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Sensitivity of the Limited Area Model to assimilation of precipitation estimates derived from lightning data

by

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Abstract.

In April 1996 a Latent Heat Nudging (LHN) scheme was successfully introduced into the Mesoscale Model to assimilate precipitation rate observations derived from the UK weather radar network. It is possible to estimate precipitation rates from observations of lightning intensity. This study examines the assimilation of such data into the Limited Area Model by the LHN scheme. It is hoped that such data will help better analyse intense convective activity in, for example, the Bay of Biscay which may later lead to severe weather over the UK.

Several experiments are described on 3 cases. There is significant sensitivity of the model rainfall forecast to the lightning data, but none of the options explored shows a consistent improvement in forecast skill. This may be due to uncertainties in both the detection efficiency of the ATD lightning detection system, and the relationship between lightning flash rate and precipitation rate. Overall benefit from the lightning data might be obtained by smoothing of the precipitation estimates, and further tuning of the LHN scheme. However, an alternative might be to develop a variational analysis scheme based on the relationship between flash rate and convectively available potential energy (CAPE).

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1. Introduction.

The Latent Heat Nudging (LHN) scheme was successfully introduced operationally into the mesoscale model (MES), in April 1996 (Jones and Macpherson 1996). Its aim is to assimilate precipitation observations, by scaling the amount of latent heat released by condensation within clouds, according to the ratio of model to observed precipitation rates.

The UK weather radar network produces high quality, high resolution precipitation data over the UK, and forms the basis for the Moisture Observation Pre-processing System (MOPS) precipitation observations used by the LHN in the MES. However the areal coverage of these data (about one third of mesoscale grid points) is not sufficient to be of significant use in the limited area model (LAM), especially as most synoptic development in the LAM occurs outside of this area.

Experiments were carried out to assess the suitability of lightning observations as a proxy for precipitation data. The cases studied were of three occasions during the summer of 1996 when thundery activity was experienced over the UK. In cases such as these, where instability is advected in from areas outside of the MES domain, initialisation of the moisture and latent heating fields within the LAM is very important in determining the nature, position and timing of the resultant storms. Therefore, these cases were expected to show sensitivity to the inclusion of proxy precipitation data.

2. Lightning and Precipitation relationship.

2.1. Lightning Data.

The Arrival Time Difference (ATD) system (Lee 1988) detects flashes of lightning across the globe (actually an area from 160W to 160E, and 60S to 80N). It works by detecting the EM radiation from a lightning strike at seven detecting sites in the UK, Gibraltar and Cyprus, and comparing the time of arrival of the signal at each site. The difference in times of arrival allows the position of the strike to be calculated. The system can position flashes over the UK to an accuracy of 5km. It is tuned to detect cloud to ground strikes and not inter-cloud strikes which are typically an order of magnitude less intense.

A major drawback to the system is its detection rate of a meagre 400 flashes per hour. Price and Rind (1994) estimated the global mean strike rate to be 77 flashes per second, which corresponds to more than a quarter of a million per hour. They also state that only 25% of these are cloud to ground strikes, so one would expect around 3400 strikes within the area 40W-40E, 30N-70N where most of the ATD detection is concentrated. Thus a detection rate of around 10% in this region is to be expected, which agrees with that stated by Hamer (1995), derived by comparison with a more sensitive system that observes just over the UK. There is therefore a significant uncertainty in inferring local flash density from ATD observations.

2.2. Inferring precipitation rate.

Once a local flash density has been estimated, this needs to be interpreted as a precipitation rate. Several studies have postulated and tested links between lightning rate and precipitation. Goodman and Buechler (1990) stated that the two would be linked, due to both being highly dependent on the updraught within a cloud (they were considering just convective rain) - the more intense the updraught, the more precipitation will be produced, and also the more lightning. They also observed that the relationship depends on the stage within the life cycle of the cloud. There is more rain per lightning flash as the storm decays than when it is growing. However this effect may not be important if the data is processed over a large enough area, and a long enough time span, so that individual clouds become "averaged out".

The correlation between flash rate and precipitation rate used in this study follows that of Buechler et al (1994):

$$\mathbf{R=4.3\ F}$$

where R=rain rate in mm/hr, and F=flash rate in lightning flashes per 15 minute interval per 10 km square. For this experiment, the factor of 4.3 was scaled to apply to periods of 1 hour, and areas of 0.25 degrees in latitude and longitude, and F has been scaled to try to account for the detection efficiency of the observing system. Sources of error associated with this relationship include the fact that it was derived for thunder storms in Florida, and the same relationship may not hold globally. There is particular doubt in this respect when considering whether the storms being observed are of marine or continental origin. Price and Rind (1992) state that marine convective clouds have updraughts a factor of 5 or 6 less than equivalent sized clouds over land, leading to less glaciation and fewer supercooled water droplets (which are important in the charge separation process that leads to lightning - see eg Mason 1971) and thus a much lower lightning rate, even though the precipitation rate may be comparable.

3. Experiment Design.

A number of experiments were performed on the main case study, namely the heavy thunder storms that broke out over England and Wales on the evening of Friday 7th June 1996. The experiments started off as fairly ad-hoc affairs and gradually evolved in sophistication as new ways of preparing and using the data were considered. A description of the experiments and how and why they were changed is given below. A subset of these experiments were run on the other two cases; July 23rd, and August 28th 1996.

Firstly, some dummy precipitation observations were crudely created "free-hand" by looking at the ATD lightning observations in the Bay of Biscay for the morning of June 7th before the storms reached the UK. The LAM was rerun from midnight using the LHN scheme to assimilate the dummy observations at 00Z, 03Z, 06Z, 09Z, and 12Z to produce an analysis at 12Z, and a subsequent 18 hour forecast. This experiment is referred to as DUMLHN from here on. Results (presented in more detail in the next section) showed that there was some sensitivity to the use of the dummy precipitation observations, but the impact was mixed in quality. A second experiment was performed, with the observation weight (relative to model background precipitation rate) reduced from 10 to 1 to reflect the low quantitative accuracy of the hand-made rates (WT1LHN). It is relevant here, that numerous studies (for discussion of these, see Jones and Macpherson 1996) have observed that LHN or similar techniques derive more benefit from information about precipitation *location* than absolute *rate,* and so it is not unreasonable to hope for some useful information to be extracted from such crudely derived observations.

The next modification to the experiment was to say that since we were not certain of the precipitation rate corresponding to the lightning strikes, the observations were used in such a way as to leave the model latent heating profiles unaltered if the model already had precipitation greater than a given threshold at that point (DUMTHRESH). The model profiles were scaled as normal at points where the model did not already have sufficient precipitation. The aim of doing this was to treat the lightning observations as sources of information about where heavy rain was likely to be, and to try to induce some if it was not already present. At the same time, it was important not to take the derived precipitation rates too literally, and so where the model already had plenty of rain, its structure was not interfered with. Results from this and the previous experiments were encouraging in that they showed sensitivity, and thus a potential for more accurately processed observations to be of benefit.

As a next stage, therefore, it was decided to create dummy precipitation observations from the lightning observations themselves, assuming a constant rate for each flash. A rate of 2 mm/hr was chosen and dummy files were created with a precipitation rate of 2 mm/hr at each location of a lightning strike. The resulting field was therefore more accurate in positioning than the hand-made one, but with no attempt to represent any kind of intensity structure within the storm area. Two experiments were run with these data, one with the normal 3 hour time window for the observations (ATDTHRESH), and one with a time window of 1 hour to reflect the fact that they are rapidly changing in time, and forcing for 3 hours may degrade the overall analysis. In both these experiments, the model heating was scaled up at grid points where the precipitation rate was less than the observation, but not scaled down if it was greater, thus preserving the models structure in regions where it had already developed precipitation. Results from these experiments were slightly disappointing in that they failed to show much difference from the hand-made observation experiments. There was not much sensitivity to the insertion period. It is possible that the lack of structure within the rain areas meant that the impact of the observations was limited. More information on gradients of heating may be required to influence the model's mesoscale circulations.

To try to create the most accurate dummy observation possible, the lightning observations were pre-processed using a scaled formula based on that given in section 2 to calculate precipitation rates from the local flash density in boxes of 0.25 degree and periods of 1 hour. Experiments were run with dummy observations created from this estimated precipitation field (ATDRATE). A run was also performed with the observed rate halved (ATDRATE-HALF). The aim of this was to assess the sensitivity of the results to uncertainty in the ATD detection efficiency, although this was expected to be close to 10% in this case (Hamer - personal communication).

Figure 1 shows the observations for 00Z on the 7th June. Figure 1(a) shows the ATD observations with each "+" denoting a strike within a 3 hour time window centred on midnight, figure 1(b) shows the "free-hand" observations of precipitation rate, and 1(c) shows those derived from ATD flash density. The observations for ATDTHRESH were the same as those shown in 1(c), but with a uniform value of 2 mm/hr. It should be noted for all the experiments described here that there was probably also other rain in the area, but this can not be estimated from the lightning observations. This should not cause serious problems, as the absence of a raining observation is not the same as having a dry observation, and will not cause the LHN to scale down the heating in that area.

The MOPS precipitation data that cover the UK are only available in files configured for the MES, and so were not available for use in the LAM in this experiment (to remake an acobsm file for use by the LAM might make an interesting further experiment, but would require a fair bit of work, and was not done here). So the only difference between the control and test experiments was the assimilation of the precipitation rate values estimated from the ATD observations.

The LHN scheme was used with the same parameters as in the MES, apart from the filter scale which was changed to be equal to one LAM grid length. The search range (in grid points), and parameters which govern the limits to any scaling remained the same. The scheme was forced to accept data from the region of the observations, which would otherwise have been outside the radar range that it uses as a cut-off.

An experiment was also performed using the new CAPE closure convection scheme in the LAM (from here on, CAPELHN), along with the free-hand observations, as it was thought that this may interact more consistently with the methods used in the LHN scheme.

Further experiments were performed to see if the impact in the LAM would feed through into the MES when the output from the LAM experiments was used as new boundary conditions. The operational MES already used LHN for assimilating the MOPS data, and this was retained in these experiments. The dummy observations were not used as they were mainly outside of the MES area. So the only difference between the operational and test runs here was the boundary files created from the LAM run. The MES was run from both 06Z and 12Z operational analyses, with 18 hour forecasts from each.

4. Results.

4.1. Results from LAM experiments.

<u>**June 7th Case.**</u>

Results from the LAM experiments showed that there is a definite sensitivity to assimilation of precipitation observations in this area. Forecast precipitation fields showed marked differences from the operational run. It was not clear which run gave the "best" forecast as some were improved at some forecast times, but degraded at others.

At the analysis time, 12Z, the control run (CTL) had a reasonable representation of the precipitation over the UK, as can be seen in figure 2. DUMLHN, WT1LHN, DUMTHRESH, and ATDTHRESH all showed a slight improvement over CTL in the positioning and intensity of the precipitation to the south of Devon and Cornwall, but overall were very similar. CAPELHN probably gave the "best" analysis (at least subjectively) by having a more realistic break between the two systems in the south west, and north east, which were treated as a continuous band in the other runs. ATDRATE was significantly different in that it had (wrongly) lost most of the precipitation in the south, but (correctly) intensified the precipitation in the north. ATDRATE-HALF performed better in this respect by keeping a small patch in the south, but was still missing the band of showers across the midlands and Wales.

At T+3, 15Z, CTL had the precipitation too far west, and extended too far into the channel, and also into the northeast (figure 3). WT1LHN, DUMTRESH and ATDTHRESH both improved slightly on the southward extent, and DUMLHN and CAPELHN improved both the south and north extent and also moved the main precipitation area slightly eastward. ATDRATE could be described as "awful", as it had lost virtually all the precipitation! ATDRATE-HALF on the other hand had the best positioning of any run, of the main area of showers over the south coast, but still did not extend far enough north.

At T+6, 18Z, CTL had a good representation of the precipitation in the west of the UK, but had not got enough spreading east (figure 4). DUMLHN had lost a large amount of precipitation at this time, but WT1LHN had kept it, and had more to the east than CTL. CAPELHN had also retained it. DUMTHRESH and ATDTHRESH moved the area of rain eastward rather than adding some in the east. ATDRATE had by this time, developed the precipitation that was missing three hours earlier, and had a fairly accurate representation of the observed precipitation, however ATDRATE-HALF had deteriorated in accuracy, by moving the rain too far south. It was the only run to have any activity in East Anglia, where a couple of small patches can be seen on the radar, but this is at the expense of the more significant areas of precipitation in the northwest which it had dissipated much too much.

At T+9, 21Z, the storms were at their heaviest, and covering much of central England. From a forecasters point of view this is the most critical frame for the model to produce accurately. CTL had the precipitation position fairly accurately (figure 5), but would have been better if it had had higher rates. DUMLHN, CAPELHN, and WT1LHN all had similar positioning to CTL, but had slightly lower intensities. DUMTHRESH and ATDTHRESH both have much too low intensities. ATDRATE had successfully increased rates compared with CTL but extends too far east, and not far enough north. It is hard to say which is better out of these two runs. ATDRATE-HALF had too little precipitation, and it was poorly positioned, too far to the south and east.

It is possible that interfering with the models heating structure in regions where it already had significant precipitation has introduced noise into the model resulting in a disruption to the precipitation fields at a later stage of the forecast. Both DUMLHN and ATDRATE suffered from losing areas of precipitation which they later regained, almost is if they had to re-spin up the storms. The ATDTHRESH run which was designed to avoid this problem has retained the rain throughout. CAPELHN had also retained the rain. All of the runs showed noticeable differences from the control run, and from each other, but which one was "the best" is subjectively very hard to say.

No objective scores are available for the LAM runs because they would need to be verified against the MOPS precipitation data, which, as mentioned before, are not available in a suitable configuration. Trials with the LHN (Jones and Macpherson 1996) showed little overall sensitivity of other forecast variables to the inclusion of precipitation data, and so no verification of, say, temperature or humidity was performed here.

July 23rd Case.

For this case, just the CTL, ATDTHRESH and ATDRATE runs were performed, again with 12 hours of assimilation from 00Z. The 12Z ATD obs can be seen in figure 6, and the 12Z analyses can be seen in figure 7. Due to the fact that there was not much thundery activity over the UK at this time, there is little difference between the forecasts in this area. Throughout the forecast period, the precipitation over the UK was very similar in all three runs. Over central Europe however, there was significant lightning observed, and the impact of this is obvious on the ATDRATE run, whereas the ATDTHRESH run showed only slight sensitivity.

Although there is no radar data to verify this against, the amount of lightning detected and the large cumulonimbus clouds that can be seen in the satellite pictures in figure 8 show that there were heavy thunder storms in the area, and so it is reasonable to assume that the intensification and extension of the area of precipitation in the ATDRATE run is realistic.

August 28th Case.

For this case, just the CTL and ATDRATE runs were performed, again with 12 hours of assimilation from 00Z. The 12Z ATD obs can be seen in figure 9, and the 15Z T+3 forecast frames can be seen in figure 10. Partly due to the lack of ATD observations over the UK, and partly due to the fact that CTL was very good over the UK in this case, there was very little difference between the two runs. The T+3 forecasts shown showed the largest differences, with the ATDRATE run having slightly heavier (and therefore better) precipitation across the country.

4.2. Results from MES experiments.

Results from the MES experiments on the June 7th case, show there to be a definite impact in the MES from the use of the new boundary conditions, but the impact was again mixed - being better at some times, and worse at others.

The 06Z runs showed significant differences. Figure 11 shows how by T+9 (15Z) the LHN boundary conditions (from the "threshold" run) had led to much better representation of the rain. The rates are heavy, and in a better position, being very accurate in a narrow intense band through South Wales and Devon with a gap to the west of this, whereas the operational run had too widespread, less intense precipitation. However, by T+12 (18Z) (not shown), the operational distribution was a good representation of the storms, but the LHN run had lost some of the rain, and had moved the rest too far east. Also the rates in the Northwest were too low in the LHN run.

The 12Z runs, however were more similar, but still displayed some differences. Figure 12 shows how the LHN boundary conditions forecast for T+9 showed a marked improvement, with the rain having both a better shape (less of a "blob"), and extent (especially to the South, but also to the North), and also better, heavier, rates in the midlands. Table 1 shows that the objective scores for this time confirm the improvement.

	Control	LHN
Hit rate (%)	40.0	49.1
False alarm rate (%)	55.3	47.6
Hansen and Kuiper score (%)	27.4	37.7
Threat score (%)	26.8	33.9
Correlation coeff.	0.263	0.346

Table 1. Comparison of objective skill scores for the two 12Z forecasts, at T+9. Scores are based on a dry/wet threshold of 0.125 mm hr^{-1}.

5. Discussion.

As expected in cases of intense instability, the precipitation forecasts for the first twelve hours were found to be very sensitive to the initial conditions. This emphasises the need to properly initialize the thermodynamic fields in the model. Also the fact that the MES proved to be sensitive to the use of the new boundary conditions shows how important it is to exploit all available, useful, data in the LAM, in order to improve the MES forecasts.

It was seen in the LAM experiments that the inclusion of these estimates straight into the LHN scheme for the June 7th case had its dangers, with the loss of the rain later into the forecast, although this was not noticed in the other two cases studied. The use of a threshold to prevent alteration of existing heating profiles where the model had significant precipitation was largely successful in removing this error, but resulted in less impact seen overall. A compromise between the two methods would be to use ATD derived rates, but to smooth them somehow, thus providing enough structure within the areas of lightning activity to ensure that the impact is not lost, but not disrupting the model fields to such an extent that the forecast is degraded.

It is interesting to note that the forecasts were also very sensitive to the convective parameterization, although reasons for this have not been investigated fully here. In some ways it might be expected that a convection closure scheme that works by calculating CAPE may be more consistent with a LHN scheme which also uses the model's vertical thermal and moisture profiles.

One aspect of the scheme that may need consideration is the fact that the observations used here are not strictly a precipitation analysis in the same sense that the radar data used in the LHN scheme in the MES is. The derived precipitation rates from ATD observations provide valuable information on where it *is* raining, but say nothing about where it *is not* raining. Thus the scheme may be adding or enhancing rain where the model is too dry, but it does not lead to the removal of spurious rain. If there is a positional error in the model, then use of these observations will not try to *move* it, so much as *extend* it. This may introduce a bias into the model. A possible solution to this problem may be to produce a precipitation analysis over the extended MOPS region that currently produces a cloud analysis for the LAM. ATD observations could then be blended with satellite observations (and possibly, eventually, European radar data) in a system more akin to that currently used in the MES.

6. Conclusions and Future Prospects.

In autumn 1997 it is anticipated that the operational MES domain will be extended southwards (C. Wilson, personal communication). Experiments on the 24th June 1994 case (a mesoscale convective system) with a MES domain extended to cover the Bay of Biscay have shown improvements over the operational MES forecasts. Experiments assimilating ATD observations into this new MES would be interesting to see if their impact depends on model resolution.

Latent Heat Nudging is not the only possible approach to assimilation of lightning data. With the introduction of a variational assimilation scheme (VAR) in the near future, more direct use of lightning information may be possible. This is most likely via a relationship with CAPE. Price and Rind (1992) discuss how both vertical velocity, w, and flash rate, F, depend on cloud height, and are thus linked by the equation:

$$w = 14.66\ F^{0.22}$$

(for continental clouds - similar equations are given for the marine case). If all the CAPE in a cloud is converted to kinetic energy, then the maximum possible vertical velocity, w_{CAPE}, is:

$$w_{CAPE} = \sqrt{2\ CAPE}$$

The actual vertical velocity will be less than this due to the effect of entrainment, and other physical processes. If these can be parameterised, then a relationship between F and CAPE can be derived. Lorenc (personal communication) states that if a "well behaved" algorithm existed for calculating CAPE from a model column, then lightning data could be used directly within VAR, without preprocessing to a precipitation rate. The algorithm would have to be smooth, even across the convective/stable threshold. CAPE can be calculated by integrating the difference between the virtual temperatures of a parcel of air, and the environment, over the depth of the atmosphere where the parcel is buoyant. Williams et al (1992) however, discuss a simple parameterisation of CAPE, namely that it varies linearly with surface wet bulb potential temperature in the boundary layer.

Overall it is apparent that lightning observations contain useful information about the location of heavy areas of rain, and that this information can be used by the LHN scheme to add detail to the model's thermodynamic fields. In cases such as June 7th 1996, studied here, the addition of such information has a significant impact on the precipitation forecast. Further work would need to be done before deciding whether or not a modified version of this scheme could be made operational, but this study has shown that there is potential for lightning data in NWP data assimilation.

Acknowledgements.

We are grateful to Gary Hamer for his advice on the workings of the ATD system, and the interpretation of the data it produces, and also to the SIAG group for producing the satellite images.

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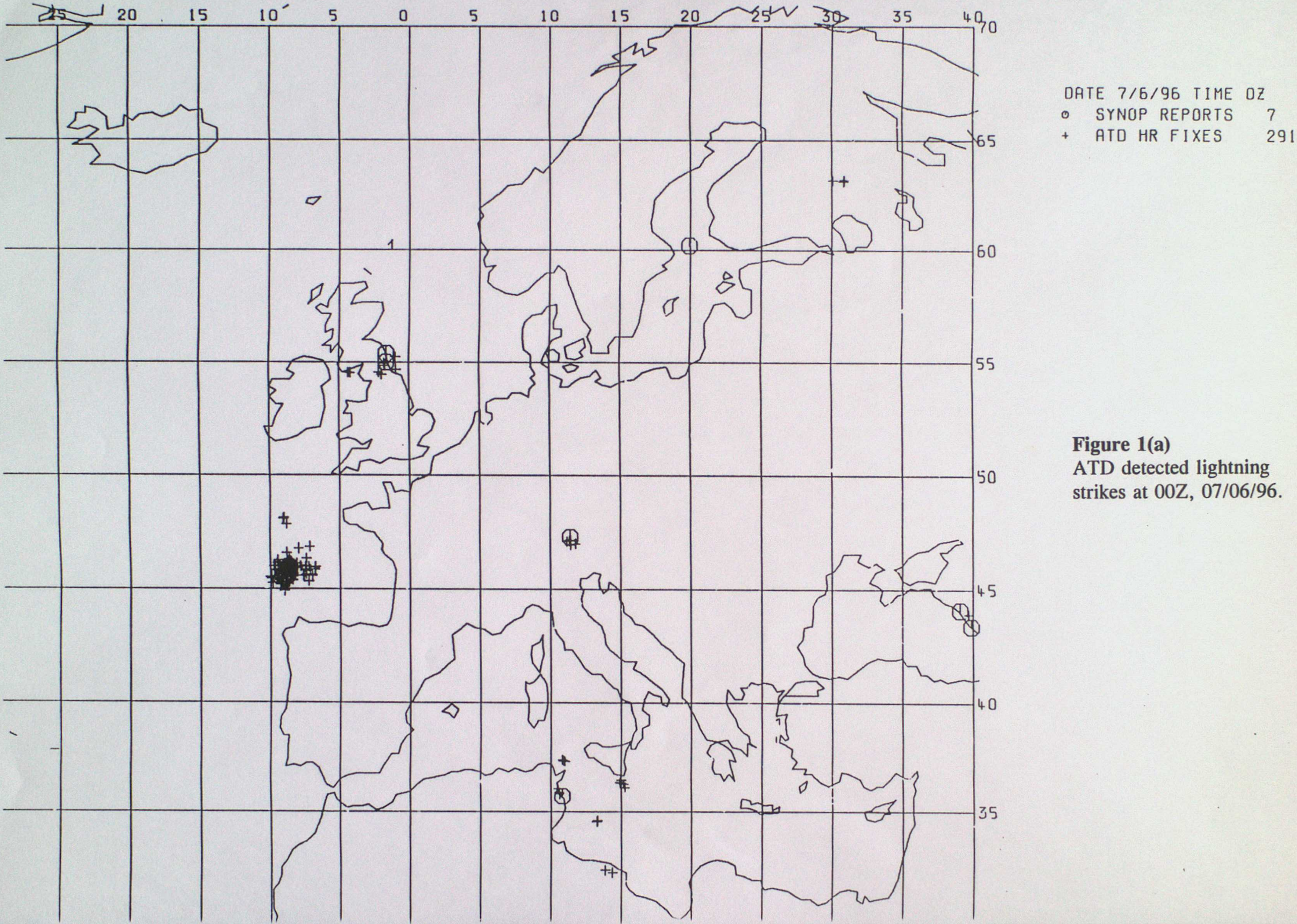
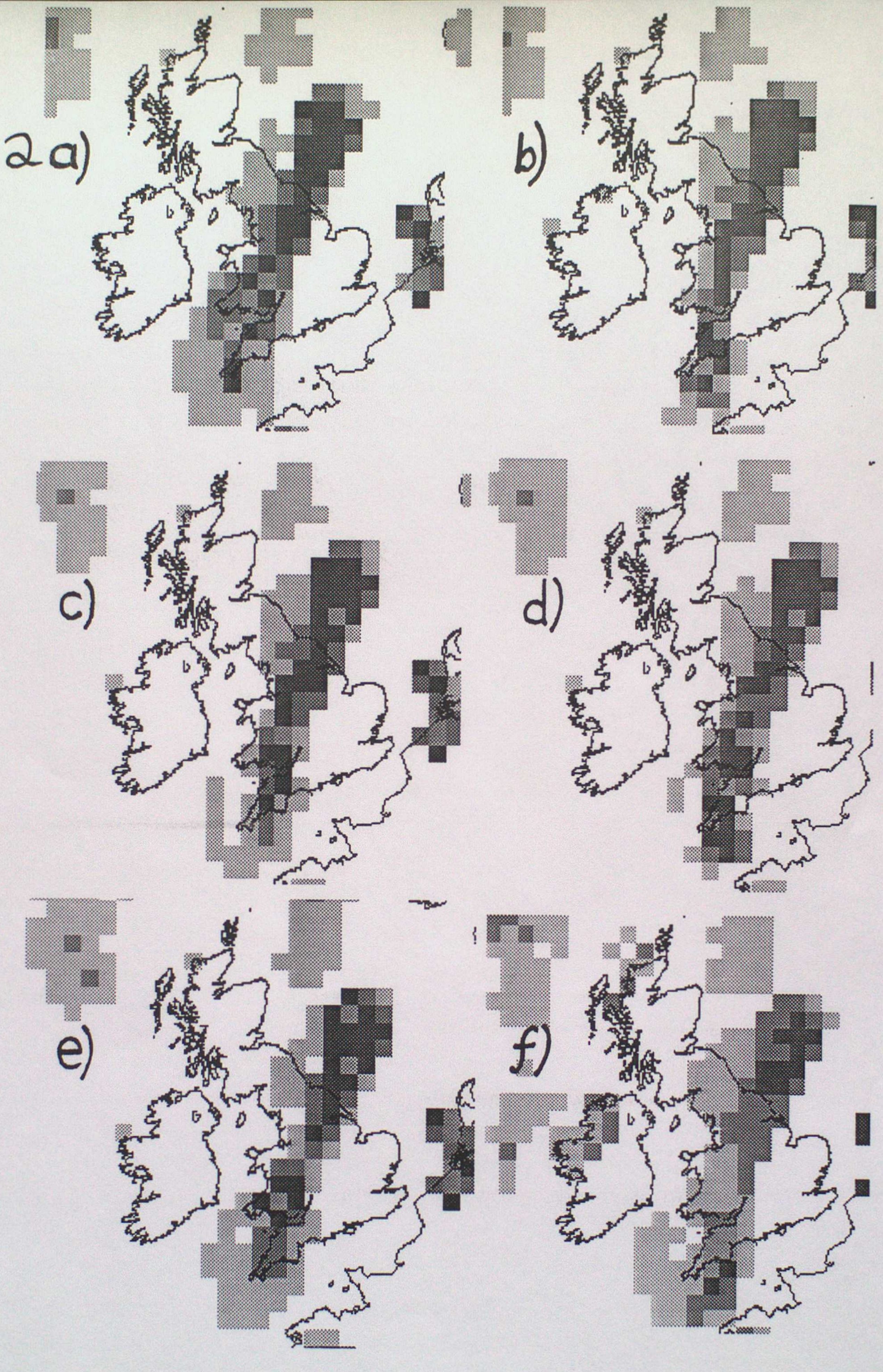


Figure 1(a)
ATD detected lightning strikes at 00Z, 07/06/96.

Figure 1(b)
"Free-hand" estimated precipitation rates
valid at 00Z, 07/06/96.

Figure 1(c)
ATD derived estimated precipitation rates
valid at 00Z, 07/06/96.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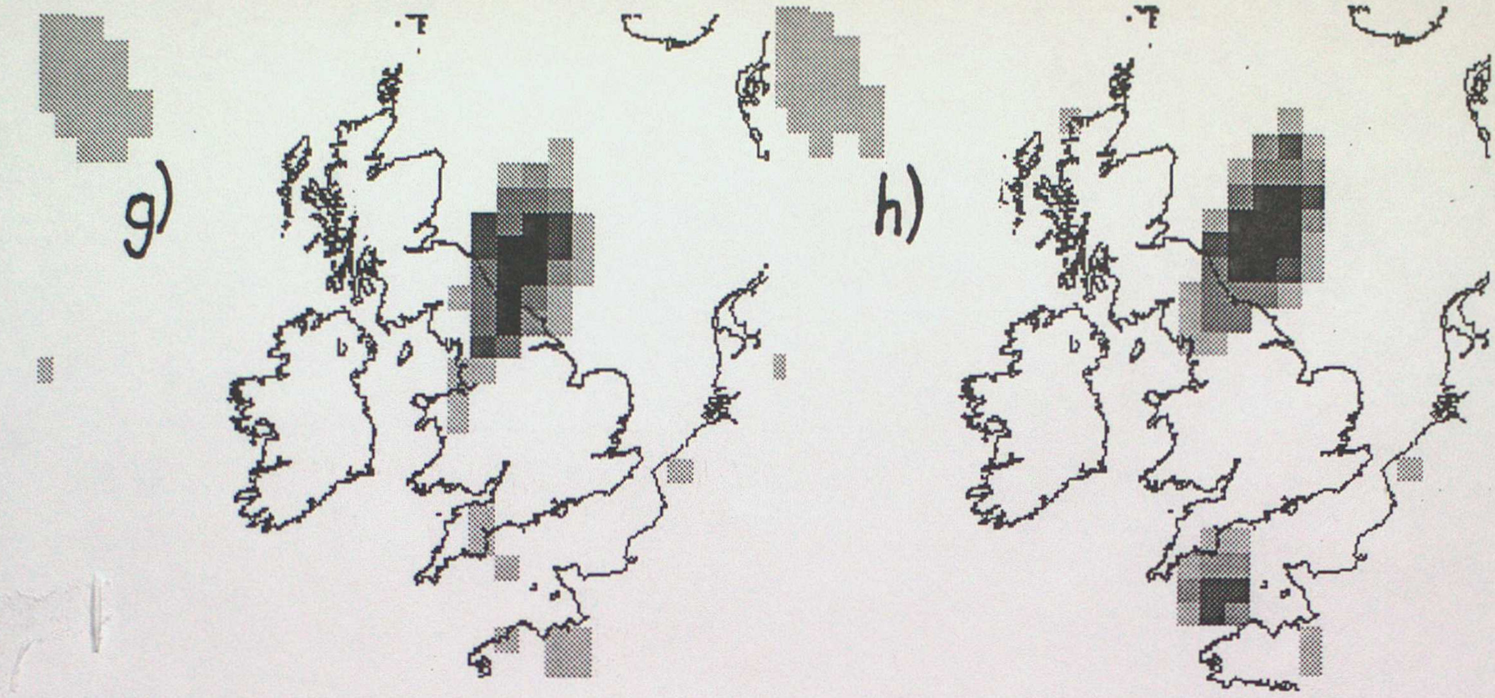


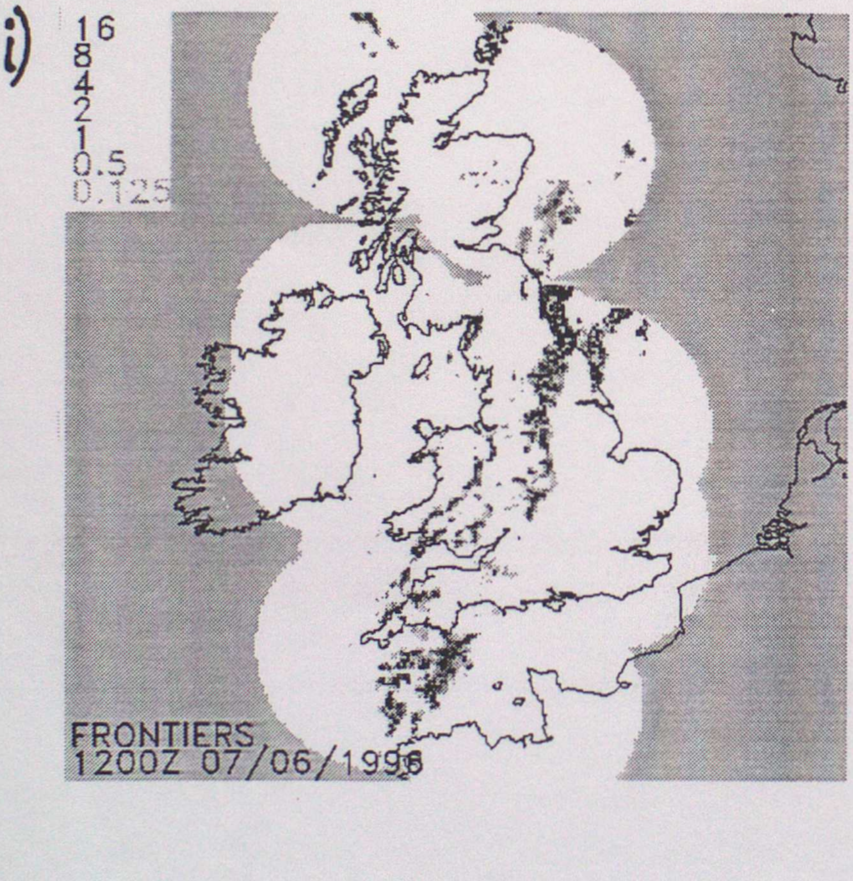
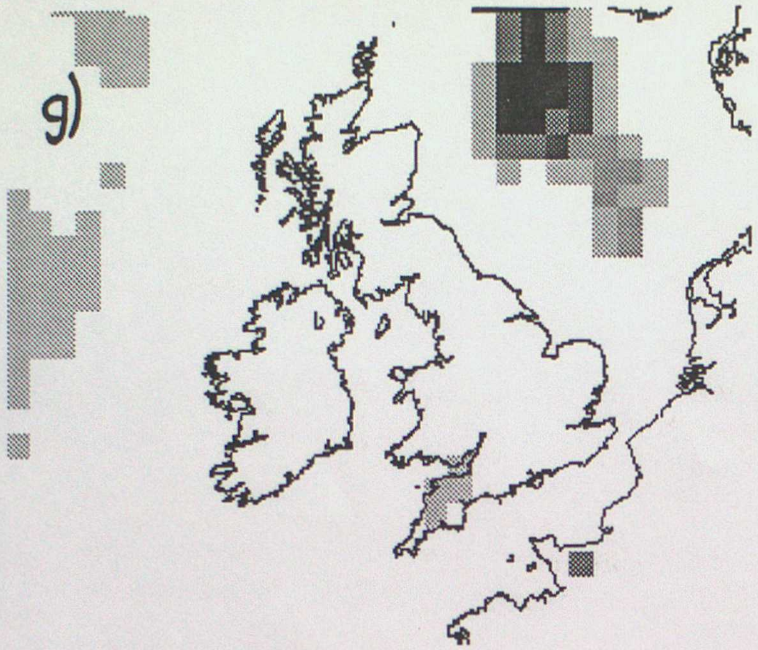


Figure 2. Analysed precipitation fields, valid at 12Z, 07/06/96.

(a) CTL **(b)** DUMLHN
(c) WT1LHN **(d)** DUMTHRESH
(e) ATDTHRESH **(f)** CAPELHN
(g) ATDRATE **(h)** ATDRATE-HALF
(i) corresponding radar image.


3 a)
b)
c)
d)
e)
f)

g)



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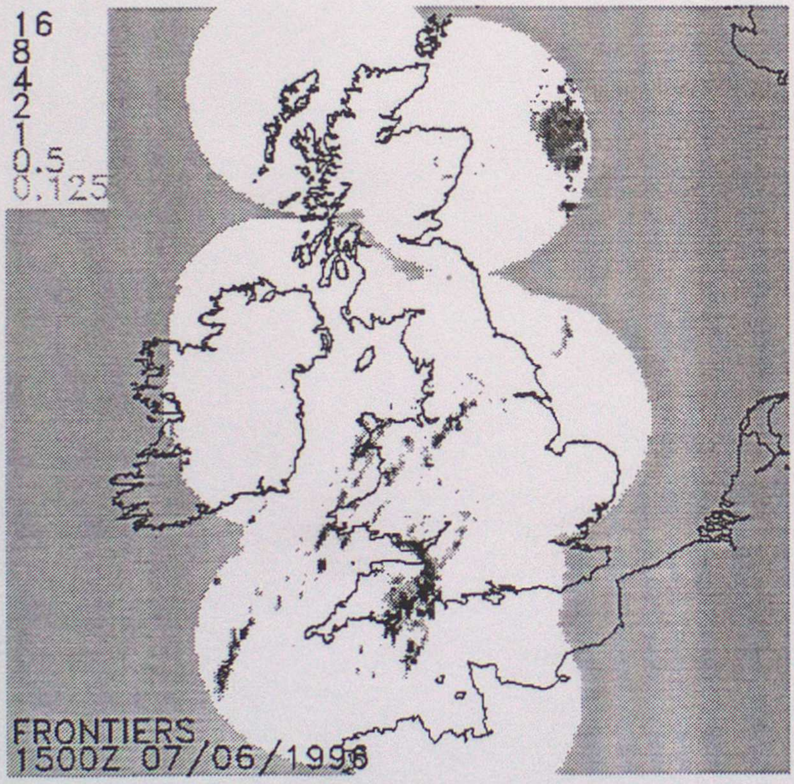

i)

Figure 3. Forecast precipitation fields, valid at T+3, 15Z, 07/06/96.

(a) CTL **(b)** DUMLHN
(c) WT1LHN **(d)** DUMTHRESH
(e) ATDTHRESH **(f)** CAPELHN
(g) ATDRATE **(h)** ATDRATE-HALF
(i) corresponding radar image.


4 a)
b)
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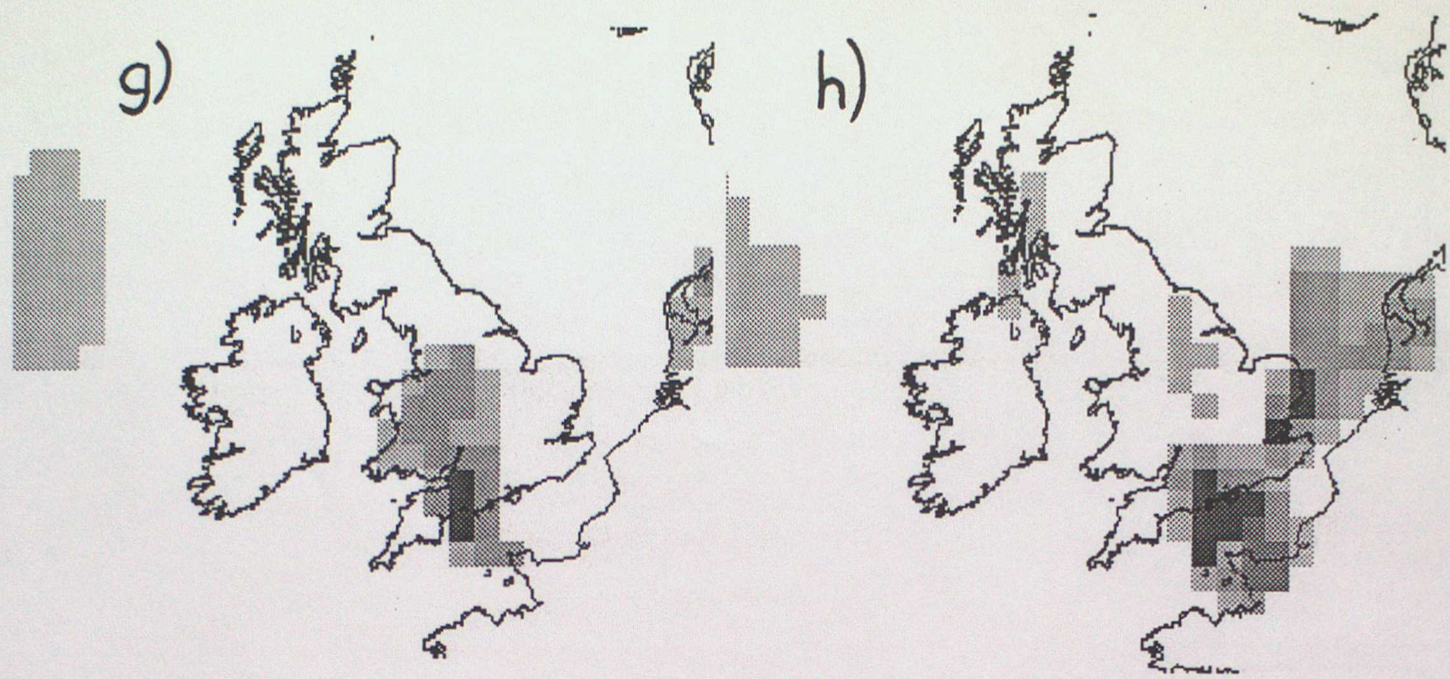
f)



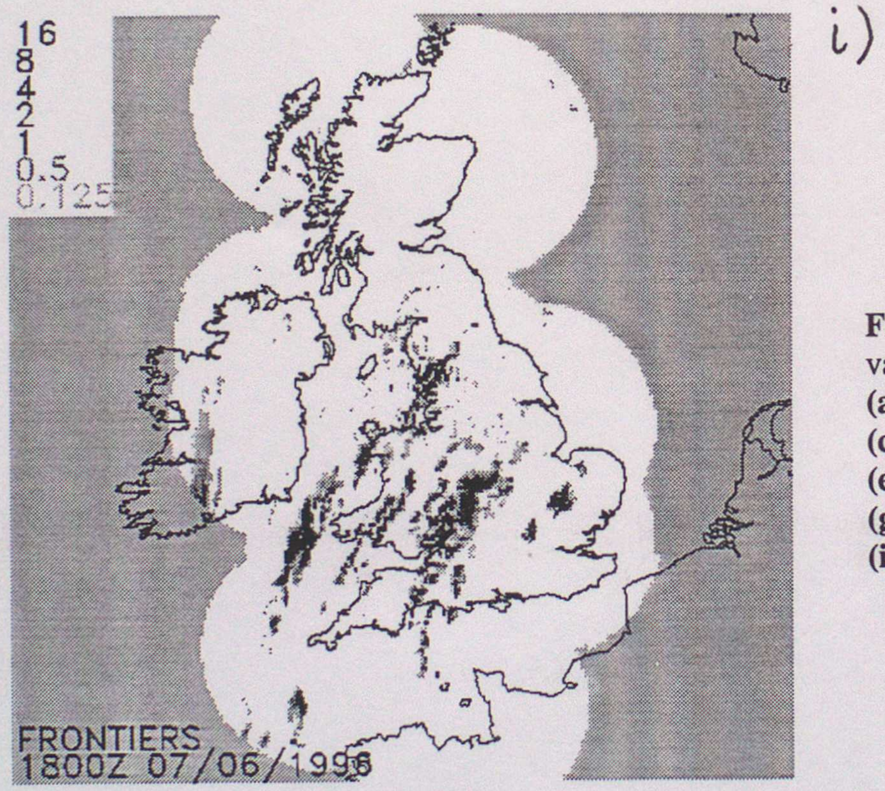


Figure 4. Forecast precipitation fields, valid at T+6, 18Z, 07/06/96.

(a) CTL **(b)** DUMLHN
(c) WT1LHN **(d)** DUMTHRESH
(e) ATDTHRESH **(f)** CAPELHN
(g) ATDRATE **(h)** ATDRATE-HALF
(i) corresponding radar image.


5 a)
b)
c)
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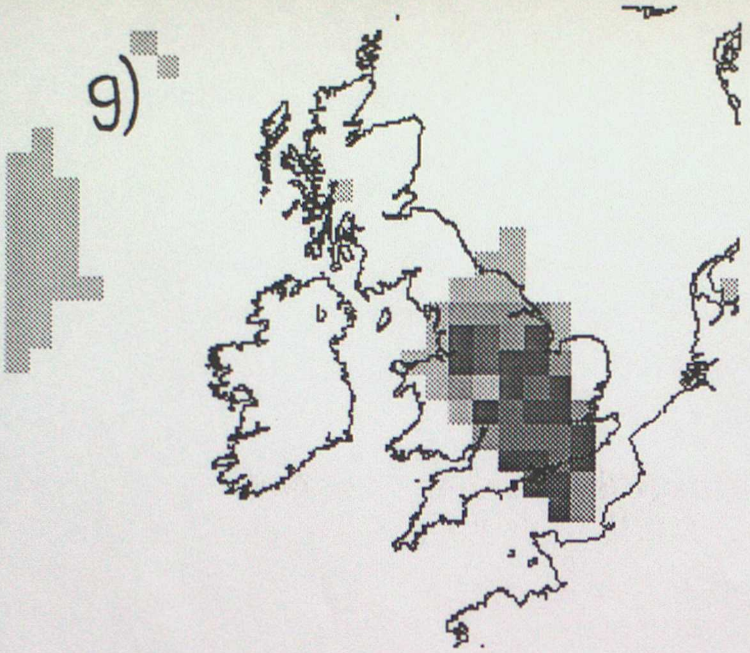

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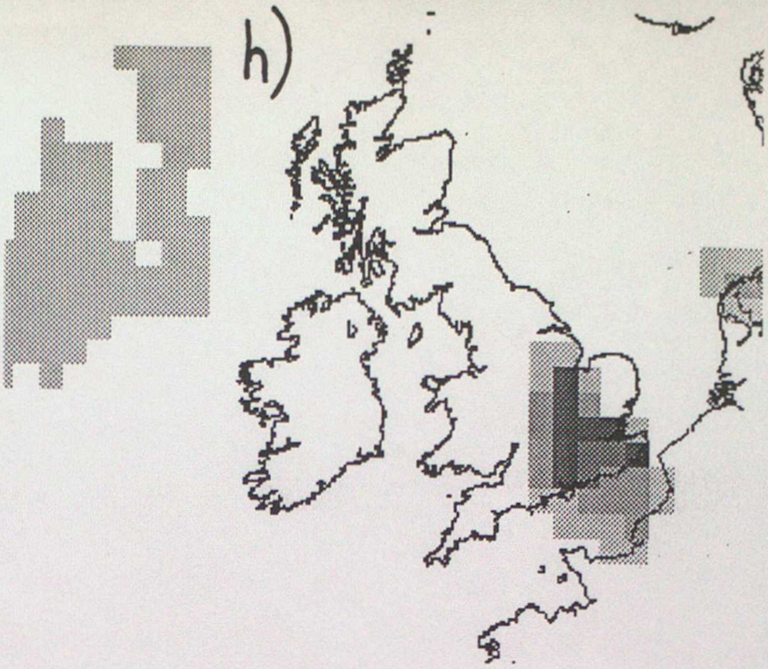

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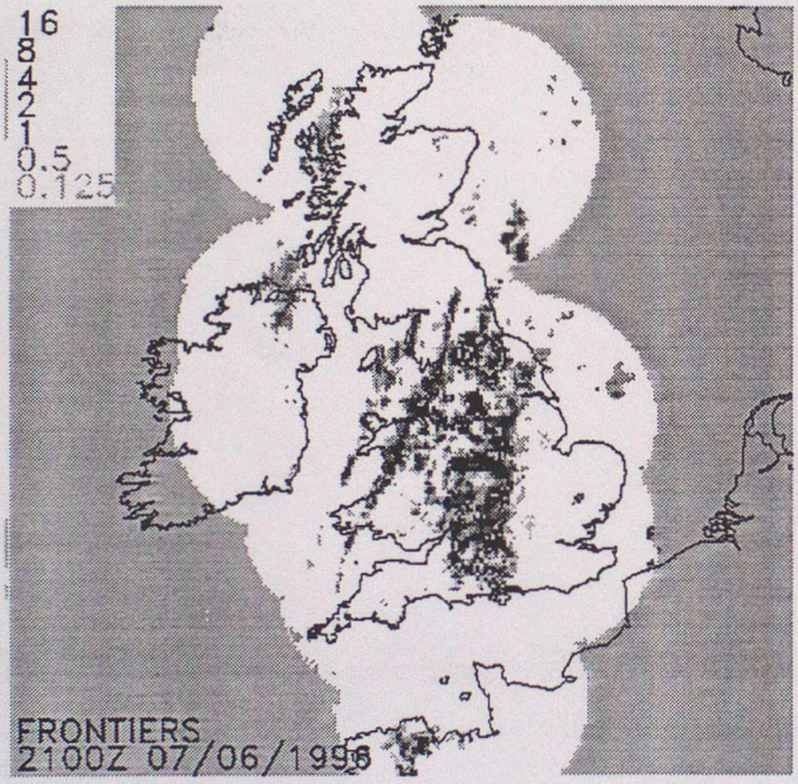


Figure 5. Forecast precipitation fields, valid at T+9, 21Z, 07/06/96.
(a) CTL (b) DUMLHN
(c) WT1LHN (d) DUMTHRESH
(e) ATDTHRESH (f) CAPELHN
(g) ATDRATE (h) ATDRATE-HALF
(i) corresponding radar image.

Figure 6.
ATD derived estimated precipitation rates valid at 12Z, 23/07/96.

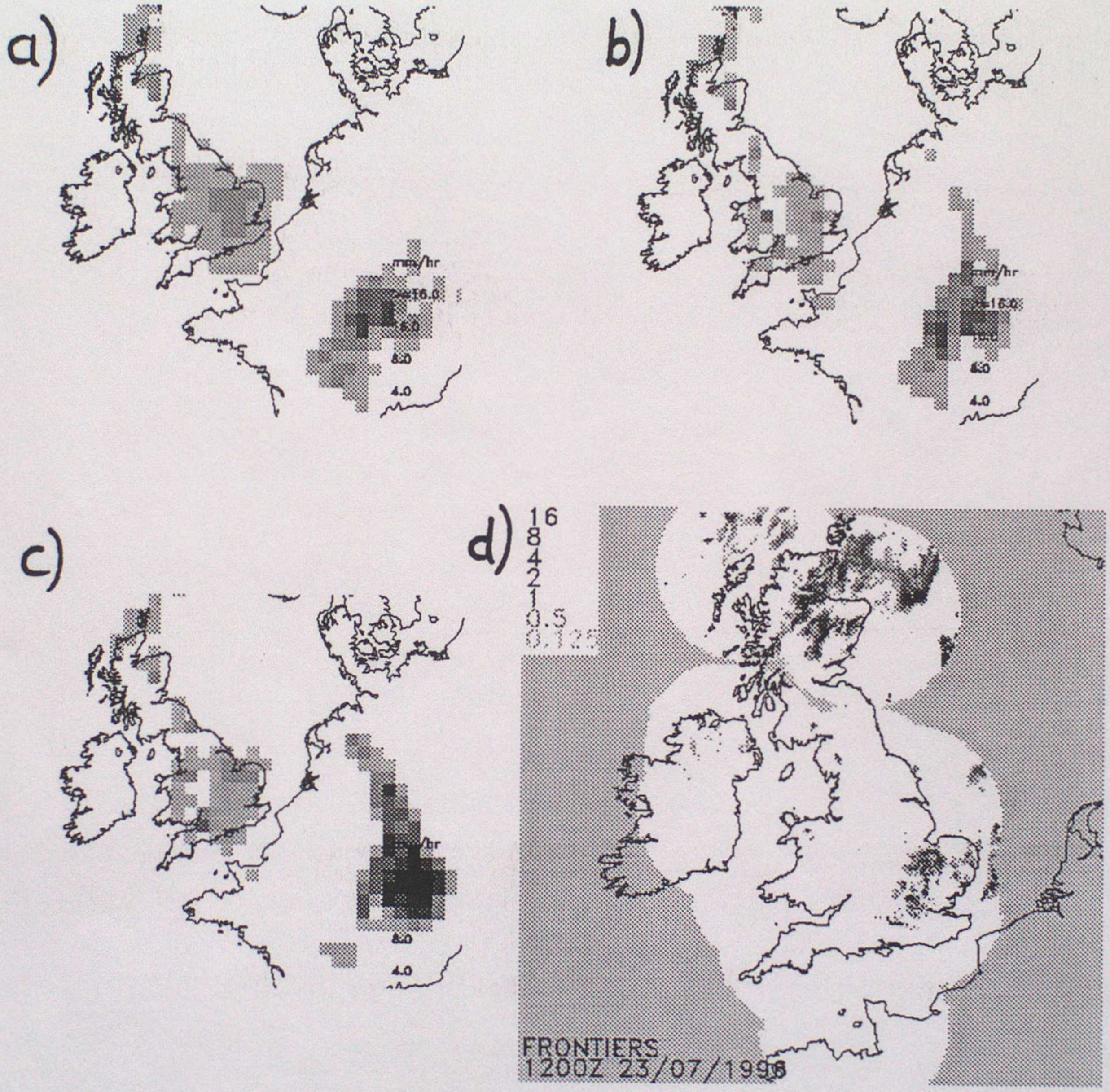


Figure 7. Analysed precipitation fields, valid at 12Z, 23/07/96.
(a) CTL **(b)** ATDTHRESH
(c) ATDRATE **(d)** corresponding radar image.

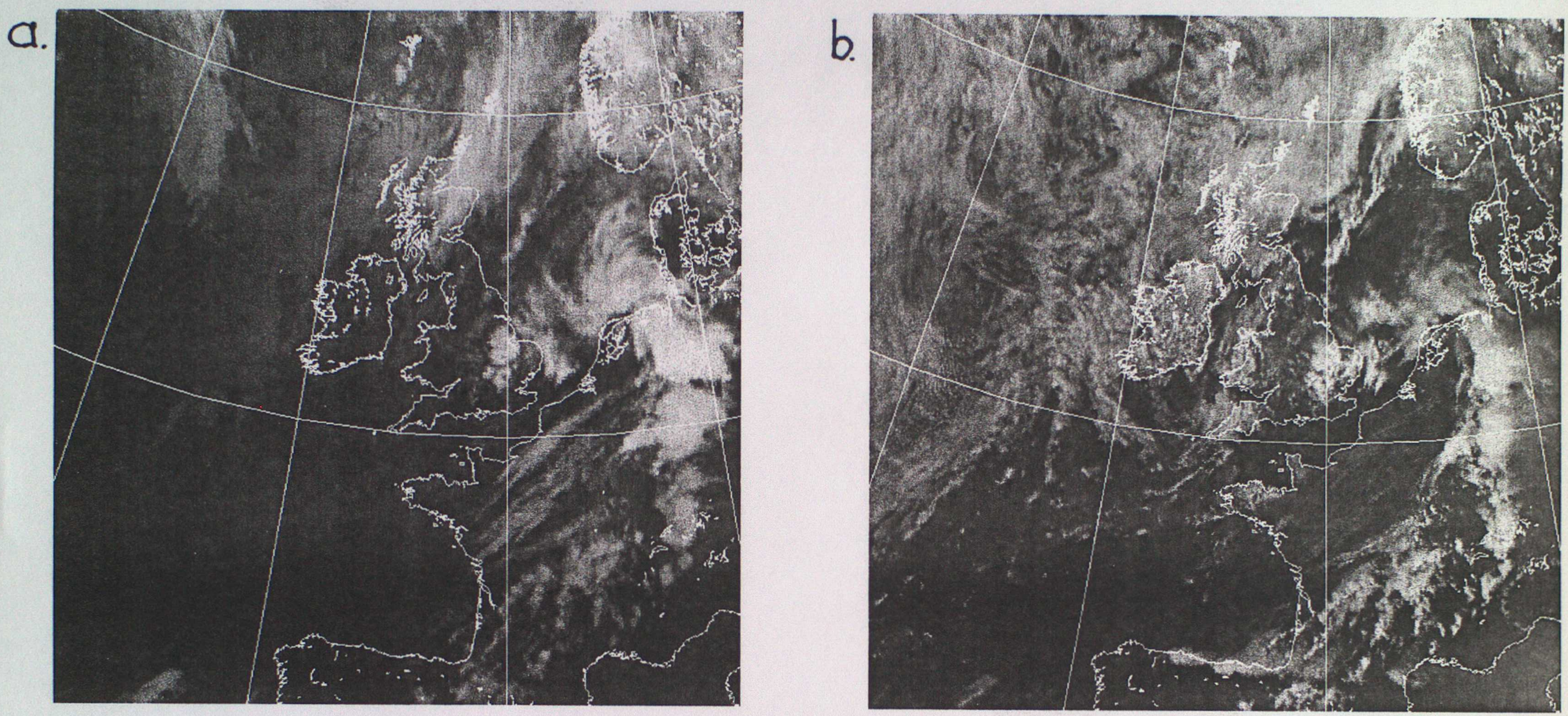


Figure 8. Meteosat satellite images for 12Z, 23/07/96.
(a) Infrared **(b)** Visible

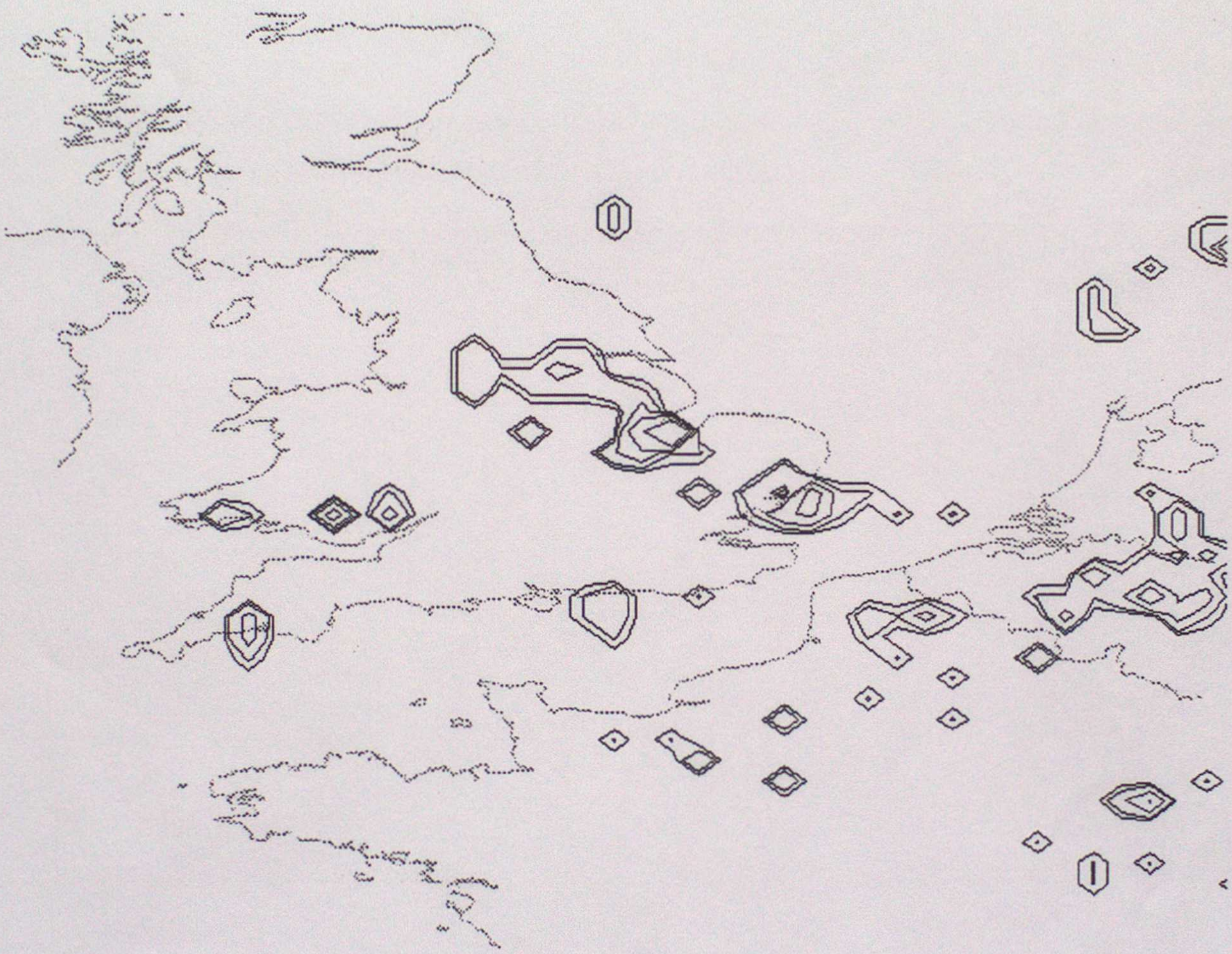


Figure 9.
ATD derived estimated precipitation rates valid at 12Z, 28/08/96.

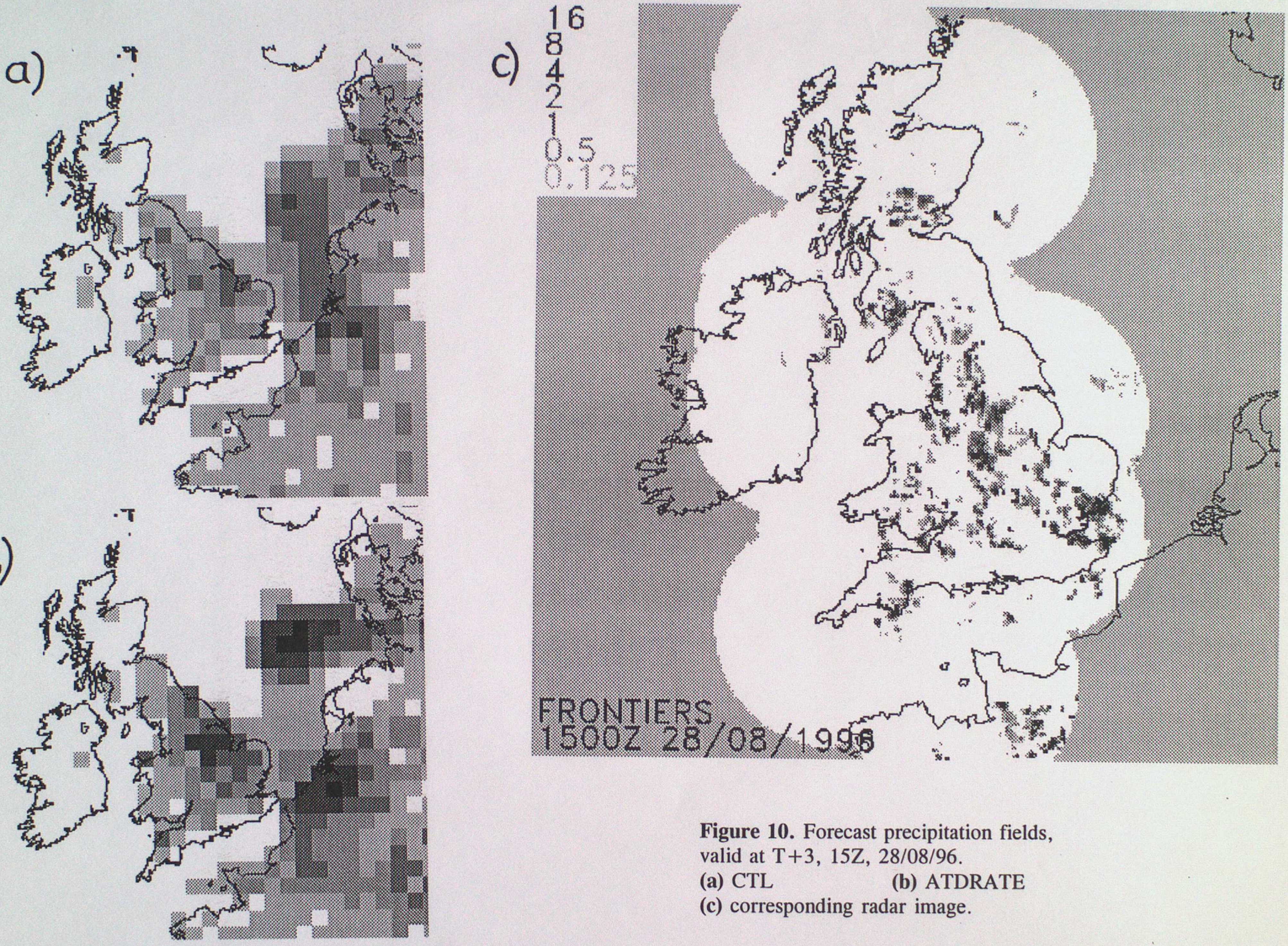
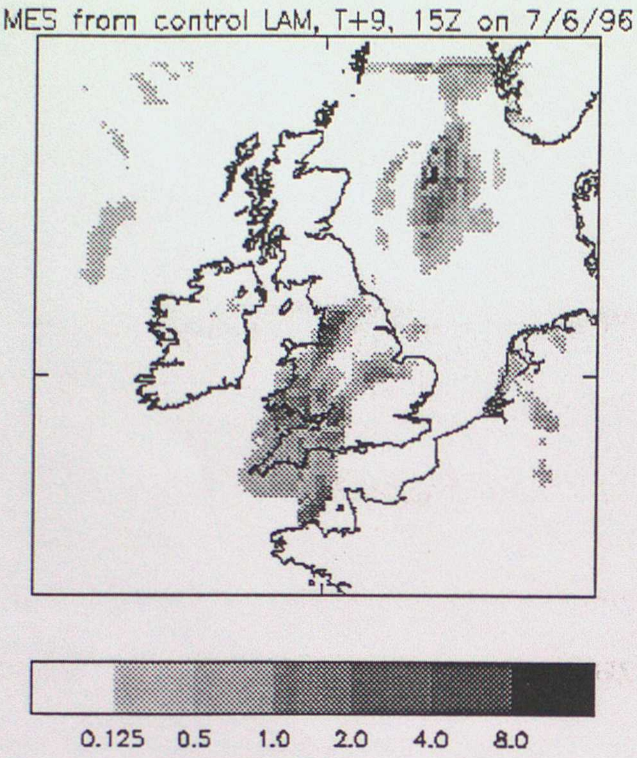
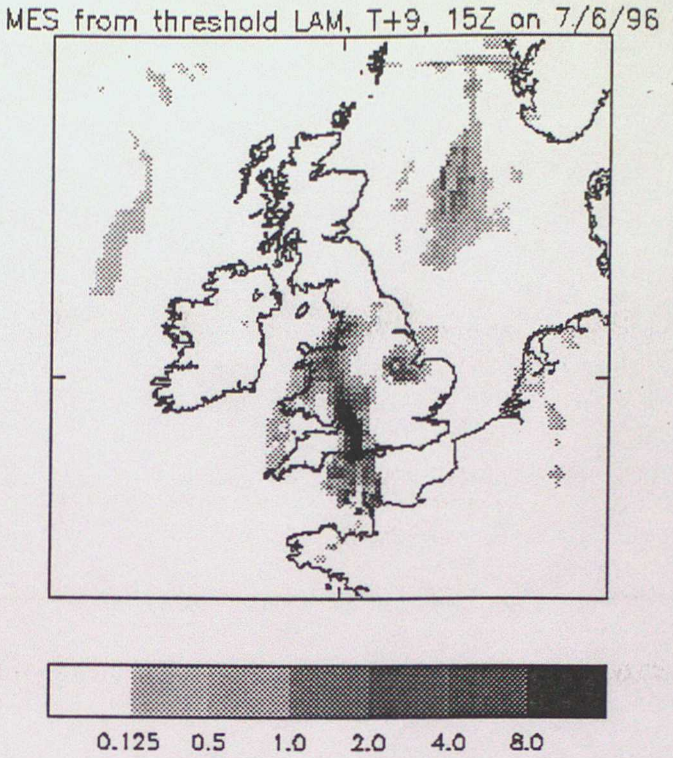


Figure 10. Forecast precipitation fields, valid at T+3, 15Z, 28/08/96.
(a) CTL **(b)** ATDRATE
(c) corresponding radar image.





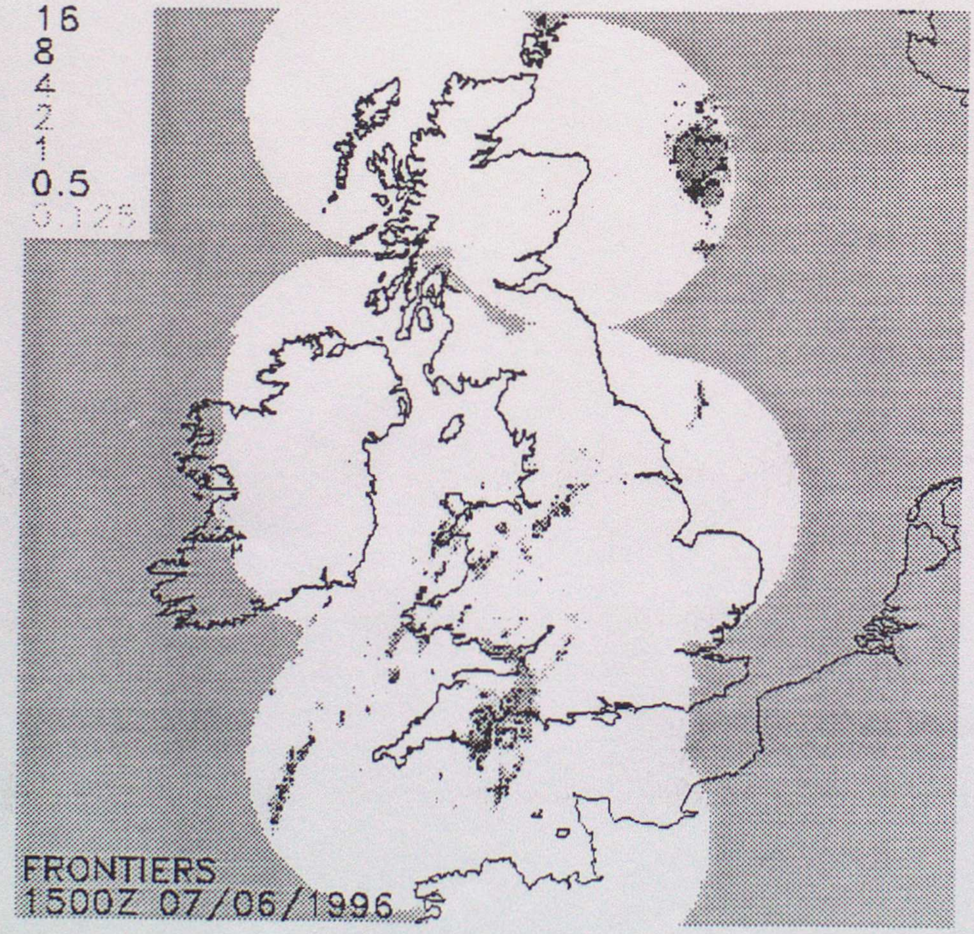
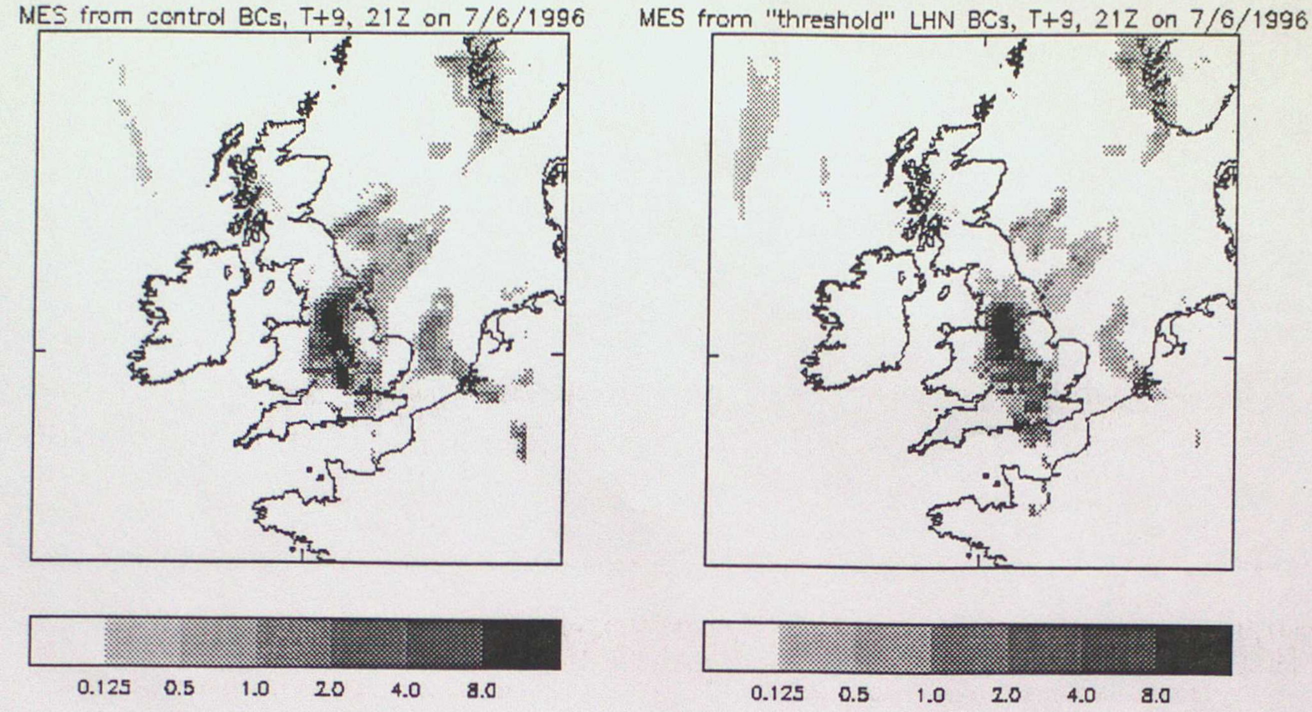


Figure 11. **(a)** CTL and **(b)** LHN boundary conditions run, at T+9, 15Z, 07/06/96. **(c)** corresponding radar image.



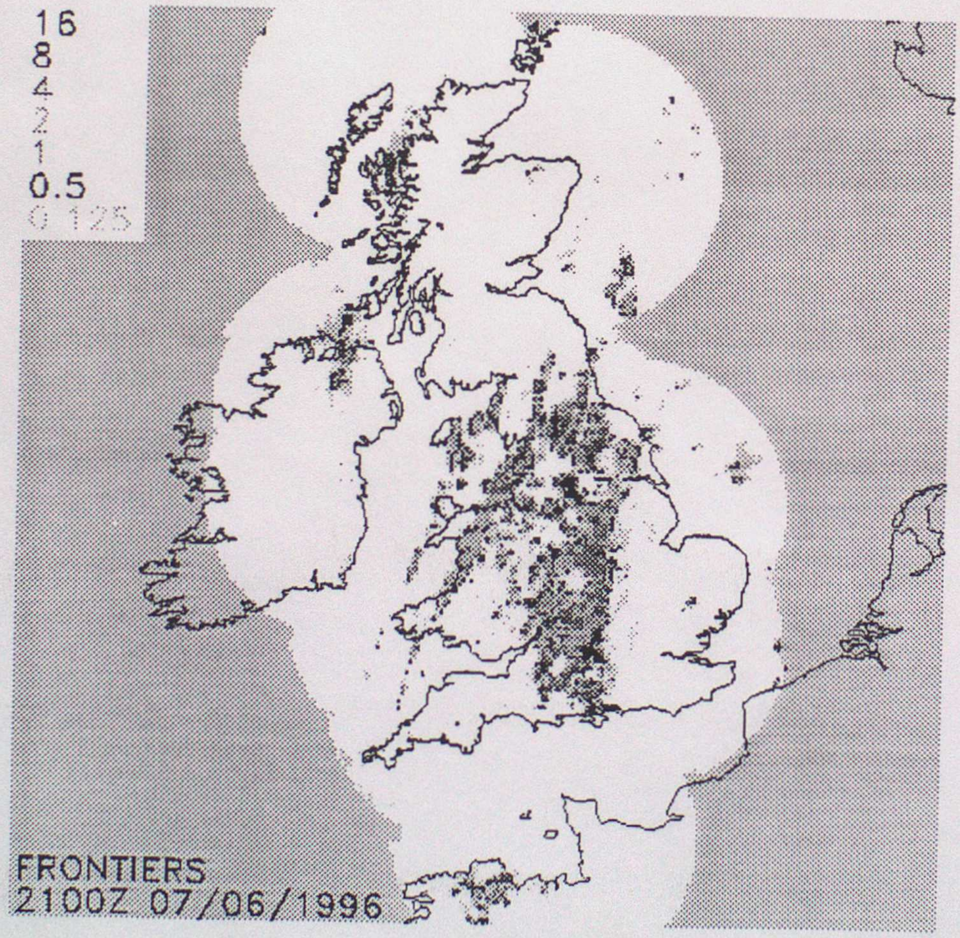


Figure 12. **(a)** CTL and **(b)** LHN boundary conditions run, at T+9, 21Z, 07/06/96. **(c)** corresponding radar image.