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A STRATEGY FOR USING RADAR & SATELLITE IMAGERY FOR VERY-SHORT-RANGE PRECIPITATION FORECASTING

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SUMMARY

The progress in synoptic-scale weather forecasting brought about during the past two decades by developments in numerical dynamical methods has not been matched by progress in forecasting for the period up to 6h ahead; nowhere has this lack of improvement been more evident than in the case of precipitation. Many meteorologists have a vision of radar and satellite data doing for very-short-range forecasting what radiosonde data have enabled numerical models to achieve on the larger scales. In this paper a strategy is described which we believe can help turn this dream into reality for forecasting precipitation in the UK. We stress the need for a whole-system design approach, with digital data handling all the way from the observational input to the disseminated forecast product; at the same time we emphasize the important role of human judgement which is required to make up for the limitations of the observational data and the incompleteness of our understanding on the mesoscale. In the scheme presented here the data from a network of radars and a geostationary satellite are composited together on an interactive video display and the forecaster does his analysis and forecasting by modifying what is on the screen whilst preserving the basic data in store. The resulting screenfull of digital information can then be tailored and disseminated to users without further manual effort. Although the emphasis in this paper is on the accurate analysis of current weather and extrapolation of current trends, these methods are considered in the context of an overall forecast system incorporating mesoscale numerical models.

1. INTRODUCTION

Very-short-range forecasts - defined here as detailed forecasts for the period up to 6h ahead - are not routinely available; when short period forecasts are issued they tend to be presented in very general terms, often as part of a forecast which emphasizes periods greater than a few hours ahead. It is our intention in this paper to present a strategy whereby very-short-range forecasts may be improved to the point at which weather, in particular precipitation, may be predicted with some considerable precision. Few attempts have been made to estimate the financial benefits of such forecasts; however, it is becoming recognized that there would be considerable potential savings from the proper use of these forecasts in such industries as water, construction and building, and agriculture (Bussell et al 1978). Detailed forecasts for the period 0 to 6h ahead, especially of thunderstorm-related phenomena, are increasingly in demand by aviation (Bromley 1977). In addition there are likely to be substantial benefits to the general public (Haas and Rinkle 1978). Indeed the general public tend to judge a national weather service as a whole by reference to the quality of its short-range weather forecasts: rightly or wrongly, it often seems to be these forecasts which determine the image of meteorology and meteorologists.

There can be no disputing the fact that major improvements have been made over the last twenty years in weather forecasting. Synoptic-scale upper air patterns can now be derived almost completely by computer and require only limited forecaster interaction (Brown 1978). The use of statistical methods along with dynamical weather prediction models has also led to significant improvements in many other products provided to forecasters (Leith 1978). Although the need for intervention continues to be stressed (eg Singleton 1975), some meteorologists (eg Klein and Haggard 1978) consider that by the end of the century all forecasts for periods greater than 12h ahead will be prepared almost entirely by computer. Yet a few important areas still resist the improvements in forecasting skill that have accompanied the advances in computer technology and numerical modelling. Very-short-range forecasting is one of these areas (Pielke 1977, Fawcett 1978): forecasting of precipitation is an area of particular difficulty (Wickham 1974, Fawcett 1978). The reason for the lack of progress in this area is that precipitation is associated with mesoscale and convective scale phenomena. The difficulty in predicting such phenomena can be attributed primarily to the inadequacy of the observational data and to the shortcomings in our understanding which result from this lack of data.

We consider that, regardless of whether the data are to be used in simple linear extrapolation forecast procedures or as input to frequently updated mesoscale models, the first step toward improving very-short-range forecasts of precipitation must be to develop the means of watching for the early signs of mesoscale outbreaks and of keeping track of their movement and subsequent development. This can be achieved only by exploiting an observational system which monitors the mesoscale structure of the atmosphere almost continuously (Ludlam 1960, Ramage 1976). In this paper we describe such a system: it is a system based on combining radar surveillance with frequent pictures from a geostationary satellite. It is not enough, however, merely to provide the observational facilities and, in fact, most of this paper deals with the important issues of how the large amounts of data involved are to be analysed as a consistent whole and converted to a forecast product which can incorporate the forecaster's judgement and yet still be disseminated to the users with very little delay.

The ingredients of a good very-short-range precipitation forecast are, briefly, (i) detailed observations, (ii) rapid analysis, followed by the application of (iii) an essentially linear extrapolation scheme for using short-range forecasts and (iv) a mesoscale numerical dynamical model to extend the period of useful forecasts; then, finally, (v) efficient dissemination. This paper deals mainly with Items (i),(ii),(iii) and (v); however, we recognize the importance of Item (iv) and consider the implementation of such a model to be complementary to the scheme described here.

2. THE CURRENT STATUS OF OPERATIONAL PRECIPITATION FORECASTING.

Before going on to propound any new strategy for very-short-range precipitation forecasting, it is appropriate to set the scene by outlining current and proposed operational practice particularly in the UK and North America. We shall consider current procedure in two categories according to the scale of observational data employed.

(a) Use of numerical models with mainly synoptic-scale input

Although there is some limited input in the form of asynoptic satellite data, operational numerical forecast products are largely based on rawinsonde data which are available only twice per day and, even over the UK mainland, are as widely spaced as 300 km. The associated surface weather may be inferred from the numerical prognosis either subjectively by means of conceptual models or objectively as in the USA and Sweden by the application of statistics ie Model Output Statistics (MOS) (Glahn and Lowry 1972; Lönnqvist 1976).

To some extent, when the effects of large-scale forcing are dominant, a numerical model with high spatial resolution can generate realistic features on scales smaller than the spacing of the input observations. The finest scale model currently in operational use in the UK is the 10-level rectangle model (Burridge and Gadd 1977). This has a grid length of 100 km and so it is only capable of generating meaningful features with characteristic scales more than 200 km. The corresponding model in the USA is the Limited-Area Fine Mesh (LFMII) model (Brown 1978) and this has a grid length slightly larger than the UK model. The resolution even of these so-called fine-mesh models is thus very coarse compared with the known variability of precipitation patterns. Finer-scale modulation of precipitation distribution by the topography may be derived objectively by using the output from the synoptic-scale models to drive fine-resolution diagnostic models which include detailed topography (eg Bell 1978). This would be a useful approach for widespread orographic rain but it cannot compensate for errors due to mesoscale variability unresolved by the synoptic-scale model.

In addition to the inadequacy of the spatial resolution in such models, there is also the problem of the staleness of the input data. The time taken to acquire the input data and to run the model is such that the numerical product is not generally available until several hours after the time of the observations. In any case the initial adjustment period during which the model is subject to random fluctuations lasts for more than 6h. Add to this the fact that a fresh set of synoptic-scale input data is available only at 12h intervals, and it becomes clear that the numerical guidance for the period up to 6h ahead of any given time is likely to be based upon very stale data indeed. In an attempt to overcome this difficulty, Moore and Smith (1972) developed an objective technique for modifying numerical precipitation guidance forecasts using radar data which becomes available subsequent to receipt of the guidance forecasts. Tests showed that the updating produced improvements with respect not only to the centralized numerical guidance but also to the official subjective forecasts. In the absence of such updating, however, the current numerical products, whilst giving useful guidance for forecasts of weather in excess of 12h ahead, are of little value for very-short-range forecasts.

(b) Methods using observational data on the sub-synoptic scale

The traditional method of forecasting the detailed pattern of precipitation for a few hours ahead, as practiced in the UK, is to make a careful subjective analysis of existing precipitation areas mainly using in-situ surface observations, followed by a simple extrapolation of recent trends appropriately modified to allow for expected synoptic-scale changes and past experience of similar systems. Delineating the precise area of existing precipitation from surface reports requires a dense network of reporting stations which provide regular and frequent observations. But, even in the UK and parts of Continental Europe where the network is comparatively dense, there are large gaps in data coverage, particularly overnight, over the sea, and over remote hilly areas. Many stations are also subject to local effects. Thus in practice it is difficult to analyse the true nature, distribution and movement of areas of precipitation. Moreover, the acquisition and portrayal of numerous up-to-date observations, as required for subjective mesoscale analysis, is a time-consuming task. Consequently, the current data often cannot be collected, displayed, analysed and a short-range forecast disseminated, before it is overtaken by events. Very detailed subjective forecasts for a few hours ahead are not normally issued by traditional forecast offices in the UK because of the difficulty in providing a cost-effective data handling system for the conventional in-situ observations. An interesting scheme has been developed recently in the USA by Charba (1977) using an objective MOS-type approach to generate 2 to 6 h probability forecasts from surface hourly observations combined with the output from a fine-mesh (LFM) model; however, Charba's scheme is aimed at the prediction of severe local storm outbreaks for which there tend to be better defined antecedent surface weather patterns than in the case of other precipitation situations.

It is generally recognised that the key to mesoscale analysis of precipitation systems lies in the improved observational fields that can be obtained using ground-based radar and geostationary satellites - radar to observe the precipitation patterns directly and the satellites to observe the cloud pattern associated with the precipitation. Operationally, however, both are still very much underexploited. Consider radar first. Many countries are still using old-style PPI scopes which are often located only at the radar sites themselves. In the USA a method of sending PPI data by telephone, known as WBRR, has been in use for many years (Bigler 1969). It is of course important to be able to transmit the data to forecast offices remote from the radars, but the WBRR system provides degraded facsimile pictures and so a start has been made to introduce digital data transmission in the so-called D/RADEX programme (McGrew 1972). The spatial resolution of D/RADEX data is 3 x 5 naut mi; time resolution is 12 min. Digital radar data are suitable for input into objective forecast models using linear extrapolation methods and there have been many research studies of these methods (see Sec 4). So far, however, they have not been used operationally except in a few pilot studies. One such study, known as SHARP (Short-term Automated Radar Prediction), has been carried out in the Montreal area since 1976 (Bellon and Austin 1978). The SHARP programme uses 3 km data available at 5 min intervals. Although the project was restricted to the area covered by a single radar the resulting forecasts were found to be operationally useful.

One of the requirements for short-range forecasting, especially with fast moving weather systems, is to have large-area surveillance using a network of radars with overlapping coverage (Hill et al 1977). There has been an extensive weather radar network in the USA for two decades but until recently the only multiple-radar information that has been routinely disseminated from this network has been in the form of manually-derived radar summary maps which are prepared from the semi-plain language coded radar reports (RAREPs) received from individual radars (WMO 1966). These radar summary maps describe the locations of lines of storms and of intense cells, and they are transmitted via the National facsimile network. These are now being supplemented by Manually Digitized Radar (MDR) reports on an approximately 80 km grid (Smith 1975). When the fully automated high-resolution D/RADEX methods are introduced more widely as part of the so-called RADAP scheme (Saffle 1976) it should become possible to produce much-improved composite maps.

The situation with regard to operational use of satellite imagery in many ways parallels that in the radar area. A few places have access to digital data and to movie loops but the majority of operational users at meteorological outstations in the UK and the USA have to make do with analogue facsimile. The US National Environmental Satellite Service (NESS) has developed a television picture terminal (TPT) satellite display with a capability of time lapse replay (Bristor 1978) but this will not be available to field sites for several years. Meanwhile, research continues into methods of using the data, although most of the research is concerned with severe local storms. Thus, for example, it has been shown that there are certain characteristic features of the infrared (IR) and visible imagery that are associated with locally heavy rains (eg Scofield and Oliver 1977). The cloud top temperature as determined from IR data is particularly important for keeping track of severe storm developments and the routine production of a cloud top temperature monitoring chart is now in an operational test phase (Waters 1977). Not much work has been done on the less convective kinds of frontal system which are common in the UK, although Barrett (1973) has shown that useful estimates of daily rainfall accumulations are possible on the basis of satellite information. Recognizing the difficulty in relating precipitation to cold cloud tops when there is abundant frontal cirrus, Barrett found that the estimates needed to take into account a consideration of the synoptic type as well as the cloud type and cloud cover upwind.

One of the first semi-operational very-short-range forecasting programmes to use radar and satellite data together in a truly local setting was carried out in the Chesapeake Bay region from 1974 to 1976 by Scofield and Weiss (1977). They used high-resolution visible and

IR imagery from the SMS/GOES geostationary satellite together with both radar data and a mesonetwork of surface observations to provide a detailed description of the current weather and 0 to 6h forecasts. This information, which they referred to as 'nowcasts', was disseminated to the Bay community by VHF radio and automatic answering telephone. Scofield and Weiss received their radar data in the WBRR facsimile format, while their satellite data were obtained on a totally different projection with considerable distortion owing to the oblique viewing angle. Nevertheless, the experiment was successful in demonstrating the feasibility of preparing and disseminating hourly-updated weather information to the local community. Another 'nowcasting' experiment has been carried out at the University of Wisconsin as a multi-disciplinary experiment involving the Departments of Meteorology and Communication Arts, the Space Science and Engineering Center and the Extension Telecommunications Center. One conclusion from this experiment was that television is the best medium for disseminating this kind of detailed weather information.

3. THE ELEMENTS OF A SYSTEM FOR DERIVING VERY-SHORT-RANGE FORECASTS OF PRECIPITATION IN THE UK.

The point was made in the previous section that most of the forecasting techniques currently in use are ill-suited for forecasting precipitation in detail over the period up to 6h ahead. The radar and satellite techniques show considerable promise but we have as yet barely scratched the surface in attempting to optimize the use of these data sources. Thus we get to the main thrust of this paper, which is to suggest that the time is now ripe for the implementation of a system to enable the full forecasting potential of radar and satellite to be exploited. The framework within which this system must be developed is indicated in Fig 1, which follows the philosophy propounded by Kreitzberg (1976). We shall be concentrating on the part of this diagram enclosed within the dashed rectangle, with the emphasis on precipitation; however, we shall keep in mind the need in a few years time to link the radar-cum-satellite system to a new generation of mesoscale numerical weather prediction (NWP) models (eg Carpenter et al 1978). As shown in Fig 1, this linkage will need to be a 2-way process, with the simple forecasts generated by extrapolating the radar and satellite data being modified in the light of output from a mesoscale MWP model* and the mesoscale model itself using inputs from the radar and satellite. The patterns of precipitation as discussed in this paper may not be useful in their own right for initialising the numerical models, but the implied fields of humidity and of vertical air motion and latent heat release probably will be. As demonstrated by Kreitzberg and Rasmussen (1977), the forecast precipitation pattern can be greatly improved by incorporating into the initial analysis areas of high humidity inferred from radar observations of pre-existing precipitation. Kreitzberg and Rasmussen also suggest that the sub-synoptic circulations produced in the model by latent heating may be well correlated with the precipitation distribution between initialization time and 3 to 6 hours earlier. Given information on that precipitation, from surface radar and satellite observations, it should be possible to infer a substantial amount about these important circulations.

We now go through a check list of the important elements that constitute the proposed radar-cum-satellite system, but first we stress the need to view the scheme as a whole system. There would be little sense, for example, in having an observational capability without adequate means of assimilating and interpreting the data, or in having the means of generating detailed very-short-range forecasts without the capability of disseminating so perishable a product promptly to the eventual users. With that introduction we now consider the elements of our system:

(i) The radars

Experiments such as the Dee Weather Radar Project(1977) have demonstrated that a high degree of quantitativeness can be achieved in the measurement of surface precipitation intensity, even in difficult hilly areas, provided the radars are calibrated using telemetered raingauge data. Moreover, modern radars, with the benefit of solid-state technology, are capable of stable and reliable operation for long periods and so they can be operated unattended (Try 1972, Aldcroft 1976). This enables them to be sited optimally and to be run with low labour costs. By using a mini-computer at each radar site pre-processed rainfall data can be sent in real-time by land line to remote locations (Ball et al 1976, Saffle 1976). Although a single radar does not cover a large enough area to permit forecasts to be made for more than an hour

*Before a mesoscale model is ready for use, direct input from an existing large-scale NWP model would be useful.

or two ahead, techniques have been developed to combine automatically on a single display the digital data being received from a network of radars (Taylor and Browning 1974, Ball et al 1979a).

(ii) Geostationary satellite imagery

Satellite-borne microwave techniques are capable of measuring precipitation directly over the oceans (Wilheit et al 1977) but their spatial resolution is poor. Moreover, these techniques have as yet been used only on polar-orbiting satellites, and these cross any given area too infrequently to be of great value for very-short-range forecasting. Geostationary satellites, on the other hand, although they are not instrumented to observe precipitation directly, are capable of providing cloud imagery with a resolution in time and space which does satisfy the needs of very-short-range forecasting. The time resolution of GOES and Meteosat is typically 30 min. Although this is just about adequate for tracking precipitation-producing mesoscale cloud systems, even more frequent observations are occasionally available in the USA from the GOES satellites and these are proving to be valuable for estimating winds from the displacement of small clouds and for keeping track of rapidly developing severe local storm situations. The spatial resolution for Meteosat at the latitude of the UK is 6 km(E-W) x 12 km (N-S) for the IR data (3 x 6 km for visible data) and this, too, is adequate fordepicting the mesoscale distribution of precipitation-producing cloud system (here again, better resolution would be desirable to identify cloud patterns before and during thunderstorm activity and for determining wind fields from the displacement of small clouds).

(iii) The marriage of radar and satellite data

Ground-based radar is superior to satellite methods for measuring surface precipitation intensity, but the coverage of radar is rather limited. In the UK, even with a network of radars perhaps linked eventually to a network on the Continent, there would still be large areas over the surrounding sea for which the satellite data would be needed to provide advance warning of approaching precipitation systems. Thus the philosophy we adopt is that of converting the two sets of data to a common format so that they can be merged together on the same display, the radar data being used where possible and the overall coverage being extended by satellite data.

(iv) The emphasis on advection

The emphasis in this paper is on forecasting by advection of existing precipitation areas identified by radar and satellite, together with some assessment of the likely development and decay of these existing areas. This emphasis on advection - which differs from that adopted in the USA - is appropriate for much of the time in places like the UK where most of the precipitation is associated with frontal disturbances. In frontal systems, even some of the more convective mesoscale precipitation areas can show considerable persistence and be tracked over many hundreds of kilometres as resolvable entities despite orographic modulation (Hill and Browning 1979). In order to address the problem of the initial outbreak of deep convection, however, it will be necessary to make greater use of higher resolution visible cloud imagery to depict the characteristic cumulus patterns that precede the outbreak of the storms (eg Purdom 1976) and to supplement the satellite imagery with mesoscale surface observations, and additional vertical profiles of temperature, humidity and wind. To achieve the required resolution in both space and time it is hoped that these data will eventually be derived from geostationary satellites using procedures similar to those described by Smith et al (1978). Although discussed only briefly in this paper, these other techniques are receiving a lot of attention in the USA where the sudden outbreak of tornadic storms is a matter of great concern.

(v) Digital data handling

A single satellite IR image as proposed in the present scheme may consist of 256 x 256 cells each with one of 256 radiance levels assigned to it, ie almost 10^6 bits of data. Such images will need to be compared and/or combined with other image data, and parts of the image will need to be rapidly accessed and manipulated in a variety of ways (Sec. 4) as well as being displayed and disseminated in different formats. All these procedures have to be completed within 15 to 30 mins if the forecast is to be issued soon enough to be of value. To handle this volume of data flexibly and rapidly, without degrading it, digital techniques should be employed at every stage from the observational input to the final dissemination of the product. Advances in mini-computer and microprocessor technology, in solid-state fast-refresh memory devices, and in digital communications systems, now make it possible to achieve this at reasonable cost.

(vi) Interactive computer-driven video displays

Video display techniques have recently become available which, when linked to a small computer, provide the capability of recalling the required image almost instantly and of permitting a large amount of human interaction with the display (Hilyard 1977). These techniques provide the key to the rapid performance of various analytical and forecasting steps as described later in Sec 4. The pioneering work in the development of interactive displays was begun in the early 1970s at the University of Wisconsin under the leadership of V Suomi. This led to the development of a display system known as McIDAS (Chatters and Suomi 1975). Other more recent systems in the USA include AOIPS (Bracken et al 1977), ADVISAR (Smith and Reynolds 1978) and NEDS (Thormeyer 1978). In the UK there is the IDP-3000(Balston 1978). The kind of activities that can be carried out using such systems are:

- Rapid data access, ie almost instantaneous selection of any required image from a set of stored images.
- Precision Navigation, ie x-y translation of the image to remove residual registration errors by reference to electronically generated coastline overlays.
- Enhancement (Contrast stretching and level slicing) ie adjusting grey shades or assigning colours at variable thresholds, either to make features of interest stand out or for the purpose of calibrating the intensity levels.
- Animation, ie replaying a time lapse sequence of images
- Zooming, ie selecting and enlarging an area of interest
- Image Combination, ie combining or comparing with great precision the images from different sources, eg radar and satellite, or satellite IR and VIS.
- Superposition of graphics, ie capability of superimposing geographical features, labels, numerical data, and line charts.
- Intervention, ie modification of the image data within areas delineated by means of a movable cursor whilst preserving the original data in store.

These activities can be carried out by means of simple analogue controls (eg a joystick) plus keyed-in instructions. In Sec 4 we discuss in some detail how by means of a well-defined sequence of steps it is possible to generate very-short-range forecasts of precipitation on the television screen itself.

(vii) Improved understanding of mesoscale weather systems

The use of an interactive display can be only as good as the state of meteorological understanding will permit. Thus, for example, the radar and satellite data first need to be analysed to convert the radar and satellite data into fields which represent the true pattern of surface precipitation intensity as faithfully as possible. The transfer function is reasonably well-established for the radar and much of the analysis of the radar data has to do with applying a variety of corrections to improve accuracy and to remove spurious echoes. However, the transfer function for converting satellite cloud data into surface precipitation intensity is not well-established, especially in mid-latitudes where there is abundant cirrus in regions far removed from areas of surface precipitation. In this case we need to use a combination of approaches:

- Empirical adjustment of satellite data to correspond to precipitation intensities given by ground truth or by nearby radar data.

- Exploitation of the different spectral response in different satellite channels (IR, visible and possibly water vapour channels). Reynolds et al (1978) and Lovejoy and Austin (1979) exploit the fact that, whereas the IR radiance is a measure of cloud height, the visible brightness tends to be more a measure of cloud thickness. Consequently low (cold) radiance values together with high brightness is indicative of precipitating cloud while low radiance and low brightness is indicative of thin cirrus alone.

- Exploitation of the texture of high resolution visible data from occasional passes of a polar-orbiting satellite to reveal the presence of characteristically fibrous cirrus which otherwise might be interpreted as being deep rain-bearing cloud.

- The use of conceptual models relating mesoscale and large-scale cloud patterns to surface precipitation in different synoptic situations. A simple example is the fact that the leading parts of baroclinic disturbances have considerable upper cloud unrelated to surface precipitation, whereas the trailing parts of such disturbances are more convective and the high cloud tops tend to be better related to the occurrence of precipitation. At present most of the conceptual models are biased toward the synoptic scale, the few existing mesoscale models (eg Browning 1974; Houze et al 1976) being derived from a limited number of detailed case studies. However, when the kind of analysis described in this paper is carried out on a more routine basis, we shall begin to accumulate the raw material for the derivation of a more systematic classification of mesoscale cloud and precipitation patterns.

Much fundamental research remains to be done to improve all aspects of the analysis of satellite data. More research is also required to enable us to derive forecasts from the analysed precipitation fields. It is sometimes possible for useful forecasts for a few hours ahead to be obtained by linear extrpolation. However, it will be important to develop methods to predict the development or decay of existing precipitation patterns that results from both internal dynamical factors and from external topographical forcing. Approaches to be used will include:

- Incorporation of large-scale trends predicted by synoptic-scale or mesoscale numerical dynamical models.

- Incorporation of topographical enhancement factors derived from mesoscale climatological statistics and from simple diagnostic models.

It will be possible to implement these approaches in a fully satisfactory way only when a substantial body of experience has been amassed concerning the way in which mesoscale precipitation patterns evolve. A precipitation archive needs to be established on the basis of detailed radar, satellite and raingauge data which have been carefully synthesized and quality-controlled to remove obvious errors and artefacts.

(viii) Optimizing the man-machine mix

As is made clear in Sec 4, there are many steps in the short-range analysis and forecasting procedure. Many of these can already be automated and, in time, more of the steps will become amenable to automation. However, it is likely to be a very long time indeed before the observational data on the mesoscale will be good enough to eliminate the need for considerable human judgement. For example, use will continue to be made of conceptual models of weather systems just as it is in current local forecast practice (Kreitzberg 1969), although, with improved data, these models should become more relevant to the mesoscale than their present-day counterparts. The use of an interactive video display will permit the man-machine mix to be optimized by automating the repetitive tasks such as data reformatting and display whilst enabling the forecaster to retain and expedite the use of his judgement. As discussed by Woodroffe (1976), use is already made of a visual display unit interactively connected to a computer for the purpose of manually intervening in the objectively analysed fields used as input to the Meteorological Office 10-level NWP model. The approach advocated in this paper involves an extension in the degree of interaction. Instead of using satellite and other information to adjust values at a limited number of widely spaced grid points, the approach here is to use the detailed radar-cum-satellite information itself as the primary material and to adjust it to bring it into conformity with other constraints so as to obtain the best possible representation of the mesoscale field of precipitation. This requires the modification of a dense matrix of data points and implies a far larger amount of interaction than is currently regarded as normal.

(ix) Dissemination of the forecast product

Existing methods of disseminating forecasts are inadequate to do justice to the wealth of perishable information likely to be contained in the forecasts generated using radar and satellite data. One approach in the future will be to transmit automatically a limited amount of digital data precisely tailored to individual user's needs. As Carpenter et al (1978) point out, the increasing use of on-site microprocessor control systems and of dial-up computer access will make automatic response to such forecast information more feasible. It will also be necessary to exploit local radio more, especially techniques for issuing flash messages (such as 'Carfax'). Another approach will be to send out picture information from which the user can select for himself the information of interest to him. The information should be frequently updated, the most recent data being accessible continuously on demand rather than intermittently at scheduled times. A number of options exist for this approach; they include:

- Special-purpose equipment capable of receiving and storing digital data transmitted by standard lines and of replaying one picture or a sequence of pictures on a television set. Simple devices of this kind are commercially available and are in use in the UK Meteorological Office and in some Water Authority Offices (Taylor 1975, Ball et al 1979b).
- Teletext ('Ceefax' and 'Oracle'). In this scheme the data would be sent in a spatially degraded format to a television company via a computer-to-computer link and could be displayed on demand on domestic television sets equipped to receive teletext.

- Viewdata (eg the "Prestel' system (Parker 1978) currently undergoing market trials by the Post Office in Britain). This is similar to teletext except that the data would be sent to regional computers operated by the telephone company and would then be called up on a domestic television set by telephoning the computer data bank. In addition to providing a larger bank of data specially tailored to the needs of the area served by the regional data bank, this scheme has the advantage over teletext that it could generate revenue for the data provider in direct proportion to the demand for the product (Meteorological Office 1978). The Viewdata scheme would also permit the monitoring of the demand for individual forecast products, which is an important requirement for a sound marketing plan.

(x) Other items

In addition to the items listed in the above check list, it is assumed that conventional mesoscale observations, especially from automatic weather stations, will be available. In due course, the output from a mesoscale NWP will also become available. However, a detailed discussion of these items is outside the limited scope of the paper (see the dashed frame in Fig. 1) and will be the subject of later papers.

4. A SPECIFIC SCHEME FOR DERIVING VERY-SHORT-RANGE FORECASTS OF PRECIPITATION IN THE UK

(a) An overview of the scheme

The system concept outlined in Sec 3 is being implemented in a short period forecasting pilot project at the Meteorological Office Radar Research Laboratory which began in 1978. (Browning 1977). We refer to this approach as the FRONTIERS programme - Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite. As part of the programme we are establishing a network of initially four radars in England and we shall be synthesizing the data from these radars with Meteosat data reduced to a radar-compatible format. We are proceeding on the assumption that there will be a continuing service of geostationary imaging for NW Europe. In this section we outline a sequence of steps as part of a systematic work flow pattern which we are planning to implement for the derivation of current weather and forecast products from the radar and satellite data. Some of the steps are straightforward and have already been implemented. Others are more complex and will require several years of experience or the accumulation of an archive of data before they can be implemented satisfactorily. Yet others may turn out to be too time-consuming or costly in relation to their effectiveness to justify inclusion in the final scheme. Only practical experience will indicate what operational compromises will be required. Clearly the system must be designed with a view to evolutionary robustness. Whilst it will be several years before the precise form of the forecasting procedures will emerge, we consider it worthwhile at this stage to describe our plans as a means of clarifying the problems that have to be addressed. After all, these problems are of a general nature even though the specific methods of dealing with them may change.

The principal stages in the proposed forecasting scheme are shown in Fig 2. The four main stages - preprocessing, meteorological analysis, forecasting, and dissemination - are elaborated upon in Figs 3 to 6. Two other areas of activity are shown in Fig 2 - archiving and forecast validation. These will be automated and will be carried out in parallel with the Stage 2 and Stage 3 activities. There are considerable potential savings to be made in the UK from a reduction in the National network of raingauges if a radar rainfall archive can be maintained (eg Bussell et al 1978). For such an archive to be acceptable, the data must be carefully quality controlled. A preliminary degree of quality control is achieved during the analysis of the radar data in Stage 2 which, as we shall see, entails a fair amount of manual checking to remove obvious errors.
Thus, as shown in Fig 2, the archive should be derived from the Stage 2 products rather than direct from the basic data. The radar archive will be adequate for many forecasting research purposes, but for hydrometeorological applications it will probably be necessary to generate off-line a further archive based upon the so-called optimum rainfall field (Harrold et al 1974) in which the radar data would be combined with a rationalized network of autographic raingauges. In the generation of the optimum field each gauge would be assumed to measure accurately the rainfall at its location (unless a gross error can be identified by comparison with neighbouring gauges), and the pattern of radar echo intensity would be used to interpolate between the gauges.

Without wishing to describe the hardware facilities in detail, it is appropriate to mention that a mini-computer or comparable digital processor is required at each of the radar sites to perform the Stage 1 preprocessing (we are using PDP-11/34 and comparable computers). The data available from the radars are in 8-bit format. Similar computers are needed to process the satellite data and to receive and combine the data from the network of radars. A further mini-computer is required to drive the interactive video display system. Although at the moment we are making the best possible use of redigitised analogue Meteosat data together with a very simple interactive display, the scheme outlined here is based on the use of 8-bit digital satellite data and a versatile interactive display.

(b) Preprocessing of the satellite and radar data

A breakdown of the activities involved in the preprocessing stage is shown in Fig 3. The on-site radar data processing is essentially as described by Taylor and Browning (1974). Two categories of data are available at the network centre. One category - areal integrations - is for hydrological use and is not used subsequently for meteorological forecasting. The other, meteorologically important, category of data is a radar composite map available every 15 min on a 256 x 256 grid with 5 km*resolution. The radar rainfall patterns are stored and can be manipulated in 8-bit form, ie 256 levels of intensity, although for ease of interpretation only eight levels are normally displayed at any one time. The standard display system, for example, has a different colour for each of the following precipitation categories: L,1,4,8,16,T,H, where L = light rain, T = probable thunder shower, H = probable hailstorm, and the numbers refer to rainfall intensity thresholds in mm h^{-1} averaged over each 5 km square. The reason for storing the data as 256 levels is to reduce quantising errors during the subsequent Stage 2 and 3 processing when a whole series of correction factors has to be applied.

As far as the satellite data are concerned, Fig 3 shows that we intend to concentrate on the frequent imagery from Meteosat. There are three channels of interest: IR, visible, and perhaps water vapour. These data are available

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*Data with a resolution of 2 km and 5 min are also available over limited areas for off-line research.

at 30-min intervals for the IR, and also for the visible during daylight hours, but less frequently for the water vapour channel. The IR data, representing approximately the temperature of the cloud top, are available around the clock and so are treated as the primary satellite data for precipitation forecasting. However, the facility is provided for automatically combining the IR data with the other channels, at times when they are available, according to empirical rules developed by off-line research, in order to improve the delineation of the probable extent of surface precipitation.

One of the first tasks with the satellite imagery is to convert it automatically to the same projection as the radar data. The next step is to use the coastlines to locate the images with the high degree of accuracy required for local forecasting purposes. This is the registration or so-called navigation procedure. The 256 radiance levels obtained from Meteosat give ample scope for colour enhancement to make the coastlines stand out clearly. The interactive display is used to position the image on a 256 x 256 grid against an electronic overlay of the coastline. This image usually covers a large enough area to ensure that at least some coastlines are unobscured by cloud. The navigation is the only task in Stage 1 that requires any manual intervention. Experience in the USA indicates that purely objective procedures are not capable of registering the images with the 5 km precision required for mesoscale applications and as a result the National Environmental Satellite Service uses an interactive video display system for this purpose.

(c) Meteorological analysis of precipitation patterns

Figs 4(a) and 4(b) show the sequence of tasks involved in combining the radar and satellite data sets and in analysing them in terms of surface precipitation intensity. The input data sets at the top of Fig 4(a) are preprocessed data in common formats, with the entire 256 x 256(5 x 5)km array filled with Meteosat data but only a part of the array filled with data from the limited-area UK radar network.

The first five tasks (Fig 4(a))all have to do with refining the quality of the radar rainfall data on the basis of manual inputs to cope with problems that cannot be fully dealt with objectively in the radar-site preprocessing:

Step 2.1: Readjustment of the calibration of individual radars.

Although it is planned that individual radars will normally be calibrated on-site and in real time by means of telemetered raingauge data, there will be occasions when such calibrations will either be unavailable (eg because of lack of rain over the calibration gauges)or unreliable (eg because of contamination of the radar beam by the strong echo from melting snow at the range of the calibration gauges). Any overall radar calibration errors arising from such effects can be identified in the manner indicated in Fig 4(a).

Step 2.2: Identification and eradication of spurious echoes due to anomalous propagation, sea clutter and radar interference.

Techniques have been developed which make use of the fluctuation characteristics of the radar signal to enable precipitation targets to be distinguished from ground echoes, including those associated with anomalous propagation (Johnson et al 1975). These techniques have yet to be implemented operationally and, in the event they do not provide a complete solution, the additional procedures shown in Fig 4(a) can be applied subjectively to reject any remaining echoes of this kind. Before applying any correction the analyst would of course have ascertained whether the atmospheric conditions were in fact conducive to the production of anomalous propagation. Sea clutter probably cannot be distinguished on the basis of its fluctuation characteristics and its presence will have to be inferred from the expected sea state or in ideal circumstances from the absence of satellite-observed cloud in the area. Radar interference can generally be recognized by its characteristic configuration, eg spokes and spiral lines. Once identified, these effects can be removed by suitable use of the joystick-controlled cursor plus keyed-in instructions.

Step 2.3 Assessment of the validity of bright-band corrections and their implementation if appropriate.

The radar bright-band is the name given to a shallow layer of intense echo associated with melting snow and where intersected by the radar beam it leads to an overestimate in the precipitation intensity. An objective method for minimizing the effect of the bright band using data from radar scans at different elevation angles has been proposed by Harrold and Kitchingman (1975). Subsequent tests by Clarke and Collier (1977) have indicated difficulties in applying it in practice. More work is required to develop this procedure and it is not clear at present whether it will be better to apply the correction at the radar sites for individual radars or centrally on the radar composite. In either case, however, there are likely to be occasions when, perhaps because of the inhomogeneous character of the precipitation, the resulting objective corrections are unreliable. Thus there may be a need to display the radar rainfall patterns with and without the corrections applied and to use subjective judgement to exploit man's superior pattern recognition capability to assess what corrections, if any, should be applied.

Step 2.4: Determination of the boundaries of usable radar data and application of range-dependent correction factors.

The extent of usable radar data depends on the radar horizon and on the vertical extent of precipitation and its intensity profile. A set of boundaries can be defined for a few broad categories of precipitation type. Within these boundaries at the longer ranges correction factors will need to be applied over and above the standard $(1/\text{range})^2$ correction applied at the radar sites. This is to allow for the fact that the radar beam may not be filled with precipitation or may be sampling precipitation echo aloft which is less intense than that close to the ground. Fields of statistical correction factors will be derived by comparing daily-integrated radar rainfall patterns with corresponding patterns of daily raingauge data and these will be computer archived in broad categories related to the nature and probable vertical extent of the precipitation.

Step 2.5: Application of orographic enhancement factors.

This step is rather similar to Step 2.4 except that the corrections will be localized to exposed hilly areas and will be a strong function of the conditions at low levels, especially the wind velocity and relative humidity. According to Browning (1979) substantial orographic enhancement can occur in the lowest 1 or 2 km in certain circumstances, and the correction factor may be significant even at ranges as close as 50 km. The correction factors due to low-level enhancement can be derived climatologically as in Step 2.4 or by using diagnostic fine-scale numerical models such as that of Bell (1978).

Step 2.6: Adjustment of the satellite levels so that to a first approximation they correspond to radar levels.

Having bogused the radar network data in Steps 2.1 to 2.5 the next step is to compare the satellite IR data (or some combination of IR and VIS data) with the by-now optimized radar data and to adjust the satellite level-slicing scheme for the display as a whole to correspond as nearly as possible to the rainfall levels used in the radar scheme (Fig 4(b)). Then, as Step 2.7, the radar and adjusted satellite data are composited together on the same display using the radar data where available and filling in the gaps with the satellite data.

Step 2.8. Subjective bogusing of the satellite data.

We then come to one of the most challenging tasks, namely modifying the parts of the display that are based upon the satellite data* in order to remove areas of high cloud not associated with precipitation and to introduce any areas of precipitation associated with shallow cloud. Two approaches are used depending on how close the correspondence is between the satellite cloud pattern and the precipitation pattern. We shall refer to these as the 'take-away' and 'build-up' methods, respectively. In cases where there appears to be a reasonable overall correspondence between the areas of high cloud and precipitation, the satellite radiance patterns are used as a first approximation to the detailed precipitation pattern outside the areas of radar cover, and the main analysis task is to 'take-away' areas of high cloud which are believed not to be associated with surface precipitation. In regions dominated by convection it is relatively easy to relate high cloud tops to precipitation cores but in areas of extensive high layer cloud such as at warm fronts it may not be obvious where the precipitation areas at the surface begin and end. Deciding what cloud to eliminate then requires the skillful weighing of diverse strands of evidence as discussed in Sec 3(vii). Such evidence may be gleaned from surface observations from ships or from the texture of the visible cloud observed at high resolution during the infrequent passes of polar-orbiting satellites. Finally, these pieces of evidence must be related to the overall cloud pattern and then reconciled by the human analyst with his knowledge of conceptual models of precipitation systems.

The other method of analysis, referred to as the 'build-up' method, is applied when the overall correspondence between cloud radiance patterns and

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*Step 2.8 is described assuming that the satellite data are based upon IR data alone, as for example during the night. The combined use of IR and VIS data, as described by Lovejoy and Austin (1979), may by itself provide a fairly good indication of the extent of precipitation. Even then, however, an abbreviated application of Step 2.8 is likely to improve the analysis appreciably in some cases.

surface precipitation is so poor that it is necessary in effect to 'wipe the slate clean' outside radar range and to build up the main features of the precipitation pattern 'from scratch'. In this case one does not use the detailed pattern of Meteosat imagery as a direct indication of the detailed pattern of precipitation but, rather, one can recall it onto the display for use as just one strand along with the other strands of evidence to delineate a rather crude outline of the probable extent of surface precipitation. With this approach the tendency would be to look for characteristic cloud patterns thought to be associated with specific categories of mesoscale organisation. A case in point is the heavy precipitation that often occurs in association with the 3 km tops of convective line-elements at sharp ana-cold fronts (Browning and Harrold 1970, James and Browning 1979). Sometimes, too, the human analyst can discern bands of medium-level cloud associated with surface precipitation lying beneath upper cloud bands of different orientation associated with non-precipitating cirrus.

Implementation of the changes to the display called for in Step 2.8 can be achieved using a joystick-controlled cursor to define the corners of polygons within which the required modifications can be effected by means of simple keyboard instructions. Different modifications may be required in different geographical sub-areas with automatically generated smooth transitions between each area; in some of these areas, 'take-away' analysis may be possible, whilst in others the cruder 'build-up' analysis will be needed. Having finished Step 2.8, one has on the TV screen a fully analysed precipitation pattern on a 256 x 256(5 x 5)km grid which is ready for immediate transmission to users interested in current weather or for input to the Stage 3 forecasting procedures. Too much accuracy must not be expected from the analysis in Step 2.8:in some cases one will have done well even if one succeeds in delineating the major areas of rain/no rain. We must remember that the critical land areas will in any case be covered more quantitatively by radar and that the role of the satellite is to provide a larger-scale context and some advance warning of approaching areas of precipitation.

(d) Very-short-range forecasting of precipitation patterns

The analysis of precipitation patterns in Stage 2 was carried out using 256 levels of intensity in order to retain the contrast enhancement facility for the satellite data and to avoid quantizing errors during the application of successive correction factors to the radar data. Further corrections will need to be applied during the forecast procedure but the level of precision justified at this stage is less; thus the number of intensity levels stored can be reduced.

Fig 5 shows that the sequence of steps in the forecasting of precipitation patterns is as follows:

Step 3.1 Removal of orographic effects The principal step in the forecast procedure is the objective extrapolation of the analysed precipitation pattern. In order to avoid the mistaken impression that the entire precipitation pattern is almost stationary, or the possibility of the extrapolation procedure spuriously advecting geographically fixed orographic maxima or rain shadows, it is first necessary to minimise the topographical effects as far as possible. This is achieved by cancelling the enhancement factors applied in Step 2.5, followed by the inverse application of a computer-archived field of topographical radar echo enhancement factors derived climatologically as a function of surface wind and relative humidity. The objective corrections will be only a first approximation and further subjective tuning may be required to further diminish probable topographically related anomalies.

Step 3.2 Filtering of the data. The previous corrections in Step 3.1 do not have to be applied too painstakingly since we may next need to smooth the 256 x 256(5 x 5)km array to one of, say, 64 x 64 (20 x 20) km* before applying the objective extrapolation. This smoothing would be done to enable the objective extrapolation to be carried out in a reasonably short time and to get rid of the more evanescent small-scale features of the precipitation pattern. Tatehira et al (1976), for example, find that a substantial improvement in predictability in the case of forecasts up to 4 h ahead can be achieved by degrading the resolution even further from 20 to 40 km. In either case Tatehira et al find that more accuracy can be achieved by using objective extrapolation procedures than by advecting precipitation patterns with the wind at some level (eg 700 mb).

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*The value of 20 km is somewhat arbitrary; the choice of the most suitable grid size for forecasting will be made in the light of experience.

Step 3.3 Objective linear extrapolation of analysed precipitation fields

There are several objective extrapolation procedures that can be used: they may be summarized as follows:

(i) A cross-correlation technique similar to that used by Austin and Bellon (1974) and Bellon and Austin (1978) and developed by Wilson (1964, 1966), Leese et al (1970) and Smith and Phillips (1971). In this scheme portions of one radar or satellite picture are matched with portions of a subsequent picture. This procedure has the advantage of taking into account the detailed shape of the radar echo or cloud being tracked, and therefore decreases the chance of mismatches. If there are large differential motions from one part of an area to another then the pattern of precipitation or cloud must be split into several sub-areas in order to produce useful forecasts.

(ii) Tracking of individual radar echo centroids or clouds using a linear least squares extrapolation (Barclay and Wilk 1970; Wilk and Gray 1970). This method has the advantage of coping well with differential motion, but unless echo or cloud clustering techniques are applied (Endlich et al 1971; Wolf et al 1977) there may be difficulty in matching echoes or clouds that change their shape significantly from one picture to the next.

(iii) Tracking of individual echoes or clouds using parameters describing the shape and intensity profile of the entire echo or cloud complex, instead of taking a single intensity threshold as in (i) and (ii) above (see Duda and Blackmer 1972; Blackmer et al 1973). This type of procedure is complex but it does describe the movement of individual clouds or radar echoes.

The overall forecasting schemes specified in this section calls for a high degree of human interaction in order to optimize the forecast. We therefore consider it unnecessary to strive for an objective technique which produces perfect results in all weather conditions - probably an unattainable goal anyway.

Step 3.4 Subjective intervention to amend obvious defects in the previous extrapolation. The previous step is capable of generating a sequence of forecast patterns over a series of 30-min intervals. This sequence can then be replayed in time-lapse as a continuation of the earlier sequence of analysed precipitation patterns. Shortcomings in the objective extrapolations will show up as discontinuities in the time-lapse sequence which can be ameliorated by subjective modification of the velocity and/or intensity of the precipitation pattern within selected sub-areas.

Step 3.5 Introduction of trends in intensity predicted by a mesoscale numerical dynamical model. The forecasts generated so far are merely linear extrapolations of the most recently observed precipitation patterns. Any broad trends in intensity predicted on the basis of a NWP model can now be introduced provided they are not inconsistent with the observed trends.

Step 3.6 Subjective reintroduction of major storm cores lost in the earlier filtering process. Thunderstorm cores may have been smoothed out during Step 3.2. Although it is appropriate that this should have been done,in view of the lack of persistence of individual convective cells (Wilson 1966), it is not unusual for compact clusters of thunderstorm cells to persist for longer periods than the component cells. If this appears to be happening on a given occasion it may be helpful to reintroduce a few of the major storm centres at appropriate locations, perhaps on the basis of a subjective interpretation of the previous time-lapse sequence.

Step 3.7 Reintroduction of orographic effects. At the beginning of the forecast sequence (Step 3.1) we were at pains to rid the precipitation pattern of orographic effects to enable the advective forecasting scheme to function properly. The final step in the forecast procedure is to reintroduce the orographic effects with 5 km resolution. The knowledge of the"disenhancement" carried out in Step 3.1 should help in applying an appropriate "re-enhancement" assuming that changes in orographic effects occur only slowly and often in a predictable manner as, for example, at the passage of well-defined cold fronts (Browning et al 1975). Having completed this step, one then has a complete set of very-short-range forecasts consisting of a sequence of identically displaced precipitation patterns subjected to varying topographical modification as the precipitation areas pass across different locations over a period of several hours. These forecast patterns are on a 256 x 256 (5 x 5)km grid and are now ready for dissemination.

(e) <u>Dissemination of the actual and forecast precipitation information</u>

The crucial aspects of dissemination are that the information should reach the users quickly, should be frequently updated, and should be in sufficient detail and in an appropriate format. Three dissemination formats are indicated in Fig 6. All of the formats shown in Fig 6 involve some form of visual display* for clarity and ease of assimilation or, alternatively, the data can go straight into the user's computer system. All of them can be disseminated automatically via standard land lines. Very frequent updating is possible.

One of the obstacles to prompt dissemination is the amount of prior data processing required in Stages 2 and 3. Nevertheless, as a result of the degree of automation and the ease with which the manual intervention can be achieved using the interactive video display techniques, these steps are not expected to be as time-consuming as might appear at first sight. It must also be remembered that only a rather small fraction of the display is likely to be filled by precipitation at any given time and, once the data have been processed for a few consecutive times, the processing of subsequent data is made easier by continuity considerations. We anticipate that the time delay between receipt of the raw data and dissemination of the forecast will be between 15 and 30 minutes. Unfortunately the basic Meteosat data are not received until about 45 minutes after real time. Thus it seems that we should aim to get the forecast product to the users within just over an hour of the time of the latest data used in the derivation of that product. If there is a risk of it taking longer than this, then it will be necessary to bypass or abbreviate some of the less important steps.

Throughout the development of these procedures we shall constantly need to be balancing the benefits of introducing additional steps against the penalties of the extra time and labour involved. In view of the rather long delay in receipt of Meteosat data from source compared with the almost real-time receipt of radar network data, there is, for example, a strong case for also disseminating actual data, based upon an abbreviated analysis of the radars alone, to some users requiring very up-to-date information on current weather.

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*Verbal dissemination will of course continue to be used for communicating limited amounts of information and additional verbal dissemination procedures may be introduced for issuing warnings to travellers. (eg 'Carfax').

5. FUTURE DEVELOPMENTS

We have described a strategy which will enable significant improvements in very-short-range forecasts of precipitation to be made by utilizing existing technology. However, the rapid pace of technological advances in three areas over the next decade will greatly influence the development of short-range weather forecasting systems. These areas of improvement are in solid-state technology, computer performance and mesoscale observing techniques.

(a) Advances in solid-state technology and their impact on short-range forecasting procedures

Solid-state technology is advancing so quickly that the costs of many of the elements involved in computer hardware are expected to fall very significantly in real terms over the next decade. For example, the cost of Random Access Memory (RAM) devices is expected to decrease by a factor of five, whilst the cost of bubble memory (Baker 1978) may decrease by a factor of 100 or more over the same period (Turn 1974). New storage techniques, such as holographic memory and laser discs may enable over 10^{10} bits of information to be stored on a single system (an increase of an order of magnitude over present memory systems), with the possibility of any bit being recalled within a fraction of a second. These developments are likely to accelerate the development and use of microprocessors (Klingman 1977), of mini-computers, and of midi-computers which combine the low cost of mini-computers with the large word length of mainframe machines (Theiss 1977).

The prospect of falling costs makes it entirely possible that fully interactive video display systems can be made available, not only at a central office, but at many regional offices as well. Such a distributed computer weather analysis and forecasting network would lead to perhaps the biggest change in meteorological operations since the advent of the large computer. Outstation meteorologists,whilst not necessarily having access to all of the detailed data, would still have a real opportunity to produce significant improvement in their forecast products on the small scales relevant to their local needs.

A major change in the mode of operation at regional forecast offices is already underway in the USA with the introduction of the AFOS (Automation of Field Operations and Services) system in which visual display units are replacing hard-copy facsimile charts for the display of synoptic data

(Klein 1976). Although the AFOS system is interactive in the sense of being a request/reply system allowing flexible access to different data formats, it is not interactive in the sense implied in the present paper in which the forecaster performs subjective analyses in which he can substantially modify the data on the video display whilst preserving all the original data in store. The impact of the strategy proposed in this paper is therefore likely to be different from that of AFOS. The introduction of AFOS, along with the concurrent introduction of MOS products and also computer-worded forecasts (Glahn 1978; Wickham 1976), will have the effect of allowing a fairly traditional kind of forecast in terms of detail and precision to be produced more efficiently, with fewer staff, and with less reliance on traditional forecasting skill. This has led many meteorologists to fear that forecasters may increasingly relinquish their subjective meteorological input to the detriment of the quality of the operational products going to the users (eg Snellman 1977). The concept discussed in this paper, on the other hand, is aimed at providing very-short-range forecasts with a degree of detail and accuracy that has previously been unattainable; the concept entails not only the exploitation of modern technology, but also the exploitation of the forecaster's subjective skill and his understanding of the atmosphere. If costs do indeed fall sufficiently for the latter concept to be extended to local forecast offices, it should improve not only the local forecasts but also the forecaster's job satisfaction. The accompanying devolution of greater responsibilities to the outstation forecasters would, of course, have major repercussions on future training needs.

(b) Improvements in the performance of mainframe computers and the introduction of operational mesoscale NWP models.

A numerical weather prediction model may require the completion of 10^{12} computer operations per simulated day (Mason, 1970), and so, in order to produce operationally useful weather forecasts, computers are required to carry out tens of millions of instructions per second (MIPS). During the 1960s manufacturers improved the design of computer logic circuits, making them smaller and switch faster. This led to rapid improvements in total speed of operation. At the same time other computers, known as array (or parallel) processors, were being designed which exploited the data structure of the problems they were meant to solve. An array processor is characterized by a single instruction stream and multiple data streams. A large array of processing elements, each element being a microprocessor, is controlled by a single control unit, and each processing element has its own private memory unit and addressing circuits. These computers are capable of speeds in excess of 100 MIPS. The availability of such computers offers the prospect of running NWP models employing smaller time steps and grid lengths than those now being used operationally.

In Fig 1 we outlined a system for short-range weather forecasting which included the operational use of a mesoscale NWP model capable of being continually updated by the output of an independent synoptic-scale NWP model and by observational data from radar and satellite as well as from more conventional sources. Parasitic mesoscale models of this type are currently being developed, with grid lengths as small as 10 km and with a structure capable of describing systems which lead to significant weather on the mesoscale (eg Tapp and White 1976). Carpenter et al (1978) have discussed the possibility of using such a model in the UK Meteorological Office for operational short-range weather forecasting. Since the powerful computers required to accomplish this are now available, it is suggested by Carpenter et al that operational implementation could be achieved within the next decade. For the effective operational use of the planned NWP models, however, more detailed and timely observational data will be required for a variety of atmospheric parameters. This will be discussed next.

(c) <u>The introduction of new observing techniques and their impact on short-range weather forecasting in general.</u>

We have restricted this paper to the description of a system for observing, analysing, and forecasting precipitation. However a whole new generation of remote probing techniques is being developed to provide mesoscale observations of other important meteorological variables. Good examples of ground-based techniques are the measurements of vertical profiles of temperature and water vapour by microwave radiometer (Decker et al 1978) and of vertical wind profiles by VHF Doppler radar (Warnock et al 1978). An important development in remote probing from satellites is the United States VAS (VISSR Atmospheric Sounder) programme, which is aimed at obtaining frequent vertical soundings of temperature and humidity with high horizontal resolution from a geostationary (GOES) satellite. Other developments in satellite observing techniques have been reviewed by

Houghton (1979). At the same time methods are being developed for communicating, rapidly and economically, the in-situ surface observations required to calibrate and supplement the remote probing observations. Undeed, microprocessors are already being used for this purpose in automatic weather stations (Harrold et al 1977). Technological advances such as these form the basis of far-reaching forecasting research projects proposed for the future. One such project is the PROFS (Prototype Regional Observing and Forecasting Service) programme (Beran and Little 1978); other long-term aspirations (forming part of the NASA Severe Storm Research Plan) are outlined by Anthony and Bristor (1978).

Thus we can look forward to a time when fairly complete four-dimensional data sets describing the mesoscale state of the atmosphere will be available (mainly in the USA at first) on an almost continuous basis. These data will be used in interactive video systems to prepare detailed analyses of the current weather. New ways of synthesizing and analysing the multifaceted data sets will be required, necessitating further development of the interactive video systems, with overlays of conventional synoptic data and radar and satellite data being produced in a variety of combinations (Anthony and Bristor 1978, Smith et al 1978). These improved analyses will be used as input to very-short-range forecasting procedures of the kind described in this paper and will also provide continuous input for initializing NWP models. This is the concept which was summarized in Fig 1.

6. CONCLUSIONS

The line of argument that has been developed in this paper is as follows:

- A key requirement for making very-short-range precipitation forecasts to be able to observe the mesoscale field of precipitation on an almost continuous basis.

- Such fields can form the basis of simple forecasts by extrapolation in the 1-6 h time frame, and can also be used to help initialize mesoscale NWP models for prediction in the 6-24 h time frame.

- It is not an easy matter to measure mesoscale precipitation fields, and data from several sources need to be carefully analysed and then combined.

- The most effective tool for the quantitative measurement of precipitation fields is radar; to get sufficient coverage for forecasting a few hours ahead an integrated network of radars is needed.

- To obtain more warning of approaching precipitation systems, especially from data-sparse sea areas in the case of the UK, it is possible to extend the coverage using cloud imagery from existing satellites; only a geostationary satellite is capable of providing data frequently enough for very-short-range forecasting.

- The transfer function between cloud imagery and surface precipitation is not well defined and radar observations are a great help in 'calibrating' the neighbouring cloud patterns in terms of precipitation; to facilitate the combined analysis of the radar and satellite data the two sets of data need to be reduced to a common format.

- Vast amounts of data are generated by radar and satellite and this calls for a high degree of automation in the handling of the data; at the same time, however, the imperfections in the observational data and in the objective forecast procedures are such that for the forseeable future a combination of objective techniques and subjective judgement will play an important role in the analysis and forecasting.

- The new technology of interactive computer-driven video displays can be exploited to enable the human forecaster to exercise his judgement effectively within the framework of an otherwise highly automated procedure; all-digital processing is required for flexibility and quantitativeness. The degree of interaction required is greater than that employed in present intervention schemes.

- Detailed forecasts for a few hours ahead are a perishable commodity whose value depends on the ability to distribute them widely and promptly, and in an easily understood format: new dissemination techniques such as teletext and viewdata offer this capability.

- Obvious errors will be removed during the analysis of the radar data using the interactive video display; this provides the kind of preliminary quality control that is necessary if the radar data are also to constitute a reliable mesoscale climatological archive.

- The systematic archive of data and the analytical experience gained by regular use of these facilities will provide an excellent opportunity for improving fundamental understanding of the structure and mechanisms of mesoscale precipitation systems; this will in turn contribute to further improvement in forecasting techniques.

A pilot forecasting programme based on the above philosophy has been initiated at the Meteorological Office Radar Research Laboratory. Small teams will be working side-by-side to develop technical facilities, to do basic mesometeorological research and to develop operational forecast techniques. There will be a mix of real-time operational research and off-line analysis on a case-study basis. It is hoped thereby to tailor the technical developments to suit the operational demands and to enable the forecasting procedures to take full advantage of improved understanding. The scheme will be built up in stages and will be operated over a period of 5 to 8 years to establish cost-effectiveness. At first the man-computer interactive analysis and forecasting will be a centralized activity. With the decreasing costs being brought about by advances in solid-state technology, however, one can foresee a time when some interactive procedures might be extended to outstations to help achieve forecasts tailored more specifically to local needs. The emphasis in this paper has been on forecasting just precipitation. However, a similar approach involving the use of interactive video displays for analysis and forecasting can be developed for very-short-range forecasting in general.

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FIG 1 : INTEGRATED FORECAST SYSTEM (this paper deals with the part enclosed within the dashed rectangle)

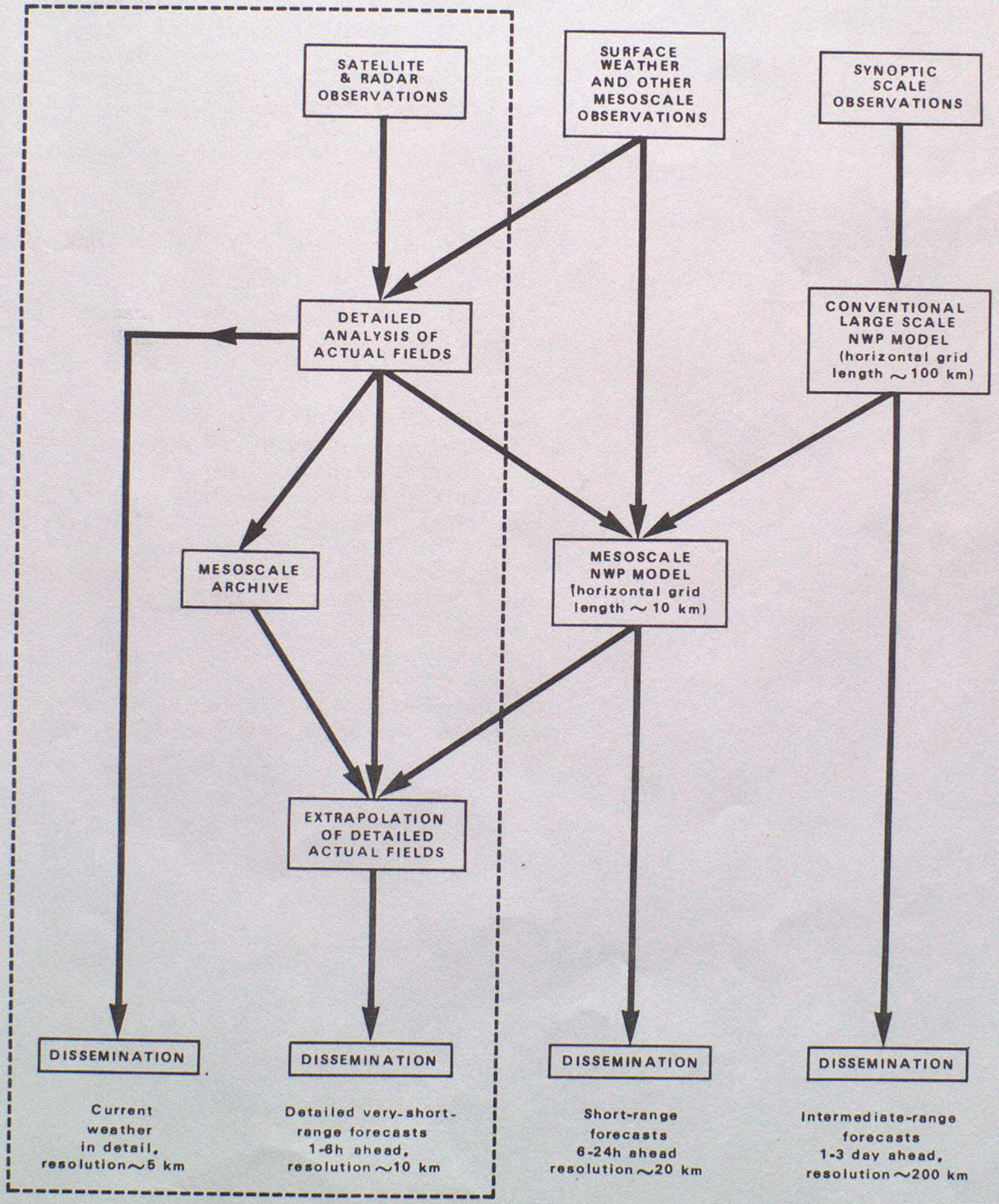


FIG 2: OVERVIEW OF SCHEME FOR VERY-SHORT–RANGE PRECIPITATION FORECASTING

(Showing major stages only)

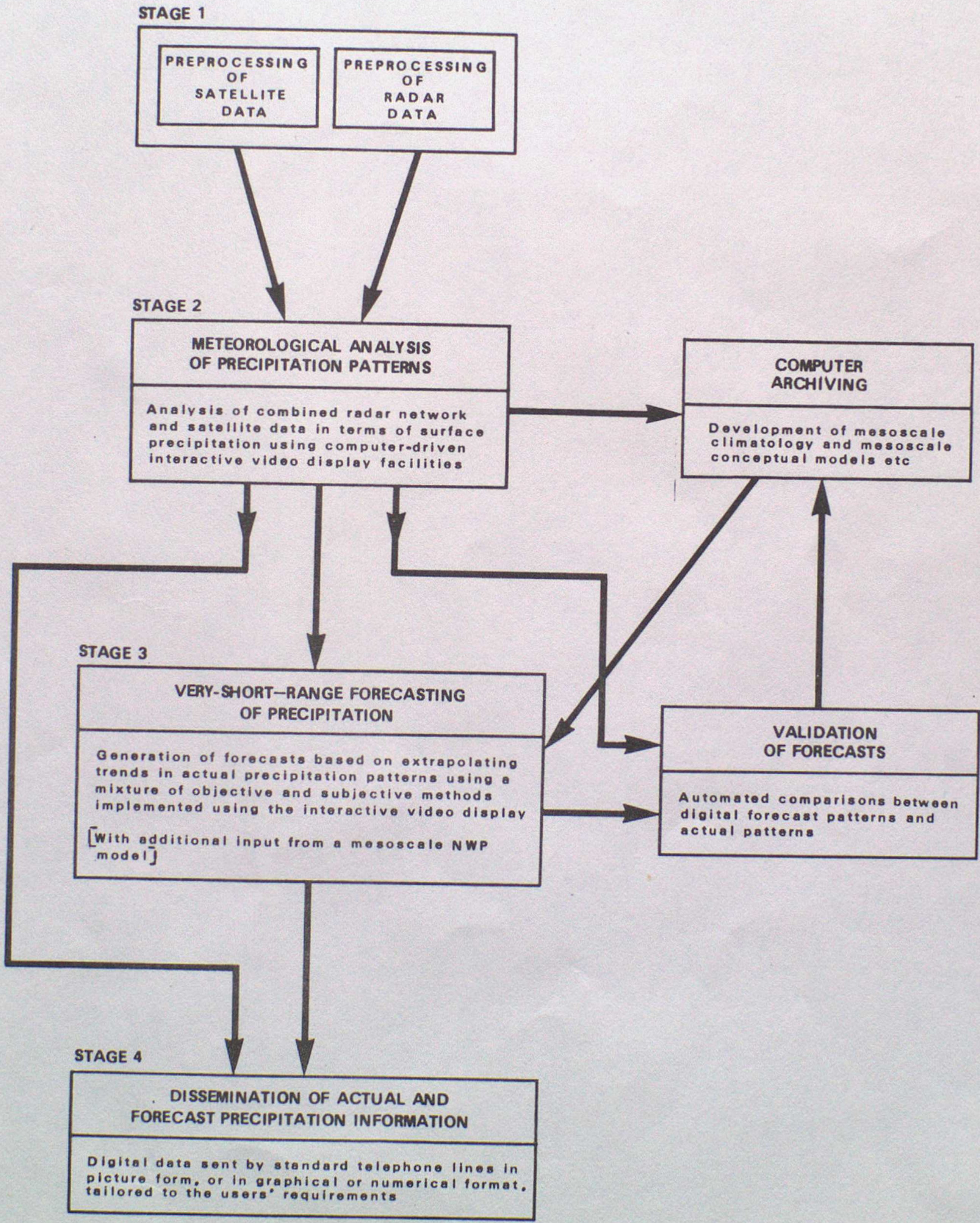
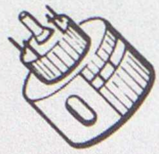


FIG 3 STAGE 1 : PREPROCESSING OF SATELLITE AND RADAR DATA



automatic

RECEIVE DIGITAL IMAGE DATA IN IR AND VIS CHANNELS EVERY 30 MIN FROM GEOSTATIONARY METEOSAT SATELLITE

automatic

TRANSFORM PROJECTION TO RADAR FORMAT

Convert to rectangular Cartesian co-ordinates on a Transverse Mercator Projection corresponding to the English National Grid. A 5 km grid size is used which corresponds to the full E-W resolution in the IR. A second-order correction can be applied for parallax errors owing to the oblique angle of view over Britain using a knowledge of the cloud top height inferred from the IR radiances

manual input

NAVIGATE THE SATELLITE IMAGES

Display on a colour TV monitor in 256 x 256 (5 x 5)km format. Up to 256 stored levels of intensity can be represented as required by colour and/or grey shades. Use contrast stretching and level slicing to emphasize land-sea boundaries in areas not obscured by cloud and adjust picture registration to correct for residual errors owing to variability in satellite geometry

automatic

COMBINE IR AND VIS DATA FOR OPTIMUM REPRESENTATION OF SURFACE PRECIPITATION PATTERN (daytime only)

automatic

BASIC RADAR DATA PROCESSING AT EACH RADAR SITE

This includes

- signal integration to minimise effect of statistical fluctuations
- correction for $\left(\frac{1}{\text{range}}\right)^2$ attenuation
- corrections for partial obscuration of radar beam
- application of various procedures to minimise ground clutter
- conversion from radar reflectivity to precipitation intensity
- calibration using telemetering raingauges
- correction for attenuation by intervening precipitation (C-Band)
- conversion from polar to Cartesian co-ordinates

Transmission of 8-bit intensity data on 2 km and 5 km grid to a central location every 5 or 15 min

3-bit data from individual radars may also be sent direct to some local users

automatic

RADAR NETWORK COMPOSITING

Generate, every 15 min, a radar-rainfall composite map on 256 x 256 (5x5) km grid with 8 intensity levels displayed and 256 levels stored

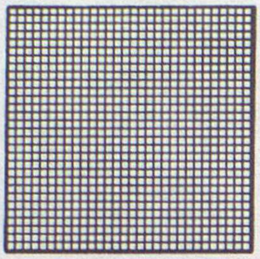
Generate detailed maps and areal integrations using data with 2 km resolution and 256 intensity levels received at 5-min intervals (These data are for research and hydrological use only)

DATA IN FORMAT SUITABLE FOR STAGE 2

METEOROLOGICAL ANALYSIS TO GENERATE SURFACE PRECIPITATION PATTERNS

FIG 4(a) STAGE 2 : METEOROLOGICAL ANALYSIS OF PRECIPITATION PATTERNS
(a) CORRECTIONS TO THE RADAR NETWORK DATA

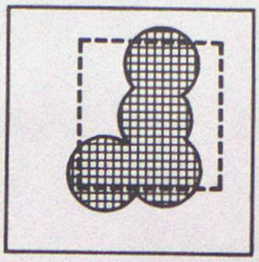
PREPROCESSED METEOSAT DATA



256 x 256 (5 x 5) km x 8-bit

EVERY 30 MIN

PREPROCESSED RADAR NETWORK DATA



256 x 256 (5 x 5)km x 8-bit

EVERY 15 MIN

STEP 2.1 manual input

USE 128 x 128 ZOOM

READJUST CALIBRATION OF INDIVIDUAL RADARS

Replay time sequence of radar network data : look for discontinuities in time and space from one radar umbrella to the next

Compare radar network data with any available ground - truth data : look for systematic errors

STEP 2.2 manual input

ZOOM

IDENTIFY ECHOES DUE TO 'ANAPROP', SEA CLUTTER AND INTERFERENCE, AND ELIMINATE THEM

View radar network and satellite data alternately, superimposed, or side-by-side : radar echoes not accompanied by appropriate cloud are likely to be spurious

View radar network data in time lapse : stationary echoes may be due to anaprop (although not <u>all</u> echoes due to anaprop are stationary). Interference can be identified as meteorologically unrealistic patterns

Compare radar network data with overlay map showing common locations of anomalous ground clutter and sea clutter

STEP 2.3 manual input

ZOOM

ASSESS VALIDITY OF 'BRIGHT BAND' CORRECTIONS AND APPLY IF APPROPRIATE

Rough corrections may be derived objectively from data at different elevation scans and their validity can be assessed by displaying the data with and without the correction applied

STEP 2.4 manual input

ZOOM

DETERMINE BOUNDARIES OF USABLE RADAR DATA AND APPLY RANGE–DEPENDENT CORRECTIONS

This can be done given a knowledge of:

(a) which radars are operational
(b) the characteristics of each radar and the horizon at each radar site, and
(c) the nature of the precipitation (eg heavy convective showers can be measured accurately to longer range than shallow frontal precipitation)

STEP 2.5 manual input

ZOOM

APPLY FURTHER CORRECTIONS IN SITUATIONS OF PROBABLE OROGRAPHIC ENHANCEMENT TO ALLOW FOR UNDETECTABLE LOW–LEVEL GROWTH AT MEDIUM AND LONG RANGES FROM THE RADARS

This can be done using a field of correction factors from a computer-based mesoscale climatological archive

CONTINUED IN FIG 4(b)

CONTINUED IN FIG 4(b)

FIG 4(b) STAGE 2 : METEOROLOGICAL ANALYSIS OF PRECIPITATION PATTERNS (CONT'D)
(b) ANALYSIS OF SATELLITE DATA AND COMBINING THE RADAR AND SATELLITE DATA

CONTINUED FROM Fig 4(a)

CONTINUED FROM Fig 4 (a)

STEP 2.6
manual input

ADJUST SATELLITE LEVELS SO THAT TO A FIRST APPROXIMATION THEY CORRESPOND TO RADAR LEVELS

View satellite and radar network data alternately or side-by-side; then adjust the satellite levels so that they correspond as nearly as possible to the rainfall levels within the areas covered by the radars. At this stage only an overall adjustment is attempted; local differences are treated later.

STEP 2.7
automatic

COMBINE RADAR NETWORK AND ADJUSTED SATELLITE DATE USING RADAR DATA WHERE POSSIBLE AND THE SATELLITE DATA ELSEWHERE

STEP 2.8
manual
input

SUBJECTIVELY BOGUS THE SATELLITE DATA

(a) "Take-away" analysis

Using the cloud data as a first approximation to the surface precipitation pattern, delete from the display those areas of cloud not associated with surface precipitation.

(b) "Build-up" analysis

In circumstances when the relationship between cloud data and surface precipitation is poor, introduce 'from scratch' simplified areas of surface precipitation

The strands of evidence used in these analyses are:

- i ground truth data
- ii comparison of Meteosat IR data with Meteosat VIS data
- iii texture of very high resolution VIS data from polar-orbiting satellites, and
- iv conceptual models of mesoscale weather systems

ANALYSED SURFACE PRECIPITATION PATTERN
FOR DISSEMINATION (STAGE 4)
AND INPUT TO FORECASTING PROCEDURES (STAGE 3)

FIG 5 : STAGE 3 VERY–SHORT–RANGE FORECASTING OF PRECIPITATION PATTERNS

INPUT FROM STAGE 2

↓

STEP 3.1
manual
input

REMOVE OROGRAPHIC EFFECTS AS FAR AS POSSIBLE

Subtract the orographic enhancement and rain shadow effects in order to prevent the extrapolation scheme from spuriously advecting these features. This is achieved by the inverse application of computer-archived fields of topographic enhancement derived as a function of surface wind and relative humidity. Additional subjective adjustment can be used to minimise topographically related anomalies

↓

STEP 3.2
automatic

FILTER (DEGRADE RESOLUTION)

Reformat the precipitation pattern into a manageable array of data (eg 64 x 64 (20 x 20) km) for input into objective extrapolation model.

↓

STEP 3.3
automatic

OBJECTIVE LINEAR EXTRAPOLATION OF ANALYSED PRECIPITATION PATTERN

Derive forecast by extrapolation of successive patterns. There are several objective extrapolation procedures that can be used which take into account the differences in motion between different parts of the precipitation pattern and between different precipitation intensities. Although the input data are in 20 km squares, the forecast patterns are displayed on a 256 x 256 (5 x 5) km grid so as to minimise quantizing errors.

↓

STEP 3.4
manual
input

SUBJECTIVE INTERVENTION TO AMEND OBVIOUS DEFECTS IN OBJECTIVE EXTRAPOLATION

View the forecast product in time-lapse for a succession of 30-min intervals as a continuation of the sequence of analysed precipitation patterns. Thereby identify discontinuities between actual and forecast sequences. Modify the velocity and/or intensity in selected sub-areas until a fairly smooth overall time-lapse sequence is obtained.

↓

STEP 3.5
manual
input

INTRODUCE TRENDS IN INTENSITY IMPLIED BY MESOSCALE NWP MODEL

↓

STEP 3.6
manual
input

SUBJECTIVELY REINTRODUCE ANY MAJOR STORM CORES LOST IN SMOOTHING PROCESS

↓

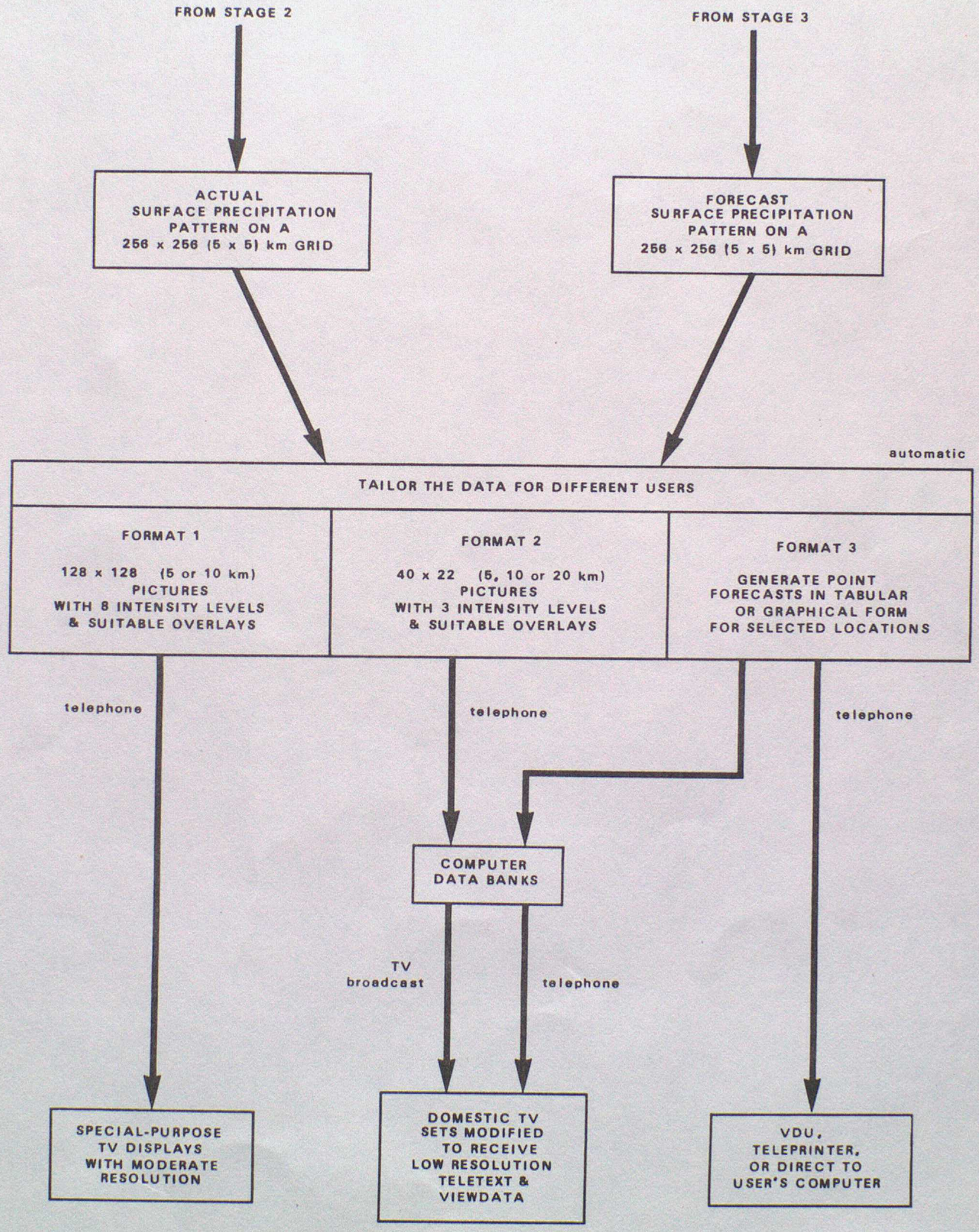
STEP 3.7
manual
input

REINTRODUCE OROGRAPHIC EFFECTS

↓

FORECAST SURFACE PRECIPITATION PATTERN
FOR DISSEMINATION (STAGE 4)

FIG 6 STAGE 4 : DISSEMINATION TO THE USERS



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No 1 The Short Period Weather Forecasting Pilot Project
K A Browning

No 2 Observation of Strong Wind Shear using Pulse Compression Radar.
K A Browning, P K James (Met O RRL). D M Parkes, C Rowley A J Whyman (RSRE)

No 3 Assessment of a Real-Time Method for Reducing the Errors in Radar Rainfall Measurements due to Bright-Band
J L Clarke, RSRE, C G Collier, Met O RRL

No 4 Meteorological Applications of Radar
K A Browning

No 5 Structure of the Lower Atmosphere Associated with Heavy Falls of Orographic Rain in South Wales.
J Nash, K A Browning

No 6 On the Benefits of Improved Short Period Forecasts of Precipitation to the United Kingdom - Non Military Applications Only
C G Collier

No 7 Persistence and Orographic Modulation of Mesoscale Precipitation Areas in a Potentially Unstable Warm Sector.
F F Hill, K A Browning

No 8 Mesoscale Structure of Line Convection at Surface Cold Fronts.
P K James, K A Browning

No 9 Objective Forecasting Using Radar Data: A Review
C G Collier

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