Inter-Agency Committee on the Hydrological Use of Weather Radar

Seventh Report

2007 to 2010

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 Seventh Report of the Inter-Agency Committee on the Hydrological Use of Weather Radar. At times over the past three years the United Kingdom has been devastated by flooding: such as Summer 2007 in England and Wales, Morpeth in September 2008 and Cumbria and South West Scotland in November 2009. These events are presenting new challenges for flood risk management and the role of weather radar. This comprehensive report is thus timely in pulling together and documenting the growing effort in the research and user communities engaged in radar, hydrology and water management.

After taking over from the previous chairman, Chris Haggett, in 2007 I was personally keen to explore whether radar was meeting the needs of hydrologists and meteorologists in the UK. As such the Committee undertook a survey of the user community, the findings of which are guiding future direction and opportunities in this sector.

There have been significant research and modelling developments that are improving our use of radar and radar-derived products. This is a reflection of the effort by the UK community which will hopefully be well represented on an international forum at the 2011 Symposium on Weather Radar and Hydrology (www.wrah2011.org). The Committee is particularly pleased to be given the opportunity to host and organise this event that will be under the scientific direction of members Bob Moore and Anthony Illingworth and an international committee.

Regarding the Committee, I would like to thank all the members for their continuing support, as without their involvement and enthusiasm the committee would not succeed in its aims. The Committee has seen a number of changes during the current session so I would like to extend my thanks to departing members Tony Deakin (Environment Agency), Malcolm Kitchen (Met Office) and Nick Martin (Thames Water Utilities) and welcome new members Tim Harrison (Environment Agency), Jacqueline Sugier (Met Office) and William Neale (Thames Water Utilities).

On a final note and on behalf of the Committee I would like to acknowledge the efforts of Professor Anthony Holt who passed away in 2008. Anthony, who was a committee member for 10 years, was an ambassador for weather radar and related technologies and made a significant leading contribution in this field.

Michael Cranston
Chairman (2007-2010)
Inter-Agency Committee on the Hydrological Use of Weather Radar
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Glossary

anaprop	Anomalous propagation - a propagation path of electromagnetic radiation that deviates from the path expected from refractive conditions in a standard atmosphere.
CEH	Centre for Ecology & Hydrology
Defra	Department for Environment, Food and Rural Affairs
EA	Environment Agency
EPSRC	Engineering and Physical Sciences Research Council
ERA	Extreme Rainfall Alert
FCRM	Flood and Coastal Risk Management
FEWS	Flood Early Warning System
FFC	Flood Forecasting Centre
FREE	Flood Risk from Extreme Events (NERC Thematic Programme)
FRMRC	Flood Risk Management Research Consortium (EPSRC Programme)
G2G	Grid-to-Grid; a distributed rainfall-runoff and routing model
graupel	Heavily rimed snow particles, often called snow pellets; Precipitation consisting of white, opaque, approximately round (sometimes conical) ice particles having a snow-like structure, and about 2–5 mm in diameter. It is formed as a result of accretion of super-cooled droplets collected on what is initially a falling ice crystal.
hail	Precipitation in the form of balls or irregular lumps of ice, always produced by convective clouds. By convention, hail has a diameter of 5 mm or more.
IACHUWR	Inter-Agency Committee on the Hydrological Use of Weather Radar
KTP	Knowledge Transfer Partnership
MCS	Mesoscale Convective System
MetUM	Met Office Unified Model
MO	Met Office
MOGREPS	Met Office Global and Regional Ensemble Prediction System
MOSES	Met Office Surface Exchange Scheme
NERC	Natural Environment Research Council
NFFS	National Flood Forecasting System
NWP	Numerical Weather Prediction
Ofwat	The Water Services Regulation Authority; it is the economic regulator of the water and sewerage sectors in England and Wales.
PDF-R	Probability Density Function to Rain-rate
PDM	Probability Distributed Model; a type of rainfall-runoff (catchment) model
PPI	Plan Position Indicator

QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecast
R	Rainfall rate
RA	Rivers Agency (Northern Ireland)
TAG	Theme Advisory Group
SEPA	Scottish Environment Protection Agency
SNIFFER	Scotland & Northern Ireland Forum For Environmental Research
STEPS	Short Term Ensemble Prediction System
STFC	Science Technology and Facilities Council
UKPP	UK Post Processing system (used by the Met Office)
VPR	Vertical Profile of Reflectivity
WaPUG	Wastewater Planning User Group
WRaH 2011	International Symposium on Weather Radar and Hydrology 2011
Z	Radar reflectivity

1. Introduction

At the start of the current session of the Inter-Agency Committee, the flood warning authorities and responder communities were coming to terms with the devastation of the Summer 2007 Floods in England and Wales. The floods resulted in 13 fatalities, flood damages in the order of £4 billion and 55,000 properties affected by flooding. This led to an independent review of flood response that was published in 2008.

The Pitt Review made 92 recommendations in total with a strong emphasis on much closer collaboration across the agencies responsible for weather and flood prediction. In particular, the review commented:

> '*There is room for improvement, particularly in relation to increased lead times for predicting events, probabilistic forecasting and more accurate local-scale forecasts at a city or town level. Closer working should deliver real changes in technical capability. This will improve the usefulness and reliability of extreme rainfall forecasts and warnings, which are essential for providing effective warnings for rapid response catchments and surface water flooding. We believe this closer working will be best achieved through a joint centre.'*

With many of the recommendations of the Pitt Report in the process of implementation - including the introduction of the Flood Forecasting Centre (FFC) for England and Wales - the UK's ability to forecast, warn and respond to another significant event was tested with the November 2009 flood affecting much of north-west Great Britain and Northern Ireland. This was most acutely realised in Cumbria where the impacts were most severe with 4 fatalities and major impacts on towns, villages and infrastructure.

Figure 1 Cockermouth during the 2009 Cumbria Floods (Copyright. All rights reserved. Environment Agency and Peter Smith Aerial Photography ©)

Service developments at the FFC and proposals in Scotland are now leading to much closer collaboration between hydrologists and meteorologists. This is resulting in an emergence of operational hydro-meteorological tools, with radar playing a pivotal part in these services. In support of this, during the last session the Inter-Agency Committee has continued to work towards its aims of serving the hydrological and meteorological radar user community. Specifically, the Committee has sought to identify the user research needs, support hydrological applications of radar and raise awareness of radar in the wider community.

Section 3 of this report provides a thorough review of ongoing research in the areas of radar capability, benefits to hydrology through meteorological forecasting and applications to water management. One such research area that is providing potential operational benefits originates from the project 'Hydrological modelling using convective scale rainfall modelling' where a distributed hydrological model is being utilised for the operational use of ensemble rainfall forecast products.

The Committee's efforts in supporting the hydrological applications of radar are presented in Section 4. One of the major achievements here has been completing the first ever UK-wide survey of hydrological use of radar-based products across the operating agencies. In conjunction with a review of the strategic drivers for these agencies, the Committee has been able to identify future research needs and operational requirements (Section 6).

Finally, the Committee continues to raise awareness of the benefits of radar as a tool in flood risk management (Section 5). The Committee's vision of publishing an educational booklet continues and this will hopefully be launched at the 2011 Weather Radar and Hydrology Symposium. This follows from the Committee's successful bid to host the next international symposium from 18 to 21 April 2011 in Exeter. The theme of the symposium will place emphasis on user applications of weather radar for flood forecasting and water management with the aim of promoting a strong interchange between researchers, practitioners and those making advances in radar technology.

2. Community Plan

2.1 Background and Aims

In the previous session covering 2005 to 2007, the Committee continued in its efforts to link radar related research to their operational application. In particular the Committee had the following two strategic areas of activity:

- Monitor and critically review ongoing research programmes and projects with a view to guiding the operational application of their outputs and influencing future research directions

- Raising awareness of hydrological applications of weather radar in the wider community

Under the 2007 to 2010 session, the Committee continued to raise the awareness of hydrological applications, but also reviewed the current activity in various strands of radar research, determined agency and community requirements for research and identified the gaps in either the research initiatives or the user requirements.

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 themes 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

To deliver these aims, the Committee has agreed to work on the following strategic areas in the 2007-2010 session, presented in Table 1.

Table 1 Strategic Areas for the 2007-2010 Programme

Strategic Area 1 **Identify Research Needs**
In the area of research, developments in radar data and their application are coming from several directions and priorities are not clearly defined. The Committee will seek to clarify arrangements where funding and effort are split across a number of research programmes e.g. FREE, FRMRC and EA/Defra TAG Programmes. It will also assess the changes and opportunities arising from the European Union Floods Directive and other European initiatives e.g. European Flood Alert System and OPERA (Operational Programme for the Exchange of Weather RAdar information).
Strategic Area 2 **Support Hydrological Applications of Radar**
Operating agencies such as the Environment Agency and SEPA have made significant strides to improve the operational application of radar-based products through systems such as NFFS and FEWS. The focus is to now identify whether such products are being used operationally and improving agency procedures.
Strategic Area 3 **Raise Awareness of Radar in the Wider Community**
The Committee will continue to raise awareness and report on the hydrological applications of radar.

2.3 Milestones and Deliverables

Within each Strategic Area the Committee set out a number of deliverables against which it will be measured. These are outlined in Tables 2 and 3, together with the lead Committee member(s) assigned to each delivery. 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 2 Milestones and deliverables for the 2007-2010 Programme

Strategic Area 1
Identify Research Needs

- Identify the broad areas of radar-related research (Chris Collier)
- Identify ongoing research in these areas.
  - Radar capability (Anthony Illingworth and Jacqueline Sugier)
  - Benefits to hydrology through meteorological forecasting (Bob Moore and Chris Collier)
  - Applications for water management (William Neale and Tim Harrison)
- Identify the gaps in the current research initiatives and the current operational requirements (see Strategic Area 2).
- Identify research needs and funding opportunities under current and new initiatives.
- Publish a review paper with a working title of '*Current research application of weather radar to hydrology: a UK perspective*'. (Chris Collier)

Strategic Area 2
Support Hydrological Applications of Radar

- Assess the current usage of radar-based products within the operating agencies through a survey of the agencies represented. (Michael Cranston)
- Host a workshop for the operating agencies to promote radar related research and discuss the hydrological application of radar (Michael Cranston)
- Prioritise the user requirements for radar related research to inform Strategic Area 1. (Michael Cranston)

Strategic Area 3
Raise Awareness of Radar in the Wider Community

- Further developments of the IAC web site hosted by the Science and Technology Facilities Council. (Chris Walden)
- Provide a summary report of the 2005 – 2007 session for BHS Circulation and RMetS Member News. (Michael Cranston)
- Publication of an explanatory 'Sense About Science' leaflet on the hydrological applications of weather radar to highlight: weather radar and related products; benefits of radar in operational, design and planning functions; the role and work of the Committee. Title '*Use of radar for flood risk management*'. (Michael Cranston)
- Identify opportunities for the funding of training, i.e. advanced applications of weather radar. (Chris Collier)
- Exploit opportunities for publicising the role of weather radar in detecting and forecasting of severe weather/flooding events. (Jacqueline Sugier)

3. Report on Strategic Area 1 – Identify Research Needs

3.1 Identify the broad areas of radar-related research

Three broad areas of radar-related research were identified:

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

Table 3 lists focussed topics within each broad area. This forms the background for the specific ongoing research activities identified for each broad area in sections 3.2 to 3.4.

Table 3 Details of the three areas that ongoing research will be identified for under Strategic Area 1

<table>
<tr><td>Radar capability (Anthony Illingworth and Jacqueline Sugier)</td></tr>
<tr><td>Attenuation corrections
Use of multi-parameter radar for QPE (Quantitative Precipitation Estimation)
Development of radar quality indicators
Refractivity/wet delay techniques
Use of radar data in NWP</td></tr>
<tr><td>Benefits to hydrology through meteorological forecasting
(Bob Moore and Chris Collier)</td></tr>
<tr><td>Analysis of Mesoscale Convective Systems to identify the likelihood of extreme flood situations (thought to be relevant to the safety of medium to large reservoirs)
Characterisation of errors in radar estimates of rainfall and their propagation through hydrological models
Assimilation of radar data (reflectivity, winds, refractivity, precipitation type etc.) into high-resolution NWP
Flash flood forecasting using radar data
Research on physical processes through the combination of radar data with other remote sensing systems such as lidar to improve short-period forecasting (representation of sub-grid scale processes; convective development)</td></tr>
<tr><td>Applications for water management (William Neale and Tim Harrison)</td></tr>
<tr><td>Use of radar for forecasting surface water (pluvial) flooding in both urban and rural areas
Use of radar for urban drainage management</td></tr>
</table>

3.2 Radar capability – ongoing research

As an introduction, a summary is provided in Section 3.2.1 of the major issues in radar rainfall estimation that are being addressed through recent and ongoing research. New approaches to attenuation corrections using storm emissions and the current single polarisation radar network are reviewed in Section 3.2.2. Then the potential improvements in rain-rate estimation from the new generation of polarisation diversity radars is considered in Section 3.2.3 along with how they can help provide data quality indicators (Section 3.2.4) and measurement error structures (Section 3.2.5). The review of direct rainfall estimation related research concludes in Section 3.2.6 with a summary of ongoing microwave link research which is an emerging and complimentary method of rainfall estimation.

Besides rainfall estimation, there is considerable ongoing research into obtaining new radar-based atmospheric humidity estimates. These estimates are derived from refractivity measurements which use either the commercial broadcasting network (Section 3.2.7) or ground clutter returns (Section 3.2.8). These humidity measurements have the potential to observe the early stages of convective storm generation and could be assimilated into NWP to improve short-term rainfall forecasts. Assimilation of radar data into NWP models is reviewed in Section 3.2.9 and research on how NWP forecasts can feed back to the radar processing algorithms is discussed in Section 3.2.10.

3.2.1 Major issues in the current methods of radar rainfall-rate estimation that are being addressed through ongoing research

Current operational radar rainfall networks derive rainfall rate (R) from radar reflectivity (Z) using an empirical relationship of the form $Z = aR^b$ where a is about 200 and b near to 1.6. There are many errors associated with this relationship, and although improvements have been made as a result of considerable research over the past 20 to 30 years, the accuracy is still deemed unsatisfactory. The major errors that are being addressed through ongoing research are:

(i) Attenuation of the beam in heavy rain leading to a reduction of Z.
(ii) Variation in drop size spectra leading to changes in the Z-R relationship
(iii) The presence of hail with very high Z leading to overestimation of rain-rate.
(iv) If the radar beam is in the snow the Z is much lower than in the rain below.
(v) If the radar beam is in melting snow the detected Z is too high.

The relevant research in this area is reviewed in Section 3.2.2 for the current single polarisation radar network and Section 3.2.3 for the new generation of polarisation radars.

In addition, the present rain-rate estimates are only supplied with a rudimentary quality indicator.

3.2.2 Radar-based thermal storm emission measurements to correct for attenuation

Attenuation of the radar beam (issue (i) above) can be a serious problem during the intense rain often associated with severe flooding events. For example, during 20 July 2007 over London the radar returns were attenuated by up to 90%, so that radar estimates of rainfall were less than half that measured by gauges. An approach to correct for this attenuation was first proposed by Frédéric Fabry (McGill University) in

2001 and is being developed further by the Met Office in collaboration with Reading University. The basic physical principle is that all absorbers are equally good emitters and so if a storm attenuates a radar signal, then it must also emit radiation at the same frequency. Therefore, if these emissions can be measured, it should be possible to quantify the degree to which a radar signal has been attenuated, thus providing more accurate estimates of rainfall during intense events.

Microwave emissions from attenuating storms are visible as an increase in measured ‘noise’ at far range (behind the storm). This noise can be detected just before a transmitted pulse, when there is no backscattered signal because the radiation from the previous pulse is at several hundred km range and above any targets. In order to relate this noise increase to attenuation, calibrated noise sources and updated versions of the radar processing system (Cyclops) have been rolled out across the UK operational radar network which includes averaging the digitised returns from the furthest 150 gates at a range of over 400 km.

Initial tests are encouraging. Noise levels are relatively stable at each radar site during dry weather, enabling successful calibration of each site, and the discrimination of noise from the radar itself and noise from atmospheric sources. Furthermore, tests during several storm events show that the emissions technique has provided comparable estimates of attenuation to the standard ‘gate-by-gate’ attenuation correction technique currently used by the Met Office.

3.2.3 Use of multi-parameter radar for Quantitative Precipitation Estimation

The new generation of radars now being installed on radar networks in various European countries and elsewhere have an additional polarisation capability. This additional information promises to reduce the errors (i) to (v) identified in Section 3.2.1 in the following ways.

(i) If the target is rain and attenuation is present, then a correction for the attenuation can be introduced depending upon the observed phase shift, and rainfall rates derived together with an error.

(ii) If the target has been identified as rain with no attenuation, then the combination of use of Z and the differential reflectivity, Z_{dr}, should provide a more appropriate Z-R relationship which can be used and an indication of the accuracy of the inferred R.

(iii) If hail is detected, then the very high Z usually accompanying hail should not be converted into an exceptionally large rainfall rate. These data should be flagged as suspect. At this stage it is difficult to know if it will be possible to supply an accurate rainfall for such situations.

(iv) If snow is detected then the value of Z is likely to be lower than in the rain near to the surface. Currently this is corrected using an assumed vertical profile of reflectivity (VPR) – the additional information should enable this VPR approach to be improved.

(v) If melting snow is detected then the value of Z is likely to be much higher than in the low level rain. As before, currently a correction algorithm is used which uses an assumed VPR; the additional information should enable this VPR approach to be improved.

3.2.4 Development of radar quality indicators

The new polarisation parameters are better able to discriminate precipitation echoes from those due to clutter, birds and non-meteorological echoes; this minimises the risk of precipitation being detected when none is present. Once it has been established that the echoes are due to precipitation then it is possible to distinguish between returns from rain, hail, snow and melting snow.

If the target is rain, then the empirical *Z-R* relationship should give a reasonable rain-rate estimate providing the rain is not heavy enough for the returns to be attenuated. Any attenuation can be unambiguously detected by the degree of differential phase shift detected by the polarisation radar, and the derived rainfall rates flagged. Once the presence of ice has been identified then a quality indicator can be flagged to indicate that derived rainfall rates are suspect; if the beam is in the snow then the inferred value of *R* is likely to be too low; if it is melting snow or hail then the inferred value of *R* may be too high.

3.2.5 Identification and use of error structures contained in radar measurements of rainfall

At present, only simple assumptions are made about the errors of rainfall when they are assimilated into models, such as an error of (say) +/- 50%, and (say) a flag when the rainfall is derived from echoes which are in the ice above the metling layer. Multi-parameter methods described above promise to provide a quantified error estimate for each derived rain-rate estimate. In addition, if the data are to be used in NWP or for incorporation into flood forecasting models, it is essential that the error covariances are known. For example if the rainfall error at one pixel is +50%, then the error at a neighbouring pixel is more likely to be close to +50% and unlikely to be –50%. In other words the errors are spatially correlated, and what is needed is a description of the error covariance matrix which expresses the degree to which errors of pixels close in space to each other are correlated.

Once such error covariances are known, then one can generate many equally likely precipitation fields from a single measurement. Such fields are useful for initiating an ensemble of rainfall fields to generate an ensemble of forecasts of future weather for feeding into models for flood forecasting. Most of the highly populated parts of the UK are within 60 km of an operational radar, so for the summer half of the year, at least, we can be reasonably sure that the beam will be in the rain and the error in rainfall arises from an uncertainty in the value of a in the $Z = aR^b$ relationship. It should be possible to establish the error covariance of the variations of the value of a by analysing rainfall observed with dual polarisation radar.

3.2.6 Use of microwave links

Until the advent of optical fibre transmission, the vast majority of UK and other countries' telecommunications were carried by a network of microwave links. Much research was carried out regarding the incidence and statistics of attenuation by rain, which affects the availability of such links. Although the percentage of traffic carried by such links is much less at present, they and their physical infrastructure still exist, and research collaborations led by Essex University have shown that a measure of integrated rain-rate can be obtained from the attenuation recorded on each 'hop'. One of the promising features of this technique is that the relationship between specific attenuation and rain-rate is substantially more linear than that between radar reflectivity and rain-rate. By the use of dual frequency links, with the frequencies appropriately chosen, the non-linearity can be reduced still further, which makes the technique even more robust to variability of the rain drop-size distribution. It is envisaged that this technique which measures integrated precipitation along the line of sight could prove useful in steep-sided valley catchments inaccessible by radar. The Essex Group reported simulations, and results of field tests in which data from links were compared with raingauge and radar data.

3.2.7 Use of refractivity information from the commercial broadcasting network

It should be possible to detect the 'wet' delay of the accurate timing information supplied with digital broadcasts and interpret this extra delay in terms of an increase in the refractive index along the path between the receiver and the transmitter. To map out the surface changes in refractivity, which in summer is a good indication of changes in surface humidity, a network of receivers is needed. By looking at the change in the wet delay detected by a series of receivers at increasing distance along an azimuth from the transmitting antenna, the humidity changes along the azimuth can be determined. Measurements from this technique would be continuous and the principle limit is the economic cost of deploying the required number of stations. Currently Bath University are assessing the feasibility of this approach using tomography techniques.

3.2.8 Use of refractivity information from ground clutter

The Met Office is currently implementing a refractivity observing system which relies on measuring the changes in the time taken for the radar signal to travel to and from ground clutter. There are many such clutter targets widely distributed around the radar, so it is possible to derive changes in the refractivity field every five minutes with a resolution of about 4 km out to a distance of 30 km. This covers an area of 3000 km^2 with about 200 independent observations. To achieve this performance from a broadcasting network (see Section 3.2.7) would need numerous receivers to be deployed accompanied by a suitable means of transmitting the data to a base station in real-time. The advantage of the broadcasting network approach is that, of course, the area covered is not restricted to 30 km regions surrounding each radar location.

3.2.9 Assimilation of radar data in NWP models

Reflectivity data

At the Met Office, the radar processing system has been upgraded to deliver quality controlled radar reflectivities to the Numerical Weather Prediction (NWP) models. The raw polar data received from the radars are processed centrally: the noise is subtracted from the raw signal and radar bins affected by ground clutter, spikes and partial beam blockage are flagged.

Then, the quality information and the radar reflectivity data are passed to the Observation Processing System (OPS) where synthetic observations are calculated using model fields interpolated at the exact observation locations. The observation operator developed for the OPS is used for both monitoring and assimilating the data. Various options have been considered to account for non-Rayleigh scattering, attenuation, beam bending and non-uniform beam filling.

Long-term comparisons between synthetic and real observations have been used to characterise differences between synthetic and real observations and to select the data for the variational assimilation step. The monitoring developed for the benefit of the assimilation has the advantage to show deficiencies of the NWP model as much as problems with individual radars.

Doppler winds and high-resolution NWP

There is an increasing demand for high-resolution weather prediction, which in the UK has an emphasis on accurate forecasts/nowcasts of strong convective storms which in recent years have been responsible for major flooding events. In response, the Met Office is developing a numerical weather prediction (NWP) system using a 1.5 km version of the Unified Model for short-range NWP and nowcasting. Such a system requires the assimilation of high temporal and spatial resolution observations. One potentially vital observation is provided by weather radar in the form of radial wind.

Currently four radars in the UK radar network provide Doppler radial winds which can potentially be used for NWP data assimilation. Work has been undertaken to assimilate the Doppler wind, initially in the UK 4 km model then subsequently in a southern England version at 1.5 km resolution. Velocity-Azimuth Displays (VADs) from Plan Position Indicator (PPI) scans were tested and are now part of the Met Office operational system. From 2007 the effort has been concentrated in assimilating Doppler wind PPI scans directly and studies are underway to explore their impact within a 3D-Var assimilation framework.

3.2.10 Possible feedback from NWP models to radar processing

Section 3.2.9 outlines the Met Office process for assimilating radar reflectivity data into NWP models. The monitoring developed for the benefit of data assimilation has the advantage to show deficiencies of the model as much as problems with individual radars. The statistical information derived from the monitoring can be used to improve the calibration of the radars in the UK network.

In addition, the height of the freezing level held in the NWP model is used as the basis of the corrections for the vertical profile of radar reflectivity when the radar is not sampling the rain close to the ground but may be sampling in the ice at higher levels. This correction technique assumes a 'standard' shape for the vertical profile of reflectivity in stratiform rain with a maximum in the bright band where there is melting snow, and a lower level in the rain below. In winter when the melting level is closer to the ground this correction can be a large effect.

At the University of Essex, a fast hybrid parabolic equation model solver was developed and used to predict anomalous propagation echoes, outputting model estimates of PPI (Plan Position Indicator) based on refractivity derived from an NWP model and a high-resolution terrain elevation database. Reasonably good agreement between predicted echoes and those believed to be anaprop rather than precipitation, in spite of limitations to the height resolution of the NWP layers, suggests that perturbation of the model fields towards closer agreement with observed anaprop regions could potentially be assimilated into the NWP model and compliment the work reported in Section 3.2.9. Subsequently, work at Essex has led to an automatic differentiation package implemented in FORTRAN, which enables the construction of an adjoint model with minimal changes to the forward model code. This would enable the sensitivity of the forward model to parameters describing the refractivity profile shape to be computed very efficiently.

3.3 Benefits to hydrology through meteorological forecasting – ongoing research

3.3.1 Nowcasting ensembles

The deterministic form of STEPS (Short Term Ensemble Prediction System) is now being delivered by the Met Office within the UKPP (UK Post Processing) system and covers forecast lead-times from 0 to 6 hours. Ensembles from STEPS became operational in 2009 with 30 members being generated every hour. The potential benefits to flood forecasting of using the STEPS ensembles has been investigated during two EA/Defra funded projects that are discussed in Section 3.3.4.

3.3.2 Blending of nowcasts and NWP ensembles

The ongoing EA/Defra R&D project 'Blending convective scale NWP with ensemble nowcasting', being undertaken by the Met Office, is looking to generate ensemble rainfall products that combine STEPS ensemble nowcasts, MOGREPS NAE (Met Office Global and Regional Ensemble Prediction System North Atlantic European domain) ensemble forecasts and outputs from the high-resolution (~1.5 or 4 km) configurations of the MetUM (Met Office Unified Model). The methods developed will cope with the different temporal and spatial resolutions of the blended products. The products aim to be of benefit to flood forecasting and this will be assessed when they are used by the EA/Met Office Flood Forecasting Centre for England & Wales.

3.3.3 High-resolution NWP ensembles

Separate to the nowcasting approach, there is a drive to develop high-resolution (~1.5 km) NWP. The Environment Agency now receive MetUM 4 km data as part of the UKPP roll out in summer 2008 (previously they received 12 km). The Met Office also produce 'on-demand' 1.5 km NWP forecasts over small domains. Currently a new 'UKV' (UK Variable resolution) model is undergoing operational testing. The UKV model has a ~1.5 km resolution over the UK with variable resolution stretching to 4 km away from the UK and will eventually replace the MetUM 4 km and small 1.5 km 'on-demand' models.

Additionally, ~1.5 km resolution ensembles with data assimilation of radar measurements and using physically-based perturbations are being progressed at the University of Reading and the JCMM (Joint Centre for Mesoscale Meteorology). This includes research funded by FREE (Flood Risk from Extreme Events - http://www.nerc.ac.uk/research/programmes/free/) with CEH Wallingford looking at the potential benefits for probabilistic flood forecasting. A first hydro-meteorological case study is looking at the convective storms which caused the Boscastle flood. Physically-based ensemble members are generated by perturbing the potential temperature at the 1280m level using a 2-D Gaussian distribution every 30 minutes.

3.3.4 Probabilistic flood forecasting

The EA/Defra R&D project 'Hydrological modelling using convective scale rainfall modelling' was a collaboration between Deltares and CEH Wallingford that produced its Final Report in early 2010 (Science Report – SC060087). The broad aim was to investigate what hydrological model concepts and associated computational methods allow for making best use of the latest Met Office developments in high-resolution and probabilistic rainfall forecasting. Regional case studies in the South West (focusing on the Boscastle flood of August 2004) and the Midlands (using the floods of summer

2007) were employed to assess the hydrological models, including their utility when used with ensemble rainfall forecasts. These case studies were subsequently extended to include a nationwide application of the G2G (Grid-to-Grid) distributed hydrological model. The potential for operational use of ensemble rainfall forecast products such as STEPS (Short Term Ensemble Prediction System), high-resolution NWP (Numerical Weather Prediction) and MOGREPS (Met Office Global and Regional Ensemble Prediction System) were examined.

Overall, the project provided an experience base for probabilistic flood forecasting when supported by ensemble rainfall forecasts. The use of hydrological models in distributed form allowed the impact of spatial storm pattern on flood response and its uncertainty to be better represented in both space and time in a probabilistic way. Forecast flood risk maps of flood flow exceedance were seen to have particular operational value for flood warning. The performance of the G2G Model when used with HyradK for gridded rainfall estimation supported its use, with England & Wales coverage, in the new Flood Forecasting Centre. This national model configuration would serve as a complement to more detailed and often more accurate regional models targeted to forecast at specific locations.

The South West, Midlands and national case studies provided valuable experience, in a hydrological modelling/forecasting context, of using weather radar alongside or jointly with raingauge data using the HyradK gridded rainfall estimation procedures. One recommendation of the project was to explore a gridded rainfall estimator that uses raingauge-only estimates where gauge coverage is good and radar-only where poor, with merging at intermediate locations. Improvements to the G2G Model formulation and its calibration nationwide were also identified.

The EA/Defra R&D project “Risk-based probabilistic fluvial flood forecasting for integrated catchment models” is a consortium project led by Atkins Ltd with collaborators from Deltares, Lancaster University, CEH Wallingford and Edenvale Young. Its main aim is 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 Report (SC080030/SR2) will be published in 2010 and Phase 3, concerned with developing guidelines and implementation plan, is scheduled for completion in Autumn 2010.

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, thereby reducing overlap with the ‘Hydrological modelling using convective scale rainfall modelling’ project discussed above. 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 presented in the form of sphagetti, quantile and envelope plots to indicate 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 Ravensboune (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.

3.3.5 Extreme Rainfall Alert service

On 2 July 2008 the Met Office launched a pilot Extreme Rainfall Alert service for category 1 and category 2 responders. See:

http://www.metoffice.gov.uk/corporate/pressoffice/2008/pr20080616a.html
http://www.cabinetoffice.gov.uk/ukresilience/preparedness/ccact.aspx

The service exploits the latest numerical weather prediction (NWP) models and post-processing techniques including time-lagged ensembles from the 4 km configuration of the Met Office's Unified Model, and ensemble precipitation nowcasts from STEPS. A dedicated team of forecasters utilise these data and their severe weather forecasting expertise to issue advance warnings of extreme rainfall which may lead to significant surface water flooding. These services were launched from the Flood Forecasting Centre in London in April 2009. An upgrade to the first-guess warning capability is planned for Summer 2010. This will involve the generation of 1.5 km NWP time-lagged ensembles.

3.3.6 Propagation of rainfall uncertainty through hydrological models

Work is on-going at the University of Leeds on rainfall error propagation through hydrological models leading to proposals for selecting flow forecast ensemble members. The manner with which radar rainfall input, and hydrological model parameter uncertainty, influence the character of flow simulation uncertainty in hydrological models, has been investigated using a stochastic model of the River Croal catchment in North West England. The errors in the input data to the model, although they are constrained by the model structure, do propagate through to the flow predictions. The results have been compared with similar work in the USA and are similar. A possible approach to selecting flow forecast ensemble members, based upon knowledge of the peak discharge mean absolute error, has been investigated. Further investigation of the methodology is needed.

Research is also being undertaken as part of the FREE Project led by Kings College London to develop a modelling structure and uncertainty cascade aimed at assessing uncertainty in flood inundation impacts.

At the University of Bristol, a fully physically-based distributed model was built for the Upper Medway catchment in the South East of England using MIKE SHE/MIKE 11. The hydrological model was calibrated and validated using 15 minute raingauge data. In order to evaluate the propagation of error from radar rainfall estimations in hydrological modelling, a simple radar error model was used that takes into account the random error and the bias in radar data. Several radar rainfall events were perturbed with this error and the results show that the bias tends to increase when propagated through the distributed hydrological model. For instance 10% and 20% bias in radar data produces 25% and 50% bias respectively in flow simulations.

Although there has been considerable progress in improving the quality of radar estimates of precipitation, including developments in radar technology such as polarisation diversity, the unpredictable nature of radar errors means that it is unlikely that all errors in radar estimates of precipitation will be removed in real-time systems. A quality index based upon the use of a Peaks-Over-Threshold (POT) parameter has been tested for several gauged catchments for different rainfall types with some success. For ungauged catchments a different approach is proposed based on the fitting and analysis of an autoregressive model to rainfall time series. It is not yet clear how practical these techniques are for real-time operation.

3.3.7 Mesoscale Convective Systems

Mesoscale Convective Systems (MCSs) are generated when a number of convective cells interact to form a new dynamic system. They are characterised by a very large cloud shield which grows rapidly in area as the MCS develops and by having both convective and stratiform rainfall areas. They can produce large amounts of rainfall over many hours at a point if they become stationary or slow moving. Their occurrence is about one per year normally in late summer or early autumn. There have been a number of detailed analyses of these systems in the UK using a wide range of data, including radar and numerical model output.

3.4 Applications for water management – ongoing research

3.4.1 Radar use within the Water PLCs

Northumbrian Water hosted a meeting for water company users of radar rainfall data on 8 October 2009. The objective of this meeting was 'To share thinking, identify and promote consistent use of rainfall radar in support of sewerage infrastructure activities'. Nine water companies sent representatives to this meeting, which is a good indication of how important radar data are viewed within the water industry.

At present, most water companies use radar data to investigate flooding events. These data are either purchased on an event by event basis, or the water company will have a contract in place with the Met Office to receive radar data on a daily basis for all or part of their regions. In addition, a number of water companies have developed their own bespoke software packages to convert Met Office radar data into useable rainfall files. These rainfall files are then applied to their sewerage network models so that the impact of the rainfall can be understood in more detail and solutions developed to prevent repeat incidents in the future.

Water companies are interested in developing methodologies that allow them to forecast rainfall events with more accuracy. This will enable them to manage their infrastructure so that strategic assets, such as storage tanks and pumping stations, are prepared for the predicted rainfall events. It will also enable water companies to mobilise operational teams, so that they are best placed to cope with any situation that may result from the rainfall.

Capital investment in sewerage infrastructure is monitored and regulated closely by the water industry regulator Ofwat. It is therefore vital that all investments are robust and that the customers receive good value for money, while the water companies maintain Guaranteed Standards of Service (GSS). Water companies are also starting to install permanent monitors and a variety of telemetered raingauges across their regions to enhance their understanding of system performance and to support investment strategies. Radar rainfall data are particularly useful over large urban areas, such as London, where the spatial variation of rainfall can be significant and the number of suitable raingauge sites is limited. The 1 km radar data can also be provided at a fraction of the cost of a corresponding network of tipping-bucket raingauges.

At the meeting hosted by Northumbrian Water, it was agreed that there was a need within the water industry to develop a common methodology for the use of radar rainfall data in post-event analysis and hydraulic modelling. This would set a common standard to which all water companies, and the engineering consultants employed on water industry projects, would adhere. It would also set the regulatory standards by which Ofwat would review and assess each company.

The general view of the water companies is that they would like to make greater use of radar data, but that there needs to be a framework that governs data checking, quality and application to current modelling techniques. This framework should help water companies to build confidence in using radar data and therefore develop a strong business case for further investment in radar technology.

Thames Water and Scottish Water have both undertaken modelling studies using radar rainfall data. Papers for both studies were presented at the WaPUG (Wastewater Planning User Group) conference in November 2008. Important work of this nature is continuing at several other water companies with flood forecasting and real-time control of sewerage systems being of greatest interest. It is hoped that these studies will form the basis of a new WaPUG code of practice for the use of weather radar in hydraulic modelling, and as such will provide the necessary framework to support greater use within the water industry.

Scottish Water in 2009 took delivery of the Centre for Ecology and Hydrology's Hyrad (HYdrological RADar) system for processing, displaying and analysing radar-rainfall and the Flood Estimation Handbook (FEH) software for rainfall return period estimation. Initially, the main interest has been in post-event analysis and urban storm drainage compliance assessments where the rarity of rainfall events causing surface water (pluvial) flooding is estimated. These assessments can be used to help determine whether drainage systems performed within design specifications or if remedial action is required.

A Knowledge Transfer Partnership (KTP) Project between the University of Leeds, Hydro-Logic Ltd, Yorkshire Water, Northumbria Water and Scottish Water began in early 2010 and is being funded jointly by the Technology Strategy Board and NERC. The Project will seek to combine radar and raingauge data in real-time and provide estimates of rainfall return periods in order to assess the rarity of the rainfall.

3.4.2 FRMRC2 – Work Packages involving weather radar

Quantitative Precipitation Estimation during extreme precipitation

The principal objective is to improve accuracy (reduce uncertainty) in obtaining the real-time spatial distribution of rainfall over urban areas which will be applicable under extreme conditions. Under extreme conditions, attenuation of the radar signal is a big problem especially at the operational frequency of 5.5 GHz used in the UK. In this work package, the algorithm proposed by Bringi *et al.*[1] will be extended by adapting more than one parameter in real-time to correct for attenuation due to very heavy precipitation. This system will be applied to a short-term precipitation forecasting system.

Short-term forecasting of storm events over urban areas under extreme conditions

This work package will extend the development of the new state-of-the-art STEPS system developed at the Met Office and apply it to the problem of urban flooding on small space scales, with lead times of 2-3 hours in extreme rainfall conditions. The nowcasting system will be enhanced by assimilating the wind fields from Doppler radar and satellite data. The main focus will be on using the STEPS approach with high-resolution radar data and convective-scale runs of a high-resolution NWP model using ensemble forecast rainfalls when appropriate to represent larger scale uncertainty. This will enable evaluation of the benefits of using the high-resolution dual-polarisation radar information developed in a previous work package, and will provide the primary input to the real-time pluvial flood forecasting work package.

3.4.3 Combining raingauge and radar rainfall data

The Knowledge Transfer Partnership (KTP) Project mentioned in Section 3.4.1 between the University of Leeds, Hydro-Logic Ltd and three Water Companies seeks to combine data from radar and a dense network of raingauges in real-time. The project will also compare different methods of merging radar and raingauge data.

As part of the EA/Defra R&D project SC060087 ‘Hydrological modelling using convective scale rainfall modelling’, the HyradK software from CEH Wallingford produced 1km gridded estimates of 15 minute rainfall accumulations using raingauges alone or using raingauges in conjunction with radar data. The HyradK rainfall grids are formed using multiquadric surface fitting methods and will be employed within the new Flood Forecasting Centre across England and Wales as part of the operational implementation of Grid-to-Grid, a distributed rainfall-runoff and routing model.

3.4.4 Defra funded R&D

Surface water flood warning scoping project

Researchers from the Flood Hazard Research Centre and HR Wallingford have recently recommended that the Environment Agency and Met Office should begin to progressively develop a pilot surface water flood warning service targeted at, and in consultation with, its professional partners. The recommendation is one of seventeen related recommendations arising from a scoping study of surface water flood warnings which follows the floods of 2007 and the Pitt Review into these floods which called for warnings for all sources.

The study looked at the Extreme Rainfall Alert service (ERA is described in Section 3.3.5), to explore responses to this service and to verify the relationship between ERAs and surface water flooding. The research found that, although many professional partners take some action in response to ERAs, effective action is currently limited by insufficient information. Professional partners want more specific and more certain

[1] Bringi, V.N., Keenan, T.D. and Chandrasekar, V. 2001. Correcting C-band radar reflectivity and differential reflectivity data for rain attenuation: A self-consistent method with constraints. *IEEE Transactions on Geoscience and Remote Sensing,* **39**, 1906-1915.

information and are currently limited by the difficulty of translating ERAs into likely flooding consequences – specifically the likely location and extent of surface water flooding.

Verification of ERA and surface water flooding relationships is currently limited by a lack of data recording of surface water flooding. Even so, results from three ERA case study areas (South Wales, South West England and Cumbria), indicate that the intensities of rainfall that are associated with surface water flooding may be lower than expected and that the current national thresholds used in the ERA service are not appropriate for all situations.

Initially a sliding scale of seventeen options for the introduction of a surface water flood warning service was examined. Through an evaluation process, these options were reduced for trialling purposes to three: (a) rainfall-based alerts with either national or local rainfall thresholds, (b) rainfall-based alerts utilising locally specific runoff thresholds, and (c) flood warnings linked to runoff and local drainage. These options were subsequently examined in two further case study areas (three communities on the edge of Rotherham and Wealdstone Brook, Brent, in North London) through the medium of professional partner workshops and public focus groups, undertaken in Autumn 2009. Apart from considering the three options, the workshops and focus groups also considered the potential for providing alerts or warnings for professional responders and for members of the public.

Apart from the principal recommendation referred to in the first paragraph, further recommendations to both the Environment Agency and the Flood Forecasting Centre are made. These are in three categories: (a) recommendations on surface water flood warning, (b) recommendations for the Extreme Rainfall Alert service and (c) generic flood warning recommendations. Each should be considered when developing a surface water flood warning service for England and Wales. The final report will be published in the Environment Agency's publications catalogue in due course.

RadarnetIV

This project was undertaken by the Met Office in conjunction with the Environment Agency. There were five packages of work, all having the aim of improving radar precipitation rate data quality by upgrading the algorithms used to process weather radar data.

The research was commissioned to enable new data processing techniques to be developed, tested and implemented, resulting in an overall improvement in the quality of radar-based precipitation estimates. Five research areas were looked into:

1. Using data from several elevation scans (as opposed to just one) to improve the corrections made for the vertical profile of reflectivity.
2. Compositing directly from polar single-site radar data.
3. Using a different method to composite radar data.
4. Using additional channels available from the Meteosat Second Generation (MSG) satellite to generate parameters used for anaprop removal.
5. Diagnosing anaprop in radar data using clutter indicator data.

The outcome was that research areas 2 and 4 produced an improvement to the quality of radar data and during 2008-2009 the appropriate changes were made to implement these findings. The final report will be published in the Environment Agency's publications catalogue in due course.

3.4.5 Environment Agency and Met Office funded R&D

The Met Office and the Environment Agency have collaborated on two projects. The first project "Improved Rainfall Detection in Upland Catchments" is aimed at improving the rainfall rate measurement in upland catchments. The second project "Radar Rainfall Uncertainty and Precision" has two objectives. The first is to increase the precision of rainfall rate measurement for faster moving rainfall by removing a known "pixel jumping" feature, and the second objective is to quantify the uncertainty of rainfall rate measurements and use these to bound and therefore to reduce the uncertainty of nowcasts.

Improved rainfall detection in upland catchments

Raingauge data in upland regions of the UK are sparse and often misrepresent intense precipitation events over small catchments. The production of flash flood warnings rely on high resolution input from the radar composite. It is therefore important that radar measurements of rainfall rate are as accurate as possible and account for the effects of orographic enhancements well. A study conducted by the Met Office in collaboration with the Environment Agency set out to make a comparison between the operational orographic enhancement scheme based on the climatology developed by Hill[2] (1983) and the physical model proposed by Alpert and Shafir[3]. The Alpert and Shafir method takes into account wind speed, wind direction, relative humidity, temperature and the topography of the region. In this study, a 1 km resolution topography is used and 1 km input fields are derived from the Met Office Unified Model output. Trial results show that, in the majority of events, the accuracy of the precipitation estimates is improved when using the Alpert & Shafir method.

The benefits of using a physical model in place of a climatology-based one are numerous. The Alpert and Shafir method allows corrections to be defined at much higher spatial resolution, with the possibility of introducing new fields, such as the vertical wind profile, and making further improvements to the physical model. Another benefit is that it brings the processing of England and Wales data into line with the way data are processed in Scotland (although using higher resolution terrain data than in Scotland).

The Alpert and Shafir method has been applied to all the radar data streams that the Environment Agency gets from the Met Office, and the change went live in May 2010.

Radar rainfall data are used to initialise a number of Met Office models such as the nowcasting scheme (STEPS), the NWP models, and the MOSES model. If the quality of the input data is improved then the quality of the output from all of these models will also be improved. As some of these products are used to form the time-series of actual and forecast rain that is fed into the Environment Agency's river models in the National Flood Forecasting System then an improvement in the quality of these products will see an improvement in the quality of the river forecasts.

Radar rainfall uncertainty and precision

Radar rainfall accumulations are calculated from instantaneous rain-rates assuming that precipitation falls at the measured rate over a particular time period. The spatial

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[2] Hill, F.F. 1983. The use of annual average rainfall to derive estimates of orographic enhancement over England and Wales for different wind directions. *Journal of Climatology*, **3**, 113-129.

[3] Alpert, P. and Shafir, H. 1989. A physical model to complement rainfall normals over complex terrain. *Journal of Hydrology*, **110**, 51-62.

resolution of the accumulation product has recently been increased from 5 to 1 km. The temporal resolution remains unchanged at 5 minutes.

During fast-moving precipitation, ‘pixel jumping’ is sometimes observed during accumulation sequences. As rainfall moves across the area of the analysis, it is possible for rainfall to be ‘missed’ from some pixels. This is known as pixel jumping and causes a spurious stroboscopic effect in accumulation images.

Pixel jumping can occur at 5 km resolution, but is not common because of the high wind speeds required. It becomes more common at higher spatial resolutions. With the resolution at 1 km, pixel jumping becomes much more common, even at relatively low wind speeds. A processing scheme is required which interpolates rainfall rates for intermediate pixels based on a wind advection scheme.

Other weather services use advection schemes to predict the movement path of precipitation between scans and linear interpolation techniques to determine the change in rainfall intensity during the scan interval. A similar approach has been used to improve the quality of UK 1 km rainfall accumulation products.

The outcome of the precision side of this project is that the Met Office will supply the Environment Agency with a new 1 km radar rainfall accumulation product which will not suffer from the pixel jumping issue and will therefore give more precise rainfall accumulations particularly during fast-moving rainfall events. In due course, the Environment Agency will use the new 1 km product as the actual radar rainfall time-series which it feeds into its river models (via a precipitation hierarchy) in the National Flood Forecasting System.

On the uncertainty side of this project, progress has been made on a number of fronts. Several techniques for the generation of ensembles of radar observations have been described in the literature. These fall into two categories. One entails a statistical description of the difference between the radar estimates and a reference; the second involves modelling the characteristics of individual sources of error. A study was conducted to evaluate two methods, one from each of these categories. The first method models sampling errors relating to the height of the radar observation above the topography, and uncertainty related to the conversion of radar reflectivity to rainfall. The second method is empirical in nature: it uses the analysis of historical raingauge and radar data to populate an error covariance matrix. Both approaches have varying degrees of merit and skill, which were assessed using a common set of radar and raingauge data for six case study precipitation events.

The ultimate aim is to implement a radar-based observation ensemble generator for use in conjunction with the Short Term Ensemble Prediction System (STEPS). STEPS is an operational ensemble precipitation nowcasting algorithm developed jointly by the Met Office and the Australian Bureau of Meteorology. It scale-selectively blends a weather radar based, extrapolated analysis of surface precipitation rate with a recent precipitation forecast from the operational, 4 km configuration of the Unified Model and a time series of synthetically generated precipitation fields (noise) with space-time statistical properties inferred from radar. The noise component serves to account for uncertainties in the evolution of the extrapolation and NWP forecast components and also to downscale the NWP forecast. Currently, STEPS incorporates an observation uncertainty algorithm based upon an analysis of *Z-R* errors. This is used to generate an ensemble of perturbation fields. The perturbations are correlated in space and time to replicate the correlations in the random fluctuations about an assumed *Z-R* relationship.

The two methods will be blended together, resulting in the statistical method being used over a 'gauge domain' and the model based on height and *Z-R* relationship being used for the remaining areas. This approach will form the ensemble of rainfall analyses used by STEPS. Although the statistical model has shown skill, development of the *Z-R*/Height model is not yet completed and a full comparison has yet to be carried out. However, based on our previous studies we can expect that the statistical model will be more skilful that the *Z-R*/Height model in areas with a dense network of raingauges.

3.4.6 SNIFFER Bathing Water Signage Project

SEPA is working to develop new modelling tools which will enhance the accuracy of our current operational daily bathing water quality predictions for real-time signage at a subset of designated bathing waters across Scotland. These new, more complex models are required to achieve acceptable levels of performance against the tighter revised Bathing Water Directive standards. The new models use decision trees to predict bathing water quality class (good or less than good) based on multiple predictor variables. The model inputs can include both numerical and categorical variables and enable interactions between variables to be explored. Decision tree models have been successfully set up for 10 of SEPA’s current signage sites using raingauge and river flow data as input. We are continuing to fine-tune these models and explore options for including other input variables (e.g. tide times and sunshine hours) to further improve predictive capacity.

Following the success of the 2008 SNIFFER funded project[4], examining methods for estimating impacts of rainfall on bathing water quality, which concluded that radar rainfall data can be more effective than raingauge data in predicting water quality at bathing beaches, steps are also being taken to incorporate radar rainfall data into SEPA’s decision tree models. Initial tests are to be conducted using historical radar rainfall data for the catchment of a designated bathing water on the west coast of Scotland (Saltcoats/Ardrossan) to build, optimise and test a new decision tree model and investigate whether the improved rainfall spatial coverage will increase model predictive performance. To examine the influence of rainfall and different potential pollutant sources the catchment has also been divided into urban and rural areas which will form separate spatial inputs to the model.

3.4.7 FLOODsite and FREE

The following projects are major research programmes in the area of flooding warning and a brief overview is provided below. Some of the work is concerned with radar and these areas are described in detail elsewhere in this report.

FLOODsite
http://www.floodsite.net

FLOODsite, led by HR-Wallingford (UK), was the largest ever European research project on flood risk management, with a budget of €14 million and a timetable of five years, ending in 2008. The programme has developed a European approach to the management of flood risks from rivers, estuaries and the sea.

The Project was managed through seven themes each of which had a number of sub-themes:

[4] SNIFFER 2008. Methods for estimating impacts of rainfall on bathing water quality. Report on results for Saltcoats, Irvine, Fleetwood and Paignton. Final Report - UKLQ07, SNIFFER, Edinburgh, UK, 239pp.

THEME 1: RISK ANALYSIS: SCIENTIFIC KNOWLEDGE AND UNDERSTANDING
- SUB-THEME 1.1 HAZARDS (RISK SOURCES)
- SUB-THEME 1.2 HAZARD (RISK PATHWAYS)
- SUB-THEME 1.3 VULNERABILITY (RECEPTOR EXPOSURE AND CONSEQUENCE)

THEME 2: INNOVATIVE MITIGATION AND SUSTAINABLE FLOOD RISK MANAGEMENT
- SUB-THEME 2.1 PRE-FLOOD MEASURES
- SUB-THEME 2.2 FLOOD EVENT MEASURES
- SUB-THEME 2.3 POST-FLOOD MEASURES

THEME 3: FRAMEWORKS FOR TECHNOLOGICAL INTEGRATION
THEME 4: PILOT APPLICATION SITES
THEME 5: TRAINING, DISSEMINATION AND RAISING PUBLIC AWARENESS
THEME 6: PROJECT NETWORKING, HARMONISATION AND ASSESSMENT
THEME 7: PROJECT CO-ORDINATION

Of particular relevance was Task 15 under Sub-Theme 2.2 entitled 'Radar and satellite observation of storm rainfall for flash-flood forecasting in small- and medium- size basins'. The specific objective of this task was to develop and test a Structured Algorithm System for radar and satellite detection and estimation of extreme storm rainfall. In addition, an assessment concerning the uncertainty of the radar rainfall estimates was undertaken.

FREE (Flood Risk from Extreme Events)
http://www.nerc.ac.uk/research/programmes/free/

FREE is a NERC directed research programme that is funding a range of research projects aimed at improving the prediction of floods over time-frames of minutes, weeks, seasons and decades ahead. The budget is £7.8m and the main research spans the period 2007 to 2010. It is one of a very few integrated research programmes which bring together meteorologists, hydrologists and coastal oceanographers. All projects aim to generate outputs relevant to improving our understanding of the mechanisms of flooding, forecasting flooding and identifying how flood risk will change in the future. One project has specific research concerning the use of weather radar for storm and flood forecasting. This is a consortium activity involving the University of Reading and CEH Wallingford, with support from JCMM, and entitled 'Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting'. Work on the project is summarised elsewhere in this Report.

3.5 Publish a review paper with a working title of 'Current research application of weather radar to hydrology: a UK perspective'

During the current session, a USA review of weather radar was published in the Bulletin of the American Meteorological Society by Krajewski, Villarini and Smith entitled "Radar-Rainfall Uncertainties: Where are We after Thirty Years of Effort?". Due to the overlap between the reviews, the UK review paper has been deferred to the next Committee session. The International Symposium on Weather Radar and Hydrology in 2011 (WRaH 2011) at Exeter will provide a good opportunity for the UK review.

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

4.1 Assess the current usage of radar-based products within the operating agencies through a survey of the agencies represented

Introduction

The Committee at the start of this session decided to assess the current usage of radar-based products within the operating agencies through a survey of the agencies represented. Consequently the Committee organised an online survey for all potential users of radar data across the operating agencies: Environment Agency (EA), Scottish Environment Protection Agency (SEPA), the Northern Ireland Rivers Agency (RA) and the Met Office. A total of 139 completed questionnaires were returned.

Organisational background and scientific discipline

As expected, the majority of responders were from the larger organisations - the EA and the Met Office - although a good sample was returned from SEPA and RA. Also, as expected, the largest discipline area for use of radar data was flood forecasting and warning (72%) with other disciplines such as hydrology and water resources having a smaller sample.

Rainfall data/network and flood warning

The role of radar data and Numerical Weather Prediction in flood warning was reported as extremely high. 92% of responders suggested radar data were fairly or extremely important for flood warning, with 83% for NWP under the same category.

A small majority of the responders (52%) suggested that the radar network only partly met their needs for flood forecasting and warning, with 8% suggesting that it didn't. Some of the key areas of suggested improvements were:

- Improving the network coverage, i.e. Highlands of Scotland, East Anglia and South Wales
- Improved convective and orographic performance

Limitations in hydrological application of radar

The responders were asked what limits their use of radar data and the results are summarised in Figure 2. One of the highest responses was for the accuracy of radar data (65%). Temporal and spatial resolution was also a high limiting factor (55%) with the radar network coverage limiting just under half of those who responded (48%). Hydrological model development, delivery time and data availability were not seen to be major limiting factors in the hydrological use of radar data.

In a similar theme the responders were asked what is required to make more use of radar data. Data accuracy was one of the strongest themes, particularly from the Environment Agency, with data resolution and network coverage also having a strong requirement.

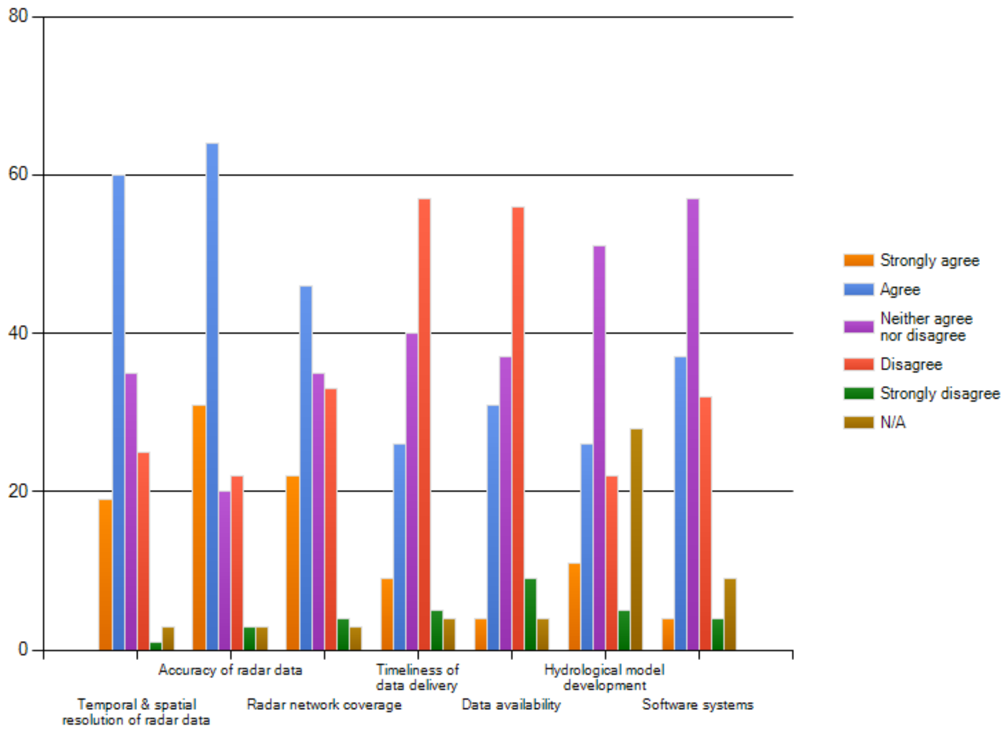

Figure 2 Summary of responses to the survey question 'What limits the use of radar within your organisation/area of work?'.

Perception of potential errors in radar

Although a difficult question to put across, responders were asked 'typically across a 10km by 10km area, what did they consider the errors in radar estimates of rainfall to be?'. Although a third of the responders stated they were not sure, for those who did respond the majority stated between 5% and 25% - a similar figure to that which the Committee suggested.

Research and development

The responders were asked what area of research and development would most benefit the hydrological application of radar. The results are summarised in Figure 3. There was general agreement on all areas; however improved rain-rate estimation had the strongest agreement amongst those who responded (>110 responders). Finer resolution in radar observations (>90), evaluation studies using radar data (>80), development of quality indicators (>80) and improved hydrological modelling (>70) all provided high returns for needing R&D focus.

Value of radar data

On a positive note for the UK Radar Network Investment, very few responders suggested that the current level of investment was not worthwhile.

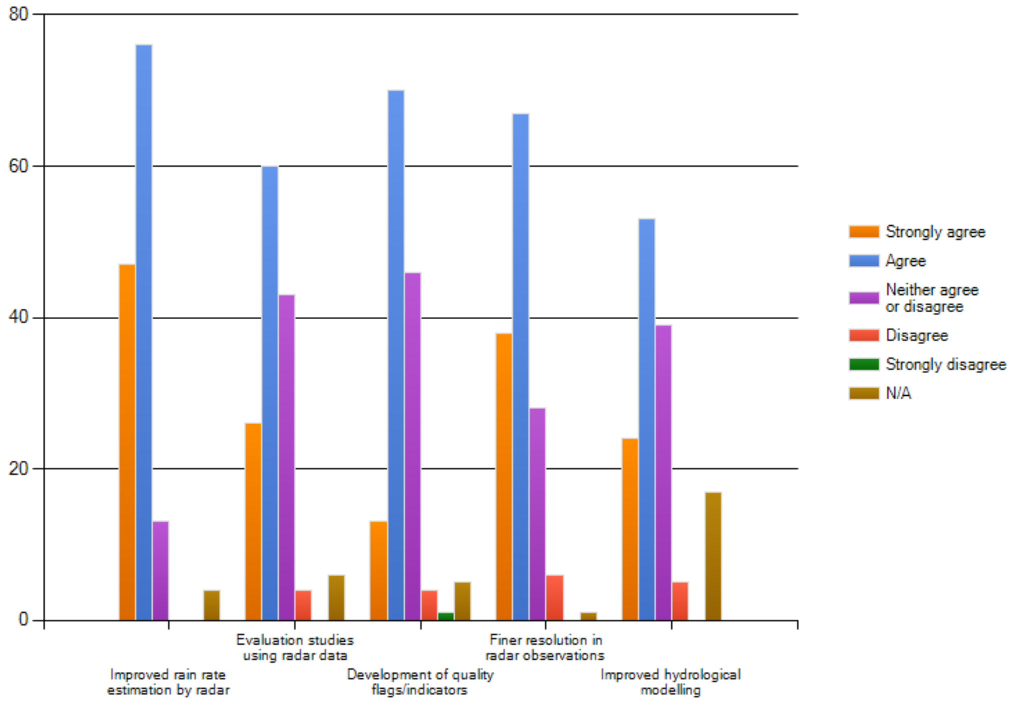

Figure 3 Summary of responses to the survey question 'What areas of research and development do you think are needed for your organisation to make more use of radar data?'.

4.2 Host a workshop for the operating agencies to promote radar related research and discuss the hydrological application of radar

As part of the survey of operational agencies discussed in Section 4.1, responders were asked if they would be interested in attending a workshop on the hydrological application of weather radar. Out of the 139 responders, 41 (29%) declared an interest. Hosting such a workshop will be taken forward under the next Committee session.

4.3 Prioritise the user requirements for radar related research to inform Strategic Area 1

As part of assessing the future requirements for research and development it is important to review not just the user requirements but also the strategic drivers. The following is a summary of these strategic requirements for the three hydrological agencies in the UK.

Environment Agency

The Environment Agency's corporate strategy states that it will ensure the consequences of flood risk are effectively managed, and people and property are better prepared and protected. To achieve this aim, its Flood and Coastal Risk Management (FCRM) Strategy to 2015 sets out the following six outcomes the EA want to achieve, all requiring input from its flood detection and forecasting services:

- improve community involvement and communications, working better with all concerned in FCRM to understand and manage risk more effectively;
- develop and support the joint EA/MO Flood Forecasting Centre;
- provide better flood forecasting and flood warnings to help others to take prompt action to reduce risk;
- play a part in multi-agency planning and preparations for, and responding to, major incidents;
- work with providers of important national infrastructure to ensure that public services are maintained during flooding;
- manage FCRM assets effectively and efficiently during incidents and encourage others to do the same.

The EA are currently finalising an internal policy on developing its flood detection and forecasting services. Subject to future funding, the following are extracts where weather radar impacts on EA service:

- Regions will expand the coverage and improve the quality of river and coastal flood detection and forecasting capability to meet the risk based standards set out in the EA's Flood Warning Levels of Service, and driven by its Corporate targets;
- There is a need to strengthen the value of flood forecasting within the flood warning/operational decision-making process, as there is variability across the regions in how forecasts are used within the decision-making process;
- through the Flood Forecasting Centre the EA will work in partnership with the Met Office to improve its flood forecasting capability and the MO's rainfall forecasting capability – to include longer lead-time lower probability forecasts, better broad-scale flood risk visualisation, and the development of new capabilities such as rapid response catchment and surface water forecasting (once a clear policy has been established on these);
- the EA will secure and improve the future of the England and Wales weather radar network through continued partnership working with the Met Office. This enables the EA to provide and develop the radar service to meet its changing needs.

Specifically on rainfall detection and nowcasting:

- in conjunction with the Flood Forecasting Centre the EA will continue to work closely with the Met Office, to drive improvements to existing weather radar and rainfall forecasting products, and develop new Quantitative Precipitation Forecasting (QPF) products that will assist the EA's ability to forecast and warn for flooding, and to expand its service to cover other flood mechanisms such as surface water flooding;
- the EA will continue to share the real-time rainfall data available from its own raingauge network and the network operated by the Met Office to deliver an improved forecasting and warning service.
- the EA will work in partnership with the Met Office to deliver the Radar Network Renewal project, subject to funding approval, and it will update the National Weather Radar Strategy for England and Wales - 2002;
- the EA will work in partnership with the Met Office to produce a real-time 1km gridded England and Wales rainfall accumulation product. This will be a 15 minute accumulation and will combine information from both raingauges and radar. This

should be seen as the authoritative real-time estimate of rainfall over England and Wales.

- The quality of the EA's service to many communities with short lead-times is critically dependent and constrained by the quality of the Met Office quantitative precipitation forecasting products. Working with the FFC and MO the EA will focus its effort into improving the quality of the QPE and QPF products rather than further improving spatial resolution.

On the wider flood forecasting service:

- The project Integrating Flood Services for Partners will review all current products to ensure that the EA are making best use of the new higher resolution/longer range products that are becoming available and not paying for products that the EA are not properly utilising.
- To maximise the benefits of radar renewal investment – the EA will aim to be using a merged raingauge/radar product as the primary rainfall time-series it uses to input to regional river forecasting and national grid-based models.
- The FFC will implement a Grid-to-Grid distributed rainfall-runoff and routing model across England and Wales on an evaluation platform in 2010. It will initially be used to inform the Flood Guidance Statement and, subject to funding approval, will be further developed within the EA's National Flood Forecasting System platform so that results in ungauged catchments will be available to feed into the more detailed downstream hydrodynamic models operated in real-time by the Regions.
- The FFC will spearhead the implementation of probabilistic flood forecasting through its project to implement the countrywide Grid-to-Grid Model fed by blended ensembles of nowcast and NWP ensembles.
- To provide an effective flood warning service for those at risk in Rapid Response Catchments or Fast Responding Urban Catchments the EA are investigating a range of forecasting methods. One of these will be to investigate the feasibility of using short lead-time Grid-to-Grid model forecasts run at an appropriate frequency. The FFC and Regions will work together to trial and evaluate this method.

Scottish Environment Protection Agency

Until recently, SEPA had discretionary powers to provide flood warning in Scotland. Significant investment and progress has been made since 2006 in SEPA's flood forecasting capabilities and the use of radar data in hydrological models through its Flood Early Warning System (FEWS Scotland).

Under the Flood Risk Management (Scotland) Act 2009, SEPA's current flood warning responsibilities have been formalised and strengthened giving SEPA a statutory basis for all flood warning activities. SEPA has now published a statement of intent on how it intends to implement the flood warning duties. In terms of flood forecasting and the use of weather radar the following are relevant.

- SEPA will aim to reduce the impact of flooding through the provision of actively disseminated, reliable and timely flood warnings to registered users of a national flood warning service and provide the necessary flood forecasting capabilities to support these activities.
- SEPA will aim to provide an effective flood warning service and to reduce the impact of flooding from all sources and work with communities to improve their response, by specifically:

- Upgrading existing flood warning schemes to ensure that they offer accurate and effective warning provision by improving flood forecasting capabilities in these areas
- Expand the coverage of flood warning schemes to cover other areas of Scotland at risk of fluvial and coastal flooding by improving flood forecasting capabilities
- Work with the Met Office to develop methods of working more closely together with the aim of improving our technical capability to forecast, model and warn against all sources of flooding in Scotland.

In response to these strategic drivers for flood forecasting, SEPA will be publishing a flood forecasting and warning strategy later in 2010. Some of the key areas of development under this strategy and linked to the hydrological applications of radar will be:

- SEPA has seen the development of a number of rainfall-runoff models for use in flood forecasting in the past 5 years. Some of these flood warning scheme improvements are on small and flashy catchments which rely in having knowledge of future rainfall to accurately predict flooding (see Figure 4 for Brechin example). The future development of flood forecasting improvements will depend on the accuracy of radar data and quantitative precipitation forecasts in these catchments.

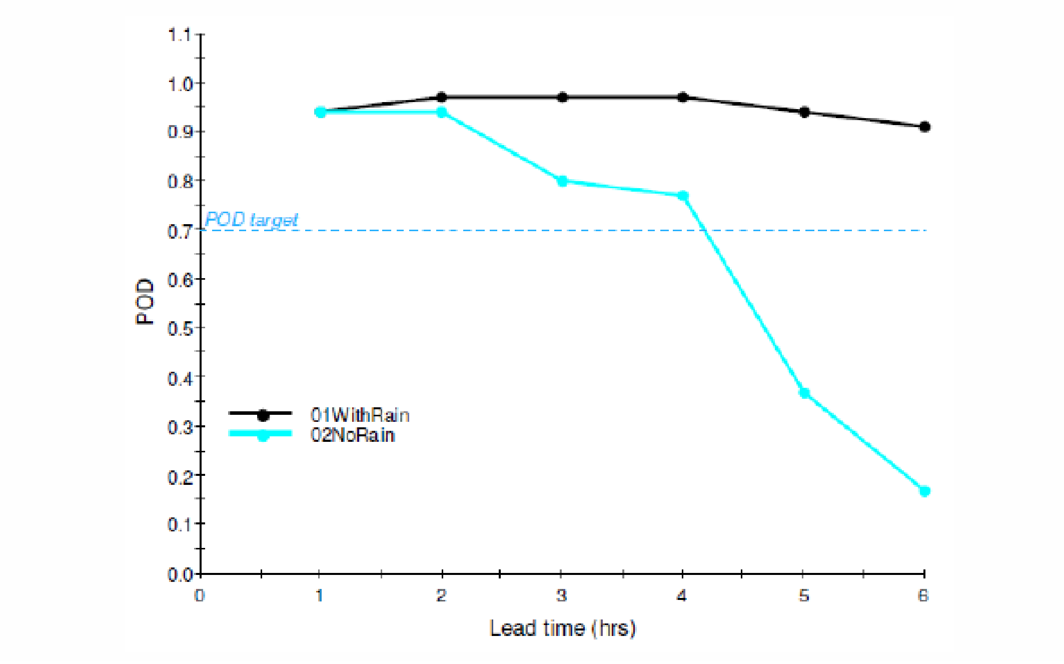

Figure 4 Example plot of Probability of Detection of threshold crossings (Brechin).

- As part of the driver to improve flood forecasting capability for the whole of Scotland and looking towards providing alerts for all sources of flooding, SEPA are looking to develop a Flood Forecasting Centre – similar to that established for England and Wales. As part of this development SEPA are looking to develop a national hydrological forecasting model to provide a countrywide forecasting service. The quality of this service will depend on the rainfall products ingested into the model.

Northern Ireland Rivers Agency

The Rivers Agency (RA) has long recognised that flood forecasting, vigilance, warning and response systems can be cost effective, non-structural means of mitigating flood hazards and have a role to play as part of wider catchment flood management strategies. It appears that the implementation of the EU Floods Directive in Northern Ireland may offer the opportunity to consider afresh options for flood detection, warning and forecasting over the next few years.

In the short-term, it is recommended that the RA continues to incrementally develop its expertise with flood detection, forecasting and warning through its internal initiatives in this area and through continuing to develop knowledge-sharing relationships with the other flood warning bodies in the UK. In addition, it is recommended that the RA seeks to explore ways in which flood resilience could be improved through its existing relationship with the Met Office. In particular, it is felt that a review of the services currently offered to the RA by the Met Office would be beneficial (for example, a re-assessment of the benefits of implementation of Extreme Rainfall Alerts for Northern Ireland).

Finally, it is recommended that the RA carry out a comprehensive review of the feasibility, costs and benefits of flood detection, forecasting and warning in Northern Ireland as part of the implementation of the Floods Directive. The suggestion is that this incorporates: the impacts of climate change on flood risk; the implications of recent advances in hydro-meteorological forecasting; appropriate structures for the delivery of any new service; and the expectations and requirements of end-users (both professional and the general public).

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

5.1 Further developments of the IAC web site hosted by the Science and Technology Facilities Council

During the session, STFC undertook a complete revamp of the Committee website (www.iac.rl.ac.uk) which was launched in 2009. This included revising the content and structure of the site, such as the community links pages, and raising the profile of the website in search engines. The intention was to make the website more relevant and useful to the research and user community.

5.2 Publication of an explanatory 'Sense About Science' leaflet on the hydrological applications of weather radar

The Committee is working with 'Sense About Science' to produce an explanatory booklet to raise the profile and understanding of weather radar and its applications in flood risk management. The booklet will also explain the role of the Committee and will be written for an interested public, following the same style as 'Making Sense of Weather and Climate'[5].

Sense About Science will:

- Help the Committee to identify the key questions it wants addressed in a public booklet.
- Co-ordinate and facilitate meetings of the Committee in order to capture and address questions about weather radar and its applications, in particular focussing on areas where there is little information and/ or misconceptions about its use.
- Help to promote and disseminate the finished booklet to key audiences as identified by the committee but also including journalists, parliamentarians and educationalists. The finished booklet would also be available for download from the 'Sense About Science' webpage.

5.3 Identify opportunities for the funding of training, i.e. advanced applications of weather radar.

Current training opportunities

Internal training on using weather radar is provided within the Environment Agency with the Met Office recently commissioned to provide the course. Similarly the Met Office and the new joint Environment Agency/Met Office Flood Forecasting Centre have internal training courses on using weather radar.

The National Centre for Atmospheric Science (NCAS) runs an annual NERC-funded Summer School on Atmospheric Measurement. This is aimed at PhD students and early career scientists that are researching a specific area of atmospheric science and/or whose research involves atmospheric related fieldwork. The next course is 7–19 September 2010 on the Isle of Arran (http://ncasweb.leeds.ac.uk/arransummerschool/).

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[5] Weblink: http://www.senseaboutscience.org.uk/pdf/Weather&Climate.pdf

The European Conference on Radar in Meteorology and Hydrology (ERAD 2010 - http://www.erad2010.org/Course.htm) has several training courses associated with it:

Nowcasting course (30 August to 3 September 2010)
- Enhanced use of satellite and radar in nowcasting
- Aimed at European Forecasters who issue warnings

Short course on dual-polarization and doppler weather radar: fundamentals and applications
- Aimed at research and operational users as well as weather radar operations personnel and analysts

Short course on radar quantitative precipitation estimation and forecasting and hydrological applications
- Aimed at students and experts

Training needs highlighted by the Committee Survey

Through the survey of operational use of weather radar in the various agencies presented in Section 4.1, the following were highlighted by respondents as specific requirements for training.
- Radar software systems
- Radar techniques and applications
- General training and awareness for flood forecasting and warning staff

Organising a training workshop that will address these needs will be considered under the next session of the Committee.

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

During the reporting period there have been several notable extreme weather and flooding events. Heavy rainfall caused severe floods in Morpeth (September 2008) and Cumbria (November 2009). For these events radar-rainfall data were useful in identifying the areas affected by the heaviest rainfall and have also been used in post-event modelling analyses which have publicised the role of weather radar to end users. Figure 5 shows instantaneous composite radar-rainfall data during both events.

A particularly severe hail (or possibly graupel) storm contributed to the extreme flooding affecting Ottery St Mary during 30 October 2008. This provided a rare opportunity to assess, and publicise, methods for detecting hail using single polarisation radar data. A summary of the findings are presented here in Section 5.4.1.

Beyond communication with end-users and stakeholders, public awareness of the capability of weather radar has been raised through a number of recent TV and Radio programmes. These mainly include work undertaken at the Chilbolton Facility for Atmospheric and Radio Research (CFARR) which is operated by the Science Technology and Facilities Council. The programmes include the BBC Four series “The Weather – A Very British Obsession” and the BBC Children’s show “Nina and the Neurons: Making Waves”. This public awareness raising will be complemented by the ‘Sense About Science’ publication discussed under Section 5.2.

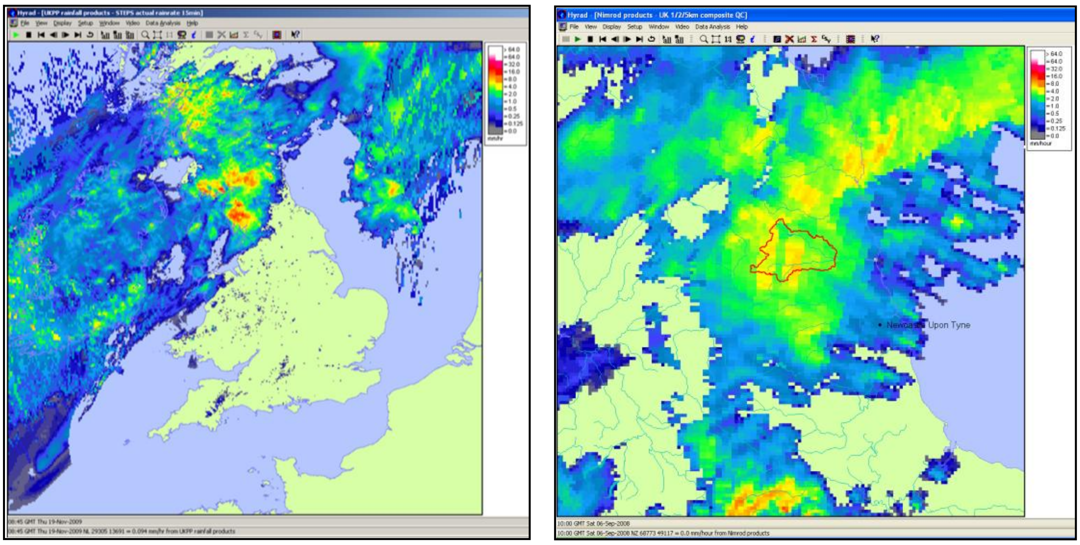

Figure 5 UK Composite radar-rainfall data during the Cumbria 2009 event (left) and during the Morpeth 2008 event (right) with the Wansbeck to Mitford catchment highlighted (courtesy Environment Agency).

5.4.1 Detection of hail from single polarisation radar measurements of precipitation during the Ottery St Mary storm, 29-30 October 2008

Radar offers the only technology for specifying in real-time the possible presence and detailed distribution of hail within meteorological situations producing extensive mixed frontal and convective rain. Considerable work over many years has led to the publication of a number of procedures for identifying hail using three dimensional radar reflectivity measurements, or, more recently, polarisation characteristics. The following discusses one approach to processing the radar data collected during the case of severe flooding exacerbated by hail[6] (or possibly graupel[6]) on 30 October 2008 over South East Devon: see Figure 6. The meteorological situation is discussed in a report on the event by the Met Office and the storm embodies both frontal and convective rainfall.

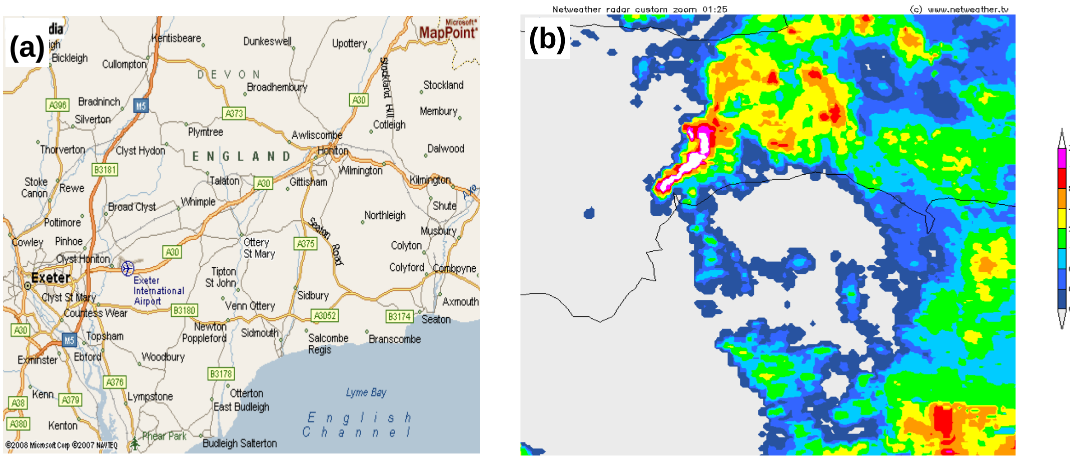

Figure 6 (a) Location map around Ottery St Mary to the east of Exeter; (b) high-resolution (1 km) radar rainfall (mm h^{-1}) at 01:26 UTC 30 October 2008 (coastline shown by the black line) (courtesy Met Office).

[6] See Glossary for definitions of hail and graupel

A modification of the radar PDF–R (Probability Density Function – Rain-rate) technique[7] for identifying the presence of hail has been tested for the Ottery St Mary storm within a study by Hydro-Logic Ltd for the Environment Agency. In spite of the unavailability to this study of three dimensional radar data the technique worked well. The correspondence between the corrected raw (site) radar rain estimates and the Nimrod estimates for the Ottery St Mary storm is indicative that the radar can provide reliable areal rainfall measurements. To identify the detailed distribution of the hail it is necessary to analyse very high resolution data (100m). However, in analysing the radar and raingauge data it is important to be aware that factors such as radar artefacts not previously removed from the radar data and raingauge siting problems may introduce uncertainties.

The PDF–R relationship for the Ottery St Mary storm was compared with two of the relationships given by Rosenfeld *et al.*[7]. A parameter E_c, the 'effective efficiency', is defined as

$$E_c = (Q_b - Q_t)/Q_b$$

where Q_b and Q_t are the water vapour mixing ratios at the base and top of the storm respectively. Hence E_c is the fraction of the water vapour carried up through the cloud base which is potentially available for precipitation. Q_t is determined by the actual height which is reached by the storm. As E_c increases from one class to another, the corresponding Probability Density Functions (PDFs) given by Rosenfeld *et al.*[7] move to larger rain-rates in a systematic manner. Therefore it is possible to stratify PDF–R relationships.

The radiosonde ascent for Camborne at 00:00 UTC 30 October shows the occurrence of deep convection giving a value for E_c of about 0.9. The relationship for the Ottery St Mary storm compares well with the relationship for E_c = 0.9 up to rainfall rates of about 60 mm h^{-1} after which it deviates significantly. It is implied from this that radar rainfall rates up to 60 mm h^{-1} are probably quite accurate but thereafter they are subject to large errors due to the presence of hail.

[7] Rosenfeld, D., Atlas, D. and Short, D.A. 1990. The estimation of convective rainfall by area integrals, Part II: The height-area threshold (HART) method. *Journal of Geophysical Research*, **95**, D3, 2161-2176.

6. Summary and look forward to the next Committee session

6.1 Research needs, operational requirements and funding opportunities

Under Strategic Area 1 of the Community Plan (see Table 2) the Committee had the following tasks:

- Identify the gaps in the current research initiatives and the current operational requirements
- Identify research needs and funding opportunities under current and new initiatives

These tasks are reported on here in the following sections for each of the three research areas:

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

This activity has been informed by the prioritised operational user requirements of radar-related research collated under Strategic Area 2 in Section 4.3.

6.1.1 Radar capability

The UK radar network will undergo a renewal programme over the next 3-4 years to provide new hardware and software, and to introduce Doppler and dual-polarisation capability at all sites. Below we identify some of the aspects which are currently being studied:

a) Increase temporal and spatial resolution
- Is a low elevation 'rainfall scan' every 5 minutes sufficient or should this be reduced to 2.5 minutes?
- Is there benefit to increase the spatial resolution over urban areas from 1 km to 500 m or better?

b) Improvement of rainfall rate estimates using dual-polarisation
- Improved ground clutter rejection and hydrometeor identification are obvious benefits.
- Use of differential phase shift for correcting attenuation; this could have considerable impact in heavy flood-producing rainfall.
- Identification of hail, and the consequent flagging of rainfall from such regions as being unreliable.
- Ultimately the reflectivity, differential reflectivity, and differential reflectivity can be combined optimally to correct for attenuation, and *Z-R* variability due to rain spectrum changes thus providing better rain-rate estimates with quantified errors.

c) Additional data for NWP

- The new radars will be able to measure emission from attenuating storms to provide an additional constraint on the storm attenuation and an indication of total water content along the radar beam.
- Mapping of surface humidity from ground clutter returns in the radar network; such data could be assimilated into NWP forecasting to provide better warning of where convection is about to break out.

d) Wind measurements

- Can the Doppler and non-Doppler scans (that is the long and short pulse) be combined?
- Can the staggered PRF (Pulse Repetition Frequency) be implemented to provide reliable winds at low PRF (high range) so winds can be mapped up to high altitudes over most of the UK when there is widespread precipitation?

Other radar-related aspects being addressed are:

e) Improved corrections of orographic rainfall growth which occurs below the radar beam; this will probably be achieved by using NWP wind, humidity and cloud water products.

f) The use of attenuation in commercial microwave links to provide rainfall estimates in steep-sided catchments inaccessible by radar.

g) Mapping of surface humidity from the 'wet-delay' in digital radio broadcasts.

Radar archive for evaluating the radar processing chain

The Met Office is currently developing a system that allows the radar processing chain to be repeated for historical periods. This facility requires the creation of an archive dedicated to hold raw radar data at the highest polar temporal and spatial resolution. Initially, this archive will be designed to operate on a rolling window of about 12 months for the whole of the UK C-band radar network; some of the capacity will be allocated for indefinitely storing events of special interest. It is anticipated that this facility will be available from autumn 2010 and will be a key resource for testing and evaluating new processing algorithms.

Electronic scanning antenna

A major research topic not covered in the current programmes is the potential use of electronic scanning antenna. The development of electronic scanning antenna for weather radars offers the prospect of introducing very rapid scanning attuned to particular user needs. However, the use of this adaptive scanning for flood forecasting over urban areas needs to be investigated. The aim would be to demonstrate that automated algorithm control of a radar antenna could be instigated to enable intense storms to be scanned rapidly in four dimensions.

6.1.2 Benefits to hydrology through meteorological forecasting

Flood forecasts based on hydrological and hydraulic models of river systems, for extended lead times, are reliant on spatial estimates of rainfall for past and future times. Raingauge networks can provide point rainfall estimates, and through interpolation, spatial estimates. Interpolation can be reinforced through use of radar estimates available in spatially-continuous gridded form. The gridded radar estimates in isolation provide a valuable indication of the spatial variation in rainfall but do not have the point accuracy of raingauge observations. *Improving methods of merging raingauge and radar estimates of rainfall* remains a challenge, and must be done in combination with *improved "quality-control" radar processing techniques*, preferably physically-based, aimed at improving the resilience and robustness of radar estimates. There are also opportunities for *improved real-time quality control of raingauge data* based on checks on spatial and temporal coherence.

Improved rainfall estimation based on radar, raingauge and other observations is also key to improved rainfall forecasting based on extrapolation of radar images. The benefits of such improvements lead in turn to improved flood forecasts obtained via hydrological models and the longer lead-time warnings they allow. Benefits also accrue in *using radar-derived variables for data assimilation with NWP models* for rainfall forecasting over lead-times beyond, say, 6 hours and up to circa 5 days.

Because of the inherent uncertainty in rainfall forecasts there is a growing requirement to provide *measures of uncertainty associated with the rainfall estimates*. Doing this for radar-based rainfall estimates remains a challenging area of research. For rainfall forecasts, characterising uncertainty via *ensemble forecasting methods* continues to be an active and important research topic. Ensuring the ensemble spread embraces the true uncertainty in forecast rainfall amounts is a challenge, as is the *use of rainfall ensembles for ensemble flood forecasting* which raises similar issues and brings in further sources of uncertainty.

New developments in *area-wide flood forecasting,* providing national coverage and based on grid-to-grid hydrological model formulations, is increasing the need for accurate estimates of gridded rainfall at the 1 km scale. These developments are bringing improved benefits to flood warning by providing indicative flood forecasts "everywhere", including ungauged areas and fast response catchments, and for longer lead-times out to 5 days. Again the need for uncertainty estimates on the observation-based and forecast rainfall estimates used as input to such distributed hydrological models presents a challenging area for future research. One important topic is the *visualisation and interpretation of flood risk maps in real-time*: combining advances in ensemble rainfall forecasting, grid-based hydrological modelling and gridded maps of flood magnitude for different return periods.

The potential benefits for flood warning can be related to the cost of flood damage: the total financial cost of river flooding in Britain is estimated at around £475million per annum. Improved flood mitigation through advances in flood forecasting and warning, supported by advances in weather radar technology and application, has clear potential to reduce these damage costs providing considerable savings.

In terms of benefits of weather radar advances to meteorological forecasting, these can be seen as falling into two categories. Firstly, benefits to operational nowcasting through the provision of real-time radar images and forecasts from procedures such as STEPS, used to enhance general forecasts for the public and more specific user forecasts, such as those supplied to local authorities for road weather information and the water industry. Secondly, benefits to numerical weather forecasting through the assimilation of reflectivity and radar winds and possibly microphysical parameters: this activity is relatively new and the benefits are not yet quantitatively established in routine operations.

Following the successful research undertaken in the NERC-funded Convective Storm Initiation Project (CSIP) and the Convective Orographic Precipitation Study (COPS), further research using radar as the principal observational tool is needed to investigate improvements in the *development and movement of convective cells leading to major flooding events*.

Forecasts of rainfall and river flows using ensemble approaches are currently being developed. However, the *identification of extreme events within an ensemble* remains problematic. Further research on the extraction of information from an ensemble needs to be undertaken.

6.1.3 Applications for water management

The strategic overview of the Committee outlined in Section 2.2 specifies three strategic work areas. The third of these is to:

- Raise Awareness of Weather Radar in the wider community

This was to be achieved by promoting and establishing international contacts and reporting on its work to the nominating bodies and the wider water industry.

These tasks have been detailed earlier in the report under Section 3.4. Significant developments have taken place during the last Committee session, but this work needs to continue through into the next session to develop further applications of weather radar in the water industry. Areas for further research are identified below.

Data quality

There are a number of projects being undertaken by water companies to trial the use of weather radar in conjunction with existing hydraulic sewerage models. Radar rainfall data are being used to assess historical flooding events and for generating robust cost-effective capital solutions. Recently there has been a move to use rainfall forecast data with hydraulic sewerage models to predict future flooding and develop Real-Time Control (RTC) operating/control systems to manage sewerage networks more effectively.

The concept promises to be a huge step forward in the proactive control and asset management of sewerage catchments. However, the issues of data quality and reliability of the radar systems are limiting the progress of this work. Further work needs to take place to improve the quality of radar data and the confidence of those engineers trying to apply these data to commercial applications. To improve the confidence in weather radar data, it has been suggested that recorded rainfall events are assigned "data confidence flags". Work to develop how these confidence flags are compiled needs to take place, but could include consideration of:

- Presence of ice/hail/bright band
- Cloud type (frontal or convection)
- Wind speed
- Peak intensity
- Total depth
- Storm duration
- Correlation with nearby raingauges
- Equipment operation (were there any system failures?)
- Which radar station formed the composite data?
- Are the data 1km or 2km resolution?

These all need to be considered so that the uncertainty in radar data can be reduced to a level where the system can be relied upon. OFWAT regulates water company finances very tightly, because any investment must be funded through customer billing. Confidence in weather radar will support the business cases put forward by water companies to increase future expenditure in this field.

Propagation of rainfall uncertainty

Section 3.3.6 discusses the propagation of rainfall uncertainty through hydrological models. This work needs to be extended to investigate the impact on hydraulic sewerage models covering urban areas.

These models have been verified using raingauge data and various runoff models to generate the correct flow in the sewerage systems. Tests have shown that when radar rainfall data are applied to previously verified sewerage models, the runoff generated can be significantly different. This results in engineers reverting back to raingauge data and the uncertainty in radar data continues.

Data sharing

The initial cost of purchasing radar data can be prohibitively expensive and is therefore a limiting factor in furthering its use more widely in the water industry. Partnerships between various government organisations and the private sector do exist and have seen new radar stations entering the UK network. This is a positive move and will improve the radar coverage over the UK, but further steps could be taken at more local levels to aid pilot studies and research in key parts of the country. Data that could be shared more openly could include:

- Water company telemetered raingauge data
- EA, SEPA and Rivers Agency (Northern Irealand) telemetered raingauge data
- Met Office telemetered raingauge data
- Local authority telemetered raingauge data
- Research/University raingauge data
- Privately owned raingauge data
- Met Office historical radar and forecast rainfall data (introductory price for research?)

Common guidelines for the application of radar data to sewerage models

When the data flags or method of determining rainfall accuracy have been developed, water companies and the engineering consultants they employ need to develop a common set of guidelines that govern the application of radar data to sewerage models. These guidelines can be in the form of the industry recognised WaPUG user notes (Wastewater Planning Users Group) which are written, reviewed and updated by leading industry practitioners.

A formal request should be made to the WaPUG committee for the development of a new user note to guide the use of radar data. Future workshops, papers and editorial sessions can then be organised to aid this.

Radar data and asset management

Water companies are looking towards radar rainfall forecast data as a means to manage the control of assets such as pumping stations, storm tanks, sewage treatment works and to mitigate possible flooding events. The ability to predict rainfall events and understand how this may affect the network is crucial to long-term investment strategies. If this understanding can then be harnessed and RTC (Real-Time Control) of assets implemented, the benefits in terms of system performance, customer service levels and long-term investment will be significantly improved.

Application of extreme events to large urban areas

It is hoped that a greater understanding of the size, shape and movement of extreme rainfall events over large urban areas will enable a more robust methodology for applying FEH (Flood Estimation Handbook) design events to sewerage catchment models. Thames Water has specific guidelines for applying FEH design rainfalls to the large London models. This is probably the case for other water companies which maintain large urban catchments. However, this is changing as we learn more about flooding patterns and systems performance. Greater study of radar rainfall patterns should aid this development.

Environmental protection

Designated bathing beaches have mandatory and guideline water quality standards under the EU Bathing Waters Directive. The Environment Agency undertakes a programme of bathing beach monitoring during the bathing season (May to September inclusive) and report findings to Defra. Where samples fail, this can lead to the beach failing to meet the required standard, can impact on its Blue Flag status and ultimately could mean the UK fails to comply with the Directive. The Directive states that deviations from water quality standards should not be taken into consideration in compliance calculations when they are the result of abnormal weather conditions (a 1 in 5 year or worse storm event).

When a sample fails, the Environment Agency assesses the rainfall in the catchment affecting the beach to identify whether an abnormal weather waiver may be appropriate. The evidence used is primarily based on raingauge data and the Environment Agency have a network of gauges along the coast for this purpose. However, radar rainfall data are used during the process in two ways. Firstly, as a qualitative check prior to requesting and analysing the raingauge data. This means the radar data are inspected for evidence of heavy rain prior to the sample being taken. If there is no significant rainfall shown, no further analysis is undertaken. However if there is evidence of rainfall then raingauge data are obtained and analysed to identify if a waiver application should be made. Secondly, radar data may be used quantitatively to assess the severity of rainfall and this is done primarily where there is evidence of convective activity or isolated heavy showers that may have been missed by the raingauge network. So if the raingauge data do not meet the criteria for a 1 in 5 year storm event, but the radar data indicates rainfall near the beach did meet the criteria, then this analysis may be used to support a waiver application. Up to now this has been used as supporting evidence, along with other information such as sewer flows, operation of Combined Sewer Overflows etc. If the quality of the radar data were better, such that they could be relied upon in a quantitative analysis, then radar data could perhaps be used as primary evidence in lieu of, or in combination with, raingauge data.

Savings may then be possible by reducing the number of coastal raingauges or through the improved decision-making a combined radar and raingauge estimate of rainfall would bring.

Post-flood analysis, reporting and evidence

The Environment Agency makes significant use of radar data for post-flood analysis and reporting purposes, and as evidence that extreme isolated precipitation has occurred where no raingauge data are available.

Again the issue of data quality arises as if the quality could be further improved then greater use of radar would be possible in a more quantitative manner for post-flood analysis, reporting and for evidence purposes.

Low flow management

The Environment Agency undertakes a range of operational low flow management tasks. These include:

- Operation of river regulation schemes (such as on the rivers Severn and Dee)
- Operation of river flow transfer schemes (such as the Ely Ouse to Essex transfer)
- River level management for navigation purposes on the Thames
- Drought management activities such as applying for Drought Permits and Orders.

Telemetered raingauge and river level and flow are generally used to make operational decisions and provide evidence to support drought permit/order applications. Radar data and radar forecast products are also used in a qualitative way to support decision-making.

Again data quality is a limiting factor, and improvement in the quality of radar data would see these data being used for operational decision-making in a more qualitative manner.

6.2 A look forward to the next Committee session

The Committee will continue to focus on ways to influence the greater use of weather radar by operating agencies and to promote areas of improvement and research in support of the user community. The main themes that the Committee is to explore are:

i) Service and system developments

There are significant developments affecting the Environment Agency, Met Office and SEPA, including:

- Developments by the Flood Forecasting Centre in an operational grid-based hydrological model (G2G) and the use of radar and radar-derived rainfall products
- Developing training in application of radar for hydrology
- UK radar network renewal to dual polarisation

ii) Research developments

Following the review of hydrological application of radar across the operating agencies, key research priorities have been identified. The following should be considered:

- Understanding current research and alignment to operational requirements
- Developing user requirements to include the water management sector

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

iii) Promoting the role of radar in flood risk management

The Committee will be taking the lead on promoting the role of radar through a number of initiatives including:

- Organisation of the 2011 International Symposium on Weather Radar and Hydrology
- Work with ‘Sense About Science’ on the explanatory booklet

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 (from May 2009) School of Earth and Environment University of Salford (up to April 2009) School of Environment and Life Sciences
Mr Tony Deakin (up to February 2010)	Environment Agency
Mr Tim Harrison (from February 2010)	Environment Agency
Dr Miguel Rico-Ramirez *	University of Bristol Department of Civil Engineering
Dr Noel Higginson	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
Mr Malcolm Kitchen (up to April 2009)	Met Office
Dr Jacqueline Sugier (from April 2009)	Met Office
Mr Nick Martin (up to April 2009)	Thames Water Utilities
Mr William Neale (from August 2009)	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

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 seven universities (Bristol, Essex, Swansea, Reading, Newcastle, Salford and Leeds) together with the Science Technology and Facilities Council (STFC) and CEH Wallingford.

C.1 University of Bristol

Research at the University of Bristol relevant to weather radar has concerned topics in the three areas described below

(a) Clutter and anomalous propagation classification

A study was designed to classify clutter echoes obtained from ground-based dual-polarisation weather radar systems. The clutter signals are due to ground clutter, sea clutter and anomalous propagation echoes: these represent sources of error in quantitative radar rainfall estimation. Fuzzy and Bayes classifiers were evaluated as an alternative approach to traditional polarimetric-based methods. Both systems were trained and validated by using C-band dual-polarisation radar measurements. A novel technique was proposed to calculate the texture function to mitigate against the edge effects at the boundaries of precipitation regions. A methodology was developed to extract the membership functions and conditional probability density functions to train the classifiers. The Critical Success Index indicated that the Bayes classifier had, on average, a slightly better performance than the fuzzy classifiers. However, when optimal weighting was applied, the fuzzy classifier gave one of the best performances. The classifiers are sufficiently robust to be used when only single-polarisation radar measurements are available.

(b) Antenna Pointing

A novel technique was developed to monitor continuously the azimuthal pointing accuracy of a weather radar antenna. 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 obtained in real-time using a Bayes 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.

(c) Radar Nowcasting

Quantitative Precipitation Forecasting (QPF) over urban areas is a challenging problem. Many attempts have been made to use weather radar to produce rainfall forecasts with lead times of a few hours ahead. In the UK, the Met Office has developed a stochastic probabilistic precipitation forecasting scheme (STEPS), which merges an extrapolation radar rainfall forecast with a high-resolution Numerical Weather Prediction (NWP) rainfall forecast. An analysis was made of several precipitation events over a small urban area in terms not only of QPF, but also in terms of flow prediction at the urban scale. STEPS was used to produce precipitation forecasts with spatial and temporal scales of 1 km and 5 min respectively and with lead times of up to 3 hours. The results of the STEPS model showed that the forecast's skill decreases not only with lead-time but also with spatial resolution (e.g. 10 km spatial scales showed a better forecasting skill than 1 km spatial scales). Also, the skill of the forecasts is better in stratiform than convective precipitation. Due to local variations at a 1 km scale, the skill of the rainfall forecast for the whole radar/NWP domain is not a direct indication for the skill of the flow forecasts.

C.2 University of Essex

The Centre for Remote Sensing and Environmetrics has been based in the Departments of Electronic Systems Engineering and of Mathematical Sciences, and now principally in the new School of Computer Science and Electronic Engineering. Its research focuses on remote sensing of weather related phenomena, which includes techniques in weather radar (particularly specializing in polarimetric techniques), but also includes aspects of radiowave propagation that relate to atmospheric phenomena. Its research output ranges from theoretical aspects of scattering and polarimetry, to modelling of propagation and scattering, evaluation of methods for quantitative precipitation for hydrology and statistical modelling of precipitation.

C.3 University of Swansea

A research group with interests in using weather radar for flood risk management applications is being established at the University of Swansea.

C.4 University of Reading

Work at Reading has concentrated on three aspects: (a) the performance of the polarisation algorithms to provide improved rainfall estimates on the newly installed Thurnham radar, (b) quantifying and correcting for radar attenuation using emissions from storms, and (c) deriving near surface changes in humidity using the wet-delay from ground clutter.

(a) Polarisation algorithms using the Thurnham radar

The performance of the Thurnham radar has been analysed, particularly for the case of 20 July 2007 storm which produced severe pluvial flooding over West London. In brief it was concluded that the new polarisation radar had 10dB less sensitivity than the other radars in the network, and the polarisation parameters were much noisier than expected and not satisfactory for operational use. To obtain acceptable data the radar should be able to measure a co-polar correlation of the Horizontal and Vertical time series in rain of about 0.98; the value achieved by the Thurnham radar was about 0.95 and accounts for the poor performance. The Met Office is developing an alternative strategy to obtain a polarisation radar which does meet their specification and should be delivered within the next couple of years.

On 20 July 2007 the rainfall observed by raingauges in London was over twice that inferred from the radar reflectivity values, and analysis has shown this was due to severe attenuation of the radar beam. The Thurnham radar observed differential phase shifts of over 200 degrees which were clearly visible above the noise and accurately indicated the regions where attenuation was occurring, thus demonstrating the ability of polarisation radar to correct for attenuation. Variational algorithms to derive better rainfall rates using differential reflectivity and differential phase have been developed. The Thurnham radar was shown to be too noisy to provide an improved estimate of rainfall rates, but tests using the same algorithms on the Meteo-France polarisation radars has demonstrated a positive impact.

(b) Correction for radar attenuation using emission.

A new technique to correction for radar attenuation has been demonstrated and is now being rolled out over the UK operational network. It is based on the idea that any target which attenuates the radar beam will also emit continuously: in other words it 'glows' at the radar frequency. This 'glowing' can be detected by the increased noise received when no pulses are being transmitted: in other words when the radar is operating as a radiometer. We can then express this increased noise as a brightness temperature of the emitting target, and then work out the attenuation of the storm by the radar beam. This value of total attenuation is derived without any assumption of the form of the hydrometeors, and can be used as a constraint for current rather error-prone and unstable techniques. The performance of the technique in an operational environment is currently being determined.

(c) Refractivity

This technique measures the additional ‘wet-delay’ from ground clutter returns caused by the small reduction in the speed of the radar returns by the humid air. Because there are many ground clutter returns within 30 km of the operational radars it is then possible to map out changes in low level humidity within 30 km of the radar. On showery days where there is a risk of severe convection, the convergence of the humidity may indicate areas where showers are about to break out. The method has been demonstrated and is currently being rolled out over the operational network. The idea is simple, but great care is needed to select appropriate clutter targets. The derived humidity observations also have an error associated with them, so the ultimate aim is to assimilate these additional humidity variations into the forecast model and improve our ability to pin-point where severe storms are likely to occur.

C.5 University of Newcastle

Radar rainfall data have been used for parameterisation and validation of rainfall models. These models have been developed and used for a variety of applications including catchment and urban flood modelling. A particular focus in recent years has been rainfall models and weather generators for climate change applications (including the national scenarios for UK Climate Projections 09). Developments of spatial models have recently focussed on high time and space resolution models (5 min and 1 km) for use in urban drainage modelling applied in the Dti SAM and EPSRC SWURVE projects, where radar data are the only source of information on spatial correlation of extremes over city scales.

C.6 Universities of Salford and Leeds

This report covers research on the hydrological uses of radar data carried out at the University of Salford (2007-2008) and the University of Leeds (2008-2009). Considerable work is being carried out on short-period forecasting at Leeds which involves the use of radar data. Work undertaken at Salford and continued at Leeds on radar hydrometeorology is summarised in the following. A review of the likely limits of predictability of flash floods has been published. The problems of assimilating Doppler radar data into a Numerical Weather Prediction model have been examined.

Research on the generation of convective rainfall by the urban area of Manchester has used both a simple numerical model and radar data. This activity has provided an incentive for investigating the impact of regeneration on rainfall distribution which is currently underway.

A Bayesian post-processor has been used to generate a representation of the likely hydrograph forecast flow error distribution using raingauge and radar input to a stochastic catchment model and its deterministic equivalent. A hydrograph ensemble was constructed. Experiments using the model applied to the River Croal in North West England found that for rainfall input to the model having errors less than 3mm h^{-1}, corresponding to about a 15% error in peak flow; the stochastic model outperformed the deterministic model. The range of hydrographs associated with the different model simulations and the measured hydrographs were compared. The significant improvement possible using a stochastic approach was demonstrated for a specific case study, although the mean hydrograph derived using the stochastic model has an error range associated with it.

Building on this work, a representation of the likely hydrograph forecast flow error distribution using raingauge and radar input to a stochastic catchment model and its deterministic equivalent has been studied. Experiments were analysed using the model applied to the River Croal. The implications for the use of radar for flood forecasting have been discussed. In particular, the propagation of errors in the radar rainfall field through the stochastic model were examined, and compared with other published work undertaken using a distributed model of a catchment in the USA. A method of constraining flow simulation ensembles using the amplification of uncertainty from input rainfall data has been proposed.

The use of autoregressive modelling as a method of quality controlling radar estimates of rainfall has been investigated. Further work on the use of autoregressive modelling for analysing forecast ensembles is currently underway.

C.7 Science Technology and Facilities Council (STFC)

The Chilbolton Group, a part of Space Science & Technology Department 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 25m 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 a number of significant upgrades have been made to enhance the capability of the facility. The 25m dish, which serves as antenna for both the 3GHz

CAMRa and 1275MHz Acrobat radars, has had a new servo drive system installed. This, together with the commissioning of a new control system was a major undertaking during 2008-2009, and allows the radar to scan at up to 3 degrees per second in azimuth. A thorough investigation has also been undertaken to quantify the pointing accuracy of the antenna. The final commissioning of a fast feed changer was also completed, enabling rapid switching between radar and other projects. This ensures radar availability to record and quantify extreme rain events, even during other campaigns. As with other CFARR instruments, such data are made available to the research community via the British Atmospheric Data Centre (BADC).

In addition, the establishment during this period of Met Office instrumentation, including a wind profiler, at Chilbolton as part of the Future Upper-air Network Development (FUND) project, has opened up further opportunities for the site.

Preliminary work has also been undertaken in collaboration with the University of Reading to evaluate new methods for identifying ground clutter in radar data.

Finally, the facility has played an important role in raising public awareness of the capability of weather radar through involvement in a number of TV documentaries produced and broadcast during this session.

C.8 Centre for Ecology & Hydrology (CEH), Wallingford

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

(a) Rainfall estimation and ungauged flood forecasting

Journal papers have been published on radar and raingauge gridded rainfall estimators, based on new integrated multiquadric surface fitting methods, suitable for use in hydrological modelling and flood forecasting. The need for frequent and spatially varying gauge-adjustment of radar rainfall data was identified as crucial. Both lumped (the PDM) and distributed (the G2G) hydrological models have been used in the assessments. The gridded raingauge-adjusted radar rainfall estimates when used as input to the distributed G2G model were shown to be of particular benefit for forecasting at ungauged locations.

(b) Rainfall sampling uncertainty

A collaborative paper with the University of Iowa on the temporal and spatial sampling uncertainties associated with rainfall estimation, supported by the HYREX dense raingauge dataset (http://badc.nerc.ac.uk/data/hyrex/), was published. It was shown that the temporal sampling uncertainties increase with sampling interval according to a scaling law and decrease with increasing averaging area. Uncertainties in spatial sampling decrease with increasing accumulation time. A description of the characteristics of the rainfall process in terms of spatial correlation was given.

(c) Case study of the Carlisle flood, north-west England

Radar data were used to portray the spatial pattern of rainfall over Cumbria for this severe flood event on 8 January 2005. Nimrod radar-extrapolation rainfall forecasts and high-resolution (4 and 1 km) NWP rainfall forecasts were used as input to PDM rainfall-runoff models for two catchments draining to Carlisle. An assessment in terms of their utility for flood warning showed that the NWP forecasts captured the orographic enhancement of rainfall well, and the resulting flood forecasts had the potential to give ~12 hours advanced warning.

(d) Probabilistic flood forecasting

CEH's work on the two EA/Defra R&D projects 'Hydrological modelling using convective scale rainfall modelling' (SC060087) and 'Risk-based probabilistic fluvial flood forecasting for integrated catchment models' (SC080030) is reported on under Section 3.3.4. Both projects assessed the use of STEPS ensemble rainfall forecasts, based on extrapolating radar images forwards in time and blending them with rainfall forecasts from a Numerical Weather Prediction (NWP) model. Probabilistic flood forecasting products were produced including "spaghetti" hydrographs and real-time flood risk maps of flood threshold exceedance. Probability bands for lumped rainfall-runoff models, obtained using a parametric ARMA (Auto-Regressive Moving Average) model error approach, allowed flow forecast percentiles along with uncertainty bands to be calculated using the STEPS ensemble members. The effect of model and rainfall forecast uncertainty could thereby be jointly assessed.

(e) Scottish Water

On behalf of Scottish Water, CEH undertook several post-event analyses of storm events associated with surface water (pluvial) flooding incidents. These analyses used radar and raingauge data records and rainfall return period estimation was performed using the Flood Estimation Handbook (FEH) software. The analyses proved to be quick and informative. The main interest was in urban storm drainage compliance assessments where the estimated rarity of rainfall events causing surface water (pluvial) flooding can be used to help determine whether drainage systems performed within design specifications or if remedial action is required.

Following these trial post-event analyses, Scottish Water have recently taken delivery of the Centre for Ecology and Hydrology's Hyrad (HYdrological RADar) system - for real-time processing, displaying and analysing radar-rainfall data - and the Flood Estimation Handbook (FEH) software. This allows Scottish Water to use and analyse radar-rainfall data in-house for the first time. A one-day training course was given by CEH to staff in Scottish Water's Dundee office.

Appendix D Summary report of the 2005 – 2007 session

A summary of the 2005-2007 Session Report was published in BHS Circulation No. 97 in May 2008[8]. A copy of the summary is reproduced below.

Weather Radar: meeting the needs of hydrologists and meteorologists in the UK

Having recently taken over the role of Chairman of the Inter-Agency Committee on the Hydrological Use of Weather Radar (IACHUWR) the above title is both a question that I am keen that the committee asks and, at the same time, a statement of the group's purpose for serving the hydrological and meteorological communities.

The committee, under its original *ægis* of the NERC steering committee, was formed in 1986 because '*while the meteorological applications of weather radar were well catered for and properly coordinated, the hydrological aspects were not*'. The opening vision continued: '*it was seen as particularly vital for hydrologists to capitalise on the great potential offered by the rainfall data from the UK weather radar network*'. However bold a vision in the mid-1980s this may have been, it is just recently that my own organisation SEPA has started using radar data quantitatively for hydrological applications; doubts still remain over the quality of these radar observations in many areas of Scotland. So how much is weather radar really meeting the needs of the hydrological, or indeed, the meteorological community?

For those not familiar with the committee, IACHUWR is a unique group that seeks to represent hydrological and meteorological users of radar data. The committee is made up of representatives from the main operating bodies including the Department of Agriculture and Rural Development Northern Ireland, the Environment Agency, Met Office, SEPA and the Water plcs. Technical representation is provided through the research councils, via CEH Wallingford and the Science and Technology Facilities Council, together with leading university groups involved in radar research. The committee reports biennially on a number of strategic areas with the aim of bringing research findings into the operational arena and considering the service delivery needs of operating agencies.

The recently completed session report for 2005 to 2007 can be found on the committee's website (www.iac.rl.ac.uk). The two-year period has seen exciting developments for weather radar in operational and research fields. The South East Weather Radar Programme has successfully delivered two new installations for the UK network: Dean Hill radar in Wiltshire and Thurnham radar, a state-of-the-art dual-polarisation radar, in north Kent. Radar has also been a valuable tool in the detection of severe weather events during this period, including the notable summer floods of England and Wales in 2007. In the research field there has been much activity, with a number of significant research programmes focussing on improving the use of radar for hydrological applications. The committee encourages this and aims to help this research find its way into the operational arena to enhance the quality of radar data and its use.

Looking to the future and ensuring that the communities' needs are met by weather radar, the committee has identified a number of key objectives on which to report in the coming two years. The committee will be carrying out a consultation within the hydrological community to assess the current status of their hydrological applications of

[8] http://www.hydrology.org.uk/Publications/Circ97online.pdf

weather radar. Its findings will inform and influence where future spending for research and development should be aimed.

The recently introduced EU Floods Directive requires that Member States, under flood risk management plans, shall '*address all aspects of flood risk management focusing on prevention, protection, preparedness, including flood forecasts and early warning systems*'. This Directive still needs to be transposed into Member States' legislation, but it clearly places a requirement on operating agencies for flood forecasting. Although in some agencies this requirement is already being met, it may mean significant developments in others. Therefore our focus should be now to ensure that weather radar does meet requirements for hydrological applications to enhance flood forecasting capabilities.

Finally, I wish to thank all the committee members for their efforts over the past two years in producing a comprehensive report. In particular, thanks to Chris Haggett who has served the committee extremely well for the past 12 years, with the last four as Chairman.

Michael Cranston
Scottish Environment Protection Agency
IACHUWR Chairman 2007-2009