Inter-Agency Committee on the Hydrological Use of Weather Radar

Eighth Report

2010 to 2012

Prepared and published on behalf of the Committee by the Centre for Ecology & Hydrology

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Preface

I am pleased to present the Eighth Report of the Inter-Agency Committee on the Hydrological Use of Weather Radar. Once again the UK has been hit with devastating flooding, with floods in summer and autumn 2012 impacting many communities.

This report has captured the growing scientific work and application in the field of weather radar and hydrology. For ourselves in Scotland, we are set to publish our latest Flood Warning Strategy at the end of 2012. At the heart of the strategy are outcomes to ensure that as an organisation we are at the forefront of developing science to ensure the best possible value for those benefiting from our services in flood forecasting and warning. One of our strategic outcomes is to increase understanding of the spatial representation and real-time measurement of rainfall. Without the UK radar network, providing rainfall observations on a countrywide scale would not be possible and is important in achieving our aims. However, there remain challenges in the application of radar data both in terms of quality and coverage and these challenges face all the operating agencies involved in hydrology, flood risk and water management. With surface water flooding becoming a key issue for many, the role of radar in helping detect and predict these types of flooding events will be the subject of various initiatives going forward.

There have been significant developments in the field of hydrological application of radar over the past two years. To highlight this, over 100 papers were presented at the 2011 International Symposium on Weather Radar and Hydrology at Exeter. This recognises the vibrant nature of activity in this area. It is on this note that I would like to thank all members of the Committee for their efforts in the organisation and delivery of this successful event that was driven by the Inter Agency Committee. In particular, Bob Moore and Anthony Illingworth for chairing the Scientific Committee and ensuring such a high quality output for the symposium and Steve Cole for his efforts as Technical Secretary and coordinating the event with the Local Organising Committee. Also I would like to thank all the industry sponsors for their support, without which we would not have been able to organise such a high quality and affordable conference.

I would like to give one final mention and thanks to departing Committee member Noel Higginson. Noel has represented the Northern Ireland Rivers Agency on this group for ten years. Noel's position is being replaced by Tim Rennie who we welcome and look forward to ensuring Rivers Agency operational requirements continue to be served by the Committee.

Michael Cranston (SEPA)
Chairman, Inter-Agency Committee on the Hydrological Use of Weather Radar
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Glossary

3D-Var	Three-dimensional variational analysis. A method used for data assimilation in NWP.
4D-Var	Four-dimensional variational analysis (includes observations that vary with time). A method used for data assimilation in NWP.
ANN	Artificial Neural Network
ARMA	Auto-Regressive Moving Average; a form of model used for error-prediction in flood forecasting.
BAe	British Aerospace
BSI	British Standards Institute
CAMRa	Chilbolton Advanced Meteorological Radar
CCA	Civil Contingency Act
CEH	Centre for Ecology & Hydrology (a NERC research centre)
CFARR	Chilbolton Facility for Atmospheric and Radio Research
City RainNet	Technology Strategy Board/NERC KTP Project
CIWEM	Chartered Institute of Water and Environmental Managers
DARDNI	Department of Agriculture and Rural Development, Northern Ireland
DIAMET	DIAbatic influences on Mesoscale structures in ExtraTropical storms (NERC-funded research project)
Defra	Department for Environment, Food and Rural Affairs
DYMECS	DYnamical and Microphysical Evolution of Convective Storms (NERC-funded research project)
EA	Environment Agency
EPSRC	Engineering and Physical Sciences Research Council
ERAD	European Conference on Radar in Meteorology and Hydrology
FCERM	Flood and Coastal Erosion Risk Management
FEWS	Flood Early Warning System
FFC	Flood Forecasting Centre. A joint centre between the Environment Agency and the Met Office covering England & Wales.
FRMRC	Flood Risk Management Research Consortium (EPSRC Programme)
FWD	Floodline Warnings Direct
G2G	Grid-to-Grid; a distributed hydrological model incorporating runoff production and routing schemes developed by CEH
GPRS	General Packet Radio Service
HyradK	Hydrological Processing Kernel developed by CEH; pre-processes radar data and merges radar and raingauge data
IACHUWR	Inter-Agency Committee on the Hydrological Use of Weather Radar
IAHS	International Association of Hydrological Sciences
K_{dp}	Differential phase shift

KTP	Knowledge Transfer Partnership
MetUM	Met Office Unified Model
MICROSCOPE	MICROphysical COnvective Precipitation Experiment (NERC-funded research project)
MOGREPS	Met Office Global and Regional Ensemble Prediction System
MOGREPS-R	Regional component of MOGREPS. Runs over the North Atlantic and Europe at 18 km resolution
MOGREPS-UK	A high-resolution (2.2 km) version of MOGREPS with UK coverage.
NCAS	National Centre for Atmospheric Sciences (a NERC research centre)
NDP	Nowcasting Demonstration Project which uses the MetUM at high-resolution (~1.5 km) and 4D-Var for very short-range forecasting over the southern UK
NERC	Natural Environment Research Council
NFFS	National Flood Forecasting System
NWP	Numerical Weather Prediction
OPS	Observation Processing System which processes raw meteorological observation data for input to NWP data assimilation schemes
OSA	Open Source Architecture
QC	Quality Control
QM	Quality Management
QPE	Quantitative Precipitation Estimation
PDM	Probability Distributed Model; a lumped, conceptual rainfall-runoff model developed by CEH
R	Rainfall rate
R&D	Research and Development
RAINGAIN	A European Union funded project that aims to improve fine-scale measurement and prediction of rainfall and to enhance urban pluvial flood prediction
SEPA	Scottish Environment Protection Agency
SFFS	Scottish Flood Forecasting Service. A joint service between SEPA and the Met Office.
STEPS	Short Term Ensemble Prediction System
STFC	Science Technology and Facilities Council
UK4	UK 4 km resolution NWP model operated by the Met Office
UKV	UK variable resolution NWP model operated by the Met Office. A high-resolution inner forecast domain (1.5 km grid) is separated from a coarser surrounding grid (4 km) by a variable resolution transition zone.
UKWIR	UK Water Industry Research
VPR	Vertical Profile of Reflectivity
WRaH 2011	International Symposium on Weather Radar and Hydrology 2011

WaPUG	The Wastewater Planning User Group that is now the CIWEM Urban Drainage Group
$\boldsymbol{Z}$	Radar reflectivity
$\boldsymbol{Z_{dr}}$	Differential radar reflectivity (between horizontal and vertically polarised reflectivity)

1. Introduction

As with the previous session report, we open reflecting on a period of significant UK flooding. The Summer and Autumn 2012 floods are still very fresh in the memory of those who have been trying to manage and respond to these events and for some the impacts are still affecting daily lives. Initial estimates indicate that the 2012 summer floods affected 2,700 properties with 70,000 properties receiving flood warnings. No doubt these damages estimates will increase as further information is gathered.

However, what has changed from the previous 2007 to 2010 session has been the further development of meteorological and hydrological forecasting approaches and the emergence of hydrometeorology capabilities across England, Wales and Scotland to help improve prediction of these types of events. Radar continues to play an important role in flood risk and water management and the application of emerging science is the focus of this report.

At the beginning of this current session, the Committee were keen to promote ways to influence the greater use of weather radar by operating agencies and to highlight areas of improvement and research in support of the user community. Specifically, the Committee wanted to explore various service and system developments, understand various ongoing research areas and their application for hydrology and water management, and promote the role of radar in flood risk management.

Section 3 of the Committee report highlights research needs and presents the considerable range of ongoing science developments across various research groups. The approaches to raingauge-radar merging and data assimilation of radar data for Numerical Weather Prediction are presented as are the requirements from an established hydrological and emerging water management community.

The requirement to provide forecasting capabilities for the whole of the country and for longer lead times was driven as an outcome of the Pitt Review. In Section 4, the efforts of some agencies in developing these capabilities are presented with emphasis on the development of countrywide grid-based hydrological models. In addition, Section 4 reflects on the largest upgrade to the UK radar network in its 30 year history and the introduction of significant radar capabilities that will benefit the user community once completed.

Section 5 presents what has been the main focal point for the Committee's attention during the session period. Following the Committee's successful bid to host the International Symposium on Weather Radar and Hydrology, most of the Committee have been in some way involved in the successful delivery of this major event. Held over four days at the University of Exeter, this was the 8th in the symposium series and attracted over 250 international delegates (Figure 1). It is worth highlighting that following the organisation of Weather Radar and Hydrology 2011, the International Association of Hydrological Sciences has now published the conference proceedings as part of their Red Book series. The volume brings together over 100 peer-reviewed papers from the symposium providing a valuable record of the current activity in this field.

Finally, the appendices to this session report provide an overview of the UK academic and operational agency activity in this sector.

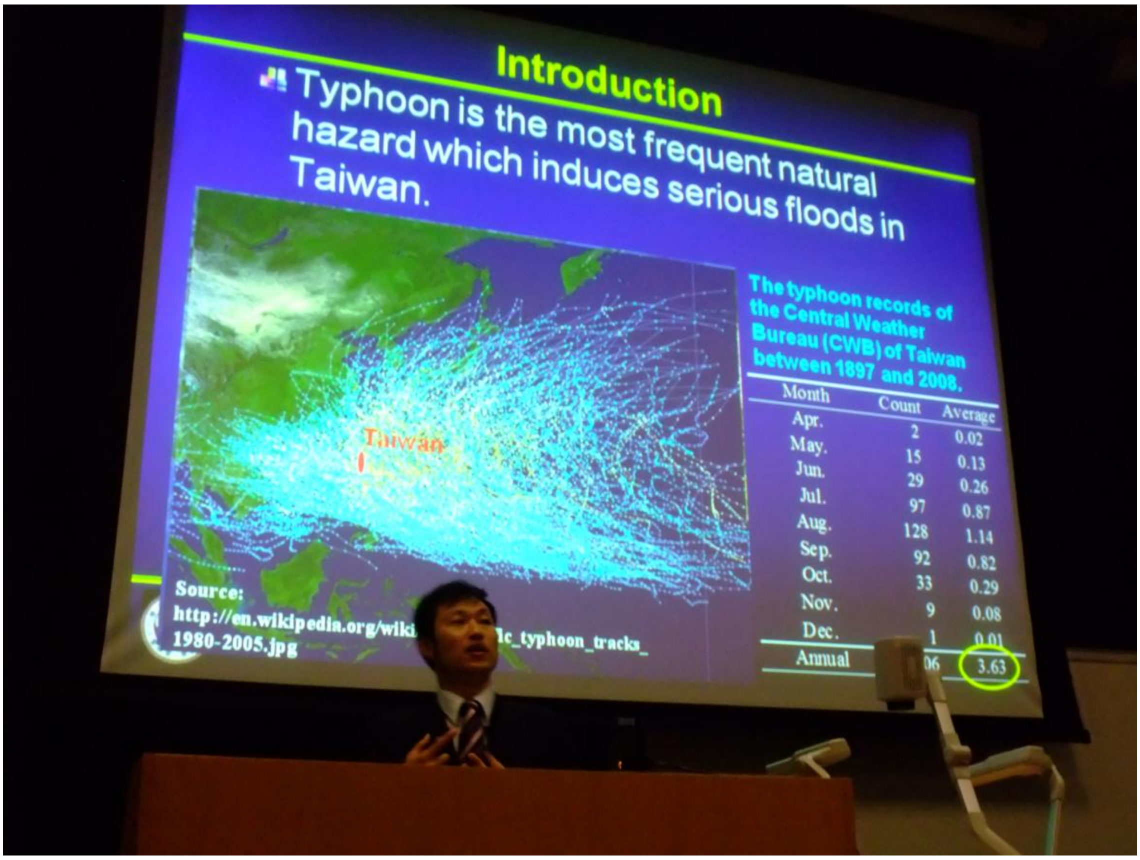

Figure 1 Presentation at the 8th International Symposium on Weather Radar and Hydrology (WRaH 2011).

2. Community Plan

2.1 Background and Aims

In the previous session covering 2007 to 2010, the Committee prioritised the user requirements for radar related research. The Committee also undertook a survey to assess the current usage of radar-based products within the operating agencies. These were used to help identify gaps in the current research initiatives and operational requirements, and identify research needs and funding opportunities. During the session there was a focus on the following three research areas:

- Radar capability
- Benefits to hydrology through meteorological forecasting
- Applications for water management

The 2010 to 2012 session continued to bring the user and research community together, most notably through organisation of the 2011 International Symposium on Weather Radar and Hydrology in Exeter. The previous survey on the current usage of radar-based products has been extended to the water companies and associated consultants to help develop user requirements for the water management sector.

Understanding the current research and alignment to operational requirements remains a strong focus during this session. This includes core scientific developments in rainfall estimation and forecasting, hydrological modelling and flood forecasting. In particular, the relevance to new countrywide flood forecasting capabilities at the Flood Forecasting Centre and Scottish Flood Forecasting Service is considered along with the significant and major UK radar network renewal programme which will bring dual-polarisation and the promise of improved rain-rate estimation across the radar network.

2.2 Strategic Overview

The Committee's constitution, terms of reference and membership are set down in Appendices A and B. The terms of reference fall under 3 strategic areas and are summarised below.

i) Identify Research Needs

- identify research needs and opportunities
- recommend priorities for future research and to coordinate research activities
- seek funding for research

ii) Support Hydrological Applications of Radar

- identify needs for and availability of data and to recommend archiving requirements
- publicise and promote hydrological uses of weather radar

iii) Raise Awareness of Weather Radar in the Wider Community

- promote and establish international contacts
- report on its work to the nominating bodies and the water industry generally

2.3 Milestones and Deliverables

To deliver the objectives, the Committee in the 2010-2012 Session agreed to work on the strategic areas set down in Table 1. Within each Strategic Area the Committee set out a number of deliverables against which it would be measured for the 2010-2012 Session. Reports on the three Strategic Areas are presented in Sections 3, 4 and 5. In addition, reports on radar related research and development by the UK research groups and agencies are given in Appendix C.

Table 1 Milestones and deliverables for the 2010-2012 Programme

Strategic Area 1 **Identify Research Needs**
• Understanding current research and alignment to operational requirements • Assess usage and experience of radar-based products within the Water PLCs and supporting consultants through a survey • Developing user requirements to include the water management sector • User requirements for flood forecasting and warning applications • Promoting significant ongoing research on rainfall estimation using raingauge and radar data in combination • Radar data assimilation into high-resolution Numerical Weather Prediction (NWP) models

Strategic Area 2 **Support Hydrological Applications of Radar**
• Development of an operational grid-based hydrological model (G2G) across UK flood warning agencies • UK radar network renewal including dual-polarisation • Quality indicators/quantified errors • Probabilistic rainfall and flood forecasting • NCAS and other NERC radar research

Strategic Area 3 **Raise Awareness of Radar in the Wider Community**
• Organisation of the 2011 International Symposium on Weather Radar and Hydrology • Developing training in application of radar for hydrology

3. Report on Strategic Area 1 – Identify Research Needs

3.1 Understanding current research and alignment to operational requirements

Radar observations from consecutive volume scans show the time evolution of clouds and precipitation at very high-resolution as well as changes in refractivity due to humidity and temperature variations. Spatial radar rainfall estimates are much valued in their own right and for input to hydrological models for flood and water management. Radar observations also contain crucial dynamic and thermodynamic information that can be used to reduce errors in the initial conditions of a NWP model forecast. Radar data are already an important source of information for operational high-resolution NWP models, with the following uses:

- radar rainfall-rates are assimilated using a latent heat nudging scheme within UK4 (4 km NWP) and soon to be included in UKV (variable resolution NWP, ~1.5 km at finest resolution),
- Doppler winds are operationally assimilated in UK4 and UKV since June 2011 and in the NWP Nowcasting Demonstration Project (NDP) which uses the MetUM at high-resolution (~1.5 km) and 4D-Var for very short-range forecasting over the southern UK (note this doesn't involve traditional radar nowcasting). The respective NWP domains are shown in Figure 2 and details of the configurations and data assimilation cycles given in Table 2.

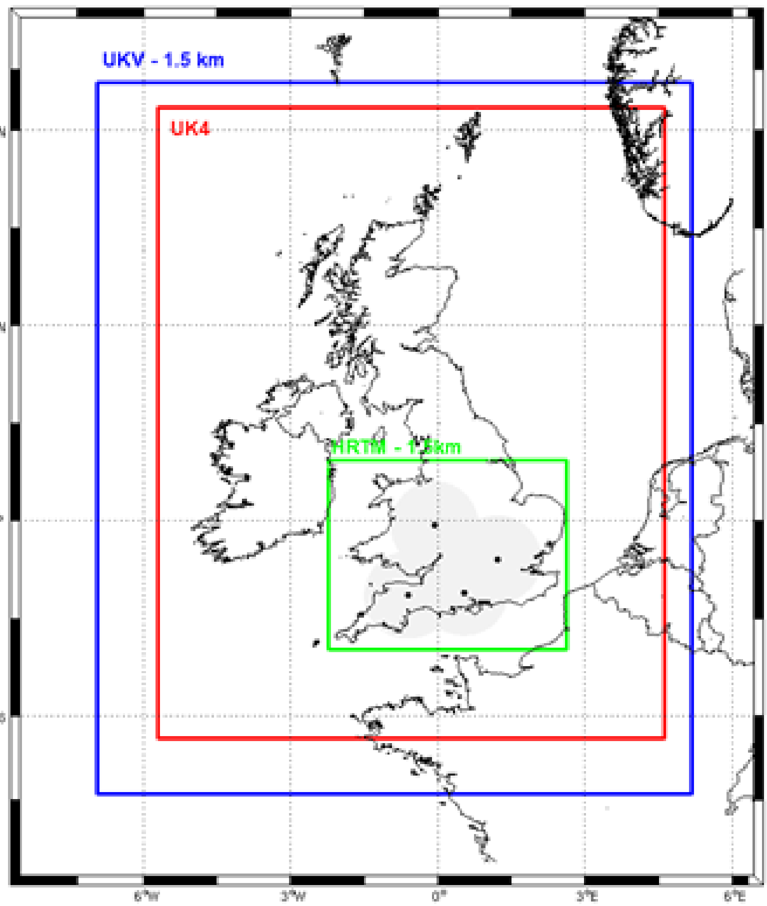

Figure 2 Domains of the UKV (blue), UK4 (red) and NDP (green) NWP models.

Table 2 Details of the UKV and NDP NWP model configurations.

NWP Model	Resolution	Data Assimilation			Forecast length and frequency
		Method	Time Window	Cycling	
UKV (UK)	1.5 km	3D-Var (3 km)	3h	3h	T+36 h (every 6 h)
NDP (Southern UK)	1.5 km	4D-Var (3 km)	1h	1h	T+7.5 h (every 1 h) Soon to be T+12 h

An ongoing problem in high-resolution weather prediction is the accurate forecasting of areas of rapid development, where small errors in the initial state of atmospheric temperature, humidity and wind can grow rapidly to produce significant errors in subsequent forecasts. These errors could manifest themselves through misplacement, insufficient intensity, or even absence of a severe event in the weather forecast, and in a hydrological forecast derived from it.

Therefore, radar research and development top priorities over the next few years should focus on the following areas:

- The improvement of current acquisition and processing systems to increase the accuracy of the retrieved products and provide uncertainty estimates.
- The research and development of new technologies, processing frameworks and retrieval methods to process radar signals and newly-available observations into information that can be efficiently assimilated in UKV and the future generation of nowcasting systems, i.e. refractivity and emissions measurements.
- Increasing the temporal and spatial resolution to process and deliver greater information to the end user.
- Monitoring the status of the acquisition and processing systems, analyse the quality of radar data and provide feedback to radar data users and assimilation systems.

These four areas are each discussed in more detail in the following sections along with a summary of the latest ensemble radar nowcasting developments.

3.1.1 Increase accuracy and uncertainty estimates for radar data

Radar coverage in the UK is such that, for most locations, there is more than one radar that can be used to estimate surface rain-rate. A technique is currently under trial to look at the benefits of infilling strongly attenuated regions in the composite by using a quality index for data selection, compared with the current technique that only uses the beam height. The quality framework allows multiple quality factors to be combined into a quality index and used, instead of beam height, in the compositing process. In addition to beam height, this quality index includes information on attenuation, radar sensitivity and signal strength. It is also tuned and weighted using gauge-radar uncertainties, and by considering gauge-radar statistics over a short tuning period characterised by intense precipitation events.

3.1.2 Newly available observations from weather radar

Dual-polarisation techniques are dealt with in Section 4.2. Here, two other new techniques are described.

Humidity derived from refractivity

The Met Office is currently implementing a refractivity observing system which has been developed in collaboration with the University of Reading and NCAS and relies on measuring the changes in the time taken for the radar signal to travel to and from ground clutter. This information is then used to map out the variation of the surface humidity field within 30 km of each radar, thus identifying regions where convection is likely to break out due to convergence of high humidity surface air. The data quality is currently being assessed by comparison with relative humidity values reported at synoptic stations. Over the next few years, this information will also be assessed against numerical models. The long-term ambition is to assimilate this information within the NWP models (see Section 3.6)

Attenuation derived from emission

Attenuation of the radar return by rain is a major source of uncertainty in rainfall estimates during heavy rain events. The emission technique, currently being rolled out across the network, relies on the fact that any objects which attenuate the radar wave also emit and 'glow' at the radar frequencies; this emission can be detected by an increase in the receiver noise level and provides an independent and absolute measure of the attenuation of both the wet radome and the heavy rain.

Recent research by the Met Office and University of Reading has established the following.

- A wet radome can produce attenuations that lead to a 50% underestimate of rainfall during moderately intense storms. Until now, it has been impossible to quantify this effect and so it has been ignored. This attenuation may be degrading radar rainfall adjustments using near-range gauges.
- The total attenuation of distance storms can be determined and used as an additional constraint on present schemes for correcting attenuation which tend to be error prone.

Work will continue over the next year with the aim of developing schemes whereby the radome and storm attenuation can be incorporated into the real-time radar rainfall estimation algorithms.

3.1.3 Increased temporal and spatial resolution of radar data

The Met Office is currently involved in a project called RAINGAIN (http://www.raingain.eu/en/raingain) organised around a consortium of 13 partners and partly funded by the European Union Interreg North West Europe programme. The aim of the RAINGAIN project is to obtain fine-scale rainfall rate estimates to enable urban authorities to adequately cope with peak rainfall and help prevent severe pluvial flood damage.

The Met Office contribution to the project is to develop a ‘super-resolution’ radar prototype system using the current UK radar Network infrastructure. The aim is to develop new signal processing software to increase the radar data resolution to 500 m or better over central London with an updated cycle time of 2.5 minutes.

The fine-scale rainfall data will provide urban water managers with detailed peak rainfall information at temporal and spatial scales appropriate to the rapid urban runoff processes. The information will be applied in flood forecast models at pilot locations in the four participating countries (London, Paris, Rotterdam and Leuven) to identify flood-prone locations and develop effective solutions for better flood protection such as early warning systems and optimised, real-time storage basin operation. These will in turn be tested based on the detailed rainfall data and flood models. The end users of the rainfall equipment, data and models will be trained so they will be able to take over the project deliverables and to resume operational and management responsibility.

The pilot study over central London is due to take place between March 2014 and March 2015.

3.1.4 Status monitoring

A dedicated radar Quality Management (QM) system has been implemented for the monitoring of data quality and the identification of radar product quality issues. Quality metrics are key to the QM cycle and evaluation of these metrics determines if action is required.

The QM system includes the following.

- The central monitoring of a range of radar hardware performance indicators (e.g. transmitter power, receiver noise, long range noise and antenna rotation rate).
- Analysis methods of high-resolution (polar form) daily and monthly Quantitative Precipitation Estimation (QPE) products to identify and quantify persistent problems.
- Performing hourly radar and gauge comparisons (available for the last 10 years) to investigate trends in QPE quality metrics.
- Routine comparison of Doppler velocities and radar reflectivity with high-resolution NWP model output.

Further features will be incorporated into the QM system over the coming years.

3.1.5 Blending convective scale NWP with ensemble nowcasts (Environment Agency/Met Office Joint R&D project)

The Environment Agency has a requirement for precipitation forecasts with a horizontal resolution of 2 km or finer, an accumulation time-step of 15 min or finer and a range of at least several days. At present, no single NWP model forecast can satisfy this requirement.

The Environment Agency/Defra storm-scale numerical modelling project (FD2207) examined the ability of a 1 km configuration of the MetUM to predict convective rainfall. It concluded that a significant increase in forecast accuracy was achievable and that the benefits for fluvial and pluvial flood forecasting could be enhanced further by post-processing the output to take account of forecast uncertainty.

Concurrently the Short Term Ensemble Prediction System (STEPS) was developed to provide ensembles of precipitation nowcasts. STEPS blends extrapolated radar and satellite observations with the most recent forecast from the 4 km configuration of the MetUM (UK4) and a time series of synthetically generated precipitation fields (noise) with space-time statistics inferred from weather radar. The noise component serves to account for uncertainties in the evolution of the extrapolation and UK4 forecast components and also to downscale the UK4 forecast.

The "*Blending convective scale NWP with ensemble nowcasts*" project was established to integrate these developments and produce a seamless, high-resolution (2 km) ensemble forecast of 15 min rainfall accumulations which are suitable for use in fluvial and pluvial flood forecasting and warning.

The project is now nearing completion. A *quick-win* blending algorithm designed as an upgrade for STEPS, and known as STEPS-2, was implemented in February 2012.

Benefits of the STEPS-2 algorithm are:

- near optimal combinations of an extrapolation nowcast and multiple NWP model forecasts of precipitation;
- quantification of uncertainties in radar rain-rate estimates, nowcasts and NWP forecasts, with this information conveyed to users in the form of ensembles;
- downscaling coarse resolution NWP forecasts (e.g. 18 km MOGREPS-R forecasts), correcting for the under-prediction of both orographic precipitation and the heavy and extreme precipitation associated with convective showers;
- generation of large ensembles of precipitation nowcasts and forecasts needed to propagate the associated uncertainty through hydrological models such as the G2G model.

A 7 hour lead-time STEPS-2 nowcast ensemble is generated every 15 minutes. Initially (since February 2012) STEPS-2 has used the UK4 deterministic forecast and generated 12 ensemble members plus a control run. In the summer of 2012, UK4 was replaced by UKV in STEPS-2 and in late 2012 the ensemble size was increased to 24. In addition, a longer lead-time run is made every 6 hours, initially out to 24 hours but soon to be 36 hours. In 2013, STEPS-2 is planned to use members from the new MOGREPS-UK 2.2 km ensemble NWP system instead of deterministic UKV and ongoing research will consider increasing the STEPS-2 ensemble size further.

3.2 Assess usage and experience of radar-based products within the Water PLCs and supporting consultants through a survey

The Committee conducted a survey into the usage of weather radar during the previous reporting period (2007-2010). This survey was targeted at key users such as the Environment Agency, Met Office, Scottish Environment Protection Agency and leading research bodies. The aims of the survey were to gauge opinions into the positive and negative aspects of weather radar and to highlight any issues and potential improvements that would benefit the users of such data. Findings of this survey were detailed in the Seventh Session Report.

The original survey was targeted very much towards an established user-base having a wealth of knowledge on the current hydrological use of radar technology. However, there is an emerging interest in radar technologies from the wider UK water industry, for example as water companies explore smarter ways to manage the performance of assets and deliver a better service to customers. It was therefore decided that a second survey should be designed to target the small, but increasing number of users within the water companies, along with their supporting engineering consultants, to understand their applications, their perception of radar data and to learn more about future development needs within this growing sector.

The survey was distributed to over 120 people and although the number of responses was very low - 35 in total - it is felt that this number represents a significant proportion of 'pilot study' users within the water companies. These 'pilot study' users are very much at the forefront of this technology within the water industry and will play a key role in setting future business plans and water company investment in weather radar. It is therefore believed that despite the low response rate, the answers and comments provided are extremely valuable to the aims of the Committee and our thanks are extended to all those who participated.

A report detailing the survey results can be found on the Committee website: www.iac.rl.ac.uk. This includes an analysis of the results from each question and draws some overall conclusions from the survey which are summarised below.

Overall there was a willingness to use radar data within the water industry, but the large majority of responses felt that the provision of radar data only partly met their requirements. From the comments submitted it is clear that many of the concerns are related to countrywide coverage particularly in Wales and Orkney & Shetland. However, an underlying theme relates to accuracy and the need to have 'some kind of confidence grading' for the data. At the time of the survey the people responding to this question would have been unaware of the huge work being undertaken on the UK radar network as detailed in Section 4.2, and on the development of quality indicators/quantified errors in Section 4.3 of this the Eighth Session Report. Hopefully this will go a long way to addressing these concerns, but the network upgrade work and developments with quality indicators must be clearly communicated to the Water Industry users to improve future confidence and usage.

3.3 Developing user requirements to include the water management sector

The questionnaire discussed in Section 3.2 has provided a useful insight into the future user requirements of the water management sector. This sector is largely classed as the main water and sewerage undertakers for the UK and the supporting engineering consultants that provide valuable assistance on projects conducted by these utility companies.

The survey results indicate that there is a wide range of activities taking place which use radar data products. These range from the Network Operations - using Flood Forecasting Centre Guidance Statements to raise awareness of future critical events that could impact on the performance of key assets and the day to day running and maintenance of the sewerage networks - through to the use of nowcast data and continuous model simulations to predict precise locations of future flooding problems.

Each type of user has a certain set of requirements, but fundamental to them all is data reliability, network coverage and accuracy. Having confidence in the radar product means that every user, whatever their role, can have greater certainty over the actions they take in response to the data they receive.

A number of water companies are undertaking studies to investigate and improve the accuracy of the radar data they receive. Notably Yorkshire, Northumbria and Scottish Water are working on the City RainNet Project as detailed in Section 3.5.1 of this report with the aim of adjusting radar data in real-time using raingauge data. The improvements this project aims to deliver should improve their confidence in radar data and help improve the decisions they make in the real-time management of their networks.

A further example is the use Thames Water has been making of 6 hour nowcast rainfall data generated from STEPS. These data have been used for over a year across parts of London with the aim of predicting when flooding events may occur and understanding the likely impact on customers and key assets within the network. The pilot area was extended in time for the London Olympic Games and incorporated the largest sewerage network in Europe. The study was judged a success in terms of linking radar actuals and nowcast rainfall data in a continual model simulation, with alarms being raised when threshold levels were predicted to be breached. The task now is to understand why so many alarms were raised by using the nowcast rainfalls and to convince the business that radar rainfall can be relied upon and is beneficial.

The survey highlighted that users were keen to understand more about the origin of the data and the quality of the rainfall estimates produced by radar. The work on quality indicators and quantified errors discussed in Section 4.3 should aid this understanding and hopefully can be fed through to the end users so that predicted alarms and real-time network management can be understood and implemented with greater confidence.

One of the largest uses of radar actuals is in the analysis of past rainfall and flooding events. Water companies need to understand why their assets performed as they did so that future solutions can be designed appropriately. Historically these events have been analysed using available raingauge data, but such data often lack the necessary temporal and spatial variation that radar rainfall data can provide. Unfortunately there has also been uncertainty in radar rainfall in terms of lower peak intensities and total volumes which has limited the use of these data. Assuming that these uncertainties are addressed by the quality indicators and quantified errors, the remaining point from the survey was how to use the data.

There is a desire for greater guidance and training when using radar rainfall data alongside or instead of raingauge data. It has been suggested that this guidance is provided in the form of a WaPUG[1] User Note and example evaluation studies. WaPUG User Note 39 “Use of rainfall from radar” already exists, but was written in 2006 with an editorial amendment in March 2009. The document remains very high level and descriptive, providing little guidance to users on how to collect, check and apply radar rainfall data. The IACHUWR should look to work with CIWEM during the next committee session so that this User Note can be updated to incorporate recent radar developments and offer greater support and guidance to those wishing to use radar rainfall data as part of their day to day hydraulic and hydrological modelling activities.

[1] WaPUG (Wastewater Planning User Group) is now the Urban Drainage Group within the Chartered Institute of Water and Environmental Managers (CIWEM)

3.4 User requirements for flood forecasting and warning applications

The "Pitt Review: Lessons learned from the 2007 floods" (Cabinet Office, 2008) identified the need for a national approach to flood forecasting and warning to complement the service offered by existing regional systems. This recognised new science capability to make indicative flood forecasts "everywhere" using CEH's Grid-to-Grid (G2G) Model, a distributed flood forecasting model that can be configured to give national coverage on a 1 km grid. This approach contrasts with existing regional systems providing potentially more accurate forecasts, but at specific locations and lacking a spatially coherent picture of future flood risk.

The requirement to make flood forecasts for longer lead-times, out to 5 days, was recognised as now possible to meet through advances in Numerical Weather Prediction (NWP) giving improved spatial resolution and accuracy. Estimates of rainfall uncertainty, captured through ensemble rainfall forecasts, would also allow their use with flood forecasting models to make probabilistic flood forecasts. Such forecasts would help pave the way to consider issuing earlier warnings with lower probability, especially for high impact locations. Radar rainfall forecast extrapolations, blended with NWP rainfall forecasts and in ensemble form, are amongst the new products being developed to support these new requirements and increased expectations for flood warning.

Administratively, the challenging new requirements posed by the Pitt Review are being delivered via a newly created Flood Forecasting Centre aimed at providing a national vision of storm and flood risk across England & Wales. This has been created as a joint centre staffed by hydrometeorologists from both the Environment Agency and the Met Office. A range of tools, most using weather radar data in some form, are used in the construction of a daily Flood Guidance Statement made available to a variety of users. A dialogue with operators of regional flood forecasting systems is maintained to provide a two-way consolidation of information on flood risk at regional and national levels.

In Scotland, the new Scottish Flood Forecasting Service operates in a similar way by combining hydrological and meteorological expertise across SEPA and the Met Office. In this case, a virtual centre running at two locations provides a Scotland-wide vision of storm and flood risk out to 5 days.

These new developments are giving the capability to provide flood warnings for ungauged locations, including those associated with rapid response catchments, using weather radar (and NWP model) gridded rainfalls as input to distributed grid-based flood forecasting models.

3.4.1 Targeted flood warning service for Civil Contingency Act Responders

From October 2011 the Environment Agency has providing a new web-based flood warning service for Civil Contingency Act (CCA) responders to help them manage their own flood response activities.

This new targeted and efficient service allows CCA Category 1 and 2 to easily monitor their assets that are at risk from flooding. The service provides customisable real-time access to digital information including EA Incident Room contacts and mapping of assets against flood risk maps and Flood Warnings that are in force.

Category 2 responders will be charged a cost-recovery fee for accessing the service and for the associated hosting and support. This charge is comparable to accessing the data directly as a Direct Data Consumer (see below). Category 1 Responders are not charged for access and use of the service. The current Floodline Warnings Direct (FWD) service will continue to be provided at no cost and will remain sufficient for some Category 1 and 2 responders.

In order to be as flexible as possible, there are two further ways for organisations to access the Environment Agency flood warning information:

1. Direct Data Consumers: Responders may wish to access the raw flood warning data for their own internal use i.e. to develop an in-house service.
2. Value Added Resellers can gain licensed access to the live flood warning data and can develop bespoke warning products and services (at a cost). Currently licensed resellers include Halcrow, Shoothill, Hydro-Logic, Landmark and JBA.

To date, 41 Category 1 and 2 organisations have signed up to receive the service and 20 others are currently in the process of signing up.

3.5 Promoting significant ongoing research on rainfall estimation using raingauge and radar data in combination

3.5.1 Real-time adjustment of radar data for water management systems: The City RainNet Project

A key challenge of the project is to develop and implement a real-time, rainfall radar adjustment software system using raingauge data. This system aims to provide rainfall data of reliable accuracy, particularly in convective storm situations. The data produced by the system must have high enough accuracy and reliability to enable Water Companies and others to be confident in using it in the operation of water management systems. This project will deliver a technically robust prototype of a commercially viable system capable of delivering these objectives. The project involves three UK Water Companies (Yorkshire, Northumbria and Scottish Water) who have or will install raingauge networks using as a guideline for the installation on a one by one kilometre grid. The approach to the radar data adjustment is based upon a 'Probability Matching Method'. Each raingauge outstation comprises a weighing principle raingauge, the OttPluvio2, linked to an ISODAQ GPRS data logger manufactured by Hydro-Logic.

The Water Companies are funding the cost of the raingauge equipment, and installation plus maintenance of a minimum of 36 gauges to be deployed in each city on a grid of minimum size area 25 km^2. Work in the Project will ascertain the most appropriate grid configuration. The raingauge network installed in the Yorkshire Water area is shown in Figure 3.

A modification of the published Probability Matching Method for combining radar reflectivity and raingauge data has been adopted. An adjustment function is derived from an analysis of historical radar and raingauge data. This can be updated and modified as more data are acquired in real-time and the rainfall type changes. One advantage of this approach is that a stable relationship between the raingauge measured rainfall and the radar reflectivity can be derived covering the full range of measured reflectivity values, particularly if there are many raingauges available. A paper giving more details was presented at the WRaH 2011 symposium. The project is due to finish at the end of 2012. Currently the software system has been written and

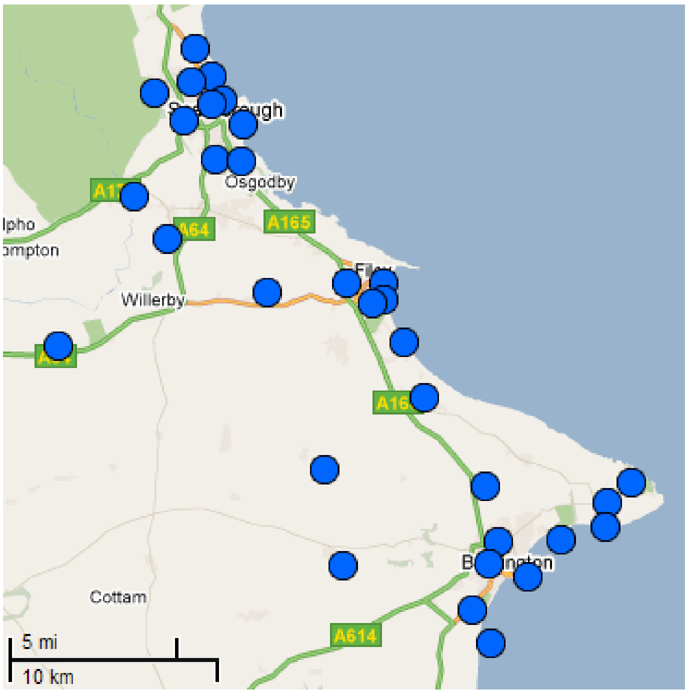

Figure 3 Yorkshire Water raingauge network. The blue circles show the locations of the raingauges currently installed in Scarborough, Filey, Bridlington, and their surrounding areas. Note that an artefact of the placement of the symbols means that some raingauges appear to be located in the sea. At the time of writing, 32 of a total of 36 raingauges were installed.

testing has begun. Installation of the raingauge network in the Dundee area of Scotland is nearing completion. Site planning for the raingauge network in the Newcastle area has been completed and installation of the raingauges has begun.

3.5.2 Improving our picture of rainfall through radar raingauge merging (Environment Agency/Met Office Joint R&D project)

This project will create synergies by 'unlocking' benefits in the existing Environment Agency and Met Office radar and raingauge monitoring networks. The overall objective is to evaluate a number of available methods for merging radar and raingauge data. This will support improved real-time operational flood and rainfall forecasting and provide a national consistent picture of observed rainfall.

Delivering these outcomes is a substantive task, which is why the project is split into three separate stages:

- **Stage 1 Initial research and evaluation.** Design of a raingauge quality-control system for real-time use and evaluation of different merging techniques in the light of user and data requirements. (15 months)
- **Stage 2 Further development.** Development and testing of a flexible and robust radar/raingauge merging scheme to deliver real-time, accurate high-resolution rainfall information (12 months).
- **Stage 3 Operational Implementation** of the real-time raingauge quality-control and radar/raingauge merging techniques for operational use by the Environment Agency and Met Office forecasters (6 months).

Stage 1 started in September 2011. Based on its findings it will provide an updated rationale and scope for subsequent stages. As part of Stage 1, the Met Office is undertaking a comparative assessment of existing gauge-radar merging techniques over large regions of the UK and during various synoptic conditions. Among the techniques being testing are Kriging with external drift, Kriging with radar-based error correction, Bayesian methods and multiquadric surface fitting. Various settings for these methods are being considered: for example, the Kriging methods have been run with spherical and exponential variograms as well as non-parametric variograms based on the radar field. Rainfall fields are validated by using the cross-validation technique, whilst synthetic rainfall fields are also used to examine the merging methods. Comparisons are made against the radar-only rainfall field, the interpolated gauge-only rainfall field, as well as between the different methods, to demonstrate any improvement of the merged rainfall products. In addition, a real-time operational raingauge quality-control system, designed to identify suspect gauge data, is also being developed. Stage 1 will run until the end of 2012.

3.5.3 Development and application of the HyradK method used by the Flood Forecasting Centre and Scottish Flood Forecasting Service

HyradK, developed by CEH Wallingford, provides a means of obtaining 15 minute rainfall accumulations on a 1 km grid from raingauge data, from radar rainfall data and a blending of the two. The methodology employed is a multiquadric interpolation procedure tailored to the particular type of rainfall estimation required. It is now used operationally to provide gridded rainfall estimates to the Grid-to-Grid Model or G2G, configured across England & Wales for the Flood Forecasting Centre (FFC), and across Scotland for the Scottish Flood Forecasting Service (SFFS).

Offline assessments have shown that the HyradK raingauge-only gridded rainfalls are more robust for use with G2G, and other hydrological models used for flood forecasting. Transient errors in the radar rainfall estimates make these less useful, although blending with raingauge data helps suppress the problem. However, radar rainfall data are available almost immediately in real-time unlike raingauge data whose availability is constrained by the polling regime invoked. This experience has led to a hierarchical use of HyradK products being configured for real-time use with the G2G flood forecasting model. Whilst the raingauge-only product is given first priority, this defaults to the raingauge-adjusted radar blended product below a threshold number of available raingauges, and then to the radar-only product. The infrequent routine polling of raingauges at present means that the radar products are most used, except for the daily “historical” run that maintains the model states which is scheduled in line with raingauge polling.

On account of the robustness of the raingauge-only product, this is used offline to support G2G model calibration. Automated methods have been developed to quality-control the raingauge data prior to model calibration, and using a software design suited to eventual real-time use. The methods aim to detect errors affecting the short- and long-term rainfall totals that adversely impact on the water-balance accounting of the G2G Model: such as blockages, missing values that are recorded as zero, anomalous large values and systematic over/underestimation.

The HyradK applications have access to the 1 km UK radar network data along with rainfall data from circa 900 telemetry raingauges across England & Wales for FFC and circa 180 across Scotland for SFFS. Whilst HyradK can operate as a standalone server application, these two applications have been configured to operate in adapter form, along with G2G, within the operational forecast system environments NFFS-FFC and FEWS Scotland respectively.

3.5.4 Updating the British Standard Guide for the estimation of Areal Rainfall

The British Standard Institute (BSI) Technical Committee for Hydrometry regularly reviews published standards and commissioned a review of standard BS 7843, *Acquisition and management of meteorological precipitation data from a raingauge network*. This has now been updated and is published in the following 4 parts:

BS 7843-1:2012. Part 1:	Guide for design, development and review of raingauge network
BS 7843-2:2012. Part 2:	Code of practice for operating raingauges and managing precipitation data
BS 7843-3:2012. Part 3:	Code of practice for the design and manufacture of storage and automatic collecting raingauges
BS 7843-4:2012. Part 4:	Guide for the estimation of Areal Rainfall.

Although weather radar was explicitly beyond the scope of the standard, it is still widely referenced. Part 1 has an Annex on the characteristics of precipitation estimates from radar which provides a brief overview of how radar rainfall estimates are produced. Also, a new section on the Use of Weather Radar was added to Part 4: *Guide for the estimation of Areal Rainfall*. This discussed how to form radar rainfall accumulations, use of radar for disaggregating raingauge totals and the radar-raingauge merging techniques currently used by FFC and SFFS.

Now that the standard has been published, this should provide a far more comprehensive and contemporary resource for users.

3.6 Radar data assimilation into high-resolution NWP

Assimilation of observations provides the start point for all NWP forecasts. Accuracy is essential; most major forecast errors can be traced to relatively small errors in the initial conditions. As NWP models are becoming more sophisticated, the data assimilation scheme must evolve to meet their needs.

Research and development currently focus on data assimilation for convective scale models and exploitation of novel data sources such as Doppler winds, reflectivity and refractivity which are discussed in more detail below.

3.6.1 Doppler winds

Radial winds from Doppler radars provide a potentially valuable high-resolution data source for convective scale (order 1 km) NWP models. The decision was taken to provide full resolution data to the Observation Processing System (OPS) and to allow any thinning or super-obbing (averaging to match the model resolution) to take advantage of the availability of the forecast background fields and to allow flexibility to easily respond to changes in the forecast model resolution.

Doppler winds have been operationally assimilated into UK4 and UKV models since June 2011 and recently into the Nowcasting Demonstration Project. At the time of writing, 6 radar sites provide Doppler winds for the assimilation. The Met Office is currently working towards extending the Doppler coverage to the whole of the UK radar network by April 2013.

3.6.2 Reflectivity

Work has been undertaken to access long pulse radar reflectivity data, to construct an observation operator, to compare reflectivity calculated from 4 km forecast fields with observed values, to pre-process data and to develop a 2D-Var along radar range/height for a given azimuth to derive increments to humidity and temperature. The aim of this work is to develop systems for assimilation of radar reflectivity data in both 3D-Var and 4D-Var assimilation schemes. Specific objectives are:

- develop a quality-control system for radar reflectivity data (including noise and spurious echo filtering; attenuation correction);
- develop observation pre-processing and super-obbing system for radar reflectivity data;
- develop monitoring system for radar reflectivity data (including monitoring of the radar calibration, and monitoring against the model background);
- develop indirect assimilation of radar reflectivity data via temperature and humidity profiles;
- develop direct assimilation of radar reflectivity data;
- investigate impact of indirect assimilation of reflectivity data via temperature and humidity profiles and compare with latent heat nudging in UK model 3D-Var scheme;
- investigate the impact of direct assimilation of reflectivity data in convective scale 4D-Var scheme and compare with latent heat nudging.

3.6.3 Refractivity

The refractivity technique is being rolled out across the operational radar network. It relies on measuring small phase changes in the return from ground clutter resulting from changes in the refractivity of the air. Great care is needed with this technique, as a target movement of 2 mm for two targets separated by 1 km is equivalent to a relative humidity change of 1%. Great care is also needed in measuring and correcting for small changes in magnetron and local oscillator frequency of less than 1 ppm. Provided these precautions are taken then hourly refractivity changes of 1ppm in air close to the surface can be retrieved within 30 km of the ground-based radars, with a spatial resolution of 4 km.

Future plans are:

- To verify data quality and errors of the derived refractivity for each radar site by comparison with synoptic ground stations.

- Compiling statistics of the differences between the observations and the background model states for the various versions of the Met Office model at 1.5, 4 and 12 km.
- Development of an operator so that ultimately the refractivity changes can be assimilated into the model

The CSIP experiment over Southern England in 2005 demonstrated that 50% of summer convection was triggered by surface convergence. The refractivity observations should help to identify areas of humidity convergence and hence, if assimilated into the forecast model, provide a few hours extra warning of where severe convection is likely to break out.

4. Report on Strategic Area 2 – Support Hydrological Applications of Radar

4.1 Development of an operational grid-based hydrological model (G2G) across UK flood warning agencies

4.1.1 Scientific development of the G2G Model

CEH's Grid-to-Grid Model, or G2G, is a physical-conceptual distributed hydrological model configured on a grid. Representation of runoff production and flow routing processes across a landscape are supported by static spatial property datasets on terrain, soil/geology and land-cover. Dynamic space-time grids of precipitation (and potential evaporation) are input to the model for past and future times from a range of sources: raingauges, weather radar, and weather models. The model is configurable: its domain extends across England & Wales for FFC and across Scotland for SFFS. Forecasts of fluvial river flows are made on a 1 km grid for a 15 minute time-step out to 5 days; other outputs can be displayed such as maps of soil moisture and surface runoff.

Developments of G2G during the term of the Report include:

(a) Improvements and extensions to model formulation

- Improved and simplified groundwater formulation that can use permeability data;
- Improved local calibration of conveyance parameters for gauged river reaches;
- Incorporation of Artificial Influences through functionality to represent abstraction/returns and simple reservoir/lake modelling;
- Development of a G2G snowmelt hydrology module.

(b) Improvements in use of observed river flows (data assimilation)

- Direct insertion of observed flows gives improved performance downstream;
- Slow state-updating scheme. This conservative scheme adjusts the water content of the deeper soil stores gradually over time so that modelled and observed baseflows are better matched;
- Constrained ARMA (Auto-Regressive Moving Average) error-prediction at gauged sites gives improved forecast accuracy at shorter lead-times.

(c) Improvements in flood hazard identification, model performance assessment and diagnostics

- County Hazard Maps use rarity of forecast river flows as an indication of flood severity and employ G2G model flow exceedance of the Q(T) (river flow Q of return period T years) flow for each 1 km grid square. The Q(T) grid (derived from Flood Estimation Handbook methods) has been adjusted with respect to the median of annual maxima modelled flows to improve the robustness of the approach.

- Model Performance Summary for river gauging station sites provides a concise synthesis of station properties along with model performance as a site guide to forecast reliability;
- Improved log messaging for G2G/HyradK gives transparency to model inputs and helps problem diagnosis.

The above G2G science developments have focused on the requirements of the FFC and SFFS in providing countrywide outlook forecasts of flooding for the next 5 days, and their use in compiling a daily Flood Guidance Statement. Future work is planned to explore the capability of the G2G for flood forecasting of rapid response catchments over shorter forecast horizons (see Section 4.4.1), in combination with the new blended ensemble rainfall product which employs radar rainfall for nowcasting (see Section 3.1.5).

4.1.2 Operational use of G2G at the Flood Forecasting Centre

The G2G Model is hosted within the National Flood Forecasting System (NFFS) and, in real-time, is fed by telemetry data from most Environment Agency tipping-bucket raingauges, and river level and flow gauges, and Met Office observed and nowcast radar rainfalls and NWP forecast products out to 5 days. CEH's HyradK software runs within NFFS to form gridded rainfall products from raingauge and/or radar rainfall sources (see Section 3.5.3). A hierarchy of the HyradK and weather model rainfall products is applied at each 15 minute time interval to determine the gridded rainfalls input to the G2G for past and future times. The output grids from G2G, such as river flow and soil moisture, can be displayed in map form and further processed, for example to produce county flood risk maps.

The latest release of the G2G model, configured and calibrated across England & Wales, was delivered to FFC in June 2011. The release was accompanied by a Performance Summary comprising a "knowledge-base" of G2G performance for each river gauging station location. This provides a one page synthesis of features of the gauged catchment and associated G2G model performance, providing a concise user guide to the reliability of forecasts. The pages, in pdf form, can be accessed from the NFFS map display through a point-and-click action (using the ToolTip functionality) on the river gauging station location of interest.

Since July 2011 the FFC have been using the G2G Model operationally to support production of its various products and services. The Duty Hydrometeorologist uses G2G as an indicative tool to inform the flood risk for each county, and therefore the colour each county is allocated in the daily Flood Guidance Statement for England and Wales. It is also used to support the overall hydromet guidance service. FFC prepare quarterly reports on the G2G performance and reference these against existing site specific regional flood forecasting models.

An internal Environment Agency review of the capability of G2G has been undertaken. The report concludes that although operation of the model has given the FFC some information on the capabilities of G2G in some locations during operational use, a complete picture will only be derived from continued operation and assessment, and that various actions need to be undertaken to see the full benefit of its capabilities.

These are summarised as:

- Provide access to the G2G model and its outputs to local flood forecasting teams allowing them to gain confidence in the G2G model, its forecasts and its capabilities
- Produce Interim operational guidance on how and where G2G could support local flood forecasting at this stage
- Conduct a longer historical evaluation of the G2G model and its performance to produce more robust information on how well G2G performs across the country when predicting floods
- Update G2G flow severity grids to provide an improved view of national flood hazard
- Revise the operational guidance to take account of results from this performance evaluation
- Prioritise and plan which further model and data improvements would be necessary to maximise the benefits of the G2G model for flood forecasting purposes
- Evaluate the benefits of high-resolution rainfall ensemble forecasts to drive G2G across all river catchments, building on evaluation work focused on rapid response catchments
- Develop and apply a consistent methodology and measures for ongoing performance assessments of G2G (including when used with NWP ensemble rainfall inputs)
- Trial G2G with the improved merged radar/raingauge product (due in 2013)
- Conduct a review of snowmelt capability, including a hindcast review of performance using MetUM snowmelt and its comparison with the integrated snowmelt component incorporated into the G2G delivered to SEPA

4.1.3 Operational use of G2G within the Scottish Flood Forecasting Service

The Scottish Flood Forecasting Service (SFFS), a partnership between Scottish Environment Protection Agency (SEPA) and the Met Office, was launched in March 2011. The service is driving development and operational implementation of new techniques in Scotland for countrywide flood guidance and improved approaches to flood forecasting for emergency responders. In recognition of the gap in countrywide forecasting capabilities, a national-scale hydrological model for Scotland was commissioned in support of the new forecasting service. The CEH Grid-to-Grid (G2G) model, presented earlier in this report, has been implemented into FEWS (Flood Early Warning System) Scotland, SEPA's operational forecasting platform and became operational in early 2012.

As explained under Section 3.5.3, both raingauge and radar are combined using the HyradK module into a best-estimate gridded rainfall feed for input to G2G. Constraints on the telemetry data feeds are currently limiting the utility of this module but, with the emergence of live GPRS data in late-2012, the HyradK module is set to be fully utilised operationally. Operating in forecast mode, G2G utilises a combination of Met Office Numerical Weather Prediction (NWP) products. Currently a 6 hour deterministic 'nowcast' along with the most appropriate data from the UK4 (at a resolution of 4 km), North Atlantic and European (NAE) (25 km) and Global (25 km) atmospheric models are used.

Despite making use of the best available rainfall observation, forecasting and post-processing there still remains some uncertainty associated with the rainfall forecasts, and in which lies the greatest challenge for hydrological prediction. In order to understand the levels of uncertainty in the forecasts, ensemble data from the Met Office's MOGREPS-R system are also ingested into the G2G model. These MOGREPS-R data, based on 24 ensemble members at a horizontal resolution of 18 km, generate a range of flows across the grid, from which the probability of exceeding user-defined thresholds can be ascertained and mapped (Figure 4) to highlight hotspots of flood risk.

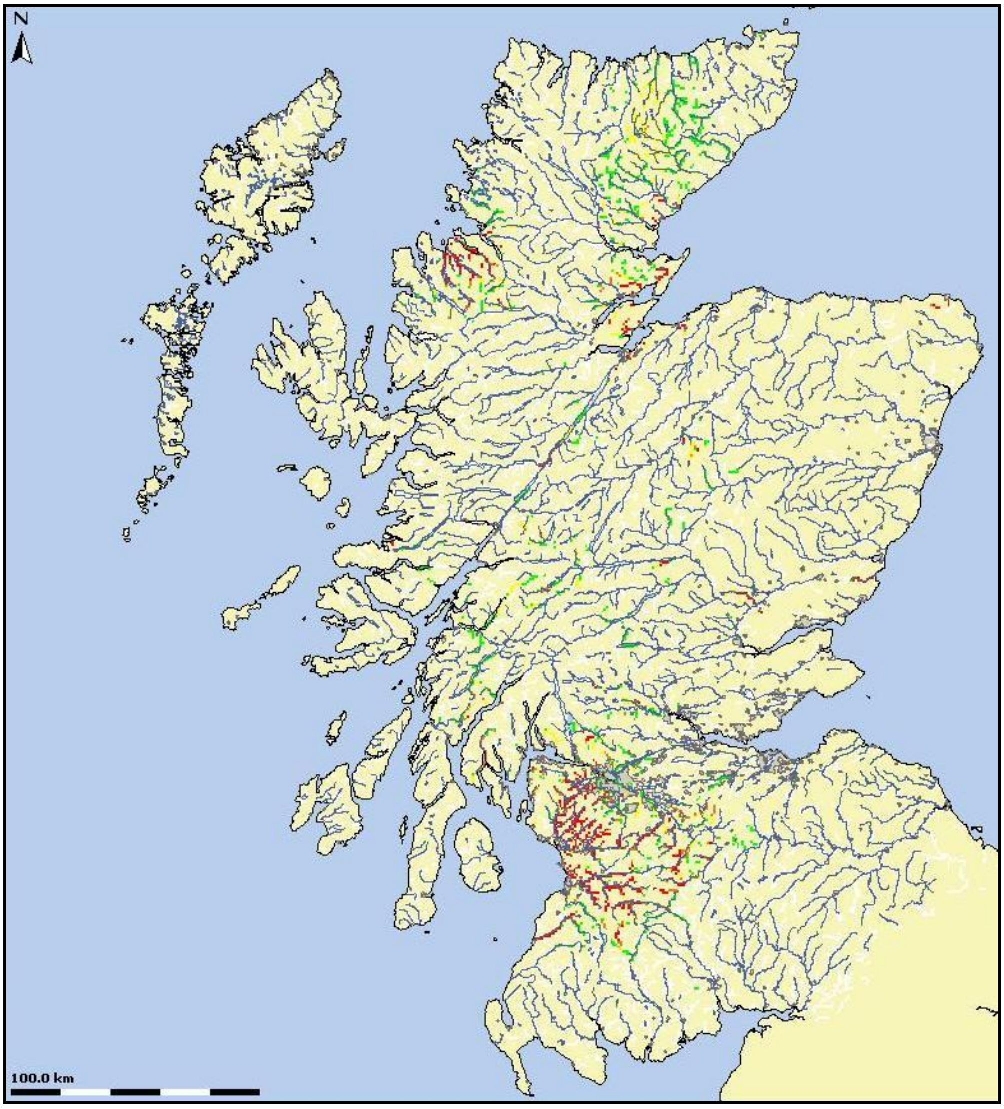

Figure 4 Gridded G2G forecast map showing the probability of exceeding a 2-year (median) flood. Green: less than 20%; yellow: 20 to 40%; orange: 40 to 60%; red: greater than 60%. This is during 4 January 2012 when minor flooding actually occurred.

From the early assessment of the operational use of G2G, and use of various associated rainfall inputs, the following has been learnt:

- spatial displays of G2G output can highlight the main areas of heightened flooding concerns, with the use of ensemble rainfall forecasts enabling the identification of the flooding hotspots, some with a lead time of 20 hours
- the G2G flood forecasts obtained using high-resolution deterministic NWP rainfalls as input to G2G have better forecasting skill
- using G2G with ensemble-based forecasts has enabled an objective assessment of the likelihood of the flood risk, and has been used to inform countrywide flood guidance.

4.2 UK radar network renewal including dual-polarisation

The Met Office and the Environment Agency are currently rolling out the largest upgrade to the UK radar network in its 30 year history. This new technology was largely developed by Met Office engineers. It will provide Doppler coverage over the whole of the UK network as well as dual-polarisation capabilities. A strong and successful history of in-house weather radar sub-system engineering development and upgrades has led the Met Office to select an innovative renewal approach based on an Open System Architecture (OSA). The system architecture was designed in the late 1990s in collaboration with the University of Essex. This design offers the most efficient and sustainable engineering solution for providing dual-polarisation capability to Plessey 45C radars. The approach proposes to overcome the obsolescence and capability shortfall of the current systems whilst adopting a modular and flexible approach to system design.

The system offers numerous benefits in terms of capabilities, some associated with the implementation of advanced technology to reduce the data repetition cycle, but primarily linked to the introduction of dual-polarisation and Doppler capability to all radars as well as providing refractivity measurements.

The first installation took place in September 2011 at Wardon Hill, Dorset. Wardon Hill radar is now used as a dual-polarisation research test-bed for the operational network and the radar research community. It is routinely producing dual-polarisation measures as well as Doppler wind, refractivity, emissions and other quality control measures.

The remaining 15 radars will be upgraded over the next 3 to 4 years starting with Thurnham (Kent) during summer 2012.

A new quality monitoring system has been developed to support this upgrade. Dual-polarisation radars produce 5 times as many measures than conventional radars, all of which require automatic calibration and monitoring. This system provides a valuable tool to assess the quality of the new radar systems soon after each installation (weather permitting).

Work is also currently under way to improve the quality control of radar reflectivity based on the additional dual-polarisation measures. This includes:

1. Spurious echo identification and classification
2. Attenuation correction
3. Radar calibration based on a self-consistency technique

Other areas of development will focus on:

4. Hydrometeor classification
5. Improvement of the VPR (Vertical Profile of Reflectivity) correction scheme
6. Improvement of the *Z-R* (reflectivity–rainfall rate) relationship

The availability of new dual-polarisation capabilities also provides opportunities for further research that promises to benefit hydrological applications. One such area is the melting layer where a current study at Essex University is investigating modelling assumptions regarding the effective dielectric constant of air-ice-water aggregates. It is hoped that the new dual-polarisation radars will facilitate improved parameterisation and characterisation of the melting layer (bright band) that will, in turn, reduce quantitative uncertainties in precipitation estimation.

4.3 Quality indicators/quantified errors

Quantified errors of radar rainfall estimates are required for their assimilation into both NWP and flood forecasting models; the error covariance is also needed to give an idea of the representativity of the error and if neighbouring estimates in space and time have independent or correlated errors.

A possible first step is to supply flags indicating good or bad data or a quality index, e.g. a number between zero and one, but such an approach is insufficient for use in NWP data assimilation. In the absence of such information, the tendency for the user is to assign a global error to the rainfall estimate; such an error is often derived *a posteriori* so that the rainfall measurement makes an optimal contribution to improving the forecast.

For hydrological application a common goal is to supply a rain-rate estimate in mm/hr for each radar pixel with a specified error (in mm/hr) and a covariance for that error so that the representativity of the error can be better understood and how this changes with time and meteorological regime; of course more complete error characterisations may be needed. Recent work in Switzerland by Germann and co-workers involving extensive gauge/radar comparisons is one example of how rainfall uncertainty estimation can be tackled using a semi-empirical approach.

Once the improved quality control and rain-rate estimation algorithms available with dual-polarisation are in place (listed 1-6 in Section 4.2) then a high priority task is to provide estimated rain-rate at the ground for each radar pixel accompanied by a quantified error. Progress achieving this goal has in the past been slow, but real progress should now be possible through exploiting new polarisation variables. It is important to know if errors over a given region are all correlated or are independent, and whether special treatment for non-Gaussian behaviour is required.

4.4 Probabilistic rainfall and flood forecasting

Forecasts of the future state of the atmosphere or rivers are often based upon estimating how the current state evolves in time using a numerical predictive computer model. However, as the atmospheric system is chaotic, very small errors in the initial state can amplify as numerical integration proceeds leading to large errors in the forecasts, which limit how far ahead the forecast detail can be specified with any certainty.

To investigate how these small differences in the input data to the models, or uncertainties in the model structures, may affect the outcome of the final forecast, the computer model may be run many times from slightly different input conditions. The ensemble of forecasts so-produced provides an indication of the reliability of the forecasts. There are a number of ways of evaluating and reducing the uncertainty arising from the partial differential equations used in specifying a model. These include initial tendency analysis, stochastic parameterisation and calibration of the ensemble spread using forecast output. Work in this area is continuing.

4.4.1 Evaluate and improve the performance of the G2G for Rapid Response Catchments (SC110003)

"G2G for Rapid Response Catchments" aims to evaluate and improve the G2G distributed hydrological model for use in flood forecasting for rapid response catchments. Flood impacts for such catchments can be severe and provision of targeted flood warnings is currently problematic using existing methodologies, especially since the catchments are typically ungauged. Rapid response catchments, however, do have the benefit of radar and weather model coverage providing gridded rainfalls, and their response can be represented through hydrological model process links to landscape properties obtained from spatial datasets on terrain, soil/geology and land-cover.

Presently, the G2G operates within the Flood Forecasting Centre and Scottish Flood Forecasting Service to provide a "national flood outlook" over the next 5 days, with forecasts updated every 6 hours. It is not routinely run to address the rapid response catchment flood forecasting problem, which requires much more frequent running of the model aligned to frequent telemetry polling of raingauge and river flow data, and use of new high-resolution deterministic and blended ensemble rainfall forecast products.

The research aims to provide evidence to help define the level of service for flood warning in rapid response catchments, made possible through using the G2G Model in conjunction with rainfall predictions for flood forecasting. This evidence will be provided through a performance assessment of G2G flood forecasts for rapid response catchments. The assessment will also be used to guide improvements in the G2G model formulation, targeted at rapid response catchments.

The project is being carried out by CEH under the Environment Agency's FCERM R&D Research Programme with support from SEPA. The main phase of work was initiated in January 2012 and planned to last one year, after which operational implications of the research will be progressed.

4.4.2 Risk-based Probabilistic Fluvial Flood Forecasting for Integrated Catchment Models (SC080030)

The EA/Defra R&D project "Risk-based probabilistic fluvial flood forecasting for integrated catchment models" was a consortium project led by Atkins Ltd with collaborators from Deltares, Lancaster University, CEH Wallingford and Edenvale Young. Its main aim was to develop and test practical probabilistic methods to quantify, and where possible, reduce uncertainties around fluvial flood forecasts. The project began in November 2008. The Phase 1 Report (Science Report: SC080030/SR1) was published in August 2009. The Phase 2 and Phase 3 reports (SC080030/SR2 and

SR3) were produced in 2010 as internal Environment Agency documents. They concern assessment of techniques on case study data and the development of guidelines together with an implementation plan.

The Phase 1 Report reviewed current experience within the Environment Agency, as well as internationally, with regard to uncertainties and identified catchment averaging of raingauge data as a key source, along with rating curves and rainfall-runoff model calibration. An “Uncertainty Framework” to support selection of an appropriate uncertainty estimation technique, developed at a high-level in Phase 1, was developed in detail in Phase 2 and applied to integrated catchment model forecasting case studies of varying complexity. Weather radar only indirectly featured by way of review in the Phase 1 Report in relation to catchment average rainfall estimation and through its use, via extrapolation, in the STEPS rainfall forecast product.

The initial brief was to exclude detailed consideration of forecast rainfall as a source of uncertainty, which was being addressed within another project: ‘Hydrological modelling using convective scale rainfall modelling’ (reviewed in the previous Session Report 2007 to 2010). However, the importance of accommodating forecasts in ensemble form within the Uncertainty Framework was recognised. A case study for the Upper Calder (a rural upland catchment draining from the Pennines) made use of STEPS ensembles of forecast rainfall for two flood events in 2008. Ensemble flood forecasts were produced as spaghetti, quantile and envelope plots as indicators of uncertainty attributable to the rainfall forecast. Model uncertainty associated with the rainfall-runoff model (PDM) when used with error prediction updating was depicted as a probability band using a parametric ARMA (Auto-Regressive Moving Average) approach. Use of STEPS allows probability bands of model uncertainty for ensemble forecast percentiles to be calculated, enabling model and rainfall forecast uncertainty to be jointly assessed.

A further case study on the River Ravensbourne (an urban tributary of the Thames in south London) employed data from the London Weather Radar at Chenies, after raingauge-adjustment using the HyradK method as implemented in CASCADE.

A synthesis paper on aspects of the project was published in the Proceedings of the British Hydrological Society 3rd International Symposium in July 2010. The Guidelines and Implementation Plan were used to initiate a follow-on project involving operational trials within NFFS. The technique chosen for further consideration was to estimate confidence limits for different forecast lead-times by a quantile regression approach as it offers the potential to make better use of existing performance information from operational flood forecasting models.

Forecast errors (from integrated catchment models) at different lead-times are obtained using the input data (rainfall and flow observations, radar nowcasts and NWP forecasts) that would be used operationally; historical records are used for “calibration” purposes to estimate the parameters involved in the quantile regression for each lead-time. The approach makes use of deterministic rainfall nowcasts and forecasts employed in regional flood forecasting systems and the river flow errors that result from these and other sources of uncertainty.

A follow-on project is currently taking place which further investigates the practicalities and benefits of applying this approach more widely to flood forecasting models in operational use.

4.4.3 Application of Probabilistic Forecasting in Flood Incident Management (SC090032)

The Environment Agency are developing a practical and transparent support framework to inform the use of probabilistic flood forecasts in Flood Incident Management. Specifically a number of approaches and methods will be developed and tested for: making transparent decisions based on probabilistic forecasts; setting probabilistic thresholds; and assessing the accuracy of probabilistic forecasts through defining appropriate performance measures. To support uptake of the range of new capabilities, good practice information with case studies will be provided along with internal training materials.

A report on the project will be published later in 2012.

4.4.4 Urban flood modelling using probabilistic radar rainfall ensembles

Flood forecasting and warning in urban areas requires measurements and forecasts of precipitation with high spatial and temporal resolutions (e.g. 1 km/5 min). Weather radars are able to provide such measurements, but unfortunately radar rainfall estimations are affected by different sources of error. These errors are often ignored when producing radar-based precipitation forecasts for urban flood forecasting. The aim of this EPSRC-funded project (EP/I012222/1, Urban flood modelling using probabilistic radar rainfall ensembles) is to develop a probabilistic urban flood forecasting system that integrates information from radar, raingauges and atmospheric observations for the real-time prediction and management of severe storms affecting urban areas.

4.5 NERC radar research

4.5.1 The NCAS mobile X-band radar

A moveable, Doppler, dual-polarisation, X-band radar (3 cm wavelength) system (see Figure 5) has been procured by the National Centre for Atmospheric Science (NCAS). The radar can measure areal precipitation, radial winds and polarisation measures. These outputs will be processed in near real-time and made available for transmission via an internet link to users remote from the radar.

Figure 5 The mobile radar delivered to NCAS, Leeds in February 2012

The system has a transmitter peak power of about 55 kW and the maximum range for reflectivity products is 200 km, although the typical operating range for dual-polarisation and Doppler products is 100 km. X-band is unlikely to allow clear-air returns to be detected from refractive index inhomogeneities (Bragg scattering), although it is anticipated that some wind measurements will be possible in the clear air from insect targets (Rayleigh scattering). Refractivity is not available as standard, but the intention is to develop the necessary software.

The new radar has a conventional parabolic, mechanically-scanned antenna with a 2.4 m diameter and 1° beam-width to reduce ground clutter, beam-filling problems and to achieve a resolution comparable with other operational radars. The system is **not** housed in a radome. The radar is movable with the use of an in-built dedicated trailer pulled by a four wheel drive vehicle. The system contains its own generator and has dual-polarisation (±45°), Doppler capability, and monitoring and product generation software.

The system underwent factory and site acceptance tests in early February 2012. Successful initial tests have been undertaken at Burn airfield, 40 km west of Leeds.

Initial activities that the mobile radar may be used for are:

- *COnvective Precipitation Experiment (COPE).* A consortium will operate in the southwest of England to examine the formation and development of precipitation in convective clouds. A movable radar system is part of this project and dual-Doppler will be achieved. Hydrologists will be invited to use the radar data.
- Proposals to use the radar for urban hydrology in partnership with other academic institutes.
- The MICROSCOPE project in the summer of 2013 (see Section 4.5.2).

4.5.2 Other NERC radar research

Other ongoing NERC radar research projects are:

- *DIAMET - DIAbatic influences on Mesoscale structures in ExtraTropical storms* This project involves the universities of Manchester, Leeds, Reading and East Anglia together with the Met Office, NCAS and the National Centre for Earth Observation.

  DIAMET aims to study mesoscale structures in cyclonic storms affecting the UK. From September 2011 to August 2012 thirteen IOPs (Intensive Observation Periods) took place with the BAe instrumented aircraft flying through major cyclonic storms over the north-east Atlantic and over Chilbolton where polarisation radar observations were made. The study aim is to analyse the dynamics observed in these mesoscale structures, using both the Chilbolton radar and the UK operational radar network, and compare them with their representation in NWP models. These data will be analysed over the next twelve months.
- *DYMECS - DYnamical and Microphysical Evolution of Convective Storms.* This project is a collaboration between the University of Reading and Met Office. It is designed to develop a statistical database of storm properties and evolution through the automated tracking of convective cells and showers by the

Chilbolton dual-polarisation radar and, on occasion, coincident flights with the instrument BAe-146 aircraft. The observations phase is now over. Forty days of data were gathered from August 2011 to August 2012 when there were convective showers or embedded convection within fronts. The final year will be spent on analysis looking at the following aspects:

i) Comparison of the evolving 3-dimensional structure of reflectivity in both the ice and rain with that produced by a forward model of the representation of the convective showers within the operational ~1.5 km Met Office weather forecast model (UKV)

ii) Comparison of the vertical winds retrieved from the radar observations using the continuity equation with those in the UKV model.

iii) Testing the sensitivity of the forecast to the model resolution and parameterisation schemes by running the UKV at 100 m resolution and changing the parameterised mixing length.

- *MICROSCOPE - MICROphysical COnvective Precipitation Experiment.* This project involves a consortium, lead by the University of Leeds, and will improve predictions of severe convective rainfall by addressing the microphysics of precipitation in convective clouds, and in particular, the initiation and evolution of the ice phase. The field campaigns will take place in the summer of 2013 with instrumented aircraft from the UK, France and the USA making in-situ measurements of clouds and aerosols while flying over the Chilbolton dual-polarisation radar and the NCAS mobile X-band radar.

5. Report on Strategic Area 3 – Raise Awareness of Radar in the Wider Community

5.1 Organisation of the 2011 International Symposium on Weather Radar and Hydrology

The International Symposium on "Weather Radar and Hydrology" (WRaH 2011) was convened from 18 to 21 April 2011 at the University of Exeter. The Symposium provided a forum for the exchange of experiences and ideas on the use of weather radar in hydrology. The Symposium theme placed emphasis on user applications of weather radar for flood forecasting and water management. All sessions combined developments in weather radar with advances in its hydrological application, serving to promote a strong interchange between researchers, practitioners in the water industry and those making advances in weather radar technology.

More than 250 people attended from a range of organisations - governments, academia, research bodies, national hydrometeorological services and consultancies – and travelling from countries spanning four continents. A total of 140 oral and poster presentations were made. An afternoon excursion to Lynmouth on the north Devon coast provided an opportunity to reflect on the devastating rapid response catchment flood of August 1952, affecting the East and West Lyn rivers, and how advances in weather radar and hydrology now help monitor and give advanced warning of such localised hazards.

This was the 8th in a series of International Symposia, begun in 1989 at the University of Salford (UK) under the title "Hydrological Applications of Weather Radar". Subsequent symposia have been convened in Germany, Brazil, USA, Japan, Australia and France. WRaH 2011 marked a return to the UK after 20 years of successful symposia across the world. The Inter-Agency Committee on the Hydrological Use of Weather Radar both initiated and coordinated the Symposium, including forming the Science and Local Organising committees, agreeing joint convening of WRaH 2011 by the Royal Meteorological Society and the British Hydrological Society, and raising sponsorship.

Submitted papers have been peer-reviewed and published as a Symposium Proceedings book by the International Association of Hydrological Sciences (IAHS) under the title "Weather Radar and Hydrology", IAHS Publ. No. 351 edited by R.J. Moore, S.J. Cole and A.J. Illingworth (all members of the Committee). A selection of papers, in extended form, is to be published in a Special Issue of the "Hydrological Sciences Journal" of IAHS. Further information is available at the Symposium web site www.WRaH2011.org .

5.2 Developing training in application of radar for hydrology

This Section gives a brief summary of relevant training courses that are available. More details can be found in Appendix D.

5.2.1 Leverhulme Lectures at University of Bristol

The Leverhulme Trust granted a visiting professorship award to Prof. Bringi from

Colorado State University to visit the Department of Civil Engineering at the University of Bristol between 26 April and 17 September 2010. During the visit, Prof. Bringi gave a series of lectures and a one-day workshop was organised on the following topics.

- The Remote Sensing of Precipitation with Radar: An Introduction
- Advances in the Radar Measurement of Rainfall: An Overview
- Workshop on Polarimetric weather radar for quantitative precipitation estimation

Further details can be found in Appendix D.1 and on the following web-site:

https://www.bris.ac.uk/civilengineering/research/water/projects/bringi-lectures.html

5.2.2 The Flood Forecasting Centre hydrometeorologist training programme

The Flood Forecasting Centre based at the Met Office in Exeter has an intensive training programme to develop the hydrometeorological capabilities and skills that their staff require. The objective of FFC is to be an internationally recognised centre of hydrometeorological expertise. Training courses are available to interested parties, on a commercial basis, who are looking to develop a hydrometeorological capability. The recent programme (September/October 2011) of training included a number of SEPA staff who are to be part of the Scottish Flood Forecasting Service (SFFS).

Radar related sessions are delivered by Met Office staff and include:

- Overview of future plans for radar product development
- Current Radarnet QC and precipitation product generation processes
- Orographic enhancements
- Radar data quality indicators
- Radar data quality monitoring

5.2.3 Hyrad training courses

Bespoke training courses are delivered by CEH to operating authorities that use the CEH Hyrad Weather Radar System such as the Environment Agency, SEPA and Scottish Water. These courses cover theory in radar meteorology and hydrological applications as well as hands-on software and systems training for viewing, analysing and using radar data.

5.2.4 Other courses that are available to internal staff of the Operating Authorities

Some of the operating authorities have a range of internal training courses which can be provided in-house or by external parties. Two Environment Agency courses which are provided by the Met Office and involve weather radar are:

T01: Weather and Met Office Product Interpretation

T02: Precipitation Forecasting

The Environment Agency are also developing a programme of training available to internal staff on how to generate, communicate and make decisions using probabilistic forecasting information. This will be relevant for using radar-based ensemble products. Descriptions of these courses are included in Appendix D.2 .

5.2.5 Other courses

ERAD 2012

The 7th European Conference on Radar in Meteorology and Hydrology (ERAD 2012) was held at Toulouse, France on 24-29 June 2012. As usual, there were several short courses held before the conference.

The courses were:

> **Dual-polarisation and Doppler Weather Radar**
> D. Moisseev and V. Chandrasekar
>
> **Millimetre Wavelength Radars**
> P. Kollias *et al.*
>
> **Radar Quantitative Precipitation Estimation and Forecasting and Hydrology**
> D. Sempere-Torres *et al.*

More information can be found at:
http://www.meteo.fr/cic/meetings/2012/ERAD/courses.html

It is likely similar short courses will be held at the next ERAD conference.

6. 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 promote areas of improvement and research in support of the user community. The main themes that the Committee is to explore are:

i) Radar capability and networks

The Committee is keen to explore the benefits of application of dual-polarisation radar both operationally and as part of research programmes. Specifically:

- Its important that the hydrological benefits of dual-polarisation radar are properly assessed for flood forecasting and water management applications.
- In addition, the assimilation of polarisation measurements into high-resolution Numerical Weather Prediction should be seen as a benefit.
- The ongoing threat of wind farm developments and their impact on the radar network continues to be a concern.

ii) Hydrological applications

Specific interests for the coming session for hydrological applications include:

- Flood forecasting in urban areas covering flooding of urban drainage systems and surface water flooding. This is the theme of a number of research proposals at present and the Committee needs to ensure pull-through of best practice to the user community.
- As with the previous session, there is a desire to provide appropriate radar rainfall quality flags and indicators for use in hydrological applications
- Developing hydrological modelling capabilities (G2G) for rapid response catchments and surface water flooding and the need for a robust radar product in support of these developments will continue to be a key priority area.

iii) Committee activities for 2013-2014

The Committee will be taking forward a number of initiatives in the coming session period, including:

- Promote the update and/or development of a User Note for radar and water management through CIWEM’s Urban Drainage Group (formerly WaPUG)
- Host a workshop or session on the ongoing initiatives for radar and raingauge merging techniques

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
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

Appendix B Committee Membership

Mr Michael Cranston *(Chairman)*	Scottish Environment Protection Agency
Dr Steven Cole (*Technical Secretary*)	Natural Environment Research Council Centre for Ecology & Hydrology, Wallingford
Prof. Chris Collier *	National Centre for Atmospheric Science (NCAS) University of Leeds School of Earth and Environment
Mr Tim Harrison	Environment Agency
Dr Miguel Rico-Ramirez *	University of Bristol Department of Civil Engineering
Dr Noel Higginson (until January 2012)	Department of Agricultural and Rural Development Hydrometric Section, Rivers Agency
Mr Tim Rennie (from January 2012)	Department of Agricultural and Rural Development Hydrometric Section, Rivers Agency
Dr David Bebbington *	University of Essex School of Computer Science and Electronic Engineering
Prof. Anthony Illingworth *	University of Reading Joint Centre for Mesoscale Meteorology
Dr Jacqueline Sugier	Met Office
Mr William Neale	Thames Water Utilities
Mr Bob Moore	Natural Environment Research Council Centre for Ecology & Hydrology, Wallingford
Dr Chris Walden	Science and Technology Facilities Council Rutherford Appleton Laboratory
Vacant	Department of Environment, Food and Rural Affairs

* co-opted member

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 nine universities (Bradford, Bristol, Essex, Exeter, Lancaster, Leeds (& NCAS), Imperial College, Reading and Swansea) together with the Centre for Ecology & Hydrology (CEH) and the Science Technology and Facilities Council (STFC). Reports are also provided from three Agencies: Environment Agency, SEPA and DARDNI.

C.1 Reports from UK Research Groups

C.1.1 University of Bradford

At the University of Bradford (Department of Civil and Environmental Engineering) research on the use of radar rainfall and quantitative precipitation forecasts for urban drainage modelling has been carried out under the Urban Flood Modelling work package of the Flood Risk Management Research Consortium Phase 2.

A high density urban raingauge network has been set up on the city campus of the University of Bradford. It has been operational since April 2012 and comprises 16 tipping-bucket raingauges over an area of less than 1 km^2. The aim of this network is to study the influence of small-scale rainfall variability on local urban drainage modelling, and to compare it with the use of radar rainfall at small urban scales.

C.1.2 University of Bristol

Algorithm to monitor antenna pointing

A novel technique to monitor continuously the azimuthal pointing accuracy of a weather radar antenna has been proposed. The technique consists of cross-correlating between modelled and measured echoes from ground clutter in real-time at low elevation angles under precipitation and non-precipitation conditions. The azimuthal angle lag with the maximum cross-correlation indicates the adjustment needed in antenna pointing. The modelled ground clutter echoes were obtained using high-resolution digital elevation model (DEM) data whereas the measured ground clutter echoes can be classified in real-time using polarimetric radar measurements in a Bayesian classifier, which identifies the clutter echoes in the presence of precipitation. The technique has been successfully tested in the Thurnham radar in Southeast England. This method can be used by data users as well as radar operators. It should complement the traditional methods based on sun measurements.

Rainfall estimation with polarimetric C-band radars

The rainfall estimation using data from an operational polarimetric C-band radar in convective storms in southeast UK is compared against a network of gauges. Four different rainfall estimators are considered: conventional Z–R relation, with and without correcting for rain attenuation; a composite estimator, based on (i) Z–R, (ii) $R(Z, Z_{dr})$, and (iii) $R(K_{dp})$; and exclusively $R(K_{dp})$. Overall, the composite estimator performed the “best” based on robust statistical measures such as mean absolute error, the Nash–

Sutcliffe efficiency, and mean bias, at all rainfall thresholds (>0.2, 1, 3, or 6 mm) with improving measures at the higher thresholds of >3 and >6 mm (higher rain rates). Error variance separation was carried out by estimating the gauge representativeness error using 4 years of raingauge data. The proportion of variance of the radar-to-gauge differences that could be explained by the gauge representativeness errors ranged from 20 to 55% (for the composite rain-rate estimator). The radar error is found to decrease from approximately 70% at the lower rain rates to 20% at the higher rain rates.

Radar-based forecasts for flood prediction in urban areas

The use of Quantitative Precipitation Forecasts to model runoff and flow processes in urban areas is a challenging problem, as rainfall data with high spatial and temporal resolutions are required. Many attempts have been made to use weather radar to produce rainfall forecasts with lead times of a few hours ahead. A nowcasting system was used to produce precipitation forecasts, which were coupled to an InfoWorks CSmodel of the sewer system of a town in Yorkshire to produce flow predictions. The simulated precipitation events were analysed in terms of rainfall and flow predictions at the urban scale of the study area. The results show that the overall performance of the rainfall forecasting system decreases with increasing rainfall intensities, and that the ensemble rainfall forecasts have a higher skill than the deterministic forecasts in predicting lower rainfall intensities. The results also show that stratiform precipitation is forecasted better than convective precipitation. More events need to be evaluated in order to define whether ensemble rainfall forecasts improve flow predictions on the urban scale. The analysis in terms of flow at this stage only supports a potential application for qualitative flood warnings in the small urban catchment considered.

C.1.3 University of Essex

In stratiform events, the melting layer remains one of the most important obstacles to accurate quantitative retrieval of precipitation intensity by radar at moderate to long ranges. Long known to radar meteorologists as the ‘bright band’, it is characterised by melting ice-crystal snowflake aggregates that scatter the radar beam more strongly than the rain drops into which they melt, and which fall away more quickly. At longer ranges the radar beam overshoots the rain and intersects the melting layer, hence returning a ‘bright band’ of high reflectivity values which, if naively interpreted, could lead to over-estimation of rainfall. At progressively longer ranges, the beam also widens, so that the profile of the melting layer also has a complicating effect.

In recent years, empirical averaged profiles have been used by a number of operational meteorological services in Europe to improve rainfall estimates. Research also continues to improve the physical modelling of the melting layer. A recent study in Germany (Chemnitz University of Technology) using dual-polarisation data identified a number of important characteristics required to match the physical model profile shape and location. It concluded that the profile of the dielectric constant of the hydrometeors had a strong influence. A current study at Essex University is investigating modelling assumptions regarding the effective dielectric constant of air-ice-water aggregates. There is as yet no fully accepted theory of effective dielectric constant for mixtures. In this study it is planned to compare existing theories with stochastic models of the scattering amplitudes using the Fredholm Integral Method combined with numerical integration.

The roll-out of the new generation of dual-polarisation radars over the UK radar network may be expected to allow improved parameterisation and characterisation of the melting layer and hopefully reduce quantitative uncertainties in precipitation measurement.

C.1.4 University of Exeter (Centre for Water Systems)

Research carried out at University of Exeter Centre for Water Systems over the Session period under the Flood Risk Management Research Consortium (FRMRC2) project, included the application of Artificial Neural Networks (ANNs) as Data Driven Models (DDMs) to predict urban flooding in real-time based on weather radar and/or raingauge rainfall data. In the first study, a 123-manhole combined sewer sub-network from Keighley, West Yorkshire, UK was used to demonstrate the methodology. An ANN was configured for prediction of flooding at manholes based on rainfall input. Output from the 3DNet/SIPSON simulator, which uses a conventional hydrodynamic approach to model flooding surcharge levels in sewer networks, was used to provide the target data for training the ANN. The trained ANN then acted as a rapid surrogate model to replace the hydrodynamic simulator in real-time. Artificial rainfall profiles derived from observed data provided the input. Both flood-level analogue and flood-severity classification schemes were implemented. The use of an ANN for nowcasting of rainfall based on the relationship between radar rainfall data and recorded raingauge rainfall was also investigated, using pattern recognition techniques. The proposed schema would then involve cascading two ANNs to predict flooding in real-time based on weather radar. The work is ongoing.

Based on the success of the initial study, UKWIR funded a second joint-agency project to carry out three more case studies to evaluate the effectiveness of ANN models to predict flood levels, manhole flood and Combined Sewer Overflow (CSO) spill volumes and outfall flow rates as a result of both design and real rainfall. Three catchments were evaluated: 1) Crossness (south-east London, UK), where effectiveness of ANNs with spatial rainfall was studied; 2) Portsmouth, UK, where use of ANNs for predictive real-time control of pumps was evaluated and 3) Dorchester, where the utility of using Net Antecedent Precipitation Index (NAPI) values as ANN inputs, to signal soil moisture variation, was assessed. This joint-agency project involved HR Wallingford (project coordination), Halcrow, Mouchel, Richard Allitt Associates (results analysis) and University of Exeter, who provided the ANN models (RAPIDS) and results analysis tools (HydroMAT). Results obtained demonstrated good ability of ANN models to predict urban drainage system flooding.

C.1.5 Imperial College London

Imperial College London, Department of Civil and Environmental Engineering, is engaged in research on weather radar calibration, applying weather radar for flood estimation and forecasting in urban and rural environments, and the testing of high-resolution short-range radar technology for urban application. Work on calibration has recently included calibration of radar systems in Malaysia and fitting high-resolution space-time rainfall models to radar data.

Catchment modelling applications have recently included participation in the DMIP2 distributed model inter-comparison project (http://www.nws.noaa.gov/oh/hrl/dmip/2/) and related research using US National Climatic Data Center products. Urban applications of weather has included projects under FRMRC1 and FRMRC2 (http://www.floodrisk.org.uk), investigating improved high-resolution dual-drainage models and nowcasting algorithms. A recently started European Union Interreg project called RAINGAIN will include applications of high-resolution radar for forecasting in several European cities, and experimental testing of new short-range radar products. For further details, see: http://www.raingain.eu/en/raingain and Section 3.1.3.

C.1.6 University of Lancaster

Lancaster University has been developing a number of techniques for the hydrological use of weather radar as part of the European Union Framework Programme 7 IMPRINTS (IMproving Preparedness and RIsk maNagemenT for flash floods and debriS flow events) project (see http://www.imprints-fp7.eu/). The focus of the work has been on developing tools for use in the forecasting of flash-flood events which are applicable in a European-wide context. Typically lead-times of up to 8 hours have been considered depending upon the catchment scale and radar rainfall product being utilised.

Research has been focused on three topics. The first is the development of suitable hydrological models, derived objectively from the available data within a data-based mechanistic framework that may be able to make use of the spatial pattern of rainfall input. The second is the assimilation, using derivatives of the Kalman filter, of real-time hydrological and meteorological data to improve the hydrological forecasts. The final topic is the characterisation of the uncertainty in the prediction of the future water levels that arises from uncertainty in the forecasts of future precipitation but also the limitations in the representation of their impact on the hydrological system.

C.1.7 University of Leeds & National Centre for Atmospheric Science (NCAS)

The University of Leeds hosts the Directorate of the National Centre for Atmospheric Science (NCAS), a distributed NERC Research Centre. NCAS has acquired a mobile Doppler dual-polarisation X-band radar (Section 4.5), which will be managed by scientists at Leeds, and which will be available for use by the academic community. Research at Leeds by NCAS and the School of Earth & Environment using this system and other radar data will include studies of the structure and behaviour of atmospheric systems building upon previous work in the CSIP (Convective Storm Initiation Project) and COPS (Convective Orographically-induced Precipitation Study) programmes funded by NERC. The City RainNet Project outlined in Section 3.5.1 is being academically led by NCAS at the University of Leeds. Further work on the propagation of radar errors through hydraulic and hydrological models is underway.

C.1.8 University of Reading

Work at the University of Reading can be divided into two categories: firstly studies directed at providing extra information from the operational radar network, and secondly using radar observations to study precipitation structures and our ability to model and forecast them.

1. Improved radar techniques in collaboration with the Met Office

a) Detecting storm emission to correct for radome and storm attenuation. Attenuation results in underestimates of rainfall during heavy flood-producing events. A new approach has been developed which is currently being rolled-out over the operational network. It involves measuring the increased noise detected by the radar receiver due to emissions from the storm, and relies on the simple physical principle that all absorbers are emitters. The increased noise can then be interpreted as due to attenuation by the radome or attenuation by a distant storm. Radome attenuation can be significant but has until now been neglected. Trials in the next year will quantify the impact of radome attenuation on rainfall estimates.

b) Measurement of refractivity using ground targets. Any increase in the refractive index of the air leads to a decrease in the speed of the radar wave, and an additional phase shift of signals reflected from stationary ground targets. By comparing the phase shift from targets along the same azimuth, a range resolved change in refractivity can be derived. Maps of hourly changes in refractivity can be mapped within 30 km of each radar with a resolution of about 4 km. In the summer, 80% of these changes are due to changes in humidity so the technique should identifying areas of humidity convergence leading to the triggering of convection. The technique is being rolled-out over the operational network and its ability to improve short-term forecasts of convection will be investigated.

2. Improved understanding and forecasting of rainfall

This is being carried out under the following two NERC grants which are described in Section 4.5.2.

- *DYMECS - DYnamical and Microphysical Evolution of Convective Storms*
- *DIAMET - DIAbatic influences on Mesoscale structures in ExtraTropical storms*

C.1.9 University of Swansea

The Swansea Climate and Water Research Group is based at the College of Engineering, Swansea University. The research group is interdisciplinary in nature with research interests ranging from hydrological modelling, radar hydrology, climate change impact and adaptation, through to coastal engineering.

Since 2009, the group has been actively involved in the EPSRC FRMRC Phase 2 project as one of the leading partners offering expertise in flood forecasting using weather radar, especially in the context of urban flooding where timely and accurate radar rainfall estimates are highlighted as an important driving factor. The major work undertaken by the group was the “Hydrological Appraisal of Radar Rainfall Data from Thurnham Dual-Polarisation Radar”. The researchers assessed the performance of the new dual-polarisation radar in the context of predicting a flooding event in one of the catchments in South-East England. Various algorithms for clutter removal and attenuation correction were developed and applied to improve the quality of radar rainfall data. These data were then used in several hydrological models developed and calibrated for the Upper Medway catchment. The study was one of the first to comprehensively look at the potential use of dual-polarisation radars for hydrological modelling, compared with the normal approach of using traditional single-polarisation radars. The findings revealed by the study laid a substantial foundation for further development in this direction.

C.1.10 Centre for Ecology & Hydrology (CEH)

Research and development relevant to weather radar at CEH over the session period is summarised below under 4 headings. A Keynote Paper prepared for WRaH 2011, published in its IAHS Red Book Proceedings, includes a synthesis of recent CEH activity as part of a UK operational perspective on weather radar and hydrology.

(a) Countrywide flood forecasting and warning across Britain

CEH's Grid-to-Grid (G2G) Model is a physical-conceptual distributed hydrological model configured on a grid. The G2G is now used operationally by the Flood Forecasting Centre over England & Wales and the Scottish Flood Forecasting Service to support national flood guidance statements. During the reporting period there has been significant work in developing, calibrating and configuring the G2G for operational use within the operational forecast system environments NFFS-FFC and FEWS Scotland as well as several training courses for EA, SEPA and Met Office staff. As part of these operational systems, CEH's HyradK algorithm is used to produce raingauge-only and raingauge-adjusted radar rainfall products at a space-time scale of 1 km and 15 minutes. Circa 900 telemetry raingauges across England & Wales for FFC and circa 180 across Scotland for SFFS are used in forming these gridded rainfall estimates.

Further details are provided in Section 4.1 of the report as well as articles in the 'Developments in operational flood forecasting in the UK' special issue of the Water Management ICE journal and the WRaH 2011 IAHS Red Book publication.

(b) Probabilistic flood forecasting and rapid response catchments

CEH's work on the two EA/Defra R&D projects 'Evaluate and improve the performance of the G2G for Rapid Response Catchments' (SC110003, with support from SEPA) and 'Risk-based probabilistic fluvial flood forecasting for integrated catchment models' (SC080030) is reported on under Sections 4.4.1 and 4.4.2 respectively. The latter project on probabilistic flood forecasting assessed the use of STEPS ensemble rainfall forecasts, which are based on extrapolating radar rainfall images forwards in time and blending them with rainfall forecasts from a Numerical Weather Prediction (NWP) model. A novel way of using the STEPS rainfall ensemble forecast was developed to produce a forecast "flow hydrograph" for a given probability of exceedance, reflecting rainfall forecast uncertainty, along with a probability envelope of model error. The project is now complete.

The rapid response catchment research is ongoing. Phase 1 of the project is complete and included an assessment of G2G forecasts using a circa 2 year archive of the latest high-resolution UKV NWP deterministic rainfall forecasts. Within Phase 2, the latest blended ensemble rainfall forecast products will be assessed along with improvements in the G2G model formulation, targeted at rapid response catchments.

(c) Automated raingauge quality control

As part of implementing the distributed G2G model for operational countrywide use by FFC, CEH performed off-line model calibration and assessment. This included use of circa 900 Environment Agency raingauges across England & Wales with HyradK to produce 1 km 15 minute grids of rainfall estimates based on (i) raingauge-only, (ii) gauge-adjustment of radar. With such a large number of raingauges and long data record (circa 2.5 years), an automated quality-control algorithm was developed to mitigate the effect of erroneous raingauge data on G2G modelling as discussed in Section 3.5.3.

To enable real-time application and computational efficiency, all gauges are processed in parallel for each 15 minute interval by the algorithm. A set of simple tests are performed on each gauge separately, before more involved comparisons to neighbours are made. The methods aim to detect errors affecting the short- and long-term rainfall totals that adversely impact on the water-balance accounting of the G2G Model: such as blockages, missing values that are recorded as zero, anomalous large values and systematic over- and under-estimation. Extensive analysis of the G2G model outputs using the different rainfall estimates led to the raingauge-only product being recommended for use in model calibration and as the first choice to use operationally. This research was presented at WRaH 2011 and a paper included in the associated IAHS Red Book publication.

(d) Rainfall return period analysis

Scottish Water use the Centre for Ecology & Hydrology's Hyrad (HYdrological RADar) system for real-time processing, display and analysis of radar-rainfall data. A particular application has been to support urban storm drainage compliance assessments where the estimated rarity of rainfall events causing surface water (pluvial) flooding can be used to help determine whether a drainage system performed within design specifications or if remedial action is required. Other applications are planned or underway such as hydraulic model verification, pollution event analysis, bathing water quality, linking to pipe bursts, consumption analysis, regulatory reporting, predictive maintenance and use within the control centre to plan day-to-day activities.

CEH are currently integrating the Flood Estimation Handbook depth-duration-frequency model within Hyrad to allow users to create automated calculations of rainfall rarity and post-event analysis reports. As part of this work, Scottish Water's entire historical radar archive was processed to provide daily records of radar rainfall return period estimates (rather than just for specific event analysis). For each day, the most extreme (highest return period) rainfall was identified over the last 24 and 48 hours using a range of rainfall durations. This database is being linked to historical flood incident records from customers to assess whether extreme rainfall was a contributing factor. This work was presented at WRaH 2011 and a paper included in the associated IAHS Red Book publication.

C.1.11 Science Technology and Facilities Council (STFC)

The Chilbolton Group, a part of RAL (Rutherford Appleton Laboratory) Space at the STFC maintains and operates the Chilbolton Facility for Atmospheric and Radio Research (CFARR). This 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.

During this session CFARR has participated in observation campaigns as part of the DIAMET project, led by the universities of Manchester, Leeds, Reading and East Anglia. This project is concerned with diabatic influences on mesoscale structures in extratropical storms, and aims to improve our understanding of how these can give rise to extreme weather events such as high winds and heavy rain. The 3 GHz Chilbolton Advanced Meteorological Radar (CAMRa) at CFARR has been used in combination with in-situ data from aircraft-borne instruments to provide high-resolution measurements of mesoscale structures. The aim is to improve our understanding of how mesoscale processes in cyclones give rise to severe weather and how they can be better represented in weather forecast models.

The high-resolution capability of the CAMRa radar makes it also the key instrument in the DYMECS project being undertaken by the University of Reading. This project commenced during this session, and is developing statistics on the properties of thunderstorm cells and showers by tracking them using the Chilbolton radar.

Automated scanning has been developed which allows the scan sequences to be selected in real-time based on composite radar data from the Met Office operational radar network. This allows individual storms to be tracked allowing detailed cell properties to be derived as a function of time in the cell lifecycle. The statistics on storm cell properties will be used to carefully test the validity of various components of convective parameterisation in high-resolution runs of the Met Office Unified Model.

C.2 Reports from UK Agencies

C.2.1 Environment Agency

The National Flood and Coastal Erosion Risk Management (FCERM) Strategy for England challenges services for flood detection, forecasting and warning to provide:

- more accurate and longer lead-time forecasts of flooding from all sources;
- forecasts that are meaningful and understandable to those who rely on them to make decisions;
- more innovative ways of sharing locally specific forecasts, warnings and flood information with people and partners, combined in a clear and accessible way to improve incident response.

The FCERM Strategy for England also recognises the need to maintain the required skills, capabilities and knowledge within teams that manage flood risk. The Single Environment Body for Wales will determine the strategy and plans for Wales from April 2013.

Exercise Watermark in March 2011 demonstrated the importance of how we present and communicate our best forecasting and warning information to enable effective action by the wider public, our emergency response partners and the media. A key action from Watermark is to improve our forecasts to not only provide our best advice on the likelihood of flooding but also, wherever possible, to convey the scale and potential impacts of incidents to our customers.

With these drivers in mind our plans for flood detection and forecasting to 2015 include:

- Supporting the Met Office to renew all the weather radars covering England and Wales with a dual-polarisation capability, and to improve their reliability and resilience (described in Section 4.2).
- Improving our picture of real-time observed rainfall by making the best use of the radar and telemetered raingauge networks operated by the Met Office and Environment Agency through merging the data (described in Sections 3.5.2 and 3.5.3).
- Improving the rainfall forecasting product we receive from the Met Office and ingest into our flood forecasting models, through the "Blending convective scale NWP with ensemble nowcasts" project described in Section 3.1.5. The resulting high-resolution ensemble product will support our efforts to improve fluvial forecasting and warning, and help us to develop forecasting and warning services for rapid response catchments, and locations affected by surface water flooding.
- Improving our national flood forecasting capability by further development of the G2G model operated by the Flood Forecasting Centre (described in Section

4.1.1), and greater operational use of the G2G model (described in Section 4.1.2).

- Evaluating and improving the performance of G2G for Rapid Response Catchments utilising the improved high-resolution rainfall forecast ensembles described above (described in Section 4.4.1).
- Developing a probabilistic river forecasting capability (described in Section 4.4.2), and applying this capability (described in Section 4.4.3) so that we can provide our best advice on the likelihood of flooding, and where possible convey the scale and potential impacts of incidents to our customers.
- Using more innovative ways of sharing locally specific forecasts, warnings and flood information with people and partners through providing a targeted flood warning service for Category 1 and 2 Responders (described in Section 3.4.1).
- Considering options to publish our forecasts on the internet.
- Continuing to invest in the coverage, quality and resilience of our local forecasting model service, supported by many of the initiatives described above, through our Regional Flood Forecasting teams, in order to deliver more accurate and longer lead-time forecasts of flooding from all sources.

C.2.2 SEPA

Following the new statutory mandate for flood warning in Scotland under the Flood Risk Management (Scotland) Act, a step change has taken place in flood forecasting capabilities in recent years. Significant investment has been made into SEPA's operational flood forecasting capabilities through the continued development of its Flood Early Warning System (FEWS Scotland). Although capabilities continue to develop, one of the biggest challenges for SEPA in the development of forecasting approaches is the varied accuracy and availability (in spatial resolution) of radar. As rainfall-runoff modelling expands to areas of greater uncertainty, with it comes increased uncertainty in flood predictions. With this in mind the flood warning strategy for 2012 to 2016 is looking to:

- Work with the Met Office to review the current weather radar network and its suitability for flood warning provision and consider options for improvements (including new installations such as temporary X-band installations).
- Make best use of the raingauge monitoring network in the radar network particularly with the emergence of GPRS datafeeds of rainfall data.
- Ensure the best possible use of emerging weather prediction through the development of a hydrometeorological capacity building.

One of the biggest challenges for the coming years is in the development of forecasting for surface water flooding. Following the Edinburgh Flood of August 2010, SEPA commissioned the Met Office to produce a hindcast run of MOGREPS UK for this storm to assess whether it was possible to quantify the threat of flood-producing rainfall with a lead-time of 36 hours. The research highlighted the challenge in forecasting these types of events even with emerging science, with a prediction of 30-40% chance of an extreme storm occurring within 25 km of Edinburgh. SEPA continue to work with the Met Office in developing a prototype approach to surface water alerting based on convective-scale ensemble predictions.

C.2.3 DARDNI

The Rivers Agency has been using raw single-site radar rainfall data in real-time flood response and analysis for around 15 years until the service was updated by the Met Office about 6 years ago. The replacement product is a GIS-based rainfall information system. For the last 6 years Rivers Agency have held licences to use Envirometas an in-house weather warning tool. At present, the Rivers Agency will not be adopting a Flood Warning policy similar to Floodline in Great Britain.

Appendix D Further details of training available for the application of radar for hydrology

This Appendix gives more information about some of the courses listed in Section 5.2.

D.1 Leverhulme Lectures at University of Bristol

The Leverhulme Trust granted a visiting professorship award to Prof. Bringi from Colorado State University to visit the Department of Civil Engineering at the University of Bristol between 26 April and 17 September 2010. During the visit, Prof. Bringi gave a series of lectures, and a one-day workshop was organised as briefly discussed below. Further details and presentations can be found on the following web-site:

https://www.bris.ac.uk/civilengineering/research/water/projects/bringi-lectures.html

D.1.1 The Remote Sensing of Precipitation with Radar: An Introduction

This first lecture focuses on the advent of dual-polarisation radar with particular reference to the US National Weather Service. It gives a broad historical perspective and the principles leading to the accurate measurement of rainfall and identification of precipitation types, especially hail.

D.1.2 Advances in the Radar Measurement of Rainfall: An Overview

Radars can often, but not always, provide the needed high spatial (few 100's of metres) and temporal resolutions (few minutes or better) needed for urban or small basin hydrology. Furthermore, dual-polarisation radar can potentially provide improved rainfall input to hydrological models for flood predictions, especially the extreme rainfall events. Dual-polarisation has long been studied at the S-band (~ 3 GHz) and C-band (~5.5 GHz) frequencies, and more recently a revival at X-band (~10 GHz) has taken hold. This talk describes the recent advances, as well as pros and cons, in measurements of rainfall using radars at these three important frequencies.

D.1.3 Workshop on Polarimetric weather radar for quantitative precipitation estimation

Many operational weather radar agencies around the world, including the UK, are upgrading their radar networks with dual-polarisation capability in order to improve data quality and rainfall estimation for hydrological and meteorological purposes. This workshop explored some of the advantages and potential difficulties in using this new technology, as well as the requirements for the hydrological community.

D.2 Other courses that are available to internal staff of the Operating Authorities

This Section gives details of three internal courses that are available to Environment Agency staff.

D.2.1 T01: Weather and Met Office Product Interpretation

Overview

This course aims to provide Flood Incident Management duty officers with appropriate meteorology training to gain a better understanding of meteorology and the key Met Office products used in their role, enabling them to perform their duties more effectively.

Target audience

This course is for Flood Incident Management duty officers and Flood Incident Management teams only. It can be taken as a refresher every three to four years.

Objectives

At the end of this course, you will:

- Understand how forecasting in the Met Office works;
- Understand the common meteorological features affecting the UK;
- Have an awareness of the Met Office products currently available to Flood Incident Management staff;
- Be able to accurately interpret and use Met Office products;
- Know the procedures for providing feedback on Met Office products and services.

Process

This is a practical and interactive one-day course delivered by Met Office trainers from the Met Office training college.

D.2.2 T02: Precipitation Forecasting

Overview

This course aims to provide Forecasting Duty Officers with appropriate meteorology training to gain a more advanced understanding of precipitation forecasting, as well as show how they should use Met Office precipitation forecasting products in their role, enabling them to perform their duties more effectively.

Target Audience

This course is for Flood Incident Management Forecasting Duty Officers and Monitoring Duty Officers where appropriate. It may also be appropriate for Flood Warning Duty Officers in some cases. This course can be taken as a refresher every three to four years.

Objectives

At the end of this course, you will:

- Be able to summarise the precipitation products currently available;
- Be able to interpret and respond to particular rainfall event types;
- Know pertinent questions to ask the Met Office forecaster on receipt of a forecast;
- Know which products are the best to use in particular situations;
- Detect faults in data delivery and how to invoke contingency arrangements.

Process

This is a practical and interactive one-day course delivered by Met Office trainers from the Met Office training college.

Pre-course work

All delegates should have attended the Weather and Met Office Product Interpretation (T01) course prior to attending this course.

D.2.3 Probabilistic Forecasting

The Environment Agency are developing a programme of training available to internal staff on how to generate, communicate and make decisions using probabilistic forecasting information. There will be four elements to this:

1. An interactive e-learning course called “Introduction to Probabilistic Forecasting”
2. A one day practitioners course delivered locally by regional Flood Forecasting staff called “Probabilistic tools for Forecasting Duty Officers”, using a Train the Trainer approach.
3. A one day course delivered by local staff, called “Communicating probabilistic forecasts and making decisions”
4. A one day practitioners course, delivered nationally, called “Setting Probabilistic Thresholds”

It is anticipated that some elements of this programme will be made available to incident management staff across all responder organisations, and other EA partner organisations involved in incident management, to help them:

1. to understand the meaning and benefits of probabilistic information
2. to make better more effective operational decisions.