Interagency Research Committee on the Hydrological Use of Weather Radar

Second Report

March 1993 - February 1995

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 Committees activities, which identifies a progressive, active, enthusiastic and expanding community of UK workers in weather radar. It has been especially pleasing to identify new and young workers and to welcome some of them to our workshop in Lancaster. The UK has also continued to play a leading role internationally, most particularly in Europe and through the World Meteorological Organisation.

The initiation by NERC of the HYREX Special Topic was welcomed in our last report and we have followed closely the substantial and innovative progress by the research groups. This committee has appreciated a close working relationship with the HYREX Steering Committee and welcomed its invitations to attend its workshops and site visits. This has allowed us to witness at first hand the cross fertilisation of different disciplines working on HYREX projects. In the past one strength of UK expertise has been joint work by meteorologists and hydrologists, but it is pleasing to find that this in now expanding to include many more disciplines. However, this will fragment at the end of the HYREX programme unless funding is forthcoming for further research and development.

I am also pleased to acknowledge the support of the professional institutions, in particular the British Hydrological Society, who arranged an open meeting in January 1995 for the benefit of the wider engineering and consultancy community. Many opportunities exist to explore applications in overseas projects. The committee continues to face a challenge in promoting to consultants the successful everyday use of weather radar by the Meteorological Office and National Rivers Authority.

At the invitation of the Inter Departmental Committee on Hydrology, we have prepared for them a statement on the scientific value of an archive of weather radar. We have emphasised the need for an archive to serve the hydrological community in earlier reports. This initiative and consideration of archiving in the strategic review of the network by Meteorological Office and NRA, are encouraging signs that the problem is now receiving serious attention.

I am leaving the NRA at the end of April and cannot therefore continue in my role as a member. It has been a privilege to serve as chairman and rewarding to see continuing progress within the UK radar community. I wish my successor, future members of the committee and all workers in the field well in their endeavours. I am confident that the UK will continue to play a leading role worldwide.

Dr Peter D. Walsh
Chairman

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1 INTRODUCTION

The Interagency Research Committee on the Hydrological Use of Weather Radar was established in 1991 and is the successor 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, and this second report carries this forward to February 1995.

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 such as the need for a national radar data archive (Section 6).

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, which are largely unchanged, 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 three times since it last reported, in November 1993, April 1994 and January 1995.

The routine business of the Committee has largely been occupied by reporting on HYREX, other research projects and general briefings on the activities of the agencies represented. Sections 3, 4 and 5 of this report describe the current status of these topics. Specific Committee activities and interactions with other groups are described below.

Changes in Membership

There have been few changes in membership and a significant number of members have served on this and the predecessor Committee for many years. Constitution of the Committee allows for up to four members (with at least two from Higher Education Institutions and/or Research Organisations) to be co-opted. Professor Cluckie from the University of Salford and Dr Illingworth from the University of Reading were both co-opted for a further term on the Committee. Dr Shepherd of the States of Jersey Public Services Department was again invited to attend the meetings as an observer. The Committee invited Professor Anthony Holt from the University of Essex and Mr Robert Sargent from the Forth River Purification Board to fill the remaining two places as co-optees. Dr David Llewellyn-Jones left the Committee in 1993, following his move from SERC to a University post. Following the reorganisation of the Research Councils, Dr John Ballard was invited to fill the vacancy for a nominee from the former SERC. He represents, initially, the Engineering and Physical Sciences Research Council and then, subsequent to further reorganisation, the Council for the Central Laboratory for Research Councils. Mr Brian Richardson from MAFF was replaced by Mr John Goudie, and in

January 1995 Mr Jonathan Moore replaced Dr Alastair Donald as the Scottish Office representative. Dr Walsh was persuaded to continue as Chairman for a second two year term.

Initiatives

The Committee had identified a growing number of new workers in the field and therefore decided to arrange an informal research workshop, which was held in Lancaster over 6-7 June 1994. This was the second such meeting associated with the Committee, being run along similar lines to that held at the inception of the Committee in October 1991. Attendance was by invitation.

The Committee was also aware that it was some years since there had been an open national meeting with the primary purpose of briefing the wider hydrological and water engineering communities on developments and applications. The Committee therefore approached the British Hydrological Society who, in association with Institution of Civil Engineers, held an open meeting on *Hydrological uses of weather radar* on 9th January 1995. Approximately 70 people attended, and the papers have been published as British Hydrological Society Occasional Paper No. 5.

First Report, and Priority Topics for Radar Hydrometeorological Research

Approximately 100 copies of the First Report have been circulated within the UK and overseas. The report included a list of priority topics, drawn up the Committee. Summaries of this list appeared in EOS 74(40), 5 October 1993, and the April 1994 issue of the WMO Bulletin, with a review of the report itself appearing in Circulation 39, August 1993.

Hydrological Radar Experiment (HYREX)

The NERC HYREX Special Topic, now in its third year, was an initiative of the predecessor committee and remains of particular interest to the Interagency Committee. Members have attended two HYREX meetings during the period of this report. The progress and status of research carried out under HYREX are reported separately in Section 4.

Bibliography on Hydrological Applications of Weather Radar in the United Kingdom

The first edition of this bibliography was produced in 1990 by the NERC committee, and has now been updated with publications notified up to the end of 1993. Copies may be obtained from the Committee Secretary (Roger Austin) at the Institute of Hydrology.

Report to the WMO 10th Commission for Hydrology

As noted in the First Report, Professor Collier is rapporteur for *Precipitation estimation and forecasting* under the *Working Group on Hydrological Forecasting and Applications for Water Management.* The Committee is supporting Professor Collier through direct contact with members, and by round-table discussion at Committee meetings.

WMO Regional Association VI (Europe), Hydrology Working Group

Mr R J Moore (as rapporteur and co-convenor) and Dr Peter Walsh attended a *Workshop on Requirements and Applications of Weather Radar Data in Hydrology and Water Resources,* held on 21-22 October 1993 in Toulouse as part of a 6 day meeting of the WMO Regional

Association VI. Dr Walsh presented a paper on *New Directions in Radar Hydrometeorology* based on the priority topics identified by the Committee in Appendix C of its First Report. The proceedings of the workshop and the report of the rapporteurs are due to be published by the World Meteorological Organisation.

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

The Meteorological Office and the National Rivers Authority have established a joint working group (to which three members of the Committee contribute) to undertake a strategic review of the UK Weather Radar Network for the next decade. At the group's first meeting, in September 1993, the views of the Committee were sought on a number of issues; in particular, data needs and archive requirements. The views of members were collated by the Chairman who prepared a report, inter-alia, restating Committee members' concerns about the lack of an adequate archive of weather radar data to meet the needs of the hydrological users and research community. The Committee is, therefore, pleased to note that the Working Group has established a sub-group to report on operational needs and costs of an archive (see also below and Section 6). The Committee have remained fully briefed on the work of the group.

Inter-Departmental Committee on Hydrology

The Chairman, Dr Walsh, was invited to represent the views of the Inter-Agency Committee at the December 1994 meeting of the Inter-Departmental Committee, in relation to their agenda item "The need for a national weather radar archive and methods for its promotion." This lead to a request for the Inter-Agency Committee to prepare a statement on the scientific value of an archive which will form part of a wider scoping document to be considered at the next Inter-Departmental meeting. A brief summary of this statement is reproduced in Section 6

3 REPORTS FROM UK RESEARCH GROUPS

Research at the **University of Essex** is currently mainly centring on the EU funded PADRE project which initially was investigating Polarisation and Doppler data at C-band from Germany and Italy, but has since been extended to include dual-wavelength radars in Romania and Slovakia. Heavy rain has been clearly identified in horizontal/vertical polarisation from the severe effect that differential attenuation has on differential reflectivity. Circular and slant (linear ±45) polarisation gives a much stronger depolarisation signal (e.g. melting band or ice region) than does linear.

Continuing research on data from Alberta is focusing on hail recognition, and is being extended to clutter removal.

A joint research programme is being undertaken between Professor H S Wheater and Dr C Onof, **Imperial College**, Professor V Isham, **University College London**, and Professor Sir David Cox, **Nuffield College, Oxford**. The programme involves spatial rainfall modelling and analysis based on the NERC HYREX radar and dense raingauge network in SW England, supplemented by other radar data from the UK and USA. Progress is reported under HYREX, Section 4.

Research at the **Institute of Hydrology**, in addition to that done under HYREX, has concerned the development of a new distributed flood forecasting model and the evaluation of Frontiers and Local Radar Rainfall forecasts in a flood forecasting context. The former was reported as NRA R&D Note 252 entitled "Development of distributed flood forecasting models using weather radar and digital terrain data". A practical model for real-time flood forecasting was developed, called the IH Grid Model, whose distributed formulation is supported by a digital terrain model which allows the number of model parameters to be small. The model is configured on a grid coincident to that used by the weather radar so that maximum use of weather radar data can be made. Results suggest that in many situations a lumped rainfall-runoff model may prove more reliable for flood forecasting but, depending on the relative scales of catchment and storm system, use of a distributed model may prove of benefit.

The second study was reported as NRA R&D Note 225 "Evaluation of Frontiers and Local Radar Rainfall Forecasts for use in Flood Forecasting Models". Best performance overall was obtained using the IH locally calibrated and forecast rainfalls as input to rainfall-runoff models, although the improvement was not significant except for the smaller catchments. The PDM rainfall-runoff model proved best overall, although the simpler and more complex models considered also had merit depending on the complexity of the catchment response.

At a more operational level IH in 1994 completed the development of the HYRAD (HYdrological RADar) system, which integrates its radar preprocessing, gauge adjustment and rainfall forecasting algorithms with a Windows 3.1 PC radar display system supporting the rapid replay of radar images. The system has an interface to the River Flow Forecasting System, supplying it with catchment average rainfalls (including forecasts). HYRAD is now used routinely by the NRA in support of flood warning of Yorkshire rivers.

Most recently IH has undertaken for MAFF a strategic review of R&D needs for flood forecasting and this is available as the report "Strategic Research and Development Needs and Opportunities for Real-time Flood Forecasting, Warning and Control".

The **Water Resources Research Group** at the **University of Lancaster** are developing an improved Adaptive Radar Calibration (ARC) System for C-band weather radar, on behalf of the National Rivers Authority, Severn Trent Region. Results show that ARC is much superior to the present raingauge calibration procedure, particularly during bright-band situations. A real-time, on-line version of the ARC system is being developed under contract with the NRA, North West Region. Associated methodological research is concentrating on further improving both the short term prediction of the calibration parameter variations and the spatial interpolation of the calibration parameters over the radar field.

The ARC system has been applied to provide rainfall estimates for river flow modelling on the River Ribble. Analysis shows that these produce better flow forecasts than those derived from the MO calibrated radar data; and the results are comparable with those obtained using raingauge data.

The group have also carried out detailed analysis and modelling of convective storms using conventional C-Band weather radar and a cloud-based, thermodynamic, micro-physical model, as part of the European Programme on Climatology and Climate Hazards. A subsequent project for the CEC Environment Programme is investigating the use of C-band weather radar for convective storm cell identification, tracking and short term forecasting. Results suggest that the model might well be useful as a tool to investigate the storm climatology at a given locality in a variety of meteorological situations.

The radar meteorology group at the **Meteorological Office** have developed a physically-based radar correction scheme for the Nimrod short-period rainfall forecasting system. It is designed to correct for the effects of the bright band, orographic growth and range. A modified version is recently under test which makes use of data from several beam elevations to improve correction at long range. Future plans include a switch from climatologically-based orographic corrections to the use of a diagnostic model run in real-time. A gauge adjustment scheme has also been tested which complements these corrections. Data from the Doppler radars at Clee Hill and Cobbacombe Cross are being evaluated, firstly to determine the accuracy of the radial wind data and then to establish the utility of these data in a mesoscale numerical forecast model.

METSTAR (a commercial research and development group within the Met Office) are engaged in a number of studies related to advanced radar measurements, precipitation forecasting, and Probable Maximum Precipitation.

Several studies are being undertaken with funding support from the CEC as part of the Polarisation And Doppler Radar Experiment (PADRE), and COST-75 to assess the benefits of polarisation and Doppler radar to providing short-period forecasting, particularly in convective precipitation. Detailed work on comparing the different features of linear vertical and horizontal, slantwise and circular polarisation is being undertaken, with an emphasis on providing guidance for operational systems. Further analysis includes the study of the amplitude and phase of the complex correlation term as a means of providing information about meteorological development in order to improve rainfall forecasts. In addition to using polarisation methods to identify precipitation type, a method has been developed to separate the effects of rain and hail using single polarisation data in combination with infra-red satellite information.

Doppler data are further being analysed to assess their potential to improve precipitation forecasts. New studies are considering the possibility of deriving large scale forcing meteorological parameters from the spectral with measurements in order to help in identifying new areas of precipitation development. In the longer term this information may also provide improved parameterisations for Numerical Weather Prediction (NWP) models.

A thunderstorm and deep convection forecasting system, specifically targeted at contributing to flash flood warning, is being developed initially for the NRA, although it has applications to other organisations. The system builds upon an object-oriented, conceptual model approach. Procedures to select the most appropriate forecasting system at any time are being tested. The aim is to test the prototype system during 1995.

Studies of the contribution radar data may make to storm Probable Maximum Precipitation (PMP) and extreme value analysis are under way. Radar derived information has been used with a simple model of convection to estimate PMP. The work has highlighted the importance of Mesoscale Convective Systems in assessing design rainfall for storms of duration between 11 and 24 hours.

The **NERC Unit for Thematic Studies** will be using weather radar data for sensitivity studies as part of a project for ESA on a proposed space-borne cloud radar. The study focuses on two aspects, one on sampling characteristics of the radar as effected by changes in, for instance, radar pulse repetition frequency, beam scanning or orbit parameters and the other on detection of radiatively important clouds. Weather radar data will be used to assess how different cloud types, insects and partial beam filling would effect radar returns as observed by a satellite based radar. It is proposed that the cloud radar may have a Doppler capability and again the weather radar data will be useful to the study. They will also be developing a 3-D cloud model from

satellite images to test how accurately monthly mean cloud coverage can be recovered by satellite, and weather radar data will be assimilated into this model.

Several projects involving the space-time modelling of rainfall and the use of radar data have been ongoing at the **Water Resource Systems Research Unit (WRSRU), University of Newcastle**, during the reporting period. The Modified Turning Bands (MTB) model, which was developed during the previous reporting period, has been used to generate rainfall fields over the Reno basin (4000 km^2) in Italy which have been used in conjunction with the SHETRAN distributed modelling system to assess the relationship between raingauge network density in the basin and forecasted runoff. This work has been carried out within the framework of an EC funded real-time forecasting project involving several European partners (AFORISM). The results obtained from a simulated ensemble of MTB storms suggest that, while a telemetering raingauge network with a density of about 1 gauge/50 km^2 could sample the rainfall field adequately for most storms, there were a small number of storms where significant errors in runoff forecasts were observed apparently due to inadequate sampling of the rainfall field. The reasons for these errors will be investigated further.

A stochastic rainfall forecasting system based on the MTB model is being developed within the framework of the HYREX project (Section 4).

A PhD project initiated during the previous reporting period has now been completed. A number of algorithms for forecasting rainfall inputs to flood forecasting models have been developed and their performance assessed. A transfer function algorithm with auxiliary inputs based on rain cell and rain band features advected with their respective velocities and a variable describing the growth/decay of the rain field has been found to give satisfactory results.

Further research has involved the development of a new generalized spatial-temporal model based on a clustered point process. This allows the modelling of multi-site rainfall with multiple cell types. The work is being undertaken as part of an EC funded project on the generation of precipitation scenarios for climate impact assessment.

The **National Rivers Authority** has commissioned research into best practice in the use of weather radar and a review of cost-benefit assessment and is supporting or sole sponsor of work reported in this section. It continues to develop the use radar in real-time flood forecasting systems. NRA regions apply weather radar data directly in several of its real-time forecasting systems. All regions display radar products in their flood forecasting or control rooms. The variety of products ranges from single site images to composite FRONTIERS forecasts for six hours ahead.

At the **University of Reading, Joint Centre for Mesoscale Meteorology (JCMM)**, forecast and analysis products from the mesoscale and limited-area versions of the Met. Office Model have been used together with radar data, satellite imagery and occasionally, special observations from the Met. Research Flight C-130 aircraft, to derive improved understanding of the structure and dynamics of precipitation-producing weather systems. A series of papers has been published in the Quarterly Journal of the Royal Meteorological Society and elsewhere.

The JCMM group are also involved in two HYREX projects, one with the Institute of Hydrology and the other with the **Rutherford-Appleton Laboratory Radio Communications Research Unit**.

The **Rutherford-Appleton Laboratory Space Science Department** has an activity which is directed toward development of radar systems for atmospheric science applications, particularly from space platforms. A frequency modulated radar has been built and deployed at Chilbolton and is being used in studies of attenuation by rain. Data from this system are currently being evaluated.

Research related to the hydrological use of weather radar at the **University of Salford** is undertaken within the Telford Institute for Environmental Systems by the **Water Resources Research Group (WRRg)**. The WRRg continues to expand its work in this area and comprises 3 full-time staff, 1 visiting professor, 2 visiting fellows, 1 post doctoral research fellow, 3 post graduate research assistants, and 12 research students. The group continues to foster and develop national and international links: the Hydrological Radar Experiment (HYREX) in particular has provided the opportunity for extensive collaboration in the UK; the group is an active member of the European Weather Radar Group collaborating with a number of member Institutions; and the close relationship with the Universities of Auckland, New Zealand and McGill, Canada continues to develop.

The main research areas related to radar hydrology are:

improving the quality of scanning radar rainfall data;
new techniques for river flow modelling;
real-time flood warning and decision support systems;
modelling and control of urban drainage systems (UDS);
the application of neural networks and genetic algorithms to hydrological modelling.

The group operates three X-band Vertically Pointing Radars (VPR) (two of which are mobile) and a prototype low cost C-band scanning radar (MARS - Multiple Attribute Radar System). Data from the VPRs are being used to support wide ranging studies including research into orographic rainfall processes, the spatially variability of the vertical reflectivity profile, and the development of an automatic bright band correction algorithm for real-time use with operational scanning weather radars.

Considerable attention is focusing on the modelling and control of UDS, and the MARS radar system is one part of what is intended to be a turnkey system for urban hydrology. Ongoing research is attempting to develop real-time UDS models which effectively utilise the high spatial and temporal resolution data (250 m, 5 minutes) provided by radar data. In addition algorithms for the on-line management and real-time active control UDS are being investigated. The work is focusing on urban systems on north-west England.

The research group possesses considerable experience in the development of real-time flood forecasting models for use with weather radar data for rural catchments. This work is continuing with the development of a dendritic model for the Bristol Avon river system. The model will be incorporated into the real-time WRRg Weather Radar Information Processor (WRIP) forecasting system. Recent modelling developments include the physically realistic transfer function (PRTF) - a model combining the advantages of the transfer-function approach with improved stability and response. The PRTF model is undergoing further refinement and testing.

Doctoral research projects into real-time drought management techniques, probable maximin flood studies, a water quality balance of the Irish Sea, and the development of a flash flood expert system have all recently reached fruition.

Thames Water Utilities have a commitment to use 2 km Type 2 radar data for urban storm water management. They have undertaken some study work to understand the performance of the radar data and will now be using this data.

4 HYREX

The HYdrological Radar EXperiment (HYREX) was initiated by members of the NERC Committee which preceded the Interagency Committee. The aim of HYREX is to undertake fundamental research in two main areas. First, the science of weather radar as a remote sensing device, and second, investigation of the precipitation process and its link with runoff response. The former involves the study of radar systems with different capabilities using various wavelengths and Doppler or dual polarisation facilities. The latter should achieve a better understanding of the structure of rainfall and other precipitation processes, as revealed by weather radar measurements, and will in turn support an improved understanding of runoff response at a range of scales in space and time.

The focus of the experiment is the Brue catchment in southern England, where use is being made of data from the Wardon Hill and Cobbacombe C-band network weather radars and the experimental S-band radar situated at Chilbolton. In addition, some projects involve work in other areas of the country, for example the study of orographic intensification in north-west England.

HYREX started in April 1993, supported by an allocation of £750,000 from NERC under its Special Topic scheme, with additional funds for capital infrastructure provided by other agencies. The NRA have established and are maintaining a dense raingauge network in the Brue catchment, and MAFF have provided funds towards setting-up of a database to hold the hydrometeorological data to serve the HYREX community. The Meteorological Office are providing radar data, radiosonde ascents, flights of its C-130 aircraft, and mesoscale model case studies. North West Water Ltd are providing data from the C-band and vertically pointing X-band radars developed jointly by the Water Resources Research Group at the University of Salford and the McGill Weather Radar Observatory.

The Steering Committee of the HYREX Special Topic Programme includes five members of the Interagency committee, and has held meetings on 9 July 1992, 4 November 1992, 7 April 1993 and 30 September 1994. At the second of these, thirteen project applications were discussed and six proposals recommended for funding, covering five of the six key research areas originally identified in the objectives of the HYREX Programme (a list of awards is given in Appendix E of the First Report). Research workshops have been held on 7-8 April 1993 at Shaftesbury and 29-30 September 1994 at Limpley Stoke near Bath. A third workshop will take place at IH, Wallingford on 20-21 April 1995, and the Royal Meteorological Society are to hold an open meeting about HYREX on 26 April 1995.

The experimental infrastructure for HYREX is now firmly established. Design of the dense raingauge network was addressed by the initial stages of the IH project "Design of radar/raingauge networks for hydrological use". A new statistical method for choosing the location for an optimal configuration of raingauges, within a square coincident with that used by weather radar, has been developed. The final design comprised 22 gauges at the centre of each 2 km radar grid square, two SW-NE lines of four squares each containing two gauges and two dense networks with 8 gauges per square in areas of low and high relief. Installation of the

raingauges over the 132 km^2 catchment of the Brue, gauged at Lovington, occurred between September and December 1993. The site work was undertaken by Allwater Technology supported by NRA funding. Additional instrumentation has been incorporated at the Bridge Farm Orchard site, near the centre of the 8 gauge network with low relief. This includes an automatic weather station from the NERC equipment pool, modified to record atmospheric pressure at 15 minute intervals, an IH Beta-test Soil Moisture Station (capacitance probes, tensiometers, soil temperatures at three depths, and rainfall) and an optical disdrometer for measuring raindrop spectra and inferring radar reflectivity - rain rate relations. Data for Wardon Hill and Cobbacombe Cross radars have been incorporated in the HYREX Archive at IH since September 1993 and February 1994 respectively. Software has been written for the quality control and preliminary analysis of these data, and provision has been made for the HYREX community to access the HYREX Archive via the academic community computer network. The group at the Joint Centre for Mesoscale Modelling, University of Reading, are responsible for the management of Intense Observing Periods (IOPs), corresponding to heavy rain events, during which 3 hour radiosonde ascents are made at 5 Met Office sites across southern England together with ascents from Bridge Farm Orchard in the Brue.

Ongoing work within the network design project concerns the use of data from the dense raingauge network to obtain empirical measures of accuracy, not based on spatial correlation functions, which will allow the dependence of rainfall estimation accuracy on rainfall magnitude to be investigated.

The HYREX joint project between the Joint Centre for Mesoscale Modelling, University of Reading and the Institute of Hydrology concerns "Methods for short-period precipitation and flow forecasting incorporating radar data". Work at Reading focuses on the use of the Mesoscale Model and moisture data analyses to support understanding of precipitation processes at the mesoscale. This mesoscale understanding and data will be used to support progress on a high resolution rainfall model under development at IH. The latter is a two-dimensional rainfall forecasting model based on the conservation of mass in a cloud column, extending a model originally developed at the University of Iowa, using weather radar to infer moisture content and storm velocity, together with surface climate observations and Meteosat-derived estimates of cloud top temperature. Plans for future work include the incorporation of the Mesoscale Model output into the high resolution model formulation.

A joint research programme on "Spatial-temporal rainfall fields: modelling and statistical aspects" is being undertaken between Professor H S Wheater and Dr C Onof (Imperial College), Professor V Isham (University College London), and Professor Sir David Cox (Nuffield College, Oxford). The programme involves spatial rainfall modelling and analysis based on HYREX and other data. Spatial-temporal models have been developed based on Poisson cluster processes to reproduce radar-rainfall images. Current work is addressing parameter identifiability using spectral analysis. Multi-variate models are being extended theoretically and applied in conjunction with general statistical analysis of the 53 raingauge Brue network. In parallel, spatial fields are being analyzed to support improved methods of desegregation of grid-square rainfall for application in GCM's and other meteorological models.

The HYREX joint project between the Joint Centre for Mesoscale Modelling, University of Reading and the Radio Communications Research Unit, Rutherford-Appleton Laboratory, is concerned with "Verification of polarisation radar techniques for improving estimates of rainfall". The Chilbolton S-Band radar is being used to measure reflectivity, differential reflectivity, linear depolarisation ratio (LDR), mean Doppler and differential phase. Measurements and inferred rain rates are compared with observations from i) a line of rapid-

response raingauges close to the radar; ii) gauges over the Brue catchment; iii) in situ particle measurements from C-130 aircraft. Preliminary results suggest that LDR may be used to recognise bright-band, and so correct for the vertical profile of reflectivity; that a combination of LDR and Doppler is better for identifying ground clutter than either in isolation; and that differential reflectivity is advantageous for high rain rates and differential phase for the highest rain rates, particularly if hail is present.

The HYREX project under way at the Water Resource Systems Research Unit (WRSRU), University of Newcastle, is concerned with "The development of a stochastic space-time rainfall forecasting system for real-time flow forecasting". A system based on the Modified Turning Bands (MTB) model is being developed and optimized with respect to forecasted runoff. Techniques for conditionally fitting the MTB model to (a) raingauge data and (b) radar data have been developed, such that the model can be run forward in time to generate multiple scenarios of possible future rainfall through Monte Carlo sampling of the rain field evolution in time and space. A sophisticated UNIX-based software system has been developed for this purpose which combines subjective and objective elements in fitting the MTB model to radar images. The next phase of the work will involve assessing the spatial scales over which rainfall inputs to a flood forecasting model can be averaged without degrading the quality of the runoff forecasts.

The Water Resources Research Group at the University of Salford are conducting a research project on "Radar hydrometeorology using a vertically pointing radar". The project aims to study the hydrometeorology of rainfall systems in orographic and non-orographic regions, and to examine the problems of bright band contamination of quantitative measurements from scanning weather radars, using high resolution X-band Vertically Pointing Radars (VPRs). It includes a programme of transect experiments to investigate orographic enhancement over the Pennines, and the deployment of mobile VPRs near Chilbolton and in the Brue catchment. A new mobile VPR has been built for HYREX, in addition to the existing mobile and the static VPR located at Salford. Results from static transect experiments have established the experimental and theoretical basis required for the more elaborate experiments. Methods for analysing vertical reflectivity profiles continue to be developed and will be used to improve the performance of the automatic bright band recognition algorithm and to implement VPR-based techniques for real time adjustment of scanning radar measurements.

5 INTERNATIONAL RESEARCH ACTIVITIES

The CEC project AFORISM (A Comprehensive Forecasting System for Flood Risk Mitigation and Control) under the EPOCH programme ended in 1994. The AFORISM group, which includes members from Italy, the Republic of Ireland, Greece, Portugal, France, Switzerland and the UK (University of Newcastle-Upon-Tyne) are producing a final report, one objective of which is to report back to European authorities with responsibility for flood forecasting and warning.

The CEC Project "Weather Radar and Storm and Flood Hazard" under the EPOCH Programme ended its two year duration at the end of 1992. A Final Report on the project is available from the Coordinator, Mr R J Moore at the Institute of Hydrology. The work was undertaken by a seven country consortium from Italy, France, Portugal, Germany, The Netherlands, Greece and the UK; representation from the UK included IH and the universities of Salford, Lancaster and UMIST (now transferred to Reading). The themes addressed covered the use of radar for rainfall

measurement and forecasting, flood warning and control and storm hazard assessment. It convened Specialist Workshops on "Rainfall Physics for Radar Studies" at the Institut de Mechanique de Grenoble, France on 14-15 April 1992 and on "Rainfall Estimation and Forecasting using Weather Radar" at the National Technical University of Athens, Greece on 25-26 June 1992; a Final Seminar on the project was held at IH, Wallingford on 15 March 1993.

The same consortium are now engaged with the CEC Project "Storms, Floods and Radar Hydrology", under the Environment Programme, which began in January 1993 and is to end in June 1995. This project extended the work of the previous project under the EPOCH Programme and initiated a number of new themes, including the development of new simulation schemes for radar rainfall measurement, the use of vertical pointing radar to identify and correct for bright band and the testing of conceptual cloud-based rainfall forecasting methods. The partners in the CEC Radar Hydrology Group expanded with this project to include representation from UPC, Barcelona, Spain and the University of Ljubljana, Slovenia. The Final Report is scheduled for release in August 1995 and a final meeting of the project is to be convened in Jersey on 3-4 April 1995, hosted by Dr G. Shepherd of the Interagency Committee. The Project organised the following Specialist Workshops: "Physics of Radar Rainfall Measurement and Forecasting", Universitat Politecnica de Catalunya, Barcelona, Spain, 1-3 June 1993; "Integrating Radar Estimates of Rainfall in Real-time Flood Forecasting", Monselice, Italy, 25-26 July 1994; and "Rainfall Measurement and Real-time Control in Urban Areas", Essen-Kettwig, Germany, 26-28 September 1994.

The consortium's first project - "Use of Weather Radar for the Alleviation of Climatic Hazard" - had been undertaken within the CEC Climatology and Natural Hazards Research Programme, To mark the close of this project an International Workshop was held in Lisbon, Portugal on 11-13 November 1991. The proceedings of this Workshop have now been published by the European Commission, in 1994, as the book "Advances in Radar Hydrology" with M E Almeida-Teixeira, R Fantechi, R Moore and V M Silva as editors.

The COST-75 project is considering future specifications for radar systems, with an emphasis on technology and algorithms. The recent meeting held on 20-23 September 1994 in Brussels was very busy, attracting around 60 papers and 130 attendees, with a strong UK contribution. New techniques were presented for both novel and conventional radars. The meeting dealt mainly with technology (producers) rather than applications (users), providing a look at the state of the art and pointing various ways forward. Proceedings have now gone to the publishers (Kluwer). A COST-75 workshop on *Improved Rainfall Estimation using Polarisation-Diversity Radar* will be held on 3-4 July 1995 at the University of Reading.

The COST-78 project was established in March 1994 to encourage European cooperation on the development of meteorological nowcasting techniques, with the overall aim of improving nowcasting services to users. Weather radar is an an important source of data for such applications.

The CEC-funded Polarisation and Doppler Radar Experiment (PADRE) started in January 1993. This was initially investigating Polarisation and Doppler data at C-band from Germany and Italy, but has since been extended to include dual-wavelength radars in Romania and Slovakia. The University of Essex are the UK partner, as mentioned in Section 3 above. The closing workshop is scheduled for 16/17 March 1995 in Bucharest.

A number of UK researchers on weather radar participated in the Fourth International Conference on Precipitation, held in Iowa in 1993. The conference is reported in the December 1994 special issue of the Journal of Applied Meteorology.

A workshop on *Rainfall Estimation and Forecasting by Radar and Satellite* was held at the European Geophysical Society General Assembly in Grenoble on 25-29 April 1994. Mr R J Moore acted as co-convenor.

Members of the Interagency Committee were involved in the planning and organisation of the *Second International Symposium on Hydrological Applications of Weather Radar* held at the University of Hannover, Germany from 7-10 September 1992. The Third Symposium will be held on 20-24 August 1995 in Sao Paolo, Brazil.

6 STRATEGIC ISSUES IN UK RADAR HYDROLOGY

The Scientific Value and Requirements of a National Weather Radar Data Archive

Archive data has applications in (inter-alia):

1. Rainfall-runoff modelling
2. Assessment of extreme rainfall
3. Urban stormwater drainage
4. Storm models
5. Climate change studies

Data requirements for such applications are for continuous records of long duration, with high spatial and temporal resolution. Scientific research needs, in addition, access to raw polar data and histories of changes to radar systems and data processing algorithms.

The MAFF Advisory Committee on Flood and Coastal Defence Research and Development assigned a high priority to development of an archive. The Meteorological Office has, following improvements in storage media, revoked a policy of archiving only "meteorologically interesting" events. The committee is pleased to note this development and that the Meteorological Office appears to have accepted the arguments for a continuous long-term archive. The committee await with interest the results of the Met. Office/NRA strategic study and further recommendations for a definite archive policy.

Future R&D Activities

HYREX projects are of limited duration and have demonstrated their value as interdisciplinary projects. A recent meeting of The Royal Meteorological Society was devoted to papers on this work. Speakers previously unaware of HYREX made many favourable comments and expressed interest in applying the findings to other investigations.

The NERC Committee's Review of Research Opportunities identified many additional topics for research. To maintain the impetus created by HYREX urgent consideration should be given to making future research funding available by those agencies with R&D duties.

APPENDIX A

Constitution

The Committee is constituted of members appointed by the following supporting agencies:

Meteorological Office	- 1
MAFF	- 1
NRA	- 2
NERC	- 1
EPSRC	- 1
Scottish Office	- 1
Water Services Association	- 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

Members

Dr P D Walsh *(Chairman)*	National Rivers Authority North West Region
Dr J Ballard *(from Jan 1995)*	Engineering and Physical Science Research Council Rutherford-Appleton Laboratory
Professor C G Collier	Meteorological Office
Dr A Donald *(to Jan 1995)*	Scottish Office Environment Department
Mr J R Goudie	Ministry of Agriculture, Fisheries and Food Flood Defence Division
Mr R W Hatton	National Rivers Authority South West Region
Mr J Moore *(from Jan 1995)*	Scottish Office Environment Department
Mr R J Moore	Natural Environment Research Council Institute of Hydrology
Mr J M Tyson	Water Services Association North West Water Ltd
Mr R M Austin *(Secretary)*	Natural Environment Research Council Institute of Hydrology

Coopted members

Professor I D Cluckie	University of Salford Department of Civil Engineering
Professor A R Holt	University of Essex Department of Mathematics
Dr A J Illingworth	University of Reading Joint Centre for Mesoscale Meteorology
Mr R J Sargent	Forth River Purification Board

Observers

Dr G Shepherd	States of Jersey Public Services Department

APPENDIX C COMMITTEE REPORTING LINES

Engineering and Physical Sciences Research Council

EPSRC representative (Dr J Ballard)
reports to
Head, Space Science Department (Prof A M Cruise)
who reports to
Head, Rutherford Appleton Laboratory (Dr T G Walker)
who reports to
Head, Daresbury and Rutherford Appleton Laboratories (Dr P R Williams)

Meteorological Office

Meteorological Office representative (Prof C G Collier)
reports to
Director, Observations (J M Nicholls)
who reports to
Deputy Chief Executive (Dr P Ryder)

Ministry of Agriculture, Fisheries & Food

MAFF representative (Mr J R Goudie)
reports to
Principal Engineer, Flood and Coastal Defence Division (Mr B D Richardson)
who reports to
Chief Engineer, Flood and Coastal Defence Division (Mr R G Purnell)
and
Science Liaison Officer, Science Division (Dr M Dwyer)

National Rivers Authority

National Rivers Authority representative (Mr R W Hatton)
reports to
Technical Director (Dr C Swinnerton)
and to
Flood Defence Research Commissioner (Mr B Empson)
who reports to
Flood Defence Managers' Committee

Natural Environment Research Council

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

Scottish Office

Scottish Office representative (Mr J Moore)
reports to
Chief Engineer, Engineering, Water and Waste Directorate (Mr A C Paton)
and
Association of Directors and River Inspectors of Scotland.

Water Services Association

WSA representative (Mr J Tyson)
reports to
WSA Waste Water Group (Secretary, Mr Ted Thairs)
which contains a representative from each of
6 of the WSCs plus Scotland and Northern Ireland
and reports to
WSA 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.

Higher Education Institutions

University of Bristol

Department of Geography
University of Bristol
University Road
Bristol BS8 1SS

*Professor E C Barrett	General use of weather radar as calibration/validation data for satellite rainfall estimation.
Dr C Kidd	Development of rainfall climatologies, and investigations of sources of errors in radar data.
Dr D Kniveton	Use of radar for cal/val studies of glosal rainfall using the DMSP - SSM/1.
Dr S Nativi	Development of techniques for analysis and interpretation of weather radar data.
Dr M Todd	Combining radar and satellite (VIS,IR and MW) data for synoptic analysis and rainfall estimation over north-west Europe.

University of Edinburgh

Department of Meteorology
University of Edinburgh
James Clerk Maxwell Building
The King's Buildings
Mayfield Road
Edinburgh
EH9 3JZ

*Dr K J Weston	Orographic enhancement of rainfall.

University of Essex

Department of Mathematics
University of Essex
Colchester

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

Department of Electronics Systems Engineering

Dr D H O Bebbington

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.

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	)	Spatial rainfall process modelling
D Mellor (RS)	)	

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)
2 Earley Gate
Whiteknights
PO Box 239
Reading
Berkshire RG6 1AI

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

University of Salford

Department of Civil Engineering
University of Salford
Salford
M5 4WT

*Professor I D Cluckie		
Dr B Barber		
Dr K A Tilford		
Dr D Han		Low cost "C" band radar for urban hydrology. Vertical pointing X-band radar.
Mr A Abes	(RS)	Active control of urban drainage systems using weather radar.
Ms Xiyi Chen	(RS)	Rainfall forecasting using weather radar data.
Mr R Griffith	(RGRA)	Engineering development of an urban flash flood expert system.
Mr Hajjam	(RS)	Radar hydrology and flood producing storms.

Ms H Y Jiang	(RS)	Modelling of wastewater treatment processes using weather radar data.
Mr A Lane	(RS)	Investigation of orographic modelling using vertically-pointing radar data.
Dr R Norreys	(PDRF)	Water quality river impact model for river basin management. Real-time radar-based large-scale urban pipe network model.
Ms S Towers	(RS)	Vertical reflectivity profiles and real-time calibration of scanning hydrological radars.
Mr N Travers	(RS)	Development of a real-time, fully distributed rainfall-runoff model for use with weather radar data.
Mr F Wang	(RS)	Development of a real-time control system for urban drainage systems using fuzzy control and weather radar data.
Mr A Wild	(RS)	Macro scale hydrological process modelling using remotely sensed data.
M J Yuan	(PGRA)	The hydrological use of weather radar data for design and rehabilitation of urban drainage systems.
Mr L Zhang	(PGRA)	Development of dendritic real-time river basin model.

Professor C G Collier	Visiting Professor, Meteorological Office.
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

Agencies and private companies

Meteorological Office

Meteorological Office
Room G26, London Road
Bracknell
Berkshire
RG12 2SZ

*Professor C G Collier	Use of radar in Hydrometeorology, GANDOLF, COST-75.
Dr P K James	Operational radar network software, central processing including European radar network, operational FRONTIERS/NIMROD.
W K Wheeler	Radar sites, hardware and software, COST-75.
Dr B Golding	Forecasting using radar data (Nimrod), data quality control.
Dr B J Conway/W Hand	Artificial intelligence, COST-78, automation.
R Brown	Radar meteorology.
M Kitchen	Radar data correction.
Dr P J Hardaker	Doppler and Polarisation radar product development, PADRE.
Ms C Brown	Interpretation and use of Doppler radar data.
Ms M Clarke	Radar data sales.

National Rivers Authority

South Western Region
National Rivers Authority
Manley House
Kestrel Way
Sowton
Exeter
EX2 7LQ

*R Hatton

L Aucott	)	General research and operations, particularly flood warning and
G Boyce	)	forecasting
S Taylor	)	

Thames Region
National Rivers Authority
Aspen House
Crossbrook Street
Waltham Cross
Hertfordshire EN8 8LX

*C M Haggett	)	
B C May	)	General research and operations, particularly flood warning and
M A Crees	)	forecasting.
G A Kennedy	)	
J Jeyakumar	)	

North West Region
National Rivers Authority
PO Box 12
Richard Fairclough House
Knutsford Road
Warrington WA4 IHG.

*Dr S Walker	General research and operations, particularly flood warning and forecasting.
I H Pearse	Flood warning dissemination and use of radar.
M S Knowles	FRONTIERS forecast and application.
Dr O Wedgwood	Background in research into the use of radar for forecasting rapid response catchments (University of Salford). Interests in radar, rainfall, runoff modelling, flood warning, return period estimation.

Anglian Region
National Rivers Authority
Kingfisher House
Goldhay Way
Orton Goldhay
Petersborough
PE2 5ZR

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

Severn Trent Region
National Rivers Authority
Sapphire East
550 Streetsbrook Road
Solihull
B91 9QT

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

Northumbria and Yorkshire Region
National Rivers Authority
Rivers House
21 Park Square South
Leeds
LS1 2QG

D Archer T Fewster *M Tinnion	)))	General research and operations, particularly flood warning and forecasting

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

*J Mosedale D Cadman	))	General research and operations, particularly flood warning and forecasting

Southern Region
National Rivers Authority
Guildbourne House
Chatsworth Road
Worthing
West Sussex
BN11 1LD

*O Pollard	Responsible for national R&D project on `Comparison of Weather Radar Correction and Adjustment Techniques'

Research Companies

Wallingford Software Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA

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

River Purification Boards

Forth River Purification Board
Clearwater House
Heriot Watt Research Park
Avenue North
Riccarton
Edinburgh EH14 4AP

*R J Sargent	Flood warning and forecasting

Tay River Purification Board
1 South Street
Perth PH2 8NJ

*J Anderson	Flood warning and forecasting

Tweed River Purification Board
Burnbrae
Mossilee Road
Galashiels TD1 1NF

*I Fox	Flood warning and forecasting

Clyde River Purification Board
Rivers House
Murray Road
East Kilbride
Glasgow G75 01A

*Dr A Bennett	Flood warning and forecasting

Water service companies

North West Water Ltd
Dawson House
Great Sankey
Warrington

*J M Tyson	Application of radar data to urban drainage planning, design and control

Thames Water Utilities
Nugent House
Vastern Road
Reading
RG1 8DB

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

Research Councils

Engineering and Physical Science Research Council

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

*J Ballard	Spaceborne radars.
J Powell	Spaceborne radars, rain and cloud measurements.

RAL Radio Communications Research Unit

*J W F Goddard	Multi-parameter weather radar techniques.

Natural Environment Research Council

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxfordshire OX10 8BB

*R J Moore	Radar calibration, rainfall and flow forecasting
D A Jones	Radar calibration and rainfall forecasting
D S Carrington	Radar rainfall forecasting
R Austin	Flow forecasting using radar

B Austin	PMP/PMF Modelling using radar storm transposition method.
V Bell	Distributed flow forecasting using radar
K B Black	Radar database management and display software
Dr D W Reed	Point and areal rainfall statistics using radar data
E J Stewart	Areal reduction factors and design storm specification from radar data
D C W Marshall	Small catchment flood response times estimated using radar data

NERC Unit for Thematic Information Systems (NUTIS)
Natural Environment Research Council
Department of Geography
University of Reading
Whiteknights
PO Box 227
Reading RG6 2AB

*Dr I Astin	Spaceborne cloud radar studies.

Government Departments

Ministry of Agriculture, Fisheries and Food

Eastbury House
30/34 Albert Embankment
London SE1 7TL

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

Field Drainage Experimental Unit

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
Jersey

*Dr G Shepherd	Radar network policy and science administration. Development of urban applications.