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The sensitivity of fine-mesh rainfall forecasts to changes in the initial moisture fields

by

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1. Introduction

The humidity analysis is perhaps one of the weakest points of the operational data assimilation scheme for the fine-mesh model. There are several problem areas which have held back improvements in the objective analyses. The major difficulty is the deficiencies in the observing network which is particularly acute over the North Atlantic . At present the operational assimilation relies solely on humidity data from radiosondes, so the analysis over data sparse areas is almost totally dependent on the background field provided by the model.

The objective use of other data types has been considered but their benefits have proved rather doubtful. The operational fine-mesh analysis has tried to make use of surface ship reports of dewpoint in the past, but these are now excluded after it was found that reports indicating large positive humidity increments could occasionally trigger the convection scheme into giving large amounts of rain with unfortunate consequences. In such cases the observations may have been perfectly valid but the model felt the influence of those increments over too large an area. Once such case was the operational fine-mesh analysis for 12GMT 26/12/85 (*pers. comm. S G Smith, Met O 2b*). Other analysis schemes have attempted to make use of surface observations to infer humidity at upper levels. *Illari (1986)* describes how such reports are used in the ECMWF analysis scheme but at the same time notes that their use is highly empirical and of little value except perhaps in conditions of complete cover. The ECMWF scheme also attempts to make use of the precipitable water content (PWC) information provided by the satellite soundings, however the cases quoted by *Illari* to justify their use all involve tropical impact studies where the PWC is large. Clearly the precision demanded of the fine-mesh humidity analyses for accurate rainfall prediction cannot be achieved by relying on sounding data which give information over very thick layers (1000-700mb, 700-500mb).

The dependence on model background in data sparse areas gives humidity analyses whose characteristics follow closely the characteristics of the model. *Bell (1986)* discusses the deficiencies of the model profiles in the lower part of the atmosphere. Common problems noted include excessive moisture in moist southwesterly warm sectors situations; excessive dryness in anticyclonic southwesterly flow; collapsed boundary layer in anticyclones; excessive dryness above capping inversions . In our repeated insertion data assimilation scheme, where the observation increments are used to nudge the model fields towards the observations during a forward integration of the model, the hope is that analysis fields remain consistent with what the model expects. Thus, even where observations are available there will be a tendency for features which the model represents poorly to also be present in the analyses. Good analyses will only be obtained if the model background fields are realistic. Changes to the physical parametrisation schemes recently *(Hammon, 1987)* have gone some way towards improving the unrealistic features mentioned above.

One method of overcoming the problem of data sparsity is to generate bogus humidity reports based on information such as satellite imagery and SYNOP reports which are not easily amenable to direct assimilation into the objective analysis. The interpretation in terms of relative humidity observations is very subjective. The intervention forecasters usually bogus in order to insert areas of high humidity indicative of cloud, but uncertainties in the value to be assigned as well the depth of cloud make results unpredictable. The operational data assimilation scheme (*Bell and Dickinson, 1987*) treats these bogus reports in a similar way to conventional radiosonde data . The observation increments are used at nearby model gridpoints in the horizontal to a range of about 600km and in the vertical over several model levels. In the statistical interpolation analysis, the weights given to the data as a function of distance from the observation position are determined according to a forecast error correlation which is quite broad. Thus, it is almost impossible to force the model to accept thin cloud layers or sharp discontinuities in the horizontal without saturation coverage of bogus humidity ascents. Some modest improvements in rainfall forecasts have been achieved using bogussing when applied with some care, particularly in the early stages of the forecasts (*eg Smith, 1986*). But on other occasions the overzealous intervention forecaster has done more harm than good . One such case was the fine-mesh forecast from 00GMT 28/7/87 which resulted in excessive rain over Scotland (*pers. comm. S G Smith, Met O 2b*)

The 10-level rectangle model analysis of relative humidity (*Atkins (1974)*) included a non-isotropic weighting function dependent on the gradient in the background field in an attempt to retain sharper gradients in the humidity field associated with frontal rainbands. Unfortunately the statistical interpolation/repeated insertion scheme now being used has not proved very flexible and a similar approach was not carried over to the 15-level model. However the revised repeated insertion algorithm (*Lorenc and Dumelow, 1987*) currently being prepared will allow for such increased flexibility.

In this paper , we are investigating the likely improvement in fine-mesh rainfall and cloud forecasts following a very detailed re-analysis of the model humidity fields. This re-analysis was univariate and no attempt was made to correct for any deficiencies in the mass and wind fields. Taking a lead from the mesoscale interactive analysis system, we examined the analyses after the data assimilation stage and compared the model relative humidity fields and diagnosed cloud fields against cloud imagery and SYNOP reports. We then simply amended each of the model levels directly as required, in the area of study to make them compatible with what observations were available. The amendments were made directly to the model sigma level fields so no further interpolation was required . Clearly a subjective interpretation of cloud base and top was still required and usually only one layer of cloud was catered for. Where cloud had to be removed , rather arbitrary values of 50-70% relative humidities were assigned. Where cloud was present, the model was assigned a value of relative humidity above the threshhold used by the radiation scheme according to the same criteria used by that scheme, namely:

$$Q = (U-U_{crit})^2/(1-U_{crit})^2$$

where Q is the cloud fraction
U is the relative humidity , when $U>U_{crit}$
U_{crit}=85% threshold relative humidity

The cases were chosen from those highlighted by forecasters during the past year. For many of the cases, the forecasters in the Central Forecast Office (CFO) have provided a subjective cloud analysis giving base, top, geographical extent and degree of coverage. This is referred to in the text as the CFO cloud analysis. We attempted to choose several cases for each type of situation likely to be encountered in the UK including frontal types, wave developments, convective cases and anticyclonic stratocumulus cases. Eleven fine-mesh cases have been provided with a modified initial humidity field and the subsequent forecast compared with the operational product. The cases chosen for study have been divided into four categories;

a) convective	*DT 00GMT 02/05/87*
b) frontal	*DT 12GMT 23/07/87*
	DT 12GMT 18/09/87
	DT 12GMT 27/01/87
c) wave development	*DT 12GMT 19/08/87*
	DT 00GMT 05/01/88
	DT 12GMT 13/01/88
	DT 12GMT 07/02/88
d) anticyclonic stratocumulus	*DT 12GMT 27/09/87*
	DT 12GMT 17/02/87
	DT 12GMT 05/04/87

In sections 2 to 5, the amendments to the humidity analyses and the impact on the subsequent forecast are discussed for several cases in each of the above types of situation mentioned above. We have concentrated for the most part on the evolution of cloud and rainfall but other products have also been examined. In section 6, we shall attempt to identify the type of situation where the model is most receptive to humidity data.

2. A convective case study

2.1 - Data Time 00GMT 02/05/87.

A depression centred just to the north of Scotland at 00GMT 2nd May moved slowly eastwards into the North Sea during the day, allowing a strong, cold and unstable northerly airsteam to become established over the U.K. In the north, it remained predominantly cloudy with frequent hail, sleet and snow showers. In the south, it remained dry until late afternoon, but then some heavy showers with hail and thunder developed there as well. The radar picture for 18GMT , displayed at figure 2c, shows that the distribution of showers over England and Wales was fairly widespread in the late afternoon.

This case was chosen because the fine-mesh forecast failed to indicate the extent of the heavy showers in the south. The operational T+18 forecast of rainfall rate and surface pressure is shown in figure 2a, where we see that the model has predicted a few showers in the extreme south (but in the wrong area) and one shower over East Anglia. Although unstable to 600mb, the T+18 model forecast tephigram for Crawley looked too dry to produce rain.

The airmass over England in the late afternoon was advected from the north and west of Scotland and a relevant area for study was selected to be bounded by 54°-61°N and 6°-12°W. The model analysis had some stratiform cloud in this region but only at medium levels. Some convective cloud was also analysed, with tops 12,000-16,000 feet, depths 10,000-14,000 feet. We decided to increase the model's humidity in the analysis in this region to 96% at the observed convective base (levels 3-5) . The modified relative humidity analysis at 850mb is shown in figure 1b and can be compared with the operational version in figure 1a.

The modified T+18 forecast is shown in figure 2b and in fact differs little from the operational version . Both have failed to predict the heavy showers over England and Wales. However, if we compare the six-hour rainfall accumulations for the period 12-18 GMT, then the modified forecast (figure 3b) has resulted in a wider distribution of rain in the south than the operational version (figure 3a). We conclude that increasing the humidity in the analysis at the base of convection had only a very small but beneficial impact on the model's rainfall forecast.

3. Frontal case studies.

3.1 - Data Time 12GMT 23/07/87.

During the 24 hours commencing 18GMT 23rd July, a frontal system moved slowly southwards over the U.K. Although accumulations were fairly small (no more than 5mm), there were nevertheless persistent and locally moderate bands of rain associated with the warm and cold fronts. In figure 5c, the radar picture shows the rainfall distribution at 06GMT 24th July, with the heaviest most widespread rain over Northern England and Southern Scotland. The narrow band of rain lying from East Anglia to South-west England is associated with the weaker warm front. As the cold front moved southwards, it weakened in the west, giving only a trace of rain over South Wales and South-west England, but the rain persisted in the east, especially over East Anglia.

This case was chosen because the fine-mesh model failed to predict the rainfall over the U.K during the 24-hour period. In figure 5a, we show the operational fine-mesh forecast of rainfall rates and surface pressure for T+18, which can be compared directly with the radar image . The forecast is much too dry over the U.K., with the cold front rainfall non-existent and the warm front rainfall confined to the North Sea.

The cause of this poor rainfall forecast is attributed partly to too much subsidence (the forecast pressure at T+18 is 2-4mb too high over the U.K), but mainly to dryness in the model's analysed relative humidity fields to the west of Scotland . In figure 4c, we show the NOAA-10 visual satellite image for 1030GMT 23rd July, showing the cloud areas to the west of Scotland. At this stage, the fronts seemed relatively weak, with little cloud showing on the infra-red image. The observed freezing levels at 12GMT were 12,000 feet over the U.K ahead of the cold front, falling to 5000 feet well to the rear. The operational relative humidity analysis for 12GMT at 700mb (figure 4a) shows that the frontal zone is defined in the model by only the 57% relative humidity contour and the model has only a small band of cloud associated with the front. The aim of intervention in this case was to improve the model's forecast rainfall associated with the cold front by increasing humidity in the analysis at 700mb (level 6). We decided to increase the relative humidity at level 6 to 97% (approximately 5 octas of cloud) in the analysis in the area bounded by 57°-60°N and 5°-25° W. The modified analysis is shown in figure 4b.

The T+18 forecast based on the modified analysis (figure 5b) shows substantial improvements over Northern England . The increased rainfall forecast over the U.K on the cold front resulting from the modified analysis lasted at least to T+18. At T+24, the forecast rainfall west of the meridian had died out although slightly bigger amounts were forecast in the North Sea.

3.2 - Data Time 12GMT 18/09/87.

At midday on 18th September, a warm front over Biscay was moving slowly north-eastwards with a ridge over England and Wales beginning to decline. By 18GMT, rain ahead of the warm front was spreading into South-west England and along the South Coast. During the next 24 hours, the warm front made steady progress north-eastwards and the radar picture in figure 8c shows the rain area associated with this warm front over Southern England at the following morning at 06GMT .

The fine-mesh forecast for this period was very poor. Although the model predicted an area of medium cloud over South-west England and along the South Coast for 06GMT 19th September, it failed to forecast any rain . The T+18 operational fine-mesh forecast of rainfall rates and surface pressure verifying at 06GMT is shown in figure 8a.

Figure 6a shows the model's cloud analysis for 12GMT over the U.K and Biscay. This can be compared with CFO's cloud analysis for the same time shown in figure 6b. The model analysis clearly lacked cloud in the crucial area in Biscay between 5°-10°W. In this region CFO analysed thick layers between 8000 and 35000 feet. In figure 7a, we show the model's relative humidity analysis at 700mb for 12GMT. The band associated with the warm front is only defined by the 57% contour with a maximum value of 75%, which is much too dry. We increased the analysed humidity in this region at level 6 to 100% in accord with CFO's cloud analysis and this gave the amended 700mb analysis shown in figure 7b. Since CFO analysed thick layers above 8000 feet, we also amended the humidity in model levels 7,8 and 9 to 95%.

The T+18 forecast run from the modified analysis (figure 8b) is a big improvement when compared with the operational forecast (figure 8a). However, the forecast rainfall is still too far south with no rain associated with the warm front north of 50°N, so clearly there was an error in the model dynamics as well.

3.3 - Data Time 00GMT 27/01/88.

This case is similar to the previous one, with a warm front pushing slowly northwards from Biscay into Southern England during the forecast period. At 00GMT 27th January, the warm front was moving slowly northwards towards South-west England. During the night, rain was confined to South-west England and the Channel Islands. The rain moved slowly north-eastwards during the day reaching a northern limit from Dublin to the Thames estuary by 18GMT. The actual rain distribution at 18GMT is shown by figure 10c with the most persistent rain in South-west England and along the South Coast.

Until the evening the operational fine-mesh forecast rainfall distribution was reasonably accurate as can be seen in figure 10a. However, the later stages of the forecast were not so accurate. After T+24, the model's forecast rainfall over the U.K. became sparse and confined to the west . In reality the area of rain over South-west

England at 18GMT was advected northeastwards across Wales and the Midlands during the following night. The actual distribution of rain at 06GMT 28th is shown by the radar picture in figure 11c, with the heaviest rain (or sleet) over the Midlands. This area was not predicted by the operational fine-mesh forecast at T+30. (see figure 11a).

The infra-red satellite image for 00GMT 27th, (figure 9c), shows a broad swathe of cloud over the English Channel, Western France and Biscay. This can be compared with the operational 700mb relative humidity analysis (figure 9a), which shows that the model's frontal zone is only defined by the 76% relative humidity contour over the Channel and France and the area of cloud over Biscay is not represented in the analysis. The modified analysis is shown in figure 9b. In this case we increased the relative humidity to above 96% at levels 6 and 7 in the model's frontal zone and also over Biscay to match the area shown in the satellite picture.

The T+18 forecast run from the modified analysis is shown in figure 10b. The impact of the increased moisture in the analysis has correctly moved the rain area to the north of London and substantially increased the rainfall in the frontal band over the continent. However , by T+30 the modified analysis gave a forecast (figure 11b) which was as poor as that from the operational run.

4. Wave development cases.

4.1 - Data Time 12GMT 19/08/87.

During the 18 hours from midday 19th August, a cold front remained slow-moving just to the west of Southern Ireland, with it's eastwards progress retarded by a succession of waves moving up from the south-west so that Eastern Ireland remained mostly dry until late in the night. The significant weather charts for 00GMT and 06GMT on 20th August (figures 13e and 13f respectively) show the observed rain area confined to Scotland and Northern Ireland at midnight with a further wave bringing back rain into South and West Ireland later.

The fine-mesh forecast from 12GMT 19th August predicted the cold front and associated waves to be slightly too far east with heavy rain over Eastern Ireland several hours too early. Figures 13a and 13b show the operational fine-mesh forecasts of rainfall and surface pressure for 00GMT and 06GMT on the 20th respectively. Comparing these with the corresponding significant weather charts , we see that the forecast rain areas are too far advanced and there is a timing error of at least six hours.

This timing error in the fine-mesh model forecast has been attributed mainly to a small spurious area of high humidity and cloud at 700mb in the analysis at 47°N, 12°W , which we can see in figure 12a. The modified analysis (figure 12b) had the relative humidity reduced to 80% in this area .

The T+12 and T+18 forecasts run from the modified analysis are shown in figures 13c and 13d. The main impact has been to delay the forecast arrival of rain over Central Ireland until after midnight. If we compare the forecasts at T+12, the modified forecast is more accurate over Central Ireland but less over Northern Ireland. At T+18, the operational and modified forecasts are very similar.

4.2 - Data Time 00GMT 05/01/88.

This 'instant occlusion' case study has been described in detail by Young (1988) There were two features of interest. A cold air vortex deepened rapidly in a strong southwesterly flow ahead of a sharpening upper trough, resulting in a deep depression (976mb), centred just south of Rosslare by 00GMT 6th January which moved towards North Wales in the following 6 hours (see figure 15c for the position at 06GMT). Also, ahead of this system, a wave developed on a cold front over Biscay and moved northeastwards to affect South-east England .

The fine-mesh model from DT 00GMT 5th January produced a poor forecast of these events after T+24. Basically, the model developed the warm air feature rather than the cold air feature. The predicted position of the wave on the cold front over the Channel at T+24 was good, but the model subsequently developed this wave into the major depression. At the same time, the model failed to deepen the cold air vortex sufficiently and the forecast pressure was 10mb too high over Rosslare at T+24. Consequently, the model predicted far too much rain over South-east England on the frontal wave and far too little in the west near the developing depression.

The failure of the model to deepen the cold air vortex sufficiently may be attributed to a poor analysis of the upper trough. However, our interest in this case was the excessive rainfall predicted by the model over South-east England on the cold front wave at T+24. This feature can be traced back to an area of high θ_w in the analysis at 39°-40°N, 15°-20°W, which looked incorrect. In the forecast, this area was advected north-eastwards into the Channel by T+24.

In the operational 850mb analysis (figure 14a) the relative humidity in this area has a maximum value of 97%. We decided to decrease the humidity at levels 3-4 to 50% in this area to see the impact on the forecast pressure and rainfall. The modified analysis is shown in figure 14b.

The T+30 rainfall and surface pressure forecast run from the modified analysis (figure 15b) may be compared with the operational forecast in figure 15a. There was a modest impact when the erroneous high θ_w area was eliminated. The development of the frontal wave was slightly slower although still overdeveloped and the position of the depression was correctly further west although not far enough west. However, the modification had little effect on the high rainfall accumulations over southeast England and the model still failed to deepen the cold air feature sufficiently.

4.3 - Data Time 12GMT 13/01/88.

During the early stages of this forecast period, the clearance behind a cold front over South-east England was delayed by a wave forming on the front in Biscay (positioned about 47°N, 5°W at 12GMT). The wave crossed South-east England during the evening of the 13th January. with the rain finally clearing soon after midnight.

The model error in this case was a small timing area with the forecast rain areas clearing the east coast slightly too fast. The operational forecasts for T+6 and T+12 are shown in figures 18 a and b. The model's relative humidity analyses at levels 4, 5 and 6 were modified in accordance with CFO's cloud analysis chart (figure 16) by increasing the humidity to above 95% in the area marked A, thus extending the boundary of the analysed cloud area slightly further east. The impact of the change in the change can be seen by comparing the modified analyses at 850 and 700mb (figures 17c and d) with the operational fields (figures 17a and b).

The T+6 and T+12 rainfall and mean sea level pressure forecasts run from the modified analysis are shown in figures 18 c and d. Modifying the analysed humidity in this case extended the area of rainfall too far east over the continent but successfully delayed the clearance over South-east England.

4.4 - Data Time 12GMT 07/02/88.

An active frontal system over Western Ireland at 12GMT 7th February moved quickly eastwards. The associated rain area reached Wales and Western England before dusk and as it spread inland the precipitation turned to sleet and snow in the north for a time. The rain cleared the East Coast during the evening but the clearance was only temporary in the south. A wave forming on the cold front at approximately 50°N moved quickly eastwards, bringing a further spell of rain, sleet and wet snow to Southern Counties overnight.

There were two errors in the operational fine-mesh rainfall forecast for the U.K. First, the initial clearance of the cold front was slightly fast by two to three hours. Also the precipitation on the wave over Southern England during the night was underestimated by the model. The operational fine-mesh surface pressure and rainfall forecasts for T+6 and T+12 are shown in figures 21a and b respectively. In the T+12 forecast, the model has predicted what appears to be a weak wave feature just to the west of Brest, but the associated forecast rain area was advected eastwards too far south over Northern France.

The CFO cloud analysis for 12GMT (figure 19) when compared with the operational 700mb relative humidity analysis (figure 20a) , shows that the model's frontal cloud band has been analysed about 2° or 3° too far east and the area to the southwest of Ireland is too dry. The model analysis was amended to follow the CFO cloud analysis by increasing the humidity at levels 4,5 and 6 to above 95% in the area marked B. Cloud was removed at the eastern edge of the frontal cloud over Wales by reducing humidity to 50% . The result of this modification at 700mb is shown in figure 20b.

Moving the cloud band further west had little effect on the timing of the clearance of rain over Eastern England. The T+6 and T+12 forecasts run from the modified analysis (figures 21c and d) show the front in much the same position as before. However, a better representation of the area of rain associated with the wave has been obtained even though this was also advected too far south over Northern France.

5. Anticyclonic Stratocumulus cases

5.1 - Data Time 12GMT 27/09/87

During the period of this forecast, a large anticyclone was centred over the U.K. giving predominantly cloudy conditions throughout. At the midday on 27th September, low cloud amounts were variable as can be seen from the visual satellite image in figure 22c. There was a good deal of cloud in the west but some good breaks in the east. Observed cloud bases were 3000-4000 feet beneath an inversion at 5000-6000 feet. During the afternoon and evening , a thin stratocumulus layer base 4000-5000 feet persisted (see Figure 24).

The operational fine-mesh model run started from a fairly dry analysis at low levels (see figure 22a) and so not surprisingly it predicted clear skies throughout the period. The operational fine-mesh low cloud forecast for the period 15-21 GMT is shown in figure 23a. In the model T+0 ascents over the U.K the inversion was not accurately represented and started at 3000 feet. This meant that any attempt to add cloud to the analysis at the observed levels would be difficult. As an experiment we decided to add cloud at a lower level to the analysis over the U.K, i.e. level 3, approximately 2000 feet, to see whether the model could retain it during the forecast. This was done by increasing the relative humidity to 100% at level 3 over the U.K. The modified model analysis at 950mb is shown in figure 22b. No attempt was made to represent the clearer areas in the east in this experiment.

The low cloud forecast run from the modified analysis for the first 9 hours is shown in figure 23b. Although some of the low cloud added to the model analysis has been retained at T+3, it has nearly all disappeared by T+6. In this case, low cloud was added to the model analysis overland in the U.K to try to improve the forecast. It was not successful and the added low cloud disappeared early in the forecast.

5.2 - Data Time 12GMT 05/04/88

On this occasion, an anticyclone was slow-moving over the North Sea and Northern England with a strong easterly airstream to the south. The visual satellite image (figure 25c) for midday 5th April shows a large area of stratocumulus covering the North Sea and Eastern England. Most of England and Wales, excluding the far west, had a cloudy night as stratocumulus continued to be advected inland from the North Sea and temperatures remained well above freezing.

The operational fine-mesh model low cloud forecast for that evening and night (T+6 to T+18) is shown in figure 26a. Apart from a small amount of low cloud in the southeast at 06GMT, the model predicted mainly clear skies overnight and the MOS minimum temperature forecast incorrectly suggested a slight frost for South-east England and the Midlands .

The base of the observed cloud at 12GMT was 1500-2000 feet with the tops 3000 feet. The model's inversion started at 950mb. The 12GMT analysed relative humidity at 950mb is shown in figure 25a. The analysis is much too dry in the observed cloudy areas when compared with the visual satellite picture. A cloud layer was inserted over the North Sea by increaing the relative humidity at level 3 to 100% and this modified analysis is shown in figure 25b.

The low cloud forecast run from the modified analysis for the first 18 hours (figure 26b) shows that this time the modification has improved the low cloud forecast especially over the North Sea and also over England and Wales at 06GMT. In this case, low cloud was added to the model analysis over the North Sea and overland in the U.K to try to improve the forecast. The low cloud added overland disappeared within the first 6 hours of the forecast but the low cloud added over the sea remained. This cloud was advected in the forecast across England and Wales resulting in a greatly improved forecast at T+18.

5.3 - Data Time 12GMT 17/02/88

On this occasion, an anticyclone was slow moving in the South-west approaches with a W-NW airstream across Ireland and the U.K., whilst a weak cold front was slow-moving over Western Scotland. At 12GMT 17th February, the visual satellite image (figure 27c) showed an extensive sheet of stratocumulus circulating around the anticyclone and into Western Ireland, with little or no cloud over Eastern England. The following night, this sheet of stratocumulus gradually spread southeastwards across England and Wales.

The operational fine-mesh low cloud forecasts for T+12 and T+24 are shown in figures 28a and c respectively. This forecast predicted little or no cloud associated with the anticyclone to the southwest, although it predicted some over Scotland associated with the slow-moving front. The observed stratocumulus had a base of 3000-4000 feet with tops 4000-5000 feet. The operational fine-mesh model's humidity analysis at 950mb at 12GMT, 17/02/88 is shown in figure 27a. The low cloud area associated with the anticyclone, shown in the visual satellite image, is not represented in the model's analysis either at 950mb or at 850mb. The model's analysed relative humidity in this area is mainly between 50 and 80%. Also there is an area of very low humidity (19-38%) in the analysis centred at 51°N, 19°W. The model inversion at T+0 over Western Ireland extended from 900mb to 800mb. Due to this it was considered better to add moisture to the analysis at levels 2 and 3, (corresponding to 1000-2000 feet) below the model's inversion rather than level 4 (corresponding to 4000 feet) in the model's inversion. For the modified analysis we saturated level's 2 and 3 in the area bounded by 51°-53°N and 7°-12°W. In the analysis for the centre of the anticyclone, the model had a very low inversion and we did not attempt to add cloud in this region. The modified 950mb relative humidity analysis is shown in figure 27b.

The T+12 and T+24 low cloud forecasts run from the modified analysis are shown in figure 28 b and d respectively There is a slight increase in the extent of low cloud over Central Northen England but in most respects the result is disappointing.

6. Conclusion

We have demonstrated that the relatively simply technique adopted here, involving the *painting over* of the model relative humidity field after the assimilation stage, can result in a significant impact on the forecast rainfall on most occasions and also a noticeable impact on model cloud on some occasions when a problem with the initial moisture field has been noted. No compensating change to other model variables was attempted or apparently required, although this might provide additional improvements if an appropriate method of achieving such changes could be devised. Where the addition of partial cloud cover was involved, we were careful to provide the model with a relative humidity value which could be interpreted as the same partial cloudiness in the model. We also avoided interpolation problems by inserting data at the model's σ-levels. in some instances we took careful note of the initial vertical profiles of moisture and temperature in order to insert information at a level where it would be most likely to be retained even if such a level was different to that inferred from the observations. This was particularly the case when thin layers of cloud were being inserted which needed to be correlated with changes in model lapse rate. The method adopted here gives much more control over the outcome than the conventional bogussing technique. The most difficult task is the interpretation of the satellite imagery in terms of model relative humidity fields. Ideally the imagery should be available reprojected onto the model grid before it can be fully useful. Clearly the technique could not be adopted for the main fine-mesh runs as there is not time to amend the fields, however corrections to the assimilation cycle at an earlier stage are likely to remain useful in the following forecast run.

Reviewing the conclusions made in the previous four sections we note that the impact on the convective case (2.1) was very modest. Clearly the deficiencies in the convective parameterisation scheme are dominant. The frontal cases demonstrate that the impact is greater in the first day and less towards the end of the forecast where presumably evolution errors begin to dominate. Cases 3.1 and 3.3 both had noticeable improvements at T+18 which were not evident at T+30. Case 3.2 demonstrates that very substantial changes in the rainfall field can be made , but no amount of tinkering with the initial moisture field can correct a positional error. The wave development cases show both that erroneous waves can be suppressed (see 4.1 and to a lesser extent 4.2) and also that waves which are too weak can be emphasised (see 4.4 and to a lesser extent 4.3) . Case 4.4 demonstrates the futility of trying to adjust the timing of a fast moving frontal system . The impact of the anticyclonic cases is less predictable. The main signal appears to be that some impact is obtained as long as the model's inversion is not too low (preferably at level 3) and the additional moisture is inserted over sea points (eg as in case 5.2) . Inserting cloud over land or where the model inversion is very low does not appear to be very productive. It would appear that further improvements to the boundary layer parameterisation are required before observations of cloud can be retained in such cases.

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Figures

<u>case 4.1</u>	DT 12GMT 19 Aug 1987	*fig 12* Comparison 700mb model RH analyses
		fig 13 Comparison forecast T+18 rainrates and T+30 with verif
<u>case 4.2</u>	DT 00GMT 5 Jan 1988	*fig 14* Comparison 850mb model RH analyses
		fig 15 Comparison T+18 rainrates with verif
<u>case 4.3</u>	DT 12GMT 13 Jan 1988	*fig 16* CFO cloud analysis
		fig 17 Comparison 700mb and 850mb model RH analyses
		fig 18 Comparison T+6 and T+12 rainrates
<u>case 4.4</u>	DT 12GMT 7 Feb 1988	*fig 19* CFO cloud analysis
		fig 20 Comparison 700mb model RH analyses
		fig 21 Comparison T+6 and T+12 rainrates
<u>case 5.1</u>	DT 12GMT 27 Sep 1987	*fig 22* Comparison 950mb model RH analyses with satellite verif
		fig 23 Comparison T+3→T+9 cloud forecasts
		fig 24 Verifying satellite imagery
<u>case 5.2</u>	DT 12GMT 17 Feb 1987	*fig 25* Comparison 950mb model RH analyses with satellite verif
		fig 26 Comparison T+6→T+18 cloud forecasts
<u>case 5.3</u>	DT 12GMT 5 Apr 1987	*fig 27* Comparison 950mb model RH analyses with satellite verif
		fig 28 Comparison T+12→T+24 cloud forecasts

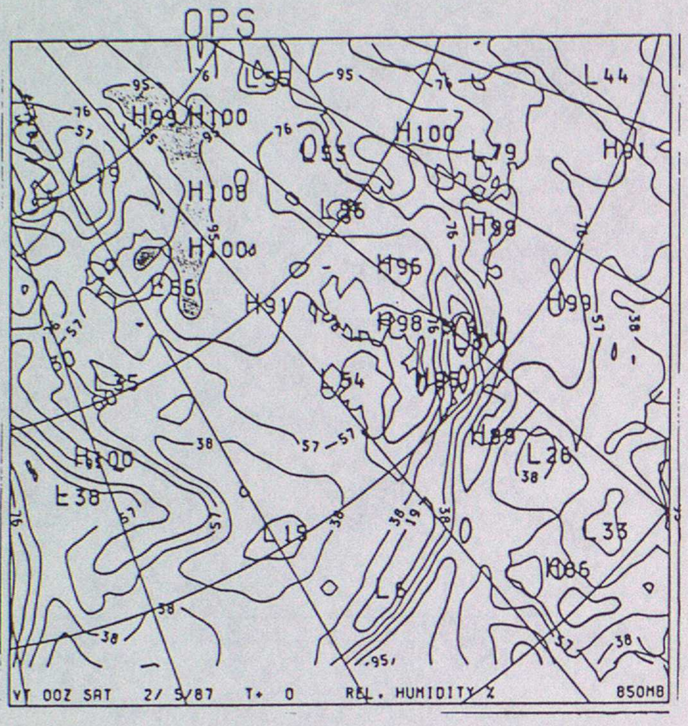


FIGURE 1a
OPERATIONAL FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 850MB FOR DT 00GMT 02/05/87

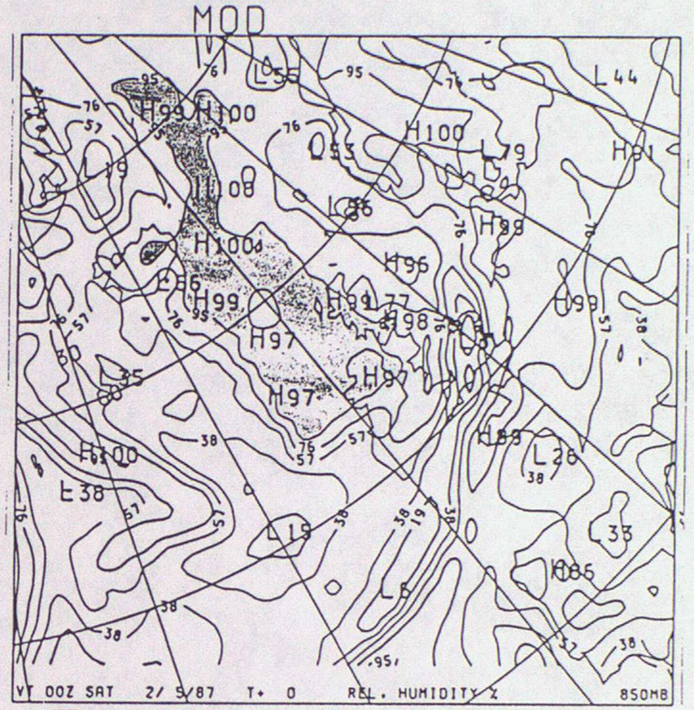


FIGURE 1b
FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 850MB FOR DT 00GMT 02/05/87 AFTER MODIFICATION. RELATIVE HUMIDITY INCREASED TO > 97% IN AREA BOUNDED BY 54-56 DEGREES NORTH, 6-12 DEGREES WEST

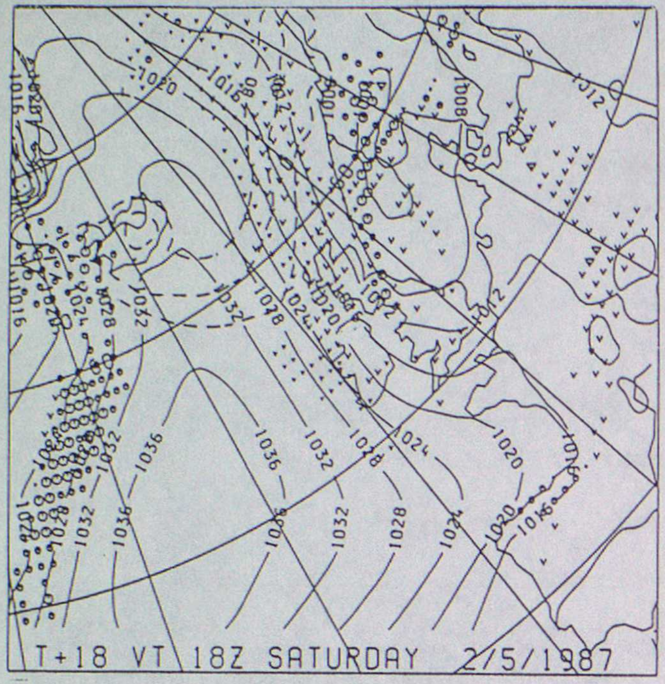


FIGURE 2a
OPERATIONAL FINE-MESH MODEL (DT 00GMT 02/05/87)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
18GMT 02/05/87

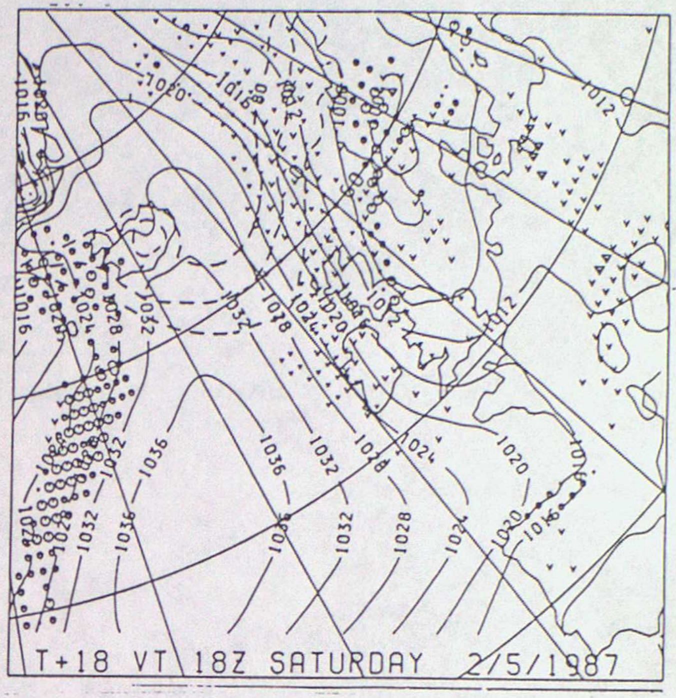


FIGURE 2b
MODIFIED FINE-MESH MODEL (DT 00GMT 02/05/87)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
18GMT 02/05/87

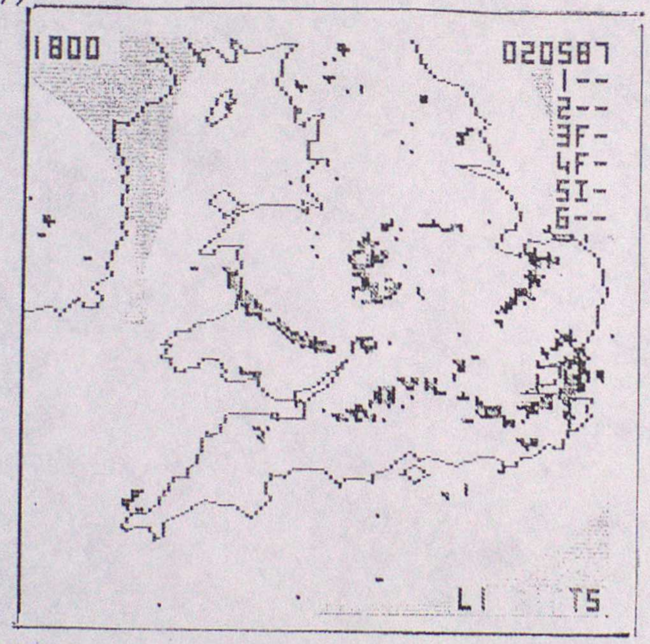


FIGURE 2c
RADAR PICTURE FOR 18GMT 02/05/87, SHOWING
[illegible] D[illegible]IBU[illegible] OF [illegible]OWE[illegible] T 1[illegible] 02[illegible]87

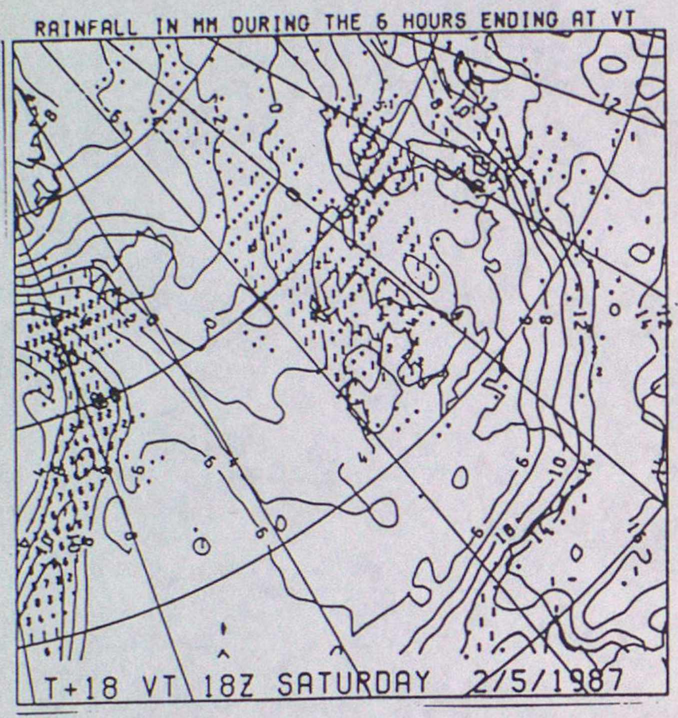


FIGURE 3a
OPERATIONAL FINE-MESH (DT 00GMT 02/05/87)
FORECAST TOTAL RAINFALL ACCUMULATION FOR
THE PERIOD 12-18 GMT 02/05/87

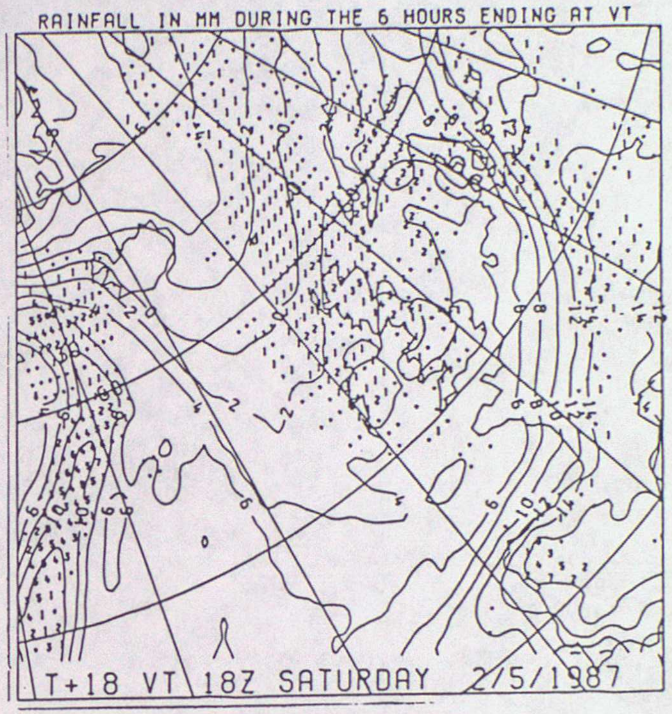


FIGURE 3b
MODIFIED FINE-MESH (DT 00GMT 02/05/87)
FORECAST TOTAL RAINFALL ACCUMULATION FOR
THE PERIOD 12-18 GMT 02/05/87

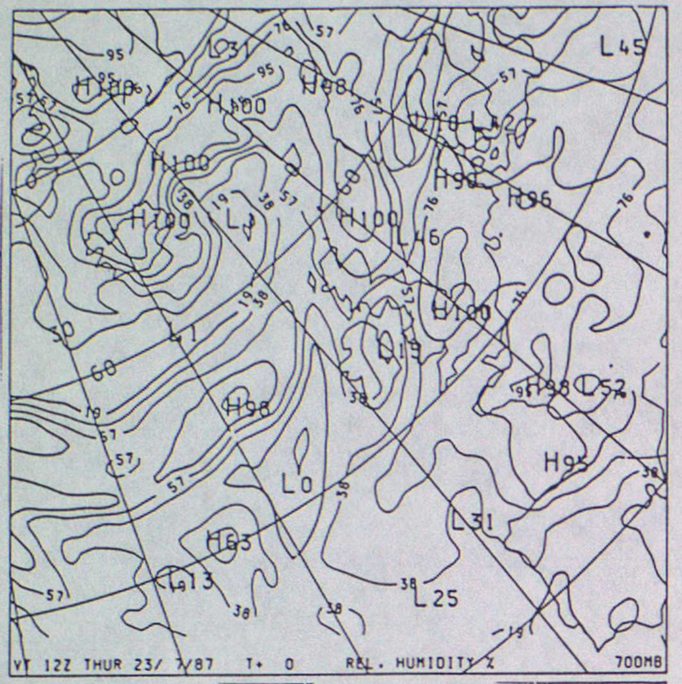


FIGURE 4a
OPERATIONAL FINE-MESH MODEL
RELATIVE HUMIDITY ANALYSIS
AT 700MB FOR DT 12GMT 23/07/87

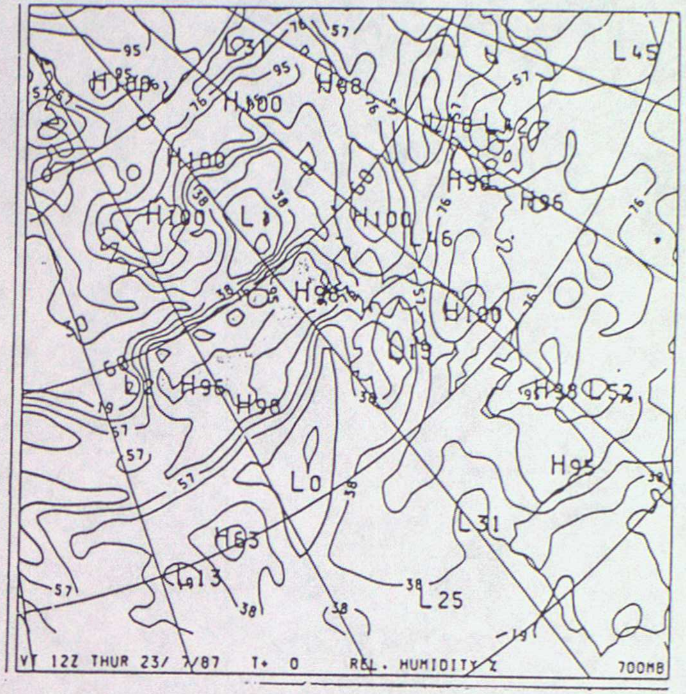


FIGURE 4b
FINE-MESH MODEL RELATIVE
HUMIDITY ANALYSIS AT 700MB
FOR DT 12GMT 23/07/87 AFTER
MODIFICATION.

FIGURE 4c
VISUAL SATELLITE IMAGE FOR
1030 GMT 23/07/87 SHOWING
THE EXTENT OF CLOUD TO THE
WEST AND NORTH OF SCOTLAND

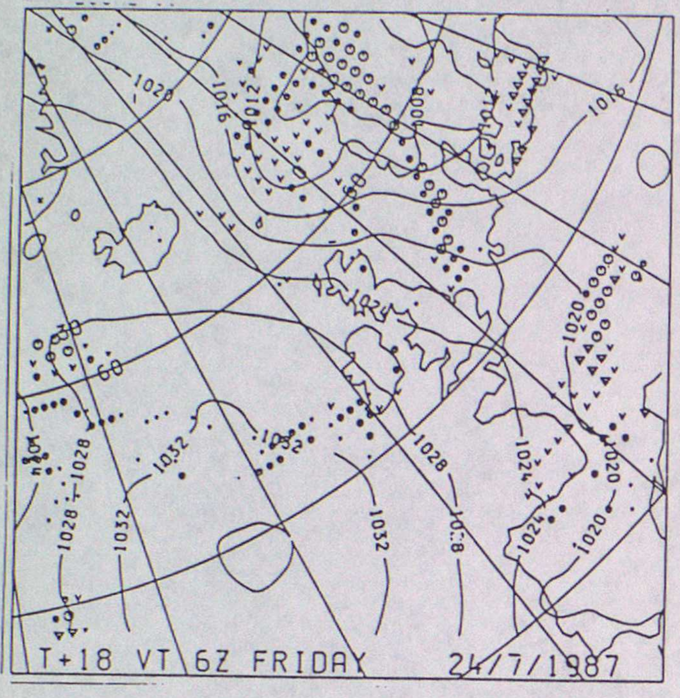


FIGURE 5a
OPERATIONAL FINE-MESH MODEL (DT 12GMT 23/07/87)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
06GMT 24/07/87

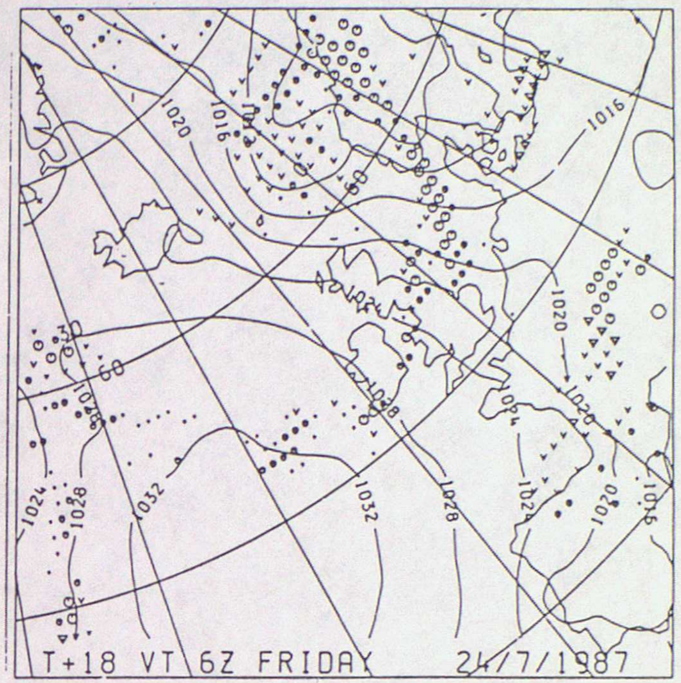


FIGURE 5b
MODIFIED FINE-MESH MODEL (DT 12GMT 23/07/87)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
06GMT 24/07/87

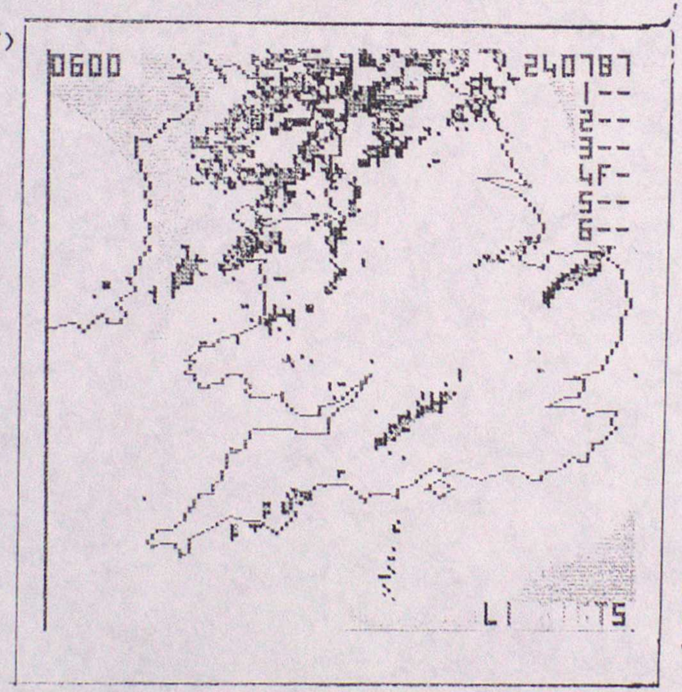


FIGURE 5c
RADAR PICTURE FOR 06GMT 24/07/87. SHOWING
THE RAINFALL DISTRIBUTION AT) 06GMT 24/07/87

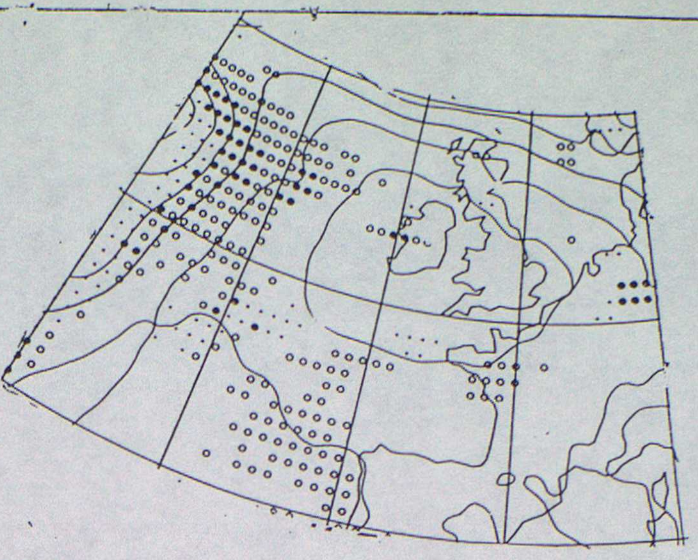


FIGURE 6a
OPERATIONAL FINE-MESH MODEL (DT 12GMT 18/09/87)
LOW AND MEDIUM CLOUD ANALYSIS FOR 12 GMT 18/09/87

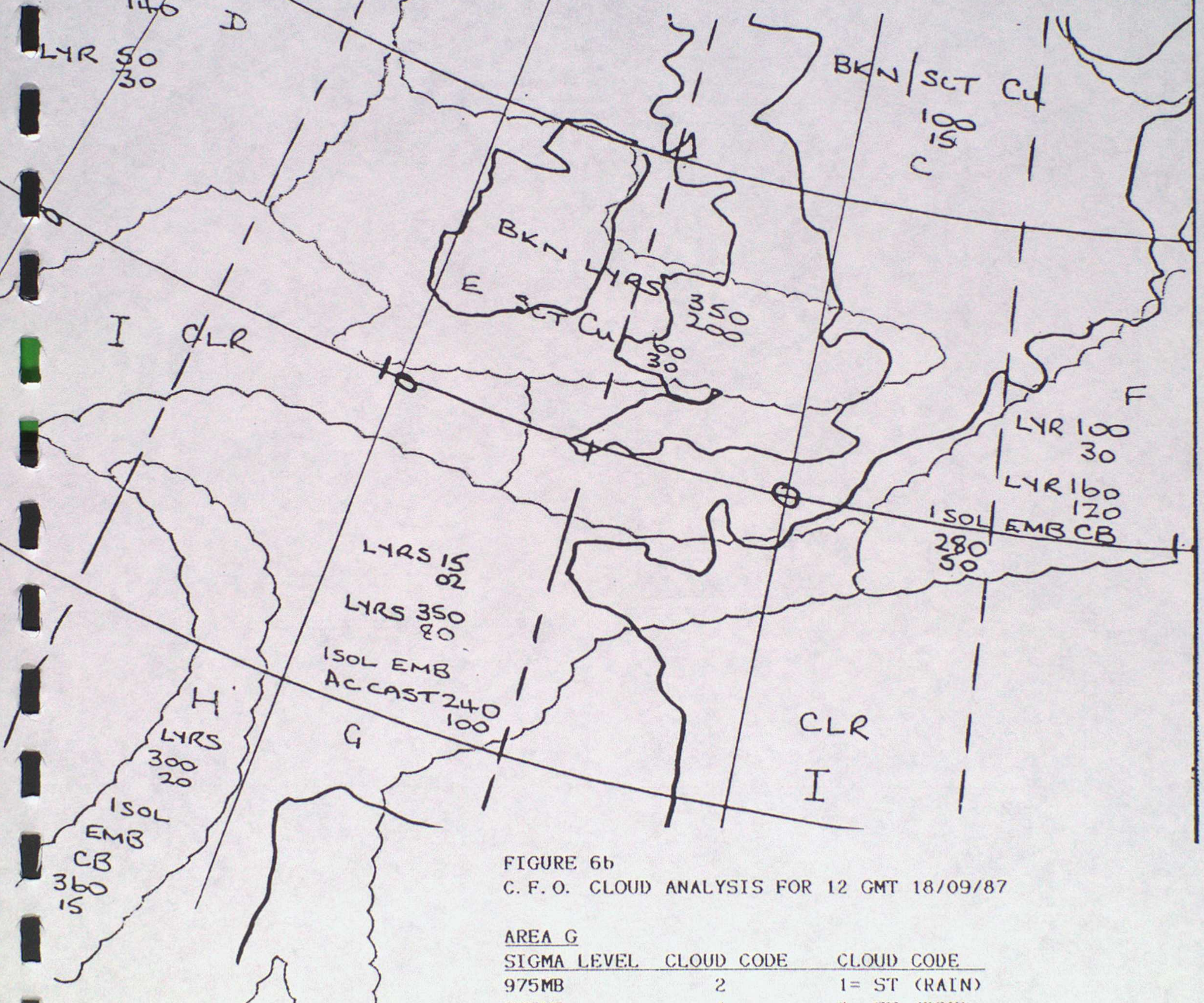


FIGURE 6b
C. F. O. CLOUD ANALYSIS FOR 12 GMT 18/09/87

AREA G

SIGMA LEVEL	CLOUD CODE	CLOUD CODE
975MB	2	1= ST (RAIN)
935MB	4	2= ST (DRY)
870MB	4	3= CONVECTIVE
790MB	4	4= CLEAR
690MB	1	
590MB	1	
490MB	1	
390MB	1	

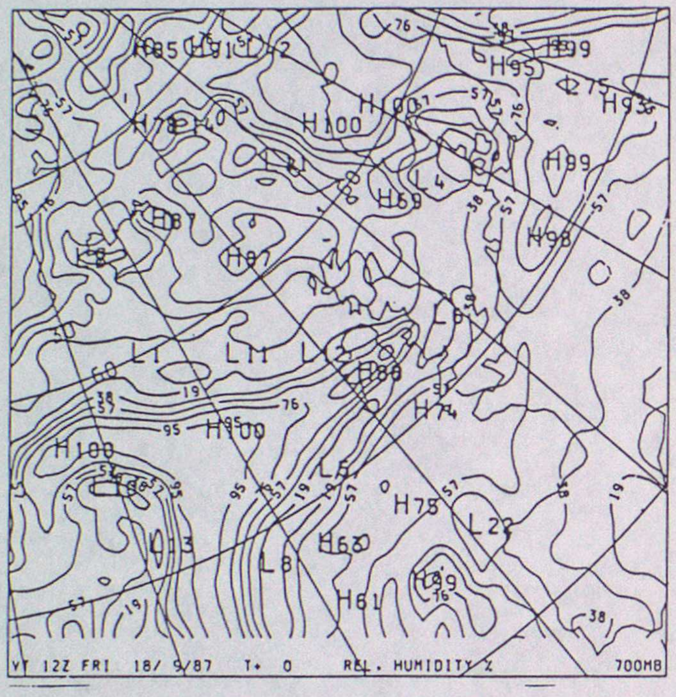


FIGURE 7a
OPERATIONAL FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 700MB FOR DT 12GMT 18/09/87

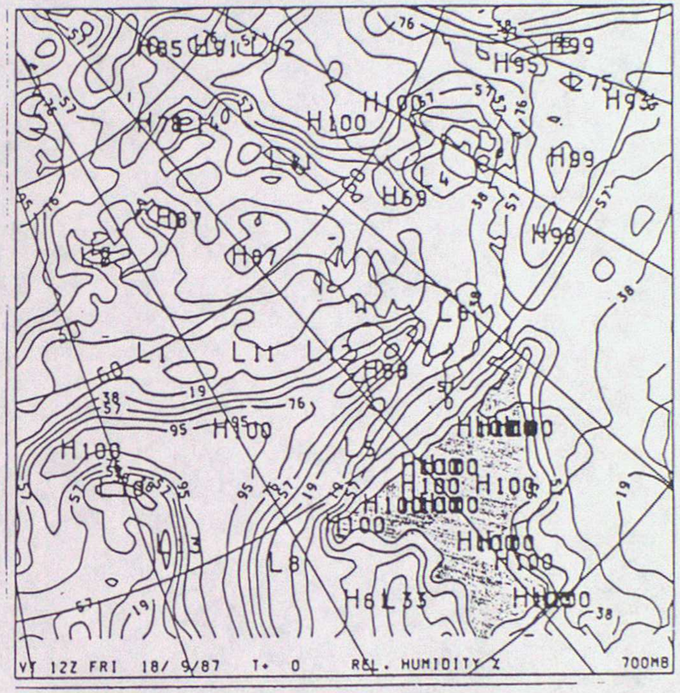


FIGURE 7b
FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 700MB FOR DT 12GMT 18/09/87 AFTER MODIFICATION.

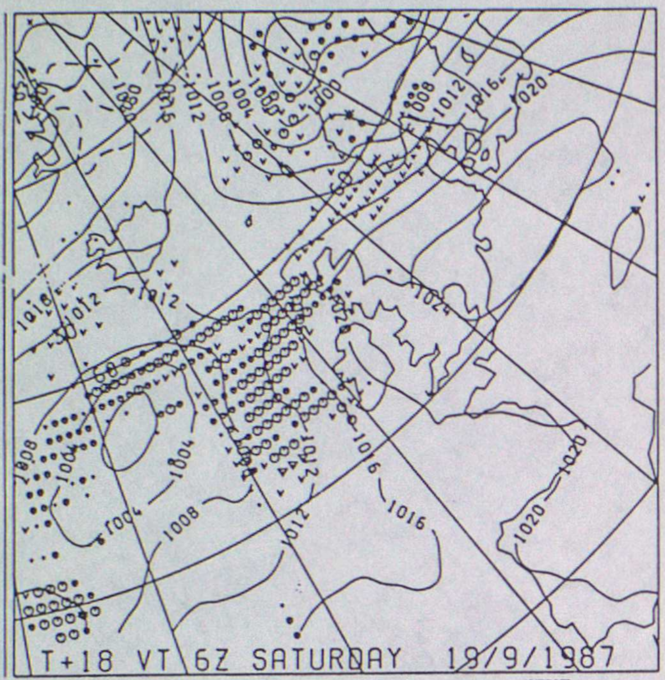


FIGURE 8a
OPERATIONAL FINE-MESH MODEL (DT 12GMT 18/09/87)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
06GMT 19/09/87

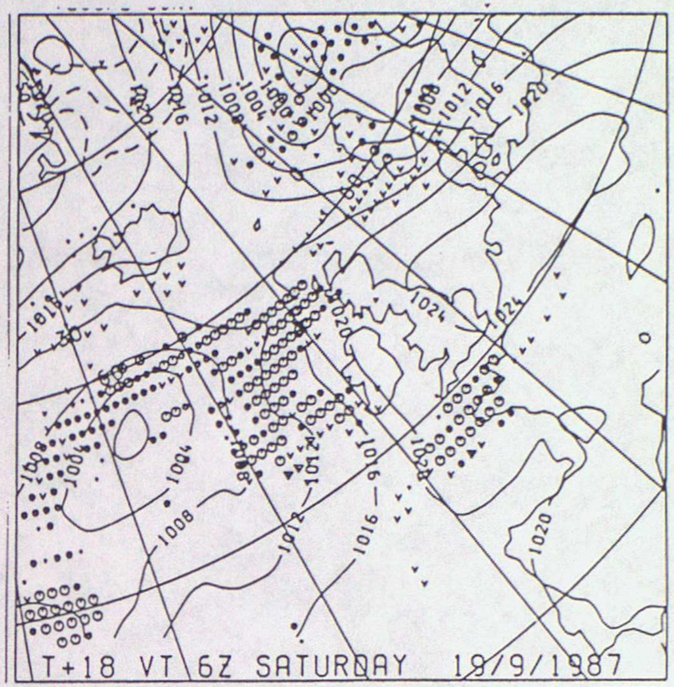


FIGURE 8b
MODIFIED FINE-MESH MODEL (DT 12GMT 18/09/87)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
06GMT 19/09/87

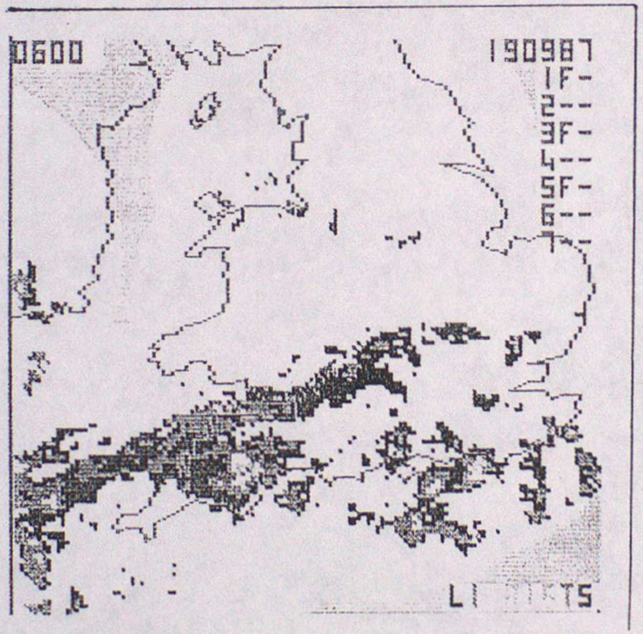


FIGURE 8c
RADAR PICTURE FOR 06GMT 19/09/87. SHOWING
THE RAINFALL DISTRIBUTION AT 06GMT 19/09/87

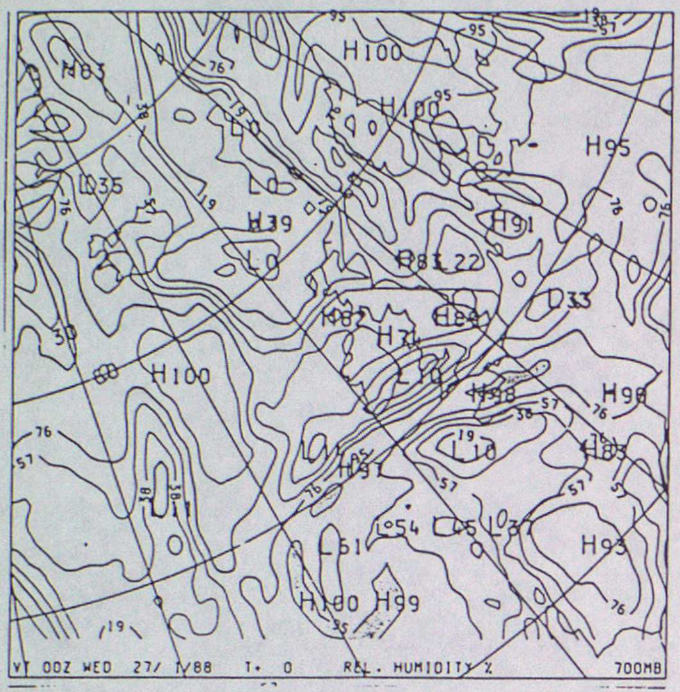


FIGURE 9a
OPERATIONAL FINE-MESH MODEL
RELATIVE HUMIDITY ANALYSIS AT
700MB FOR DT 00GMT 27/01/88

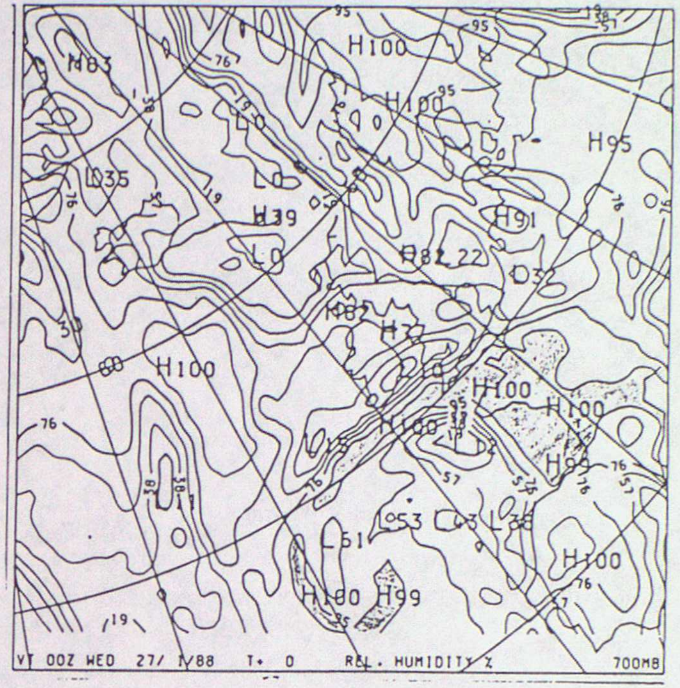


FIGURE 9b
FINE-MESH MODEL RELATIVE HUMIDITY
ANALYSIS AT 700MB FOR DT 00GMT
27/01/88 AFTER MODIFICATION.

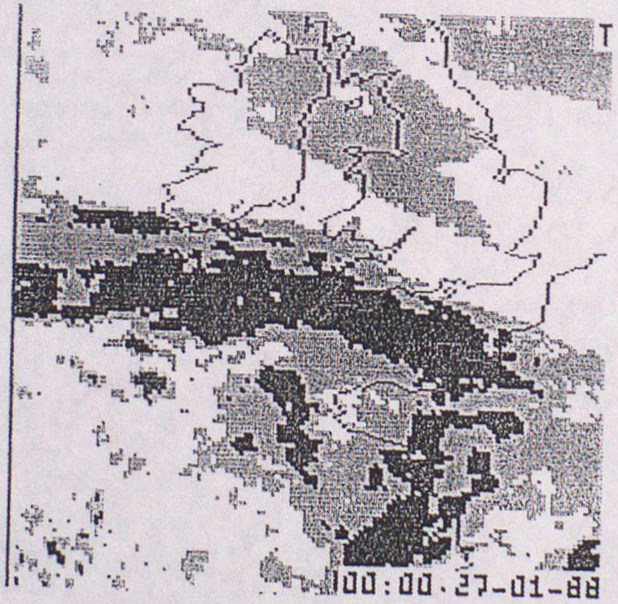


FIGURE 9c
INFRA-RED SATELLITE IMAGE
FOR 00 GMT 27/01/88 SHOWING THE
EXTENT OF CLOUD IN THE SOUTHWEST

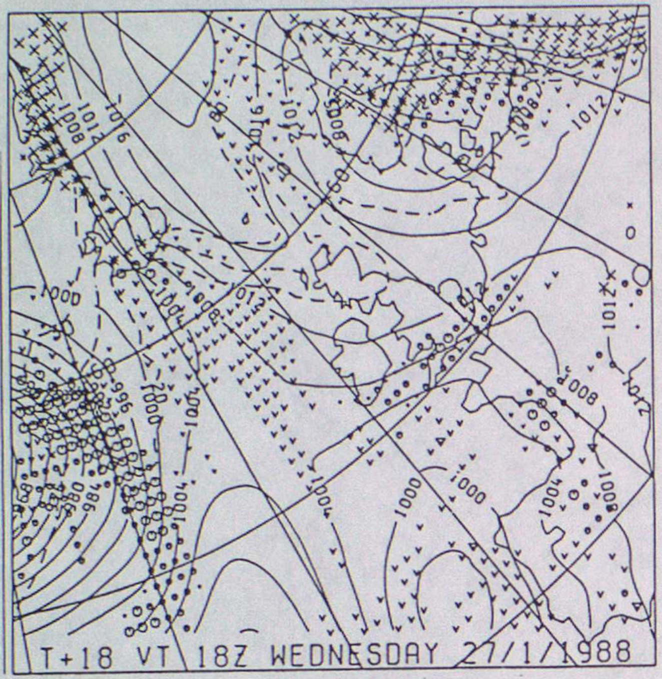


FIGURE 10a
OPERATIONAL FINE-MESH MODEL (DT 00GMT 27/01/88)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
18GMT 27/01/88

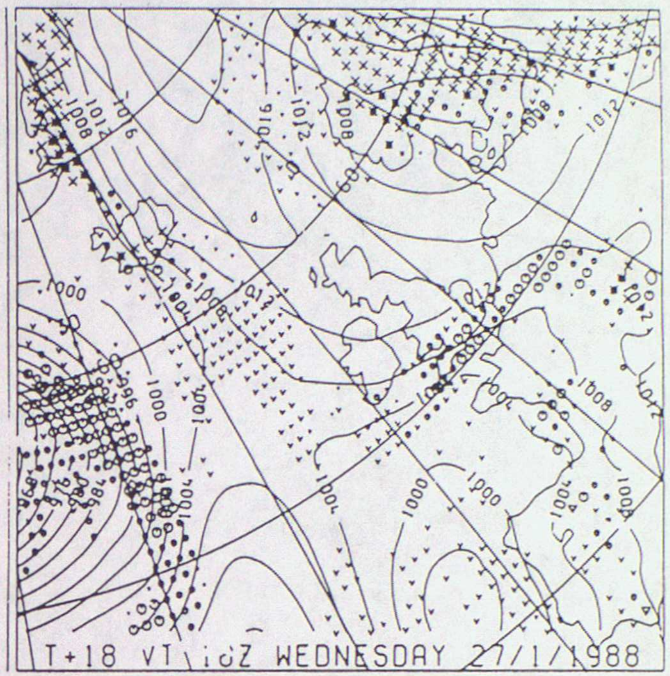


FIGURE 10b
MODIFIED FINE-MESH MODEL (DT 00GMT 27/01/88)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+18, VERIFICATION TIME
18GMT 27/01/88

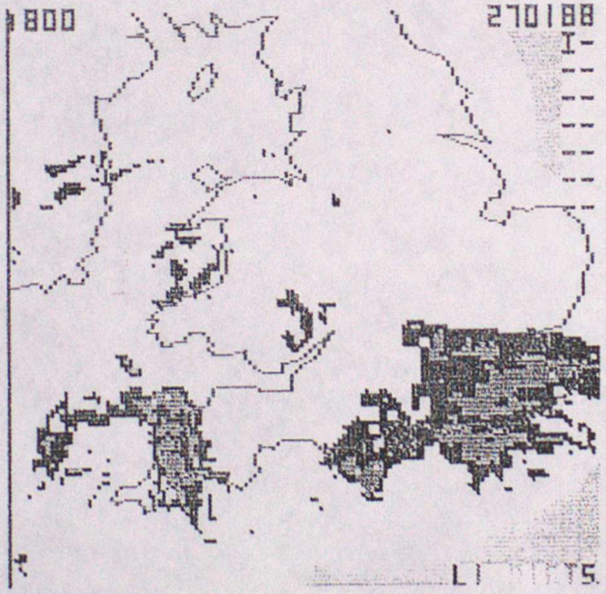


FIGURE 10c
RADAR PICTURE FOR 18GMT 27/01/88. SHOWING
THE RAINFALL DISTRIBUTION AT 18GMT 27/01/88

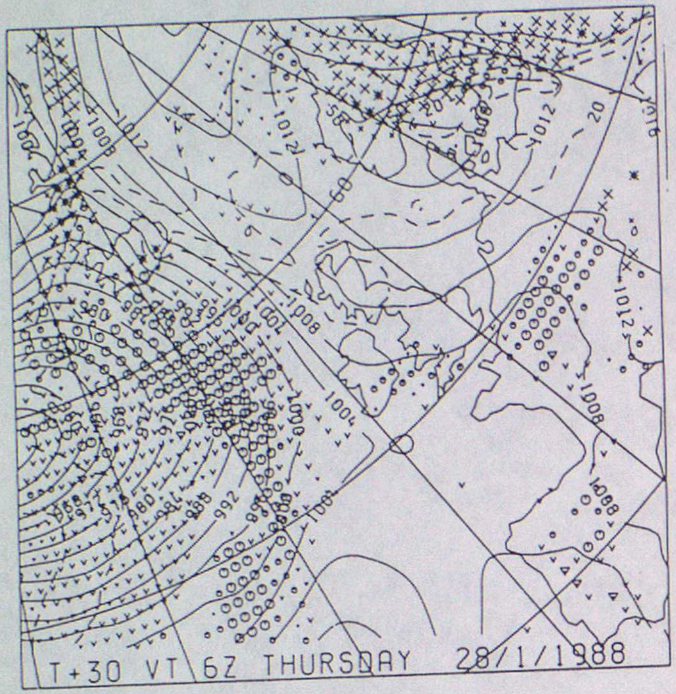


FIGURE 11a
OPERATIONAL FINE-MESH MODEL (DT 00GMT 27/01/88)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+30, VERIFICATION TIME
06GMT 28/01/88

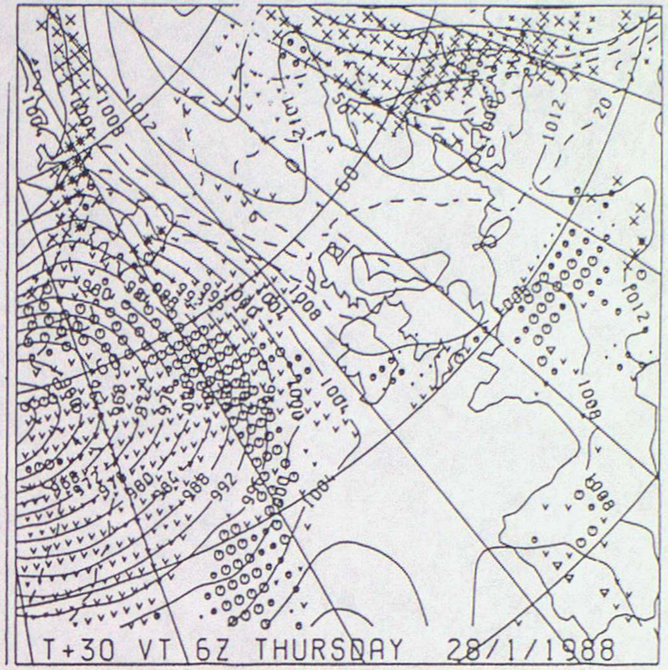


FIGURE 11b
MODIFIED FINE-MESH MODEL (DT 00GMT 27/01/88)
FORECAST OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+30, VERIFICATION TIME
06GMT 28/01/88

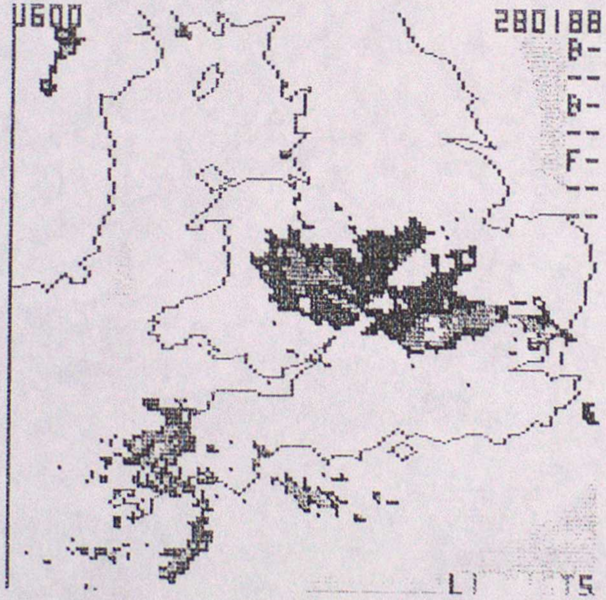


FIGURE 11c
RADAR PICTURE FOR 06GMT 28/01/88. SHOWING
THE RAINFALL DISTRIBUTION

FIGURE 12a
OPERATIONAL FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 700MB FOR DT 12GMT 19/08/87

FIGURE 12b
FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 700MB FOR DT 12GMT 19/08/87 AFTER MODIFICATION.

T+12------OPERATIONAL FINE-MESH FORECAST------T+18

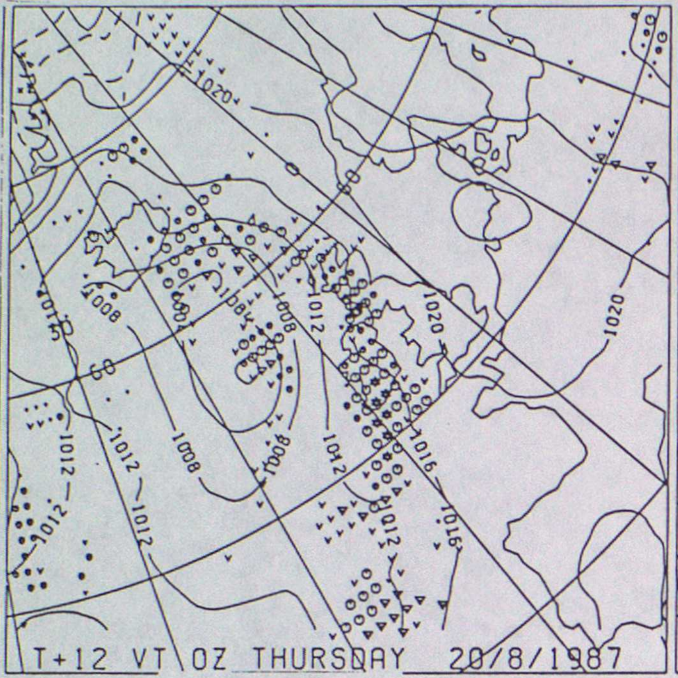


FIGURE 13a

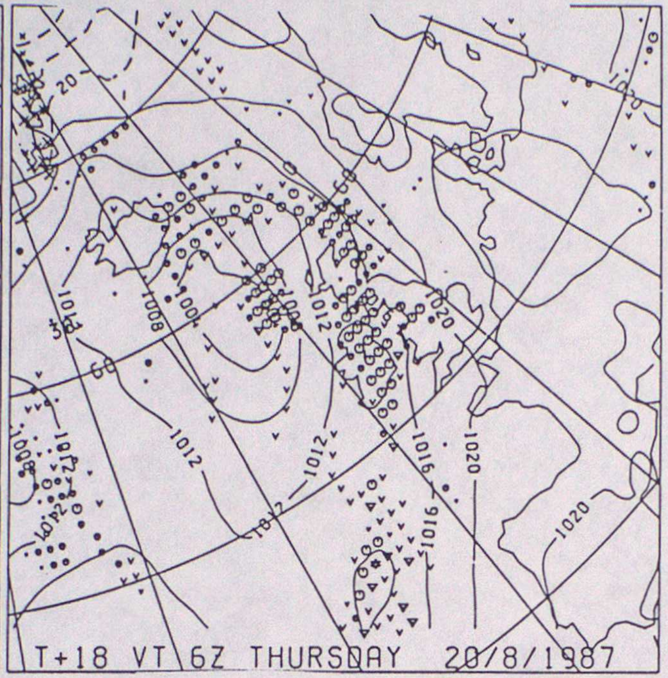


FIGURE 13b

SIGNIFICANT WEATHER 0Z 20/8/87

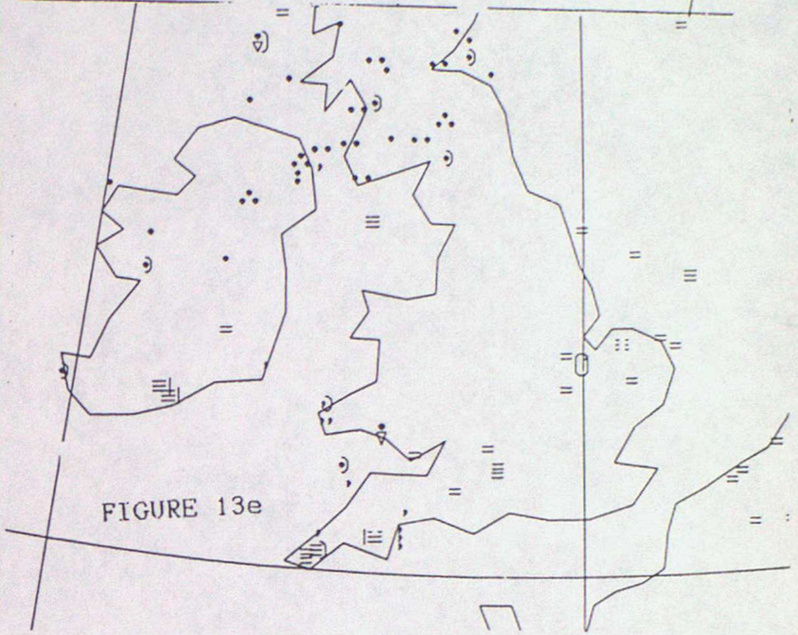
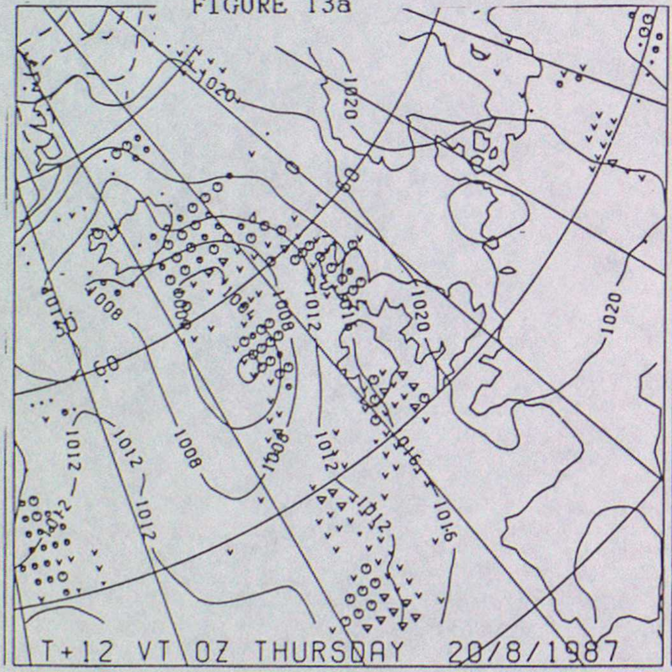
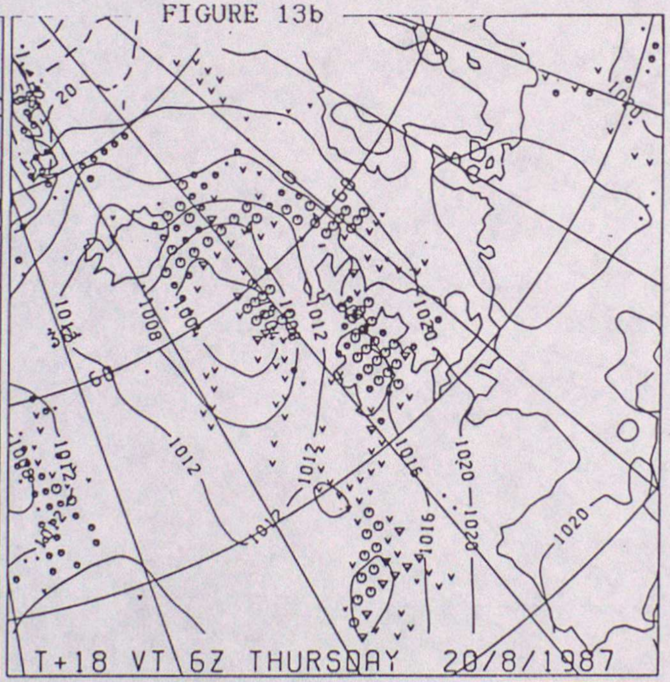


FIGURE 13e





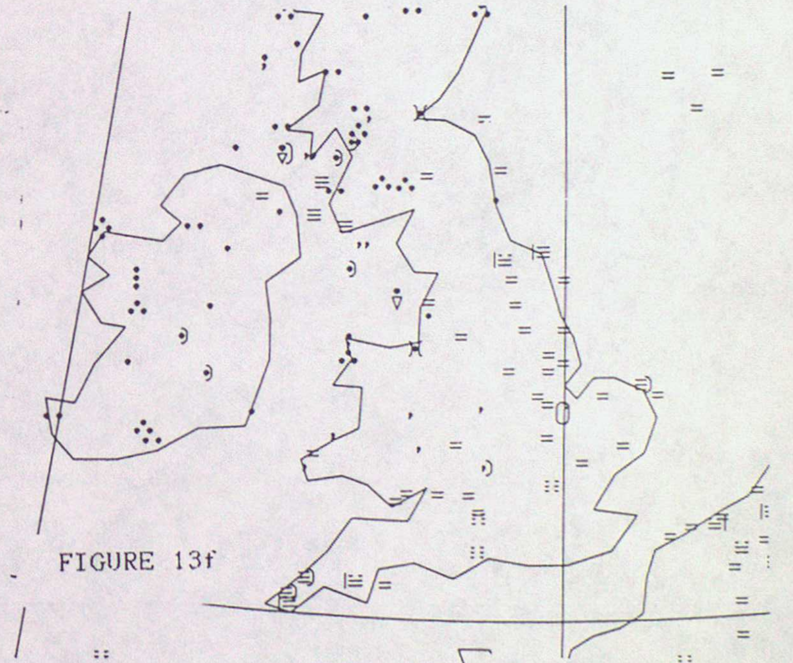


FIGURE 13f

SIGNIFICANT WEATHER 6Z 20/8/87

FIGURE 13c T+12------MODIFIED FINE-MESH FORECAST------T+18 FIGURE 13d

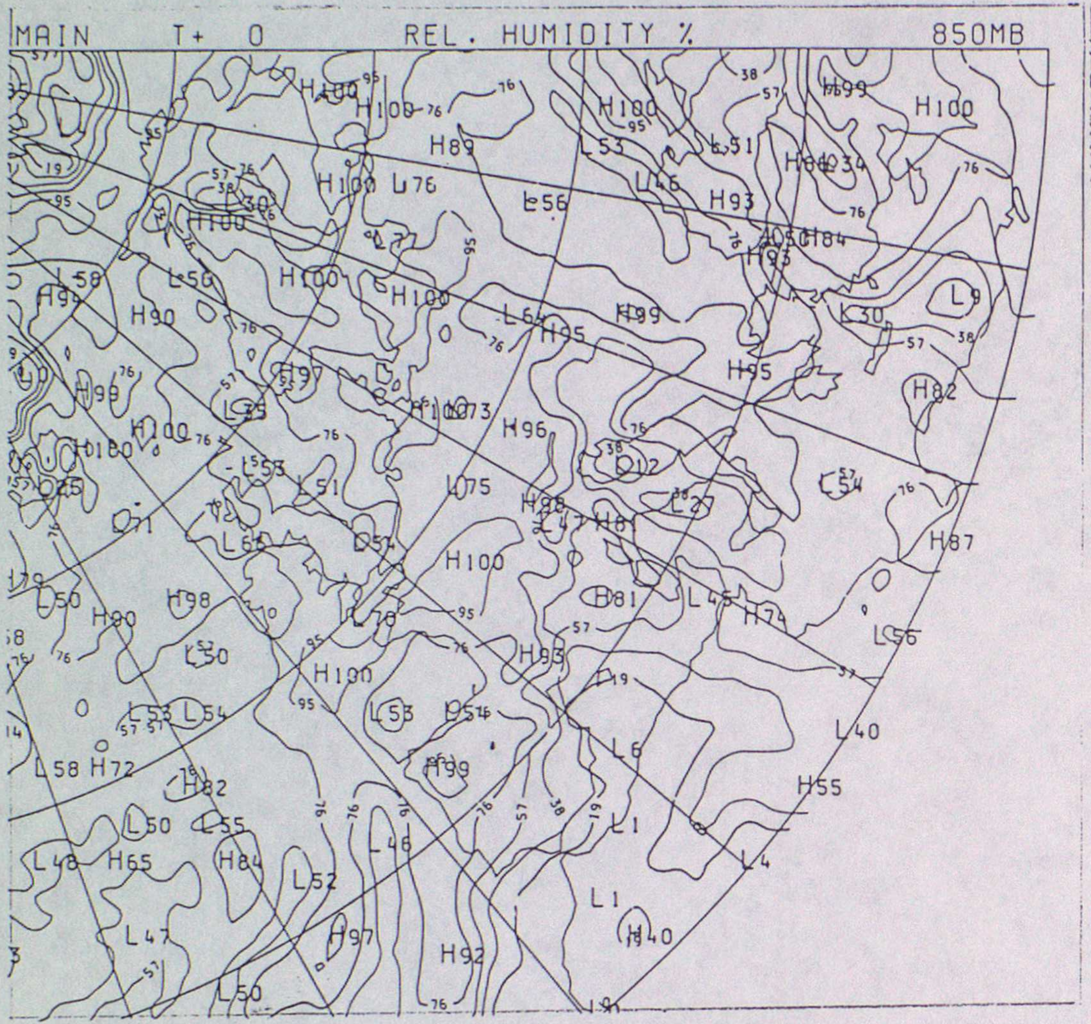


FIGURE 14a
OPERATIONAL FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 850MB FOR DT 00GMT 05/01/88 SHOWING MOIST AREA AT 38-40 DEGREES NORTH, 15-25 DEGREES WEST

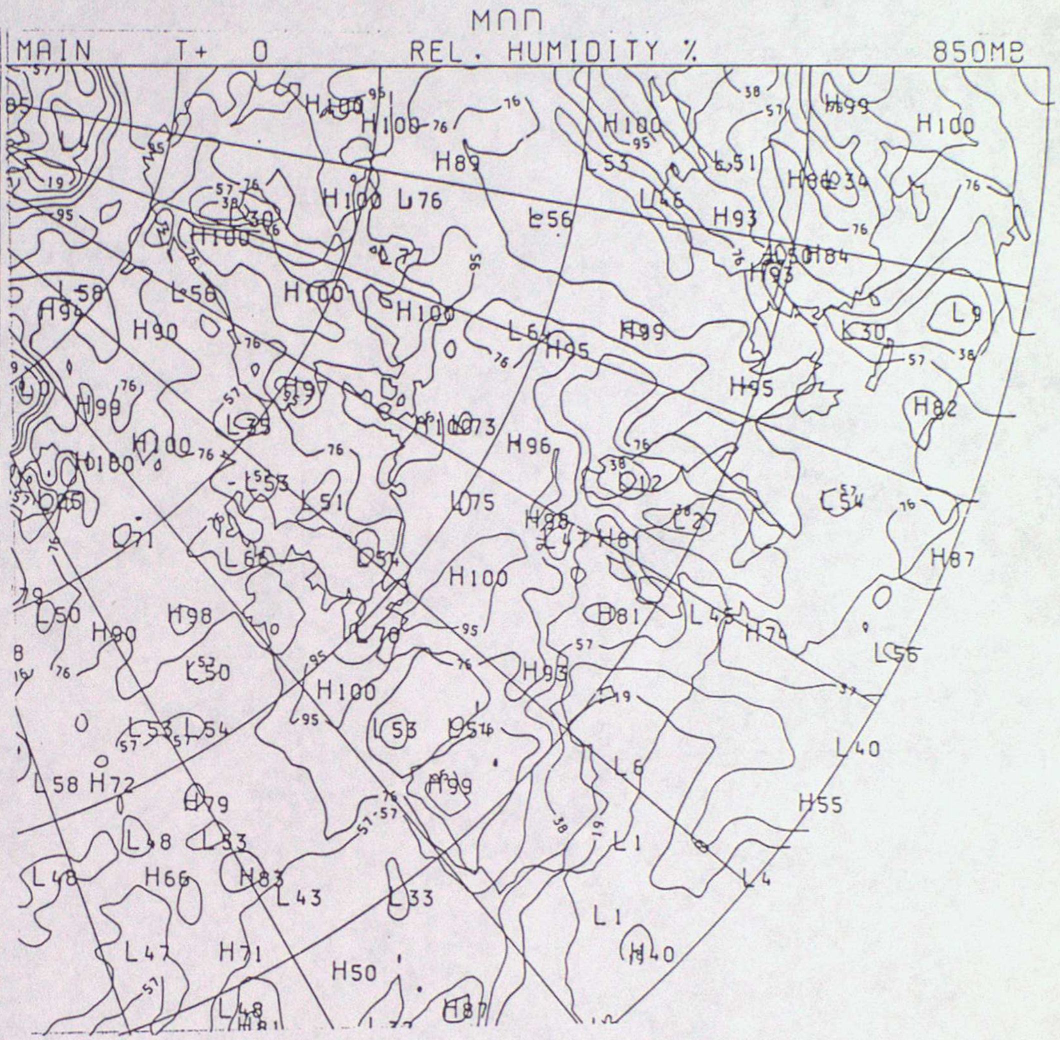


FIGURE 14b
FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 850MB FOR DT 00GMT 05/01/88 AFTER MODIFICATION.

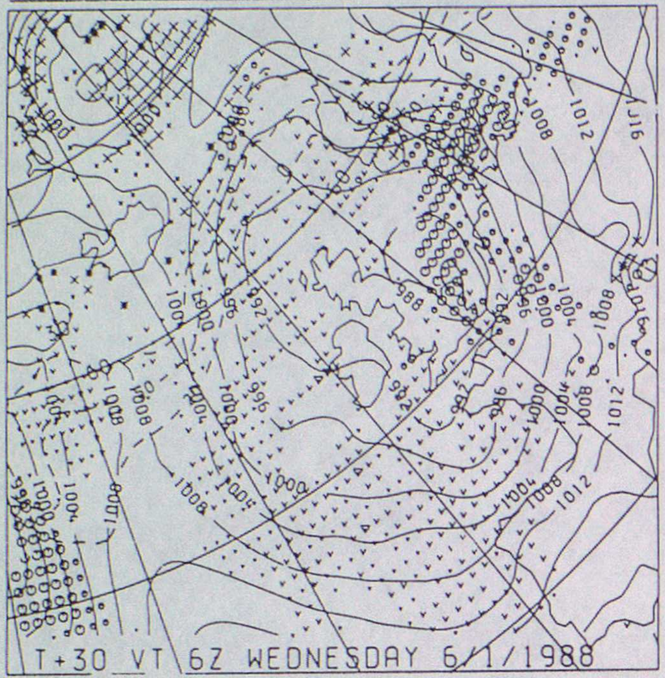


FIGURE 15a
OPERATIONAL FINE-MESH MODEL
(DT 00GMT 05/01/88) FORECAST
OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+30,
VERIFICATION TIME 06GMT 06/01/88

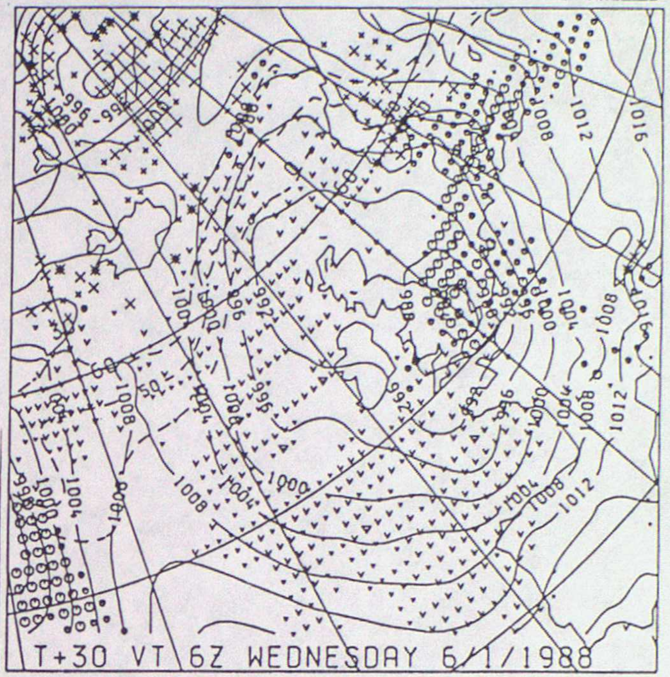


FIGURE 15b
MODIFIED FINE-MESH MODEL
(DT 00GMT 06/01/88) FORECAST
OF MEAN SEA LEVEL PRESSURE AND
RAINFALL RATE FOR T+30,
VERIFICATION TIME 06GMT 06/01/88

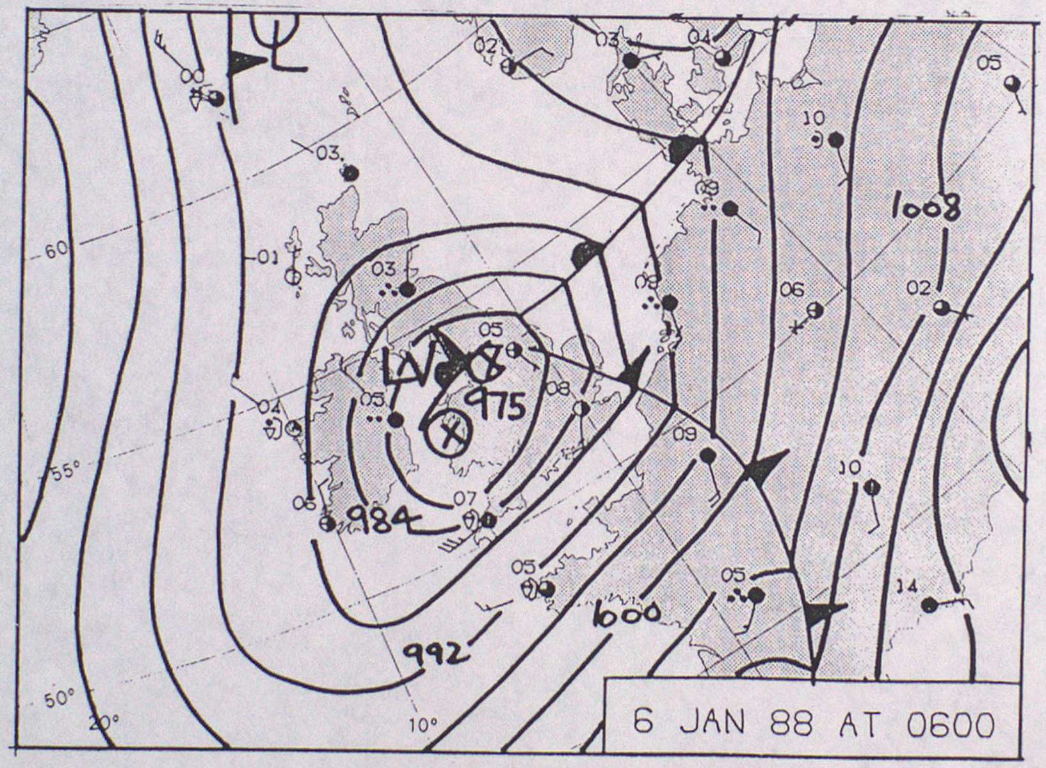


FIGURE 15c
ANALYSIS FOR 06 GMT 06/01/88

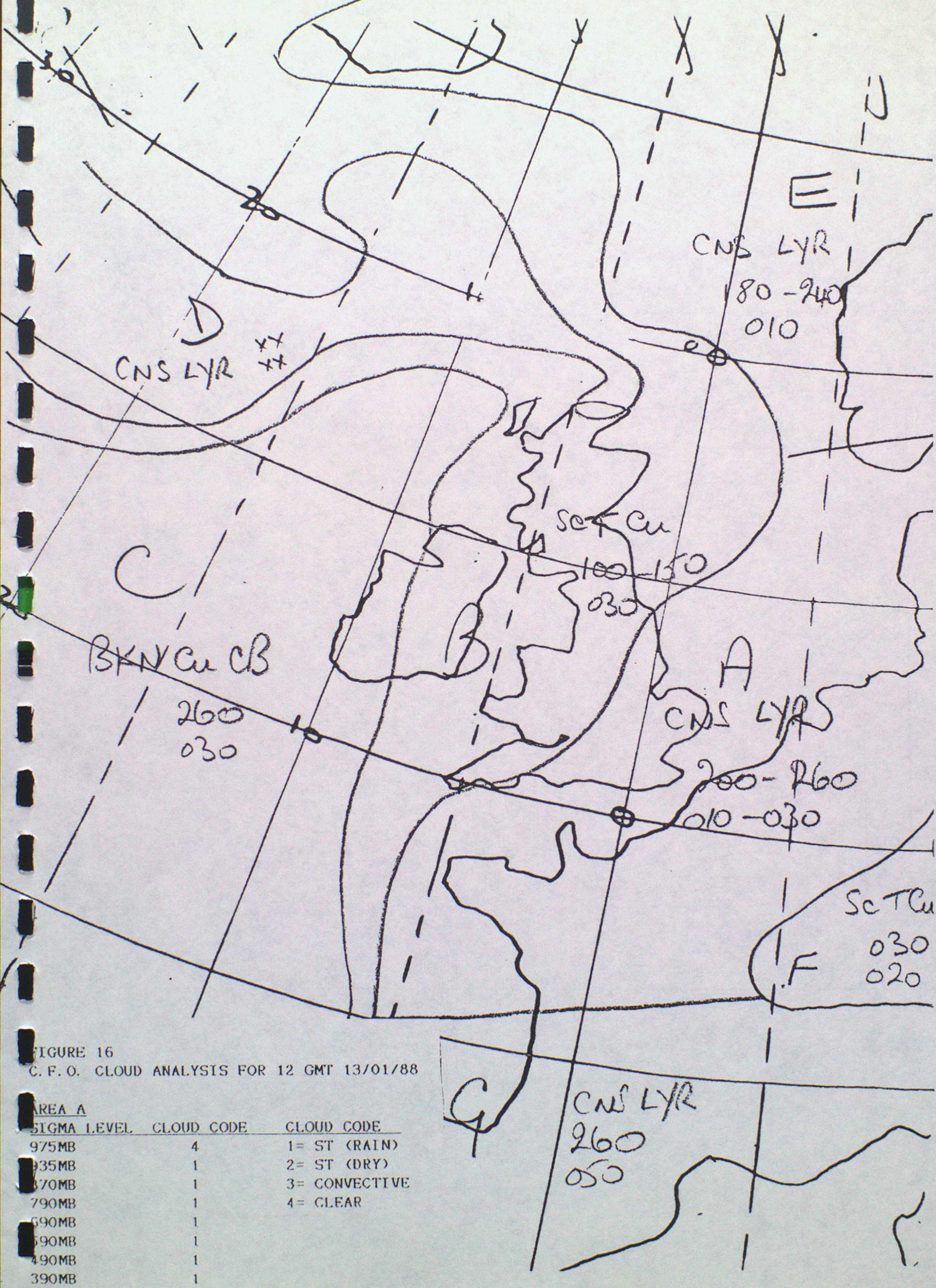


FIGURE 16
C.F.O. CLOUD ANALYSIS FOR 12 GMT 13/01/88

AREA A

SIGMA LEVEL	CLOUD CODE	CLOUD CODE
975MB	4	1= ST (RAIN)
935MB	1	2= ST (DRY)
870MB	1	3= CONVECTIVE
790MB	1	4= CLEAR
690MB	1	
590MB	1	
490MB	1	
390MB	1	

OPERATIONAL FINE-MESH
MODEL RELATIVE HUMIDITY
ANALYSIS

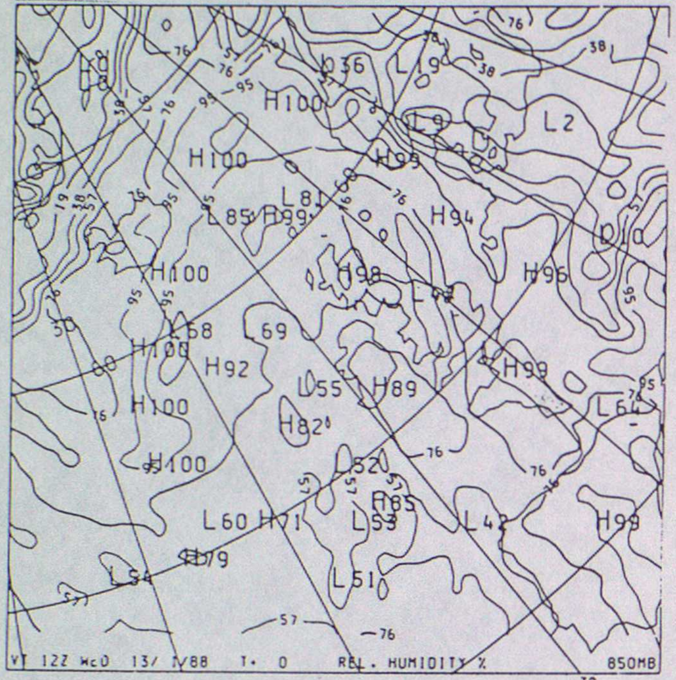


FIGURE 17a 850MB

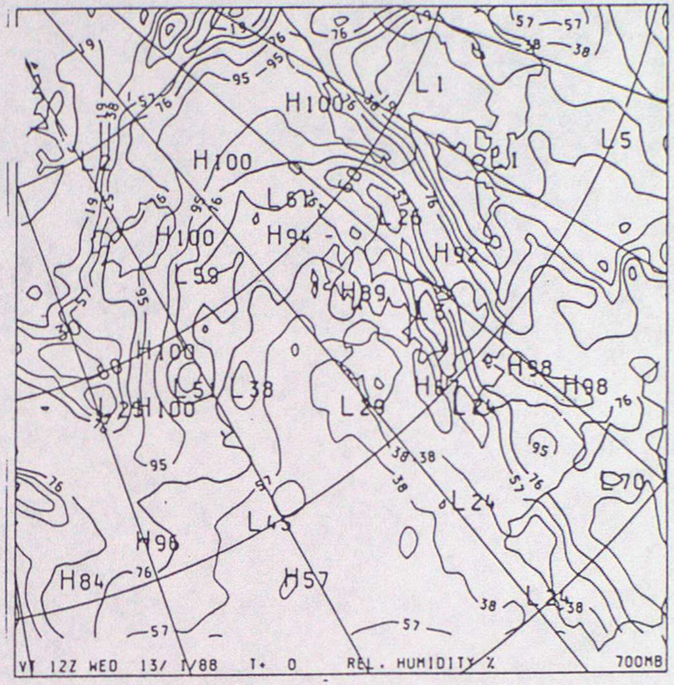


FIGURE 17b 700MB

MODIFIED FINE-MESH
MODEL RELATIVE HUMIDITY
ANALYSIS

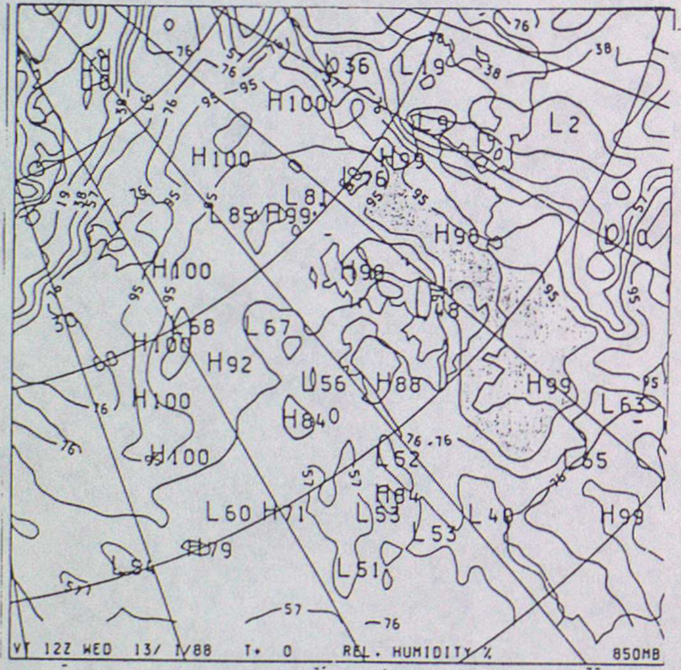


FIGURE 17c 850MB

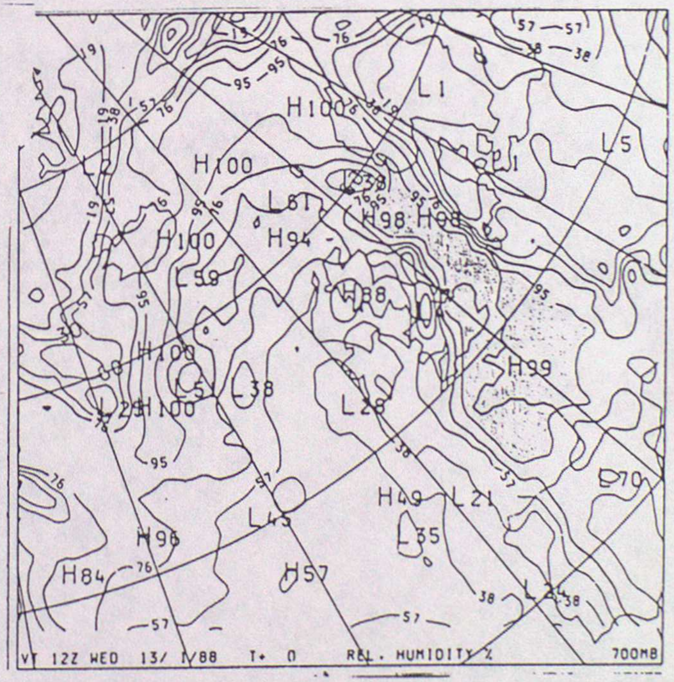


FIGURE 17d 700MB

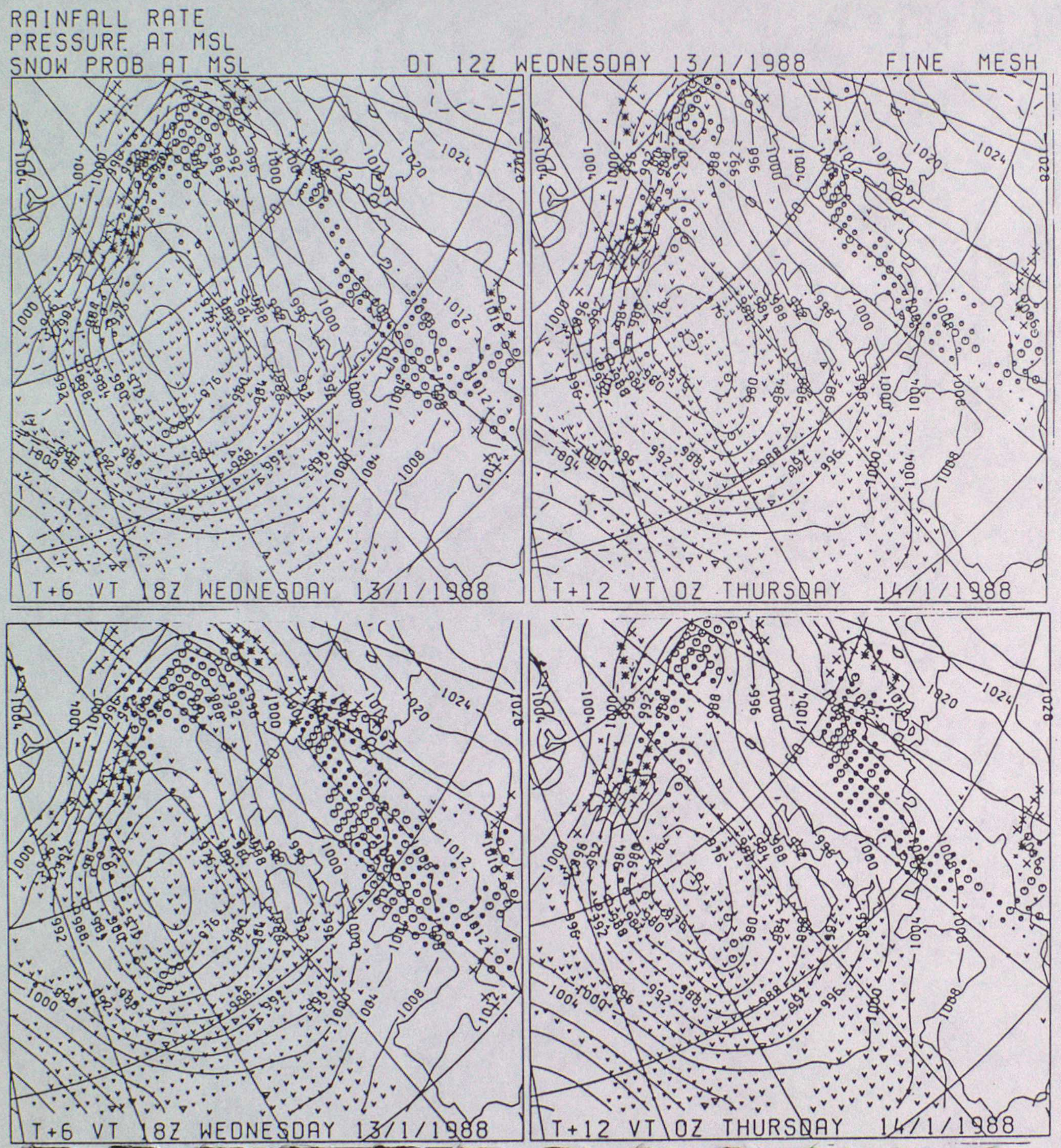


FIGURE 18 a and b
OPERATIONAL FINE-MESH MODEL (DT 12GMT 13/01/88)
FORECAST OF MEAN SEA LEVEL PRESSURE AND RAINFALL
RATE FOR T+06, VERIFICATION TIME 18GMT 13/01/88
and T+12, VERIFICATION TIME 00GMT 14/01/88

FIGURE 18 c and d
MODIFIED FINE-MESH MODEL (DT 12GMT 13/01/88)
FORECAST OF MEAN SEA LEVEL PRESSURE AND RAINFALL
RATE FOR T+06, VERIFICATION TIME 18GMT 13/01/88
and T+12, VERIFICATION TIME 00GMT 14/01/88

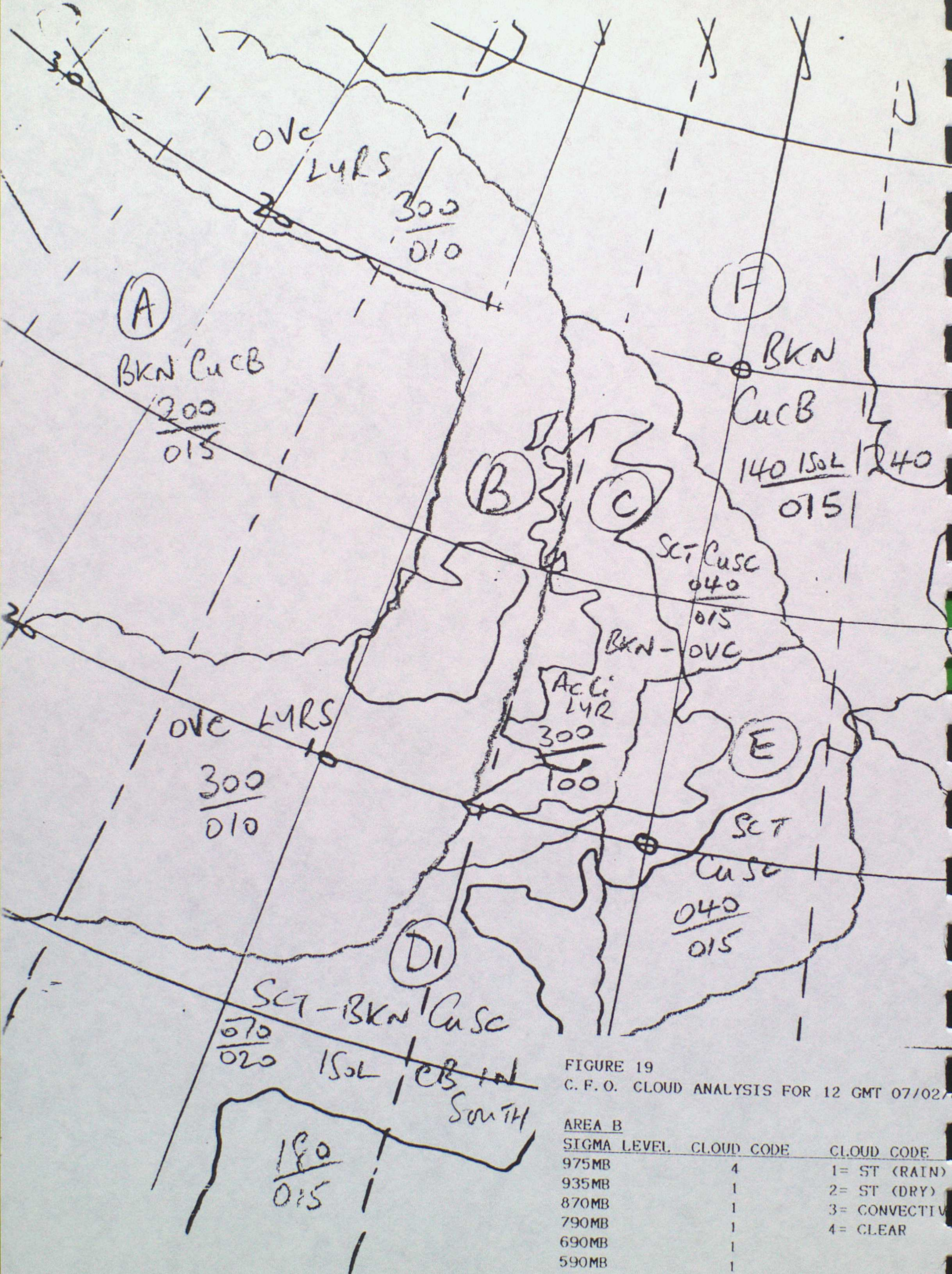


FIGURE 19
C.F.O. CLOUD ANALYSIS FOR 12 GMT 07/02/88

AREA B

SIGMA LEVEL	CLOUD CODE
975MB	4
935MB	1
870MB	1
790MB	1
690MB	1
590MB	1
490MB	1
390MB	1

CLOUD CODE
1= ST (RAIN)
2= ST (DRY)
3= CONVECTIV
4= CLEAR

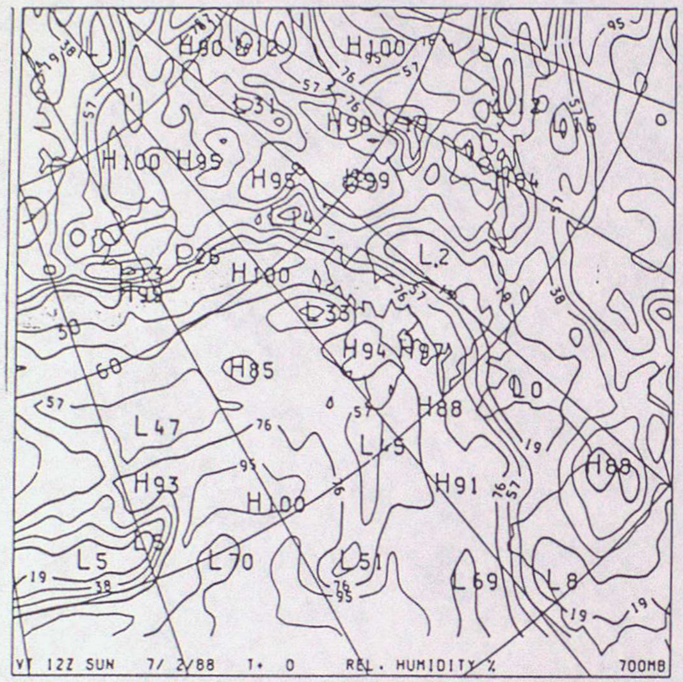


FIGURE 20a
OPERATIONAL FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 700MB FOR DT 12GMT 07/02/88

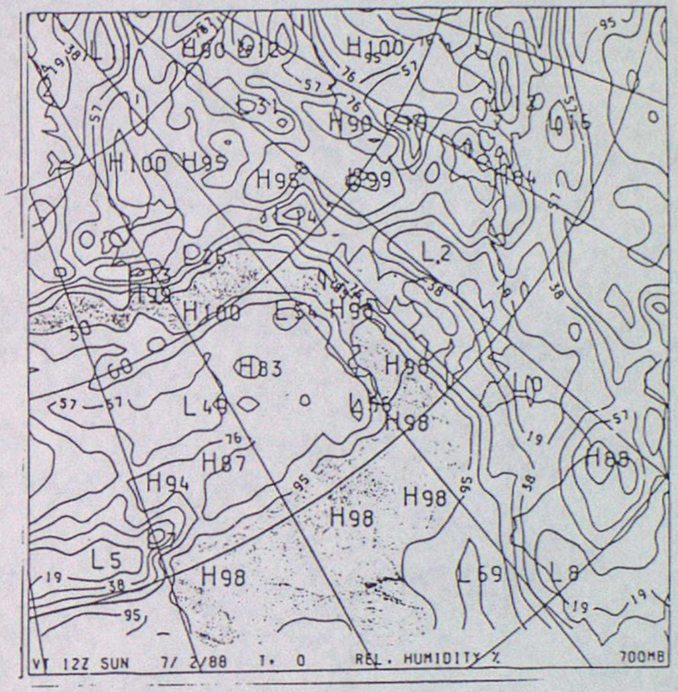


FIGURE 20b
FINE-MESH MODEL RELATIVE HUMIDITY ANALYSIS AT 700MB FOR DT 12GMT 07/02/88 AFTER MODIFICATION.

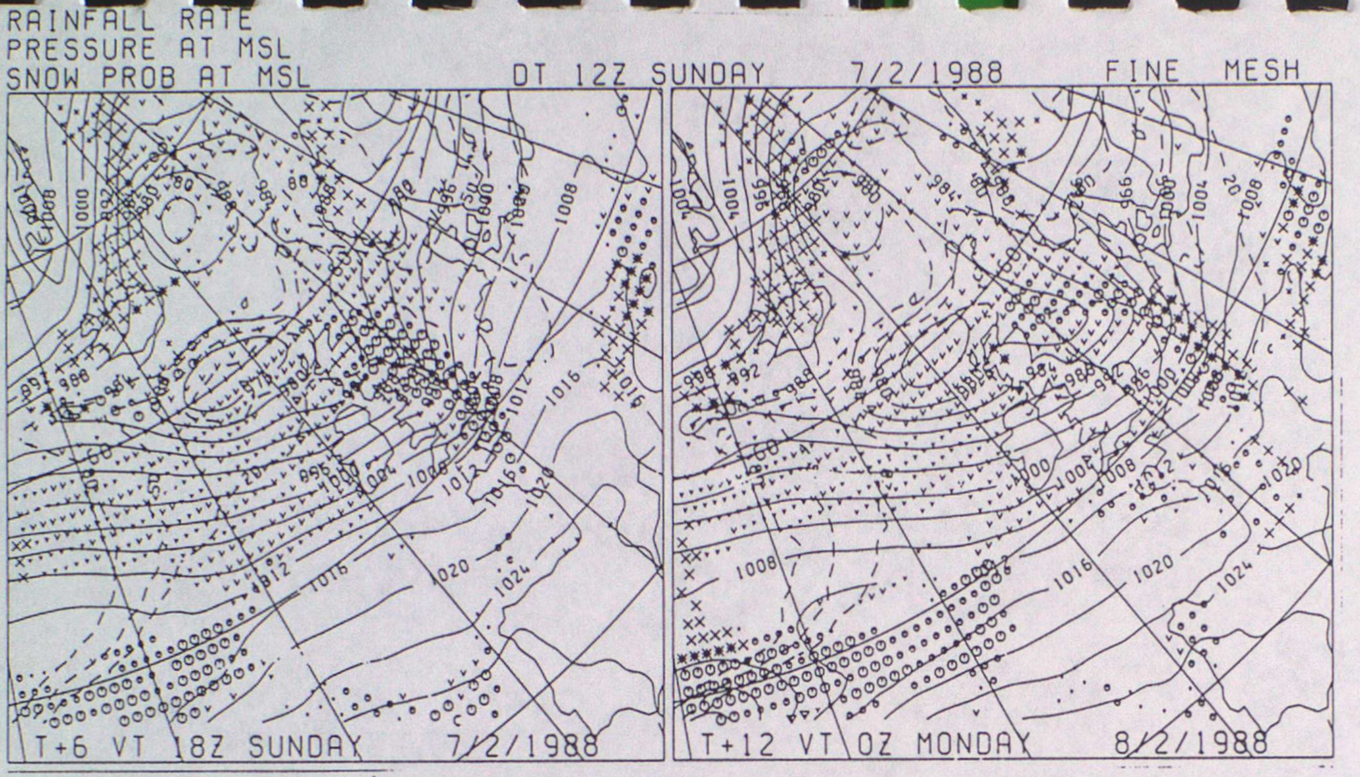


FIGURE 21 a and b
OPERATIONAL FINE-MESH MODEL
(DT 12GMT 07/02/88)FORECAST
OF MEAN SEA LEVEL PRESSURE
AND RAINFALL RATE FOR T+06,
VERIFICATION TIME 18GMT
07/02/88 and T+12, VERIFICATION
TIME 00GMT 08/02/88

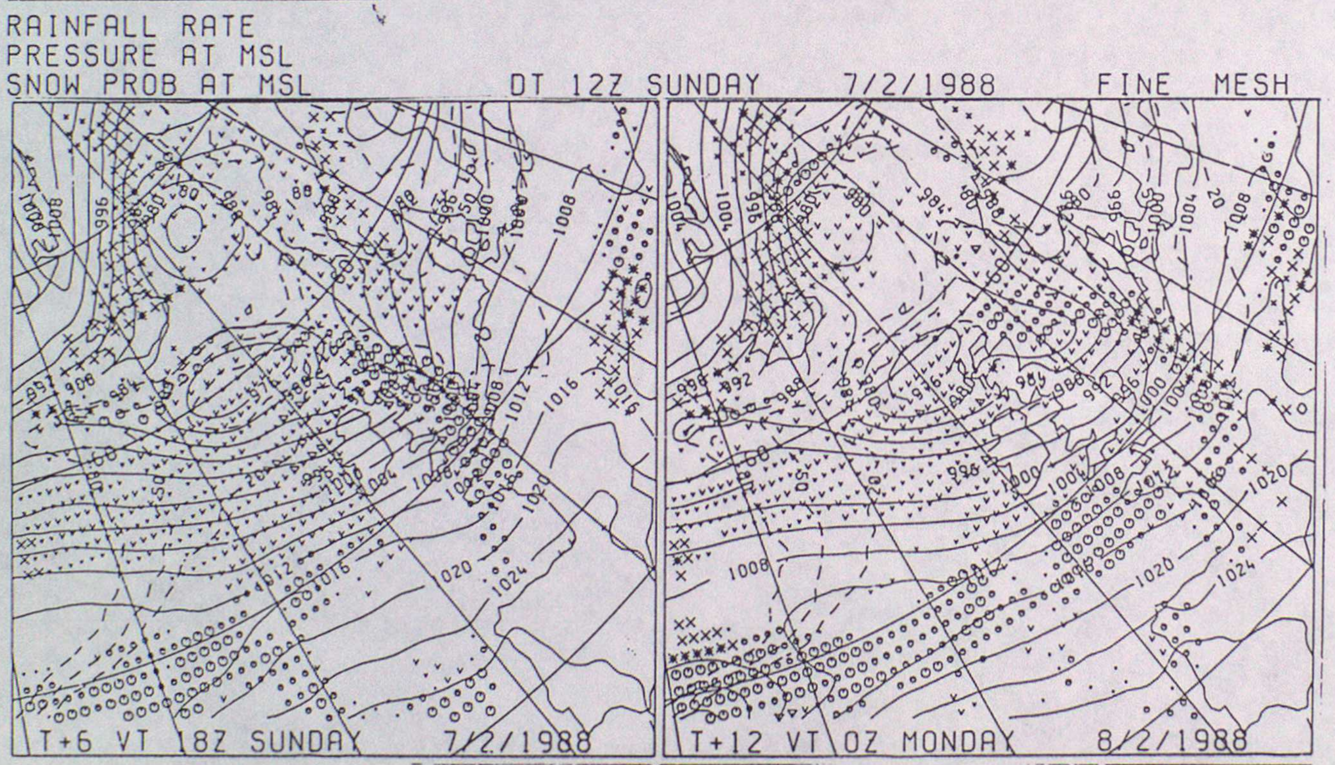


FIGURE 21 c and d
MODIFIED FINE-MESH MODEL
(DT 12GMT 07/02/88)FORECAST
OF MEAN SEA LEVEL PRESSURE
AND RAINFALL RATE FOR T+06,
VERIFICATION TIME 18GMT
07/02/88 and T+12, VERIFICATION
TIME 00GMT 08/02/88

OPS

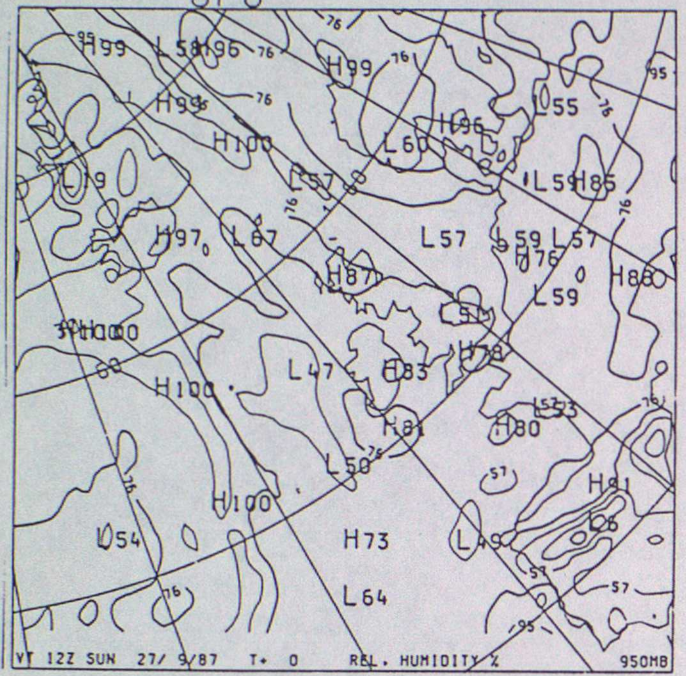


FIGURE 22a
OPERATIONAL FINE-MESH MODEL
RELATIVE HUMIDITY ANALYSIS AT
950MB FOR DT 12GMT 27/09/87

MOD

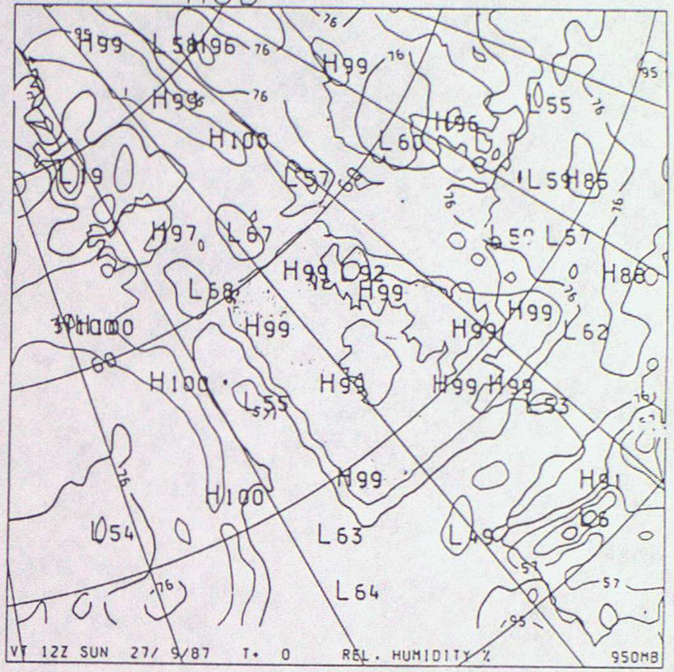


FIGURE 22b
FINE-MESH MODEL RELATIVE HUMIDITY
ANALYSIS AT 950MB FOR DT 12GMT
27/09/87 AFTER MODIFICATION.

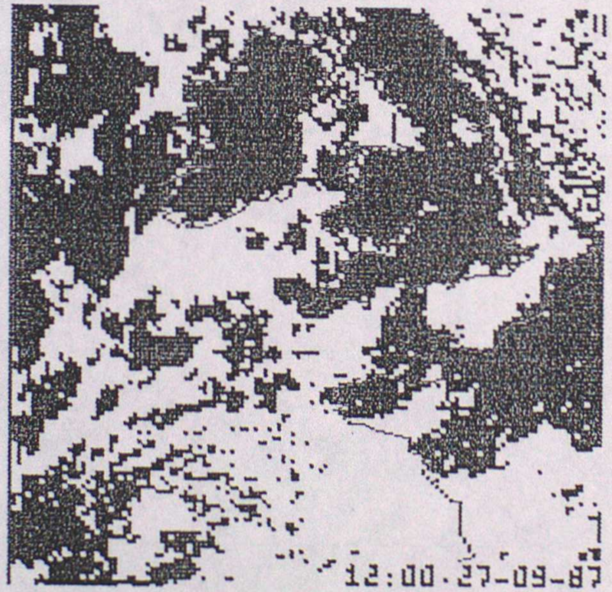
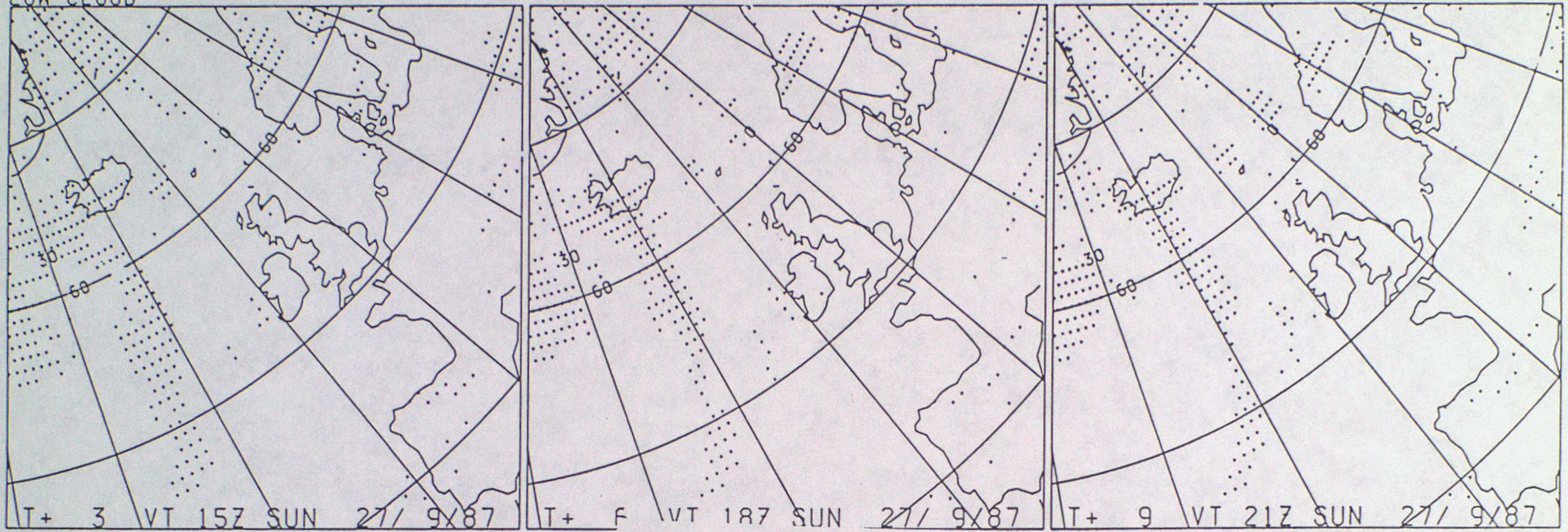


FIGURE 22c
VISUAL VISUAL SATELLITE IMAGE
FOR 12 GMT 27/09/87 SHOWING THE
EXTENT OF LOW CLOUD

DT 12Z SUN 27/ 9/87 MAIN

FIGURE 23a T+03-T+09--OPERATIONAL FINE-MESH FORECAST-

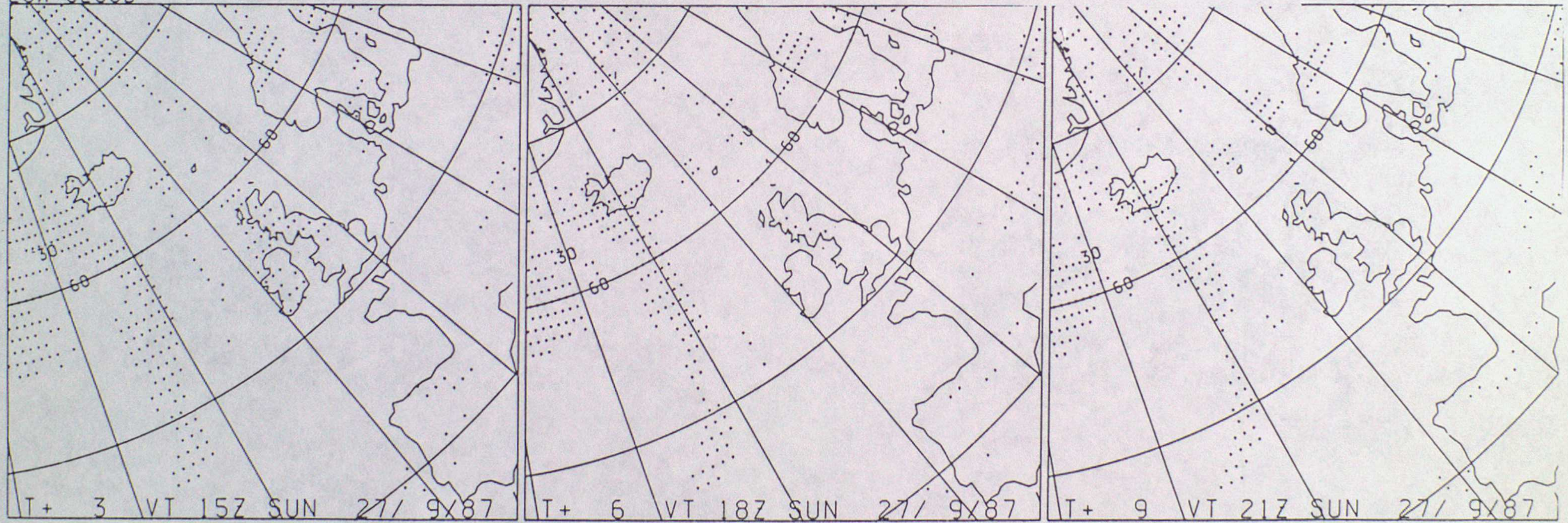
LOW CLOUD



DT 12Z SUN 27/ 9/87 MAIN

FIGURE 23b T+03-T+09---MODIFIED FINE-MESH FORECAST-

LOW CLOUD



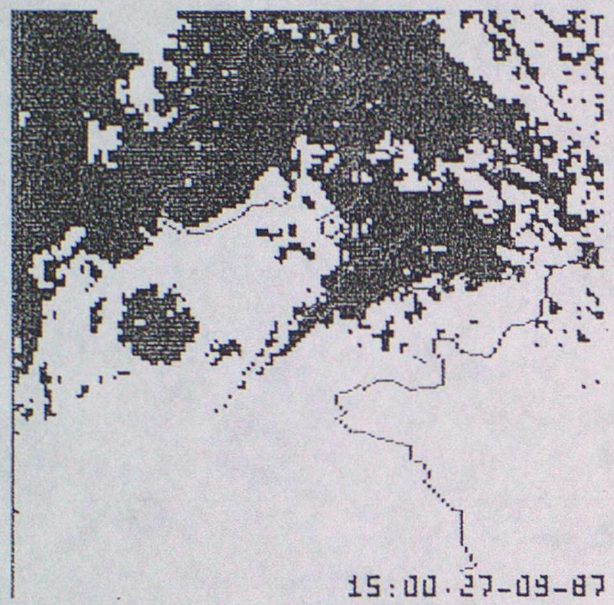


FIGURE 24a
SATELLITE IMAGE
FOR 15 GMT 27/09/87 SHOWING THE
EXTENT OF LOW CLOUD

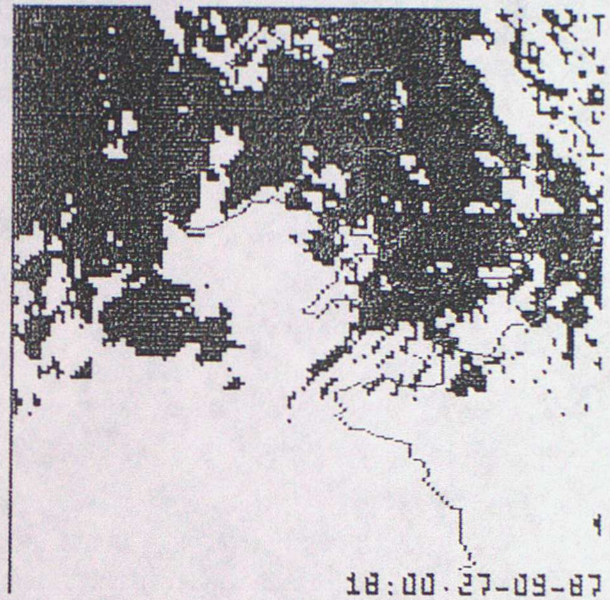


FIGURE 24b
SATELLITE IMAGE
FOR 18 GMT 27/09/87 SHOWING THE
EXTENT OF LOW CLOUD

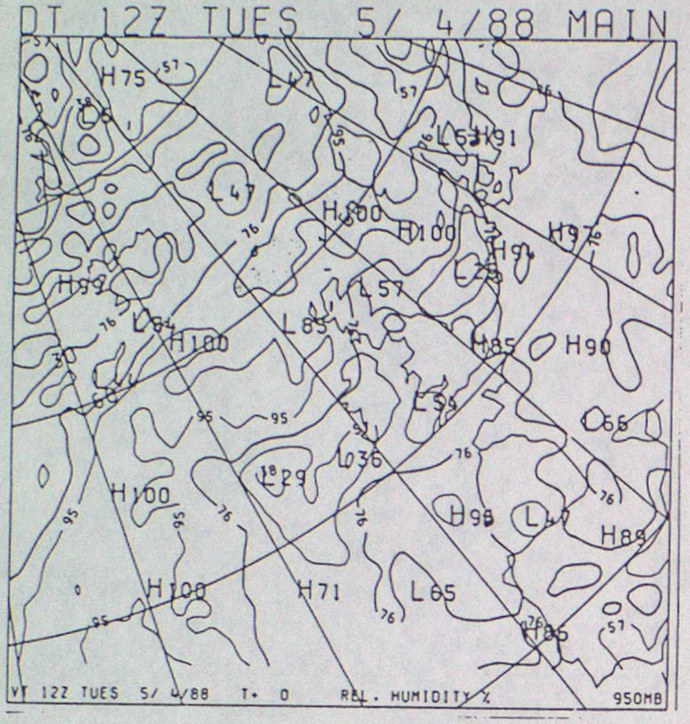


FIGURE 25a
OPERATIONAL FINE-MESH MODEL
RELATIVE HUMIDITY ANALYSIS AT
950MB FOR DT 12GMT 05/04/88

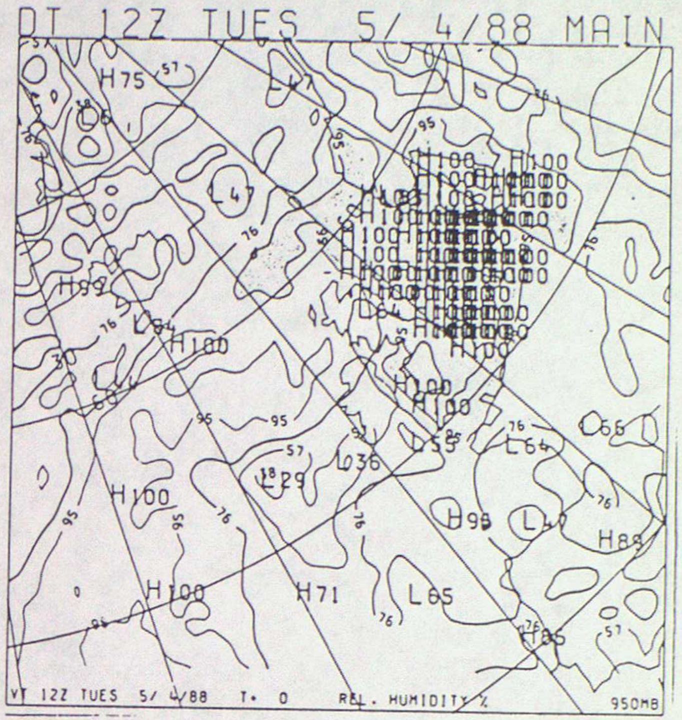


FIGURE 25b
FINE-MESH MODEL RELATIVE HUMIDITY
ANALYSIS AT 950MB FOR DT 12GMT
05/04/88 AFTER MODIFICATION.

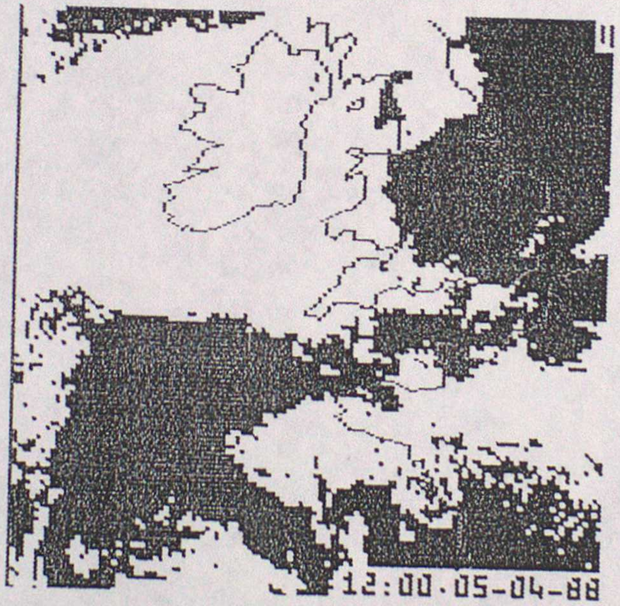
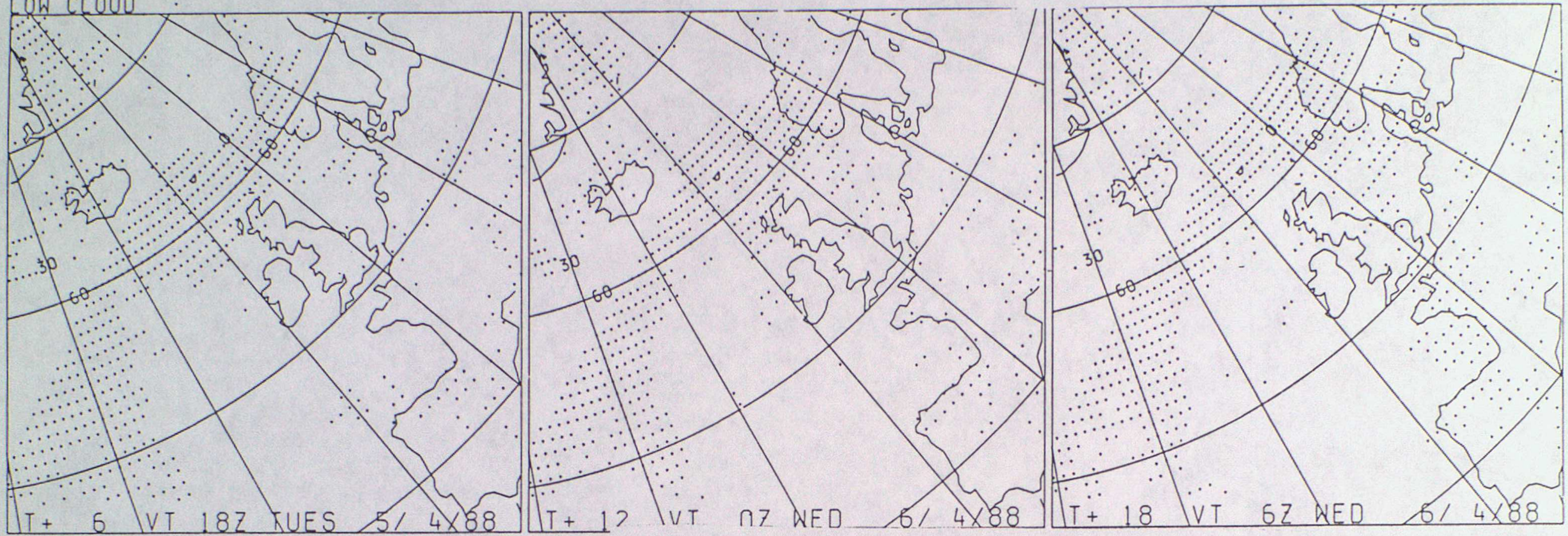


FIGURE 25c
VISUAL SATELLITE IMAGE
FOR 12 GMT 05/04/88 SHOWING THE
EXTENT OF LOW CLOUD

DT 12Z TUES 5/ 4/88 MAIN

FIGURE 26a T+06-T+18--OPERATIONAL FINE-MESH FORECAST-

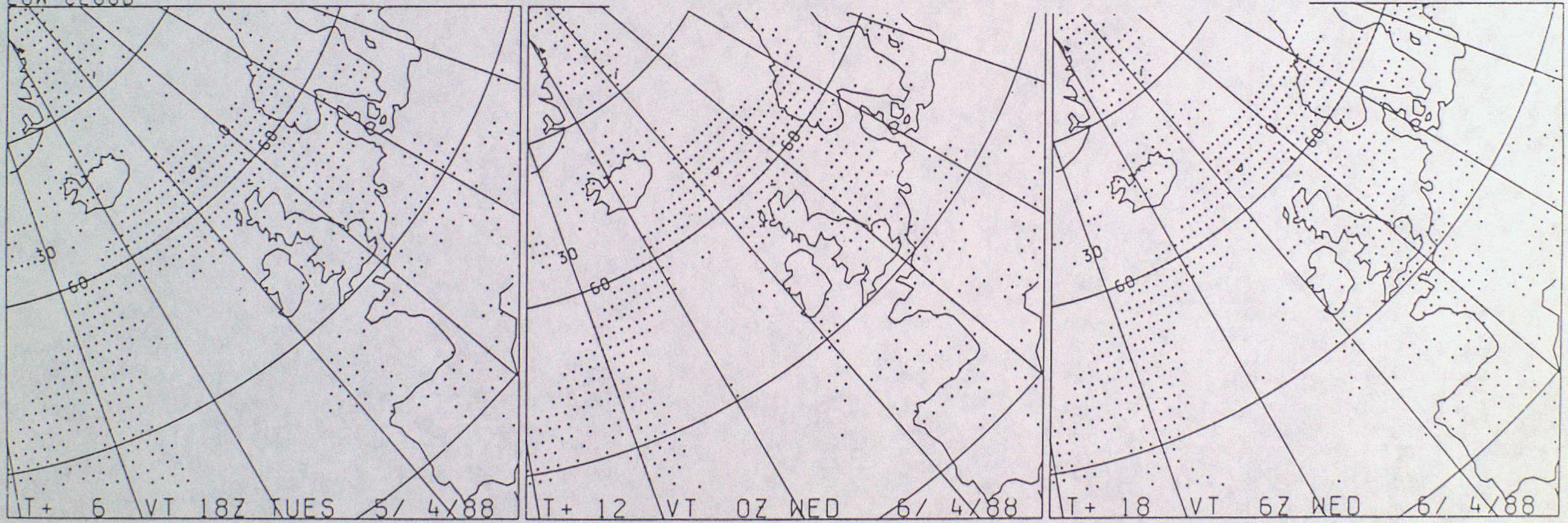
LOW CLOUD



DT 12Z TUES 5/ 4/88 MAIN

FIGURE 26b T+06-T+18---MODIFIED FINE-MESH FORECAST-

LOW CLOUD



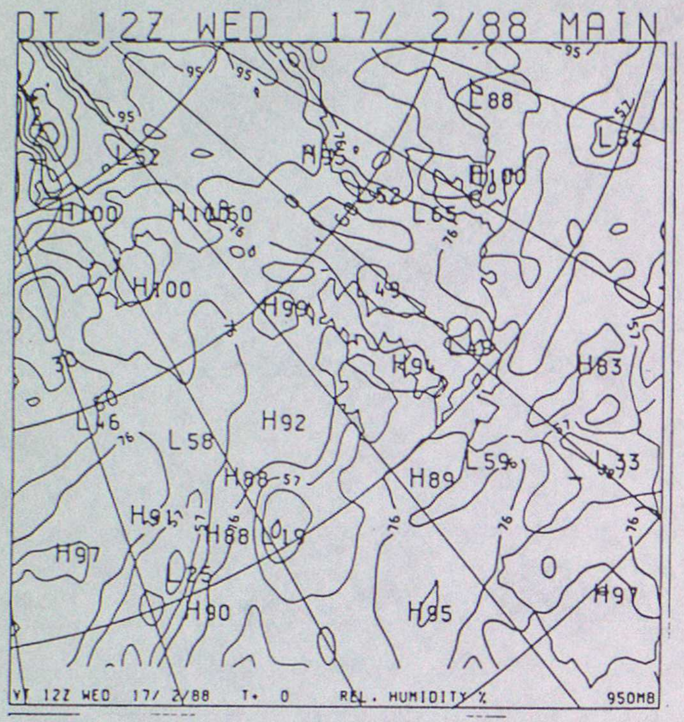


FIGURE 27a
OPERATIONAL FINE-MESH MODEL
RELATIVE HUMIDITY ANALYSIS AT
950MB FOR DT 12GMT 17/02/88

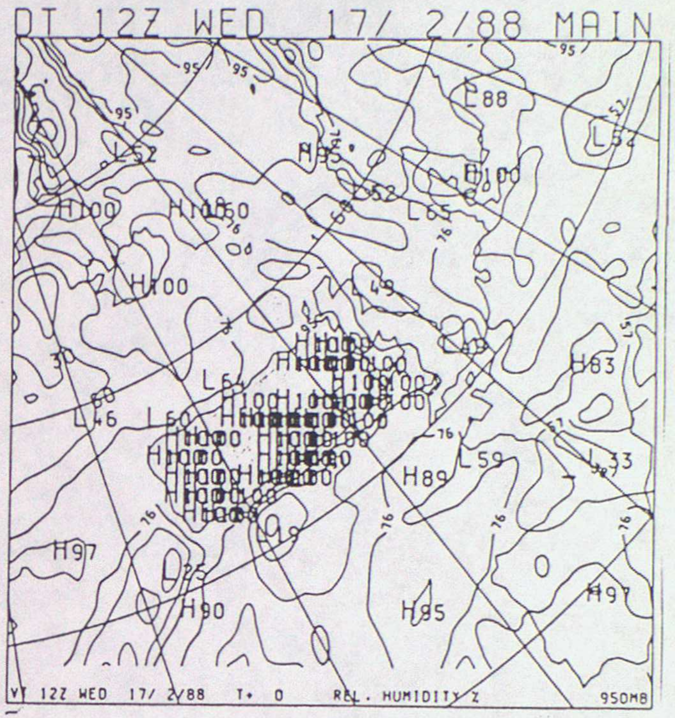


FIGURE 27b
FINE-MESH MODEL RELATIVE HUMIDITY
ANALYSIS AT 950MB FOR DT 12GMT
17/02/88 AFTER MODIFICATION.

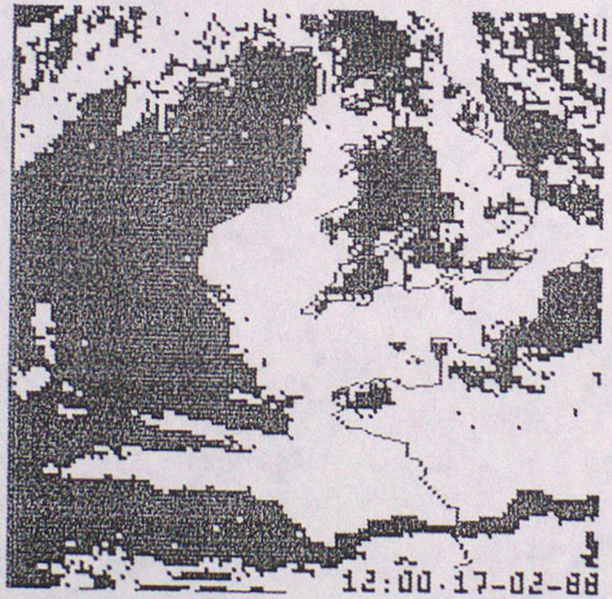


FIGURE 27c
VISUAL SATELLITE IMAGE
FOR 12 GMT 17/02/88 SHOWING THE
EXTENT OF LOW CLOUD

FINE-MESH MODEL LOW CLOUD
FORECAST AT T+12 VERIFYING
AT 00GMT 18/02/88

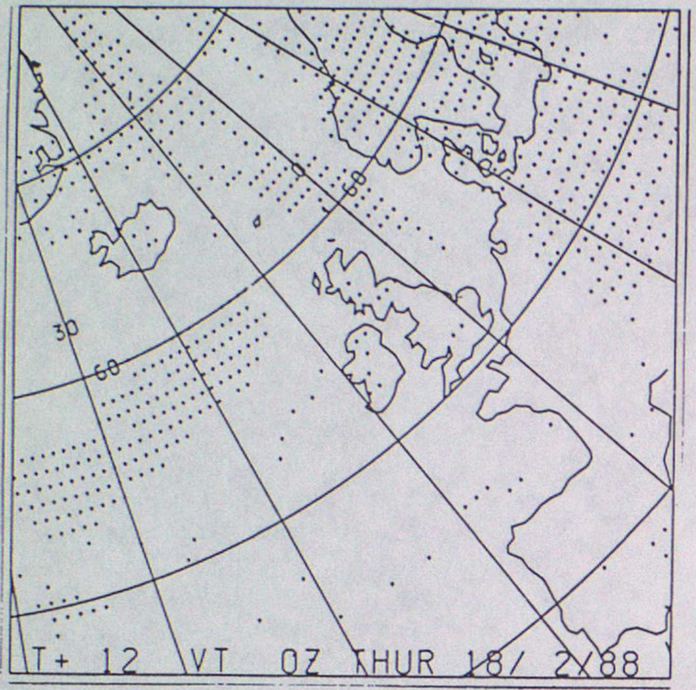


FIGURE 28a
OPERATIONAL

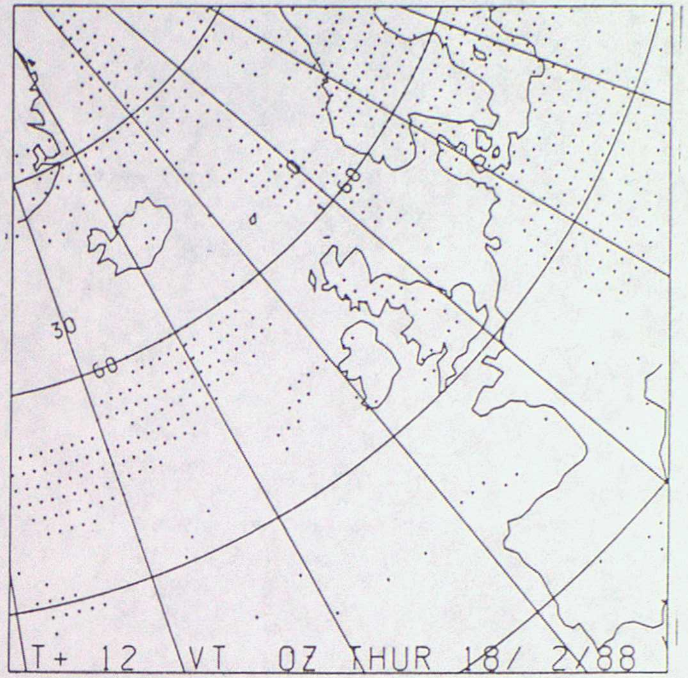


FIGURE 28b
MODIFIED

FINE-MESH MODEL LOW CLOUD
FORECAST AT T+24 VERIFYING
AT 12GMT 18/02/88

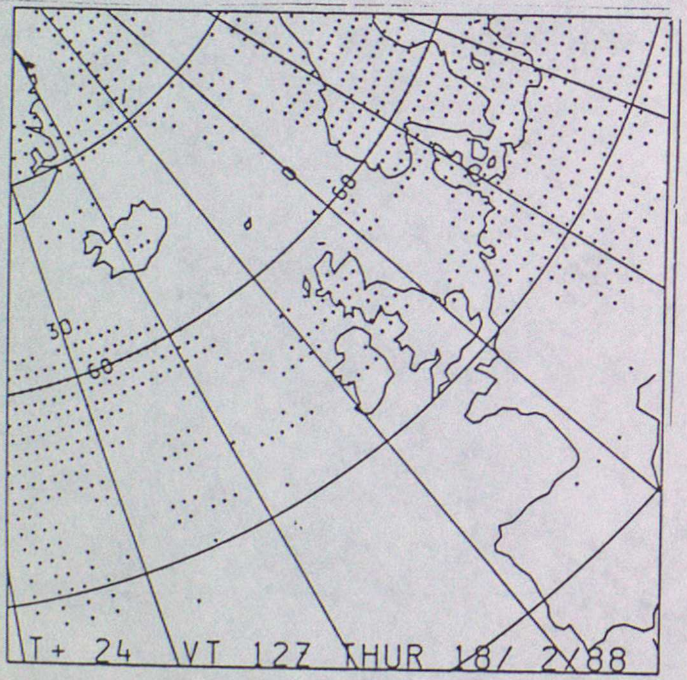


FIGURE 28c
OPERATIONAL

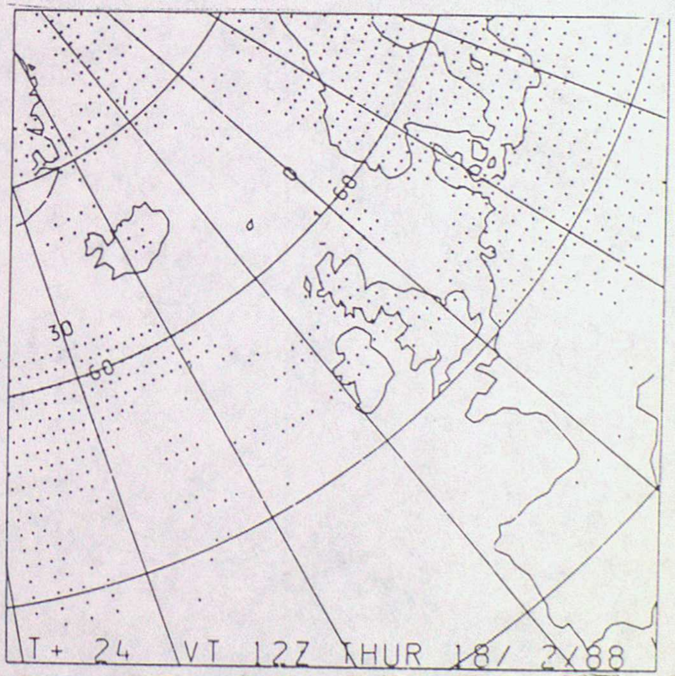


FIGURE 28d
MODIFIED