise the radar network has been taken. This will be done through hardware at 8 sites and a software approach will be trialled at the remaining sites.
- If precursors of convection are best identified through ‘new’ radar observations such as deriving boundary layer refractivity from the phase of clutter returns, then these need to be implemented by the Met Office on the radar network

What training plans have been put in place?

- Joint meetings are held between the university academic groups and Met Office scientists to discuss the implications of the analysis of the CSIP observations for improvements to the mesoscale model.

How will the programme/project deliverables be disseminated and to whom?

- The forecasts of the Met Office high resolution mesoscale model will be delivered to customers by the same means as are used for the present model.
- Several papers have been submitted for publication in the open literature and further papers will be submitted shortly.

What are the scientific risks?

- The improved parameterisation schemes introduced into the model could result in no impact or degradation to the forecast of future precipitation. However, before such a model is released for operational use the Met Office will carry out a detailed analysis of model performance to ensure that it is superior to the current model.

What are the operational risks?

- The new high resolution mesoscale forecasts would only be released to users when they have been demonstrated to be superior to the current forecasts so the operational risks are low.

What further developments are required and what are the funding opportunities?

- Developments in the observing network and/or measurements taken may be required; for example (i) the implementation of the refractivity technique using the phase of clutter returns and (ii) the derivation of Doppler line-of-sight winds (with errors) from insect returns.
- The CSIP dataset of observations and model runs will be stored on the BADC and made available to bona fide academics for research purposes.
- UK scientists are involved in the COPS experiment (The Convectively Orographically-induced Precipitation Study) to take place in the Black Forest, Germany in the summer of 2007 examining the initiation and development of convection over mountainous terrain. The UK will be supplying instruments for measuring aerosols, lidars for sensing air flow, whilst the BAe 146 aircraft will be making airborne cloud and aerosols observations. A proposal for the analysis of these data was submitted in Dec 06 to NERC. This will tackle five aspects: (i) the thermally driven flows in the complex terrain, (ii) the composition and size distribution of the aerosols, (iii) the structure of the boundary layer features, (iv) the development of precipitation and (v) experiments using the Met Office Unified Model to quantify the predictability of the convective precipitation.

3.5 Defra/Environment Agency project FD2208: Extreme Event Recognition – Phase 2

The Defra/Environment Agency project FD2208 “Extreme Event Recognition – Phase 2” has five work packages associated with it. Those that have a significant hydrological application of weather radar component are Work Package 3 "Evaluation of a vorticity indicator for extreme events" (University of Salford) and Work Package 4 "Spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models" (CEH Wallingford).

What are the deliverables and are they relevant to hydrological applications of weather radar?

- *WP4 - Historical extreme storm selection.* Consultation with Met Office and Environment Agency staff identified a selection of extreme storm events that were recent enough to have radar data coverage. Some of these storms generated floods in catchments that had historical gauged flow records. The extreme storms and associated case study catchments were chosen to encompass the main types of extreme storm: convective, frontal and orographic. The supporting data received from the Environment Agency and Met Office forms a basis for model calibration and testing using radar data and/or raingauge data and for generating artificially enhanced storms that are more extreme for use in hydrological model destruction testing and considering "what if?" scenarios (see below).
- *WP4 – Assessment of hydrological modelling performance over the historical events for case study catchments using a lumped and distributed model.* Two hydrological models were used in the assessment and were selected as being representative of the types of model likely to be encountered in practice, now or in the future. The PDM (Probability-Distributed Model) is a simple lumped rainfall-runoff model that is used operationally and forms part of the Environment Agency's NFFS (National Flood Forecasting System). The Grid-to-Grid model is of spatially-distributed form and able to take full advantage of spatial weather data but is not currently used operationally by the Environment Agency.

  Three types of rainfall estimator were considered: (i) radar data, (ii) raingauge data and (iii) a combination of raingauge and radar data. New methods for deriving rainfall estimates over catchments and/or gridded areas were developed that produce linear raingauge weights using an integrated multiquadric surface. These were extended to obtain estimators that combine radar and raingauge estimates. The assessment exercise revealed the importance of areal rainfall estimation on rainfall-runoff model performance: generally the raingauge estimators provided the best modelled response. The best hydrological modelling results using radar data were obtained when it was combined with raingauge data and occasionally this outperformed the raingauge-only results.

  The research shows that radar data can be successfully used in rainfall-runoff modelling and is particularly effective when combined with raingauge data. These are important messages that need to picked up and used in future research and operational practice.

- *WP4 – Develop a credible approach for creating extreme rainfall scenario datasets and provide guidelines for their use in evaluating the extreme event performance of hydrological models.* A methodology for transforming an historical extreme radar rainfall dataset to create a more extreme one has been developed. The rainfall transformation tool can change the position, movement, orientation, size and shape of a chosen storm so that – for a given catchment, duration and return period – the modified storm attains rainfall amounts derived by the Flood Estimation Handbook methodology. These modified storms have been used in flood response experiments involving the hydrological models – allowing a storm to be transposed over a catchment and modified in speed and direction, as well as shape and magnitude – to understand the genesis of flood response as a function of storm characteristics, catchment form and soil wetness. This has highlighted how the spatial information contained in radar data, combined with the spatially-distributed form of the Grid-to-Grid model, can provide improved flood forecasting in extreme and/or unusual storm to catchment situations.

A key deliverable to the Environment Agency is the Extremes Dataset. This contains historical radar, raingauge, river level/flow and MORECS potential evaporation data for the case study events, calibrated PDM parameter files and the modified storm data. The spatial rainfall data can be viewed and processed (e.g. constructing catchment average rainfall) through Hyrad. Software has been developed to allow users to upscale any storm (historical or modified) in the dataset and relocate it to a desired location/catchment. The Extremes Dataset and associated software provides a unique platform for hydrological model testing and development, including the use of weather radar data, and should be used to its full potential.

- *WP3 – Evaluating the vorticity indicator.* The aim of this WP was to assess the utility of vorticity analysis in identifying extreme convective events. The proposed technique was to be assessed using NWP (Numerical Weather Prediction) model output data and data from the Chilbolton S-band Doppler radar and, possibly, the new south-east C-band radar system. Unfortunately data from the south-east radar was not available in time. Results show that a model resolution of 1 km or better is needed for the vorticity tipping term to provide any useful information in predicting convective development. Although the Met Office are moving to a 4 km operational grid scale for NWP soon, a 1 km grid scale is someway off. Therefore the operational benefit for improved convective event recognition and the possible implications for flood forecasting are difficult to assess at present and should be re-visited when a 1 km NWP model is operational.

What are the timescales for delivery?

- *WP3&4* - The Technical Report, Technical Summary and Work Package reports have been completed and links were added to the Defra/Environment Agency R&D website (http://www.defra.gov.uk/environ/fcd/research) in September 2007.
- *WP4* - The Extremes Dataset DVD is complete and has been passed to the Environment Agency as part of the March 2007 dissemination workshop.

How will the pull-through mechanisms to operational application be implemented?

- *WP4* - Environment Agency staff representation on the Project Board should ease the operational pull-through of relevant research output. In particular the Extremes Dataset will be passed to the Environment Agency for use in model destruction testing and running “what if?” scenarios. Guidelines for applying the Extremes Dataset have been created and reinforced during a training workshop.
- *WP4* – The PDM models that have been calibrated for the case study catchments have been made available to the Environment Agency as part of the Extremes Dataset. As the PDM is available throughout the Environment Agency as part of the NFFS, these can easily be put into operational practice.
- *WP4* – The spatially distributed Grid-to-Grid formulation is ideally suited to use spatial radar-derived rainfall estimates and proved especially successful in modelling catchments controlled predominantly by topography. The model should add value when forecasting the area-wide flood response, at gauged and ungauged locations, from extreme and/or unusual storms. An operational trial of the Grid-to-Grid model is recommended but as this does not form part of the FD2208 “Extreme Event Recognition – Phase 2” project brief, additional funding is required.

- *WP3* – Had the vorticity tipping term proved useful at grid scales in current operational use (12 km) an agreement was in place to include it as part of an operational trial under WP2 (not reviewed here).

What training plans have been put in place?

- *WP4* – A workshop took place during March 2007 to give key Environment Agency staff training on using the Extremes Dataset. The accompanying documentation includes training exercises that could be used for in-house training.

How will the programme/project deliverables be disseminated and to whom?

- *WP3&4* - Contract reports will be communicated to the scientific and user community through the Environment Agency/Defra website and copies circulated to key individuals. In addition journal papers and conferences will be used to communicate the research outcomes.
- *WP4* - The Extremes Dataset and accompanying documentation have been delivered to the Environment Agency during the training workshop and all regions have a copy. The Environment Agency may pass the dataset on to contractors where appropriate. However, there is no definite plan for a wider dissemination of the Extremes Dataset (e.g. the BADC website) at present but this should be pursued.

What are the scientific risks?

- *WP3* - The south-east (Thurnham) radar data may not become available in time. This proved to be the case but sound planning of the project meant the Thurnham data were only to be used in addition to the already available Chilbolton data and so did not impact on project completion.

What are the operational risks?

- *WP4* - There is a risk that users may not use the Extremes Dataset in an appropriate manner. This should be mitigated by the accompanying documentation and training workshop.
- *WP4* - There is a risk that the calibrated hydrological models are not implemented operationally, particularly in regions that do not currently use the PDM routinely.
- *WP3* – Since the vorticity analysis did not (under current operational conditions) improve the prediction and identification of extreme convective events it will not be brought into current operational practice.

What further developments are required and what are the funding opportunities?

- *WP4* - The raingauge-adjustment of radar data, at a 15 minute time interval using a multiquadric surface fitting technique, provided significantly improved rainfall-runoff model performance relative to using unadjusted radar data. Since this was only implemented for the case study catchments, further work might investigate its implementation on a nationwide scale and its role in nowcasting rainfall.
- *WP4* - The spatially distributed Grid-to-Grid formulation is ideally suited to use spatial radar-derived rainfall estimates and proved especially successful in modelling catchment flood responses controlled by topography. Funding has been provided from the Environment Agency/Defra R&D programme to trial the model within the NFFS operational framework.
- *WP4* – Conceptual-physical distributed models (like the Grid-to-Grid model) should be improved to capitalise on spatial soil/geology/land-cover datasets, thus allowing full exploitation of the spatial information provided by radar-based rainfall estimates.
- *WP4* – The Extremes Dataset provides a unique platform for hydrological model testing and development, including the use of weather radar data, and should be

used to its full potential. Its wider dissemination beyond the Environment Agency should be considered if possible (e.g. the BADC website).

- *WP3* – Within the next 5 – 10 years it is likely that the Met Office will use a grid scale of 1 to 1.5 km for operational NWP. Therefore the use of the vorticity tipping term couplet as an indicator of convective development should be re-visited when a model at this resolution is operational.

3.6 Assimilation of Radar Data into Numerical Weather Prediction Models in the UK

What are the deliverables and are they relevant to hydrological applications of weather radar?

The goal of the assimilation of radar data into the Met Office mesoscale model is to replace the existing nowcasting system and improve the short period forecasts of hazardous weather, especially flood risk. The assimilation of radar data and its interaction with microphysics and dynamics into numerical prediction models is a challenging scientific problem.

The aim is to deliver a 1-1.5 km resolution forecast over the UK from 0 – 6 hours which is run every hour. This will represent a major advance on the present system which over the UK has a 4 km resolution and is run every three hours; the radar data, smoothed to 15 km resolution, is currently incorporated together with 15 km cloud and relative humidity information and introduced to the model via latent heat nudging of the forecast. Work is underway testing direct assimilation of precipitation rates in 4D-Var, initially at 12 km resolution in the NAE (North-Atlantic-European) model. The next step is to develop the direct use of radar reflectivity for assimilation in 4D-Var at the convective scale (1.5 km).

The new data sources are: (i) radial Doppler winds following the initial development with the Chilbolton radar on the operational radar, the major requirement is to define the observation errors, (ii) direct assimilation of surface precipitation rates and/or accumulations, (iii) reflectivities – the forward model is currently being constructed, and (iv) refractivities and clear air Doppler winds from insects. Sources (i), (ii) and (iii) are currently being investigated by the Met Office whilst (iv) is being pursued in the recently approved FREE grant. This grant is a collaboration between Reading University, the Met Office (JCMM at Reading) and CEH, and aims to interface the probabilistic rainfall forecasts with a hydrological model to produce an ensemble of flood predictions.

The development of a 4D-Var system at 4 km resolution is underway and Reading University (DARC) is exploring the use of Kalman filters.

Delivering more accurate 1-1.5 km resolution forecast over the UK from 0 – 6 hours, run every hour and with quantified estimates of the errors, would be of benefit to hydrologists.

What are the timescales for delivery?

- The 1 to 1.5 km model with forecasts from 0 to 6 hours every hour should be operational in 2009-2010.
- The Met Office is running a 4 km version of their operational model since early 2005. The 1.5 km version is now (Dec 06) available 'on demand' for various selected areas of the UK.
- The probabilistic forecasts of flood risk should be available at the end of the FREE project in early 2010.

How will the pull-through mechanisms to operational application be implemented?

- The Met Office are responsible for the overall development of the new system and its operational implementation.
- A decision to Dopplerise the radar network has been taken. This will be done through hardware at 8 sites and a software approach will be trialled at the remaining sites.
- The refractivity technique is currently being tested on the Cobbacombe radar. Results are encouraging with good data being derived out to about 50 km. The data are recorded on a case study basis. Work by the Met Office is required to test this data further, examine implications for the data transmission bandwidth, and ultimately incorporate into the operational system and deliver the data to researchers.
- This work will be pulled through to hydrological application through use of these improved products within the flood forecasting systems operated by the Environment Agency across England and Wales and by SEPA in Scotland.

What training plans have been put in place?

- Joint meetings between the university academic groups and Met Office scientists together with internal Met Office meetings are held to review the progress.
- A communication plan is needed as required by the FREE Science Plan.

How will the programme/project deliverables be disseminated and to whom?

- The forecasts of the Met Office high resolution mesoscale model will be delivered to customers by the same means as are used for the present model.

What are the scientific risks?

- The Doppler velocities derived from insect returns might not be representative of the air motion.
- The keyhole samples of refractivity and insect winds close to the radar might not be truly representative of winds on a larger scale.
- The improved assimilation schemes introduced into the model could result in no impact or degradation to the forecast of future precipitation. However, before such a model is released for operational use the Met Office will carry out a detailed analysis of model performance to ensure that it is superior to the current model.

What are the operational risks?

- The Dopplerisation of the network may be delayed and the implementation of the resources for observing refractivity operationally may not be approved.
- Possible operational difficulties in using ensemble rainfall forecasts within networks of hydrological and hydraulic models of river systems.

What further developments are required and what are the funding opportunities.

- The definition of the error covariances of the new data is a crucial aspect and their use to develop an ensemble of initial conditions.
- A system of quality control of the new refractivity data and insect winds is required.

3.7 FLOODSITE Programme

What are the deliverables and are they relevant to hydrological applications of weather radar?

The main objective of the FLOODsite Integrated Project is to provide an integrated framework for flood risk management from operational to strategic planning time horizons. The research in FLOODsite, therefore, is dealing with the development of a European methodology for a consistent approach to risk analysis, risk assessment and risk reduction. FLOODsite is considering the whole flood risk system; this comprises the natural hazard, the socio-economic and ecological vulnerability as well as societal interventions by physical measures and policy instruments.

Flooding is considered from rivers, estuaries and coasts in a uniform way. Specific flood processes and mechanisms are being investigated, ranging from the high level of risk at a river-basin, estuary and coastal-process-cell scale down to the detailed site specific conditions. Of special interest are simulations of comprehensive risks of river floods including multiple areas of vulnerability, flash floods and flash flood forecasting, coastal extremes and coastal morphodynamics. FLOODsite, moreover, seeks to identify technologies and strategies for sustainable flood mitigation and defence, recognising the complex interaction between natural bio-physical systems and socio-economic systems, to support spatial and policy planning in the context of global change and societal advance.

Several pilot studies are included in FLOODsite representing all main types of floods. These are the Elbe River basin, the Tisza River basin, four flash flood basins (in Italy, France and Spain), the Thames River estuary, the Scheldt River estuary, the Ebro River delta coast and the German Bight coast. The integrated methodology of the project will be developed under consideration of the specific requirements of flood risk management at these sites. Thus, in some sites emphasis is put on sustainable risk reduction in the long-term (e.g. the Elbe River basin), whereas at other sites the operational defence plays an important role (e.g. the Thames River estuary). The work on flash flood forecasting is aimed in the flash flood basins and includes research into the statistical analysis of flood occurrence, the quality control of radar estimates of precipitation, the merging of radar and raingauge data and the use of radar in hydrological studies. In terms of integration, FLOODsite will also develop decision support systems (DSS) for long-term planning and operational flood risk management.

What are the timescales for delivery?

FLOODsite is a EU FP6 programme of research covering a four year period due to end in 2008. However some research output is now beginning to emerge in the literature.

How will the pull-through mechanisms to operational application be implemented?

- The radar work is being carried out in France, Italy and Spain with some support from the Netherlands. Any operational applications are only likely in these countries as the work is unlikely to add much to procedures currently employed in the UK.

What training plans have been put in place?

- The research using radar data is being carried out by postdoctoral researchers and postgraduate students working with established scientists.

How will the programme / project deliverables be disseminated and to whom?

- The FLOODsite programme has a website on which are placed project reports etc. However at present much of this material is only available to those participating in the programme and a few others having special access.
- However research papers are now being written and published in the open literature. FLOODsite will generate a final report for the EU which will be available in due course.

What are the scientific risks?

- There is no doubt that scientific output will be generated and published. However so far the output has not been particularly ground breaking and it seems likely that it will not be of particular relevance to UK operational practice.

What are the operational risks?

- The field programmes are being implemented, and therefore the risk of no data being generated is low. The relevance to UK operational practice is also low at present.

What further developments are required and what are the funding opportunities?

- FLOODsite has brought together a number of groups working with radar data, although not any radar groups in the UK. It is possible that these groups will consider joining consortia bidding for further funding in the EU FP7 programme. Those working with radar in the UK might consider joining such consortia if the opportunities arise.

3.8 Environment Agency/Defra project SC040023: Assessment of Radar Data Quality in Steep Upland Catchments

What are the deliverables and are they relevant to hydrological applications of weather radar?

This study has provided an assessment of radar data quality in upland areas. The uncertainties in radar measurements provided by the current operational radar processing chain have been quantified for three upland regions of contrasting terrain and radar coverage. Case study analyses have provided an indication of the variability of radar data quality between events characterised by the orographic enhancement process in upland regions and highlighted the main factors which affect this quality. The potential options for improving this quality by addressing these factors have been discussed.

It has been shown that radar data quality at long range over hills is currently worse than over lowland areas. Comparison of radar data with rainfall measurements from surface raingauges over a year period show that typically 97% of hourly rainfall accumulations in excess of 1 mm are detected by the radar, similar to the average detection rate across all regions of the UK. However, the quantitative accuracy of those data is as much as three times worse than observed in more lowland areas. Range from the radar is the most important factor affecting radar data quality across upland areas.

The impact of applying orographic corrections to the background radar data was found to be most beneficial for measurements across the Upper Conwy region, leading to improved agreement between radar and gauge data by typically 56%. The application of the current orographic correction scheme was found to improve radar data quality in each of the upland regions considered.

Radar data quality is highly variable between different events characterised by orographic effects and between different gauge locations within each region for a given event.

Radar data quality over upland areas is currently of insufficient quality for quantitative use in flood forecasting. Analysis of total rainfall accumulations during rainfall events has shown that typically only 50% of rainfall events during the study period when in excess of 30 mm was recorded by surface gauges would have been detected as exceeding that threshold using the available radar data. The application of spatially and temporally varying orographic corrections was identified as having considerable benefit to these data. While gauge measurements are best suited to measuring surface rainfall at a given location, the inadequate spatial resolution provided by gauge data in upland areas has been highlighted. Used in conjunction with available gauge data and given the knowledge concerning radar data quality gained from this study it seems clear that radar data can be used as a key tool for flood forecasting in upland regions, particularly in those locations where gauge data is unavailable.

An assessment of the likely impact of improving the radar coverage across North Wales suggests that there is little to be gained for flood warning and forecasting in the Upper Conwy region from such a development, particularly given the practical limitations on suitable locations for additional radars in the region. The benefits of developing the radar coverage across the North Wales region should be reconsidered once the performance of the proposed improvements to the orographic correction scheme has been assessed.

Improvements to the radar data processing are likely to contribute most significantly to improving flood forecasting in upland areas. The quantitative accuracy of radar measurements in upland areas has been found to critically depend on the orographic corrections applied to the available background data, particularly in those upland regions where radar coverage is only available at ranges in excess of 50 km. The dependence of the orographic corrections applied across England and Wales on climatology has been identified as a potential source of error, and it is thought that adoption of a physical modelling approach across the entire radar domain may improve quantitative accuracy of the radar system. This development is likely to bring benefits to radar data quality across upland regions across the UK, other than those considered in this study.

What are the timescales for delivery?

- The final report was published on 1 November 2006.

How will the pull-through mechanisms to operational application be implemented?

- Several possibilities for improving the orographic corrections applied to radar data have been identified during this study. Given that the current corrections applied across England and Wales are based on climatology, there is little scope to modify the distribution or magnitude of these corrections or to take advantage of any developments to the available model output or of improved understanding of the characteristics of the enhancement process. Modifications to the correction fields applied across England and Wales therefore require a change to the approach used. The simplest option would be to replace the current correction scheme with the new one across the radar network domain.

What training plans have been put in place?

- It is recommended that the training material provided to Environment Agency flood forecasters should be updated to reflect the new understanding of radar data quality in upland areas and of its use for flood warning applications in these regions provided by this study.
- The training material provided to Met Office forecasters should also be updated to include guidance on radar data quality in upland areas.

How will the programme/project deliverables be disseminated and to whom?

- Results will be communicated through the scientific community through the Environment Agency/Defra website and the final report will be circulated to key individuals.

What are the scientific risks?

- It will prove impossible to resolve additional variability in the orographic enhancement.

What are the operational risks?

- Computing the orographic corrections required in real-time as part of the radar data processing chain is likely to prove computationally expensive, particularly given increasing demands on the radar processing system from additional radars and other product developments.
- Comparison of the available radar data during these events with the corresponding surface gauge rainfall measurements has illustrated varying quality of radar performance, between different cases, between different regions, for different available radars with coverage across a region, and at different gauge locations within each study area.
- The quantitative use of these data during any given rainfall event still requires careful comparison between the radar measurements with surface rainfall measurements from at least one gauge at an upland location within the rainfall region. The analysis has highlighted several deficiencies of radar rainfall measurements across upland areas and several factors which may contribute towards these deficiencies.

What further developments are required and what are the funding opportunities?

- Conduct an additional study to assess the relative benefits of applying model derived orographic corrections compared to climatologically based corrections. If resources permit, it is recommended that alternative correction formulations are considered. The potential for locating a radar at closer range for coverage across North Wales might need to be reconsidered at this stage if the new formulation is found to improve data quality.
- If found to produce the necessary improvements to data quality, implement the model-derived correction scheme as part of the operational radar data processing chain. It is suggested that this is conducted using the orographic enhancement fields currently produced as part of the STEPS post-processing system (Section 13). Should a comparison study of several alternative model approaches be conducted, the best performing correction algorithm should be implemented for use in both the radar and STEPS post-processing systems.
- Monitor operational performance of radars across upland areas during future events characterised by orographic effects. In particular, it would be beneficial to analyse a strong rainfall event in the Upper Exe region involving northerly flow for which it is known that orographic enhancements in the region are largest. This would provide a very useful characterisation of radar performance at close range in conditions of orographic enhancement.
- Develop radar data quality indicators, based on the magnitude of orographic corrections applied and complexity of the underlying terrain, to highlight regions and periods of increased uncertainty of the radar data. It is envisaged that these quality indicators should vary both spatially and temporally, defined for each radar pixel for every radar scan. Such information may be utilised in the selection of radar data to include in the composite product and is likely to be of use to highlight the level of uncertainty in rainfall measurements to flood forecasters.

3.9 Weather Radar and Bathing Water Quality Signage Project

This forthcoming SNIFFER (Scotland and Northern Ireland Forum for Environmental Research) Research and Development project is aimed at improving the accuracy of bathing water quality predictions through the use of weather radar. SEPA provides daily information on predicted water quality at 10 EC bathing water sites during the summer bathing water season. Current forecasts are based on recorded rainfall and river flow information using SEPA's network of gauges. However, in some instances the water quality conditions can change rapidly due to changing weather patterns. This research aims to develop a method that uses radar data linked to a water quality model that better predicts poor quality events.

In March 2006 the revised Bathing Water Directive (2006/7/EC) entered into force and will be enacted in the UK by Regulations by March 2008. Key features are tighter microbiological standards to be met by 2015 and increased provision of public information, with includes real-time predictions of bathing water quality.

4. Report on Strategic Area 2

4.1 Further development of the Committee website

The Committee website (www.iac.rl.ac.uk) has been updated during this session to include further work undertaken by the Committee, and to reflect changes in membership. Under the 'Community Information' heading links have been added to the NERC Flood Risk from Extreme Events (FREE) and EPSRC Flood Risk Management Research Consortium (FRMRC) programmes. In addition, all session reports of the Committee since its formation in 1991 have now been made available, together with reports from the earlier NERC Steering Committee on the Hydrological Applications of Weather Radar.

4.2 Identify opportunities for raising awareness of weather radar

4.2.1 Opening of the Thurnham Weather Radar on 12 October 2005

Seven members of the Committee attended the opening ceremony of the dual–polarisation radar at Thurnham in Kent (see Figure 2). The radar arose out of the need for improved detection and forecasting of storms and floods following the Autumn 2000 floods when 2,500 properties were affected. Work started in August 2001 to secure funding and identify a potential site and project approval was secured in December 2003. One of main challenges has been the specification, procurement and construction of this new generation of radar.

At the opening ceremony, Chris Haggett gave a presentation of the work of the Interagency Committee and copies of the 5th Session Report were circulated to those in attendance.

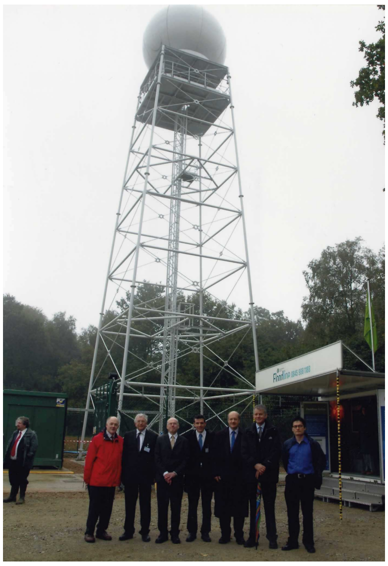


Figure 2 Opening of the Thurnham weather radar. Left figure: (l-r) John Hammond (BBC), John Horne (The Mayor of Maidstone) and Russell Turner (Environment Agency). Right figure: Members of the Committee, (l-r) Anthony Holt, Bob Moore, Malcolm Kitchen, Steven Cole, Noel Higginson, Chris Haggett and Miguel Rico-Ramirez.

4.2.2 BHS and ICE conference 'Real Time Flood Forecasting - Developments and Opportunities', 14 November 2006.

This conference was held to present and discuss new research and technological advancements in hydrometeorology and flood forecasting. The Committee supported the conference by providing three speakers.

Michael Cranston (SEPA) gave a presentation on the flood forecasting challenges in Scotland and the development of a flood forecasting system for 3 significant river basins in the Clyde, Irvine and Kelvin. Michael presented work on the development of the FEWS (Flood Early Warning System) Scotland and the use of PDM rainfall-runoff models, emphasising the importance of radar in these models and welcoming the addition of a new radar for Central Scotland.

Bob Moore (CEH Wallingford) presented work on extreme event recognition and flood response modelling, covering in particular how extreme storm events detected by radar can be used to understand the genesis of floods and to destruction test models. The convective storms of Boscastle (16 August 2004) and Carlton-in-Cleveland (10 August 2003) were used in case study catchments, having been first transformed spatially and temporally, to assess changing flood response. New distributed grid-based models had the power to 'shape the flood' for a given storm pattern, identify situations of high flood vulnerability and provide a basis for flood warning at ungauged locations.

Chris Haggett (Environment Agency) gave a presentation on the Floodline Warnings Direct service, the first integrated multimedia warning system in the UK that has recently been launched. The new service places increasing emphasis on the need for accurate and timely forecasts to ensure the delivery of improved flood warning messages to new and existing customers.

There were also presentations on developments in precipitation forecasting including the UK Post Processing system (a continuation from the Nimrod system) and the use of ensemble methods to provide probabilistic forecasts.

4.2.3 Audio-visual archive

During the session period, the Committee has made a catalogue of videos (e.g. educational videos, TV interviews, documentaries) where weather radar has been prominent and, in particular, where it's role in flood forecasting has been discussed. These have been transferred to a single DVD which is available on loan from:

National Hydro-Sciences Library, Centre for Ecology and Hydrology, Wallingford, Oxon, OX10 8BB, UK.

A full listing of the holdings is given in Appendix D. The Committee welcomes any other suggestions of UK-based video material that could be added to the archive - please contact the Technical Secretary with suggestions.

4.2.4 Upcoming conferences where the role of weather radar will be prominent

The role of weather radar will be prominent at the following conferences and meetings:

International Symposium on Weather Radar and Hydrology,
10-15 March 2008, Grenoble, France. http://www.wrah-2008.com

Weather Radar Rainfall, BHS South West meeting,
March 2008 (Date TBC), University of Bristol.
http://www.hydrology.org.uk/meetings_events.asp

ERAD 2008, 5th European Conference on Radar in Meteorology and Hydrology,
30 June – 4 July 2008, Helsinki, Finland. http://erad2008.fmi.fi/

4.3 Exploit opportunities for publicising the role of weather radar in detecting and forecasting of severe weather/flood events

During the session period several examples were identified where weather radar was used in detecting and forecasting severe weather/flood events. This is not intended to be an exhaustive list but is a selection that promotes the role of weather radar in the detection and forecasting of such events.

4.3.1 The Boscastle storm and flood, 16 August 2004

Heavy, thundery downpours developed by midday across south-west England on 16 August 2004. These showers formed bands which aligned themselves with the wind helping to maintain the heavy rain across certain areas of north Cornwall for several hours. The trigger mechanisms for these storms appeared to be convergence of winds along the coast and the high ground in the local area which also helped to generate showers. The serious nature of these floods was exacerbated by the local topography around Boscastle.

The catchments around Boscastle are within the area covered at 2 km resolution by the Cobbacombe Cross radar, see Figure 3. In this event, the highest measured accumulation occurred within the Valency catchment, upstream of Boscastle. Thus the radar was able to correctly identify in real-time the catchments at greatest risk. The radar data also reveals that the spatial distribution of rainfall was correlated with the topography.

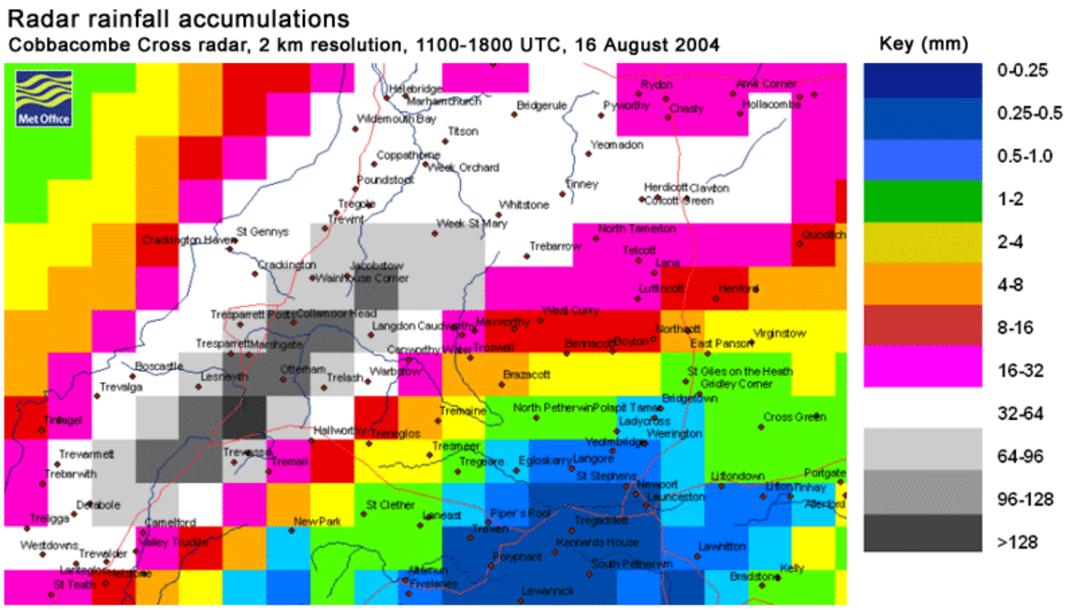


Figure 3 Radar rainfall accumulations using 2 km Cobbacombe Cross radar data for the period 1100 - 1800 UTC, 16 August 2004.

4.3.2 Trossachs and Central Highland Storm, 18 August 2004

Introduction

On 18 August 2004 locally very heavy rainfall caused severe disruption to Callander and the Ogle and Ample Glens. The damage caused by the torrential rainfall included a significant landslide that caused major erosion to one hillside and damage to the A85 Stirling to Crainlarich Road and the destruction of the historic Eden Ample Bridge.

As the most intense area of rainfall was quite narrow, SEPA's two raingauges in the area – Strathyre and Auchinner – failed to record the most intense area of the storm. The Strathyre and Auchinner gauges recorded 43.8 mm and 18.0 mm respectively. However, the more intense area of the storm was detected using the Corse Hill radar with both 5 km and 2 km resolution observations: see Figure 4.

Rainfall Assessment using Single Site Corse Hill Radar

The Corse Hill radar measures out to 250 km at 5 km resolution. Storm rainfall (08:00 to 20:00) as measured by the 5 km resolution is 67.22 mm over Callander and 63.96 mm across Glen Ample: see Figure 5 a and b. Peak intensities for the event were 98.3 mm/hr at 15:30 and 58.9 mm/hr at 15:55 respectively.

A more detailed resolution for 2 km radar cells can be provided out to 100 km, which covers Callander and Glen Ample: see Figure 5 c and d. These provide a better spatial representation of rainfall, particularly for convective events. This is seen in the higher rainfall totals measured in comparison with 84.54 mm over Callander and 75.84 mm over Glen Ample. Peak intensities are also higher with 147.0 mm/hr at 15:25 and 98.0 mm/hr at 15:45 respectively. Put another way, Figure 5 c illustrates that across Callander 47.7 mm of rain is measured in the twenty minutes between 15:25 and 15:40.

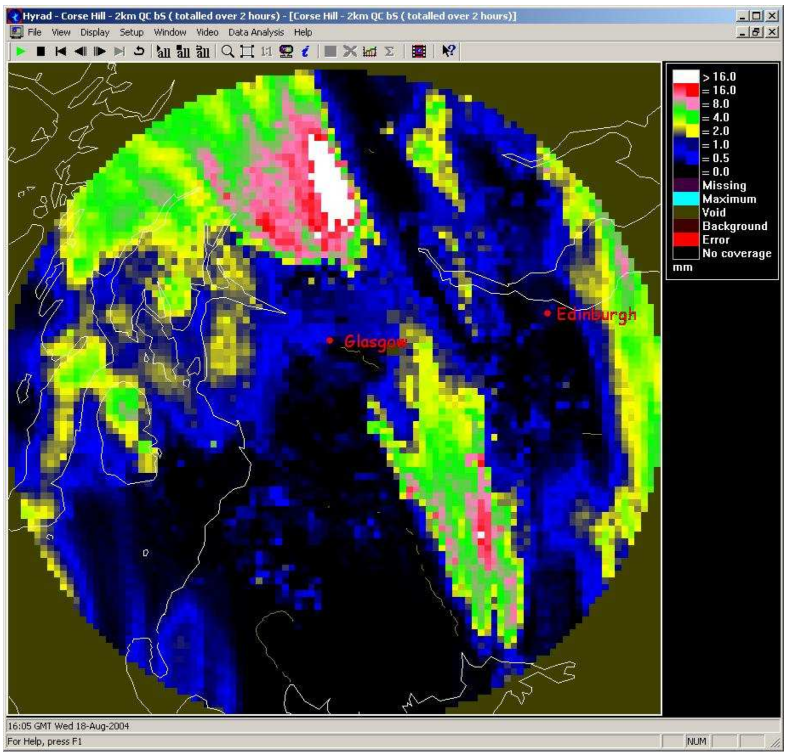
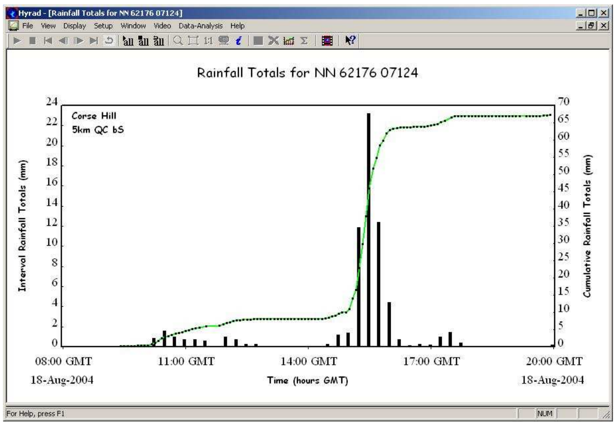
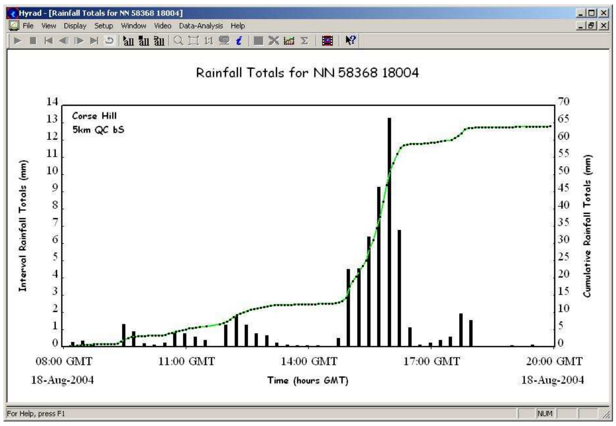


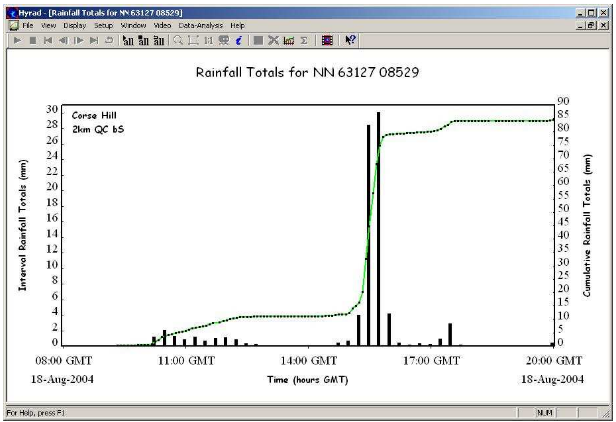
Figure 4 Radar rainfall accumulations using 2 km Corse Hill radar data for the period 14:00 to 16:00, 18 August 2004

(a) 5 km radar data, Callander **(b) 5 km radar data, Glen Ample**





(c) 2 km radar data, Callander **(d) 2 km radar data, Glen Ample**



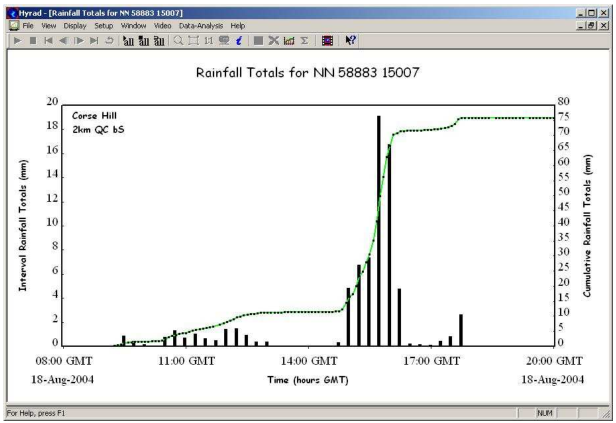


Figure 5 Hyetographs using 2 and 5 km Corse Hill radar data for the cells covering Callander and Glen Ample

4.3.3 The London tornado, 7 December 2006

During 7 December 2006 a tornado damaged around 100 homes in North-West London. The tornado formed on a squall line about 25km to the south-east of the Chenies radar. Figure 6 is a Doppler wind image from Chenies and reveals a horizontal wind shear of about 50m/s over a horizontal distance of order 1km. There is also evidence of rotation in two or three 'embryonic' tornados further south along the squall line.

4.3.4 Line convection over Tayside and Perthshire, 14 December 2006

A period of extremely wet weather affected many parts of Scotland over the 13th and 14th December 2006. This spell of wet weather resulted in flooding to a number of Tayside and Perthshire communities, with several hundred homes being evacuated in Milnathort as a result. The image displays a line convection detected in the early hours of the 14th December. The narrow nature of this band of rain meant that many of SEPA's raingauges were unable to detect the high intensity rainfall as shown by the radar image in Figure 7.

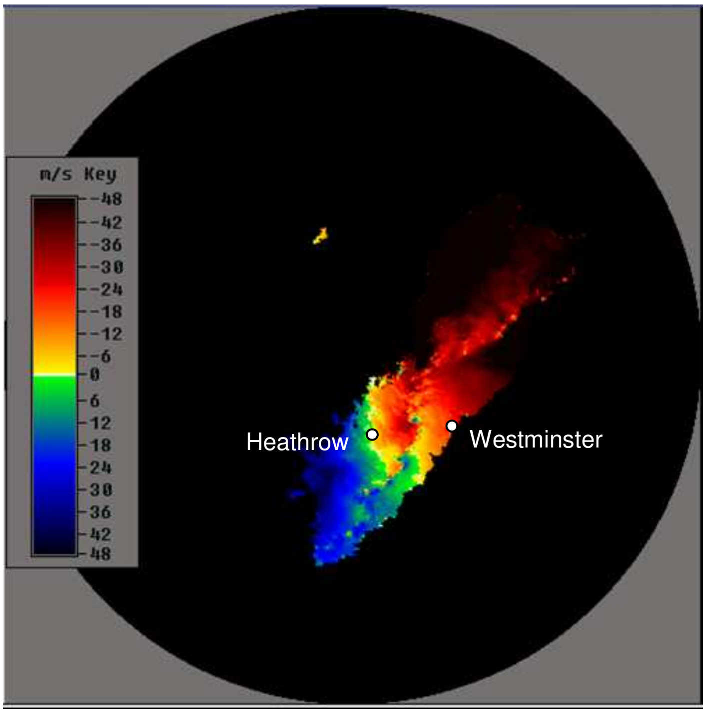


Figure 6 Chenies Doppler wind image of the London tornado. The key shows speed towards/away from the radar.

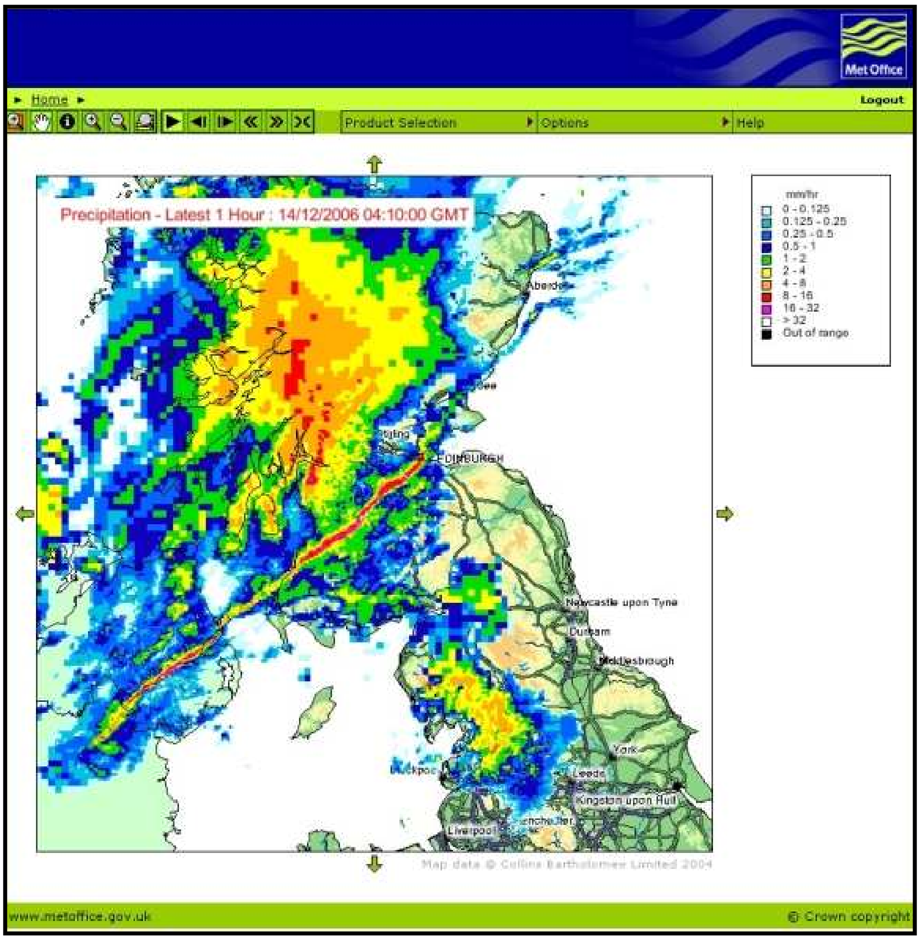


Figure 7 Radar rainfall accumulations using Nimrod 1/2/5 km composite radar data for the period 03:10 to 04:10, 14 December 2006

4.4 Identify opportunities for the funding of training

Training in weather radar and its hydrological application is important for Operating Agencies and for stimulating research. A major external source for funding is available through EU Framework Programme 7, including Marie Curie awards. Section 4.4.1 outlines the relevant research areas of the Programme and section 4.4.2 gives details of the Marie Curie Actions. A case study of how a Marie Curie Research Training Grant may be used for training and research into the Hydrological Use of Weather Radar is given in section 4.4.3.

4.4.1 EU Framework Programme 7 (FP7)

Under the EU FP7 there are several different forms a bid for funding may take, including Marie Curie awards and Networks of Excellence. However, the main vehicle for funding basic research is known as a Collaborative Project. The specific research activity that might include the use of weather radar is Activity 6.1: Climate Change, Pollution and Risks. A summary of Activity 6.1, focussing on the possible relevance to radar, is given below.

The focus of Activity 6.1 is integrated research addressing the functioning of climate and the earth system, including the ocean and the polar regions. This is needed to determine the causes of changes in the past and to predict better their likely future evolution. Observation, analysis and modelling must be used to assess climate-induced changes to the water cycle and the occurrence of extreme events. Multidisciplinary/interdisciplinary research aiming to better understand the underlying processes should be pursued to improve detection, prediction and forecasting methods. Environmental and societal resilience as well as damages due to major natural hazards need to be quantified.

Research topic ENV.2007.1.3.1.1. (European Storm Risk), within Activity 6.1, has particular relevance to the hydrological use of weather radar. The main aim is to develop a probabilistic mapping and early warning and information system for the multiple risks triggered by storms, supporting long-term disaster reduction as well as timely relief operations. The topic is identified as:

Sub-activity 6.1.3. Natural hazards (Indicative available budget: 13 M€)
Area 6.1.3.1. Hazard assessment, triggering factors and forecasting
ENV.2007.1.3.1.1. European storm risk

4.4.2 Marie Curie Actions under the EU Framework Programme 7 (FP7)

Marie Curie Actions will be funded under the Framework Programme 7 Specific Programme 'People'. Its main objective is to strengthen the human potential in research and technology in Europe and to make Europe a more attractive place for researchers to work. A key focus of the 'People' programme therefore is to have a structuring effect throughout Europe on the organisation, performance and quality of research training, on the active career development of researchers, on knowledge-sharing through researchers between sectors and research organisations, and on strong participation by women in research and development.

The 'People' programme will be implemented through a set of Marie Curie Actions addressing researchers at all stages of their professional lives, from early-stage research training to lifelong training opportunities. They will provide opportunities for individual researchers and organisations - universities, research institutes and companies - to develop their research skills and training capacity, by building on industrial and academic expertise within Europe and across the world, through staff exchanges, secondments, postgraduate and postdoctoral fellowships.

A key feature of the Marie Curie actions is the mobility requirement, and all fellows funded under the programme will be expected to undertake mobility from one country to another, subject to specific requirements for the different schemes. The Marie Curie Actions are:

1. The initial training of researchers (the first five years)
2. The life-long training and career development of experienced researchers
3. Industry-academia partnerships and pathways
4. The international dimension (for Member States and Associated Countries with which the EU has an agreement)
5. Specific actions (creation of a genuine European labour market)

In order to be eligible, researchers must meet certain requirements in terms of minimum or maximum number of years' of research experience (full-time equivalent) and transnational mobility.

More information
The first FP7 calls for Marie Curie actions are now open. See:
http://ec.europa.eu/research/future/index_en.cfm

4.4.3 Marie Curie Research Training Grant: A radar hydrology case study

The EU issues Marie Curie Research Training Grants for the mobility of young researchers under their Framework Programmes. Prior to FP7, Marie Curie Research Training Grants were available under the Training and Mobility of Researchers (TMR) programme of the European Union (EU). The Information Package and the Application Forms can still be seen in electronic form at http://www.cordis.lu/tmr/src/grants1.htm whilst the home page of TMR is at http://www.cordis.lu/tmr/home.html.

The Grants provide a valuable opportunity to promote research between EU partner countries. A case study example is given here to illustrate how the Training Grant may be used to advance research on the Hydrological Use of Weather Radar. In this case, it supported a two year study undertaken at the Institute of Hydrology (now CEH Wallingford) over a two year period ending in the year 2000. Prior to the grant award, there had been existing collaboration with the University of Padua (Italy) under previous EU projects concerned with radar hydrology. The grant provided the opportunity for Dr Enrico Frank to work at Wallingford for two years under the scientific supervision of Bob Moore in the Host Country and Marco Borga in the Grant Holder's country Italy. The proposal, entitled "Use of radar-derived rainfall data for hydrological modelling in hilly and mountainous regions" was submitted in July 1996 and approved by the European Commission in September 1997. Initial meetings in Padua and Wallingford in September and December 1997 were used to develop the collaboration.

The Information Pack, dated 1996, provided details of the Grant application procedure. The proposal submission required a description of the research project to be carried out at the host institution under the following headings:

Title of the research
1. Current state of the art
2. Detailed description of the research project, including innovative aspects
3. Work planning and methods
4. Expected impact and benefit of the requested training

5. Expected results of the project
6. Links with any other Community programme
7. Reasons for the choice of the host institution

The project began in January 1998 with Enrico Frank's arrival at Wallingford. Scientific reporting requirements of the Grant were for an annual report and a final report at the end of the second year. The Final Report was entitled "Long-term analysis and assessment of radar rainfall estimates in hilly terrain".

The scientist in charge was required to complete a Financial Report (the grant covered salary costs and mobility and travel allowances) and Grant Questionnaire (identifying benefits to: advancement of science, to host institution and grant holder, to developing links with other research groups, and to training). A Scientific Report was also needed on the assessment of the project in terms of its science and training content. This included consideration of the potential applications of the results, interaction with industry and benefit to the community.

4.5 Determine the need for a workshop to bring together the research community and operating agencies

The need for a workshop to bring together the research community and operating agencies was considered during the present Session. It was generally felt that ongoing projects and programmes were already convening workshops bringing together researchers and stakeholders, some involving the use of weather radar. However, two initiatives did emerge, one taking place during the Session and the other involving future planning.

With respect to the former, the Met Office held a User Group meeting at Exeter in June 2007 with four Water Plcs: Thames, Northumberland, Yorkshire and Anglian. This served to promote consistent use of weather radar by Water Plcs and explored potential application areas.

The second initiative worked on is longer term and aims to make the UK host to the 8th International Symposium on the Hydrological Applications of Weather Radar, scheduled for 2010 or 2011. It was recognised that the UK, through this Committee, was responsible for the inception of this symposium series, with its first meeting held at the University of Salford in August 1989. After 20 years, it was now thought appropriate by the Committee to offer to host the 8th Symposium. A proposal was developed and submitted to the Chair of the current Organising Committee. The proposal has received a favourable response, although the final decision on venue will be agreed during the next symposium meeting at Grenoble (France) in March 2008. Support has been secured from both the Royal Meteorological Society and the British Hydrological Society.

5. A look forward to the next Committee session

The Committee will continue to focus on ways to influence the greater use of weather radar by operating agencies and to guide the operational application of outputs and influence future research directions. Raising awareness of weather radar and the benefits that can be obtained will continue to be explored by the Committee in the next session.

Three strategic areas have been identified:

Strategic Area 1	Strategic Area 2	Strategic Area 3
Assessing the quantitative use of radar products by the operating agencies and identifying obstacles for implementation.	Guiding the operational application of research outputs and influencing research directions.	Raising awareness of weather radar and the potential benefits it can offer.

1. Now that the operating agencies, the Environment Agency and SEPA, have the software capability to routinely use radar-based products in their real-time hydrological models, the focus must now shift to whether such products are being used operationally. To help in this process, the Committee will be looking in particular at the following aspects:

    - Which regions are using radar products and what for?
    - What are the results and benefits?
    - If regions do not use radar in hydrological forecasting models, why not?
    - What lessons can be learned and shared?
    - What impact will the new radar data types have on operational practice?

2. In the area of research, developments in radar data and their application are coming from several directions and priorities are not clearly defined. The Committee will seek to clarify arrangements where funding and effort are split across a number of research programmes e.g. FREE, FRMRC and Environment Agency/Defra TAG programmes. It will also assess the changes and opportunities arising from the European Union Floods Directive and other European initiatives e.g. European Flood Alert System and OPERA (Operational Programme for the Exchange of weather RAdar information).

3. Initiatives, such as the publication of an explanatory leaflet, will be taken forward to further raise the profile and understanding of:

    - weather radar and related products
    - the benefits of radar in operational, design and planning functions
    - the role and work of the Committee

Appendix A Committee Constitution and Terms of Reference

A.1 Constitution

The Committee comprises members appointed by the following supporting agencies:

Met Office	1
Department for Environment Food and Rural Affairs (Defra)	1
Environment Agency	1
Natural Environment Research Council (NERC)	1
Science and Technology Facilities Council (STFC) [1]	1
Scottish Environment Protection Agency (SEPA)	1
Department of Agriculture and Rural Development, Northern Ireland (DARDNI)	1
States of Jersey	1
UK Water PLCs	1

and up to four members (of which at least two should be from Higher Education Institutes and/or research organisations) to be co-opted for a two year period at the invitation of the Committee. The Chairman is appointed from amongst the representatives of the supporting agencies for a two year term of office. The Secretary to the Committee is provided by CEH Wallingford.

A.2 Terms of Reference

1. To identify research needs and opportunities

2. To recommend priorities for future research and to coordinate research activities

3. To seek funding for research.

4. To identify needs for and availability of data and to recommend archiving requirements.

5. To publicise and promote hydrological uses of weather radar.

6. To promote and establish international contacts.

7. To report on its work to the nominating bodies and the water industry generally.

[1] On 1 April 2007 the Council of the Central Laboratory of the Research Councils (CCLRC) merged with the Particle Physics and Astronomy Research Council (PPARC) to become the Science and Technology Facilities Council (STFC). Previously, CCLRC provided a Committee Member.

Appendix B Committee Membership

Dr Chris Haggett *(Chairman)*	Environment Agency
Ms Linda Aucott (up to September 2006)	Department of Environment, Food and Rural Affairs, Flood Management Division
Dr Steven Cole (*Technical Secretary*)	Natural Environment Research Council, Centre for Ecology and Hydrology, Wallingford
Prof. Chris Collier *(co-opted)*	University of Salford, School of Environment and Life Sciences
Mr Mike Cranston	Scottish Environment Protection Agency
Prof John Goddard (up to April 2006)	Central Laboratory for the Research Councils, Rutherford Appleton Laboratory
Dr Chris Walden (from September 2006)	Science and Technology Facilities Council, Rutherford Appleton Laboratory
Dr Miguel Rico-Ramirez *(co-opted)*	University of Bristol, Department of Civil Engineering
Dr Noel Higginson	Department of Agricultural and Rural Development, Hydrometric Section, Rivers Agency
Prof. Graham Upton *(co-opted)* (March 2005 to September 2006)	University of Essex, Department of Mathematics
Dr David Bebbington *(co-opted)* (from September 2006)	University of Essex, Department of Computing and Electronic Sciences
Prof. Anthony Illingworth *(co-opted)*	University of Reading, Joint Centre for Mesoscale Meteorology
Mr Malcolm Kitchen	Met Office
Mr Bob Moore	Natural Environment Research Council, Centre for Ecology and Hydrology, Wallingford
Mr Graham Squibbs (up to September 2006)	United Utilities plc

Appendix C Reports from the UK Research Groups and Agencies

Information on existing research programmes in the UK in the field of weather radar and related technologies is collated here for the Reporting Period. Reports are provided from research groups in six universities (Bristol, Essex, London: Imperial College and University College, Newcastle, Salford) together with the Science Technology and Facilities Council (STFC) and CEH Wallingford. Reports are also provided from four Agencies: the Environment Agency, the Met Office, SEPA and DARDNI.

C.1 Reports from UK Research Groups

C.1.1 University of Bristol

Research at the University of Bristol relevant to weather radar has concerned topics in the following areas:

(a) *Algorithms for correction and detection of the bright band*

The study of the Vertical Reflectivity Profile (VRP) of precipitation is important in order to develop algorithms to correct scanning weather radar measurements for the variation of the VRP at long ranges. The presence of the so-called bright band (or melting layer) contaminates the quantitative precipitation estimates and can cause significant overestimates of precipitation. An algorithm to detect the extent of the bright band using high-resolution VRP's has been developed. The boundaries of the bright band are identified by rotating the coordinate systems in the upper and lower parts of the bright band. This overcomes some of the difficulties experienced when using the gradient of the reflectivity in conventional bright band detection algorithms. This algorithm has enabled the study of bright bands in different regions in order to correct for the bright band enhancement in scanning weather radar measurements.

Additionally, hydrometeor classifiers have been proposed to classify rain, snow and melting snow using dual-polarisation weather radar measurements. The proposed hydrometeor classifiers are based on fuzzy logic and linguistic decision trees.

(b) *Clutter classification using dual-polarisation radar*

The clutter signals are due to ground, sea and anomalous propagation echoes, which represent a source of error in radar rainfall estimation. An analysis of clutter classification using data from the Thurnham radar was carried out. The performances of Fuzzy and Bayes classifiers were evaluated in the context of clutter/precipitation classification. Both systems were trained and validated using C-band dual-polarisation radar measurements. A novel technique was proposed to calculate the texture function to mitigate the edge effects in the boundaries of precipitation regions. A methodology is presented to extract the membership and probability density functions to train the classifiers. The critical success index indicates that the Bayes classifier has on average a slightly better performance than the fuzzy classifier. The classifier is robust enough to be used when only single-polarization radar measurements are available. The code of the clutter classifier has been provided to the Met Office for further evaluation.

(c) *Algorithms for rainfall estimation using dual-polarisation radar*

Several polarimetric rainfall estimation algorithms at C-band frequencies were evaluated. The polarimetric rainfall algorithms were obtained using simulated radar measurements with a scattering modelling assuming a wide range of measured drop size distributions with an optical disdrometer in the UK and well known experimental drop deformation equations. The performance of the proposed algorithms is evaluated assuming real levels of noise in the polarimetric radar measurements. This analysis highlights some of the rain rate algorithms, which are more robust to noise effects. A dual-polarisation radar was used to test the proposed algorithms and a dense network of raingauges was used to validate the rainfall estimates. The overall results were compared with the conventional Marshall and Palmer (MP) relationship. The results indicate that the algorithm $R = aZ_h 10^{cZ_{dr}}$ outperforms the MP relationship only when using large averaging windows (e.g. ~4.25 km x 3 deg), which implies a loss in resolution when using distributed radar rainfall estimations for hydrological purposes. The code to estimate rainfall rates using dual-polarisation radar measurements has been provided to the Met Office for further evaluation.

(d) *Dual-polarisation radar rainfall estimation system*

The University of Bristol have developed and implemented a radar rainfall estimation system, which includes algorithms for automatic clutter recognition and removal using single- or dual-polarisation (DP) radar measurements, digital filtering using moving average windows in polar coordinates, attenuation correction in reflectivity and differential reflectivity using differential phase measurements and dual-polarisation rainfall estimation. This system works with single-elevation scans and it produces intermediate output files that can be easily access with the adequate software. The system has been implemented for the Met Office in order to further evaluate the benefits of using C-band dual-polarisation radars.

(e) *Blending of weather radar and high-resolution Numerical Weather Prediction (NWP) models to improve Quantitative Precipitation Forecasting (QPF)*

Weather radar and NWP are two important sources for quantitative precipitation forecasts. Radar nowcasting provides short-term forecasts with higher skill than the NWP model. The former technique has shown better skill when using a very short lead time forecasting since radar can capture very well the initial precipitation, whereas NWP models have an approximately constant skill, and will excel the advection-based radar nowcasting after a threshold time because the radar nowcasting leaves the development/decay unresolved. However, the uncertainties in QPF from NWP models are propagated in hydrological forecasting. Very often the rainfall forecasts from NWP models predict the precipitation cells but in the wrong location. In an attempt to improve the forecasting skill of NWP models, an algorithm that combines weather radar has been proposed. The estimated radar rainfall field at time t is cross-correlated with the NWP rainfall field. This allows obtaining an estimate of the displacement of the NWP rainfall field with respect to the radar. This displacement can be applied to subsequent forecasts from NWP at times $t+1$, $t+2$, etc. The displacement is updated as new radar measurements become available. The final product is able to incorporate high accuracy forecast field locations from radar and growing-decaying mechanisms from NWP models.

(f) *Quantization analysis of weather radar data*

Quantization is a process by where continuous signals are transformed into discrete values. It is an important part of the signal processing involved in using weather radar. Research has been conducted in the past demonstrating the error statistics of quantized rainfall, although these studies have used real radar data. The novelty of this study is in using synthetic rain, generated with a Poisson cluster model to represent hourly rainfall, and subsequently disaggregated using a fractal cascade to a fine 5 minute time scale. The advantage of this approach is the length of time series that can be generated far outweighs the limited duration of historical rainfall series, especially at such fine time scales. This provides sufficient rainfall data, especially high intensity rainfall, to say something statistically significant about the error statistics. The models are parameterised for different months and also for a non-seasonal set. Rainfall is then generated for a summer case, a winter case, and for the non-seasonal case. It is discovered that the error distribution varies significantly as the parameters change for 3 bit rainfall. This error distribution is relatively constant for 8 bit data, within its working range (up to 126 mm/hr). At a fine time scale, such high intensity events are not uncommon. This knowledge is useful when investigating historical radar data at lower quantization levels, for the purpose of flood frequency analysis, and remains relevant, especially, if as some studies have shown, the occurrence of high intensity storms is likely to increase.

(g) *Distributed Hydrological Modelling using MIKE SHE and Nimrod radar data.*

A physically distributed model for a wetland based catchment was built using MIKE. The model covers about 1,700 km^2 of the Parrett Catchment. A sensitivity analysis was carried out using different temporal and spatial resolution of rainfall data. This analysis included the use of point raingauge data (hourly and daily) and 15-minute Nimrod radar rainfall data.

The study was aimed to investigate the sensitivity of using point raingauge data and distributed radar rainfall. Radar and raingauge comparisons at raingauge locations have a relative lower error as the rain accumulation interval increases (e.g. 2 hr). The hydrological modelling of three sub-catchments in the upper catchment (Parrett, Yeo and Isle) showed high correlation between simulated and measured discharge values. However, each sub-catchment showed different results. The Upper Parrett gave in overall similar results through all simulations, the Pen Mill site for the Yeo had better results with the Nimrod radar data, but the River Isle had relatively poor results with both raingauge and radar data.

C.1.2 University of Essex

Research has been continuing into the use of a dual-frequency microwave link for estimating path-averaged rainfall. The current experiment in Bolton has been focusing on the possibility of using a link, rather than gauges, to adjust radar data from the Hameldon Hill radar. It has been found that good agreement occurs between the rainfall estimates of the high frequency link attenuation and the radar. The (Cartesian) radar data was used to help determine the start of an event. To date, the radar adjustment results suggest that adjustment using the high frequency link attenuation data is as accurate as the current procedure using twelve gauges.

A second focus of the research has been the measurement of total one-way differential phase for the 23 km link. For many, but not all, of the events, a differential phase versus attenuation scatter plot is linear, though the gradient varies from one event to another. This is also evident in scatter plots of high frequency attenuation against low frequency attenuation, showing that path-average drop-size distributions vary from event to event.

A study into the use of a link to correct X-band radar data in Germany was completed, though our German partners have since extended the correction process to the whole radar image.

Work has also been done on the modelling of anomalous propagation (anaprop) in weather radar imagery using NWP data to obtain volume refractivity distributions. In collaboration with a research team in Barcelona, a variant of the split-step parabolic equation method was used to generate PPI (Plan Position Indicator) anaprop images, as an adjunct to existing methods for anaprop detection.

C.1.3 University of London (Imperial College and University College)

A range of stochastic models for space-time rainfall has been developed for hydrological application. Daily models use Generalized Linear Models as these are suitable for fitting using daily raingauge data. These can represent non-stationarity in space (i.e. location effects) and in time (e.g. climate variability). Sub-daily modelling is based on models in continuous space and time that represent the clustering of raincells within storm events and the movement of storm systems over an area. Radar data are necessary to allow the appropriate clustering to be identified. A long (13 year) sequence of Chenies radar data has been adjusted using raingauge data and provides the dataset to support the modelling research. The radar dataset has also been used to investigate the hydrological significance of spatial rainfall for flood simulation and to develop a simple spatial-temporal disaggregation procedure for observed or simulated daily rainfall spatial fields.

C.1.4 University of Newcastle

Stochastic or deterministic extrapolation of radar precipitation fields clearly offers useful alternative techniques to Numerical Weather Prediction (NWP) for short term rainfall forecasts (rainfall nowcasting). The main calculation variable is often either raw reflectivity data from the radar or precipitation. Thus, compared with NWP, the computational load is reduced (allowing high resolution forecasts), assimilation issues are simplified, the time taken to make a forecast is reduced and certain formulations offer the possibility of stochastic ensemble forecasts.

As reported in the Fifth Inter-Agency report, a nowcasting methodology based on radar precipitation field extrapolation by means of spectral decomposition was implemented, developed and tested. This methodology explicitly models the link between the temporal development and the spatial scale of precipitation features. Thus, the evolution of small features is more rapid than large features. Further, stochastic ensemble forecasts are a natural extension of this scheme. An inter-comparison of deterministic nowcasting skill with four complex radar nowcasting models confirmed that the spectral decomposition methodology was the most appropriate for forecasting extreme rainfall events. The results were found to be reasonably consistent across three study locations (two in northern Italy and one in Poland).

This nowcaster was developed as a component of the EC MUSIC project (contract number EVK1-CT-2000-00058). The overall aim of which was to develop a very short term (1 to 6 hours) flood warning system applicable to small and medium size catchments and designed to improve upon the reliability, precision and lead time of existing flood forecasting and dissemination methodologies. This nowcaster is suitable for application within other extreme rainfall and flood forecasting systems and therefore applications with relevant partners are being considered. Publications are currently in preparation based on the MUSIC project's deliverables, available on the project website (http://www.geomin.unibo.it/hydro/music/).

C.1.5 University of Reading

Two new aspects of weather radar have been exploited in the past three years which should lead to improved observations of rainfall rates and better forecasts of convective rainfall.

In the first aspect, work has been carried out in association with the Met Office to implement improved rainfall-rate algorithms on the new operational polarisation radar which was installed at Thurnham near Maidstone and accepted for use in 2006. Previously, a researcher had tried to apply the new information from the polarisation radar for each radar gate which has a size of typically 600 m by 600 m. However, the polarisation parameters are noisy, and so, instead, properties of the new parameters are integrated over areas of typically 5 by 5 km and used to fix the value of parameter a in the empirical relationship $Z = aR^b$ which links observed radar reflectivity, Z, with rainfall rate, R. Currently, the conventional radar network uses fixed values for a and b; in the new approach the value of b is fixed and natural variations in a are derived from the new parameters. This should lead to improved rainfall rate estimates.

The second topic involves using the recorded phase of the return from ground clutter to map the low level values of humidity in the cloud free atmosphere. Ground clutter is stationary, so the phase of the return should be constant; any changes in phase must be caused by changes in the refractive index in the air between the radar transmitter and the ground target. Such changes are mostly caused by changes in humidity, so by analysing the returns from the many ground targets surrounding the operational radars it is possible to map out the field of humidity in the surface layer. Tests are now being carried out to see if these fields of humidity can be used to detect convergence of humidity as a predictor of where convection is likely to break out. Further research on assimilating this information into Numerical Weather Prediction models has commenced under the FREE programme.

C.1.6 University of Salford

Work at Salford of relevance to the hydrological applications of weather radar has focussed on the use of a stochastic state-space hydrological model, WaterAspects, to investigate and identify the uncertainties in hydraulic and hydrological forecasts of flow.

These uncertainties arise from errors in the input data used and the model formulations. The model has been linked to a Bayesian post processor to analyse the impact of input error from raingauges, radar and microwave communication link estimates of rainfall in the River Croal catchment in North-West England. More recently the Bayesian post processor has been used to generate hydrograph flow ensembles from different rainfall inputs. The aim is to investigate ways of recognising the errors in radar estimates of rainfall in order to assess the uncertainty in model flow forecasts. Currently work is underway to develop an approach to the derivation of quality indicators for model flow forecasts made using radar data.

In addition to the above, a simple approach to the assimilation of Doppler radar radial winds into the Met Office high resolution Numerical Weather Prediction model was completed. This work is part of a major effort in the Met Office to assimilate radar data in order ultimately to improve short-range weather forecasts. This initial work has demonstrated the difficulties of achieving balance between different types of data. A review of flash flood forecasting was completed which considered the role of radar in preparing forecasts of such events.

C.1.7 Science Technology and Facilities Council (STFC)

The STFC Group is responsible for the Chilbolton Facility for Atmospheric and Radio Research (CFARR). This includes the 3 GHz polarisation-Doppler CAMRa and 1275 MHz ACROBAT radars. These and other CFARR and visiting instruments played a central role in the NERC Convective Storm Initiation Project. There has been collaborative research with Essex and Salford on path-integrated rain-rate estimation using differential phase measurements from microwave links and with CEH involving the design and construction of a scintillometer for evaporation measurement.

(a) *Chilbolton Facilities*

STFC owns and operates the Chilbolton Facility for Atmospheric and Radio Research (CFARR). CFARR is a ground-based atmospheric remote sensing facility which supports the NERC atmospheric science, hydrology and Earth Observation communities. The combination of radars mounted on the 25 m diameter dish together with other radars, lidars, radiometers and meteorological sensors provides the UK with a world-class set of facilities supporting a broad range of science.

In June, July and August 2005, the site hosted the Convective Storms Initiation Project (CSIP), a £1.4M NERC consortium project designed to improve the forecasts of thunderstorms leading to flooding events. Over 40 UK researchers and 15 overseas researchers operated equipment at the site, or in the vicinity.

Many instruments were brought for the campaign including a wind profiler, Doppler lidar, ozone lidar, radiometers, and sodars. Four radiosonde stations were placed around the site with a further station on site. Sixteen automatic weather stations were built for the campaign by Leeds University and stationed in an array around the site. Visiting aircraft included the Manchester Cessna, the BAS aircraft, the NERC Dornier and the German Dornier. The Chilbolton dish radars played a crucial role detecting individual and groups of thermals and cumulus clouds. In addition, a new technique was developed on the 1275 MHz ACROBAT radar to produce maps of low-level relative humidity using information on phase changes between clutter targets.

Other work of relevance to hydrology includes collaboration with the University of Reading, where differential reflectivity (Z_{dr}) data from CAMRa derived from dwells above the CFARR site at Sparsholt are being compared with disdrometer data. This is aimed at improving drop shape parameterisation to enable better exploitation of Z_{dr} in rainfall rate estimation.

(b) *Microwave link and scintillometer research*

Members of the STFC group have been joint Principal Investigator on two NERC-funded projects. One, with the Universities of Essex and Salford, has involved the use of differential phase measurements on microwave links to estimate path-integrated rainfall rate, and has been exploring the possible use of microwave links to adjust radar estimates of precipitation, as an alternative to gauges. The STFC group was responsible for design and construction of the 4 links, two of which are radial to the Met Office Hameldon Hill radar. The second project, with CEH, involved the design and construction of a scintillometer for evaporation measurement, initially in the Lambourne catchment, where it has been operating since late 2005. It will be moved to Chilbolton in 2007 for intercomparisons with other scintillometers.

C.1.8 Centre for Ecology & Hydrology Wallingford

Research and development relevant to weather radar at CEH Wallingford over the Session period is summarised below under four headings. Further information is available under the "Reports on Research Activities" of the Joint Centre for Hydro-Meteorological Research (JCHMR) via the website www.jchmr.org.

(a) *Hyrad and RFFS*

CEH's Hyrad system supports the real-time receipt, processing and display of weather radar and hydro-meteorological space-time images, especially for use in flood and water resource management. It is in operational use in the UK within the Environment Agency (England and Wales) and SEPA (Scotland). Two major releases of Hyrad were made over the Session period. The 2005 release included the following new features: (i) IT Management Tool providing statistics on successful product delivery, (ii) Summary Rainfall Statistics (minimum, mode, mean, median and maximum) for image-on-view and image sequences for a selected catchment or area, (iii) generation of time-series of catchment average and maximum rainfall accumulations to pass to telemetry/modelling systems for alarm generation, and (iv) self management of user prioritization to allow a wider user pool. The June 2006 release provided three further enhancements: (i) display of averages and totals for rainfall forecasts within a user-specified time window, (ii) support to ESRI Shapefile import of overlays to the Display Client and catchment boundaries to the Server (for catchment average rainfall estimation for onward transmission to Flood Forecasting Systems), and (iii) export of image data as CSV files from Display Client.

CEH's RFFS (River Flow Forecasting System) suite of forecast models are now in use by the Environment Agency within NFFS (National Flood Forecasting System) and also by SEPA. The modelling suite includes the PDM rainfall-runoff model, the KW Channel flow routing model and methods for model state_correction and error prediction. With these developments, the Environment Agency and SEPA have the capability to use Met Office Nimrod products (radar, NWP and MOSES), via CEH's Hyrad system, for use in flood warning and water resource management throughout England, Wales and Scotland.

A test release of Hyrad was made in December 2006 to support RFFS/FloodWorks applications in Dender, Centrale and Demer catchments in Belgium. Following operational trials and training, a Final Operational Release was made in July 2007. The Met Office in the UK supplies a live feed of European Nimrod analysis and forecast products to the system, to complement the Belgium High Resolution Radar Composite actuals and Aladin NWP forecasts. Hyrad has been provided with a new Merging Tool that combines actual and forecast products from raingauge, weather radar and NWP (Numerical Weather Prediction) model sources for differing time and space resolutions (on possibly varying map projections).

(b) *Extreme Event Recognition (Defra/Environment Agency project FD2208)*

This Defra R&D Project involved a Met Office lead consortium encompassing inputs from CEH and the University of Salford. It has been critically reviewed by the Committee under Strategic Area 1 (see Section 2.4). The overall project objective was to improve the capability to provide warnings of extreme flood events via improving rainfall forecasts and flood forecasting models/procedures (including decision-support).

CEH has used radar and raingauge data from historical heavy rainfall events and enhanced them, via a rainfall transformation tool, to generate spatio-temporal extreme rainfall datasets Severe storms of frontal, orographic and frontal origin were chosen from historical records. Areal rainfall estimates for catchment and grid-square areas, used as model input, were obtained by multiquadric interpolation methods applied to raingauge data alone and in combination with weather radar data. A rainfall transformation tool was developed and applied to historical storms to change their speed and direction of movement and their magnitude and shape to create artificial storms of greater return period. The flood response was investigated using lumped and distributed hydrological models for catchments co-located with the storm and, by invoking storm transposition, to other catchments of different form. Animated images of flood forecasts with area-wide coverage, obtained from the distributed model, provided fresh insight into the space-time shaping of the flood by the catchment form. They served to highlight the potential value of distributed models in forecasting unusual extreme storms. The results of the project have particular relevance to flood warning for ungauged locations.

The Final Report on the CEH component of the work, together with a companion report documenting the Extremes Dataset and associated Storm Transposition Software was completed in 2006. These reports, together with a consortium report on the overall project FD2208, are available via the Defra website. They contain a summary of the conclusions and recommendations of relevance to the Environment Agency's flood risk management function.

The Extremes Dataset and new Storm Transposition Software is now available on DVD in support of model development and destruction testing, and for providing forecasters with an experience base of extreme events. Hyrad can be used to visualise the spatio-temporal datasets and to export space-time rainfalls for use with rainfall-runoff models. This allows the user to perform further flood response experiments, to destruction test models and to perform "what-ifs?" in an operational environment.

(c) *Flood modelling for ungauged basins*

The Environment Agency are seeking improved ways of providing warnings for ungauged and low benefit locations that presently receive only a general Flood Watch service. CEH was commissioned, under the Environment Agency/Defra National R&D Programme, to develop and evaluate improved techniques for flood forecasting at such locations with the eventual aim of the Agency offering a more targeted and technically sound flood warning service.

A review of best practice was carried out along with proposing, investigating and prototyping some new improved methods. Seeking physically-based methods of applying conceptual hydrological models to ungauged catchments using digital datasets on basic properties, as opposed to employing empirical relations between model parameters and catchment characteristics, was identified as an important research area deserving further investigation. New grid-based model formulations were explored that are particularly well suited for use with weather radar data in gridded form. A new method of representing runoff production under the control of soil properties and topography, with an emphasis on lateral water transfers, was developed in prototype form and used to illustrate the benefits of area-wide grid-based modelling.

An extensive Science Report on the work was completed in 2006. This is complemented by an Operational Guidelines Report that provides an overview of approaches and serves as a “roadmap” to the Science Report.

(d) *Modelling using Numerical Weather Prediction rainfalls*

The NERC FREE (Flood Risk from Extreme Events) programme has funded a three year project, that started in January 2007, entitled “Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting”. This project provides an important opportunity for collaboration between meteorologists at Reading (the University and Met Office JCMM) and CEH hydrological modellers at the JCHMR, Wallingford. The aim is to obtain probabilistic flood forecasts through using ensembles of high resolution NWP rainfalls as input to hydrological models, using data assimilation to improve the initialisation of the models. Two new types of weather radar data are to be assimilated into the NWP models: (i) Doppler winds from insect returns, and (ii) radar refractivities.

C.2 Reports from UK Agencies

C.2.1 DARDNI

The Rivers Agency has been using raw single-site rainfall radar data in real-time flood response and analysis for around 10 years. This comes at a relatively modest cost, but is becoming increasingly outdated - a DOS-based software program that will not be developed because there is insufficient demand. Corrected data products have not been taken up to date as this would result in a significant increase in cost. Standard replacement products by the Met Office and others do not meet the vital requirement to have sub-catchment data and are significantly more expensive. The recent Met Office approach is targeted at fulfilling this need - the development, in parallel with Environment Agency, is a GIS-based rainfall information system. The Rivers Agency has looked at a number of possible software packages.

No decision has been taken as to what product should be used (either Hyrad or Enviromet (or both)). At present it has been decided that the Rivers Agency will not be adopting a Flood Warning policy similar to Floodline in Great Britain. Whatever software is adopted, the project is likely to involve additional investment and training of staff, but should produce a working operational system much superior to that being used at present.

C.2.2 Environment Agency

(a) *National Flood Forecasting System (NFFS)*

- NFFS is now operational in all regions.
- NFFS has been implemented with a standard configuration of input data where raingauge data is supplemented with observed radar, radar nowcast and NWP forecast data for all rainfall-runoff models.

- The Environment Agency is now in a position to carry out routine comparisons of catchment average rainfall derived from observed radar and raingauge data plus radar-based forecast nowcasts and NWP forecasts. This is performed across approximately 1000 catchments. These results will inform decisions about the acceptable quality of radar data for real-time runoff model use and development.

(b) *Met Office joint working*

- Improved resilience of communication links with the Met Office is being secured so that the reliability of data delivery to Hyrad and NFFS is increased.
- Through the Environment Agency/Defra TAG, the Met Office are developing further improvements to the RadarnetIV algorithms. The first benefit of this work will be an enhanced radar compositing scheme that should be available in autumn 2007.
- The real-time exchange of raingauge data between the Environment Agency and the Met Office is almost operational and data from both organisations will be used in the radar adjustment scheme.
- Phase 1 of the joint Environment Agency/Met Office study "Assessment of Radar Data Quality in Upland Catchments" is complete. A number of improvements have been identified and it is intended that these will be addressed in Phase 2 of the study due to commence soon.

(c) *Other initiatives underway*

- The Environment Agency/Defra TAG funded investigation (FDK0603) on the use of high resolution NWP forecasts will investigate options for linking spatial precipitation forecasts and observations with distributed hydrological models.
- Two new radar installations are planned, one in Northumbria, the other in East Anglia. The Agency is represented on the project boards but most of the funding is coming from other organisations (e.g. the Water Utilities).

C.2.3 Met Office

(a) *Operations and protection*

- The Met Office continues to operate the UK weather radar network on behalf of the funding partners - currently the Met Office (public weather service), the Environment Agency of England and Wales and the Royal Navy.
- Work to protect the network from detrimental impacts of wind farm development is ongoing, involving monitoring planning applications.
- Proposals to change frequency allocation and moves towards trading of the radio frequency spectrum pose risks which have to be considered and responded to.
- Specific cases of interference have been investigated.
- Radar reflectivity data and other products from the Chenies, Thurnham and Hameldon Hill radars, continue to be supplied to the BADC for research use.

(b) *Network development*

- In partnership with the Environment Agency, new weather radars were installed at Dean Hill (Hants) and Thurnham (Kent) in 2005.
- A project is now in progress to install a new radar at High Moorsley, Co. Durham, in partnership with Northumbrian Water PLC and the Environment Agency.
- A similar installation at Old Buckenham in Norfolk is the subject of a project planned with Anglian Water PLC.

- In Scotland, the Corse Hill radar is being lost to wind farm development, but new sites are being established at Holehead and Munduff Hill in compensation. The Holehead radar has been installed and became operational in September 2007. Munduff Hill should follow later in 2007.

(c) *Radar rainfall*

- A project to examine the quality of radar rainfall estimates in upland areas was funded by the Met Office and the Environment Agency/Defra TAG.
- A follow-on project to implement the recommendations is about to start.
- A project with a wider remit to improve data quality is also in progress with a similar funding mechanism. This is intended to deliver improvements in radar compositing method, spurious echo removal and reflectivity profile corrections.
- The dual-polarisation data from the new Thurnham radar is being evaluated by a consortium including the Met Office, the Environment Agency, Reading and Bristol Universities and MeteoFrance. Funding is coming from the Environment Agency, Met Office, EPSRC and EUMETNET (the Network of European Meteorological Services). The aim is to quantify the accuracy improvement that can be obtained with dual-polarisation.
- Work has started towards direct assimilation of radar reflectivity data into high resolution Numerical Weather Prediction (NWP) models. This approach obviates the need for separate correction of radar data and surface rainfall estimation. It also allows the model to exploit data from different elevation scans, and gains maximum advantage from the model parameterisations of physical processes. The complexity of this process means that operational implementation is likely to be many years away.

(d) *Radar network renewal*

- Work has started on preparation of the business case for renewing the hardware deployed in the radar network. Options include procurement of COTS (Commercial Off The Shelf) radars and a move towards an 'open system' type architecture.
- In the meantime, work continues to counter the effects of obsolescence in the radar systems when and where it develops. The radar signal and data processing systems are currently being replaced to give a common interface for both Doppler and non-Doppler radar hardware. The new system incorporates a fully digital receiver and novel frequency control system to give higher precision wind data.

(e) *Other projects*

- Five of the radars in the UK network are currently delivering Doppler winds. Wind profiles derived from these data are being routinely assimilated into NWP. Experiments are about to start on the assimilation of the basic radial wind data into high-resolution NWP.
- A study has been completed in collaboration with Reading University on the feasibility of using the radar network to provide opportunistic measurements of refractivity. The aim would be to assimilate fields of refractivity into high resolution NWP and improve the forecasting on the onset of convective storms. This work is now continuing at Reading with NERC funding under the FREE programme.
- EUMETNET funded the development of a pilot European radar data hub, hosted by the Met Office. The hub generates real-time precipitation maps covering most of Europe. The products are currently for evaluation only.

- The Met Office/Royal Haskoning are installing 4 new weather radars in the Caribbean to improve hurricane warning. The first installation is due to be completed at the end of 2007
- Consultancy has been provided to the Cuban Met Service about the modernisation of their radar network.
- The Met Office and the Australian Bureau of Meteorology have continued collaboration on the development of the Short Term Ensemble Prediction System (STEPS), intended as a replacement for precipitation nowcasts generated by the Met Office's Nimrod and Gandolf systems. This has included development of an algorithm for quantifying the uncertainty in surface estimates of radar-inferred rainfall using collocated distrometer and radar data.

C.2.4 SEPA

Some notable strategic, operational and research developments in the hydrological use of weather radar have occurred during the 2005-2007 Committee reporting period.

- As part of the development of the Clyde, Irvine and Kelvin flood warning schemes, SEPA commissioned the development of the Flood Early Warning System (FEWS) Scotland. Developed by WL Delft, and a similar platform to the Environment Agency's National Flood Forecasting System, FEWS Scotland integrates hydrological data, output from externally derived model forecasts with hydrological and hydraulic models developed for the flood warning schemes. Actual data from the Corse Hill radar and Nimrod rainfall are routinely sent by the Met Office and processed by HYRAD into catchment average observations for use in the 11 rainfall-runoff models in FEWS.
- The weather radar network in Scotland is being expanded. Due to wind farm developments to the south of Glasgow the Corse Hill radar is being lost from the network and replaced by new sites at Holehead and Munduff Hill. The Holehead radar became operational in September 2007 and Munduff Hill should follow later in 2007. SEPA support these proposals as it provides a minimum of 2 km resolution across the entire Central Belt and could improve flood forecasting in some critical urban catchments.
- Finally, research at Dundee University has been looking into the use of weather radar for flood forecasting in an upland catchment in Perthshire. The research demonstrated that radar observations may provide a useful quantitative observational tool for flood warning and that the use of radar observations may also provide improvements to hydrological forecasting when compared with traditional raingauge observations.

Appendix D Audio-visual archive holdings

1. NRA Thames Region – Flood Warning 1993

2. Footage of Chenies and National Radar Network Launch, 16 January 1985. London Weather Centre /GLC Flood Warning Centre

3. BBC Weather Show. Flood warning and weather radar, Environment Agency Flood Warning Centre

4. The River Cherwell Floods of Easter 1998

5. Plessey & The Met Office weather radar video

The above set of videos has been transferred to a single DVD. This is available on loan from:

National Hydro-Sciences Library
Centre for Ecology and Hydrology
Maclean Building
Crowmarsh Gifford
Wallingford
Oxon
OX10 8BB, UK.