Interagency Research Committee on the Hydrological Use of Weather Radar

Third Report

March 1995 - February 1998

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Report prepared on behalf of the Committee by the Institute of Hydrology

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PREFACE

I am pleased to present this report of the Committee's work, which identifies the continuing activity and influence of UK workers in weather radar both nationally and internationally.

The HYREX Special Topic, initiated by the NERC, was reviewed in our last report. The programme has now finished and dissemination of the results is vital so that the knowledge and understanding gained is made available to the wider community. I am pleased to acknowledge the support of the Royal Meteorological Society, the British Hydrological Society and NERC in holding a joint meeting in November 1996 at which HYREX researchers were able to report their findings to an audience of fellow researchers and end-users. A forthcoming special issue of the journal "Hydrology and Earth System Sciences" will be devoted to the results of the HYREX programme. Also worthy of note is the availability of the HYREX datasets on the World Wide Web thanks to support from MAFF, IH and NERC Seedcorn funding.

The Committee has registered its concern that neither the water utilities nor the UK Environment Agencies make sufficient use of the potential of weather radar to provide detailed precipitation information. Professor David Newsome was commissioned by the Committee to examine the potential benefits of radar-derived precipitation data in urban areas and to identify the areas where science- and application-driven research projects are necessary to improve the confidence of end-users and enable the full benefits of such data to be realised. It is my strong hope that funding bodies will support the recommendations of Professor Newsome's report and so make possible the achievement of practical, sustainable, cost-effective solutions to issues of flooding and pollution in urban areas.

On this theme it is very pleasing to report that the GANDOLF thunderstorm forecasting system, developed by the Met. Office for Thames region of the Environment Agency, is now in operational use and proving beneficial.

I close these remarks with a plea for a substantial improvement in communication between the radar community and operational hydrologists. The radar community needs to be much more positive about the capabilities of weather radar systems; the user community needs to have a greater understanding of the actual and potential benefits from the use of radar-derived precipitation data. As well as the outstanding science and application questions, the issues of communication and education need to be firmly addressed.

John M Tyson
Chairman (1995 –1999)

CONTENTS

1 INTRODUCTION

The Interagency Research Committee on the Hydrological Use of Weather Radar was established in 1991 and is the successor to the NERC Steering Committee on Hydrological Applications of Weather Radar. It provides a UK forum for the exchange of ideas between areas of research, application and commercial exploitation of weather radar, regularly reviews the status of UK research, and acts to facilitate and promote the hydrological use of weather radar. The Committee's first report covered the period from October 1991 to February 1993, the second report carried this forward to February 1995, and this Third report covers from March 1995 to January 1998.

The report begins with a review of the Committee's activities over the reporting period (Section 2) and goes on to summarise the current status of UK research (Section 3) and, in particular, HYREX (Section 4). There follows an overview of international research activity in which UK researchers are involved (Section 5). Finally, the report addresses strategic issues.

The Committee's Terms of Reference are given in Appendix A, full details of membership are provided in Appendix B, and the agency reporting lines are listed in Appendix C. The updated *Directory of UK Expertise in the Hydrological Use of Weather Radar* forms Appendix D.

2 REVIEW OF COMMITTEE ACTIVITIES

Committee Meetings

The Committee has met six times since it last reported. The business of the Committee has largely focused on two of its Terms of Reference: to identify research needs and opportunities, and to recommend research priorities and coordinate activities. The Terms of Reference were also reviewed but no changes were made. Specific Committee activities and interactions with other groups are described below.

Changes in Membership

A number of changes to membership occurred during the reporting period. In 1995 Mr Tyson took over from Dr Walsh as Committee Chairman. Also, representation from the Meteorological Office changed from Professor Collier (who transferred to the University of Salford) to Dr Caughy and then to Dr Hardaker. Mr Haggett replaced Dr Walsh as the NRA representative and remained so when the NRA became the Environment Agency. In 1996 SEPA accepted an invitation to join the Committee and representation was provided by Mr Sargent as a full core member of the Committee. Mr Sargent was later replaced by Dr Curran. Similarly, the CLRC became represented on the Committee by Mr Goddard, also as a full core member. Dr Shepherd from the States of Jersey, who had been acting as an observer on the committee, also became a full member. Professor Collier rejoined the committee as a coopted member representing the University of Salford. Mr Hatton, representing the Environment Agency, retired and consequently stepped down from the Committee, leaving Mr Haggett as the sole EA representative. In 1997 Professor Cluckie moved from Salford to Bristol University but remained on the Committee; Dr Curran was replaced by Mr Burns as the SEPA representative.

Reports

Professor Collier, in his role as WMO rapporteur to the *Working Group on Hydrological Forecasting and Applications for Water Management*, presented a report to the WMO 10th Commission for Hydrology on the subject of precipitation estimation and forecasting. His report was highly commended by the Committee.

Initiatives

The Committee, concerned that both the water utilities and the UK Environment Agencies make only limited use of the potential of radar-derived precipitation data, commissioned Professor David Newsome to carry out a scoping study on the Hydrological Applications of Weather Radar in Urban Areas. The study report found that the main reason for this limited use lies in the uncertainty in radar-derived rainfall estimates caused by unusual and varying error characteristics. Several recommendations are made for both science-driven and application-driven research to resolve many of these uncertainties. The report is now available and the Committee hopes that the appropriate funding bodies will support the recommended work.

EA/Meteorological Office Working Group on the Development of the National Weather Radar Network

This Working Group, which has cross membership with the Committee, was originally formed in 1993 to undertake a strategic review of the UK Weather Radar Network for the next decade. During the reporting period a data archiving subgroup produced a report on the archiving of weather radar data which incorporated the Committee's views (via a submission by Mr Moore). However, the Committee perceives additional data archiving needs for the research community. Although the Working Group were to present business cases to the EA and MO Boards in 1997, further action on data archiving was suspended until after the signing of the MoU between the EA and MO which is planned for the start of the 1999/2000 financial year.

Inter-Departmental Committee on Hydrology

A link to the Inter-departmental Committee on Hydrology is currently maintained through Dr Hardaker who reports their activities back to the Inter-Agency Research Committee.

3 REPORTS FROM UK RESEARCH GROUPS

Professor Cluckie moved to the **University of Bristol** in 1997 and founded a new Water and Environmental Management Research Centre in the Department of Civil Engineering. He remained co-ordinator of the EU Hydromet project through which the group has furthered its work on rainfall and flood forecasting using weather radar and studies of the vertical profile of radar reflectivity. The group's interests have continued with the HIRE experiment (Hydromet Integrated Radar Experiment) based in Marseilles and preparations for the forthcoming SALPEX 2000 International Experiment planned in New Zealand. During the summer of 1998 the group organised and hosted an EU Short Course on Radar Hydrology for Real-time Flood Forecasting and also extended its WRIP flood forecasting system into the whole of the South West peninsular. Work also continues in the area of real-time control of large urban systems and the group had a major involvement in the 'Bolton' project undertaken with United Utilities and indirectly with Yorkshire Water.

At the **Environment Agency** the following research is currently underway in the North West Region Flood Warning section.

1. Adaptive Radar Calibration (ARC)

This is the continuation of an R&D project, leading to the implementation of the ARC system in the North West Region Flood Room, to allow operational assessment of the system output in real-time. The ARC approach consists of image processing (to remove clutter and other anomalies), together with calibration using an optimised number of telemetered raingauges (using surface fitting techniques), and aims to improve upon the radar rainfall estimates achieved by the existing Collier-Larke system. Research on the project is being carried out at the **University Of Lancaster** by Martin

Lord and Peter Young (see above). The system is due for implementation in the Region in the near future.

2. Comparison of different forecasting models

This research project assesses the suitability of the real-time flood forecasting models used throughout the Environment Agency (and a number of newly developed systems) for use in a number of different forecasting conditions. These include a variety of catchment sizes, forms, and degrees of urbanisation. The aim of the project is to produce a working document which will enable flood forecast modellers to match the optimum model to the catchment, data availability, forecast accuracy, lead time required and so on. Within this brief, radar rainfall data are being used as one of the model inputs as radar provides the unique ability to monitor precipitation spatially and forecast its development. The use of different types of model format is facilitated by the increasingly modular form of the modelling and forecasting systems being commissioned by the Agency. The research comparison is being carried out by Bob Moore and Vicky Bell at the Institute of Hydrology and is due for completion in 1999.

A third project on low cost C-band radar is reported under Water UK activities.

The EA has found that the present radar products do not satisfy their needs because improved and more accurate radar data estimates are required before they can be used quantitatively. Thus, the South Region commissioned 'A Review of Radar Correction and Adjustment Techniques' from W S Atkins Water. A number of recommendations have resulted from the review, such as: the accuracy of radar products needs to be improved, especially at long ranges; radar hardware should be systematically monitored; data pre-processing approaches need comparing and evaluating in order to determine optimal practice; adjustment schemes need comparing, particularly for heavy rainfall; an optimal network density needs to be defined; great potential exists for vertical pointing radar in urban areas; a central agency should be responsible for data treatment to ensure uniform adjustments which are consistent in time and space; correction could be improved for occultation, clutter and attenuation; and dual-polarization and Doppler techniques have potential for detection of hail, bright band and precipitation type.

The **University of Essex** has been involved in three projects related to measurement of rainfall. Two of these are directly related to radar, the third less directly so. The first project, EU funded DARTH (Development of Advanced Radar Technology for application to Hydrometeorology), involves 7 partners, 2 of which are from the UK. Its aims are to develop the use of radar data to improve the measurement and forecasting of rainfall. Work at Essex is focusing on the use of polarisation, visualisation, and anomalous propagation. The second project, EuroTRMM, relates to the space-borne monitoring of rain using data from the TRMM satellite. The Essex component is concerned with modelling volume scattering. The third, NERC funded project, is to design an experiment to test the ability of dual-wavelength microwave links to obtain accurate estimates of path-averaged rainfall, and to apply such estimates in the management of waste water systems. This work is a collaboration with Salford University and the Rutherford Appleton Laboratory.

The Department of Civil Engineering, **Imperial College**, is working with the Department of Statistical Science, UCL, and Nuffield College Oxford on a range of issues related to spatial rainfall using radar data, with funding support from NERC and MAFF. New stochastic methods for modelling spatial rainfall are being developed, using Poisson-processes in space and time, based on the HYREX raingauge/radar database in SW England. Good performance has been obtained for the spatial properties of individual storms. Attention is currently focused on parameter estimation and the reproduction of storm sequences.

Rainfall disaggregation is a major issue for General Circulation Models of global climate. Analyses of large-scale radar fields, based on UK data and the US NEXRAD network over the Mississippi basin, have been used to improve simple disaggregation methods. In addition, a new family of

methods has been developed, which preserves the temporal memory of spatial location of disaggregated rainfall using Bayesian procedures based on Markov Random Fields.

Under the HYREX project the **Institute of Hydrology** investigated the accuracy of radar/raingauge networks with the benefit of the dense raingauge network over the Brue catchment. Problems of raingauge data quality control and the effects of precipitation type on the accuracy of raingauge measurement were addressed. The variability of rainfall over the spatial scale of the radar data (2 by 2 km) and the catchment (135 km^2) was investigated as a function of rainfall intensity. For the 2 km case accuracy was shown to be related to the accuracy of the areal rainfall estimates themselves. For the higher rainfall situations, variability of around 20 % and 50 % at the 2 km and catchment scales respectively was found. Consideration of radar recalibration by raingauges explored how the use of a single gauge, typically available operationally for a catchment the size of the Brue, affected the accuracy of rainfall estimation. A dynamic raingauge calibration was shown to be only effective over a relatively short distance whereas a long-term climatological correction proves more useful at greater distances. A tapered calibration factor method was developed that behaves as well as the dynamic calibration at close distances and takes the form of the climatological correction at larger distances.

A second project under HYREX investigated a simple two-dimensional rainfall model, based on advection and conservation of mass in a vertical cloud column, for use in short-term rainfall and flood forecasting at the catchment scale during convective storms. The model is capable of assimilating weather radar, satellite infra-red and surface weather observations, to obtain frequently updated forecasts of rainfall fields. Forecasts from a mesoscale numerical weather prediction model can also be incorporated if available. Such data assimilation helps compensate for the simplified model dynamics and taken together provides a practical real-time forecasting scheme for catchment-scale applications. The results obtained from two convective events over southern Britain show that (i) a simple advection-type forecast may be improved upon by using multiscan radar data in place of data from the lowest scan, and (ii) advected, steady state predictions from the dynamic model, using 'inferred' updraughts, provides the best performance overall. Updraught velocity is inferred at the forecast origin from the last two radar fields, using the mass-balance equation and associated data, and is held constant over the forecast period. This approach proved superior to the buoyancy parameterisation of updraught originally employed. Selected rainfall forecasts were used as input to a catchment flow forecasting model to assess their effect on flow forecast accuracy.

A Japanese government sponsored researcher worked for a year at IH from March 1997 on the topic of rainfall forecasting based on disaggregation of the UKMO Mesoscale Model forecasts (16 km scale) using a rainfall model (2 km scale) which adds the effect of small-scale topography. An EC Marie Curie Research Grant has been awarded to fund a researcher for 1998 and 1999 to work at IH on the "Use of radar-derived rainfall data for hydrological modelling in hilly and mountainous regions", in collaboration with University of Padova, Italy. This is initially focussing on radar calibration using corrections based on the vertical profile of reflectivity using multi-scan radar data over the Brue catchment and catchments in Italy.

December 1997 saw the start of an 18 month EA-funded project at IH to intercompare eight rainfall-runoff models on nine catchments for use in flood forecasting; radar and raingauge data are being used in the intercomparison.

Quality control and data management of the HYREX archive at IH continues with the support of MAFF and IH Science Budget, the latter also supporting the Automatic Weather Station & Soil Water Station in the Brue. NERC Seedcorn funding has helped IH give support to the World Wide Web access to the HYREX archive via BADC.

The radar meteorology group in the **Joint Centre for Mesoscale Meteorology** in the Department of Meteorology at the University of Reading has been using the Chilbolton polarisation radar to develop improved methods of estimating rainfall from radar and using mm wave radar for characterising cloud properties. Three papers to appear in the *Quarterly Journal of the Royal Meteorological*

Society describe the results of the rainfall work financed as part of the NERC HYREX programme. The first paper describes how the vertical profile of the radar reflectivity is used to recognise areas of embedded convection. When such areas are recognised the bright band correction algorithm should be suppressed. This method is undergoing trials within the UKMO NIMROD scheme. The second paper deals with a new method for recognising and correcting for attenuation. This relies on measuring both the differential phase shift and the differential attenuation along a path through rain to provide an estimate of the total attenuation caused by the rain. The third paper presents a new method of recognising where the reflectivity may be affected by the presence of hail. This relies on the relationship between the differential phase shift and differential reflectivity in rainfall also to identify areas where the return is from hail and to provide a method of automatically calibrating the reflectivity return in rain to within 0.5dB (15%).

Radar research at **Lancaster University** is primarily concerned with the calibration of C-band weather radar rainfall estimates to obtain improved estimates of the true surface rainfall intensity. Further, research into the use of these data in improved flood forecasting models is carried out using two types of time-variable transfer-function models and a non-adaptive forecasting model as a benchmark for measuring improvements in adaptive forecasting. Both rainfall-flow and flow-flow transfer function models are used, and the effect of using different methods of estimating the rainfall input from both raingauges and radar rainfall is investigated.

The Adaptive Radar Calibration (ARC) system devised at Lancaster University performs real-time raingauge-based calibration using tipping bucket raingauge rainfall intensity estimates from a small network of remote sites. The ARC system consists of three main calibration stages: the default calibrated radar image data are processed to reduce the impact of known anomalies, and to process for clutter, range and bright band effects; time-varying parameter estimates are calculated at each of the remote raingauge sites; and the time varying parameter estimates are combined to permit adaptive calibration of the entire radar image. The system uses time varying parameter regression models to allow the calibration parameter estimates to change smoothly through time at each of the remote raingauge sites.

Improved estimates of surface rainfall intensity are obtained over the whole 150km diameter radar area. Evaluation of the calibration performance for a variety of meteorological conditions has been carried out in two main ways as follows.

1. Using raingauge data from up to sixty tipping bucket raingauges sited throughout the radar area, the ARC calibrated radar rainfall estimates have been assessed. The bias observed to be present in the default calibrated radar data is entirely removed, and the instantaneous accuracy (assessed in terms of the reduction in magnitude of the mean squared error between radar and raingauge time series rainfall intensity estimates) is improved by 47%. This system is found to be greatly superior to the present raingauge calibration procedure which, in contrast, is shown to reduce the instantaneous accuracy of the rainfall estimates by 42%. In particular, the ARC system is able to process radar data affected by bright band - which is often the cause of the most severe radar rainfall estimation errors.

2. Four-hour ahead flow forecasts at Samlesbury, on the River Ribble, made by different model inputs have been compared with the observed flow. The ARC calibrated radar rainfall estimates produce better flow forecasts than radar data calibrated using the present raingauge calibration procedure, and the results are comparable with the flow forecast made by raingauge data (which is the best way to measure rainfall at ground level). The transfer function model generates significantly improved flow forecasts at Jumbles Rock in contrast to the EA model. Further, the adaptive models consistently outperform the non-adaptive models: the adaptive noise model (based on the Kalman Filter) consistently and radically improves the rainfall-flow forecasts while the Dumfries model is better at adaptive flow-flow modelling. This study demonstrates the hydrological application of the ARC-calibrated radar rainfall estimates and that the use of ARC

calibrated radar data improves the flow forecasts with respect to the other radar calibration methods.

An integrated spatio-temporal modelling approach is now being applied to the radar-raingauge relationship. In addition to spatial and temporal changes in calibration parameter values, this novel approach will model the inter-relationships between calibration sites. This improvement to the ARC system is expected to result in a greater level of accuracy in the areal rainfall estimates.

At the **Meteorological Office** the semi-automatic FRONTIERS system was fully automated in a new system called Nimrod. Nimrod provides radar-based observations and forecasts of precipitation amount, rate and type. Considerable effort has been directed at improving the correction and quality control procedures within the Nimrod system in order to improve the estimation of rainfall for hydrological customers. A number of studies are also underway to review the radar hardware in order to improve availability and reliability of operational radar observations.

A scheme has also been developed for the assimilation of the surface precipitation data into the mesoscale Numerical Weather Prediction (NWP) model. The scheme improves the analysis and short period precipitation forecasts from the model, and has been operational from April 1996.

Research on weather radar by **Newcastle University** is reported under HYREX in the next section.

The Radio Communications Research Unit of the **Rutherford Appleton Laboratory** have continued to develop infrastructure at the Chilbolton Observatory for sensing of the atmosphere. This is in support of the main instrument, the S-band polarisation-Doppler radar, CAMRa. The 35 GHz polarisation-Doppler radar, Rabelais, on loan from the University of Toulouse, and a new 94 GHz radar, Galileo, on loan from ESTEC, have provided new information on cloud properties. RCRU engineers, with NERC funding, have recently completed an upgrade to the Galileo radar which improves sensitivity and adds a Doppler capability. The group have also designed and built a transportable polarisation-Doppler radar that has been used to study rain in Tropical regions, initially Papua New Guinea, and currently Singapore. The latter system is operated as part of the EU-funded EoroTRMM project. RAL have also been involved in the EU MEFFE project. MEFFE stands for Satellite and combined satellite radar techniques in meteorological forecasting for flood events. It's objective is an improvement of the predictive skills of rainfall rate intensity for hydrological risk management. This will be achieved by coupling satellite data, radar data and numerical Limited Area Models. RAL's role was to provide rainfall data from the Chilbolton radar, particularly during SSMI overpasses.

The Water Resources Research Group at the **University of Salford** continued their detailed work in Radar Hydrology at the University of Salford up to September 1997. During this period the work included a major involvement with the NERC HYREX research programme, the SALPEX (Southern Alps Precipitation Experiment) experiment in New Zealand and their continued co-ordinatorship of the HYDROMET EU research programme under Framework 4. In 1997 Professor Ian D Cluckie and the majority of his co-workers moved to the University of Bristol (see above).

More recent work (under Professor Collier) has been undertaken to develop techniques for identifying the quality of radar rainfall estimates for use in hydrological models. This work, funded within the EU DARTH Project, has led to the development of an electrical circuit analogue model of a river catchment. Research into the use of radar data to identify and forecast active cold frontal rainfall, using the Met. Office GANDOLF system as a foundation, is currently underway. Another area of work is the use of radar data for flow forecasting in ungauged river catchments. The possibility of using the attenuation produced on microwave links by rainfall to adjust weather radar estimates of rainfall, and as direct input to urban storm sewer models, is being investigated together with the University of Essex and RAL.

The **Water UK** (North West Water and Yorkshire Water Services) are supporting, along with the EA North West, a project concerning the use of low power C-band radar. This research project was set up to examine the performance of a high resolution 40km range C-band radar for potential application to real-time control of urban drainage systems. The research work, carried out by the Water Resources Group under Professor Ian Cluckie, then at the University of Salford, was satisfactorily completed and the radar plus software installed at the North West Water HQ site near Warrington for operational use. Consequent upon the move of Professor Cluckie to the University of Bristol, the work continues at Salford under Professor Collier.

4 HYREX

Overview

The Hydrological Radar Experiment (HYREX) was a UK Natural Environment Research Council (NERC) Special Topic which ran from May 1993 to April 1997. Initiation of HYREX was via this Committee's activity in identifying research opportunities and submitting a proposal to NERC. The broad aim of HYREX was to gain a better understanding of rainfall variability, as sensed by weather radar, and how this variability impacts on river flow at the catchment scale. Six projects were funded involving groups from the Institute of Hydrology, the Rutherford Appleton Laboratory and the universities of London (Imperial College and University College), Newcastle, Reading (including the Joint Centre for Mesoscale Meteorology or JCMM) and Salford. The projects ranged from research on improved precipitation measurement using polarisation and vertical pointing radars, through network design of radar/raingauge networks and spatial-temporal modelling of rainfall fields, to rainfall forecasting based on stochastic and meteorological concepts. A final conference on HYREX, sponsored by the BHS, NERC and the Royal Meteorological Society, was convened on the 6 November 1996 at the Institution of Civil Engineers.

Monitoring facilities

The experiment was centred on the Brue catchment in Southwest England with a river gauging station at Lovington measuring flows draining from an area of 135 km^2. The common experimental infrastructure comprised two national network C-band radars at Wardon Hill (Doppler) and Cobbacombe Cross, a purpose-built dense raingauge network, an automatic weather station, an automatic soil water station, and the river gauging station. These instruments have provided a continuous record throughout HYREX, and data collection is still ongoing.

Further instrumentation, deployed on an occasional basis, included an experimental S-band Doppler dual polarisation radar at Chilbolton and an associated line network of rapid-response raingauges (operated by Rutherford Appleton Laboratory), a transportable vertically pointing X-band radar (operated by the University of Salford), the UK Meteorological Office (UKMO) Research Flight and radiosonde network, and a disdrometer (operated by the Institute of Hydrology). The JCMM provided output from special runs of the UKMO Unified Model (UM). Infrastructure support was provided by the UKMO, the Environment Agency, NERC, Rutherford Appleton Laboratory, the Ministry of Agriculture, Fisheries and Food and North West Water Ltd.

The occasional deployment of some instruments was scheduled to coincide with a number of one or two day Intense Observing Periods, triggered by meteorologically interesting conditions, during which radiosonde ascents and aircraft overflights were made, and for which special runs of the Unified Model were made.

The dense raingauge network

The dense raingauge network comprises 49 Cassella 0.2mm tipping bucket raingauges, each recording time of tip to a time resolution of 10 seconds. The network provides at least one raingauge in each of the 2km radar grid squares that lie entirely within the catchment. In addition, there are two parallel lines of greater gauge density extending SW to NE across the catchment, aligned with the prevailing wind direction and running from lowland to upland. Within each line there is one 2km grid square containing a super-dense sub-network of 8 raingauges arranged in a square-within-a-diamond configuration, with one sub-network in a lowland area and the other in an upland area.

Research using data within HYREX

The Institute of Hydrology was responsible for the quality control of the dense raingauge network as part of its project concerned with the accuracy of radar/raingauge networks. Disdrometer data were also used to gain a better understanding of how the raindrop size distribution affects the relation between radar reflectivity and rain-rate. The University of London consortium were also major users of the dense raingauge network in the context of carrying out basic statistical analyses of both raingauge and radar data. Their primary interest lay in the use of the network weather radar data for modelling the space-time structure of rainfall fields for hydrological design applications. The University of Newcastle employed both the dense raingauge data and network radar data for developing and evaluating a stochastic space-time rainfall forecasting system; they also used catchment flow data to develop a rainfall-runoff model for the catchment in order to convert forecasts of rain to flow. The University of Reading and Rutherford Appleton Laboratory were the primary users of the Chilbolton radar, aircraft flight and rapid-response raingauge data in their investigation of improved rainfall measurement using polarisation radar. Salford University focussed on the capture and analysis of the vertical pointing radar data and the prospect it offered for improved surface rainfall measurement, via corrections for the vertical reflectivity profile. The JCMM were the main users of radiosonde data for assimilation in the Unified Model for improved rainfall forecasting. The Institute of Hydrology, in collaboration with JCMM, were a major user of the UM output data along with multiscan network radar data in their development of a storm model for short-term rainfall forecasting.

The Future

Whilst formal funding for HYREX as a NERC Special Topic ended in April 1997 the Environment Agency will maintain the dense raingauge network over the Brue until the year 2000. Also MAFF are continuing to support IH's work on the quality control and data management of the HYREX archive, IH is funding the automatic weather and soil stations, and NERC Seedcorn funding has helped support Web access to the archive. A number of research projects continue to make much use of the HYREX dataset as reported in Section 3. A special issue of the journal "Hydrology and Earth System Sciences" reporting the results of HYREX is to be published in 1999.

Web Access

Further details of HYREX, including access to the dataset, are available via a web site located at NERC's British Atmospheric Data Centre with the address **http:/www.badc.rl.ac.uk/data/hyrex**.

5 INTERNATIONAL RESEARCH ACTIVITIES

The Met Office has been involved in a number of international programmes including COST-75 and the CEC-funded PADRE and DARTH projects, both co-ordinated by the University of Essex. Under PADRE and DARTH the Met Office has been investigating the operational benefits of new radar technology (of polarisation diversity and Doppler radar) to operations, and in partnership with the

University of Salford have been examining the impact of these data on hydrological flow forecast models. Proceedings of a 1994 COST-75 seminar were published as a CEC document, and Professor Collier and Dr Illingworth are preparing the final report of the COST-75 initiative. The initiative has been seen as successful in raising the profile of the UK weather radar network.

The EC Concerted Action RIBAMOD started and held its first Expert Meeting in Copenhagen in October 1996 and its first workshop in Delft in February 1997, both of which were attended by members of the Committee. At the Copenhagen meeting Mr Moore presented a keynote lecture reviewing EC-funded research on flood hazard over the last decade, with special reference to weather radar; Professor Cluckie reviewed the HYDROMET project he coordinated for the EU. The project had arisen in response to the Rhine-Meuse flooding but its scope extends to Mediterranean-style flash flooding and the need for radar. At a workshop/expert meeting of RIBAMOD in September 1997 at Monselice (Italy) Mr Moore presented work under HYREX on a water balance storm model using multi-scan radar and satellite data.

Also of some interest to weather radar is the COST-76 project on wind profiling which had its first meeting in May 1996.

Professor Holt and Mr Goddard became involved in EuroTRMM - the European contribution to TRMM which is concerned with space-borne monitoring of rainfall over the Tropics. The project is coordinated by Jacques Testud and involves ECWMF and the Max Planck Institute. Mr Goddard's involvement concerns the use of cross-polar/Doppler radar in Singapore, while Professor Holt's involvement concerns the modelling of volume scattering. Mr Goddard (RAL) provided Chilbolton radar data to the EU MEFFE Project.

6 STRATEGIC ISSUES IN UK RADAR HYDROLOGY

It is essential that quality control of radar estimates of rain-rate be established so that radar data can be used with confidence operationally for real-time flood forecasting.

Given that increased communication with the end-user community is essential if radar application is to realise its potential, then the Committee identifies as a key strategic issue the need to develop ways and means by which this might be accomplished.

The new NERC TFSTB Strategy includes hydrological science as a high priority "core science" area. In particular, it highlights "process hydrology focussed on the study of the land surface, including the urban environmental and sub surface factors which affect rates of precipitation, evaporation, infiltration, groundwater flow and runoff, and the quality of fresh water". The Committee recognises that accurate measurement of rainfall is a *sine qua non* underpinning this area of work and thus calls for further research on weather radar.

The Committee recognises that the Penning-Rowsell Report is under preparation and contains important information on science and user needs in relation to the use of weather radar in flood defence.

Since the last report of the Committee progress has been made towards a strategy for a National Weather Radar Data Archive. Improvements on access to historical radar data are eagerly awaited as part of an agreement between the Environment Agency and the Met. Office.

APPENDIX A

Constitution

The Committee comprises members appointed by the following supporting agencies:

Meteorological Office	- 1
MAFF	- 1
EA	- 1
NERC	- 1
CLRC	- 1
Scottish Office	- 1
Water UK	- 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 the NERC Institute of Hydrology.

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 MEMBERS

Current Members

Mr J M Tyson *(Chairman)*	Water UK
Mr J C Burns	Scottish Environment Protection Agency, West Region
Professor I D Cluckie *(co-opted)*	University of Bristol, Water Management Research Centre
Professor C G Collier *(co-opted)*	University of Salford, Department of Civil and Environmental Engineering
Mr R Austin (*Secretary* during reporting period)	Natural Environment research Council, Institute of Hydrology
Mr J W F Goddard	Central Laboratory for the Research Councils, Rutherford Appleton Laboratory
Mr J R Goudie	Ministry of Agriculture, Fisheries and Food, Flood and Coastal Defence with Emergencies Division
Mr C M Haggett	Environment Agency, Thames Region
Dr P J Hardaker	Meteorological Office
Professor A R Holt *(co-opted)*	University of Essex, Department of Mathematics
Dr A J Illingworth *(co-opted)*	University of Reading, Joint Centre for Mesoscale Meteorology
Mr R J Moore	Natural Environment Research Council, Institute of Hydrology
Dr G Shepherd	States of Jersey Public Services Department

Past Members

Dr J Caughy *(to 1995)*	Meteorological Office
Dr J Curran *(to October 1997)*	Scottish Environment Protection Agency
Mr R W Hatton *(to March 1996)*	National Rivers Authority, South West Region
Mr J Moore (*September 1995*)	Scottish Office, Environment Department
Mr R J Sargent *(to 1997)*	Scottish Environment Protection Agency
Dr P D Walsh (*Chairman to 1997*)	National Rivers Authority, North West Region

APPENDIX C COMMITTEE REPORTING LINES

Council for the Central Laboratory for the Research Councils

CCLRC representative (Dr J W F Goddard)
reports to
Head, RCRU (Dr K Craig)
reports to
Head, Applied Science Department (Dr H Price)
reports to
Chief Executive, CCLRC (Dr A Westwood)

Environment Agency

Representative (Mr C M Haggett)
reports to
National Flood Warning Strategic Board
reports to
National Flood Defence Managers Group
reports to
Director of Water Management (Dr G Mance)
reports to
Chief Executive (Mr E Gallagher)

Meteorological Office

Meteorological Office representative (Dr P Hardaker)
reports to
Director, Observations (Dr J Caughey)
who reports to
Chief Executive (P Ewins)

Ministry of Agriculture, Fisheries & Food

MAFF representative (Mr J R Goudie)
reports to
Chief Engineer, Flood and Coastal Defence with Emergencies Division (Mr R G Purnell)
and
Science Liaison Officer, Chief Scientist's Group (Dr J M Lock) through the
Deputy Science Liaison Officer, Chief Scientist's Group (Mr D R P Leonard)

Natural Environment Research Council

NERC representative (Mr R J Moore)
reports to
Director, Institute of Hydrology (Prof J S Wallace)
who reports to
Director, Centre for Ecology and Hydrology (Prof W B Wilkinson)
who reports to
Chief Executive, NERC (Prof J R Krebs)

Scottish Environment Protection Agency

SEPA representative (Mr J C Burns)
reports to
Regional Scientist (Dr A J N Haig)
reports to
Regional Director (Mr J Beveridge)
Reports to
Chief Executive (Mr A C Paton)

Water UK

Water UK's representative (Mr J Tyson)
reports to
Water UK Director of Water Services (Mr Graham Setterfield)
which contains a representative from each of
6 of the Water UK's plus Scotland and Northern Ireland
and reports to
Water UK Environmental and Quality Groups

APPENDIX D DIRECTORY OF UK EXPERTISE IN THE HYDROLOGICAL USE OF WEATHER RADAR

The contactee within each organisation is indicated with an asterisk. Research Students and Postgraduate Research Assistants are indicated by (RS) and (PGRA) respectively.

Higher Education Institutions

University of Bristol

Department of Civil Engineering
Water & Environmental Management Research Centre
Lunsford House
Cantocks Close, Bristol, BS8 1UP

*Professor Ian D Cluckie
Director Water & Environmental Management Research Centre

Dr Dawei Han
Radar hardware and software development; real time radar flood forecasting systems; development of radar data correction methodologies; use of hydroinformatics in radar hydrology.

Dr Richard J Griffith
Use of weather radar data in real time control of urban drainage systems and flood forecasting models; studies of vertical profile of reflectivity using vertically pointing radars; hydrological radar experiments.

Dr Andrew Lane
Real time weather radar data correction using a vertically pointing radar; Southern Alps Precipitation Experiment.

Ms Hong-Yan Jiang
Analysis of data from a high resolution urban radar system

Mr Liming Zang
Development of a dendritic river modelling system using radar data inputs

Mr Ziping Yang
Real time model parameter updating for radar flood forecasting

Ms Kathleen M Kozyniak
The development of coupled hydrological-meteorological models

Mr Regis Malinge
Radar data analysis and comparison with raingauge network data

University of Essex

Department of Mathematics
University of Essex
Colchester

*Professor A R Holt
Analysis and interpretation of polarisation-diversity and dual-wavelength radar data.

Dr C J Walden
Multiple scattering

Department of Electronics Systems Engineering

Dr D H O Bebbington
Polarimetry: modelling in radar meteorology

Imperial College

Environmental and Water Resource Engineering
Department of Civil Engineering
Imperial College of Science, Technology and Medicine
London
SW7 2BU

*Professor H S Wheater
Hydrological modelling and analysis; rainfall, surface water, soil water and groundwater systems.

Dr C Onof
Rainfall modelling, water resource systems analysis and stochastic hydrology.

Dr M J Lees
Real-time forecasting and control applied to floods, water resources and water quality management.

University of Lancaster

Centre for Research on Environmental Systems and statistics (CRES)
IEBS
Lancaster University
Bailrigg
Lancaster
LA1 4YQ

*Prof P C Young
Statistical identification and non-parametric/parametric estimation of novel nonlinear rainfall-flow and transfer function models for use in hydrological research and radar rainfall-flow forecasting systems.

Mr M E Lord (RS)
Real-time adaptive calibration of C-band weather radar data using the CRES/NRA Adaptive Radar Calibration (ARC) system developed at Lancaster University.

Mr J E Mann (RS)
Calibration of radar performance in severe convective storms; storm tracking; and short term forecasting of storm movement and growth.

Mr F C Tsang (RS)
Rainfall-flow modelling, flow routing and adaptive forecasting using conventional and radar rainfall measurements.

Dr J F R McIlveen
The use of weather radar in meteorological research.

Prof K J Beven
Hydrological implications of weather radar and the effects of uncertainty in hydrological models.

University of Newcastle-upon-Tyne

Department of Civil Engineering
University of Newcastle-upon-Tyne
Newcastle-upon-Tyne
NE1 7RU

*Professor P E O'Connell and Dr D Mellor
Spatial rainfall process modelling

Department of Engineering Mathematics

Dr A V Metcalfe
Spatial rainfall process modelling

University of Reading

University of Reading
Department of Meteorology
(Joint Centre for Mesoscale Meteorology)
Earley Gate
University of Reading
Reading RG6 6BB

Professor K A Browning
Mesoscale meteorological research; observational and modelling studies of the structure and mechanisms of precipitation-producing weather systems, including frontal and convective systems.

*Dr A J Illingworth
Radar measurements of rainfall; development of techniques to correct for vertical profiles of reflectivity, providing automatic self-calibration of reflectivity using consistency of polarisation variables, and correction for attenuation of radar reflectivity by heavy rain using polarisation techniques; radar measurements of cloud properties using mm wave radar.

University of Salford

Department of Civil and Environmental Engineering
University of Salford
Salford
M5 4WT

*Professor C G Collier
Environmental remote sensing. Hydrometeorology.

Dr R Barber
Engineering design; fluid flows.

Ms K Chester (RS)
Doppler infra-red lidar; air quality measurements; atmospheric flow near the ground
Mr N I Fox (PGRA)
Surface fluxes and rainfall estimation using satellite data.

Dr P J Hardaker
Visiting Fellow, Met. Office.

Ms J Reddaway (RS)
Rainfall forecasting using weather radar and numerical model data.

Dr K A Tilford
Weather radar; hydrological modelling.

Dr G W Shepherd
Visiting Fellow, States of Jersey.

University of Strathclyde

Department of Pure and Applied Physics
University of Strathclyde
John Anderson Building
107 Rottenrow
Glasgow G4 0NG

*Dr J Crowther
Application of radar to environmental physics

Agencies and private companies

Meteorological Office

Meteorological Office
Room B103
Beaufort Park
East Hampstead
Wokingham

Berkshire
RG40 3DN
http://www.meto.gov.uk/

*Dr P J Hardaker
Doppler and Polarisation radar development.

Mr M Kitchen & Ms D Harrison
Operational radar network software, central processing including European radar network, data quality control, radar data correction, operational FRONTIERS/NIMROD.

Mr W K Wheeler
Radar sites, hardware and software, COST-75.

Dr B Golding
Forecasting using radar data (Nimrod/Gandolf).

Mr W Hand
Artificial intelligence, life cycles.

Mr R Brown
Radar meteorology.

Mr E Archibald
Interpretation and use of Doppler radar data.

Ms M Clarke
Radar data sales.

Dr B J Conway
COST-78

Environment Agency

South Western Region
Environment Agency
Manley House
Kestrel Way
Sowton
Exeter
EX2 7LQ

*Ms L Aucott
General research and operations, particularly flood warning and forecasting

Mr G Boyce & Mr R Quinn
Flood forecasting

Thames Region
Environment Agency
Aspen House
Crossbrook Street
Waltham Cross
Hertfordshire EN8 8LX

*Mr C M Haggett
General research and operations, particularly flood warning and forecasting

North West Region
Environment Agency
PO Box 12
Richard Fairclough House
Knutsford Road
Warrington WA4 IHG.

*Mr J.M. Knowles
Applications of radar in real-time systems. Application of Gandolf system and Low Cost C-band radar techniques.

Mr I. H. Pearse
Applications of radar in real-time systems, orographic enhancement and recalibration. Application of Adaptive Radar Calibration (ARC) system, Vertical Pointing Radar (VPR) techniques and Low Cost C-band radar techniques.

Dr O. Wedgwood
Research background into the use of Radar with Expert Systems for forecasting rapid response catchments (University of Salford). Application of Adaptive Radar Calibration (ARC) system. Interests in radar, rainfall-runoff modelling, flood warning, return period estimation and artificial intelligence.

Anglian Region
Environment Agency
Kingfisher House
Goldhay Way
Orton Goldhay
Petersborough
PE2 5ZR

*Mr N Fawthrop, Mr J East, Mr S Dines & Ms J Stanton
General research and operations, particularly flood warning and forecasting.

Severn Trent Region
Environment Agency
Sapphire East
550 Streetsbrook Road
Solihull
B91 9QT

*Mr R Goodhew & Mr C Dobson
General research and operations, particularly flood warning and forecasting.

Northumbria and Yorkshire Region
Environment Agency
Rivers House
21 Park Square South
Leeds
LS1 2QG

Mr T Fewster, *Mr M Tinnion
General research and operations, particularly flood warning and forecasting.

Welsh Region
Environment Agency
Rivers House
Plas-yr-Afon
St Mellons Business Park
St Mellons
Cardiff
CF3 0LT

*Mr J C Mosedale
General research and operations, particularly flood warning and forecasting.

Southern Region
Environment Agency
Guildbourne House
Chatsworth Road
Worthing
West Sussex
BN11 1LD

*Mr O Pollard
Agency Project Manager responsible for the national R&D report on "Review of Radar Correction and Adjustment Techniques"

Scottish Environment Protection Agency (SEPA)

West Region
Rivers House
Irongray Road
Dunfries DG2 0JE

Mr J C Burns
Flood warning and forecasting

West Region
SEPA West
Redwood Crescent
Peel Park
East Kilbride

Mr M Becker
Flood warning and forecasting

East Region
42 Tay Street
Perth

Mr J Anderson
Flood warning and forecasting

East Region
Clearwater House
Heriot Watt Research Park
Avenue North
Riccarton
Edinburgh EH14 4AP

Mr I Fox
Flood warning and forecasting

Research Companies

HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA

*Dr R K Price
Application of weather radar to urban drainage management.

Water UK
1 Queen Anne's Gate
London
SW1H 9BT

*Mr G Setterfield
Application of radar data to urban drainage planning, design and control

Thames Water Utilities
Nugent House
Vastern Road
Reading
RG1 8DB

*Mr N E Martin
Application of radar data to urban stormwater management

Research Councils

Council for the Central Laboratories of the Research Councils

Rutherford Appleton Laboratory
Applied Science Department
Chilton
Didcot
Oxfordshire
OX11 0QX

Mr J W F Goddard*, Deputy Head, and Head of Radar Group
Hydrological Applications of Radar Polarisation Techniques

Mr J D Eastment, Chief Engineer
Polarisation Radar System Design and Construction

Dr J Tan
Theory of Particle Scattering, and polarisation techniques

Dr M Blackman
Radar data acquisition systems and rainfall estimation

Dr C A D Kilburn
Meteorological Radar Applications

Mr P Simpson
Radar Data Archiving and Calibration

Mr C Wrench
Cloud systems and radiometry

Engineering and Physical Science Research Council

Rutherford Appleton Laboratory
Space Science Department
Chilton
Didcot
Oxfordshire OX11 0QX

*Dr J Ballard
Space-borne radars.

Natural Environment Research Council

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxfordshire OX10 8BB

*Mr R J Moore
Radar calibration, rainfall and flow forecasting.

Dr V A Bell
Distributed flow forecasting using radar

Mr K B Black
Radar database management and display software

Mr D S Faulkner
Radar for flood design studies

Dr D A Jones
Radar calibration and rainfall forecasting

Mr D C W Marshall
Small catchment flood response times estimated using radar data

Dr D W Reed
Point and areal rainfall statistics using radar data

Mrs E J Stewart
Areal reduction factors and design storm specification from radar data

Earth Systems Science Centre
Natural Environment Research Council
Department of Geography
University of Reading
Whiteknights
PO Box 227
Reading RG6 2AB

*Dr I Astin
Space-borne cloud radar studies.

Government Departments

Ministry of Agriculture, Fisheries and Food
Flood and Coastal Defence with Emergencies Division

Eastbury House
30/34 Albert Embankment
London SE1 7TL

*Mr J R Goudie
Radar network policy and science administration.

Field Drainage Experimental Unit

Dr A D Muscutt
Small catchment flood response studies using radar data.

Scottish Office

The Scottish Office
Environment Department
27 Perth Street
Edinburgh EH3 5RB

*Mr J C Moore
Radar network policy and science administration.

States of Jersey Public Services Department

PO Box 412
South Hill
St Helier
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*Dr G Shepherd
Radar network policy and science administration. Development of urban applications.