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LOCAL WEATHER FORECASTING

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presented at the Royal Society).

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ABSTRACT

Good progress has been made in forecasting the broad pattern of the weather for periods up to a few days ahead as a result of developments in mathematical weather prediction models. However, our ability to forecast the detailed weather for specific locations just a few hours ahead still leaves a lot to be desired. In this lecture it is suggested that local forecasting, after a quarter century of stagnation, is poised for a decade of slow but steady improvement. Changes will come as a result of new programs which exploit and integrate advances in several areas. These areas include better weather observations, especially from satellites and radar, improved methods of data processing and analysis, and the development of more detailed numerical prediction models. New methods of communications, such as viewdata, will enable the improved local forecasts to be disseminated promptly and in a wide range of specially tailored formats. This will contribute to the development of a more user-oriented meteorological service.

1. Introduction

Atmospheric motion systems can be classified according to their characteristic space and time scales. It is customary to divide the spectrum into four parts - the planetary scale, synoptic scale, mesoscale and microscale (table 1). In recent years there has been substantial progress

Table 1. Scales of motion in mid-latitude weather systems

Category	Examples	Horizontal Scale	Lifetime
Planetary scale	Rossby waves Sub-tropical anticyclones	>5000 km	>500 h
Synoptic scale	Depressions Anticyclones	500 - 5000 km	50 - 500 h
Mesoscale	Some smaller depressions and troughs Fronts Squall lines Mountain waves	20 - 500 km	2 - 50 h
Convective scale	Showers Thunderstorms Tornadoes	1 - 20 km	$\frac{1}{10}$ - 2 h
Microscale	Boundary layer eddies	< 1 km	$< \frac{1}{10}$ hr

in forecasting the state of the atmosphere on the synoptic scale for periods up to several days ahead. Improvements have been achieved largely through the continuing development of objective mathematical prediction methods (see the Royal Society Review Lecture by Mason 1978). These methods depend mainly on standardized measurements of temperature, humidity and wind made worldwide at 12 h intervals. The measurements are used to solve equations of motion, mass continuity and thermodynamics, taking into account effects of the water substance and its changes of phase. Such methods cope well with the broad features of depressions and anti-cyclones. But they have not led to correspondingly large improvements in forecasting the detail of the weather at individual locations over the period 0 to 12 h ahead with which we are concerned in this lecture. This is because local weather is greatly influenced by mesoscale and convective-scale disturbances, and the synoptic-scale numerical weather prediction (NWP) models do not fully resolve these disturbances nor do they adequately represent their physics.

Consider the following example of the challenge the local forecaster faces. The synoptic-scale numerical model on a given occasion predicts an unstable westerly airstream over the British Isles which is expected to produce "bright intervals and scattered showers some of which may merge into longer periods of rain". The local forecaster has the task of converting this tantalisingly ambiguous information into something more specific and useful. He needs to be able to say that an organized region of heavy showers will arrive at a certain location in 2 h, whilst other specified areas are likely to remain dry. To make it worthwhile attempting such a forecast it is necessary first and foremost that the atmosphere should have some coherent and recognizable organization on the mesoscale. Studies of mesoscale weather systems over the past two decades indicate that this is often the case. Thus, although individual showers on the convective scale may come and go, areas of showers on the mesoscale tend to maintain a coherent pattern.

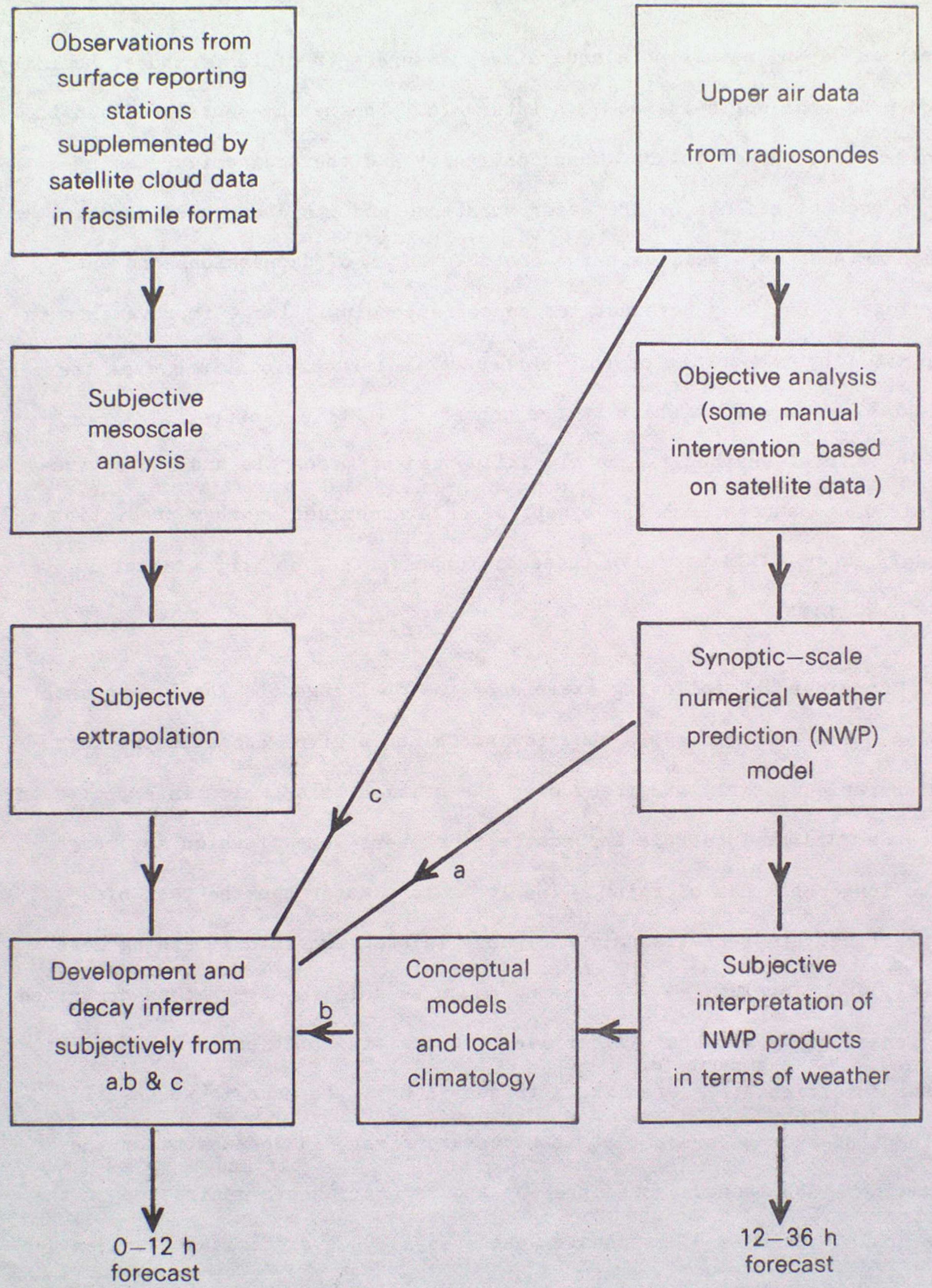


Figure 1

Figure 1   Preparation of local forecasts by traditional methods.

Operational forecasters do not at present have adequate facilities either to identify and track mesoscale weather systems or to predict their evolution. However, good progress is being made toward remedying this situation. In the first place, weather satellites and ground-based radars are capable of providing many of the required mesoscale observations, and, as a result of advances in digital data processing and communications, it is becoming possible to make more effective use of these observations. Secondly, increases in the speed of mainframe computers are permitting the development of numerical models with the much higher resolution needed to represent mesoscale phenomena. At the same time statistical methods are being introduced to improve the interpretation of existing numerical forecast products. The purpose of this lecture is to review progress in these areas and to discuss ways in which these techniques are likely to be combined and extended over the next decade to form the basis of a system capable of providing significantly improval local weather forecasts for the period 0 to 12 h ahead. The emphasis will be on forecasting for mid-latitude regions such as the United Kingdom.

2. Traditional methods

Current forecasting practice can be summarized as in figure 1. The forecaster treates the synoptic-scale numerical model predictions as general guidance which he interprets in the light of his knowledge of the weather typically associated with the synoptic situation predicted for his area of interest, and in the light of the location and evolution of the observed weather events in and upwind of his area. Although objective statistical methods are becoming more widely used, the forecaster's knowledge of local climatology is often a matter of personal experience, applied subjectively. His knowledge of the current weather pattern is fragmentary, being based on widely scattered observations from surface reporting stations some of which are greatly influenced by local (eg coastal) effects. Today's forecasters may have access to satellite and radar pictures but what little information he does have is not in an easily used or quantitative format. Hence, as every forecaster knows to his cost, it is possible for the synoptic-scale guidance to be correct in terms of the broad predictions of pressure or even rainfall, yet for him to be unable to forecast with any accuracy the detailed weather at a particular town or airport a few hours ahead.

3. New approaches

The approaches to local forecasting now being pursued (figure 2) are logical developments of existing techniques. Apart from the continued development of empirical forecasting rules, the main techniques can be categorized broadly into the following types:

(i) Objective interpretation of the output of a synoptic-scale numerical-dynamical model in terms of local weather using climatological statistics.

(ii) Use of very-high-resolution mesoscale numerical models. The most widely applicable models are based upon the full set of dynamical equations in their general or 'primitive' form. Simplified models tailored to specific phenomena can also be used.

(iii) Extrapolation of the detailed pattern of current weather as observed using a combination of conventional and remote probing techniques.

Examples of these approaches will be presented in later sections but first we compare them in broad terms.

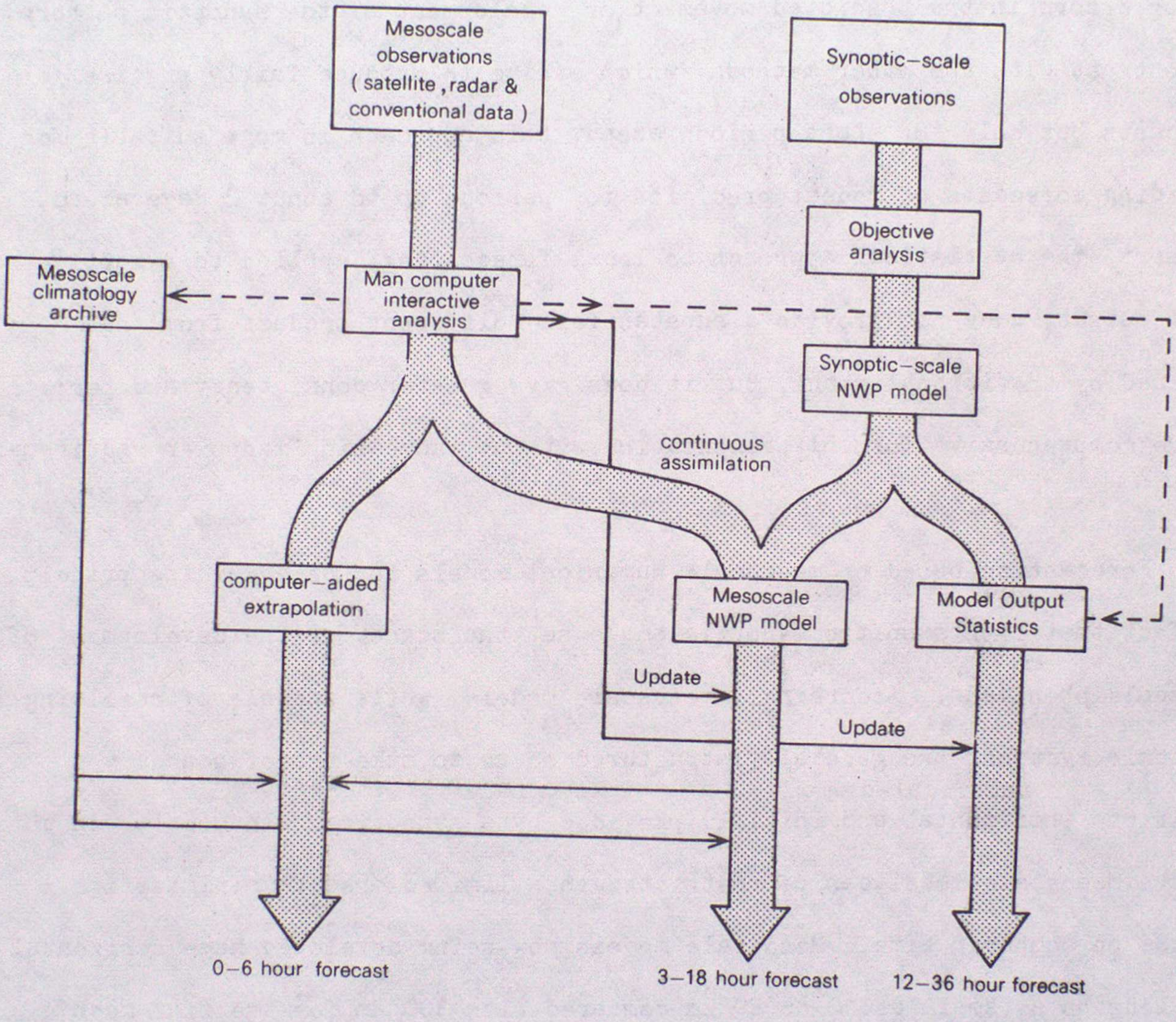


Figure 2

Figure 2 Outline of local forecasting approaches.

The statistical approach, as presently being developed, is a way of making the best possible use of synoptic-scale numerical model guidance; it does not seek to exploit new methods of numerical modelling or new forms of observations except insofar as better observations, from satellites for example, can remove some of the errors in the initialization of the synoptic-scale model or correct timing errors in the predicted movement or development of the synoptic pattern. In contrast with the other methods, which strive to produce fairly precise forecasts but only for short periods ahead, this approach is more suitable for providing forecasts of modest precision for periods up to about 2 days ahead. In short, the statistical approach to local forecasting, applied to synoptic-scale model output, does not provide a substantially different product from that obtained by traditional means, but it does give greater consistency and permits a more comprehensive form of presentation without increasing manpower requirements.

Forecasting based on mesoscale numerical models has as a guiding principle the fact that events on the synoptic scale set the scene for the development of mesoscale phenomena. Accordingly mesoscale models, while capable of resolving mesoscale systems, are generally structured so as to make use of boundary conditions (horizontal and initial) provided by a synoptic-scale model. In this way the mesoscale model can be restricted to a limited area to minimize its demands on computer time. Mesoscale models now being developed have horizontal grid lengths as small as 10 or 20 km compared with 100 km for the fine-mesh synoptic-scale models now in use. This resolution is such that, even using the synoptic models to drive them, it still takes 5 h of CPU time on an IBM360/195 computer for a mesoscale model of this kind to produce a 24-h forecast (Carpenter 1979). However, the advanced vector computers now available enable the computational time to be cut by over an order of magnitude and this is making the use of such models a practical proposition for operational forecasting.

The ease with which a mesoscale model can represent a particular weather phenomenon depends in large measure on the extent to which the phenomenon is constrained by the underlying topography. In tables 2 and 3 mesoscale phenomena are segregated into two categories: both categories are forced by events on the synoptic scale but the phenomena in table 2 unlike those in table 3 are modulated strongly by local forcing functions prescribed by geographically fixed features such as hills and land-sea boundaries.

Table 2

Examples of mesoscale weather phenomena that are strongly constrained by surface effects

- Effect of hills on winds over a deep layer (eg mountain waves, lee waves, rotors, and föhn winds)
- Effect of hills on surface winds (eg deviating effects, sheltering effects, funnelling through valleys, upslope and downslope flows induced by daytime heating and nighttime cooling, respectively).
- Orographic cloud and the orographic enhancement of frontal precipitation by hills.
- Diurnal land and sea-breezes, with associated changes in temperature, humidity and wind.
- Preferential initiation of air-mass thunderstorms in the vicinity of high land and sea-breeze convergence zones.
- Enhancement of frontal precipitation by low-level coastal convergence (eg when warm air from the sea overrides a shallow pool of cold air over land or when low-level convergence occurs due to differential friction in an air-stream flowing parallel to the shoreline).
- Coastal snowstorms due to cold air having recently traversed a warm lake or sea
- Mesoscale circulations and the intensification of convection associated with urban heat sources.
- Low nighttime temperatures and the formation of frosts and radiation fogs in valleys on clear nights.
- Nocturnal low-level jets to the east of mountain barriers.

Table 3:

Examples of mesoscale phenomena that are not strongly constrained by surface effects

- Fronts, sometimes with sharp wind and temperature gradients associated with them.

- Rainbands (several rainbands are sometimes associated with a single front).

- Mesoscale areas of precipitation (areas of heavier precipitation tens of kilometres across which are often embedded within widespread frontal precipitation and are associated with mid-tropospheric convective instability.

- Squall lines, consisting of lines of intense convective storms.

- Severe thunderstorms

- Small polar air depressions and short wave troughs producing organized mesoscale areas of moderate-to-heavy precipitation.

- Low level jet streams ahead of many cold fronts.

- Clear air turbulence due to Kelvin-Helmholtz instability on strongly sheared frontal zones or at the edges of upper tropospheric jet streams (enhanced by hills but also occurring in their absence).

Preliminary investigations suggest that the topographically constrained type of phenomenon may be forecast reasonably well using a mesoscale numerical model given no more than a broad synoptic-scale description of the state of the atmosphere, provided the model contains the relevant physics and the geographical features are represented in appropriate detail. The output of the model in this case is more sensitive to the local topography than to the initial state of the atmosphere on the mesoscale (Kreitzberg 1976). Thus, despite the limitations of the observations that are currently available, useful forecasts can be expected up to 18 h ahead in some cases. Although this timescale is short compared with that of forecasts from synoptic-scale models, it can be considered long for a forecast containing a fair amount of detail. Indeed, because it takes time for the topographical forcing to enable the model to generate mesoscale features absent in the initial data, such forecasts are likely to be better after 6 h than during the first few hours.

In contrast to the phenomena listed in table 2, those in table 3 have a mesoscale structure, which, although influenced by the lower boundary conditions, is not primarily determined by them. The interplay of atmospheric instabilities with the latent heat sources and sinks associated with the water substance is one potent mechanism for maintaining this kind of mesoscale system, and the atmosphere has many modes in which this interplay can occur. Given only the synoptic-scale field of motion and state parameters as input, it should still be possible in principle for a mesoscale model to predict the likely occurrence (although not the precise location) of these mesoscale events before they develop. But, in practice, an adequate forecast of the development of one of the events in table 3 depends on a positive identification of the phenomenon itself at an early stage in its development, or the observation of some mesoscale precursor (such as strong low-level moisture convergence before the outbreak of severe thunderstorms). The burden is thus shifted to obtaining the necessary fields of mesoscale observations, and to deriving ways of reconciling such observations with the fields derived by the model from earlier input data using 4-dimensional objective analysis.

The development of methods of assimilating large amounts of data, often obtained at non-standard hours, is still at an early stage. In the Forecasting Research Branch of the Meteorological Office experiments are being conducted on the assimilation of observational data in a mesoscale model. It is already possible to prepare good synoptic-scale analyses by assimilating data into a forward-running numerical model and a similar technique, if it could be applied successfully on the mesoscale, would provide continuously updated analyses from which to initiate forecast integrations. This should provide the means for avoiding the problems of starting from excessively smooth or badly adjusted initial data.

Mesoscale observations can also be put to good use independently of a numerical model. And this brings us to the last in our list of three approaches to local forecasting, which relies heavily on descriptions of current weather obtained from satellies and ground-based radar, using a procedure often referred to as 'nowcasting' (Scofield and Weiss 1977). This approach is based on the belief that many of our present difficulties in local forecasting are attributable to ignorance of the current weather. Given frequently updated and detailed descriptions of the current weather, the procedure is to extrapolate the observed motion and changes in intensity of the phenomenon of interest using objective methods as far as possible. Such forecasts are useful for very short periods ahead. In their simplest form they do not take into account future development or decay and so, unlike the numerical models, they are not well suited to forecasting more than 6 h ahead. In fact there are special circumstances in which great value is attached to detailed forecasts of a weather hazard even for periods only minutes ahead. In such cases the mere detection of the hazard is the main requirement, as for example when Doppler radar is used to detect a tornado vortex signature or a region of low-level wind shear at an airfield (eg see the review by Browning 1978).

One might have expected that, even for very-short-range forecasts, the best possible results would have been obtained by using the detailed observational data to initialize a mesoscale model. However, the basic observational data have to be degraded before they can be input to a numerical model. Not only does the resolution of the data need to be coarsened but also some important features of the observed weather cannot be directly incorporated. Precipitation, for example, has to be expressed in terms of implied fields of relative humidity and vertical air motion. Thus, if considerable detail is required in a local forecast, the simple observational approach tends to be the best method for forecasts up to a few hours ahead. Although straightforward in concept, forecasting by extrapolation calls for sophisticated data handling facilities and it is only recently that good progress has been made in this area.

The nature of the forecasts obtained by the three approaches described above is summarized schematically in figure 3 in terms of the lead-time of the forecast and the 'quality' of the forecast, which we define loosely as the product of the accuracy achievable and the amount of detail in the forecast.

This figure makes the point that the three approaches are complementary. Each has its place according to the lead time and detail required of the forecast. For most applications the economic value of a forecast increases with lead time; however, the quality of the forecast falls with increasing lead time and the relative cost-effectiveness of the different types of forecasts depends on the particular needs of the user.

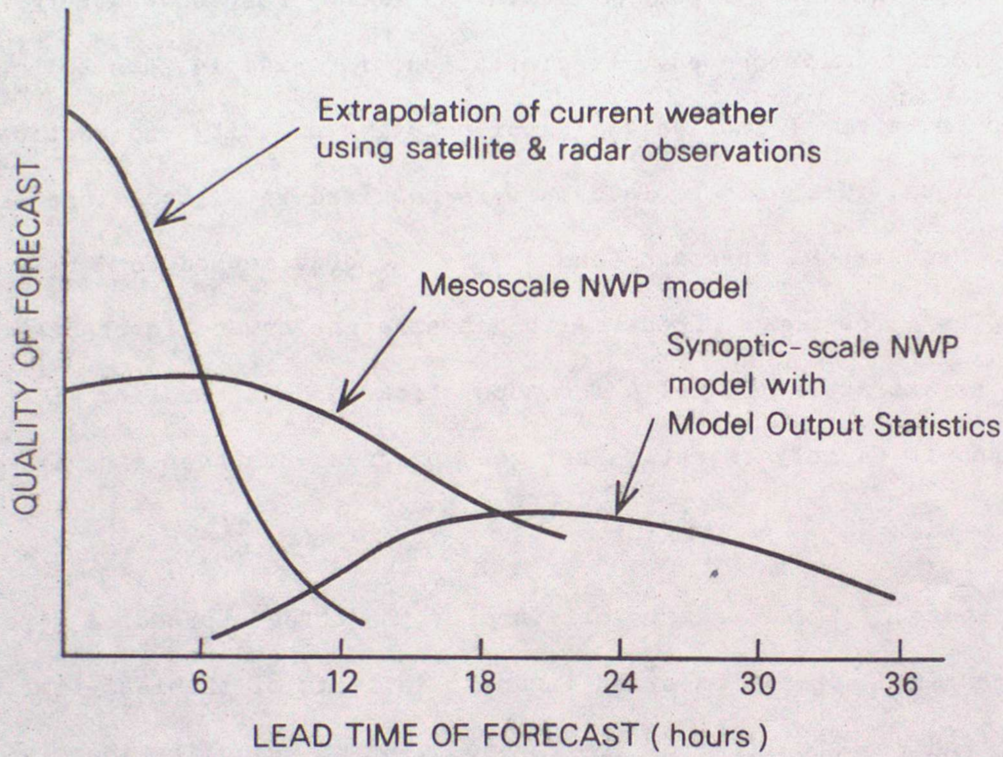


Figure 3

Figure 3 The quality of weather forecasts, defined as the product of the accuracy and detail achievable, shown as a function of lead time for 3 different forecasting methods. The figure is highly schematic and the stage at which the quality of one technique becomes superior to another will not only change over the years with the development of the different methods but will also depend on the particular phenomenon being forecast.

4. Statistical methods

The use of objective statistical methods to refine the raw output from a numerical model is limited at present to the output from synoptic-scale models; however, they can and should be applied to the output from mesoscale models when these become operational. The advantages of statistical methods are that they can provide forecast information on local scales when the dynamics of the local weather phenomena are not fully understood and when the computational time is too long for the model to resolve a phenomenon in the required detail. One statistical approach is to specify local weather conditions from multiple regression equations derived from observed parameters of the large-scale circulation and then to apply these relationships to the predictions of the model. A better approach, referred to as Model Output Statistics (MOS) (Glahn and Lowry 1972), is one in which the statistics are derived by correlating the local weather directly with the output from the numerical model. In this way any systematic bias in the model is automatically taken into account.

The method of Model Output Statistics is being used operationally to produce automated local forecasts for many individual locations in the USA. Figure 4 is an example of the forecast format. Worded summaries of the kind shown at the foot of the figure are now being derived entirely by computer. These centrally-generated products are well suited to dissemination via the newly automated forecast outstations as part of the scheme known as AFOS (Automation of Field Operations and Services) (Klein 1976) Forecasts of this kind are, however, derived from rather

THURSDAY 13 SEPT 1979

WASHINGTON, DC

ELEMENT	UNITS		12Z		18Z		00Z		06Z		12Z		18Z		00Z		06Z		12Z
			(---TODAY---)				(--TONIGHT--)				(-TOMORROW-)				(-TMRW NIGHT-)				
TEMP M/M	DEG F				82				68				81				66		
TEMP	DEG F	71	71	76	80	80	76	73	72	71	70	74	78	77	74	71			
POP(12)	PERCENT						28				87				71				44
POP(6)	PERCENT				2		30		63		75		47		58				
POF(P)	PERCENT		0		0		0		0		0		0		0				
POZR(P)	PERCENT		0		0		0		0		0		0		0				
PREC TYP	CATEGORY		3		3		3		3		3		3		3				
R SHR(L)	PERCENT				66				19				54						
DRZL(L)	PERCENT				15				9				14						
RAIN(L)	PERCENT				19				72				32						
TSTM	PERCENT				6				8				12						
SVR T(T)	PERCENT																		
OPF	CATEGORY						1				3				3				
CLOUDS	CATEGORY		1		4		4		4		4		4		4		4		4
FOG	PERCENT																		
WIND D/S	DEG MPH		1106		1508		1405		1510		1611		1910		2410				
CIG	CATEGORY		6		5		5		4		4		4		4				
VIS	CATEGORY		3		4		4		4		4		3		3				
SNOW AMT	CATEGORY																		

WASHINGTON, DC

SUNNY THIS MORNING. BECOMING OVERCAST WITH A CHANCE OF SHOWERS IN THE AFTERNOON. LITTLE CHANGE IN TEMPERATURE. HIGH IN THE LOWER 80S. LIGHT AND VARIABLE WINDS. TONIGHT--RAIN, HEAVY AT TIMES. LOW IN THE UPPER 60S. LIGHT SOUTHEASTERLY WINDS. FRIDAY--SHOWERS AND THUNDERSTORMS LIKELY, HEAVY AT TIMES. HIGH IN THE LOWER 80S. PROBABILITY OF RAIN 30 PERCENT TODAY, 90 PERCENT TONIGHT, AND 70 PERCENT TOMORROW.

Figure 4 An automated forecast matrix derived by the method of Model Output Statistics, and the resultant computer worded forecast (courtesy of Dr W H Klein). The list of forecast elements includes temperature (TEMP), probability of precipitation (POP) etc.

stale observational data. The forecast shown in figure 4 was based on a numerical model using observations at 0000 GMT and the time of issue of the forecast was about 10 h later. This limits the utility of this approach when the local forecast is required to be fairly precise. This difficulty can be ameliorated by updating the model output just before the forecast is issued using more recent observational data. One area in which this approach has proved worthwhile is in the application of digitized radar data to improve forecasts of the probability of precipitation (Moore and Smith 1972).

A more recent development applied to the prediction of severe thunderstorms is to supplement the numerical model products with objectively analyzed surface observations of temperature, humidity and wind, which are available from a much denser network than the synoptic upper air network used to initialize the model. The most important predictor of severe thunderstorms is an index representing the convective instability. Although the index is derived chiefly from forecasts of the upper air structure by means of the synoptic-scale numerical model, it proves to be a better predictor when modified using detailed surface observations made 6 h after the time of data input to the numerical model. Using such an approach an operational procedure has been derived for predicting severe storms 2 to 6 h ahead of the time of the surface observations (Charba 1979). Forecasts for the period 20 to 24 GMT, corresponding to the diurnal maximum of thunderstorm outbreaks in the USA, issued at 19 GMT, are thus based on a numerical model with data input at 12 GMT supplemented by surface observations at 18 GMT.

5. Mesoscale numerical models

We present some examples in this section of situations in which mesoscale models can provide detailed predictions using the synoptic-scale input data now routinely available. The examples refer to some of the topographically forced phenomena listed earlier in table 2.

Of all the mesoscale phenomena, sea and land-breezes occurring over rather flat terrain are arguably the most amenable to mesoscale modelling given the observations currently available. The cool sea breezes that sometimes travel inland during a sunny summer day are caused by the temperature difference when the sea surface is colder than the adjacent land. At their leading edge there is a region of strong wind shifts and low-level convergence. Sometimes this convergence is responsible for triggering and localizing thunderstorms, especially when the shape of the coast causes two convergence lines to intersect and reinforce one another. The movement inland of the sea breeze depends on the latitude, roughness of the ground, and the intensity of the differential heating between land and water(which in turn is influenced by cloud cover, surface albedo, wetness of the ground, and the thermal conductivity of the soil). The intensity and location of the convergence lines also depends on the strength and direction of the synoptic flow: prevailing offshore winds, for example, tend to concentrate the atmospheric temperature gradient along the shore.

Three-dimensional mesoscale primitive equation models (Pielke 1974, Tapp and White 1976) are capable of representing the effect of coastlines of complex shape on the development of sea breezes. A recent application of one of these models (Carpenter 1979) shows that quite realistic forecasts can be produced. Figure 5 shows the forecast surface flow at 10, 16 and 22 GMT on a summer day over England and Wales. The mesoscale model was initialized at 04 GMT using the output from an independent synoptic-scale model. The actual flow pattern as observed at 18 and 22 GMT is shown in figure 6.

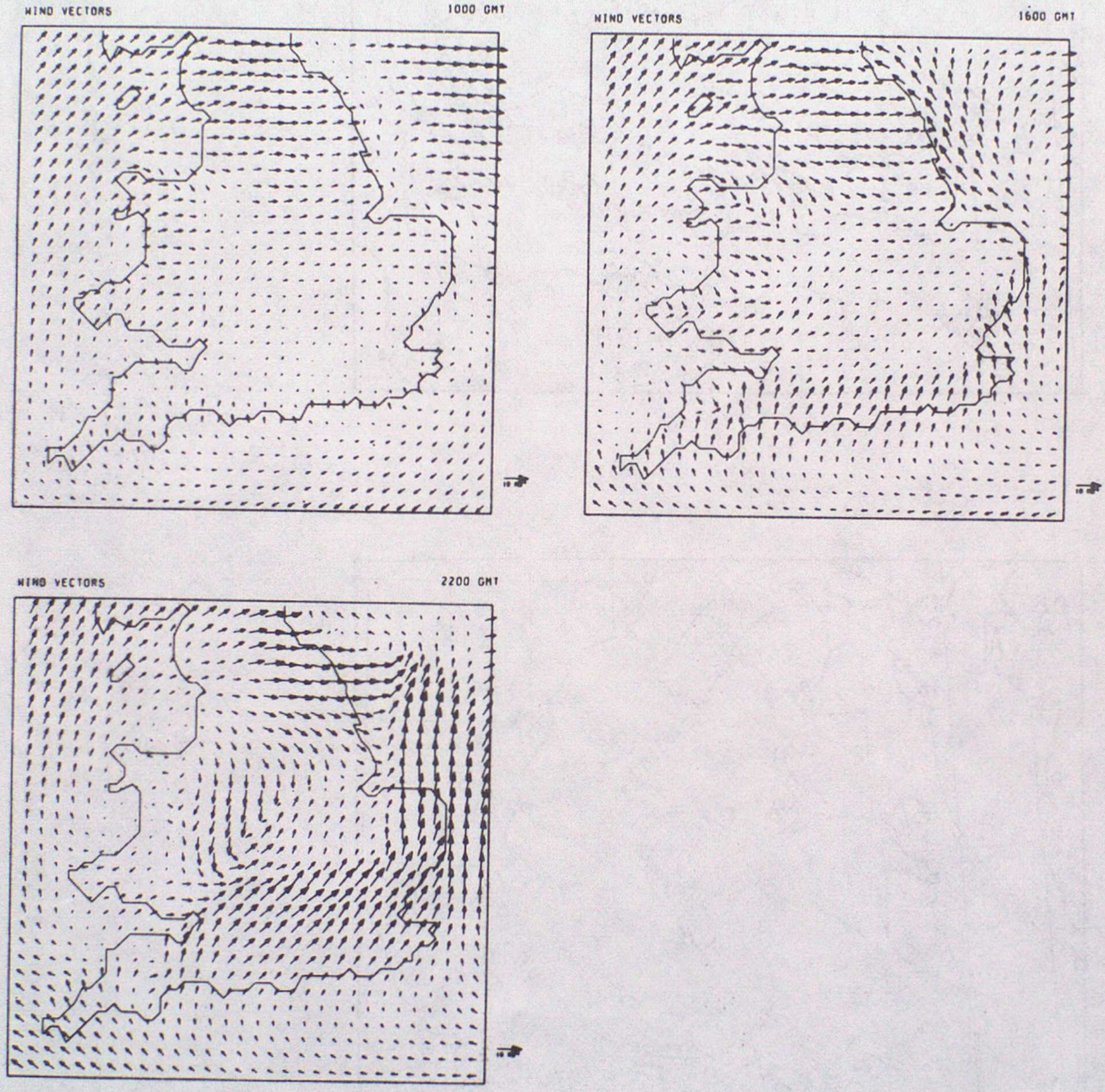
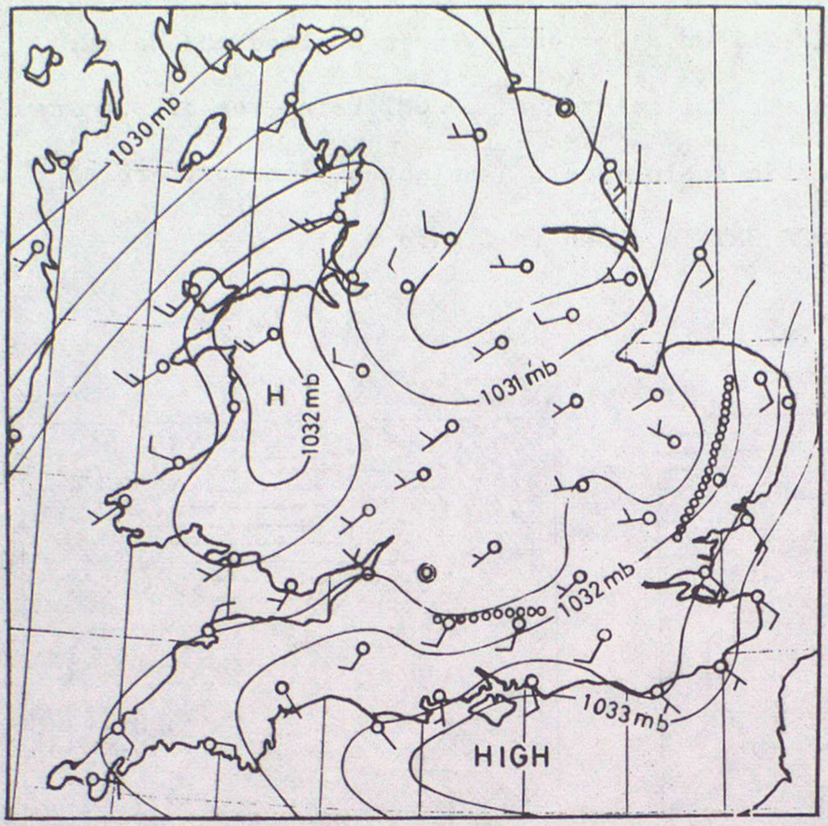


Figure 5 Forecasts of the wind near the surface at 10, 16 and 22 GMT on 14 June 1973 obtained using a mesoscale numerical model (from Carpenter 1979).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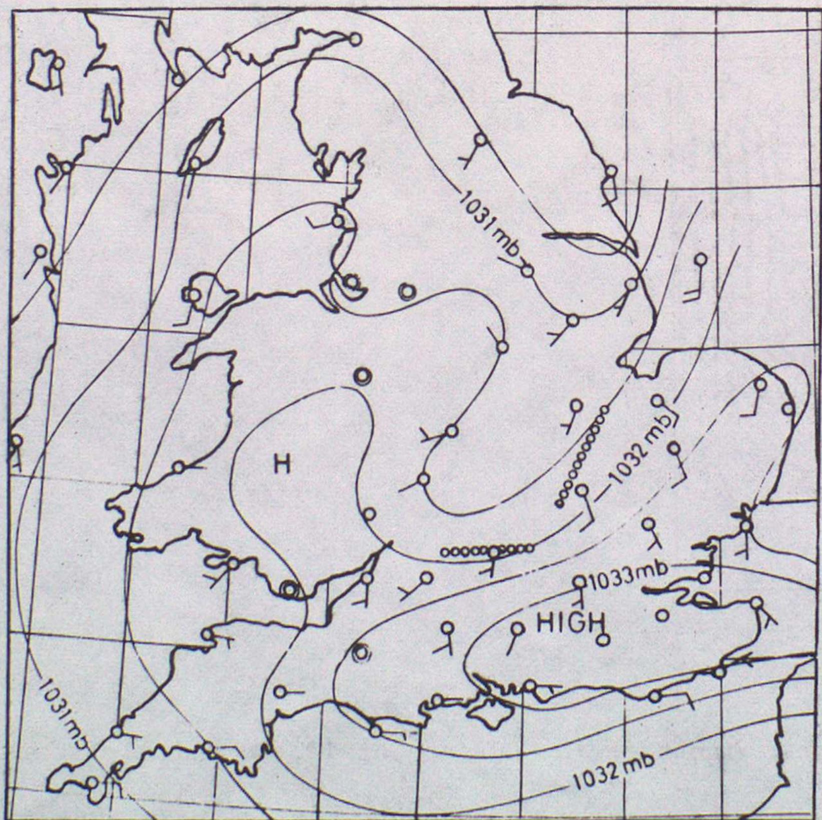
6(a)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HIGH
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6(b)

The inland advance of the two sea breezes marked over Southern England and East Anglia are seen to have been well modelled; so too is the convergence zone along the NE coast which although not identified as such in figure 6 is evident from the plotted winds. Sensitivity tests demonstrated that the accuracy of the mesoscale model predictions depended most critically on the initial temperature field. Different mesoscale phenomena are probably sensitive to different physical parameters and many more experiments of this kind are needed to establish the primary observational requirements in different circumstances. We have given an example in which a dry model was used; however, there appear to be no difficulties of principle about introducing moisture (Carpenter 1979).

Another phenomenon that is strongly forced by surface-effects and is amenable to mesoscale modelling is the enhancement of precipitation on a windward coast in winter when cold air travels over warmer water, e.g. when northwesterly winds blow across the Sea of Japan towards the west coast of Japan and, to a lesser extent, when cold easterly winds cross the North Sea towards England. The important factors are roughness differences between land and water, topography, latent heat release, and surface heating over the water. Figure 7 shows an example of the successful application of a mesoscale model for a flow across an inland

Figure 6 Surface winds and pressure observed (a) at 18 and (b) at 22 GMT on 14 June 1973 for comparison with figure 5. Rows of circles show the positions of sea-breeze fronts (from Simpson et al 1977).

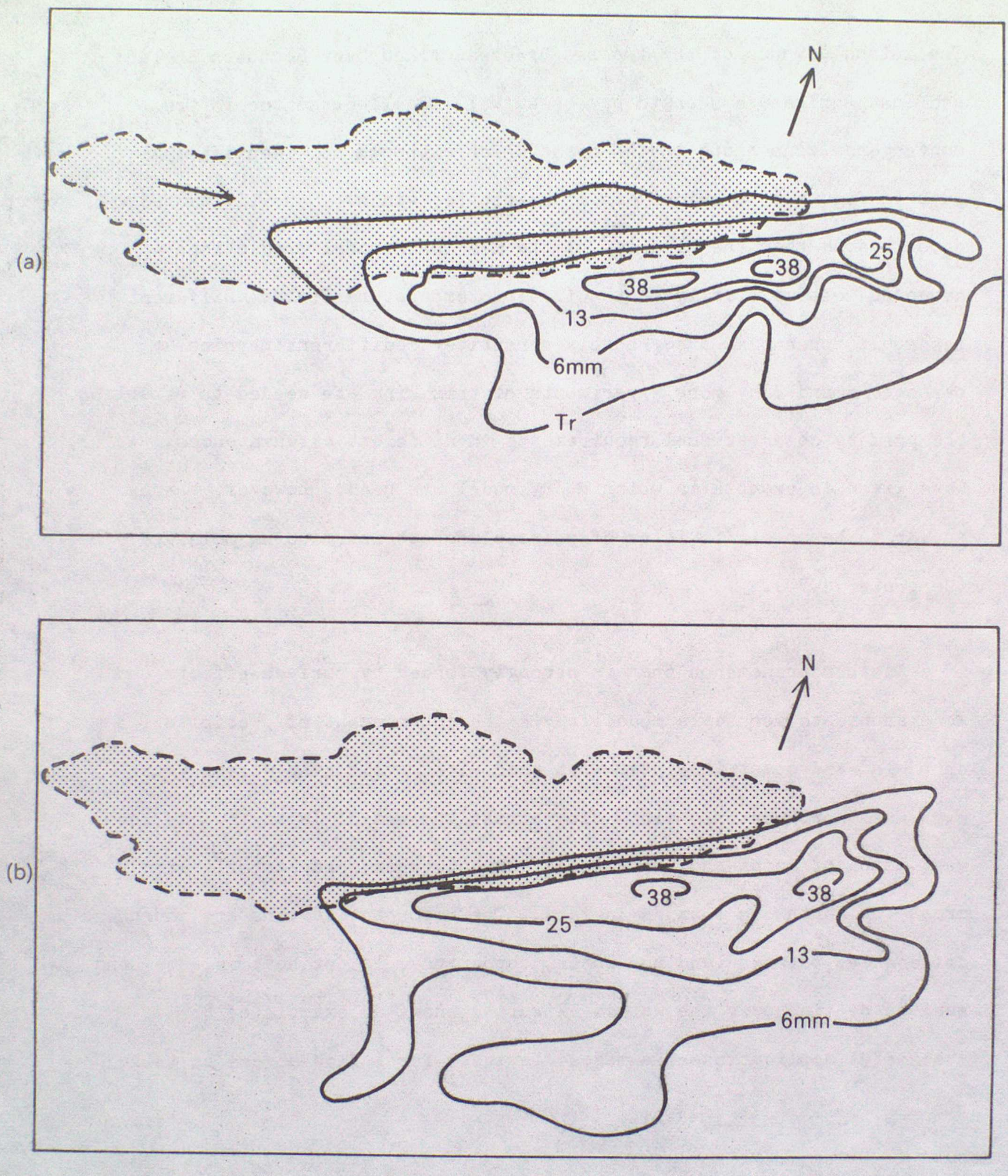


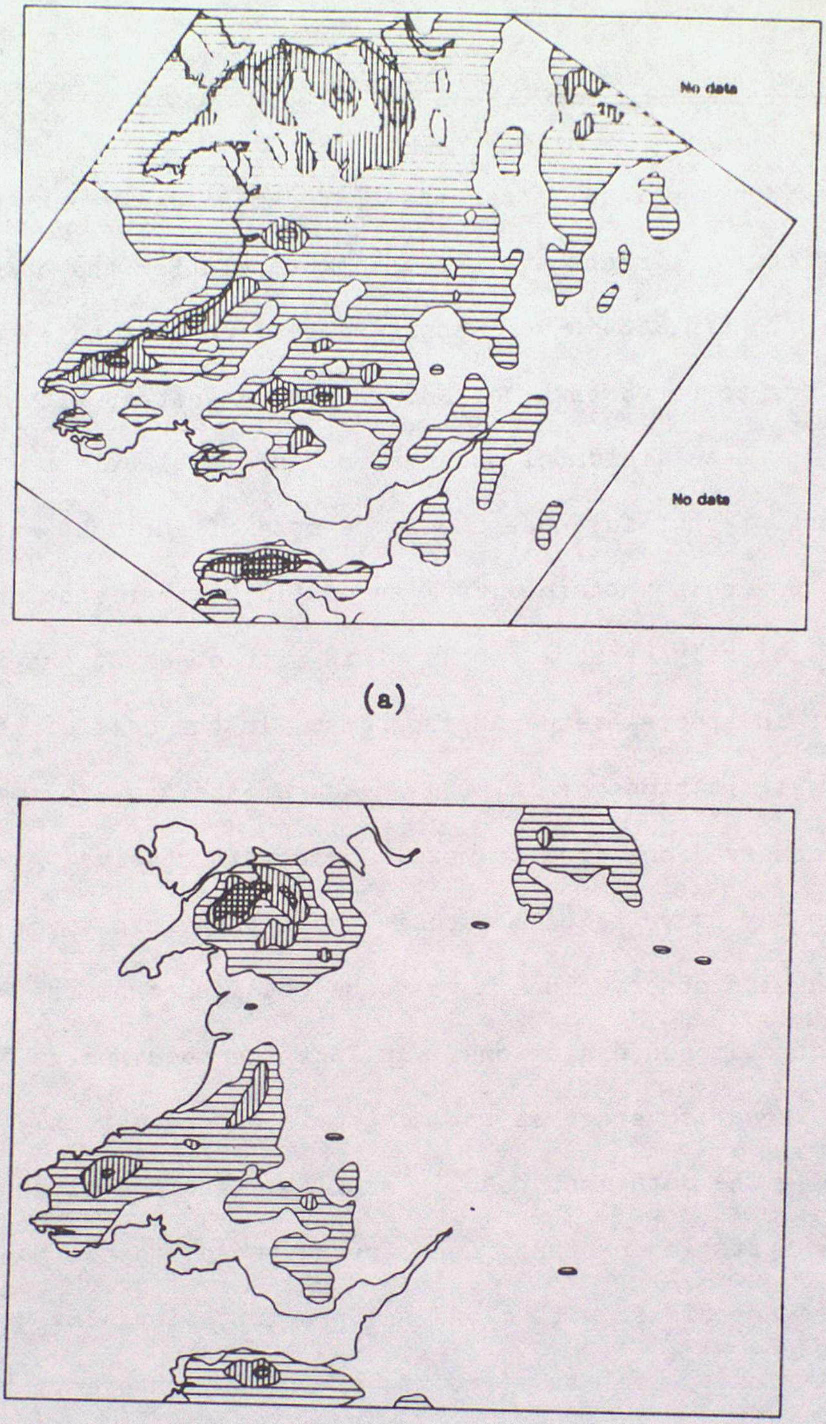
Figure 7 Accumulated precipitation on the wind-facing shore of Lake Erie during a 30-h snowstorm on 1-2 December 1966, (a) as derived from a mesoscale numerical model and (b) as observed. Isohyets represent melted precipitation in mm (from Lavoie 1972).

body of water; it depicts the snowfall amounts in upper New York State during a cold outbreak across the warm Lake Erie in what on the synoptic scale would have been called a 'fair weather' situation (Lavoie 1972). In this case the primitive equations were solved for a simplified atmospheric structure using data from a single upwind sounding. Figure 7(a) shows that the (melted) accumulation of precipitation during a 30-h snowstorm was predicted to reach 38 mm along a narrow strip 20 km inland from the wind-facing shore, in good agreement with the observed values in figure 7(b). The wind was from the west and the maximum accumulations occurred in association with the longest fetch of air across the lake surface. This is consistent with the view that mesoscale models work well when clear-cut features of the topography exert a dominant effect on the weather.

There are many numerically simple models that have been tailored to predict specific phenomena, such as lee waves, wind gusts, cumulus convection, hail size and so on. These all have the advantage of avoiding the expense of a full primitive equation mesoscale model. We shall give just one example, related to the prediction of orographically enhanced rainfall in frontal conditions. In this example a high-resolution diagnostic model (Bell 1978), containing no time derivatives in the equation, is used to interpret the output from a coarse-resolution prognostic model in which the time development is taken into account in deriving the broad-scale state of the atmosphere. The diagnostic model predicts orographic rainfall on a roughly 3 km grid using the output of temperature, humidity and wind from the fine mesh version of the Meteorological Office 10-level model (Benwell <u>et al</u> 1971). The vertical air motion is derived from the sum of the ascent predicted by the synoptic-scale model and the topographically-induced component calculated in more detail assuming that the flow follows the terrain at the surface but that the effect of topography decreases to zero in the middle troposphere. Over hills of modest size in Britain most of the orographic rain is generated in the lowest kilometre or two (Browning 1980), and so the enhancement depends on the water content of the cloud at low levels. This in turn depends on the relative humidity and the local terrain-induced vertical velocity. Another important factor is the efficiency with which the pre-existing precipitation falling from aloft can 'sweep up' and bring to earth the very small cloud droplets in the orographic cloud. A scheme developed by Bader and Roach (1977) is employed to estimate this efficiency. An example of a rainfall forecast for Wales is shown in figure 8.

The output from the synoptic model alone (not shown) grossly underestimated the rainfall over the hills because the effect of topography was smoothed out by the 100 km grid length of that model, but the modified forecast of 24-hour rainfall accumulation (figure 8(a)) is a much closer representation of the actual rain that occurred (figure 8(b)). In fact the mesoscale model tends to overpredict rainfall to the lee of the hills, but this can probably be overcome by taking account of the modification to the large-scale humidity field in the synoptic-scale model due to the local removal of water by orographic processes. In other words, there needs to be some feedback between the diagnostic mesoscale model and the parent prognostic model.

Methods of the kind discussed above at present take little account of mesoscale features that originate independently of topography. For example, they fail to identify the intensity and location of the frontal rainbands, minor troughs and squall lines, which often dominate the distribution of precipitation over periods of the order of hours. The identification and forecasting of these and other phenomena listed in table 3 must be based upon more detailed observational data (see §6 & §7).



(a)

(b)

Figure 8 Rainfall totals over Wales for a 14h period on 14 October 1976, (a) as produced by a mesoscale numerical model and (b) as observed. Horizontal hatching indicates rainfall between 25 and 50 mm, vertical hatching rainfall between 50 and 75 mm, and cross-hatching rainfall in excess of 75 mm (from Bell 1978).

6. Extrapolation of existing weather patterns

We now consider the local forecasts that can be derived by making detailed descriptions of current weather and extrapolating the observed trends ofer a period of 0 to 6 h. Such very-short-range forecasts have to be fairly specific if they are to be worthwhile, and in active weather situations this is possible only if complete fields of observations are available on the mesoscale. Whilst it is important that full use should be made of surface weather observations, some of which are now being obtained from automatic weather stations, the attainment of sufficiently dense networks of in-situ observations is not an economic proposition except in special research programs. In the case of observations of the upper air, the limitations of in situ measurements are even more obvious: although weather observations from commercial aircraft received automatically via satellite or radar may prove helpful especially in the vicinity of major airfields, the bulk of the in-situ observations have to be obtained from the widely spaced synoptic network of radiosonde stations. In fact the requirement for widespread observational coverage on the mesoscale can be met only by remote probing techniques. The data most readily available include cloud imagery from satellites and precipitation patterns from ground-based radar. Many important weather hazards are associated with cloud and precipitation. Even when the cloud and precipitation are not the features of primary interest, they still provide important clues from which other weather conditions can be inferred or in the context of which conventional in-situ weather reports can be interpreted with greater understanding.

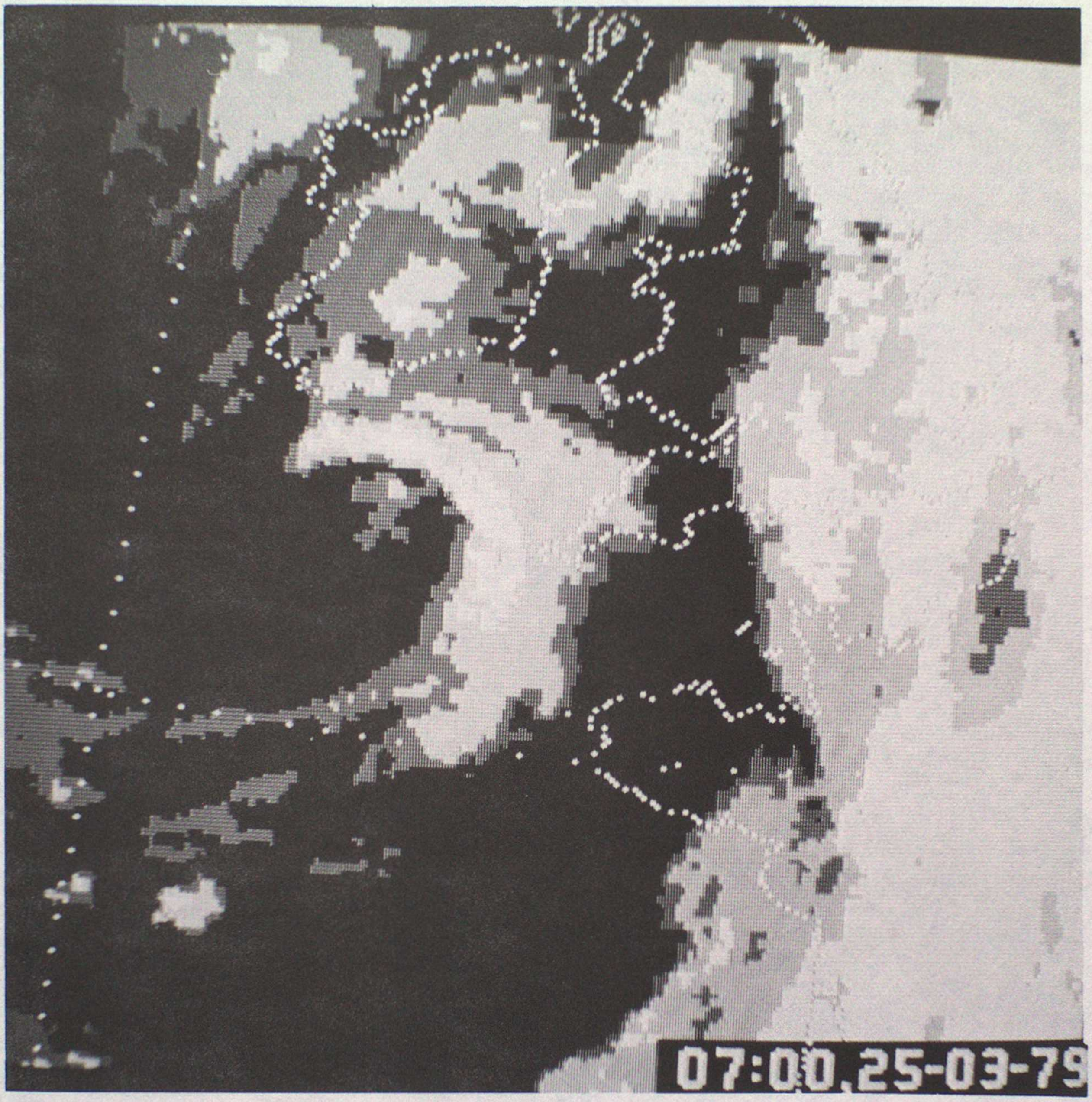
Until recently the only satellite information was from the 12 hourly (now 6 hourly) passes of polar-orbiting satellites. Although the imagery from these satellites has a good spatial resolution, of about 1 km, the poor time resolution causes it to have only limited value for assessing the short-period trends in the weather. The major advance for local forecasting came with the advent of the geostationary satellites, the one with coverage of the United Kingdom, known as Meteosat, having been launched toward the end of 1977. These satellites, stationed over fixed locations above the equator, provide cloud images in at least two spectral wavebands (visible and infra-red) at half-hour intervals. The IR data are particularly valuable in giving radiance information related to cloud top temperature (ie height) by both day and night. Although the spatial resolution is typically 5 to 10 km, it is nevertheless adequate for keeping track of many mesoscale phenomena. The oblique angle of view at high latitudes introduces some difficulties of interpretation, but the data appear to be useful as far as the extreme northern parts of the British Isles (60°N).

One of the simplest applications of geostationary satellites is in the detection and tracking of rather large mesoscale disturbances such as short wave troughs or polar air depressions which form over the ocean and would often go undetected as they approach land were it not for the characteristic comma-shaped cloud pattern seen by satellite (Reed 1979). These disturbances account for the occurrence of organized areas of continuous precipitation within polar airstreams that otherwise might be expected to contain irregularly distributed showers. An example is shown in figure 9.

The sequence of IR pictures in figure 9 shows a large area of high cloud associated with a major frontal system retreating eastwards over Britain; behind it is a short wave trough which can be tracked as a clearly defined entity approaching southwest England at about 50 km h^{-1}. The trough produced about 2 h of moderate rain as it progressed inland.

Infra-red imagery from a geostationary satellite is particularly valuable for identifying intense thunderstorms (Scofield and Oliver 1977). The regions of heaviest rain, together with any hail and damaging winds or turbulence, are associated with tall cumulonimbus towers, up to several kilometres across, which often penetrate above the level of the tropopause. The highest and coldest cloud tops can be pinpointed by means of a precise radiance thresholding procedure referred to as enhancement. Special rapid-scan data in which enhanced IR pictures are obtained at 5-min intervals, although not yet widely available, promise to be useful for identifying the vigorous growth of cloud towers that often precedes the development of hail and tornadoes (Adler and Fenn 1979). Another indicator of an intense thunderstorm is the observation of merging storm cells. Yet another is the detection in the satellite imagery of expanding areas of high cirrus 'anvil' cloud due to the divergent outflow from thunderstorm towers. Although the rate of expansion of the anvil can be used as a measure of the intensity of the convection, it must be kept in mind that the damaging weather is restricted to the regions beneath the highest towers. These are generally located in the upwind parts of the anvil and bounded by a sharp gradient in cloud top temperature.

Fig 9 (Pages 30 - 33 inc) Sequence of four infra-red cloud pictures from Meteosat showing a short wave trough approaching SW England between 0700 and 0830 GMT on 25 March 1979. These pictures were received in near real time at Malvern following digitisation and rectification to a National Grid format (Transverse Mercator Projection). Each picture is a matrix of 256 x 256 5 km squares displayed on a colour television which had facilities for time-lapse replay. For simplicity, only three cloud radiances are depicted: dark grey in these photographs corresponds to a cloud top temperature of about $-15^{\circ}C$, medium grey to $-20^{\circ}C$ and light grey to $-30^{\circ}C$.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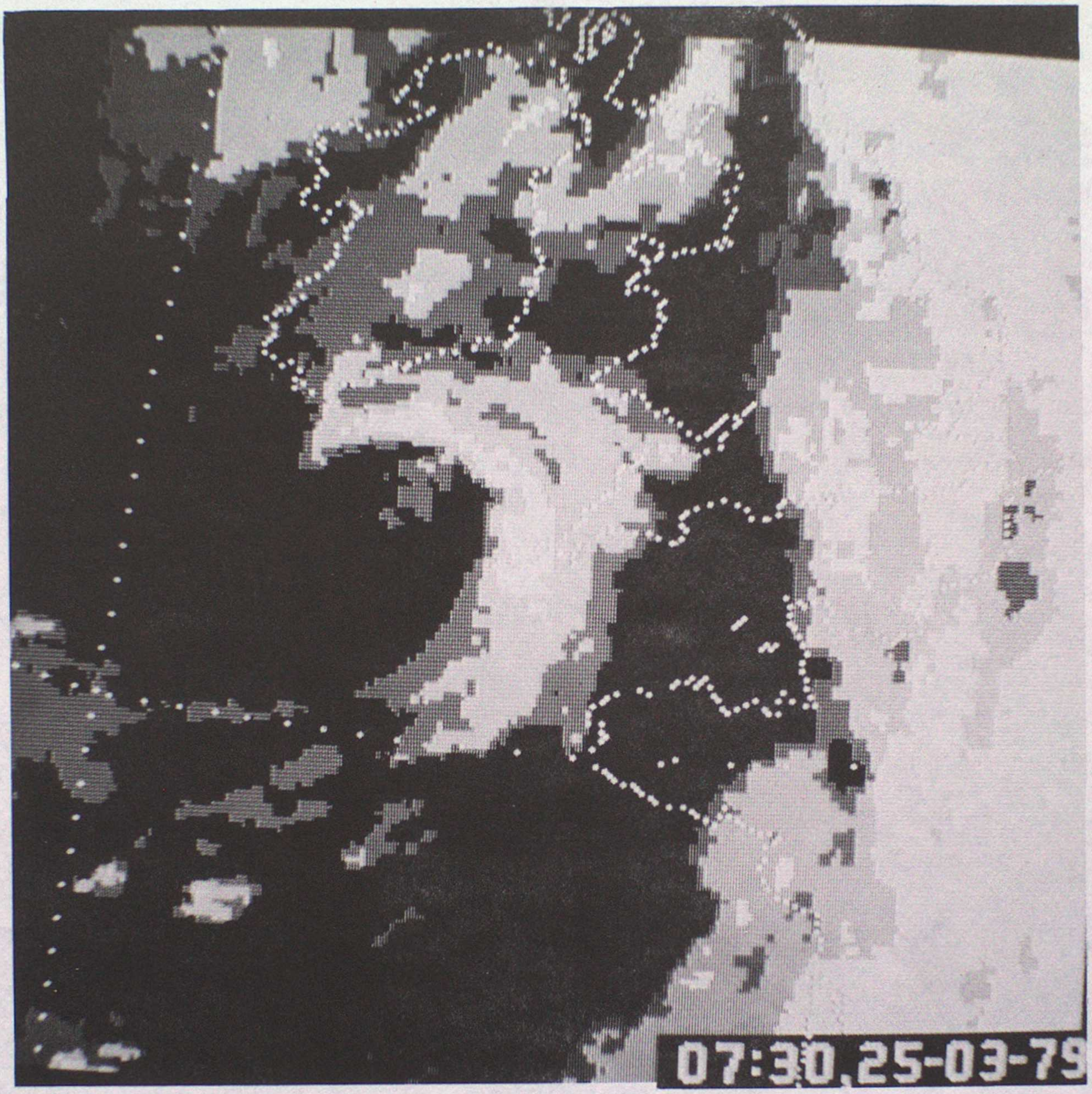
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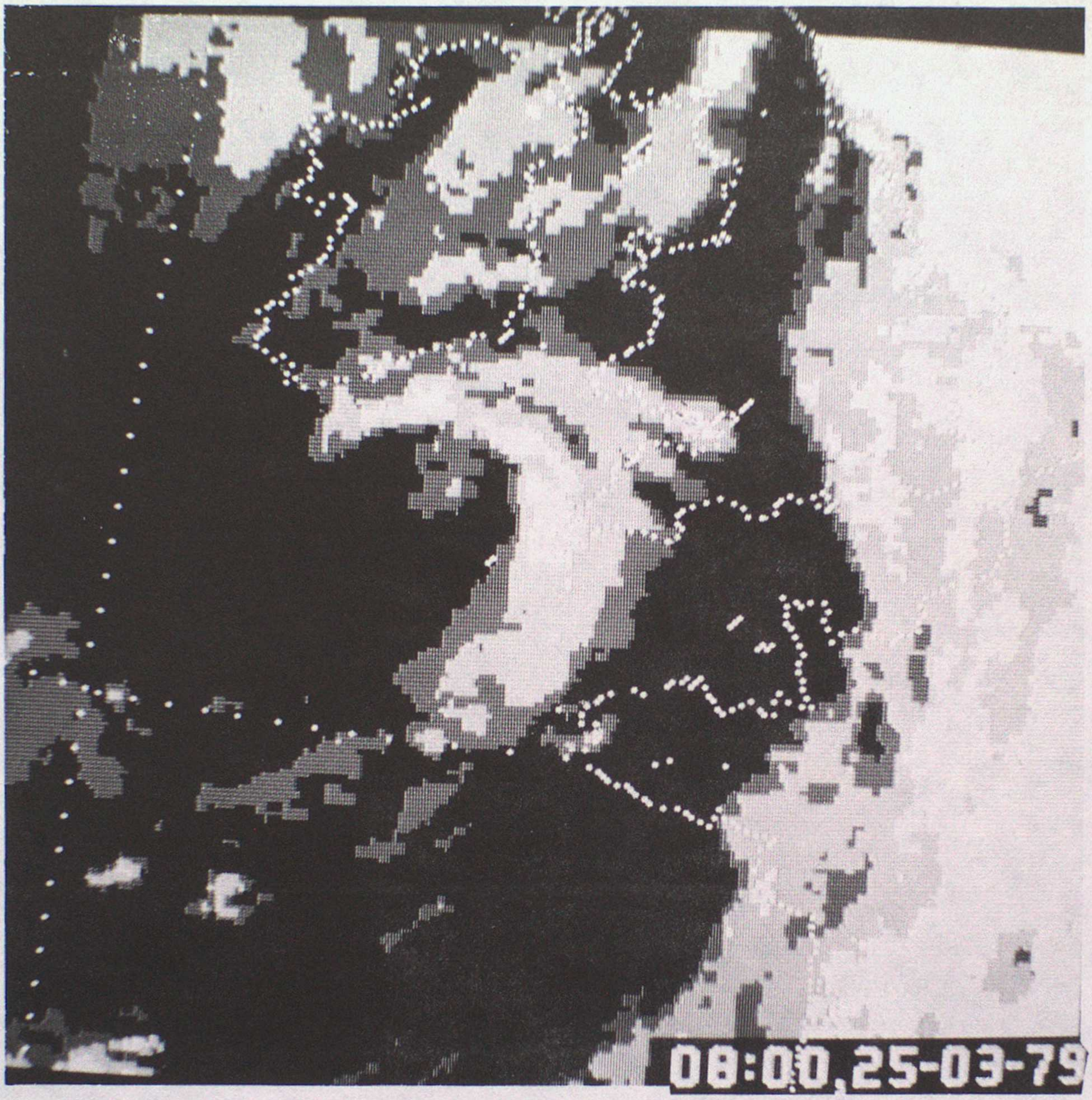
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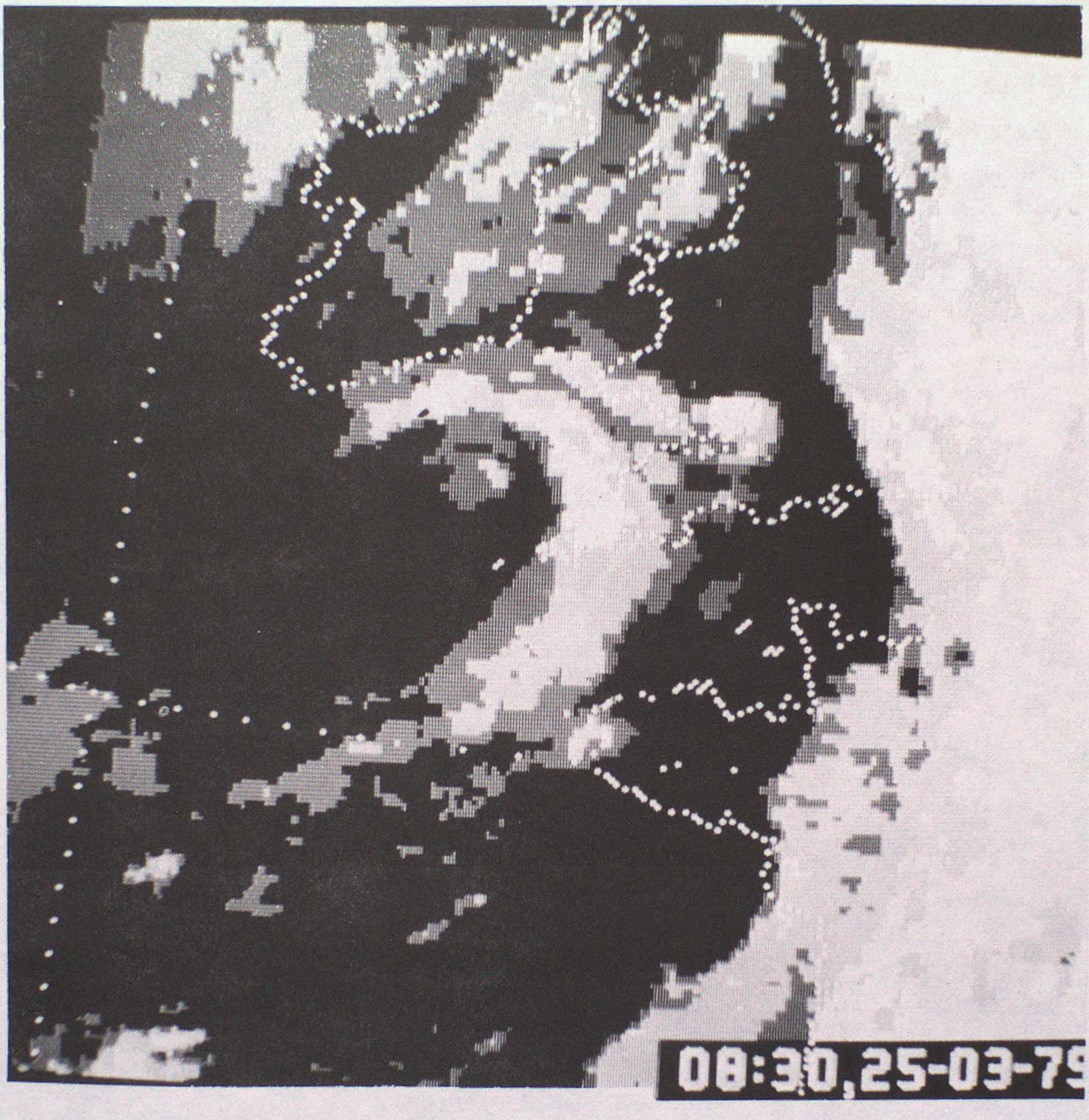
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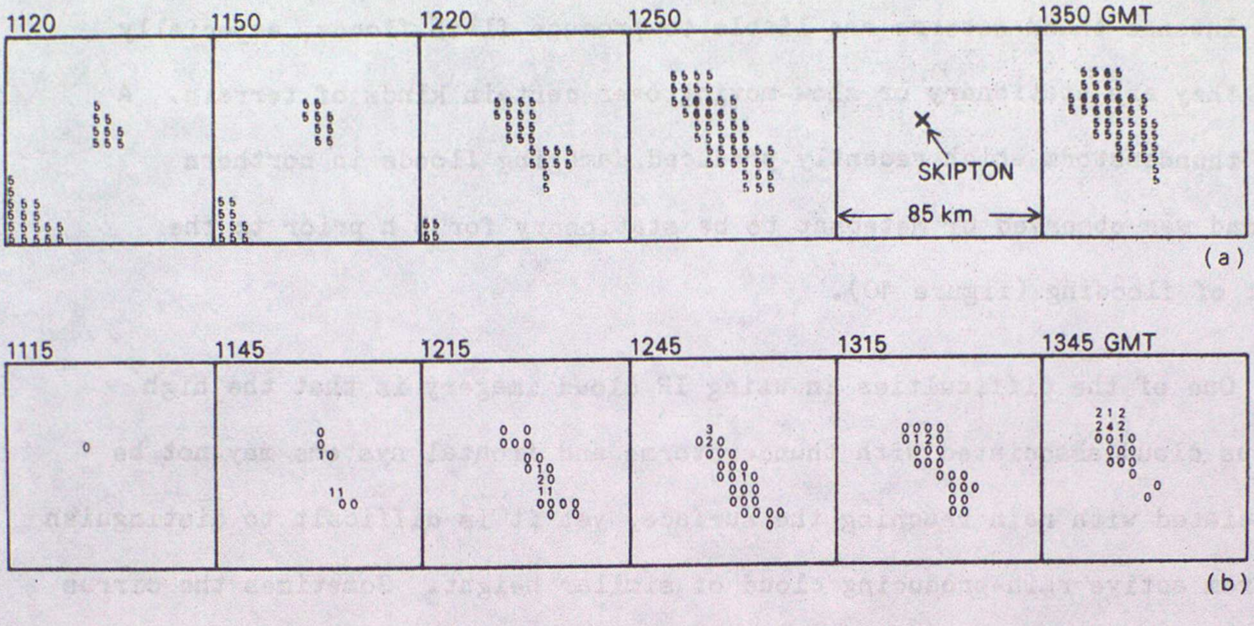


Figure 10

Figure 10 Sequence of digital print-outs of (a) the IR cloud data from Meteosat and (b) the corresponding rainfall intensities inferred from a ground-based radar for an 85 x 85 km^2 area of northern England showing the almost stationary thunderstorm that produced a flash flood in Skipton, Yorkshire, after 1400 GMT on 13 June 1979. Both sets of data are displayed in a matrix of 5 km cells based on the National Grid, the numbers 5 and 6 in (a) corresponding to cloud top temperatures below -13 and -25°C, respectively, and the numbers 0, 1, 2, 3 and 4 in (b) corresponding to estimated rainfall rates exceeding 4, 8, 16, 32 and 64 mm h^{-1}. Meteosat data were missing at 1320 GMT and the location of Skipton is indicated in the corresponding frame. Because of registration difficulties in this case the satellite data have been positioned in conformity with the radar data.

Intense thunderstorms are liable to produce flash floods, especially when they are stationary or slow-moving over certain kinds of terrain. A thunderstorm which recently produced damaging floods in northern England was observed by Meteosat to be stationary for 3 h prior to the onset of flooding (figure 10).

One of the difficulties in using IR cloud imagery is that the high cirrus cloud associated with thunderstorms and frontal systems may not be associated with rain reaching the surface, yet it is difficult to distinguish it from active rain-producing cloud of similar height. Sometimes the cirrus can be distinguished by its fibrous texture especially when viewed using higher resolution visible imagery. Alternatively it is possible to exploit the different spectral response in the IR and visible channels, the IR radiance being a measure of cloud top height and the visible brightness more a measure of cloud thickness (Lovejoy and Austin 1979). Thus, low (cold) radiance values together with high brightness in the visible spectrum is indicative of precipitating cloud while low radiance and low brightness is indicative of cirrus alone. This appears to be a useful way, in the daytime at least, of distinguishing between rain and no-rain (figure 11).
In the absence of visible imagery, the IR cloud data can be calibrated in terms of surface precipitation with the aid of any available 'ground truth' observations including radar, together with conceptual models based on an understanding of the physical mechanisms and resulting structure of cloud systems. In the longer run the use of space-borne microwave techniques will probably remove some of the present ambiguities; however, existing microwave techniques suffer from limited resolution and they tend to be troubled by

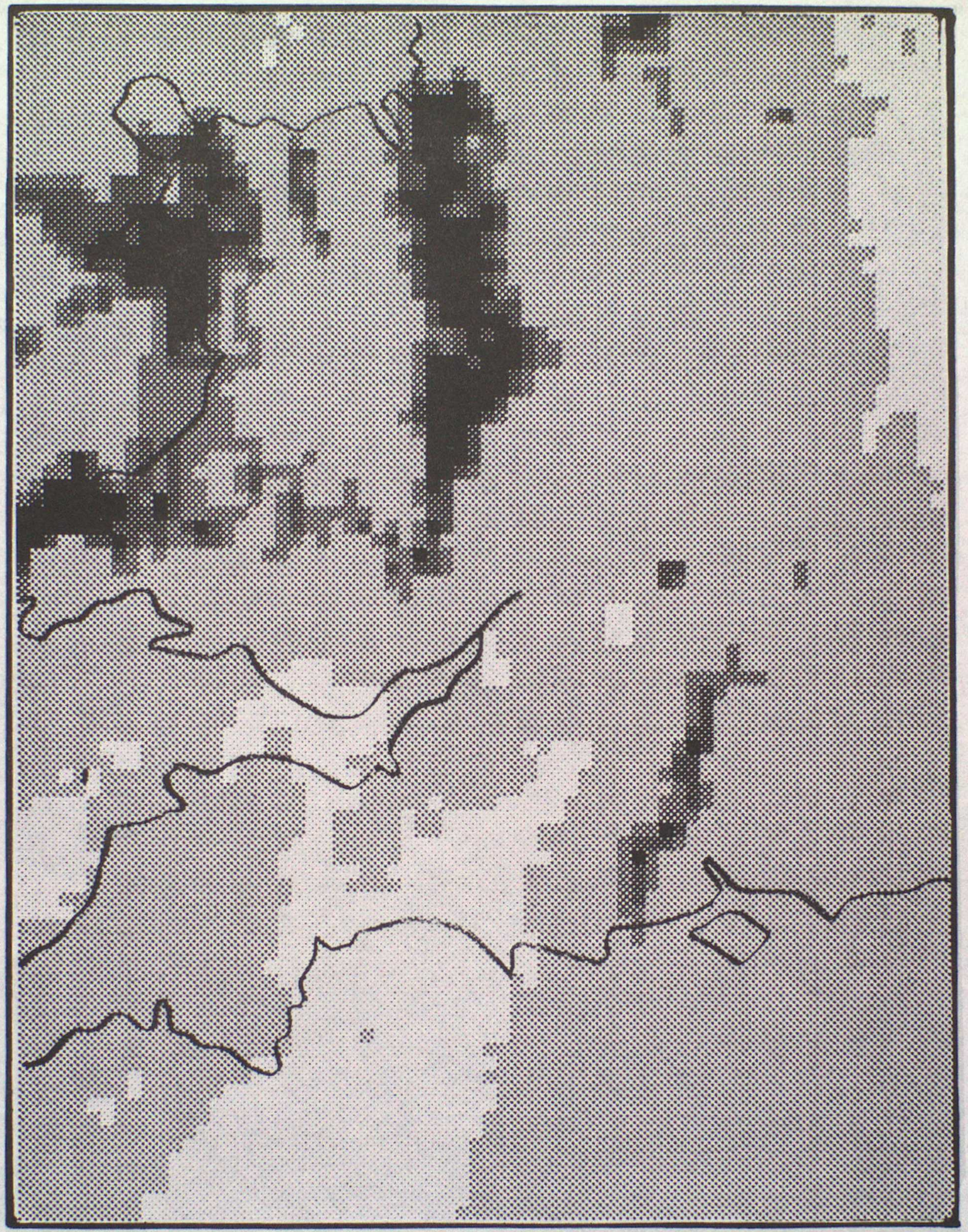


Fig 11(a)

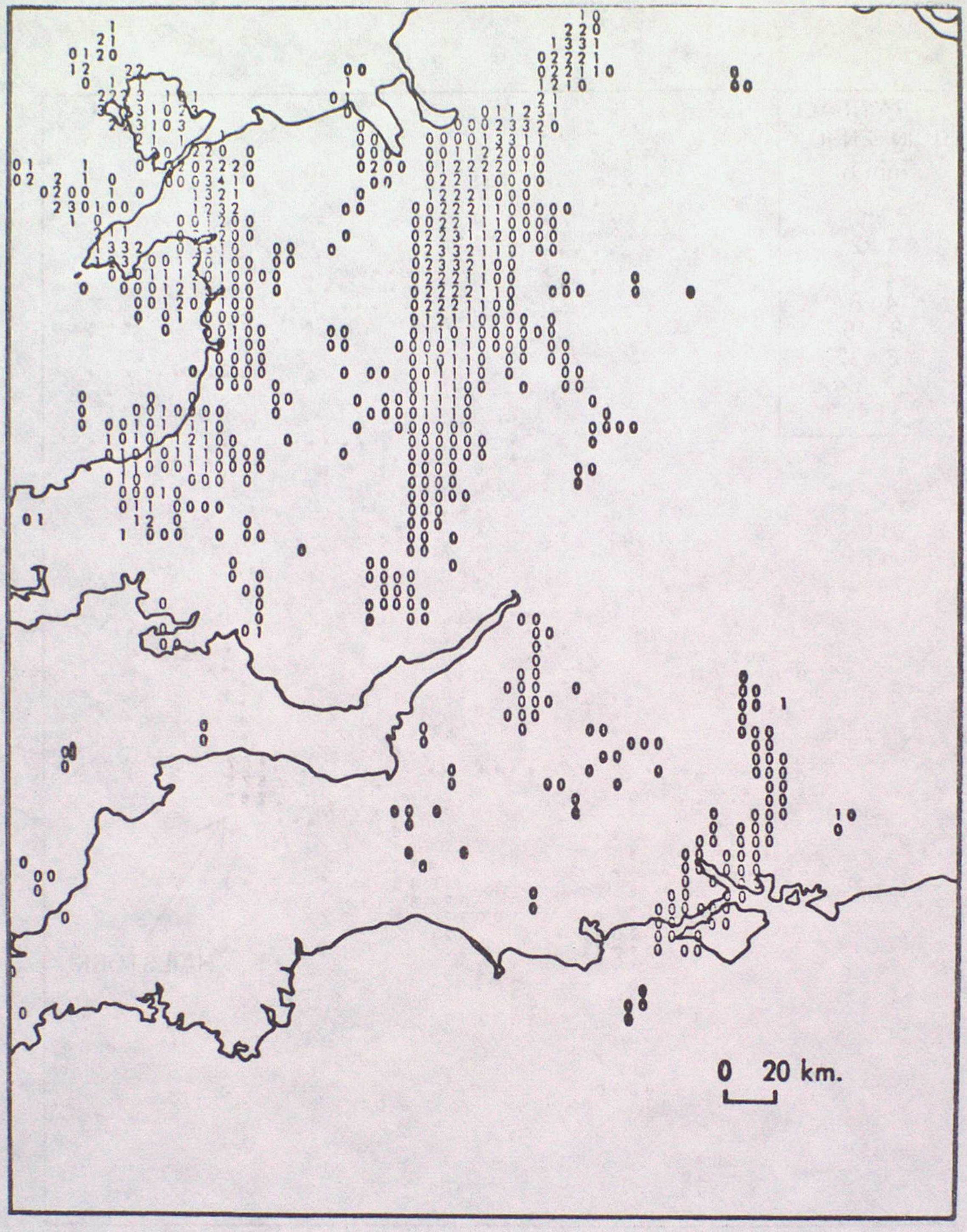
CLEAR SKIES

CLOUDY SKIES

20% < PROBABILITY OF RAIN < 35%

35% < PROBABILITY OF RAIN < 50%

PROBABILITY OF RAIN > 50%



11(b)

Figure 11 Rainfall distribution over part of England and Wales at 1100 GMT on 25 September 1979 (a) as inferred from a combination of visible and IR cloud data from Meteosat and (b) as derived from a network of three weather radars. The stippled shading in (a) represents rainfall probabilities as shown in the key. The numbers 1, 2, 3 and 4 in (b) correspond to rainfall rates in excess of 1, 2, 4 and 8 mm h^{-1}, respectively, the symbol 0 representing light rain. The data in (a) were obtained as part of a joint project between the Radar Research Laboratory and Systems Development Branch of the Meteorological Office and the Radar Weather Observatory, McGill University.

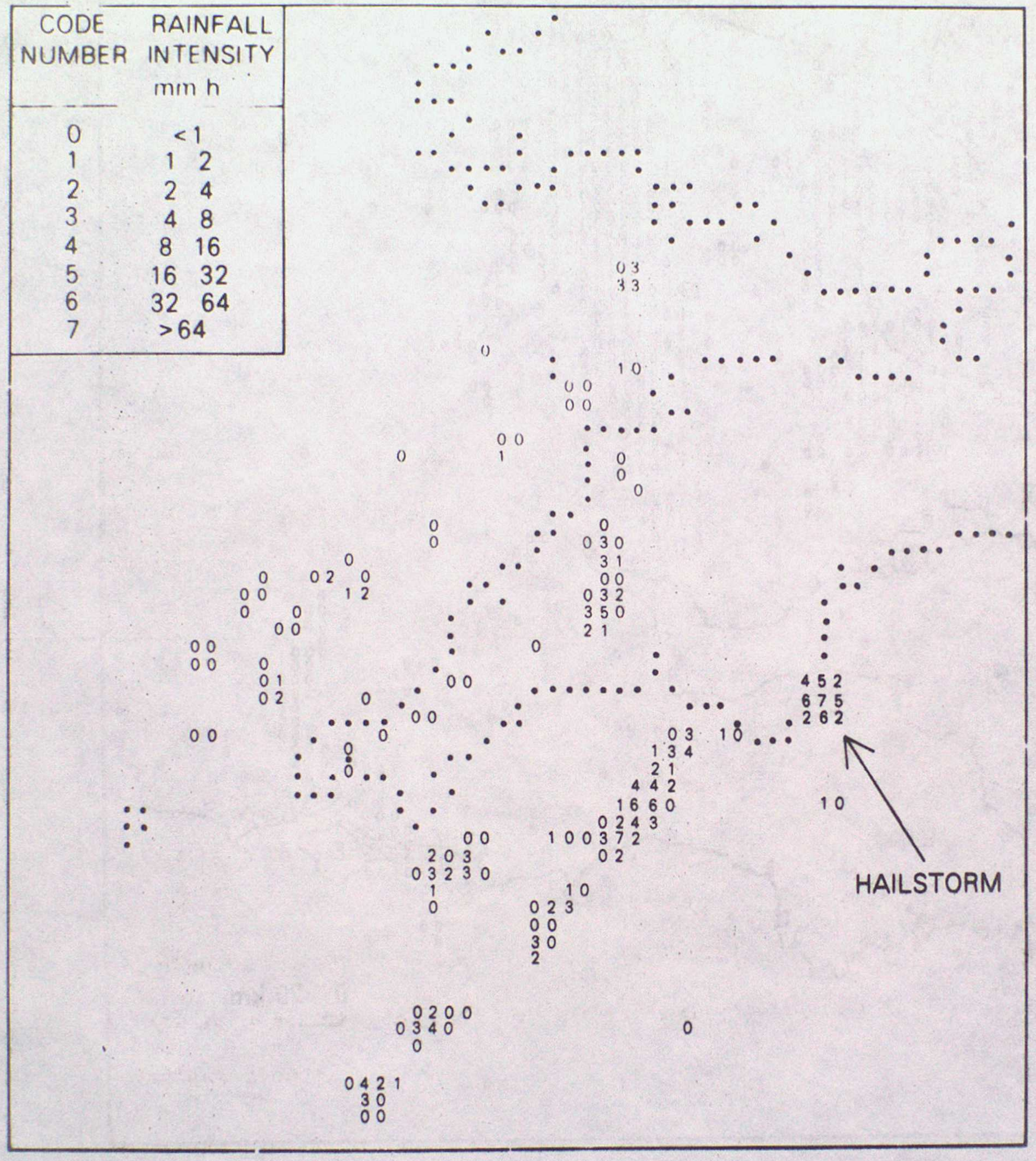


Figure 12(a) Digital print-out of data from a radar at Camborne, Cornwall showing the distribu tion of echo intensity at 1545 GMT on 13 December 1978 when a damaging hailstorm was occurring in southeast Devon. The data are displayed in a matrix of 5 km squares with values representing rainfall intensity according to the indicated code.

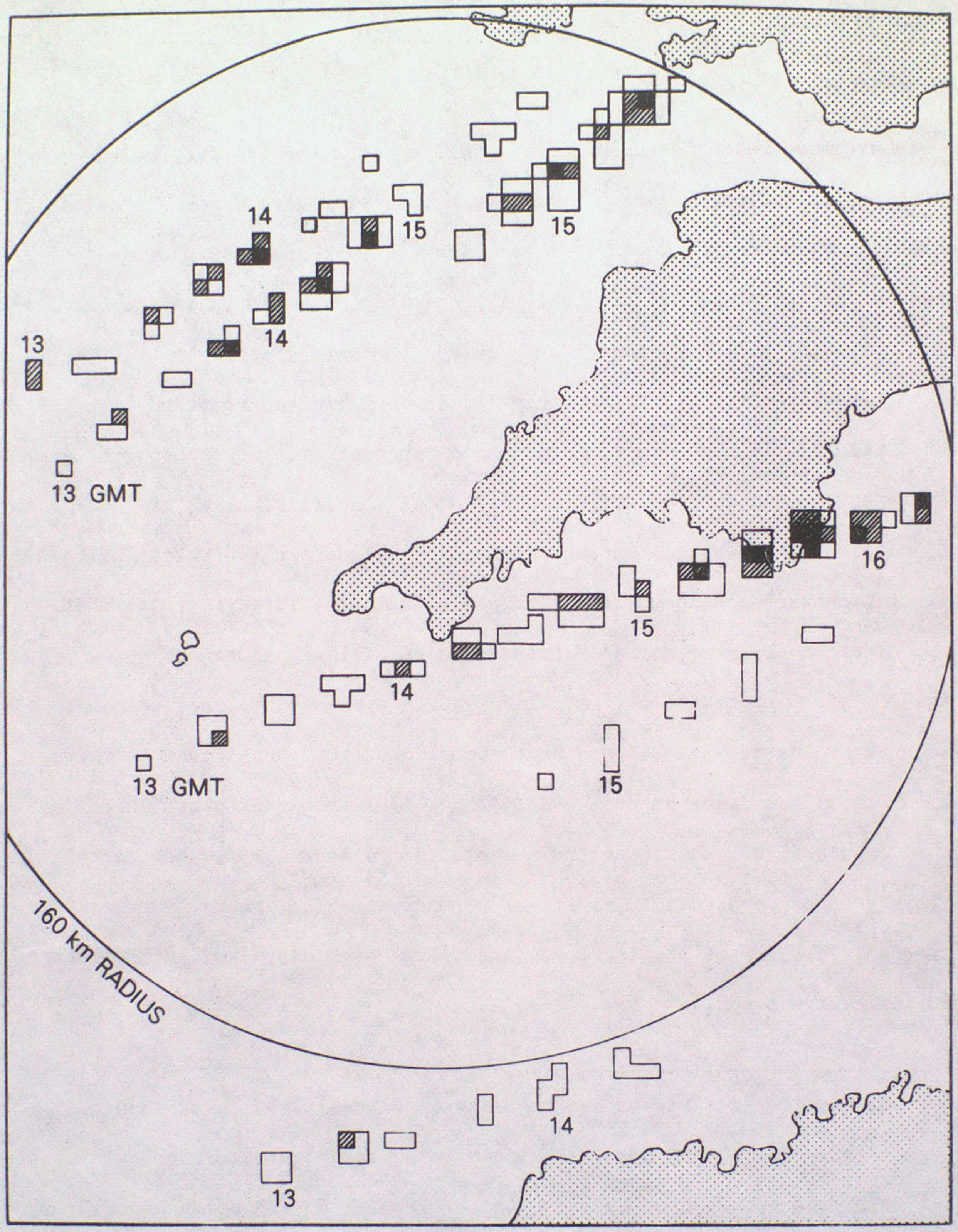


Figure 12(b) Successive positions of storm cores at 15-min intervals from 1300 to 1615 GMT. Areas of rainfall in excess of 8 and 32 mm h^{-1} are depicted by hatched and solid shading, respectively; areas of lighter rain are unshaded.

emissions from the ground.

Ground-based radar is superior to satellite data for identifying and tracking precipitation systems. Even though radar may give errors in rainfall intensity of a factor of two on some occasions, it nevertheless provides information on the areal distribution of precipitation which is invaluable for local forecasting and which cannot be acquired as cost-effectively by other means. The areal coverage of any one radar is very limited compared with that of satellites and it tends to focus attention on precision forecasting of small-scale events. As an example, figure 12(a) shows the distribution of radar echo on an occasion of widespread showers as seen by a radar in southwest England. The plotted numbers get larger with increasing rainfall intensity such that, at the top of the scale, the number 7 represents rainfall in excess of 64 mm h^{-1} averaged over a 5 km square or, more likely, the presence of large hail. In fact, the value of 7 on the southeast coast of Devon corresponds to the location where 3 cm diameter hail was falling. The tracks of storm cores, shown in figure 12(b), show that there was evidence as much as 2 h beforehand that this part of Devon was likely to be a target for showers or thunderstorms, although the severity of the storm could not have been suspected until about 15 min before it struck.

In the case of frontal systems the extent of precipitation exceeds the coverage of any one radar and so techniques have been developed whereby digital data from a number of radars with overlapping coverage can be sent by telephone to a mesoscale analysis centre where they may be combined automatically on a single display (Taylor and Browning 1974). A composite radar display, depicting the rainfall distribution during the passage of a cold front, is shown in figure 13(a).

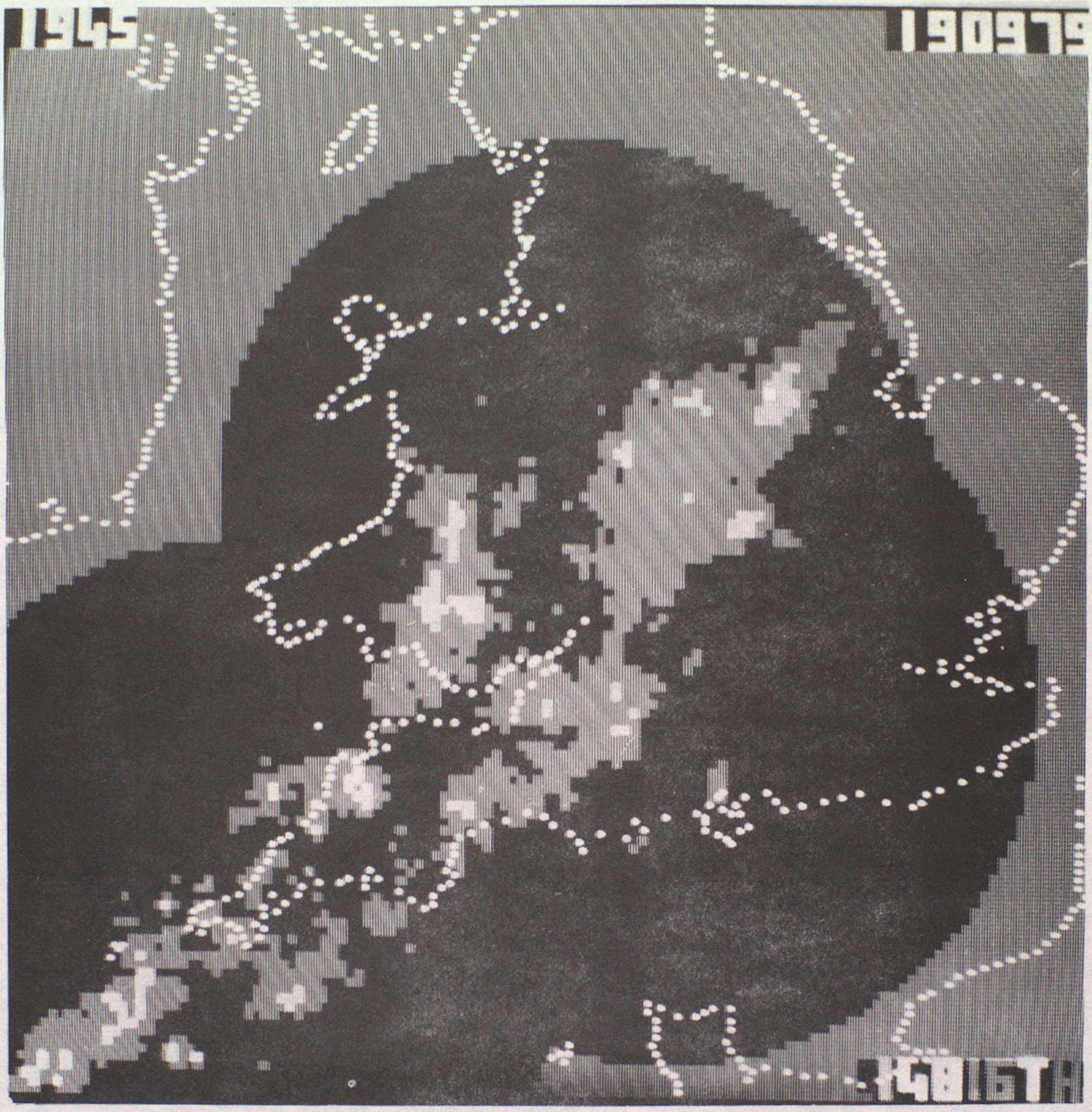


Figure 13(a) Photograph of a composite radar display showing the rainfall distribution in England and Wales at 1945 GMT on 19 September 1979. This composite was generated within 4 min of real-time from data received at Malvern from 3 radars with approximate coverage as indicated by the circles. The display consists of a matrix of 128 x 128 5 km squares which was displayed on a colour television capable of replaying a sequence of pictures; medium and light grey in the monochrome photograph represent light-to-moderate, and heavy rain, respectively.

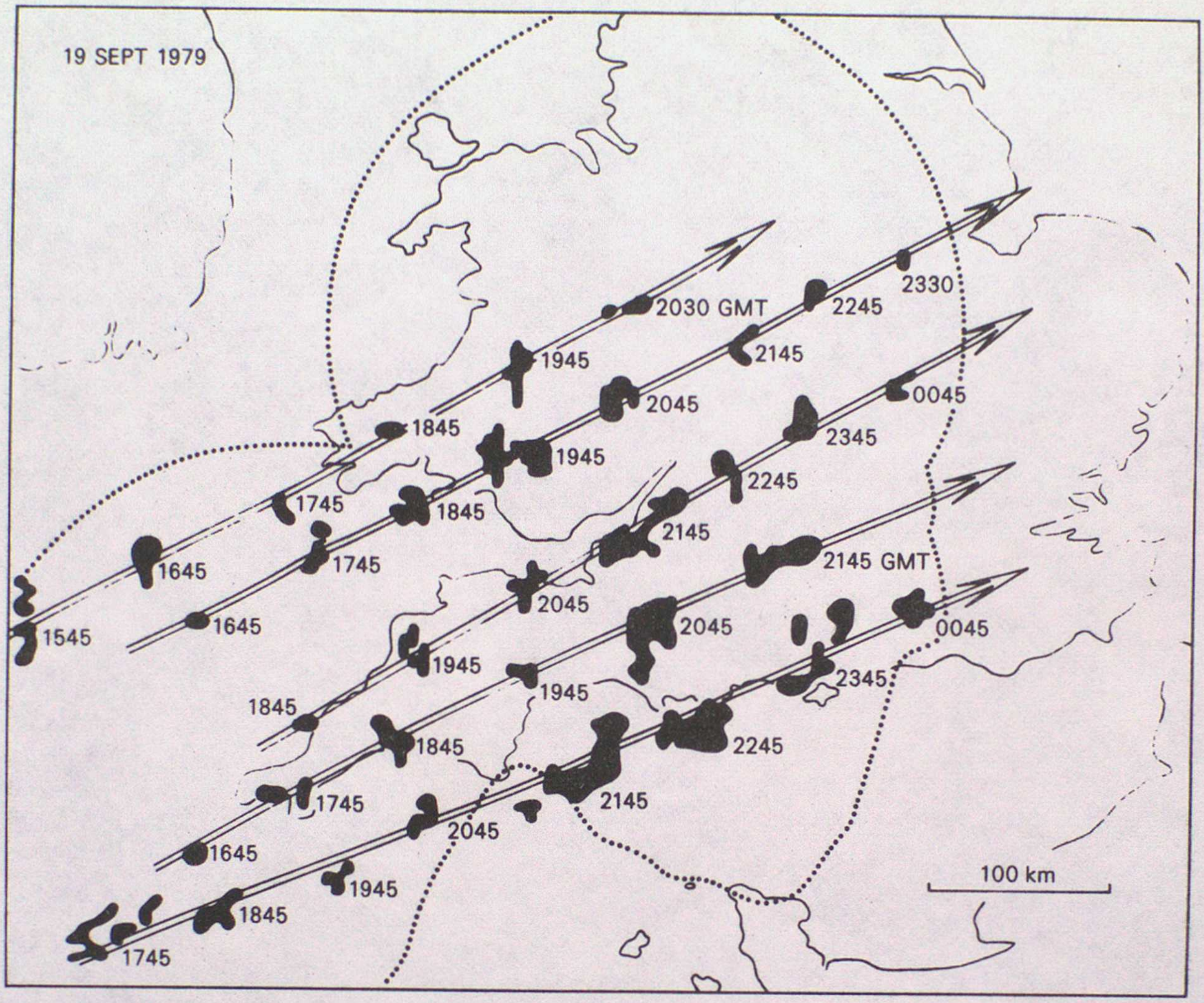


Figure 13(b) Successive positions of some of the areas of heavy rain in (a) depicted at mainly 1-hour intervals.

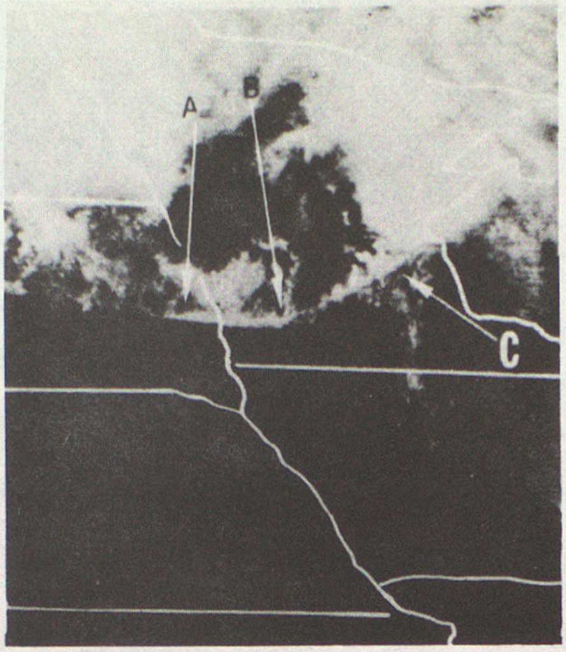
A close relationship existed in this case between the main rain belt and the synoptic-scale cold front but, as often happens, the distribution of rain along the front was patchy. Figure 13(a) shows that mesoscale rain areas existed which were typically a few tens of kilometres across. The rainfall intensity was mainly light-to-moderate but there were a few patches of heavier rain. Mesoscale areas of heavy precipitation are usually composed of clusters of middle-tropospheric convective cells with characteristic dimensions of a kilometre or so. These convective cells are individually short-lived but the mesoscale areas may be trackable for periods of hours (eg figure 13(b)). There is evidence that mesoscale precipitation areas can be tracked even when the intensity of the rain at the surface is strongly modulated by orography (Hill and Browning 1979).

Objective forecasts of rainfall can be made from successive pairs of digital radar or satellite images using computerised pattern matching techniques to provide a linear extrapolation. Sequences of pictures can also be replayed on a television screen to provide a subjective check on the forecast. A simple objective extrapolation procedure has been in use in Canada since 1976 (Bellon and Austin 1979). Its successful application was helped by the absence of major orographic effects in the area concerned. When orography is important, as in western Britain, it is necessary to use computer-archived maps of orographic enhancement factors. Sets of enhancement factors will need to be derived from observational data and/or numerical models for a range of weather conditions, the surface wind speed and direction and relative humidity being particularly important. These factors will need to be applied not only in a positive sense as a rainband moves in from the sea toward regions of high land but also in a negative sense when a rainband is already over high land in order to eliminate orographic effects as far as possible prior to the application of objective extrapolation procedures.

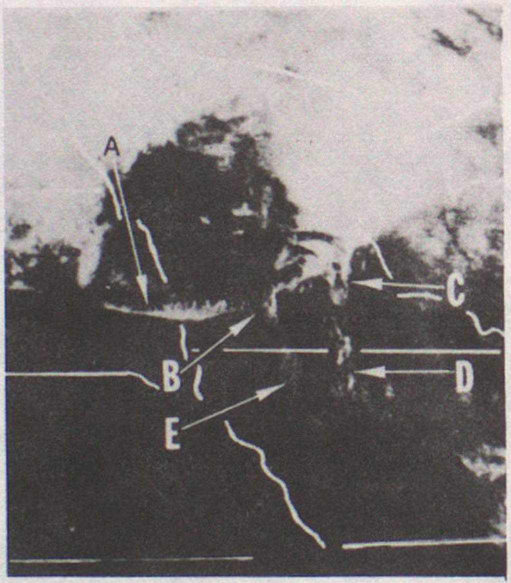
The techniques outlined above entail the detection and tracking of existing phenomena. Thunderstorms, however, often break out suddenly and a key requirement is to detect precursors which indicate the likelihood of such developments and their probable location. One approach involves the subjective identification of convergence lines near the surface using high resolution visible imagery from a geostationary satellite (Purdom 1976). Surface convergence lines occur as sea breeze fronts, dry lines, cold fronts and also at the boundaries of outflows from existing thunderstorm systems. They are often visible as thin lines of cumulus convection. Such lines are preferred regions for triggering thunderstorms, especially where two lines merge (figure 14). The utility of this approach is diminished in the United Kingdom, however, by the relatively poor spatial resolution of the current geostationary satellite as well as by the tendency for these features to be obscured by more general cloudiness.

7. Towards improved observations for mesoscale models

Detailed observations are needed as input to mesoscale numerical models to correct the phase and amplitude of the large-scale features input from the parent synoptic-scale models and, also, to resolve the smaller-scale features which cannot be derived from them. However, a mesoscale model with a grid length of 20 km itself only resolves disturbances with characteristic dimensions greater than 40 km and so the observational input need not have a horizontal resolution any better than this. More detailed observations are used as the basis of forecasts by extrapolation (§6), and the predictions of mesoscale models should provide the context within which to interpret and extend these more detailed extrapolations (Kreitzberg 1976).



(a)



(b)

(c)

Figure 14 Visible imagery with 1 km resolution from the GOES-2 satellite showing the development of thunderstorms over Minnesota on 29 June 1975 (from Purdom 1976). (a) shows a line of cumulus (A-B-C) at 1445 GMT situated along a convergence line associated with the cold outflow from an existing thunderstorm system. (b) shows two new convergence lines B-E and C-D which by 1545 GMT were merging with the original line. (c) shows new thunderstorms which by 1645 GMT had developed at B and along C-D.

The primary observational requirement is for fields of temperature, humidity, wind and pressure. As a start methods can be developed for relating existing surface observations in a dynamically consistent way to the upper air structure derived from sparse radiosonde data. However, major progress with mesoscale models requires the kind of 3-dimensional observational coverage on the mesoscale that can be provided only by a variety of remote probing techniques, especially those from satellites. The possibilities offered by new satellite observing techniques over the next 1 or 2 decades are far-ranging (Atlas et al 1978), but we shall restrict consideration here to 3 techniques whose meteorological utility is actively being tested:

(a) inferring humidity fields from cloud and precipitation patterns,

(b) measuring wind fields by tracking clouds, and

(c) measuring temperature and humidity profiles by means of radiometers.

The distribution of humidity is highly variable in meteorologically active regions and its measurement on the mesoscale is important especially for the quantitative prediction of convective rainfall. Radiosonde observations often grossly underestimate the relative humidity and its gradients, and although numerical models develop their own humidity fields given information on the initial wind and temperature distribution, too low a first-guess of humidity will cause models to underestimate the effects of latent heat and hence the rate of development of mesoscale systems (Kreitzberg and Rasmussen 1977). Mesoscale patterns of relative humidity can, however, be inferred from cloud and precipitation measurements made by satellites and radar. Figure 15 shows an example of the improvement in performance of a model achievable through the use of radar data to infer humidity fields. Further improvements can be expected through the use

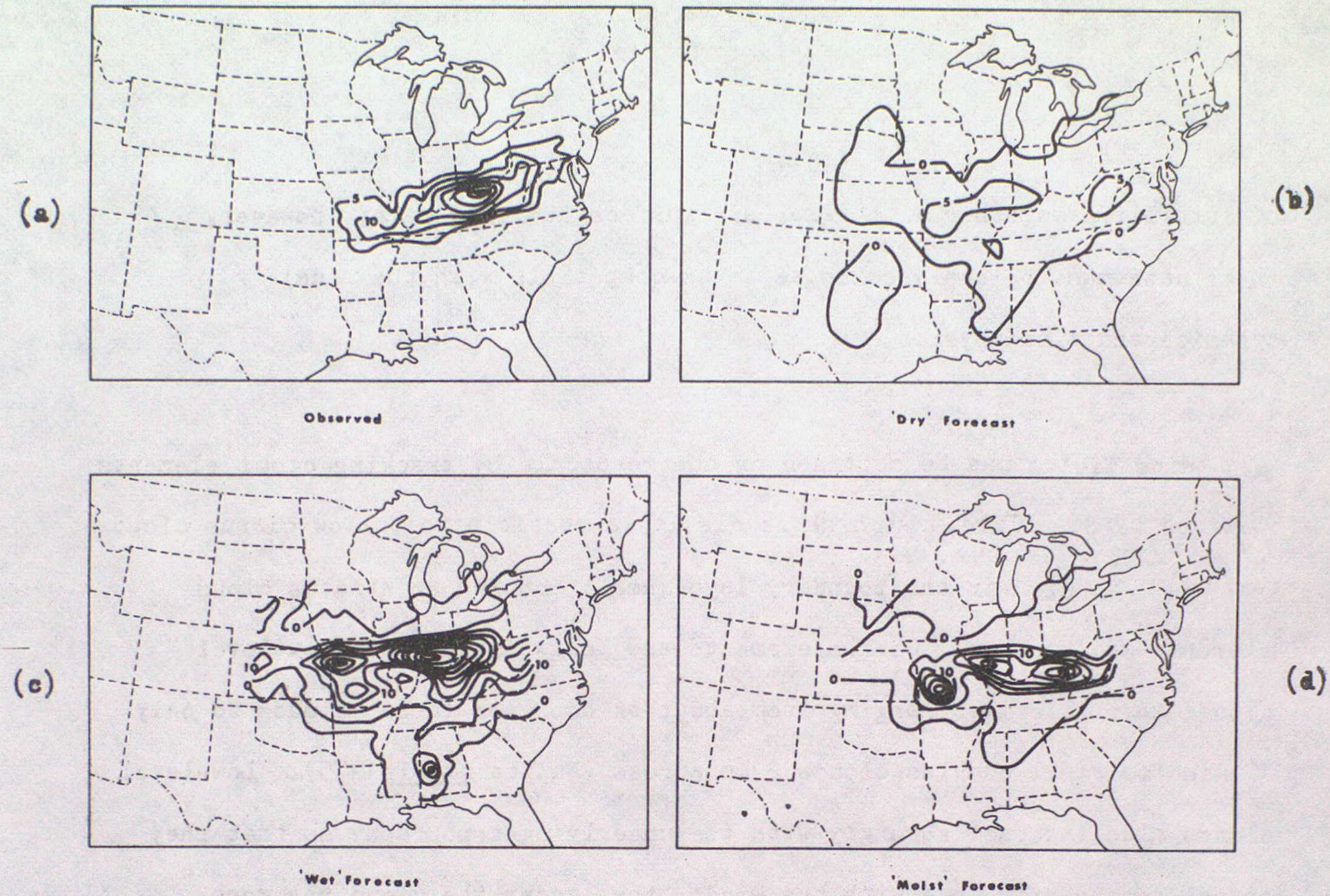
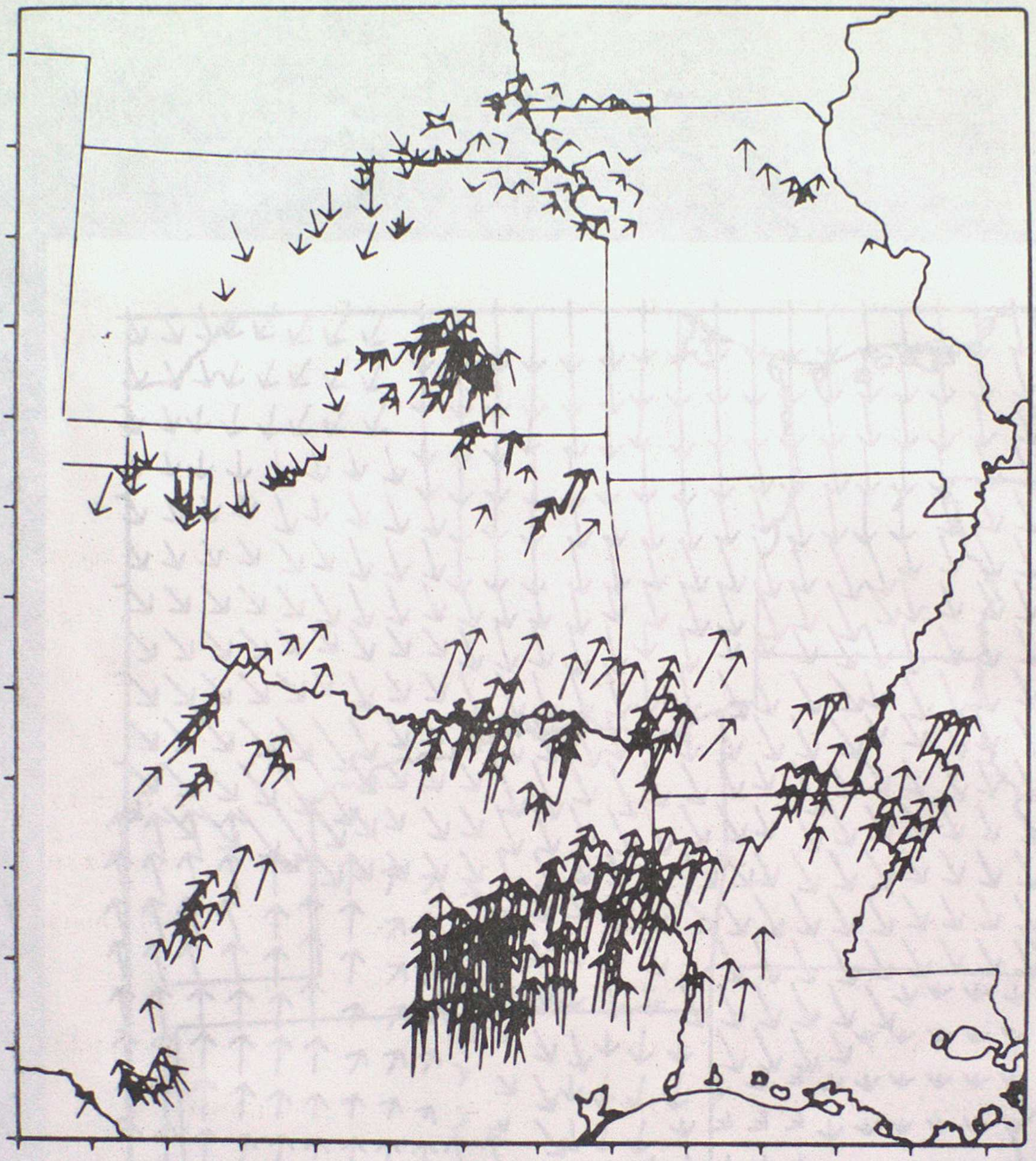


Figure 15 Illustration of the sensitivity of quantitative precipitation forecasts to changes in the initial field of relative humidity (from Kreitzberg and Rasmussen 1977). All diagrams depict 12-h precipitation amounts over part of the USA for the period commencing 1200 GMT 24 April 1975. Isohyets are at 5 mm intervals. (a) shows the observed amounts; (b) shows the model forecast using radiosonde data only; (c) shows the model forecast with relative humidity set equal to 100% in regions where there were radar echoes at 12 GMT; (d) shows the model forecast with relative humidity set half way between the values used in (b) and (c).

of satellites together with radar and surface humidity data; however, these data must be analysed so as to be compatible with the model dynamics and microphysics.

Wind fields can be obtained on the mesoscale by tracking cloud elements observed by satellite. At high levels it is possible to follow cirrus cloud features; but in the boundary layer small cumulus or stratus cloud elements may be used. Cirrus elements are long-lasting, but low-level clouds have lifetimes ranging from about an hour for larger clouds to only 10 min for small cumulus clouds 2 km across (Fujita et al 1975). Low-level clouds also interact strongly with the underlying topography so that they do not necessarily move with the wind: the larger the cloud the more significant is the velocity difference likely to be. Hence it is desirable to track the small short-lived clouds. At present only the gross features of the low-level wind field can be determined using the widely available half hourly satellite imagery; however, reasonably detailed mesoscale wind fields have been achieved in the USA using rapid-scan (5 min) visible data with 1 km resolution from the GOES satellite (figure 16). One of the chief difficulties with such data is in assigning the cloud vectors to the appropriate altitude. This can be done using satellite IR measurements to estimate cloud top temperatures, making allowance for the emissivity being less than unity and the field of view being incompletely filled in the case of small clouds (Smith 1975).



Low-level flow patterns over part of the United States Mid-West at 1800 GMT on 24 April 1975, derived by tracking small cumulus clouds in a sequence of 4 high-resolution GOES satellite pictures obtained at 5-min intervals. (a) shows the individual cloud vectors; (b) shows an objectively gridded wind field derived from the same data. Latitude and longitude are labelled at 1° intervals. A vector of unit grid length represents a wind component of 17.8 ms^{-1} in the north-south direction and 22.2 ms^{-1} in the west-east direction (courtesy of A J Negri).

Fig 16(a)

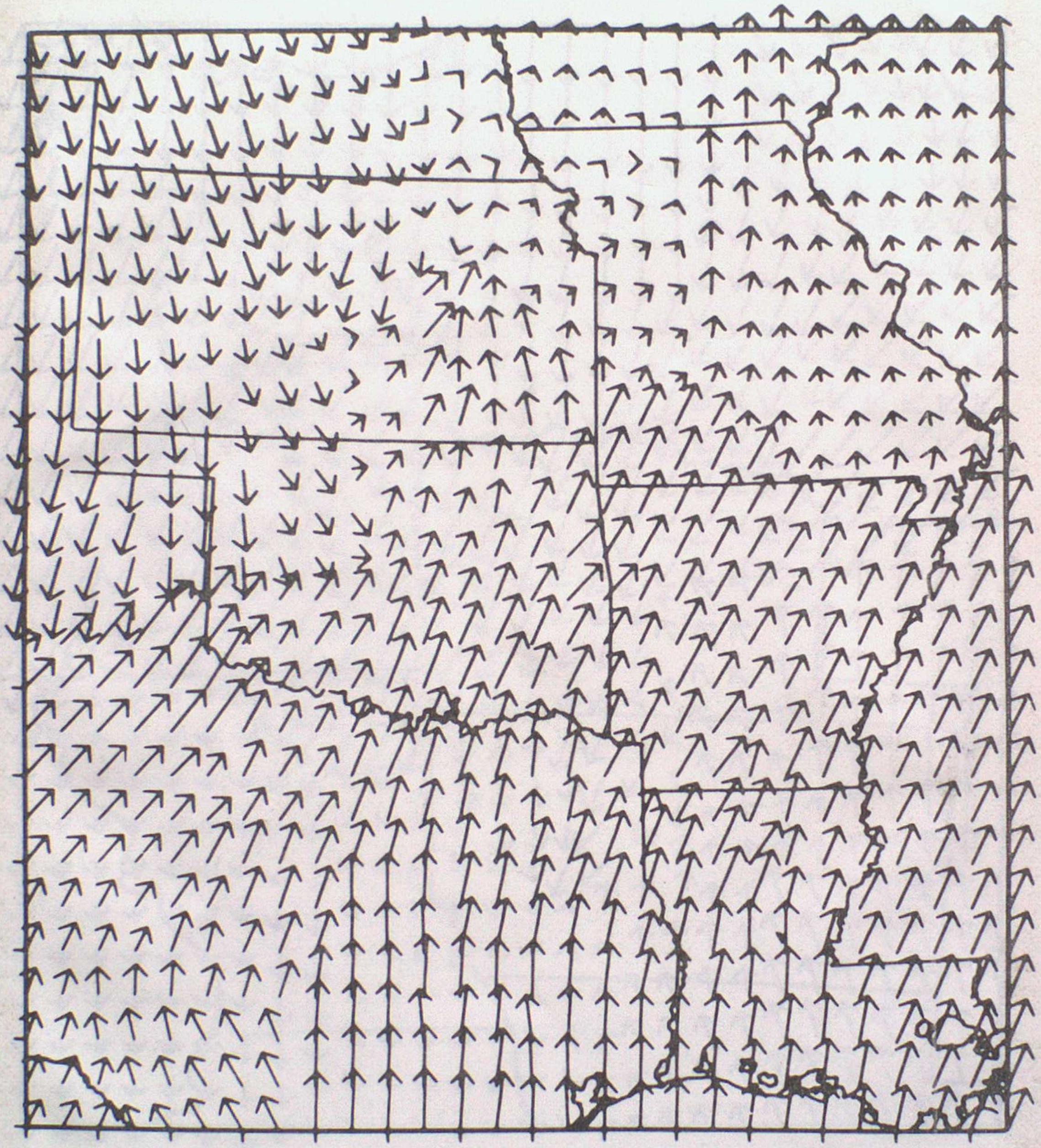


Fig 16(b)

An important task in areas prone to severe thunderstorms is to obtain mesoscale wind fields with sufficient accuracy to reveal the associated regions of low-level convergence. Initial investigations suggest that rapid-scan cloud imagery can be used to detect the areas of strongest convergence (Wilson and Houghton 1979). An extension of this technique (Vonder Haar 1977) would then be to combine the measurement of such areas of convergence with measurements of boundary layer moisture content, since the mesoscale field of moisture convergence is considered to be one of the best indicators of imminent severe storm outbreaks. Perhaps the main difficulty is that, although the satellite measurements provide more observations than can be obtained conventionally from radiosondes or surface reports, they suffer from being biased toward those areas where suitable clouds exist and are not obscured by higher clouds. Thus the satellite measurements should not be used in isolation but, rather, in combination with the more evenly spaced conventional observations.

The measurement of 3-dimensional fields of both temperature and humidity by means of satellite-borne radiometers is a particularly promising area for the future. Radiometers carried on the polar-orbiting satellites, Nimbus-6 and Tiros-N, are already capable of achieving soundings with a horizontal resolution of 30 km; the problem is that they provide good data only in regions devoid of cloud. These same satellites, however, also carry microwave sounding instruments which are capable of providing soundings in the cloudy regions, albeit with a lower resolution of 150 km. Thus, this kind of data provides information which, while coming nowhere near to matching the vertical resolution of conventional radiosonde profiles, especially in the lower troposphere. can be used to fill in horizontal detail not resolved by the widely-spaced radiosonde stations (Hillger and Vonder Haar 1977). Again, an important task is to combine the different forms of data in an optimum manner. An approach now being devloped is to use cloud imagery from the same satellites to identify the clear regions where the high-resolution infra-red data can be trusted (Smith et al 1978). The satellite imagery can also be used to reveal the boundaries of major cloud systems and so provide an indication of expected regions of sharp gradients.

Input data with good time resolution is just as important as data with detailed spatial resolution. Thus a significant step is the launching in 1980 of a sounding system known as VAS, originally conceived by the group led by V.Suomi. (VAS is a second order acronym standing for VISSR (Visible and infrared spin scan radiometer) Atmospheric Sounder). Based on a geostationary satellite, VAS will for the first time provide high resolution infra-red radiometer soundings of temperature and humidity at sufficiently frequent intervals to provide for continuous data assimilation by a mesoscale model. Further developments of geostationary satellite systems during the next decade are likely to be in the direction of increasingly frequent scans over limited areas, improved spatial resolution, and the use of microwave sensors for providing soundings in cloudy conditions (Adler et al 1977). Detailed individual soundings will continue to be needed to complement the satellite data, but it is likely that the current network of radiosonde stations will eventually be superseded by continuous soundings using ground-based remote probing techniques (Beran and Little 1978).

8. Man-machine interactive processing

The thrust towards improved methods of local forecasting owes much to the development of remote sensing techniques capable of providing detailed fields of observational data, and we have discussed how the forecasts can be made either by extrapolating these fields or by using mesoscale models which assimilate the data via a 4-dimensional objective analysis scheme. Either way, however, one is faced with the need to convert large observational data sets into a usable form, and to do it quickly enough for the data to be of value for short period forecasting.

The central issues are those of quality control and of ensuring internal consistency from one data source to another (Houghton 1979). There is, for example, the need to combine remote sensing data with in-situ observations, thereby combining the advantage of continuous coverage of the former with the advantage of greater absolute accuracy of the latter. Then there is the need to intercompare different sets of satellite data. For instance, we have discussed how cloud imagery needs to be used to identify those IR soundings that are contaminated by cloud. We have also discussed how wind fields can be determined from sequences of visible cloud images, the height of the cloud being determined from IR imagery. Much of these analyses can be automated but, in order to achieve the accuracy and reliability required for mesoscale prediction, the meteorologist needs to interact with the computer. He must, for example, ensure that soundings are achieved with the highest possible resolution and density in the meteorologically active regions. He may need to enhance or edit the objective product by adding soundings where strong gradients exist or by removing soundings on the basis of the meteorological consistency of the results (Smith et al 1978).

The requirement for automatic handling of large data sets, together with the need to exercise subjective judgement at a few critical stages of the analysis, can be met using interactive computer-driven video displays capable of performing the kinds of functions listed in table 4. (Overleaf)

Table 4: Functions that can be performed by interactive video display systems

- Rapid access to data, ie almost instantaneous selection of any required image from a set of stored images.

- Precision registration, ie translation of the image to remove registration errors.

- Image enhancement, ie assignment of colours at adjustable thresholds, either to make features of interest stand out or for the purpose of calibrating intensity levels.

- Animation, ie replaying time-lapse sequences of images.

- Zooming, ie selection and enlargement of an area of interest.

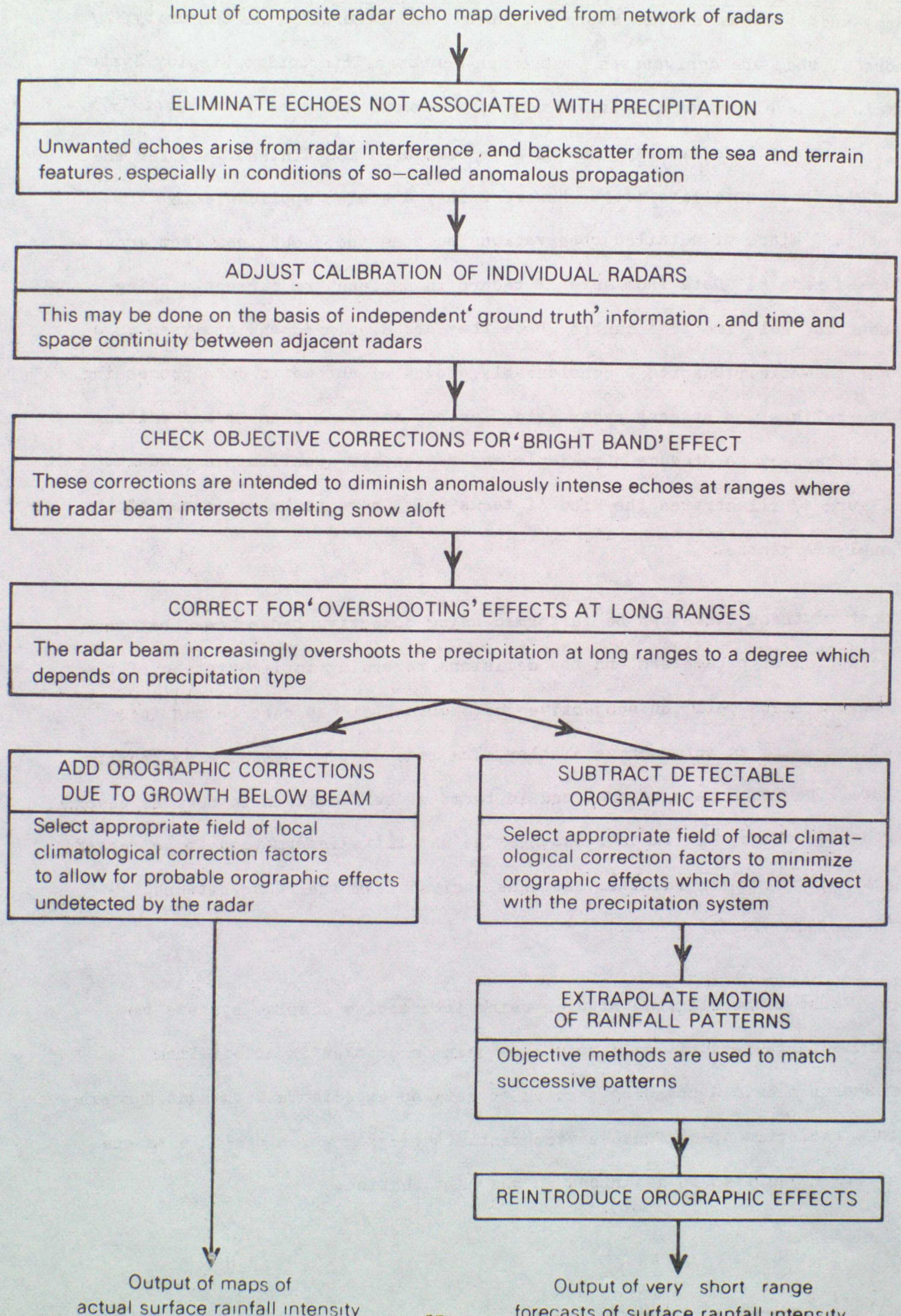
- Image combination, ie combining or comparing with great precision the images from different sources.

- Superposition of vectors and graphics, ie capability of superimposing geographical features, labels, alphanumeric data, and line charts.

- Intervention, ie modification of the image data whilst preserving the original data in store.

Figure 17 (on p.55) Steps in the quality control and analysis of radar network data in terms of surface rainfall intensity. Tasks such as these can be implemented at a mesoscale analysis centre using an interactive video display system (after Browning 1979).

Figure 17


Input of composite radar echo map derived from network of radars
ELIMINATE ECHOES NOT ASSOCIATED WITH PRECIPITATION
Unwanted echoes arise from radar interference, and backscatter from the sea and terrain features, especially in conditions of so-called anomalous propagation
ADJUST CALIBRATION OF INDIVIDUAL RADARS
This may be done on the basis of independent 'ground truth' information, and time and space continuity between adjacent radars
CHECK OBJECTIVE CORRECTIONS FOR 'BRIGHT BAND' EFFECT
These corrections are intended to diminish anomalously intense echoes at ranges where the radar beam intersects melting snow aloft
CORRECT FOR 'OVERSHOOTING' EFFECTS AT LONG RANGES
The radar beam increasingly overshoots the precipitation at long ranges to a degree which depends on precipitation type
ADD OROGRAPHIC CORRECTIONS DUE TO GROWTH BELOW BEAM
Select appropriate field of local climatological correction factors to allow for probable orographic effects undetected by the radar
SUBTRACT DETECTABLE OROGRAPHIC EFFECTS
Select appropriate field of local climatological correction factors to minimize orographic effects which do not advect with the precipitation system
EXTRAPOLATE MOTION OF RAINFALL PATTERNS
Objective methods are used to match successive patterns
REINTRODUCE OROGRAPHIC EFFECTS
Output of maps of actual surface rainfall intensity
Output of very short range forecasts of surface rainfall intensity

Many such systems are now being set up by the meteorological community; most of them are derivatives of the Man-Computer Interactive Display System (McIDAS) developed at the University of Wisconsin (Chatters and Suomi 1975).

Interactive display systems have been used most intensively for the analysis of satellite data. However, they are also applicable to other kinds of detailed observations such as those obtained from ground-based radars. Data from several radars in England are currently being sent in real time to a centre where they are displayed and analysed as a merged whole. Despite a considerable amount of automatic data processing and calibration at each radar site, further data enhancement and editing is necessary to produce a reliable and reasonably quantitative product. Figure 17 illustrates the kind of tasks which need to be performed at the analysis centre.

Most of these tasks can be performed using objective procedures, but the selection of parameters and the decisions regarding implementation of the various steps call for subjective judgements that can best be put into effect using an interactive display. The same display system also permits satellite imagery to be analyzed in terms of surface rain in regions beyond radar coverage; it further enables the satellite information to be merged optimally with the rainfall patterns derived from the radar network. (Browning 1979).

Most meteorological studies using interactive display systems to handle large sets of image data have been undertaken in an off-line research mode.. A pressing need is to develop experience with such systems in a real-time operational environment. A program which has this as one of its objectives is described in the next section.

9. A pilot project in the United Kingdom

The Meteorological Office, recognizing the important technological advances taking place in several fields, has established a Short Period Weather Forecasting Pilot Project, extending from 1978 into the mid '80ies. The aim of the Pilot Project is to exploit satellite and radar along with other data to develop methods for producing more accurate and detailed local forecasts and to optimize the impact of such techniques on the local forecasting capability of the Meteorological Office. In order to provide a focus, the initial emphasis is on the forecasting of precipitation. As a start, the Pilot Project is concentrating on the accurate description of current weather combined with simple extrapolation for the period 0 to 6 h ahead (c.f. § 6). This approach, with its emphasis on advection rather than development, works reasonably well with the frontal disturbances that dominate the weather in the British Isles. In a parallel program the Meteorological Office is continuing the development of mesoscale numerical modelling techniques so as to extend the period of these forecasts, albeit with less detail, up to about 18 h ahead (c.f. § 5). Progress with these models can be expected with the development of improved assimilation schemes using conventional data inputs supplemented with simplified data from the Pilot Project itself, but major advances in the modelling area require mesoscale sounding products especially from geostationary satellites (c.f. § 7), and it may be quite a few years before these are available outside the United States.

The Short Period Forecasting Pilot Project can be considered in two phases. During the first phase the primary goals are:

To set up semi-operational facilities to provide integrated fields of precipitation and cloud from a network of radars and satellites.

- To undertake fundamental research using these improved facilities so as to gain a better understanding of the structure, mechanism and predictability of precipitation systems.

- To develop practical forecasting techniques.

Most of the effort so far has been devoted to setting up the facilities. Digital data from the four radars shown in figure 18 can be transmitted both to local users and to the Project Centre at Malvern where they are composited to give rainfall maps similar to that shown earlier in figure 13 (a). Cloud imagery from Meteosat covering the larger area in figure 18 is remapped and converted into a digital format virtually identical to the radar data (see examples in figure 9). The use of a common format permits easy comparison of the satellite imagery and radar rainfall data, and an interactive video display system of the kind described in § 8 is being developed to expedite this analysis. In an attempt to speed up the transfer to operational use of techniques developed in this project, an operationally oriented Forecasting Techniques Group has been established at the Malvern laboratory to work alongside groups developing the facilities and carrying out the basic research. It is hoped thereby to enable forecasters to take quick advantage of new opportunities and improved understanding, and to enable them to provide feedback into the design of the system.

The second phase of the Pilot Project will, amongst other things, address the issue of marrying the digital satellite and radar data with conventional meteorological data which, during the '80ies, will also be available in

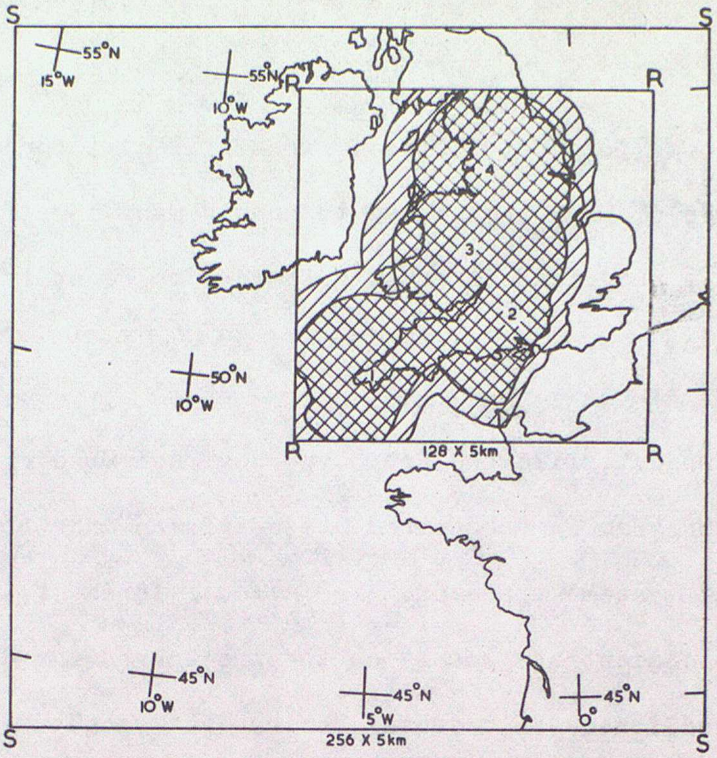


Figure 18 Coverage of the radar network and radar-compatible satellite data available in the Meteorological Office Short Period Weather Forecasting Pilot Project. The shading indicates the approximate area within which precipitation can be observed qualitatively using radars located at (1) Camborne (Cornwall), (2) Upavon (Wiltshire), (3) Clee Hill (Shropshire), (4) Hameldon Hill (Lancashire). The cross-hatched shading illustrates the typical year-round coverage; the single-hatched shading depicts the typical coverage in summer-time conditions. The square frame RRRR denotes the boundary of the television display on which colour-coded digital rainfall data from the radars are combined in a 128x128 matrix of 5 km cells. The larger square frame SSSS denotes the boundary of the television display on which colour-coded digital satellite cloud data are displayed in a 256x256 matrix of 5 km cells. The radar network data can be superimposed in the appropriate area. Man-machine interactive processing is used to merge the two data sets so as to produce an optimum overall analysis of surface rainfall.

 (Figure and legend only on this page)

digital form at some forecast offices. This will call for an extension of the interactive display techniques to enable many more forms of data, and also mesoscale numerical forecast guidance, to be analysed together on a common display.

The Pilot Project, like the Prototype Regional Observing and Forecasting Service (PROFS) program in the United States (Beran and Little 1978), involves a 'total system' approach. For a local forecast to be useful it is not enough to concentrate solely on the procedures for deriving good frequently-updated forecasts, because just as vast amounts of observational data are worthless without the means to process them so, too, a forecast (especially a short period forecast) has little value unless it can be communicated to customers both quickly and in a format suited to their needs. Hence the Pilot Project has two further aims:

- To exploit modern techniques to disseminate the forecasts promptly, automatically and selectively to large numbers of users.

- To develop improved means of tailoring the forecasts to suit the needs of different users.

Although the spoken word will continue to be used for disseminating some information, perhaps with new procedures for automatically interrupting radio programs to issue warnings on a strictly local basis, information can in general be conveyed more clearly using visual dissemination systems such as teletext (Ceefax and Oracle) and the even more versatile viewdata system (e.g. Prestel). Major opportunities for providing a more user-oriented service will arise, given the necessary market research, because the information on the forecasters' working displays will be in an appropriate digital format for automated tailoring and dissemination. Some users will want picture data while others will require input directly into their own computers. Water Authorities, for example, require rainfall totals integrated over predetermined river subcatchments for input into hydrological streamflow models. The increasing use of on-site microprocessor control systems and dial-up computer access will enable Industry in general to respond to, and gain more benefit from, the new forms of local weather information.

It would be a mistake to leave the impression that there will be early dramatic improvements in local weather forecasts. We have shown in this lecture that the opportunities opening up in the fields of observation, data processing, communications and numerical modelling, also pose major challenges, especially if these different facets are to be blended together as a workable system. We have only just begun to face these challenges. However, I believe that, so long as we in Europe retain a forward-looking meteorological satellite program and the research and development in short-period forecasting continues to gain momentum, then the ingredients are there for a steady improvement over the next decade in the accuracy, precision and utility of our local weather forecasts.

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