MET O 11 TECHNICAL NOTE NO 134

The effect on the rainfall of various topography schemes that can be used in the 10 - level model.

by

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Abstract

The effects of various topography schemes on the distribution of forecast rainfall over the British Isles is investigated. The use of the mean topography to represent the topography in each grid square gives little topographic component to the rainfall. The results can be improved by incorporating the subgridscale topography schemes of Riddaway (1978), but a deficit in rainfall remains. The best results occurred when the topography was represented by the maximum topographic height in each grid square. The use of this scheme was an attempt at modelling the barrier effect of mountains.

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1. Introduction

Recently several attempts have been made at improving the amount of rainfall predicted by the fine mesh version of the 10-level model. The necessity for improvement was illustrated by Wickham (1977) who examined the rainfall forecasts from the model over a four year period for the British Isles and the adjacent continental areas; he found that there was a general deficiency in rainfall. However, although rainfall was collected for separate climatic regions, the statistics produced by Wickham were for all the regions combined so that it was not possible to deduce if

(i) there was an underestimate of rainfall in all regions; this could be caused by inadequacies in the analysis, initialisation or model resolution.

(ii) the underestimates are mainly confined to specific regions; this could be associated with inadequate modelling of the topographic influences on rainfall.

(iii) the underestimates are due to a combination of both (i) and (ii).

This problem was examined further by Minhinick and Findlater (1979) who investigated the geographical distribution of the rainfall errors. Rainfall predictions from the midnight run of the operational forecast model were archived every day for 6 months. From this information the accumulated rainfall over each rainfall day starting at T+9 was estimated for 37 100 km squares covering the British Isles. The average predicted daily rainfall was then compared with that estimated from the raingauge network. It was found that the 10-level model predicted too little rain in mountainous regions but over flat low-lying areas, such as much of Southern England, the model performed quite well. This suggests that the rainfall deficiencies reported by Wickham are likely to be mainly due to our inability to model adequately the effects of the topography. However it should be noted that Bell (1978) found that, even in a non-mountainous regions, the reduction of the gridlength from 100 km to 50 km could produce a sizeable increase in rainfall. Therefore it is unlikely that by simply improving the representation of topography it will be possible to remove all the errors in the average predicted rainfall.

As well as investigating the rainfall forecasts from the operational model, Minhinick and Findlater examined forecasts from two other models that were designed to improve the prediction of the topographic component of rainfall. These models are

(i) the $3\frac{1}{3}$ km model devised by Bell (1978) that used data from the 10-level model to recalculate the dynamic rainfall on this fine grid.

(ii) the simple subgridscale topography parameterisation scheme devised by Riddaway (1978) which attempts to take into account the roughness of the topography by using the standard deviation of the topography about its mean height in each grid square. Unlike the $3\frac{1}{3}$ km model, this scheme can never produce less rain than the operational model.

The same statistics were derived for these two models as for the operational model. They showed that the Bell model produced reasonable results in lowland regions, but in mountainous regions it forecast too much rain. For example, in a 100 km square in Central Scotland the Bell model predicted an average rainfall of 15.1 mm whereas that estimated from the raingauges was 6.7 mm (the corresponding average for the operational model was 2.7 mm). The Riddaway model tended to overestimate small amounts of rainfall and underestimate large ones, but overall it produced the best distribution of average rainfall (in the sample square in Scotland the average was 8.2 mm). However in both this model and the Bell model the maximum rainfall in Scotland was over the central region rather than on the west coast. This appears to be a defect in the model but we must exercise caution when interpreting this discrepancy because the estimated rainfall is unreliable for square which include both sea and upland areas. In such squares we might expect that using the land based raingauge network would overestimate the actual average rainfall over the whole square. However this may not necessarily be so - if we have a westerly wind blowing onto the west coast of Scotland then there is usually enhancement of the rain over the sea due to the mountains that are downstream. Therefore the average rainfall derived from the land stations may not be very different from the actual, but unknown, average over the complete square.

So far both the Bell and Riddaway models have been used in a non-interactive way; they do not feed information about the small scale topography back into the large scale model. However the Riddaway model was designed to be interactive and it was recommended by Minhinick and Findlater that it should be tested in this mode. This has now been done for a few cases and the results will be presented later in this report. Ideally we would also like to have run some forecasts with an interactive version of Bell's model; unfortunately no such version of the model is available and even if it was the computation time required would make it impractical as a way of parameterising the effects of topography on rainfall in an operational model.

In this report we also present some more evidence which emphasises the inability of the present operational model to represent the effect of the topography on the rainfall. Finally we suggest a simple pragmatic way of alle viating this problem.

2. The Experiments

This report describes a series of experiments carried out in an attempt to improve the prediction of the topographic component of rainfall. For each case considered it was possible to perform forecasts using the following topography schemes over the British Isles (elswhere the topography was the same as that in the operational model).

(a) the topographic height set to zero

(b) the topography used in the present operational model- this is the mean topographic height in each gridsquare which itself has been smoothed (the values for each grid square are given in Figure 1a)

(c) the mean topographic height in each grid square - this is similar to (b) but is unsmoothed (see Figure 1b)

(d) the topography used in (c) along with the Riddaway subgridscale parameterisation scheme in its non-interactive mode.

(e) similar to (d) but with an interactive parameterisation scheme.

(f) the representative topographic height in each gridsquare was taken to be the maximum height derived from the $3\frac{1}{3}$ km topography data set (see Figure 1c); the rationale behind this will be considered in the next section.

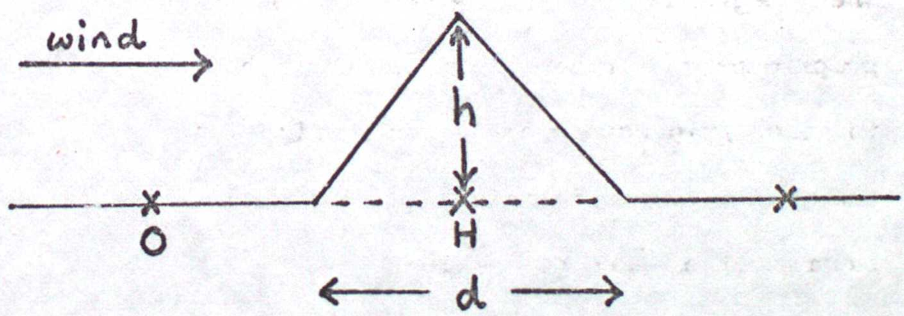
Before proceeding it should be emphasised that the rainfalls derived from the above schemes was computed every timestep and the accumulated rain collected for T+9 to T+33 (this corresponded to a rainfall day since all the forecasts started at midnight. The rainfall calculations in the Minhinick and Findlater experiments were done in a slightly different way; they computed the rainfall rate every 6 hours and assumed that this was representative of conditions over a 6 hour period centred on the time of the calculations. This will lead to some errors and so in the following discussion care must be taken when comparing the Bell forecasts done by Minhinick and Findlater with the forecasts using schemes (a) to (f).

In the experiments described here the rainfall was predicted for 100 km squares centred about the model grid but these were then transformed onto a 100 km grid aligned with the National Grid. This was necessary so that comparisons could be made with results from the Bell model that were only available on such a grid. Obviously the transformation will introduce some errors, but these appear to be small.

3. The maximum topography scheme

In this section we attempt to indicate why it may be advantages to represent the topography in each grid square by its maximum value when deriving the rainfall.

Since the vertical velocity induced by the topography depends upon the gradient of the topography, it is important to model these gradients correctly. Consider the simple two-dimensional example illustrated below



Suppose there is a symmetric ridge of height h centred about a model gridpoint (denoted by H); the ridge spans just one gridlength (d say). If $h_a(H)$ and $h_a(0)$ are the actual topographic heights at H and the upwind gridpoint O, then the actual mean topographic gradients between these points is

$$G_a = \frac{h_a(H) - h_a(0)}{d} = \frac{h}{d}$$

The corresponding gradient G_m calculated from the topographic heights stored in the model ($h_m(H)$ and $h_m(0)$ say) is

$$G_m = \frac{h_m(H) - h_m(0)}{d}$$

Consider the following two cases

(i) If the model uses the mean topographic height to represent the topography in a grid square, then

$$h_m(H) = \frac{h}{2} \quad , \quad h_m(0) = 0 \quad \text{giving} \quad G_m = \frac{h}{2d}$$

Hence the actual gradient G_a is underestimated and thus will be so far any arbitary shape of symmetric ridge (the only exception being a plateau with vertical sides).

(ii) If the maximum height in each grid square is used

$$h_m(H) = h \quad , \quad h_m(0) = 0 \quad \text{giving} \quad G_m = \frac{h}{d}$$

Therefore representing the topography in this way gives the correct mean gradient.

This simple example illustrates the effectiveness of using the maximum topography scheme. In reality the topography is much more complicated than that considered above and this could be taken into account by replacing the maximum height by the average barrier height perpendicular to the wind. Obviously this would then be a function of wind direction and so in the simplest possible scheme we would have to store the barrier height for two orthogonal directions; the barrier height for any arbitary direction would then be a combination of these. However this may be unnecessarily sophisticated for such a simple basic idea and so in the experiments described here we simply use the maximum height in each grid square.

4. The first case - general results

Here we consider a series of 36 hour forecasts based on initial data from 00Z 1/11/78.

Figures 2a and 2b show the CFO analyses at the beginning and end of the forecast period. At the start of the period there was a small amount of rain associated with the weak front across Southern England. This soon ceased leaving most of the British Isles in a moist southwesterly airstream; the only remaining precipitation being in isolated areas on the south coast. During the evening a cold front approached Scotland from the Atlantic and the first signs of rain over the country were in the Western Isles at about 1800 - the front then travelled southeastwards over Scotland and Northern

England. The front brought heavy rain to many parts of Scotland and this was followed by further rain and showers, particularly in the west.

Several other features of the rainfall distribution along the front are worthy of note. As the front crossed Wales there were isolated outbreaks of rain well ahead of the front in Southern England. These mainly occured near the south coast, although rain was reported as far away as Bedford at 0900 Z. Further north the rain was confined to the vicinity of the front, but by midday on the 2nd the portion of the front over Northeast England was so weak that there appeared to be no rain associated with it. The few observations over the North Sea confirm the lack of rain on the front although further east near the Norwegian coast there were reports of moderate rain.

Figure 2c shows the 36 hour forecast using the operational topography (the corresponding results using the maximum topography are given in Figure 2d) and the verifying analysis is shown in Figure 2b. These indicate that the model predicted the general synoptic development very well; it successfully forecast the movement of a rainbelt across the British Isles followed by another rain area approaching Scotland from the west. Also the model correctly predicted the development of showers on the west coast of Scotland behind the first rain belt.

Figure 3 shows the estimated 24 hour accumulations of rainfall derived from the CARP data set for the rainfall day starting on the 1st. The next figure has the results from the forecasts carried out by Minhinick and Findlater - that is with the operational model (Figure 4a), the operational model with the subgridscale parameterisation scheme (Figure 4b) and the Bell model (Figure 4c). In each case the accumulated rain was computed from rainfall rates that were available every 6 hours throughout the forecast. The most striking feature of those forecasts is the inability of any of the models to adequately predict either the amount or distribution of the rainfall over Scotland. Overall both the Riddaway and Bell models produced similar results that were only marginally better than those from the operational model.

We now consider forecasts using the topography schemes listed (a) to (f) in section 2. In all of these the accumulated rain is derived from rainfall rates that have been calculated every timestep (ie every 10 minutes).

Figures 5a, 5b and 5c shows the results using zero topography, the operational tropography and the unsmoothed topography. Clearly these show that there is minimal orographic enhancement of the rainfall and that the use of the unsmoothed topography produced only a marginal improvement over the smoothed version; overall the rainfall forecasts are rather poor.

Figures 5d and 5e show the results of incorporating the subgridscale topography scheme in its non-interactive and interactive modes respectively; in both cases the inclusion of this scheme was beneficial in that it increased the rainfall over Scotland. The effect of making the subgridscale topography scheme interactive was to produce a slight reduction in rainfall; this has an adverse effect in Central Scotland but was of benefit in the east.

The results from the last of the schemes, the maximum topography formulation, are given in Figure 5f. Comparison with the results already shown indicates that this scheme has produced some large increases in rainfall and an improvement in its distribution. For example, the rainfall in Scotland was increased (though not enough in the east), and the maximum rainfall was shifted towards the west coast.

In this case the maximum topography scheme gave the best results, but it would be interesting to know how effective the relatively sophisticated Bell model would be if it was used every 10 minutes rather than every 6 hours. Hopefully such a model would give the best results, although this may not necessarily be so if we accept the following simple argument. It was noted earlier that the forecasts run by Minhinick and Findlater using the Riddaway model and the Bell model were very similar (see Figures 4b and 4c). Now comparing Figures 4b and 5d reveals that increasing the frequency at which the non-interactive subgridscale topography scheme was used from 6 hours to 10 minutes increased the maximum rainfall over Scotland but did not improve its position - the maximum was still in Central Scotland rather than in the west. This leads us to speculate that increasing the frequency of use of the Bell model will not necessarily shift the maximum rainfall towards the west in Scotland.

5. <u>The first case - further results</u>

When the maximum topography results are examined more carefully they reveal that some of the improvement in rainfall in Western Scotland was due to an increase in the convective rain. For example, if the grid square shown in Figure 1a is considered, it is found that using the maximum topography in place of the operational topography produced a ten-fold increase in rain for which the convective rain increased from 0.4 mm to 1.9 mm and the dynamic rain from 0.8 mm to 10.1 mm. Unfortunately it is not known what proportion of the actual rain was convective, but it is not unreasonable for there to be a significant amount of convective rain caused by orographic uplift. Also it is worth noting that the maximum topography scheme was the only one that had much effect on the convective rain over the British Isles.

It is interesting to consider the rainfall from this gridsquare further. Figure 6 shows the hourly accumulations of rainfall using both the maximum and operational topography. Also shown are estimates of the actual mean hourly accumulations derived from raingauge records and hourly synoptic observations. Such estimates are difficult to make, but it is thought that those shown are essentially correct. Comparison of these distributions again illustrates the effectiveness of using the maximum topography scheme, but it does have some deficiencies. The maximum rainfall was predicted to occur about 2 hours early - this could be due to a slight error in the speed of the front. Also the forecast distribution of rain with time is broader and has a smaller maximum than that observed; however this difference in shape is hardly surprising when the smoothing inherent in any forecast model is taken into account. The combination of the broadening of the rainfall distribution and the possible mistiming of the front meant that the model predicted the onset of rain 6 hours before it actually occured. Another interesting feature in the forecast is what appears to be an overprediction of the convective rain that followed the cold front. However during this period there are doubts about he validity of the estimate of the actual rainfall since it is very difficult getting realistic estimates of convective rainfall in upland areas where there are few observations. Overall the maximum topography scheme has produced a encouraging forecast of the sequence of hourly rainfall amounts in the gridsquare.

Before considering another case it is worth noting two important effects on the distribution of rainfall across the British Isles caused by replacing the operational topography by the maximum topography (see Figures 2c and 2d). The use of the new scheme extended the area of rain ahead of the cold front in Southern England and reduced the frontal rain over Northeast England and the North Sea. Examination of the actual rainfall described earlier reveals that both these changes were beneficial, although the drying up of the front over the North Sea may be too severe.

6. The second case - general results

In this section we present the results from a series of forecasts based on a data time of 00Z 28/9/78.

During the forecast period a slow moving low approached Scotland from the west whilst its associated fronts crossed the British Isles bringing rain to nearly all areas (see Figure 7a and 7b). After the passage of the cold front most of the country was left in a showery northwesterly airstream - these showers were only responsible for a small proportion of the rain that fell.

Figure 7c shows the forecast chart at T+36 when the operational topography is used (the corresponding results for the maximum topography are in Figure 7d). Comparison with the verifying analysis given in Figure 7b reveals that in both forecasts the movement of the depression and its rainbelts was predicted accurately. The forecast distribution of convective rain will be considered later.

The estimated rain that fell during the rainfall day starting on the 28th is shown in Figure 8. Note the strong gradient of rainfall across the country with the maximum rainfall being in the west. This distribution suggests that there was a strong topographic component in the rainfall.

Figure 9 shows the results from the Minhinick and Findlater forecasts where the rainfall forecasts where the rainfall calculations were performed every 6 hours. When the operational topography was used (see Figure 9a) there was a definite underestimate of the rainfall in the west which resulted in there being very little gradient of rainfall across the country; the inclusion of the non-interactive sub-gridscale topography scheme produced only a marginal improvement (see Figure 9b). The results from the Bell model shown in Figure 9c are very impressive - note the accurate forecast of the magnitude of the rainfall maxima over Scotland although it is located in the central region rather than in the west. Elsewhere the Welsh maximum is correctly predicted, but in Southeast England too much rain was forecast.

We now consider the topography schemes listed in section 2. The results of using zero topography, the operational topography and the unsmoothed topography are shown in Figure 10. These confirm our previous findings about the lack of topographically induced rainfall when the average topography scheme are used. Indeed these forecasts tended to have the maximum rainfall in the east rather than the west - the opposite to what actually occured.

Figures 10d and 10e show the results of using the subgridscale topography scheme in its two forms. In both cases the inclusion of the scheme was beneficial - in particular the rainfall over Scotland was increased and the maximum shifted westwards. The effect of making the scheme interactive rather than passive was to cause a slight reduction in rainfall, but the overall pattern was unchanged.

Now consider the results from the maximum topography scheme given in Figure 10f. Comparing these with the results from the operation topography (Figure 10b) shows that the new scheme caused an increase in rain over Scotland and Wales as well as a significant shift in the rainfall maxima towards the west; also the rainfall in Southeast England was reduced and became more like that observed. Overall the use of the maximum topography is place of the operational topography produced a marked improvement in the rainfall forecast, although there is still a general underestimate in the more mountainous regions.

For this second case the Bell model gave by far the best results. However in producing the forecast the Bell model was only used four times (once every 6 hours) to derive the rainfall accumulations, and so it is likely that the high quality of the forecast is somewhat fartuitous. Of the simpler schemes that were used every timestep the maximum topography scheme produced the best results.

7. The second case - some further results

It is interesting to consider the effect of using the operational and maximum topography schemes on the distribution of the post-frontal convective rain.

First consider the observed distribution of showers. Embedded in the unstable airstream behind the cold front was a trough which marked the eastern edge of the showers. By midday on the 29th (see Figure 7b) the showers had reached the eastern areas of England. Further east over the continent there were more showers associated with the cold front. Between these two showery regions there was a dry area that covered most of the southern end of the North Sea.

Figures 7c and 7d show the forecast for 12Z on the 29th using the operational topography and the maximum topography. Comparison with the verifying analysis given in Figure 7b shows that both forecasts predicted the main cyclonic area behind the front to be too far to the west with a spurious ridge (most apparent with the operational topography) between it and the front.

Now consider the forecast distribution of showers. For the operational topography there were widespread showers predicted to the south of the low; over the North Sea these appear to be at variance with the marked ridging in the surface pressure field (see Figure 7c). This inconsistency could be due to an inadequate formulation of the convection scheme. When the maximum topography scheme was used some of the showers were suppressed leaving a dry region over the southern North Sea (see Figure 7d). Although the resulting shower distribution was different from that observed (the showers over the British Isles do not spread far enough east), the predicted distribution was at least consistent with the forecast pressure field. It is suspected that the reason the maximum topography gave a more reasonable distribution of showers than the operational topography is that the increase in topographic height enhanced the drying of the air to the lee of the Welsh hills; this then suppressed the unrealistically widespread showers forecast using the operational topography.

8. The third case

We now consider one further case based on data from 00Z 7/4/79. For this case the Minhinick and Findlater forecasts were not available, and so we do not have predictions from the Bell model. Also in the following discussion we will only consider forecasts using the operational and maximum topography.

This third case is different from the two described earlier in that there is a cyclonic easterly flow over the British Isles. During the forecast period there was a slow moving low just to the southwest of the country. This low and its associated fronts brought rain and drizzle (especially in the east). Figures 11a and 11b show the analysed surface chart at the beginning and end of the forecast period, and Figures

11c and 11d show the forecasts at T+3b using the operational and maximum topography respectively. These show that the predicted evolution of the surface features was quite reasonable, though in both forecasts the depression centred on the Scilly Isles lost its identity during the last 6 hours.

Figure 12 shows the estimated rainfall during the rainfall day starting on the 7th (marked a) as well as the predictions from our two forecasts (marked b and c). Clearly the use of the operational topography led to an underestimate of the rainfall in Southern England and Scotland. However these deficiencies were rectified by using the maximum topography scheme which produced a forecast distribution of rain that could hardly be bettered. A particularly pleasing aspect of this forecast was the introduction of the topographically induced rainfall in Eastern Scotland - this is apparent in both the accumulated rainfall and the surface forecast chart given in Figure 11c.

9. Conclusions

The results examined here suggest that

(i) using a mean topography (either smoothed or unsmoothed) provides hardly any topographic component to the rainfall.

(ii) including the subgridscale topography scheme is beneficial, but still does not produce enough rainfall; making the scheme interactive tends to reduce the rainfall and has only a small effect on its distribution.

(iii) using the maximum topography gives very good results - in particular the scheme appears able to correctly place the rainfall maximum in Scotland near the west coast in a westerly situation. However the scheme still underestimates the rainfall in mountainous regions.

Ideally we would like to compare the Bell model with those mentioned above, but this is not really possible because the only version of the Bell model available did the rainfall calculations every 6 hours and was non-interactive. Minhinick and Findlater found that on average the Bell model produced too much rain in mountainous regions and that in Scotland the rainfall maxima was not far enough west; these conclusions are supported by the results from the first case and to some extent by the second. It appears unlikely that simply increasing the frequency at which the Bell model is used would reduce these systemmatic errors, but making the model interactive may do this.

Overall these experiments indicate that the maximum topography scheme gives better results than the present operational scheme (with no extra computation required). The new scheme still underestimates the rainfall but this is not too serious since we know that we can increase the rainfall from the model by reducing the grid length. Soon it is hoped to examine more carefully the effects of reducing the gridlength of the model whilst incorporating a corresponding increase in the resolution of the topography.

As well as changing the total amount of rainfall the introduction of the new scheme has a marked effect on the distribution of showers to the lee of mountains - it tends to inhibit them. Physically, this is reasonable, but whether we get the correct distribution of showers depends upon the way we parameterise both the convection and the topography. In any further tests of the scheme special attention should be given to the effect of it on the distribution of showers.

Since information about the maximum topography in each grid square over the whole of the forecast area is not readily available, there is no reason why the scheme should not just be used over the British Isles (as in the present study). However, if it is used in more mountainous regions, thought should be given to whether it is desirable to have just one value representing the topography or if we need one value for the rainfall calculations (the maximum height) and another for the surface exchanges (the mean height).

Although the topographic height should not be treated as a disposable parameter, these experiments indicate that a judicious choice of the representation of the topography in the models can lead to a significant improvement in the rainfall forecasts.

Bell, R.S.	1978	"The forecasting of orographically enhanced rainfall accumulations using 10-level model data". Met. Mag., <u>107</u>, 113-124.
Minhinick, T.J. and Findlater, J.	1979	"A comparison of rainfall amounts predicted for G.B. by numerical models". Met O 11 Tech Note No. 126.
Riddaway, R.W.	1978	"The parameterisation of subgridscale topography". Met O 11 Tech Note No. 117.
Wickham, P.G.	1977	"Errors in rainfall forecasts by the 10-level model, 1973-1977". Met O 11 Tech Note No. 99.

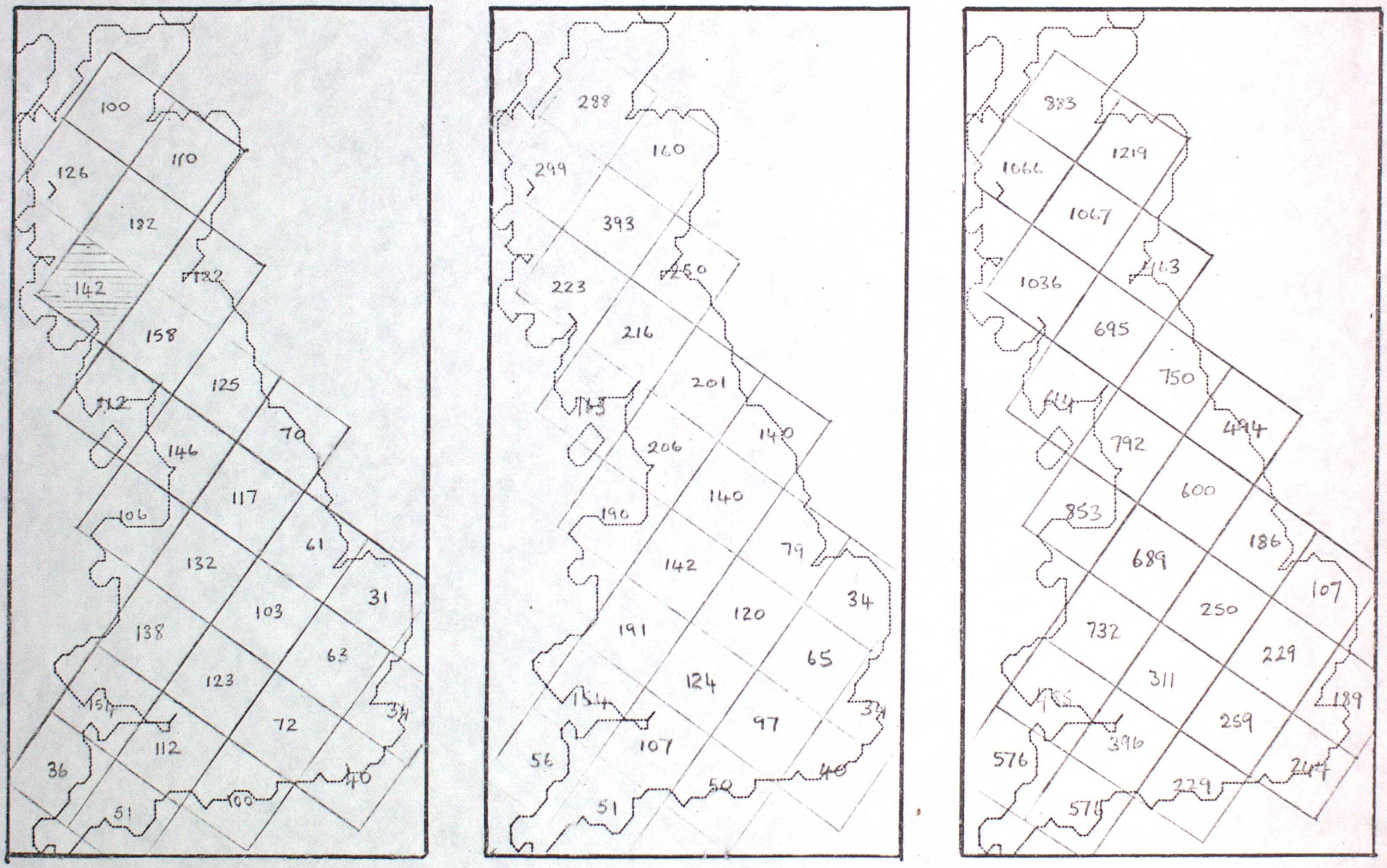
<u>Key for the rainfall symbols</u>

<u>Frontal rain</u> (some dynamic rain forecast)

✡ ⦶ ⦶ ⊙ : Total Rate > 4.0 ; 0.5 ; 0.1 ; 0.01 mm/hr

<u>Showers</u> (nil significant dynamic rain)

▽ V v : Local Convective Rate > 4.0 ; 0.5 ; 0.1 mm/hr

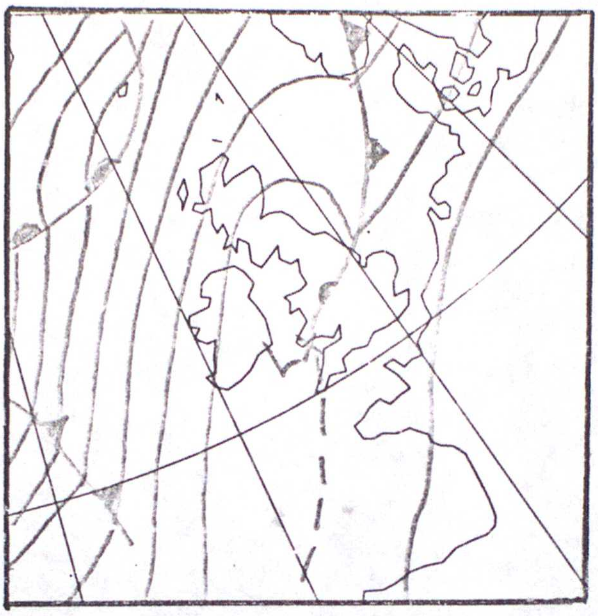


(a) operational (b) unsmoothed (c) maximum

Figure 1 - gridpoint values of the topographic heights used in the experiments

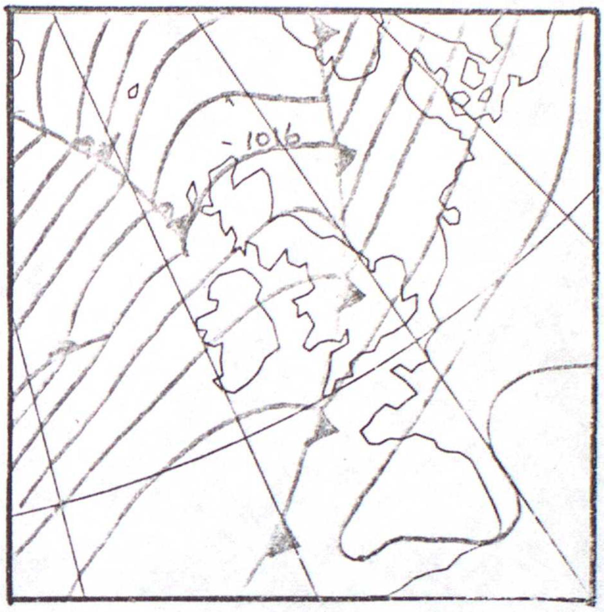
(a)

00Z 1/11/78



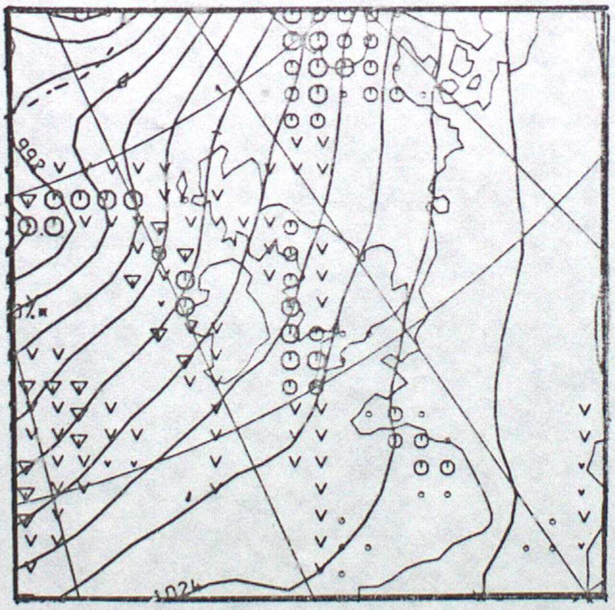
(b)

12Z 2/11/78



(c)

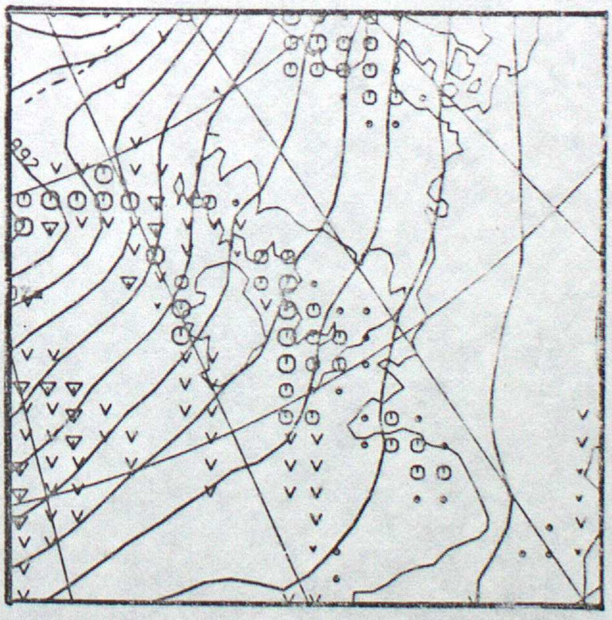
12Z 2/11/78



36hr forecast using operational topography

(d)

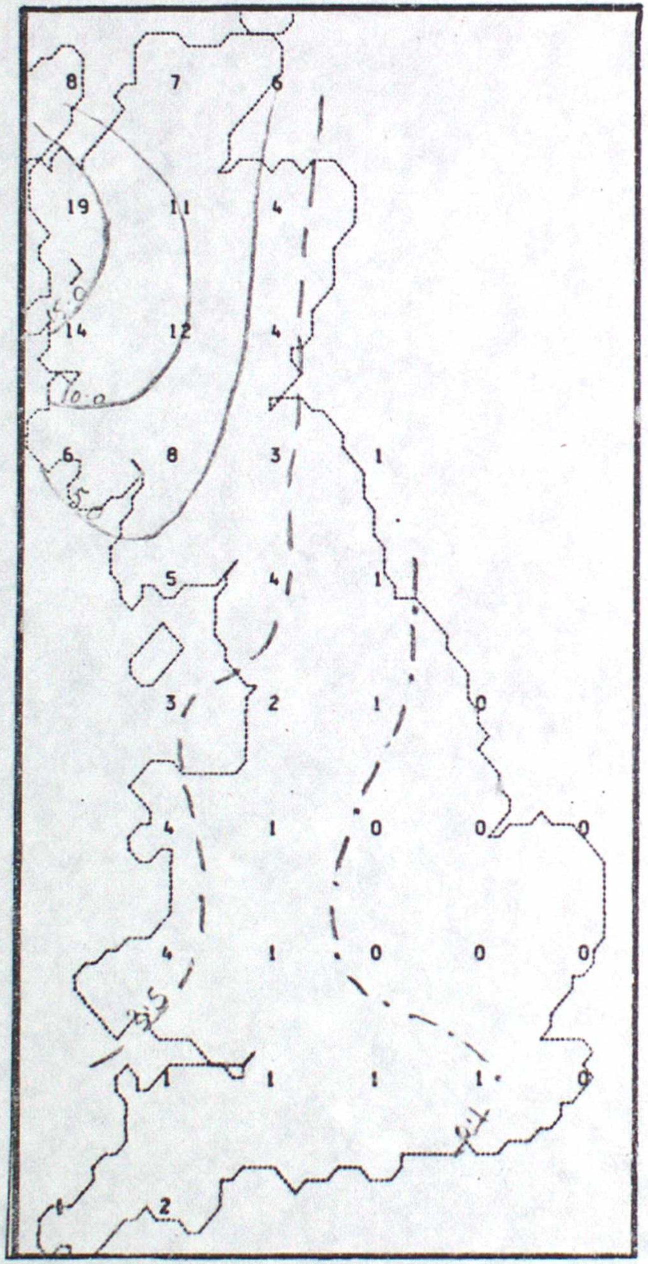
12Z 2/11/78



36 hr forecast using maximum topography

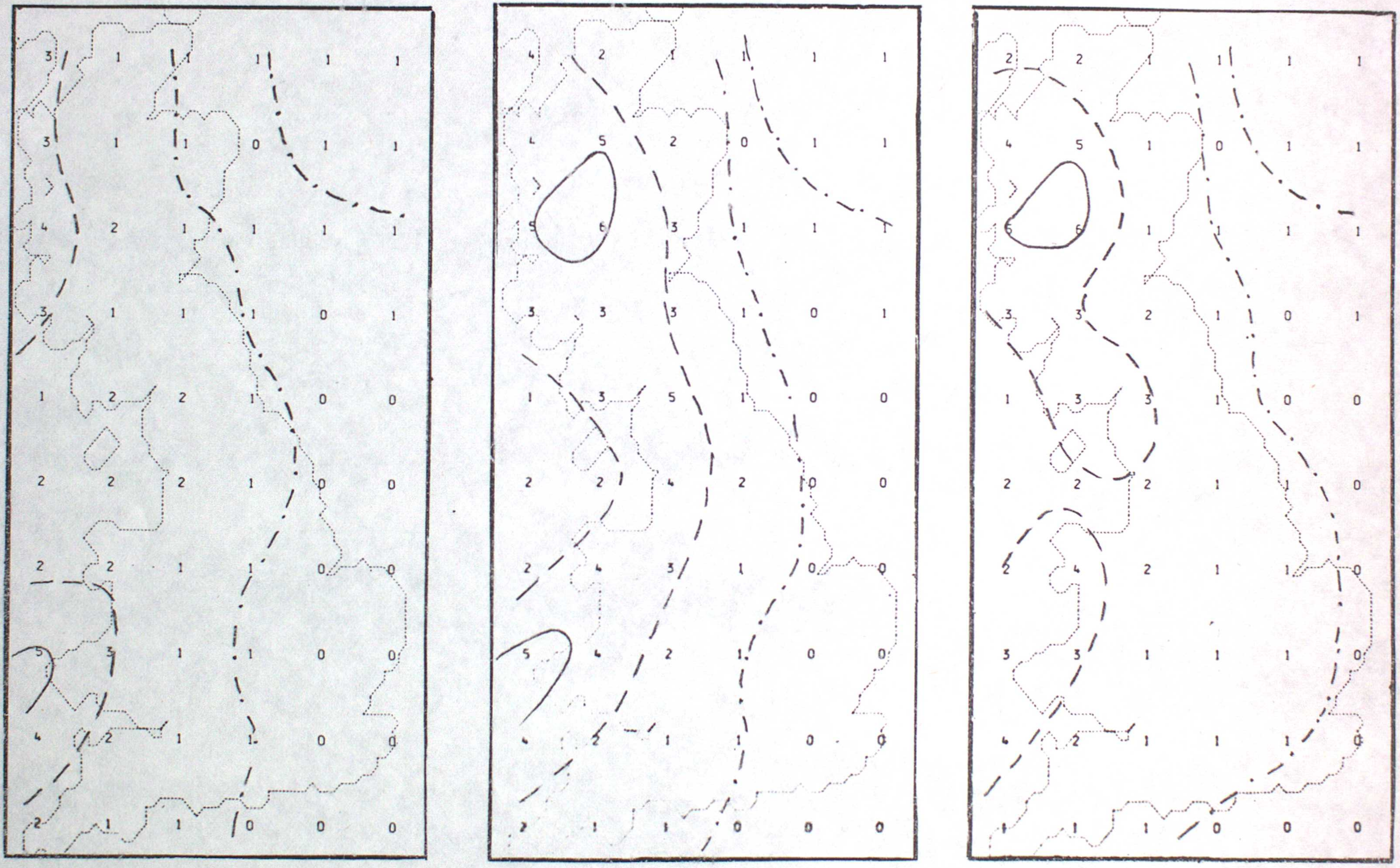
(The key to the rainfall symbols is on page 14)

Figure 2



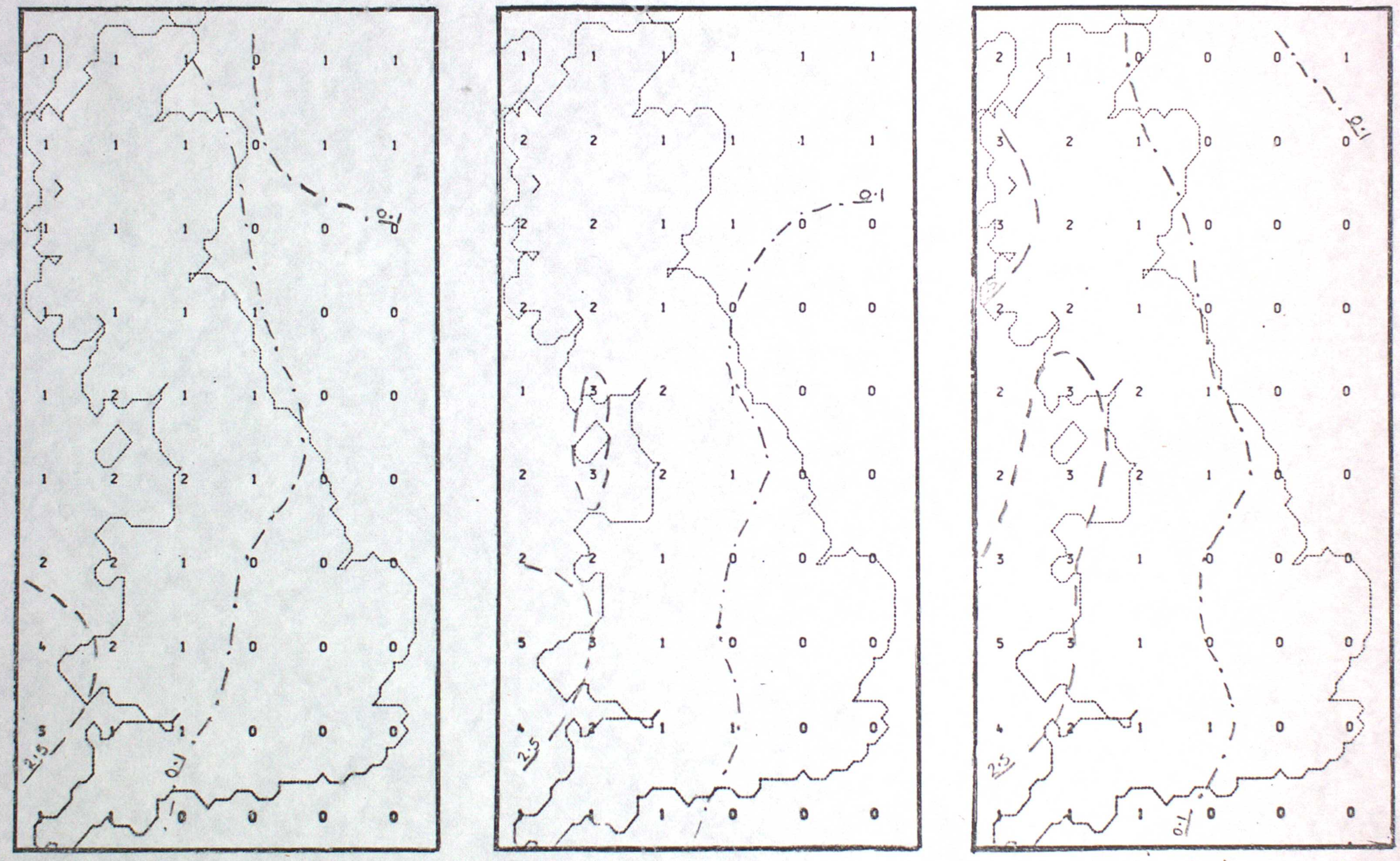
Isohyets drawn at intervals of 0.1 mm (-·-), 2.5 mm (---), 5.0 mm, 10.0 mm etc (—).
Amounts shown are to the nearest mm except for small amounts of rain less than 0.5 mm which are indicated by a 1.
These conventions apply to all the rainfall charts.

Figure 3 - CARP estimates of the 24 hr accumulations of rain starting 9Z 1/11/78.



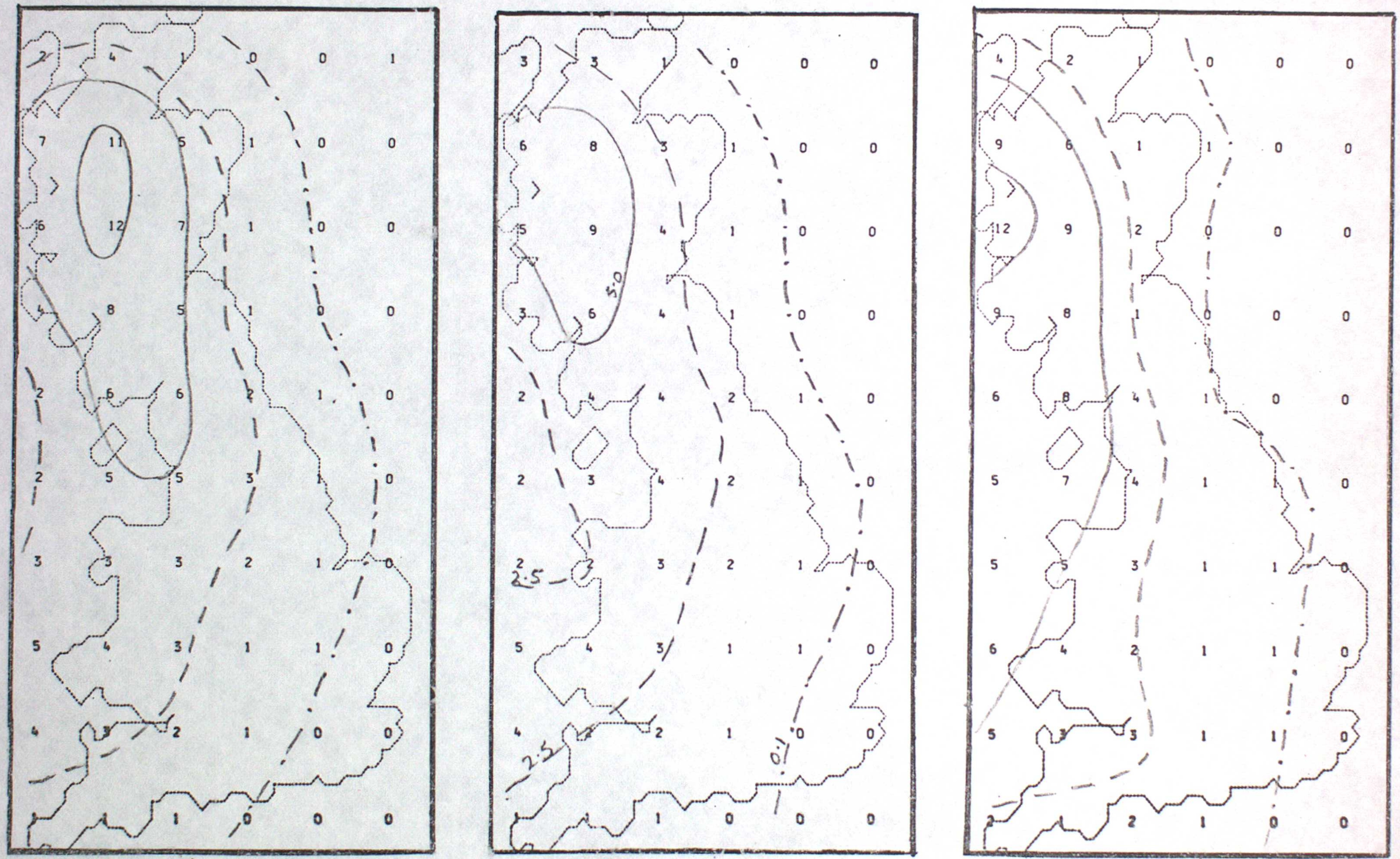
(a) operational model (b) Riddaway model (c) Bell model

Figure 4 - 24 hr accumulations of rain (in mm) starting 9Z 1/11/78 from the Minhinick and Findlater (1979) forecasts.



(a) zero topography (b) operational topography (c) unsmoothed topography

Figure 5 - 24 hr accumulations of rain (in mm) starting 9Z 1/11/78.



(d) subgridscale parameterisation scheme (non-interactive) with unsmoothed topography

(e) subgridscale parameterisation scheme (interactive) with unsmoothed topography

(f) maximum topography

Figure 5 (cont.) - 24 hr accumulations of rain (in mm) starting 9Z 1/11/78

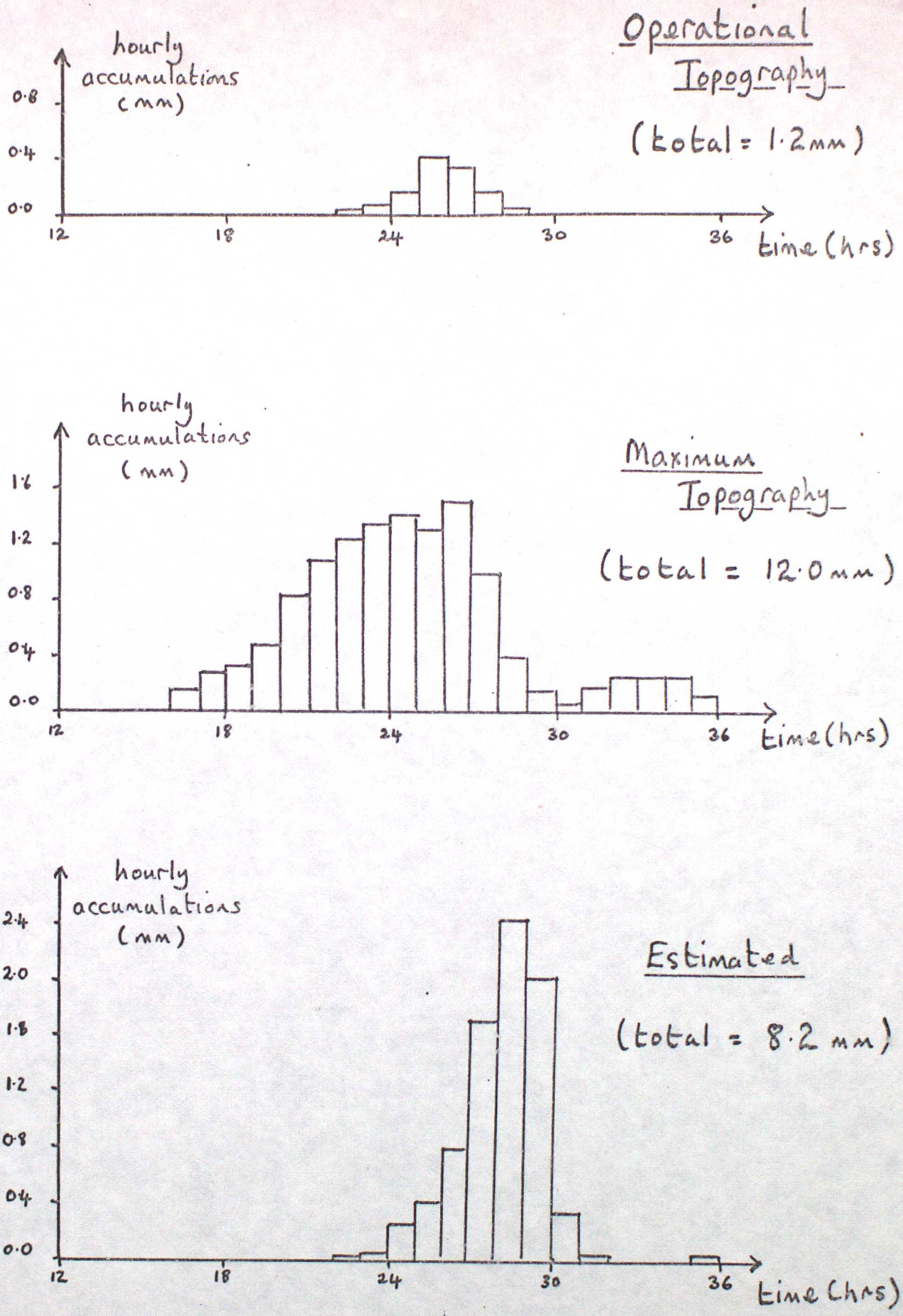


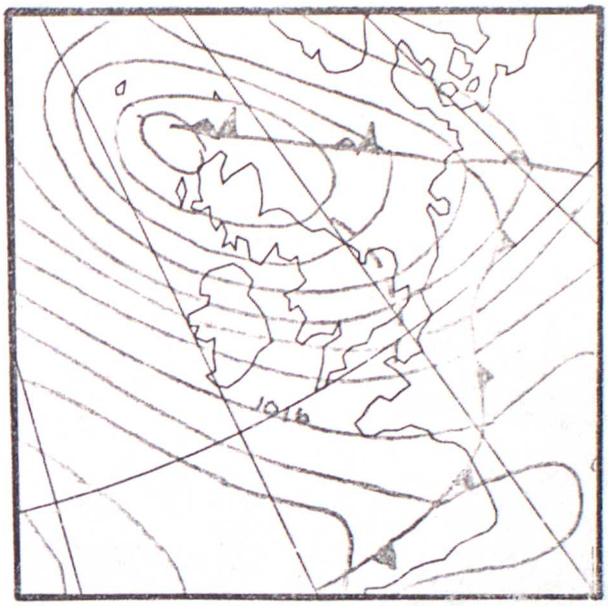
Figure 6 - hourly accumulations of rain for the gridsquare marked in Figure 1.

(a)

00Z 28/9/78

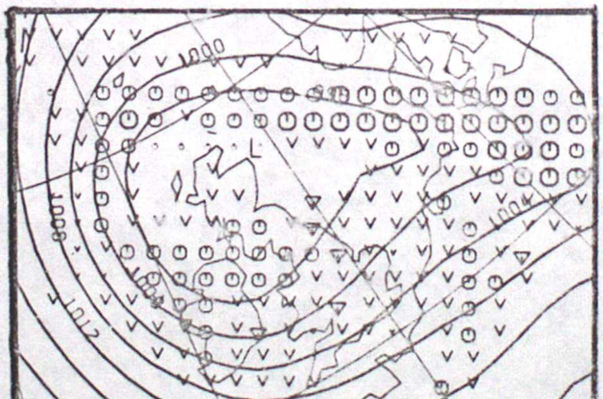
(b)

12Z 29/9/78



(c)

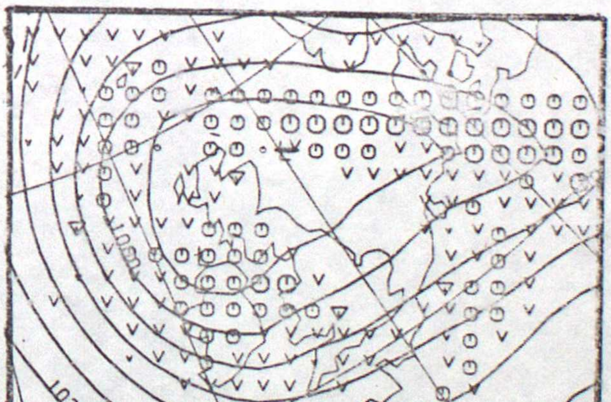
12Z 29/9/78



36 hr forecast using operational topography

(d)

12Z 29/9/78



36 hr forecast using maximum topography

Figure 7

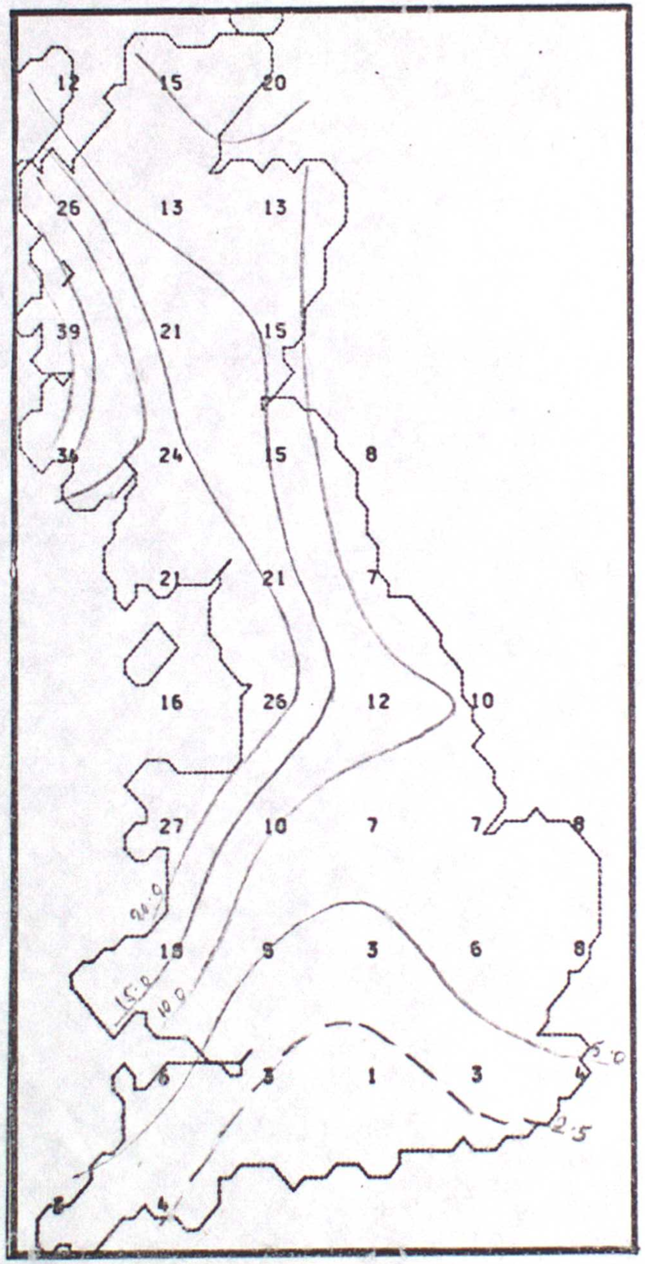
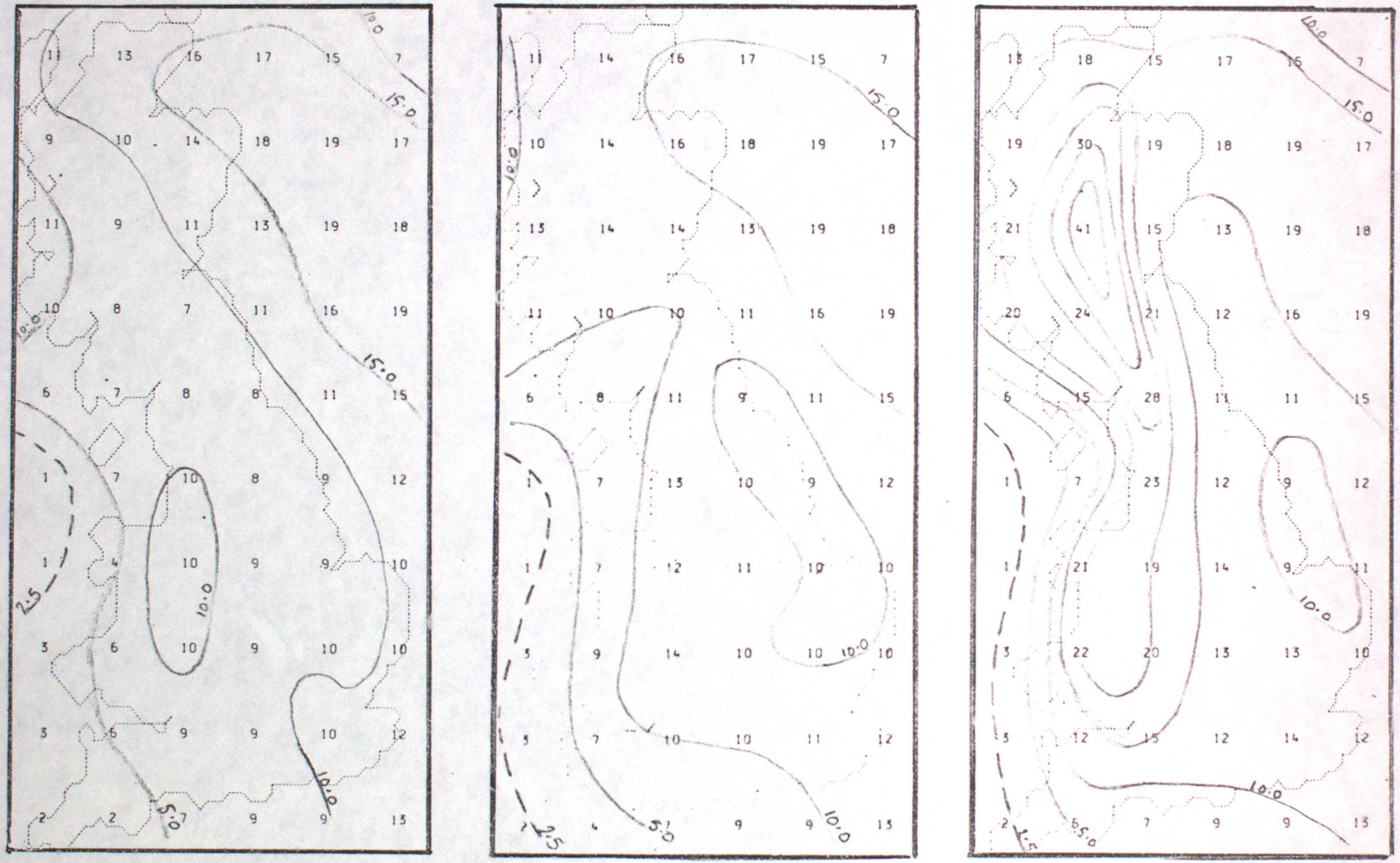
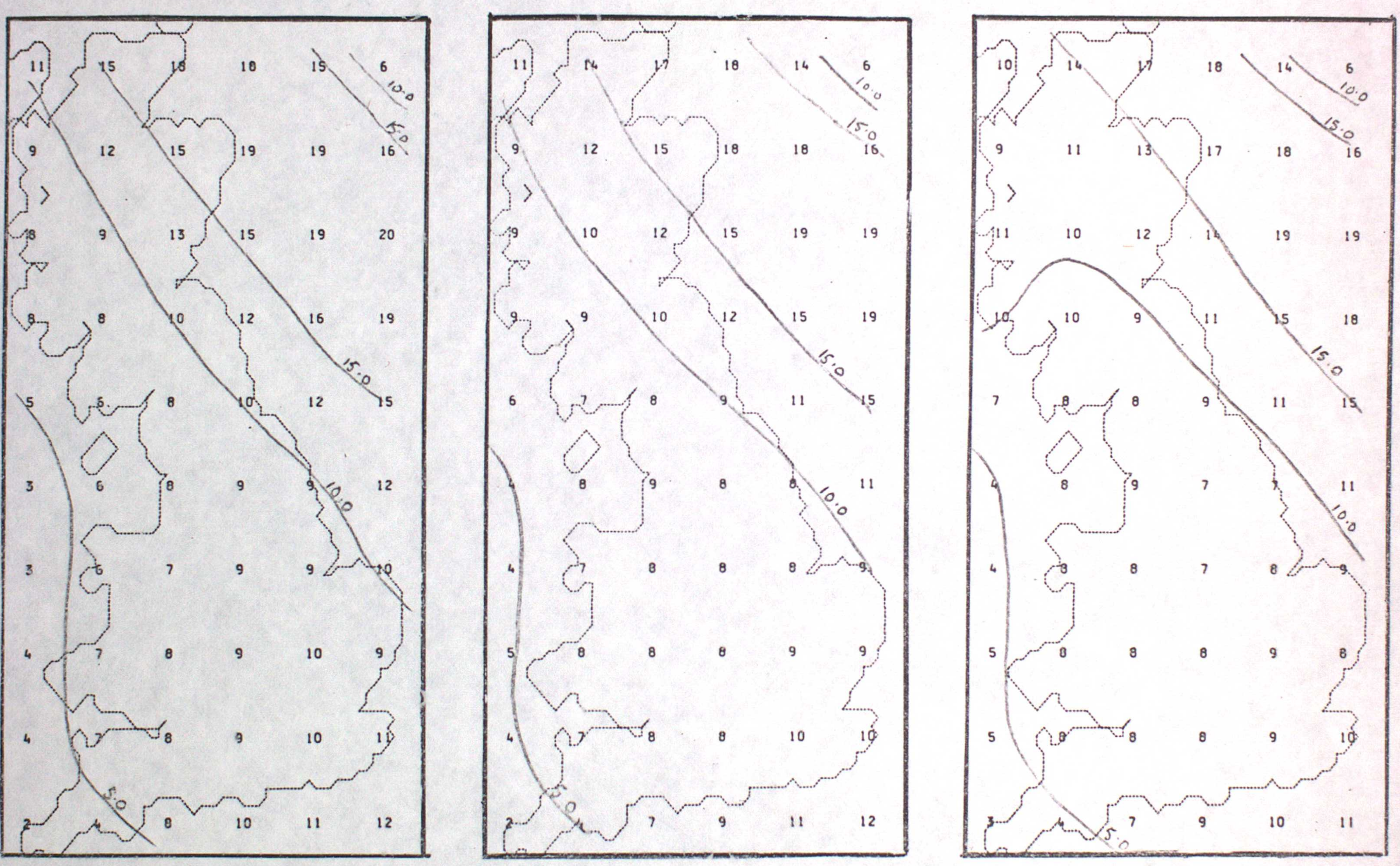


Figure 8 - CARP estimates of the 24hr accumulations of rain starting 09Z 28/9/78



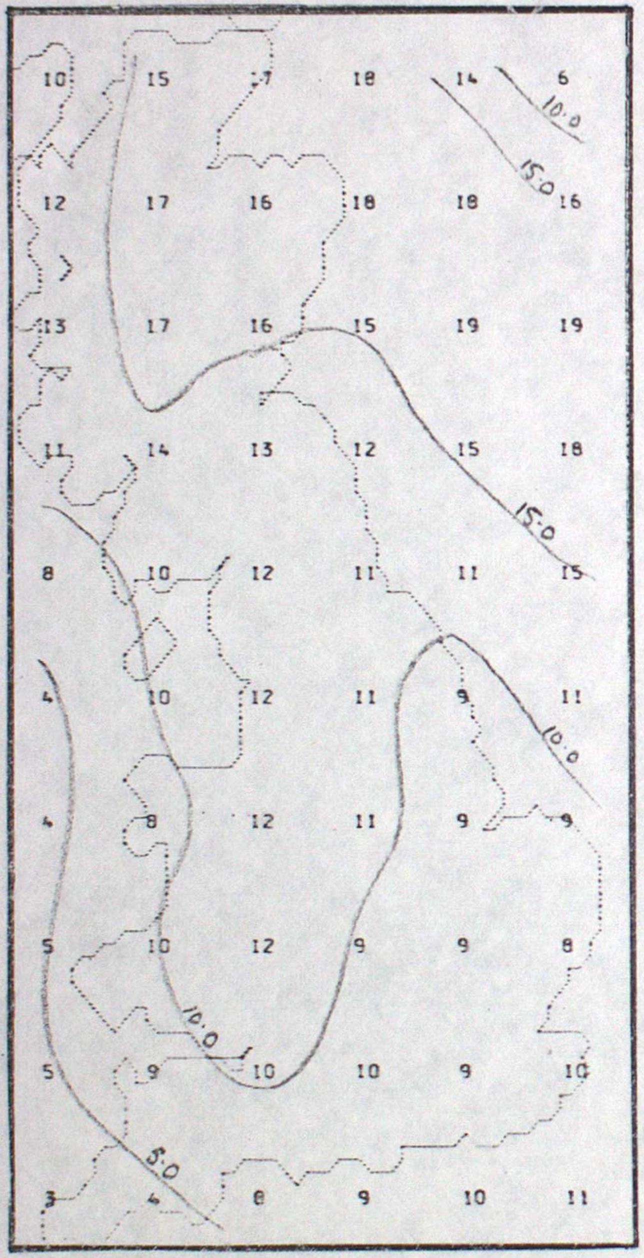
(a) operational model (b) Riddaway model (c) Bell model

Figure 9 - 24 hr accumulations of rain (in mm) starting 9Z 28/9/78 from the Minhinick and Findlater (1979) forecasts

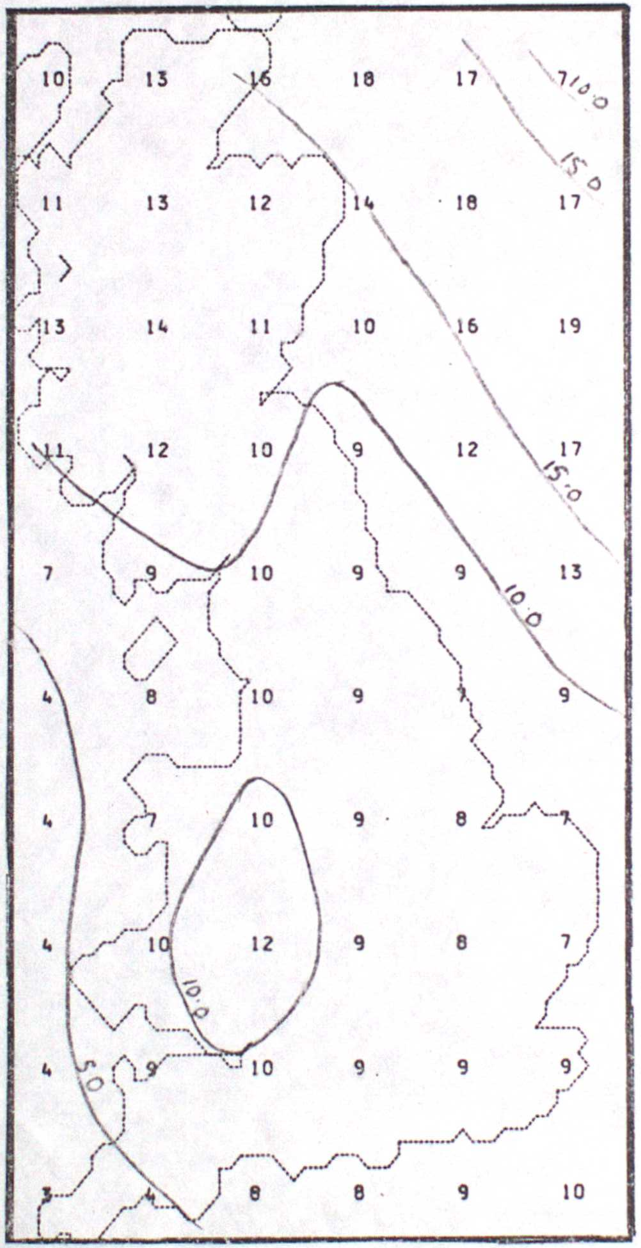


(a) zero topography (b) operational topography (c) unsmoothed topography

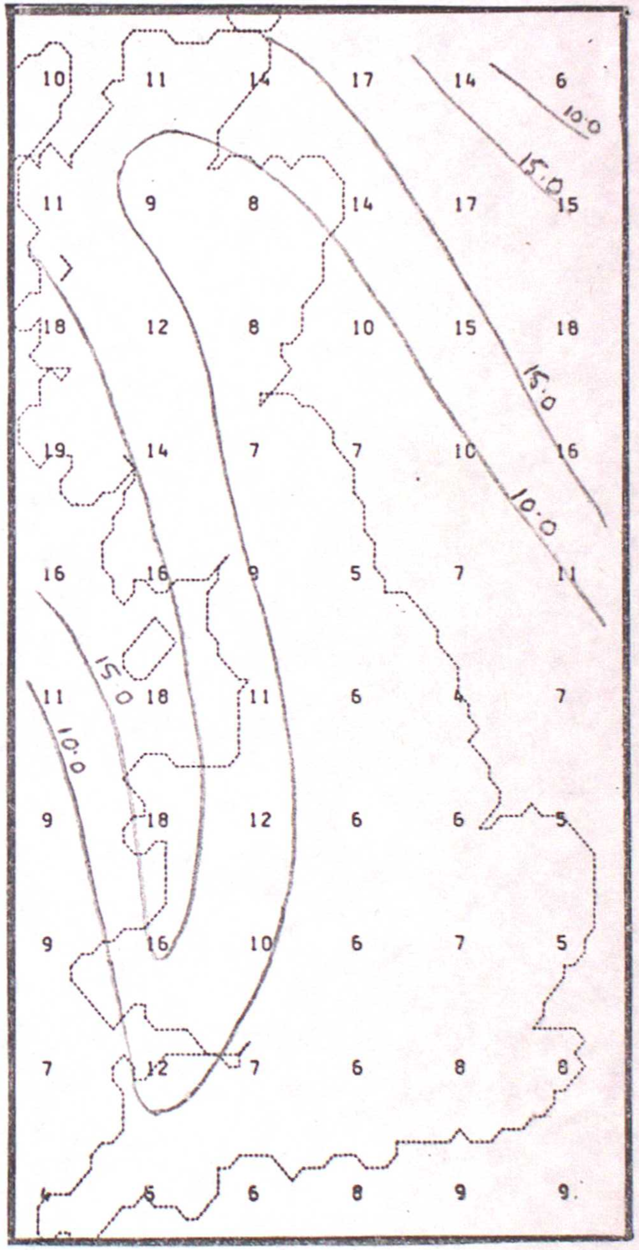
Figure 10 - 24 hr accumulations of rain starting 9Z 28/9/78



(d) subgridscale parameterisation scheme (non-interactive) with unsmoothed topography



(e) subgridscale parameterisation scheme (interactive) with unsmoothed topography

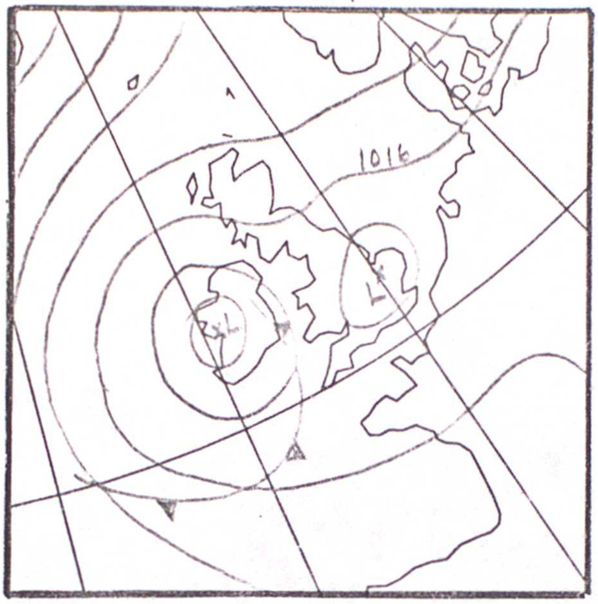


(f) maximum topography

Figure 10 (cont) - 24 hr accumulations of rain starting 9Z 28/9/78

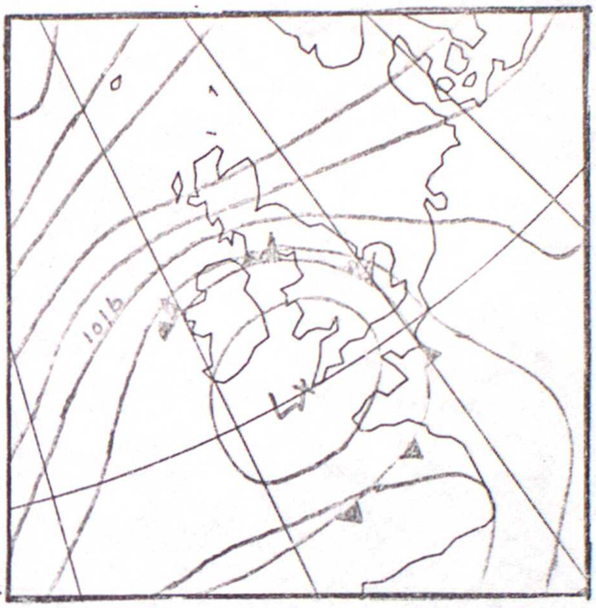
(a)

00Z 7/4/79



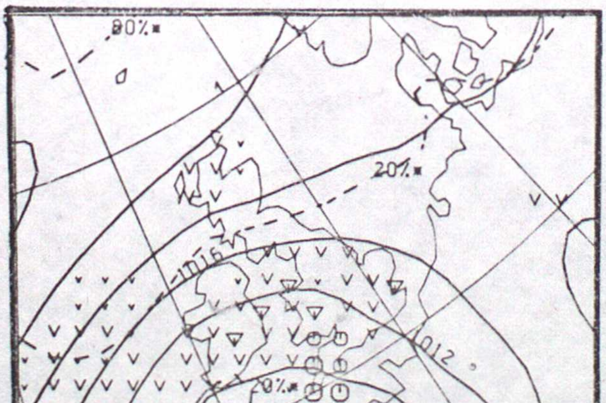
(b)

12Z 8/4/79



(c)

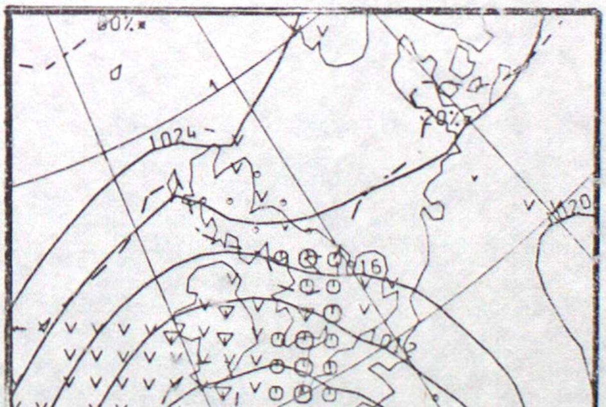
12Z 8/4/79



36 hr forecast using operational topography

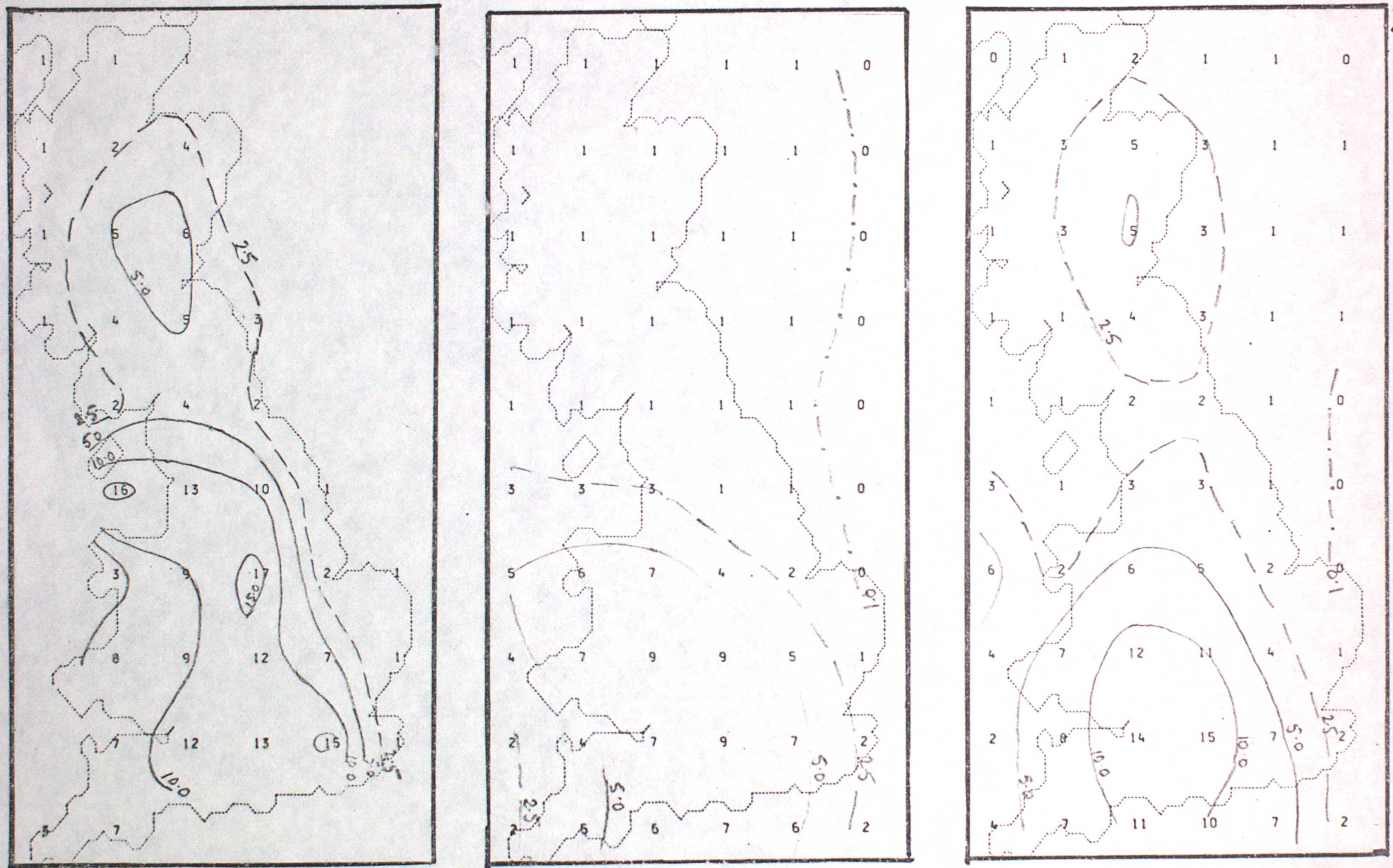
(d)

12Z 8/4/79



36 hr forecast using maximum topography

Figure 11



(a) estimated rainfall (b) operational topography (c) maximum topography

Figure 12 - 24 hr accumulations of rain (in mm) starting 9Z 7/4/79