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Representation and recognition of convective cells using an object-oriented approach

by

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September 30th 1991

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Abstract

Object-oriented techniques have been developed to represent convective cells in all stages of development as meteorological objects within a possible future Nowcasting system. Methods of recognising these objects from radar and METEOSAT satellite data (corrected for parallax) are presented, and the general problem of detecting convective cells with current observational data is discussed. A case study has been performed whereby convective cells have been identified over part of southern England. The results have been compared with conventional surface reports with some encouraging conclusions.

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1 Introduction

The Nowcasting Development Group within the Nowcasting and Satellite Applications branch has been involved in developing techniques to automate and improve the FRONTIERS short period forecasting system. Within the present FRONTIERS system, forecasts are largely based on the advection of radar and satellite derived rainfall patterns. This can be successful for 'well-behaved' meteorological systems, however, performance can be poor in convective situations in which there is always a lot of development and decay. In seeking ways of improving forecasts involving convection it was decided to examine the possibility of using object-oriented programming techniques to define and represent convective cells from observational data. This was done with a view that, if they could be defined with sufficient accuracy, then knowledge of the typical life-cycle of these cells would allow their future behaviour to be predicted and therefore the associated weather, particularly rain. This note describes how, using an object-oriented approach, convective cells can be diagnosed and represented. These techniques have been tried on data for a typical convective day in April and the results are presented and discussed as a case study at the end of this report.

2 Object oriented programming

This is a method of programming where the emphasis is on 'data to which things are done' as opposed to 'procedures that do things to data', which is the traditional approach. In object-oriented programming one seeks not to define procedures that will manipulate data but to define data objects, their attributes and the way in which they may be examined or changed. Objects are generally capable of doing two things. They can store information about themselves and they can receive or handle messages which might ask them for information or to change some aspect of their internal state. The internal data are stored in locations called, variously, 'slots', 'attributes', or 'instance variables' and the description of how to handle a particular message is called a 'method'. Objects can be grouped into classes wherein each object will have the same types of attributes. In object-oriented programming a distinction is made between a class of objects and an instance or example of a class. For example, we can describe the features that are common to all cold fronts (the class of cold fronts) and then have instances of cold fronts called, say, 'CA' and 'CB'. Features or attributes of cold fronts might include their slope, velocity, and horizontal temperature gradient. Messages that a cold front may respond to might, for example, include 'move', 'intensify', 'weaken'. Both 'CA' and 'CB' in their capacities as cold fronts ought to be able to respond to the same messages, but the values that they have for their attributes (such as slope and temperature gradient) should be different. In the language of object-oriented systems 'CA' and 'CB' are both instances of the class 'cold fronts'. As members of the same class they have values for the same attributes and are capable of responding to the same messages. As different instances the actual values they have for the attributes are likely to be different.

In almost all object-oriented systems the process of 'specialization' or 'inheritance' is available. This allows one to define a class such as 'fronts' which encapsulates all the relevant features of fronts and then to define another class which belongs to the same class but is a specialization of it, for example 'cold fronts'. A cold front is a kind of front and has all the attributes or characteristics that fronts possess but also some special additional attributes relevant to cold fronts, for example, a low-level jet. The class 'cold fronts' is said to inherit from the class 'fronts'. All attributes of an instance, including those passed down by bequest, may or may not contain values for a particular occasion. The process of putting in values for attributes is called instantiation. As already mentioned these values may be changed by messages which may trigger other processes or messages. For example, the message to move a front will alter the position attribute but may fire other messages such as to change stability if the front moves from sea to land. Additional messages that are fired after a message are called 'after daemons'. The 'after daemons' will contain instructions to change attributes or may fire more messages with their associated 'after daemons'. Before a message is processed certain tasks may be performed, these processes are called 'before daemons'. 'Before' and 'after' daemons can have the same name for different object classes, however the methods may be different. For example, a message to the class of fronts may have an 'after daemon' for both the cold and warm front classes, however, the actions could be very different. Thus a cold front object receiving a message to change an attribute inherited from the fronts class will activate an 'after daemon' whose method is defined in the cold front class. A more concrete example of this will be given when convective cells are discussed.

This section has briefly described the general characteristics of object -oriented programming. Using these techniques, convective cells have been represented using an object-oriented package called FLAVOURS implemented using the POP-11 programming language which is available within the POPLOG programming environment [1]. POP-11 is a language well suited to object-oriented programming and most of the work covered in this note has been programmed in POP-11.

3 Convective cells as objects

Before describing how convective cells are represented it is important to state what we mean by a convective cell. In this note a convective cell is an individual convective cloud at any stage of its life-cycle. The description caters for small cumulus humilis clouds a few hundreds of metres wide to mature cumulonimbus clouds covering areas of 25 square kilometres or more. The convective cells will typically develop in unstable polar maritime airmasses over the UK with an average lifetime of about an hour. This description will not be relevant for MCS's or for other large organised convective clusters such as supercells and line squalls which may be regarded as separate classes of objects within the broad class of convective systems.

In the implementation defined in this note convective cells are taken to be objects which inherit attributes from the class of clouds and which possess attributes themselves. That is, convective cells are a specialization of clouds. We shall now look at the attributes defined for clouds and convective cells.

3.1 Attributes of clouds

- **name** - this is a unique identifier given to the particular instance of the cloud system whatever it may be. (Convective cell, trough, MCS etc). It labels the instance and distinguishes it throughout its life from other instances of the same type.

- **base** - cloud base height.
- **area** - cloud base size. All clouds are assumed to be topologically equivalent to an ellipse (or circle). The area is expressed in the program as a list containing the elements 'major' and 'minor', that is, [major minor]. 'major' is the length of the major axis of the cloud and 'minor' is the length of the minor axis, circular clouds will obviously have 'major' identical to 'minor'.
- **depth** - depth of the cloud.
- **top** - cloud top height (depth + base).
- **cloud_top_temp** - cloud top temperature.
- **composition** - describes the phase of the cloud droplets in the top of the cloud, (water, water and ice, or ice).

This list should be sufficient to describe most convective cloud systems. However, it may need to be extended for other systems, for example, fronts. In a frontal system the top and base could be expressed as a list containing the minimum, maximum, and mean value, also shape and texture attributes may be appropiate.

3.2 Attributes of convective cells

Convective cells are objects that inherit the attributes of clouds but also possess the following additional attributes:

- **stage** - stage of development of the cell. For example, mature or dissipating.
- **position** - is the centroid location of the cell. This is represented by a two element list containing the x y coordinates.
- **velocity** - is the mean motion of the cell expressed in terms of the same units as the position attribute.
- **ppn_rate** - precipitation rate at the surface beneath the cell.
- **ppn_type** - phase of the precipitation, rain, graupel, snow etc.
- **lightning_frequency** - frequency of lightning expressed as flashes per minute.
- **age** - age of the cell in minutes.

These attributes define cells sufficiently for estimates of their future behaviour to be made. The list, however, has been restricted to those attributes that may be instantiated and verified using current observing systems such as FRONTIERS radar and synoptic reports. It would be easy to extend the list to include other attributes such as vertical motion profiles (which uniquely determine the stage of a cell) when more sophisticated radar data become available to measure such fields.

3.3 Messages to clouds

The attributes of clouds may be changed by sending the following messages:

- **grow(factor)** - will change the cloud depth by a factor of its original depth. The base is preserved but the cloud top height will change. Since the cloud top height changes, the cloud top temperature is adjusted assuming an ICAO lapse rate from the old cloud height to the new height.
- **expand(major_factor, minor_factor)** - will expand (or contract) the area of the base of the cloud by multiplying the major and minor lengths by factors. This message can also be used to change the shape of the cloud.
- **dissolve** - will get rid of the cloud object. This is achieved by making the 'name' attribute undefined.
- **basetop(base_amount, top_amount)** - this will change the cloud base and cloud top heights. Either or both may be raised or lowered. This message will also change the depth, and if the cloud top height has changed, the cloud top temperature.
- **change_cloud_top_temp(value)** - the cloud top temperature is changed to the value specified. The cloud top height is then recalculated assuming an ICAO lapse rate and a check is made on the new cloud depth. If it has become negative then the cloud is dissolved.
- **alter(type)** - this message will alter the cloud top composition to that passed in 'type' and is sent only if the cloud top temperature changes.
- **grown** - this is a special message that does nothing except fire any 'after daemons' for objects that inherit from clouds. The 'grown' message is sent within any method that changes cloud depth , that is, 'grow', 'basetop', and 'change_cloud_top_temp'.

3.4 Messages to convective cells

- **set_defaults(stage)** - this message will set default values for all attributes according to cell stage. The defaults will have some seasonal dependence and are based on those documented in [2].
- **birthday(i)** - will make the cell *i* minutes older.
- **change_ppn_rate(rate)** - will change the precipitation rate to *rate*.
- **change_ppn_type(type)** - will change the precipitation type to *type*.
- **change_lightning_frequency(frequency)** - will change the lightning frequency to *frequency*.
- **alter_stage(new_stage)**- will change the stage of development to *new_stage*.
- **move(x,y)** - will change the position attribute to [*x y*]. The cell is moved to a new location defined by x and y coordinates.
- **change_velocity(vx,vy)** - this will change the x and y components of the cell velocity to *vx* and *vy*.
- **print_cell** - this message is used to print out an instantiation of a convective cell. All current values of attributes are printed out.

- **change_instancs(newname)** - is used to create a new instantiation of a convective cell. The 'name' attribute is given the word contained in *newname*. This is effectively a christening message that calls a procedure to create a new instantiation. The message is used frequently in the cell analysis stage but could also be issued by mature cell objects to generate daughter cells in a forecasting package.

Most of the messages listed above will fire 'after daemons', the effects of these and the one fired by the 'grown' message discussed earlier will now be described.

3.5 'After daemons' for convective cells

- **after grown** - this daemon seeks to realise the consequences for convective cells of changing cloud depth. The method first examines the new aspect ratio (depth/width). The aspect ratio is not allowed to exceed 3.5 for developing cells, 2.0 for mature cells, and 1.5 for dissipating cells. The width in the calculation is the length of the major axis in the 'area' attribute. If the new aspect ratio exceeds the prescribed limits then the cloud base is expanded so that the new ratio equals the limiting value. Both major and minor axes are expanded identically to preserve shape. Constraining the aspect ratio prevents ridiculously tall thin clouds being developed. Changing depth changes the cloud top temperature. If the new temperature is < -39C then the cloud top composition is changed to ice and if the temperature is >0C the composition is changed to water.

- **after birthday** - if the cell's age exceeds 70 minutes then the cell is deemed to be past retirement age and is dissolved. Any 'living' cells older than 44 minutes have their stage altered to dissipating.

- **after alter** - if the new cloud top composition is 'water' then the stage is altered to 'developing'. Most convective clouds composed of water droplets in the UK are developing cells.

- **after change_ppn_rate** - if the new precipitation rate exceeds 5.0 mm/hr then the stage is altered to mature.

- **after change_ppn_type** - if the new precipitation type is hail then the cell stage is altered to mature. Also if the cloud top temperature is > -20C then the cloud top temperature is changed to -20C. This is to ensure that the cloud top temperature of the cell is cold enough for hail to form and fall out.

- **after change_lightning_frequency** - if the new lightning frequency is > 1 flash per minute then the stage is altered to mature.

It can be seen from the above that certain messages will have the effect of firing sequences of messages and their associated 'after daemons'. This effect is perhaps best demonstrated by an example. Suppose a message is sent to a cell, identified with the name 'cell100', to change its precipitation type attribute to hail. In POP-11 this would be coded as follows:

cell100 < – change_ppn_type('hail');

The effect of this would be to:-

- Change the attribute **ppn_type** to the string 'hail'.
- Fire the 'after daemon' **after change_ppn_type** which will then:-
- Change the attribute **stage** to the string 'mature' by sending the message **alter_stage('mature')** to cell100.
- Examine the cloud top temperature attribute and if it is greater than -20C change it to -20C by sending the message **change_cloud_top_temp(-20)** to cell100. The effect of this would be to adjust the cloud top height of cell100 and change the depth of the cell. The message **grown** would then be sent to cell100 which would do nothing but fire the 'after daemon' **after grown** which would then:-
- Check whether the aspect ratio was > 2.0; if it was the **expand(..)** message would be sent to cell100 to adjust the cell base area such that the aspect ratio was equal to 2.0.
- Control would then return to the procedure originating the message to change precipitation type to hail.

This exchange of messages and daemon processes depending on the value of the attributes of an object is the very essence of an object-oriented approach to programming.

In this section and the previous one it has been shown how convective cells may be represented in an object-oriented framework. In the next section the problem of recognising and instantiating cells using observational data is addressed.

4 Instantiation of convective cell objects

Before a convective cell can be instantiated its stage in its life-cycle has to be identified. For this work the assumption has been made that all objects to be recognised will be convective cells or clouds associated with convective cells. One must now consider how convective cells will appear to currently available observing systems.

4.1 Recognition using FRONTIERS radar data

4.1.1 Theoretical discussion

FRONTIERS radars are able to detect targets with drop sizes and number densities in the ranges illustrated in figure 1. Targets containing droplets in categories within the yellow area will produce an echo on the FRONTIERS display provided they are large enough. It can be seen that droplets have to reach at least 'drizzle' size before they can be detected. This means that developing convective cells composed entirely of cloud droplets can not be detected using the FRONTIERS radar network. It may just be possible to pick up the very large cloud droplets (about 100 microns) developing in the upper half of a towering cumulus cloud, though this is doubtful. However, cumulonimbus clouds, because of their size and microphysical spectra should produce returns up to the end of the dissipating stage when rainfall production ceases. Convective clouds typically go through several stages of development that will affect the vertical profile of radar reflectivity [3]. It is this property that has been explored in using FRONTIERS radar data to detect cell stage.

The 6 idealised stages of evolution of a convective cell that we hope to be able to observe are summarised below:

1. **Young developing cells (y) -** These are the first visible clouds of a cell. They are typically 5 minutes old, about 500 metres wide with depths up to 1500 metres. They would be observed as either cumulus humilis or cumulus mediocris clouds and encoded as cumulus type 1 in the coded messages for surface synoptic reports.
2. **Developing cells (d) -** These are quickly growing clouds typically about 10 minutes old. The cloud outline becomes well defined at the top due to rapid growth of supercooled water droplets in the developing strong up-current. Their base size is expanding but is often less than 3km and cloud top temperatures will typically be in the range -10C to -30C. These cells would be observed as cumulus congestus (type 2) or cumulonimbus without anvil (type 3). They are sometimes referred to as towering cumulus.
3. **Young mature cells (m) -** Typically 20 minutes old, this is the stage when the first rain appears at the surface, and perhaps followed by the first ground lightning strike. Glaciation at the cloud top also begins. These clouds would be observed as cumulonimbus with or without the beginnings of an anvil (types 9 or 3). Cloud top temperatures would typically be lower than -30C with base sizes increasing from around 3km.
4. **Fully mature cells (M) -** These are the classical cumulonimbus clouds with developed anvils (type 9), with associated heavy rain and possibly hail and thunder. Very strong updraughts and downdraughts will co-exist within the cloud with gustiness at the surface.
5. **Early dissipating stage (E) -** In this stage the cell is starting to decay, rain becomes lighter and lightning becomes less frequent and may become confined to the anvil region. Typical age is about 45 minutes, with the cell beginning to occupy an area > 25 square kilometres. An observer would still encode the cloud as cumulonimbus type 9.
6. **Dissipating stage (D) -** During this stage rain dies out and the cloud becomes stratified and starts to dissolve. Weakening downdraughts predominate throughout the cloud which will by now typically occupy an area of more than 100 square kilometres with cloud top temperatures < -20C. An observer would probably still call the cloud a cumulonimbus type 9 but perhaps altocumulus cumulonimbogenitus (medium cloud type 6) or stratocumulus cumulonimbogenitus (low cloud type 4).

The next section will outline a procedure for detecting the probable presence within a FRONTIERS pixel of each of these cell stages.

4.1.2 Procedure adopted

In FRONTIERS, radar data from up to 3 beam elevations are available. Since each radar site uses different elevations, three broad beam categories for the beam elevation (E) have been prescribed:

BEAM 0 $0.0 \leq E \leq 0.5$

BEAM 1	$0.5 < \mathbf{E} \leq 1.2$
BEAM 2	$1.2 < \mathbf{E} \leq 1.5$

Assuming a beam width of 1 degree the maximum and minimum height of each beam category as a function of range is shown in figure 2. Typical cloud top heights for different cloud types are indicated on the left-hand side of the figure. It can be seen that up to ranges of about 100km all beams will intersect all but the smallest of cumulus clouds. However, at longer ranges, particularly those greater than 150km, beam number 2 will intersect the upper half of a large convective cell whereas beam 0 will intersect lower down. Thus, cells will appear differently according to range and to the beam which intersects the object. The expected radar returns expressed as rainfall rate for each cell type as a function of beam and range are depicted in figure 3. These returns have been determined by a mixture of theoretical considerations, experiment and commonsense. It can be seen that for ranges less than 100km the expected minimum and maximum returns for each cell do not depend on beam number. Beyond 100km, however, there are some interesting variations. For example, for young mature cells (m) between 150 and 200 kilometres from a radar, the maximum expected return is greatest for elevations in beam category 1. This is because beam 1 is centred at 5000m where cloud temperatures will be around -20C and is a very productive region for precipitation growth. Note also that fully mature cells (M) are expected to produce very high returns irrespective of range or beam, however, beyond 150km the minimum return for beam 2 is lower than the others since part of this beam is likely to be looking at or over the top of the anvil. It must also be noted that the determination is not unique. For example, a radar rainfall measurement of 0.8 mm/hr from a radar using beam 0 up to a range of 100kms would give cell type classifications of (m), (E) or (D). What we are saying here is that there is likely to be part or all of a 'young mature' or 'early dissipating' or 'fully dissipating' cell within the FRONTIERS pixel from which the rainfall measurement was obtained. However, we cannot say which type prevails. Also a zero radar rainfall rate could mean the presence of either, or a mixture of, (y), (d), (m), (D) cells or none at all. Many of these uncertainties can be resolved by using satellite data as we shall see later, however, it was felt desirable to introduce a priority of cell stages. The priority adopted (highest first) was (M) (m) (E) (D) (d) (y) . This order is the decreasing order of meteorological severity of convective cells. Therefore, returning to our example earlier, the radar rainfall measurement of 0.8mm/hr would produce a list of cell type candidates [m E D] which would subsequently be compared with satellite data.

It is obviously very important to be able to detect mature cells that are producing hail and thunder. Recent work in Canada by Goyer et al [4] suggests that the location and number of lightning flashes appears to be intimately related to the presence of large areas of high (> 40dbZ) reflectivity in the radar echo. 40dBz converts to a radar rainfall range of 9 - 12 mm/hr depending on the Z-R relationship. The higher value of 12 mm/hr has been selected. Since fully mature cells are expected to produce a high return irrespective of beam elevation, a simple scheme, which says that if the radar rainfall rate is > 12mm/hr then the cell is likely to be thundery, has been tested (see case study later). Thundery cells are indicated by the letter (T) and are always first in the output priority list.

It can be seen from the above discussion that FRONTIERS radar data alone are not sufficient to determine cell stage uniquely. We must therefore look to other data sources if we are to resolve uncertainties.

4.2 Recognition using METEOSAT Infra-red (IR) data

4.2.1 Problems with METEOSAT IR (MIR) data

There are two things to consider before using MIR data for this application. The first is the horizontal resolution. Between 50N and 60N the effective pixel resolution is approximately 10km north-south and 5km east-west. This means that only fully mature or dissipating convective cells may be resolved. Also the temperature derived from the MIR data may not be that of any underlying surface but a non-linear combination from different sources. For example, a thin cirrus layer would allow an unknown contribution to the overall IR radiance from warmer surfaces below. This problem whereby the measured temperature of a MIR pixel comes from a variety of heat sources is well known but can present severe problems when one is seeking to look for objects at or below the MIR resolution. The second difficulty is that of errors introduced by satellite parallax. These arise from the fact that medium or high clouds in middle and high latitude regions appear to be located further north than they really are when viewed from a satellite centred over the equator. The errors can be considerable, particularly for convection nowcasting. This problem has been studied by Cheng [5]. Cheng calculated that for cloud tops higher than 10km the parallax error increases from 0 at the equator to 15km at 50N and to 50km at 70N. Cheng proposed a correction scheme for FRONTIERS MIR images based on cloud top height and 3 east-west bands within the FRONTIERS area approximately corresponding to regions north of 55N, 50N to 55N, and south of 50N. The corrections are a southward displacement of the FRONTIERS pixel. The displacements range from 6 pixels for cloud tops higher than 14km and north of 55N to 0 pixels for all cloud tops lower than 1km. Since obtaining cloud height accurately from MIR data is difficult, it has been decided that the heights and displacements calculated by Cheng be simplified according to MIR temperature values (T). The displacements used are as follows:

$T > 0C$	no displacement
$0C > T \geq -20C$	1 pixel southwards
$-20C > T \geq -40C$	2 pixels southwards
$T < -40C$	3 pixels southwards

(They were chosen for the limited latitude band, 55N - 50N, of the data in the current case study). In the ICAO atmosphere 0C, -20C, and -40C correspond to 2km, 5km, and 8.5km respectively. On most convective days in the UK these heights will be correspondingly lower and the displacements based on temperature will broadly agree with those produced by Cheng within the areas covered by FRONTIERS radars. These modified corrections are very easy to apply to a FRONTIERS METEOSAT image. However, after displacement there will be pixels that will contain no MIR data. Where this occurs the empty pixels are given the temperature value of the next pixel to the north that does contain a value after adjustment. Corrected and un-corrected images have been compared and an example is illustrated in figure 4. It can be seen that the very cold cloud in the centre of the image has been moved 3 pixels south and that some of the warmer cloud just to the south has been obscured. This has the effect of increasing the gradient of cloud top temperature on the southern edge of large clouds. This can be realistic in a convective situation, since in UK latitudes METEOSAT will partly view the sides of large cumulonimbus clouds, measuring a warmer temperature than if the cloud was viewed from overhead. The corrected image also correlates better with the radar rainfall data than does the un-corrected image.

4.2.2 Procedure for using METEOSAT IR data

After correcting for parallax MIR data are compared on a pixel by pixel basis with the cell stages determined using radar data alone. This is achieved by using prescribed lists within the POP-11 program :-

[y 0 50 y]	[y -15 0 d]	[y -70 -15 C]
[d 0 50 y]	[d -15 0 d]	[d -70 -15 C]
[m -10 50 m]	[m -30 -10 D]	[m -70 -30 D]
[M -10 50 #]	[M -30 -10 #]	[M -70 -30 M]
[E -10 50 m]	[E -30 -10 #]	[E -70 -30 E]
[D -10 50 m]	[D -30 -10 D]	[D -70 -30 D]
[T -10 50 #]	[T -30 -10 #]	[T -70 -30 T]

The first item in each of the 21 lists is one of the cell stages determined using radar data only. The second and third items define a MIR temperature category. Item 2 is the minimum value and item 3 the maximum. The fourth item is the resulting likely cell stage using both radar and MIR data. Two new categories have been introduced here. The '#' symbol represents a small mature cell (ie one that has a small base area) and 'C' represents dense cirrus possibly originating from anvil debris. Strictly speaking this is not a cell stage but can be a useful interpretation of the MIR data. The procedure takes the list of possible cell stages assigned to that pixel from the radar data and extracts the first item (X) of that list. Each of the 21 lists above is then examined and the one where the first item corresponds to (X) and the MIR temperature category contains the MIR temperature for the FRONTIERS pixel is selected. If in this list the resulting likely cell stage matches the stage using radar data (X), processing stops for that pixel. If a match is not found then the next possible stage in the radar stage list is extracted and the procedure is repeated until either a match is found or until the cell stage possibilities from radar data are exhausted. If a match cannot be found then the most likely cell stage is taken to be the result (4th item) of the comparison for the first item in the radar data list. For example, the list of possible stages [m E D] from radar data and a MIR temperature of -21C would give a cell stage of D as the most probable. The temperature categories have been chosen to allow for the size of the object to be found. For example, a young mature cell is expected to have a MIR temperature in the range -10C to +50C because METEOSAT will sense the heat of the surface surrounding the cell as well as from the cloud top. Similarly, a fully mature cell with a MIR temperature > -30C will be categorised as small (#). It must be emphasised that if a mature cell is categorised as small it does not necessarily mean that the cell is small. It may also be interpreted that there is a mature cell partly within the FRONTIERS pixel whose base area only covers a fraction of the pixel area. Since young mature cells and small fully mature cells typically occupy areas less than a FRONTIERS pixel the MIR temperature cannot be used directly to instantiate the cloud top temperature. To obtain a realistic cloud top temperature (T) for these cells a simple parametrisation is used -

T (deg C) = MIR temperature - 10(A - major_diameter)

A is the size of a FRONTIERS pixel in kilometres (currently 5). The 'major_diameter' attribute is set to 3 kms by default for both young mature cells and small fully mature cells.

4.3 Recognition using other data sources

Up to now we have considered the use of radar and MIR data in the cell stage identification process. These data sources are considered to be the primary ones for this task. However, other sources are available, namely METEOSAT visible and water-vapour imagery, AVHRR data, synoptic reports, and sferics.

METEOSAT visible data are only available during the day, however, most convective activity is usually during daylight hours. Like MIR, visible data must also be corrected for parallax for which the cloud top heights are required since, unlike temperature, there is no definite relationship between the measured albedo and cloud top height. Any parallax correction would also need to be carefully bound to the process of normalisation to a vertical sun angle. Correcting for parallax would mean a slight change in sun-angle with a corresponding small effect on observed radiance values. Visible radiances are also difficult to intepret since different types and combinations of reflecting surfaces can produce identical values. An advantage of METEOSAT visible data, however, is that they may be obtained with twice the resolution of IR data.

The difficulty with METEOSAT water vapour data is one of interpretation and information content. It is felt that these data can offer little to the problem of determining cell stage, however, they may be useful in the broader task of pre-determining areas of potential convective activity.

AVHRR data have the same problems as METEOSAT data, however, they are not as severe because of the higher horizontal resolution. Unfortunately these data have a much lower temporal resolution than METEOSAT, and since the lifetime of individual cells is of the order of an hour, are of limited value.

Synoptic reports from manned observing stations are the only source of data which provide cloud type and base directly. Unfortunately they are usually only available hourly and at scattered locations. Moreover, there is no indication in the message where the cloud is located. Thus an observer will report a cumulonimbus cloud at the station if he can see it; the cloud may be up to 60 kilometres away in any direction, or overhead. The present weather could be a useful cell stage indicator, although it must be remembered that observations are not always completed exactly on the hour or half-hour and may only represent weather conditions up to 10 minutes prior to the nominal observation time. However, it is felt that surface reports can be useful in verifying cell stage determinations from remotely sensed data and could perhaps be used to supply confidence measures. This is discussed further in the case study presented in the next section.

The relationship of sferics reports to radar and satellite data is discussed in [6]. Potentially sferics data should be capable of locating the thundery cells and of instantiating the 'lightning frequency'. However, ATD data currently available in the synoptic data bank can only be retrieved to a temporal resolution of 5 minutes and are not sufficiently accurate in space to be able to associate particular flashes with cells [7]. Other sources of sferics data, for example Electricity Research and Development Council, can suffer from reliability problems and availability over rather small service areas [7]. For these reasons sferics data at the moment are treated in a similar way to synoptic surface reports to verify cell stage judgements made using the remotely sensed data.

To summarise, only FRONTIERS radar and METEOSAT infra-red data are used in the current scheme to determine the stage of convective cell objects. Synoptic reports and sferics data have been used subjectively to verify results and may prove useful in later versions for modifying instantiations and producing estimates of confidence.

4.4 Instantiation

Once the probable stage of development of convective cells within a FRONTIERS pixel have been determined, each convective cell object is then instantiated. Each pixel within the area of interest is examined and if that pixel does not contain dense cirrus then the convective object in this pixel is christened with a 'name' that contains information about the pixel location in the FRONTIERS grid and the time of instantiation. This is so that the origin of cells that have moved may always be determined. Default values for each of the attributes apart from 'name' and 'stage' are then ascribed according to the analysed stage of development of the object. Certain attributes are then modified according to object location. This is achieved by sending messages as described in section 3. A 'move' message sets the 'position' of the object to that of the centre of the FRONTIERS pixel in National Grid (NG) coordinates. Precipitation rate is set to that specified by the radar. The cloud top temperature is set to that of the MIR temperature value or a parametrisation of this. The attributes of each object can then be printed out or displayed graphically where appropiate. It is important to note here some important points on the interpretation of the convective cell object instantiations:

- Developing cells cannot usually be detected by FRONTIERS radar. The size of these objects also means that their detection by METEOSAT is imprecise. The cell stage classification of (y) or (d) means that no other cell type is present within the pixel and that the presence of (y) or (d) cells is inferred given a convective meteorological situation. Also it is highly likely that there are several developing cells within a FRONTIERS pixel; the instantiation will be that for an average cell within the pixel.
- Mature and dissipating cells can be resolved using FRONTIERS radar and intelligent use of METEOSAT data can resolve discrepancies. However, the instantiation does not necessarily preclude other cell types being present within the pixel. The instantiation is best interpreted as **'this pixel contains partial or complete convective cells of which the predominant type is ..'**
- The classification 'dense cirrus' means that (y) or (d) cells may also be present as well as other cloud types.

5 Case study

This case study is for 12th April 1989. The synoptic description is given in [6] and is basically one of afternoon showers developing over southern England due to insolation and synoptic forcing by an upper trough. In the presentation here all images refer to the same geographical area, 130N to 230N, and 400E to 500E (NG coordinates). This area is shown in figure 5 which also shows the manned synoptic reporting stations and the topography. Radar and MIR images for 1400 and 1500 GMT are shown in figure 6. The radar images show that during the hour to 1500 GMT the main region of convective activity transferred northeastwards and developed. High rainfall intensities were associated with cloud top temperatures near to or below -40C. However, some echoes were associated with warmer cloud tops, particularly in the south and east of the region. The region was routinely sensed by radars at Clee Hill, Chenies and Upavon. The pixels covered by each of these radars and the corresponding beam elevation category and range are shown in figure 7. It can be seen that every pixel is within 100km of its radar. Pixels seen by the Upavon radar are for beam elevations 1 and 2. This radar geometry, together with radar rainfall and MIR temperature data, were used within each FRONTIERS pixel inside the 100km x 100km region to detect and instantiate cells. Analysed convective cell stages for 1400, 1430, and 1500 GMT are presented in figure 8. The cell stages are best discussed in conjunction with the imagery shown in figure 6. At 1400 the mature cells are located mainly where radar rainfall is greater than 8 mm/hr (cyan). Some of these pixels have been designated as thundery. These designations match the distribution of sferics data from the ERDC location system which is not shown here but may be seen in [6]. In the southeast corner of the region (rows 4 and 5), a 2 x 2 cluster of echoes with rainfall rates up to 8 mm/hr is coincident with MIR temperatures warmer than -10C, these cells have been analysed as either 'young mature' or 'small fully mature'. At 1500 the cold cloud with no radar rainfall on the northernmost row has been analysed as dense cirrus. The 2 x 2 cluster in the northeast corner at rows 18 and 19 with rainfall rates up to 32 mm/hr is also interesting. Because of the warm cloud top temperatures these pixels have been analysed to contain 'small fully mature' cells with one of them 'thundery'. This cluster and its associated thundery cell matches a group of sferic reports from the ERDC system which were closely grouped in this area. The sferics reports also agree with the other thundery classifications. Generally figure 8 shows that mature cell classifications tend to be surrounded with cells analysed as being in an 'early dissipating' stage of development. Previous work on this case indicated that daughter cells should be expected to form on the northeast side of fully mature cells.These are not evident since the cold cloud surrounding the mature cells means that given a choice of 'm' or 'E' classifications from the radar data , 'E' is preferred. However, it may be that in some cases an 'm' classification would be better, assuming development is taking place beneath high level cloud cover.

Without close and detailed analysis the information presented in figure 8 may seem confusing. However, some interesting conclusions may be arrived at if one just looks at the mature cells. Figure 9 shows all mature cells identified between 1400 and 1500 GMT. The images in this figure may be thought of as being a synthesis of the radar and MIR information shown in figure 6. It is important to note that the analyses in figure 9 could not be arrived at using image processing techniques alone (eg thresholding). Considering now just the fully mature cells (coloured red in figure 9). Those in the northern half of the region at 1500 cannot all be traced back to corresponding cells at 1400. For example, clusters (a), (c), and (f). However, if we include the young mature cells (coloured green) then we can see an evolution of the mature cells from 1400 to 1500. Naturally, a mature cell at 1400 would not be the same mature cell at 1500, however, given the concept of multicell development or regeneration of convective activity it is clear how the clusters, (particularly (a), (b), (c), and (f)), evolve. This result is quite exciting since a simple extrapolation northwards of the radar data (perhaps using upper winds) would not produce a good forecast at 1500 GMT, for example, clusters (a) and (c) would be under-developed. However, using the cell stage information presented in figure 9, it is possible to develop simple schemes based on conceptual knowledge to predict where the mature cells are likely to be (and therefore the heavy rain) at 1500. Such techniques may partly solve some of the problems of nowcasting convection, however, it is not clear yet how one may predict the initiation of thundery cells.

Figure 10 illustrates how cell stage and precipitation rate instantiations may be presented to, say, a forecaster. In this diagram precipitation rate has been put into categories according to the accepted definitions of light, moderate, and heavy convective precipitation. Also to simplify the presentation 'small fully mature', 'fully mature', and 'early dissipating' stages have been grouped together. The display is meant to simulate the predominant cloud types that an observer would see if he were to sample the region at 1500. This leads us to verification. Observations during the period from 1200 to 1800 GMT were assembled for each of the observing stations shown in figure 5. The observations from Brize Norton, Benson and Boscombe Down are shown in figure 11. Each of these stations had a thunderstorm during the afternoon. Beneath each observation plot are shown convective cell stage instantiations for the pixel within which the observing station is located and the 8 surrounding pixels. The graphical representation of the cells is the same as that for figure 10. There is no cell stage analysis for 1600 since MIR data were unavailable in the FRONTIERS archive for this time. None of the cell stage instantiations showed thundery cells near the stations at these times, however, investigations in [6] revealed that the storms were not always active at the observing locations at the given times. For example, the cell producing the thunderstorm observed at Benson at 1500 was actually over Benson at 1445 and by 1500 was 5 to 10 kms to the north with another thundery cell 10 to 15 kms to the south-southwest. Most of the cell stage instantiations compare well with the observations. For example, at Brize Norton, the tendency for convective cloud to develop and increase in coverage of the sky during the early afternoon and then to decay leaving predominantly dense cirrus by 1800 GMT, is well portrayed. However, the problem (which was discussed earlier) of distinguishing dissipating cells from young mature cells when there is an overhang of upper level cloud, is revealed by the observations from Benson at 1300 and 1400 GMT. During these times convective activity is developing, as revealed by the 1300 report of precipitation in sight but not reaching the ground (virga). Also 2/8 and 1/8 of cumulonimbus type 3 clouds are recorded. The cell stages from the POP-11 program are indicated as dissipating because of high level dense cirrus (reported at 1300) and stratocumulus tops (reported at 1400) producing a cold MIR temperature. These problems were not apparent at Boscombe Down with only small amounts of upper cloud reported at 1600, 1700 and 1800 and cell stages of 'young mature' being correctly analysed at 1500. Observations from Lyneham, Odiham and Farnborough, which are not shown here, also verified well. The success of these verifications is encouraging, however, one must be cautious about drawing too many conclusions given the uncertainties regarding timing and field of view of the human observations.

6 Conclusions

A method of representing convective cells as meteorological objects possessing various attributes has been described. Many problems of instantiating these objects using currently available observing systems have still to be resolved. However, the scheme described above which uses radar and METEOSAT Infra-red temperature data looks to be promising. The resolution (both spatial and temporal) of all the observational data sources is a major drawback in identifying developing and small convective cells. METEOSAT resolutions of 1km are sought [8], however, any improvement on the current resolution would be welcome. The lack of volume scan radar data within the FRONTIERS system is also a drawback for cell identification and the possible value of Doppler radar data is being investigated. However, with intelligent use of currently available radar data from different beam elevations, cell stage classifications are possible. The case study has shown the value of surface synoptic reports in providing the only 'ground truth' identification of convective cells. Their value in instantiating attributes such as cloud base, precipitation type and cell stage has still to be assessed. Uncertainty about the long term future and accuracy of such observations in an increasingly automated observing network also raises concern about how these observations are to be used. The problem of identifying those cells which are producing lightning remains difficult. However, the simple method based on Goyer's work [4], has worked extremely well so far and justifies further elaboration and testing with UK data. The sferics data were useful in verifying the thundery classifications from the radar data, however, the current precision and accuracy of these data is not yet good enough to instantiate the lightning frequency. A spatial accuracy of <5km and a temporal precision of 1 second for each flash are desirable. Given all of the constraints of the current observing network a scheme which identifies the likely stage of convective activity within a FRONTIERS pixel has been developed. The usefulness of such a scheme in providing an analysis from which nowcasts can be made remains to be seen. However, it seems likely that owing to their relatively large size, mature cell clusters can be confidently identified. Knowledge of their typical life cycle and surrounding environmental factors should allow forecasting algorithms for heavy rain to be developed which, hopefully, should be an improvement over existing techniques in convective situations. Obviously environmental factors have a key role in any forecasting scenario. It is anticipated that the Mesoscale Model may be able to provide the atmospheric framework within which convective objects can develop and interact. The current (15km) horizontal resolution of the model means that its use in cell instantiation is limited to 'environmental attributes' such as cell velocity which may nevertheless be very useful in a forecasting method.

An important conclusion that can be drawn from this paper is that the object-oriented techniques described for representing convective cells could also be used for representing a large number of other meteorological objects such as fronts, convective complexes, and areas of low cloud. Some of these objects, for example fronts, occur on much larger scales than convective cells and may be easier to instantiate using present observing systems. The inheritance facility provided by the programming package could be used to build up a framework of classes of objects each of which would communicate with each other in an ordered and structured manner. This paper has also outlined a framework whereby conceptual atmospheric structures, (for example convective cells), can be represented and reconciled with observational data. There is an analogy here with parametrisation schemes for deep convection in NWP models where mass-transfers are used to represent crude models of sub-grid-scale processes. Object-oriented methods may offer a route for assimilating and representing meteorological objects in an NWP model. They certainly offer the opportunity to look at data 'in a new light' and may provide the key to an improved nowcasting system.

7 References

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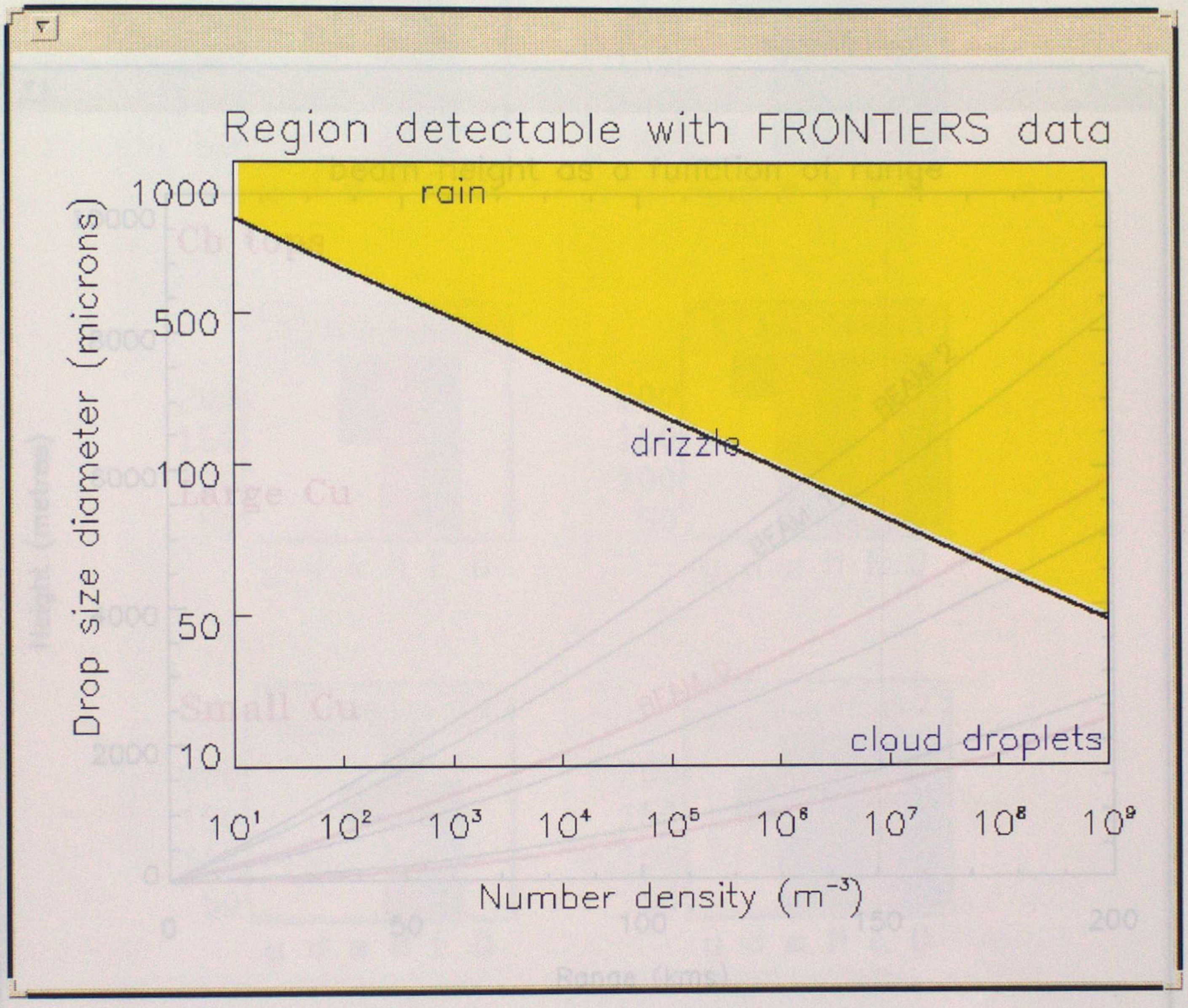

Figure 1)

Ranges of drop size diameter and number density for targets to be detectable by FRONTIERS radars. All targets containing droplets in the region coloured yellow can be detected.

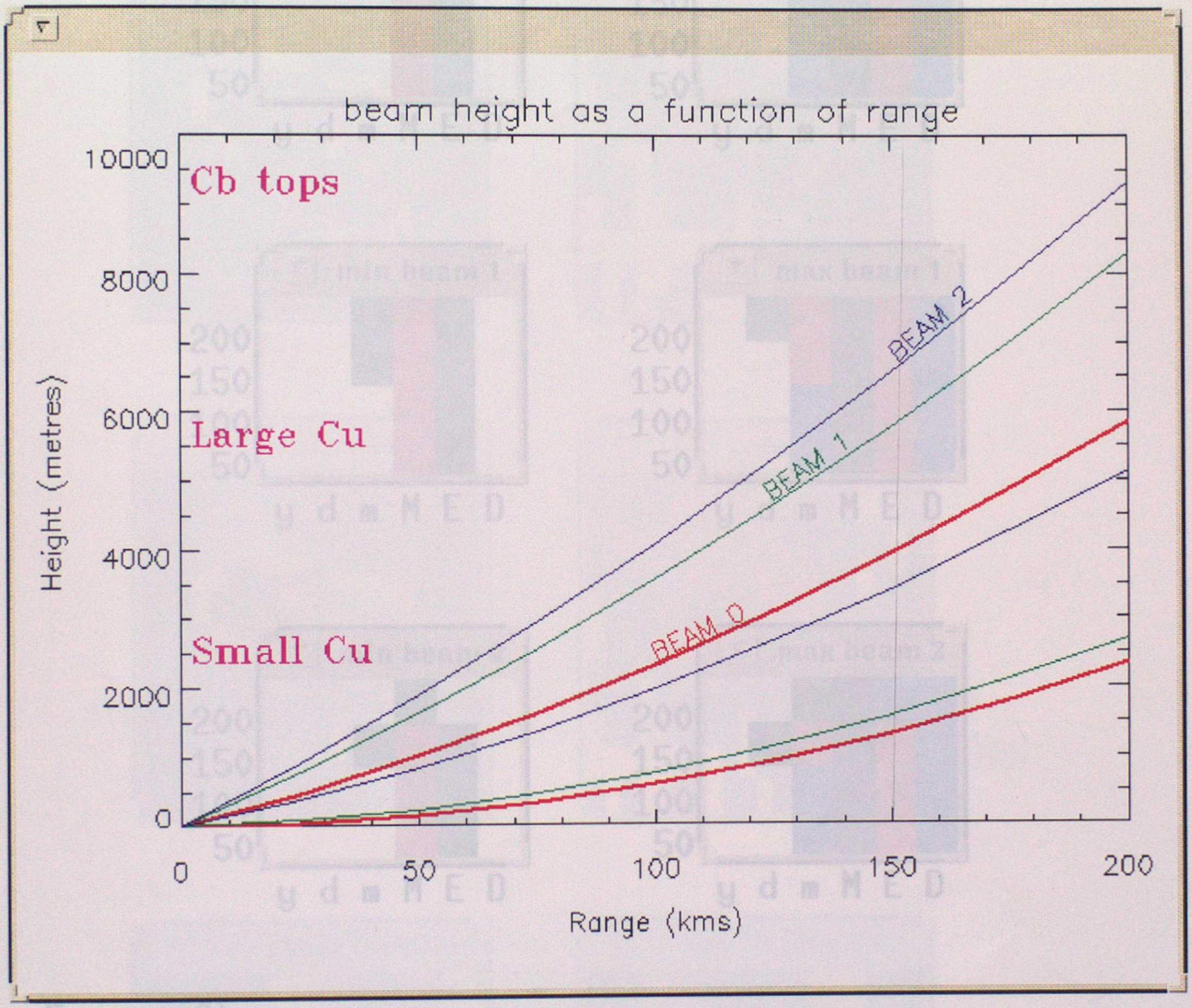

Figure 2)

Maximum and minimum heights of each beam category (see text for explanation of category) according to range. Typical cloud top heights are shown down the left-hand side of the plot.

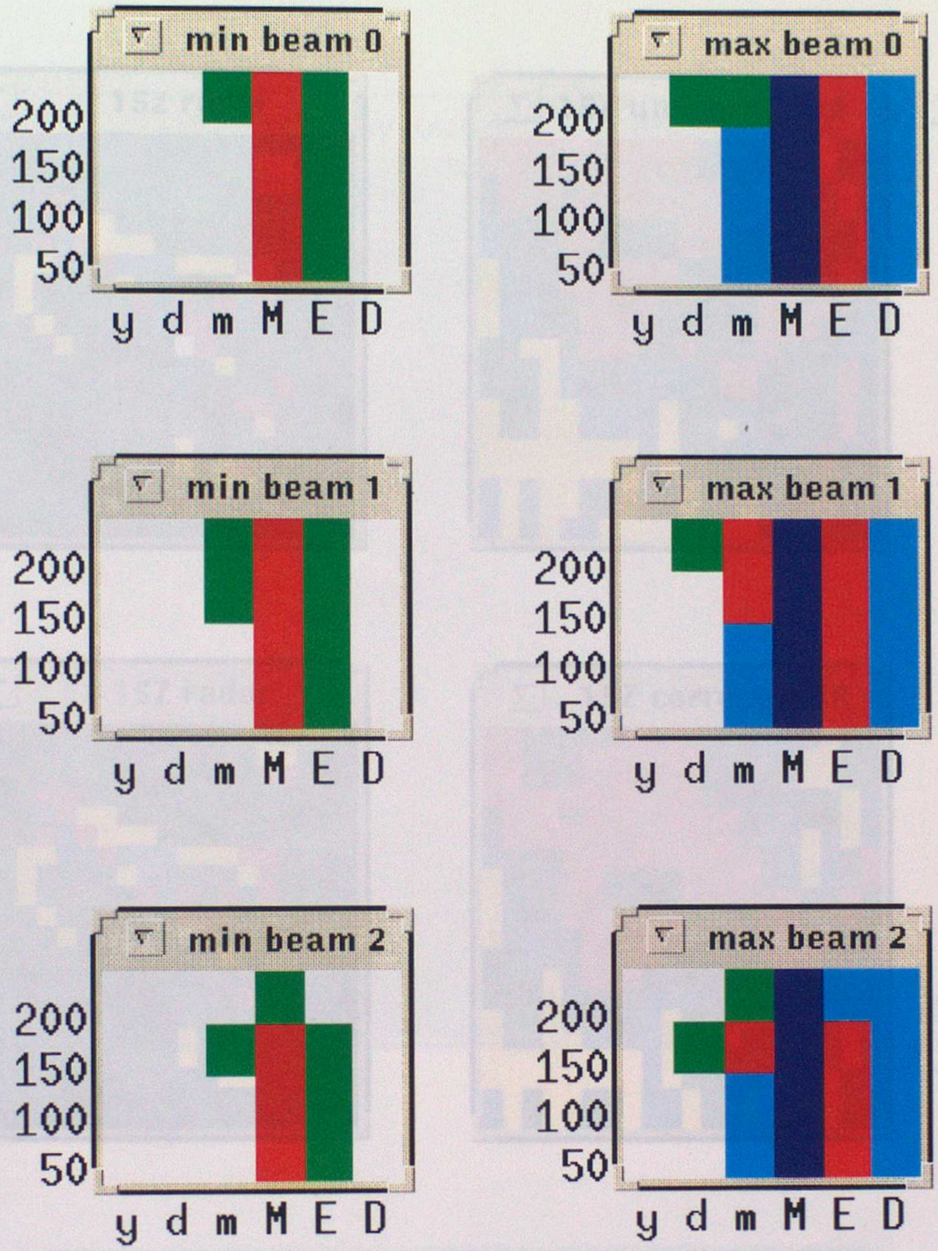

Figure 3)

Expected minimum and maximum radar rainfall rate according to beam category,range,and predominant cell type within pixel.(See section 4.1.1 for explanation of cell types).
White = 0.0, green = 0.5, cyan = 1.0,
red = 5.0, blue = 126.0 mm/hr

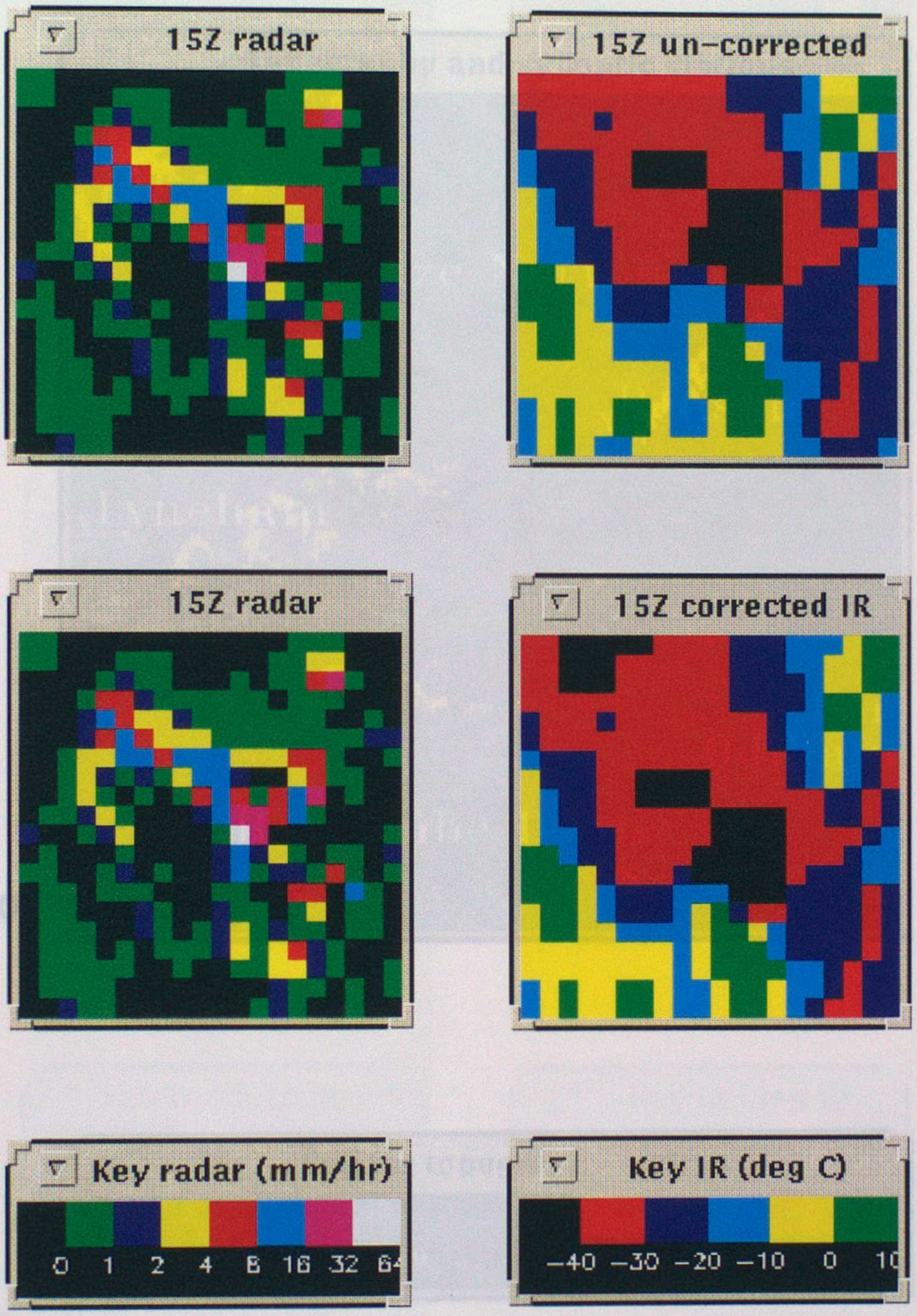

Figure 4)

Comparison between radar and METEOSAT IR images corrected and un-corrected for parallax at 1500 GMT 12/4/89.

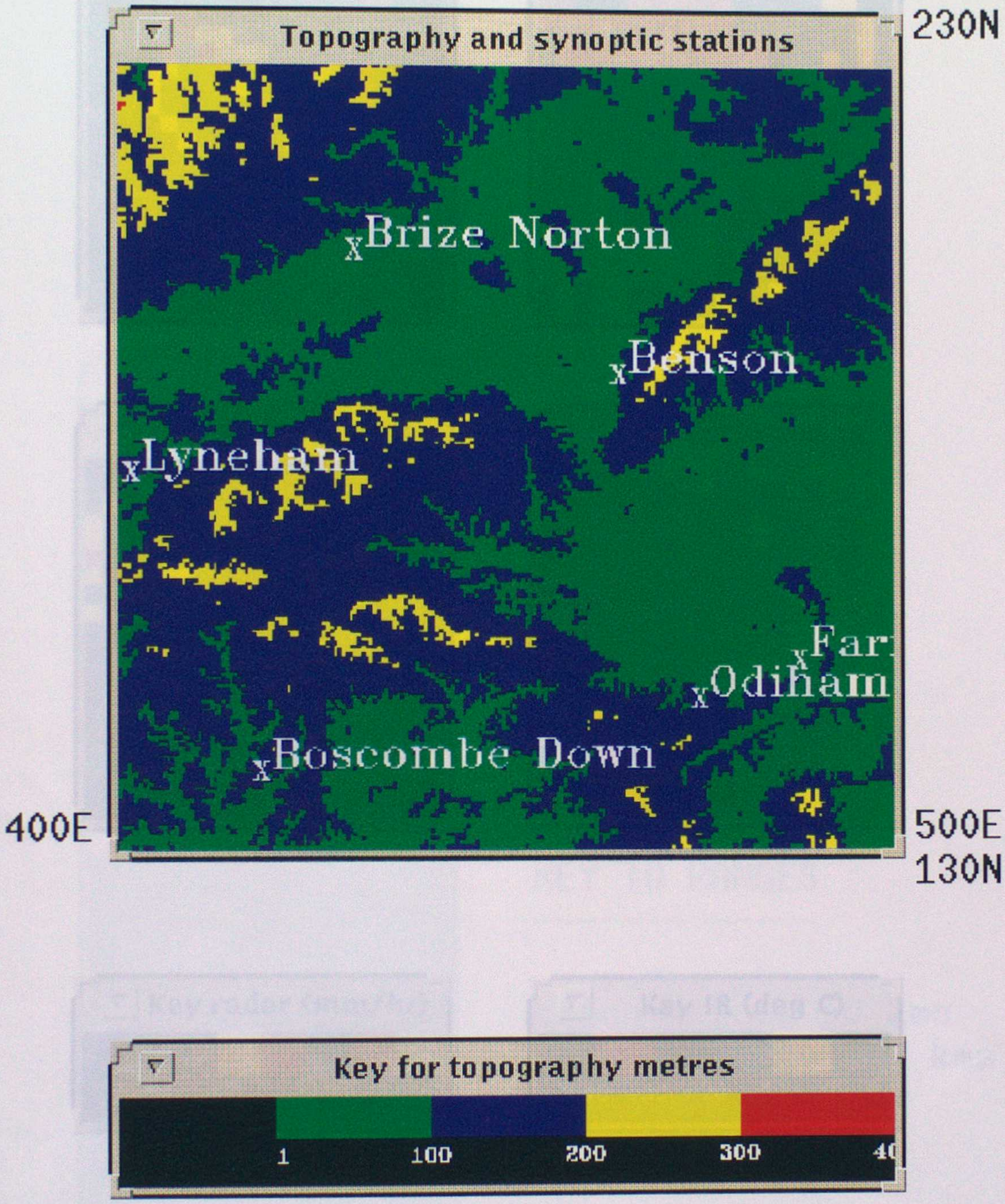

Figure 5)

Topography and main observing stations in region examined for case study.

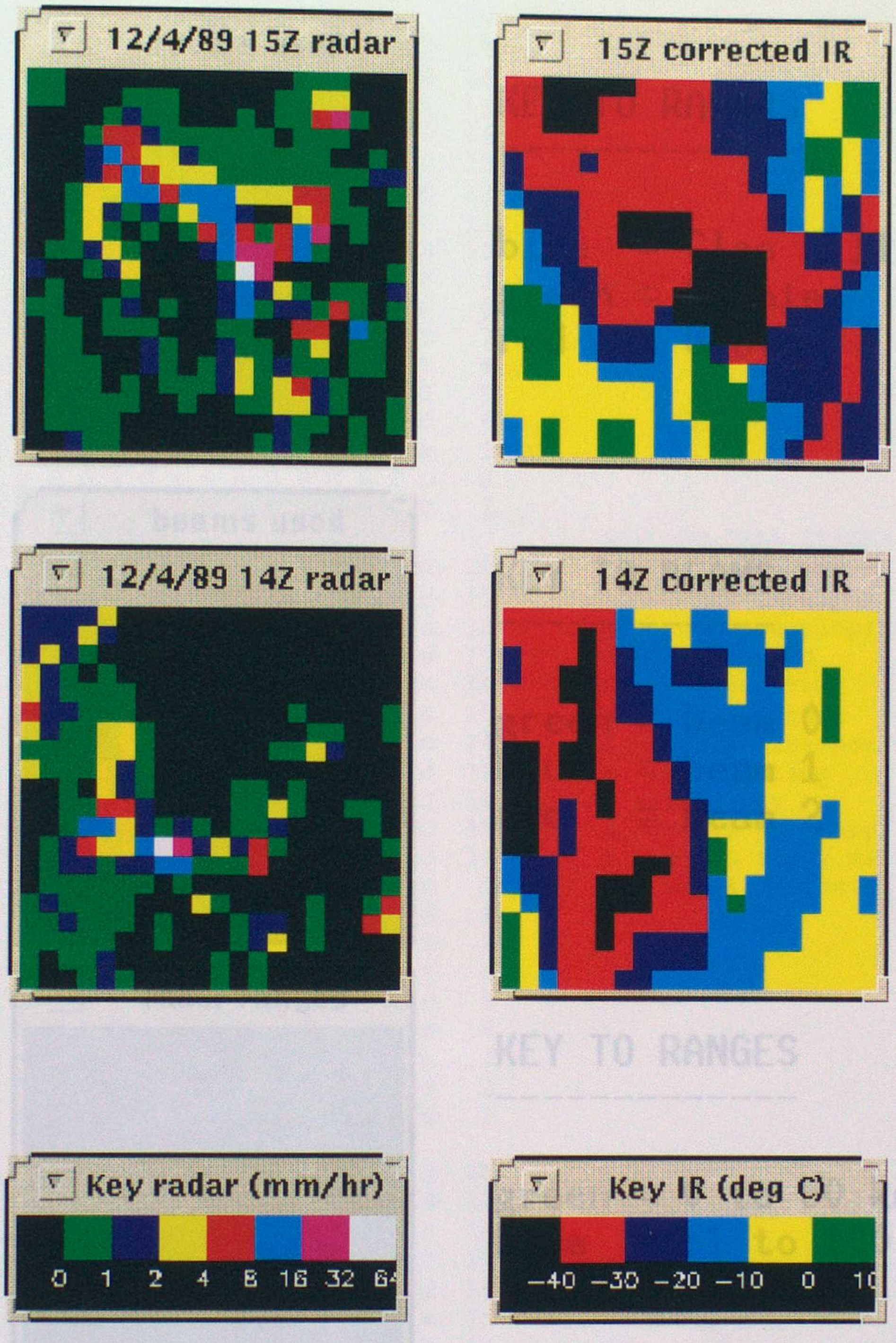

Figure 6)

Radar and METEOSAT IR images corrected for satellite parallax for 1400 and 1500 GMT on 12/4/89.

```
                    1500
D E C C C C C C C C C C C C D D D d y     20
D D C C C D D D C C C C C D D # # d y     19
C C C C E E E D C C C D C D D # t m y     18
C C C D E M E D D D D D D C D D m y d d   17
C C C E M M E E E D D D D D D D d y m d   16
C C C E E M M E E E D D E D D D D D m #   15
C C D # E M M M M M M E E E # # D d C D   14
d C D # E E E E E M M E C C # # D D C C   13
d C D # D C D C D M T M D E M T C D C C   12
d D D # E E C C C E M T T E M D C C C C   11
m d C D # E C C C C D T T C C C C C C D   10
y m C C C D C C C C E M E E D C E D C #    9
m m y d D E C D C C E M D E E D # D C D    8
y m m d D D D C C d D D C C # # C # E C    7
d m m d C C # D d d m D D C D # C D D C    6
d m m m d d # D d m m m m # D D C D D C    5
d m m m d m d D D m m m m # # # D C C C    4
d m m m D m d d D d d m m m # # D C C D    3
C m m m m d y d d C d y y m D D C D C D    2
C d m m m d y d d C d y m m D C C D C C    1
                  1430
E E E D D C C C C C C C C d d d D d d d   20
E E E D C C C C C C C d C d d d d d d d   19
M E E E C C C C C C C d d d d D d d d d   18
M E D D D D E C C C C d C C d D D d d d   17
D D D E E E E C C C C C C C d # # d d d   16
E D D E E E E C C C C C C C d # # d d d   15
C C C D E E E C C C C D C C d d d d d m   14
C C C E T E D E D C C C D D m d d D d d   13
C C C M T # E E E C D D D D m d m D d d   12
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y m # # D D C C C E # D C C C d d d d d    8
  m D # E E C C C D C M E D C C C D d #    7
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d d d C D D C C D C C D C D d d d D C d    4
d m d D C D D C d d D D D D m m d C C m    3
d m D D C D D C d m m m m m # m d C d d    2
m m d # m m m d m y   m m m # D C C d d    1
                  1400
E E E E E C C d d d d d d d d d d d d d   20
E E E E E C C C C d d d d C d C d d d d   19
# E E E C C C C C C C C d C C C d d d d   18
# E E C D C C C C C C C d d C d d d d d   17
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C C D E M M E C C C C D D # m d d D D d   10
C C E T T E E D E D C m D D d d d d D d    9
C D E M E E T T T E # m # D d d d d d m    8
C D # E E E E M M D D m m d d d d d d d    7
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m # D D D D C C C E E d d d d D d d m #    5
m D # E E E C D C C C D # # d D d d m m    4
m D D D D C C D C C C D # # d D d d d d    3
m d D D E C C C C C D d D d d d d d d d    2
m d C D E D C C C d D d D d d d d d d d    1
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KEY TO CELL STAGES
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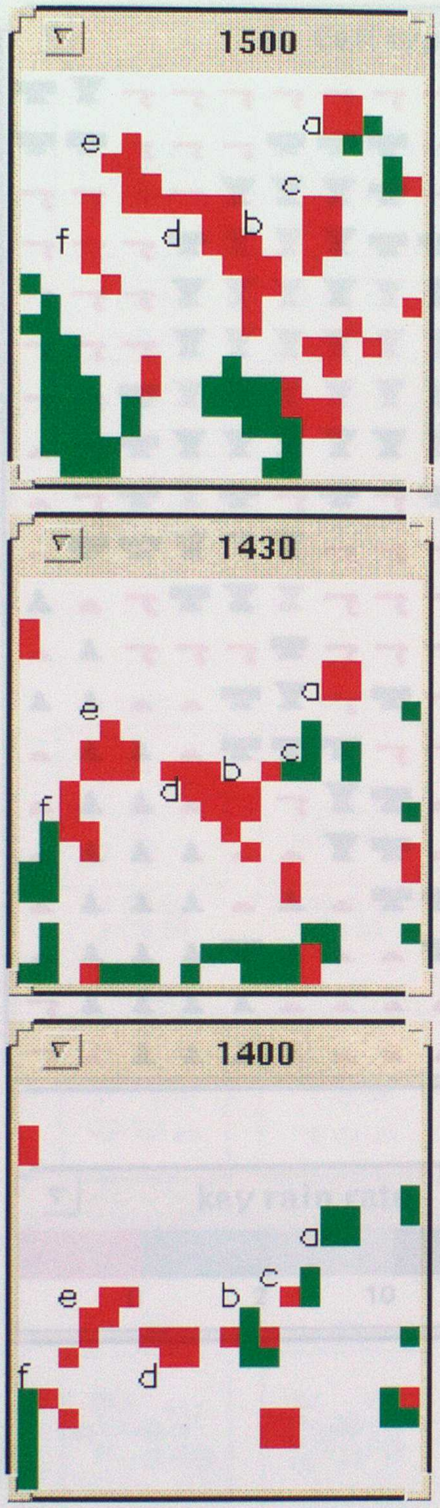
y = young developing
d = developing
m = young mature
M = fully mature
E = early dissipating
D = dissipating
T = thundery
t = small thundery
# = small fully mature
C = dense cirrus

Figure 8)

Analysed convective cell stages for 1400 to 1500 GMT 12/4/89. Numbers at side indicate row number of region.



KEY TO CELLS
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green = young mature

red = fully mature

Figure 9)

Analysed mature cell clusters between 1400 and 1500 GMT 12/4/89.

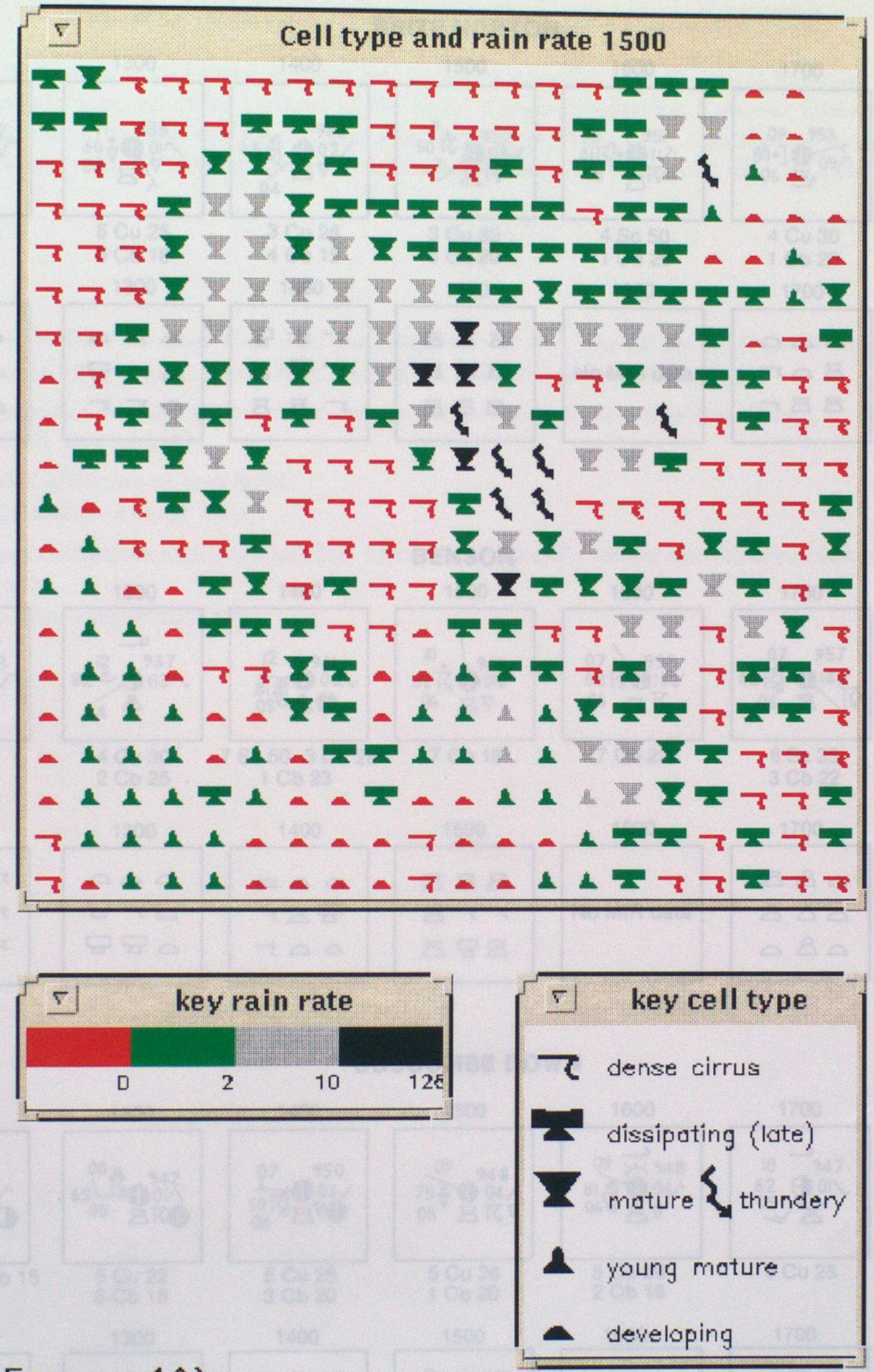

Figure 10)

Cell type and rain rate for 1500 GMT 12/4/89.

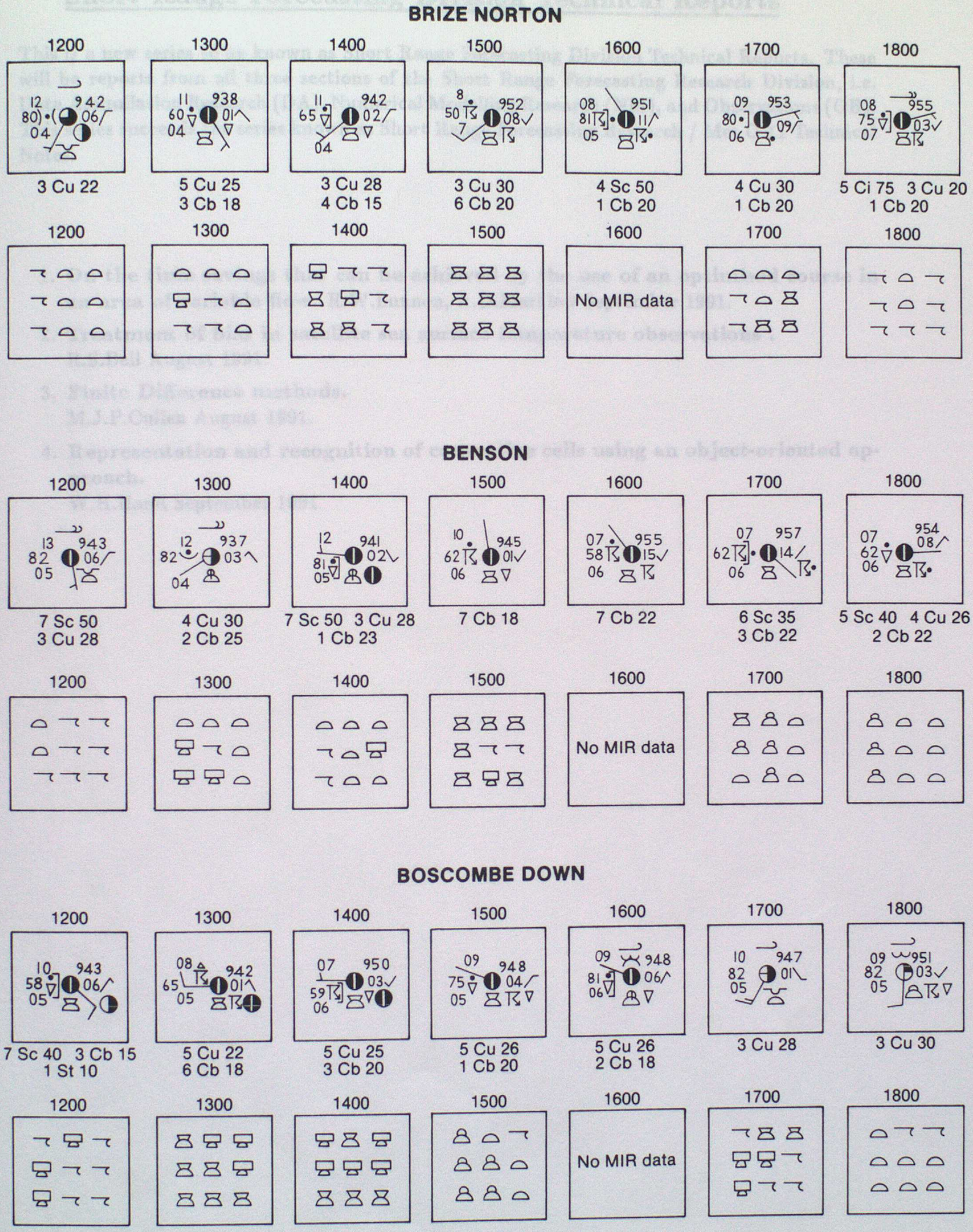

Figure 11) Surface synoptic observations between 1200 and 1800 GMT 12/4/89 and convective cell types determined surrounding the station which is in the centre pixel. (Cell type is the same as in Figure (10)).