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**RESEARCH REPORT**

**No.7**

**February 1978**

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PERSISTENCE AND OROGRAPHIC  
MODULATION OF MESOSCALE PRECIPITATION AREAS  
IN A POTENTIALLY UNSTABLE WARM SECTOR

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SUMMARY

In this paper we use data from radars and raingauges in England, Wales and southern Ireland to study the motion and changes in intensity of mesoscale precipitation areas (MPAs) some tens of kilometres across as they traversed two regions of high land and an intervening stretch of sea. The MPAs studied were associated with an area of middle-level potential instability within a windy and moist wintertime warm sector, a situation known to produce major orographic effects. Despite the very large modulation of the rainfall intensity by orography, it was found that most of the MPAs could be tracked for 6 h over a distance of 600 km, all the way from the west coast of Ireland to southeast England. The implications of this are discussed with regard to short period forecasting using radar and satellite data.

1 INTRODUCTION

Many of the largest orographic falls of rain in the hilly parts of western Britain are associated with strong winds in the warm sectors of depressions (Douglas and Glasspoole 1947, Nash and Browning 1977). In a detailed study of one particularly wet warm sector, Browning, Hill and Pardoe (1974) found that most of the rainfall was associated with rather irregularly distributed mesoscale precipitation areas (MPAs) with



characteristic horizontal dimensions of 20 to 50 km. These MPAs were associated with clusters of convective cells generated by a 2 km-deep layer of potential instability (PI) with its top near 600 mb. The MPAs travelled (at typically  $120 \text{ km h}^{-1}$ ) at the velocity of the winds at the generating level and they developed rapidly in both intensity and extent over and upwind of the major hills. It seemed to us that this kind of situation would constitute a severe test of the utility of radar for the short-period prediction of rainfall, and accordingly we set out to examine the behaviour and persistence of rain areas within wet and windy warm sectors.

First we re-examined the case studied by Browning et al (1974) and noted that, despite the high velocity of individual MPAs, they could be tracked for 3 to 5 h (Fig 1). Unfortunately, the period for which they could be tracked was restricted by the limited radar coverage. In the present paper we examine another wet and windy warm sector for which better data are available. The warm sector described here resembles that studied by Browning et al (1974) in that it was characterised by fast-moving MPAs associated with middle-level PI. We have exploited data from a recent field program in which information was available from a weather radar in southwest Ireland in addition to information from our own research radars in Wales and central England. This permitted us to observe rain areas as they crossed two areas of high ground separated by the Irish Sea. As a result, we have been able to demonstrate that, although there were very large modulations in surface rainfall owing to the influence of surface topography, most of the MPAs could be tracked for 6 h over a distance of 600 km from the west coast of Ireland to southeast England. The implications of this for forecasting are discussed.



## 2 THE CASE STUDY

### (a) Nature of the Data

From January to March 1976, a mobile 10 cm weather radar from our laboratory was located near Pembroke (location P in Fig 2) to observe the pattern of rainfall during the passage of frontal systems. The high-powered 10 cm radar at Defford (D) was also available to extend the coverage across the English Midlands. The coverage over Wales and the Midlands was completed by incorporating data from the 5.6 cm radar operated by the Dee Weather Radar Project at Llandegla (L). In addition the Irish Meteorological Service provided hourly photographs of the PPI display of the 10 cm radar at Shannon Airport (S) in western Ireland. In order to calibrate the radar data and also to extend the analysis to include those parts of Ireland and southern England which could not be observed adequately by the radars, we have used autographic raingauge data supplied from several sources.

The upper-air analyses shown in this paper incorporate data from the regular radiosonde network together with eleven radiosonde ascents which we launched over a fifteen-hour period from the radar site near Pembroke. Several extra ascents were also flown by the radiosonde staff at Camborne and Aughton (C and A in Fig 2).

### (b) Synoptic Description

Fig 3 shows the surface analysis and the satellite nephanalysis at 0900 GMT on 12 February 1976. The nephanalysis is based on high-resolution VHRR images in the visual and infra-red bands. The surface warm front (SWF) was moving eastwards at  $60 \text{ km h}^{-1}$  and, as is shown later, a large area of rain was covering England and Wales at this time. Rather less rainfall than is usual for an occluding frontal system affected Scotland; indeed the satellite shows a weakness in the cloud structure over southern Scotland with an area of broken cumuliform cloud approaching from the west. Continuous



cloud covered much of the warm sector, extending 1000 km behind the SWF, to the northwest of Ireland. As we show shortly, much of the cloud in the warm sector appeared to have been associated with middle-level PI, mainly in the layer 800 to 600 mb. The analysed surface cold front (SCF) marked the northern limit of the continuous cloud and PI, but otherwise it was a weak feature.

In order to portray the plan distribution of middle-level PI and the likelihood of its being realised, we show in Fig 4 the difference in the values of the wet-bulb potential temperature ( $\theta_w$ ) at 800 and 600 mb as a measure of the stability and also the maximum dew-point depression (DPD) in the layer 800 to 600 mb as a measure of the humidity. Previous sequences of sondes which we have launched at intervals of one to two hours have shown that if  $\theta_w$  (as measured by Mk IIb sondes) increases by less than about  $1^\circ\text{C}$  over this layer then regions of significant PI are likely to exist somewhere within it. A maximum DPD of  $7^\circ\text{C}$  or less (as measured by Mk IIb sondes) appears to be associated with areas of fairly widespread precipitation. A combination of these properties gives the appropriate conditions for precipitation within a potentially unstable airflow.

The analysis for the 800-600 mb layer, shown in Fig 4, indicates that the air was dry at these levels in a zone extending WNW-to-ESE across Scotland, but moist in the warm sector and ahead of the SWF. The 800-600 mb layer was markedly stable where the warm frontal zone intersected it beyond about 100 km ahead of the SWF but it became less stable close to the SWF and within the warm sector. The combination of PI and moist air necessary for the occurrence of middle-level convection prevailed throughout much of the warm sector.

A more detailed view of the vertical distribution of  $\theta_w$  and relative



humidity is shown in Fig 5 which is a time-section based on the radiosonde data obtained from Pembroke from early morning until the evening. This shows that at midday thin layers of PI were observed between 700 and 300 mb. These layers became deeper within the warm sector and lowered to 850 mb at times, but the top descended to 500 mb after 1500 GMT in association with the downward penetration of dry air aloft.

(c) General description of the precipitation patterns

The location of the principal rainfall areas in relation to the surface fronts is indicated in Fig 6, which shows the hourly rainfall totals at intervals of three hours. The original analyses were made for each hour using the amounts shown on the autographic charts, but first the indicated rainfall maxima which marked the passage of MPAs were compared with the radar patterns so as to eliminate major timing errors. Some of the MPAs have been given letters to assist in the identification of their movement and to relate them to the more detailed radar data shown later.

During the main period of warm-frontal rain, the heaviest falls were over the hills of north and mid-Wales. The large rainband marked A, which was located just to the east of the region of maximum surface pressure falls, gave fairly general rainfall. Between this band and the SWF the rainfall patterns were more irregular, much of the variability being induced by the topography. As the surface winds near the SWF gradually veered to WSWly, sheltering by the hills of SW Ireland caused SE Ireland and neighbouring parts of the Irish Sea to become rain-shadow areas. On the Pembroke radar display the large area of rain over Wales and SW England was in sharp contrast to the more scattered rain areas to the west. During this time the rear edge of the area of widespread rain advanced eastwards only slowly because the initially weak rain areas to the west were enlarging while crossing Cardigan Bay and the Bristol Channel and were merging to become part of the area of widespread rain. Area B is an example of an MPA which ran to the south of the sheltered area of SE Ireland to merge with the orographically enhanced rain over Devon.



By midday the SWF had reached the west coast of Wales, and there was a rain-shadow over central England. Although drizzle and slight rain occurred generally over the Midlands, only the MPA labelled C gave significant rainfall there. This MPA was clearly in the warm sector when it reached NW Ireland at 0900 GMT and appears to have originated about 100 km south of the SCF. Moving at about  $100 \text{ km h}^{-1}$ , it caught up with the SWF over north Wales at 1300 and was still detectable as it crossed SE England around 1700. Thus the rain near the SWF was probably due to the widespread ascent of the low-level warm, moist and stable air, occasionally intensified by precipitation generated at mid-levels within fast-moving MPAs which formed within the large area of PI in the warm sector and overran the SWF.

During the afternoon numerous MPAs within the warm sector (eg D, E, F, G, H) moved ESE'ward across Ireland at 95 to  $110 \text{ km h}^{-1}$  toward south Wales and southwest England. It is not possible to get a clear impression of the persistence and life history of these MPAs by reference to the relatively infrequent observations depicted in Fig 6. In particular it is not clear from Fig 6 the extent to which these MPAs diminished in intensity as they crossed the Irish Sea and were invigorated upon encountering high land again in Wales and southwest England. To bring out these features as vividly as possible we use a different form of presentation shown shortly in Fig 7.

#### (d) Persistence and orographic modulation of the MPAs

Most of the MPAs which occurred within range of the Shannon radar (location S in Fig 2) subsequently moved across the area covered by the radar at Pembroke (P in Fig 2). Their mean direction of travel was from  $298^\circ$ . We have defined four lines oriented at right angles to this direction -  $y_1y_1$ ,  $y_2y_2$ ,  $y_3y_3$ , and  $y_4y_4$  in Fig 2 - and have generated four corresponding t-y diagrams from the sequence of PPI photographs obtained from these radars so as to represent the passage of the MPAs across each of these lines in



turn. The lines have been chosen to be at nearly the same range upwind and downwind of their respective radars in order to minimise differences in echo intensity due to differences in range. Because PPI data were available only at discrete intervals (8 min for the Pembroke radar and 1 hr for the Shannon radar), continuity in time has been achieved by appropriate space-time conversions based upon the known velocity of the MPAs. The resulting four t-y diagrams in Fig 7 have then been displaced relative to each other according to the mean velocity of the MPAs so that corresponding MPAs are located beneath one another in each of the diagrams for easy comparison.

Fig 7 shows that most of the MPAs in the warm sector could be identified in each section. In some cases, owing to either relative motion between the cells or ~~the~~ development of new cells, the detailed structure altered. However, the basic mesoscale patterns can be seen to have been well preserved. We also see that only a skeleton of the middle-level structure was observed as the rain areas crossed the Irish Sea (section  $y_3y_3$ ), this being followed by a substantial enhancement of the echo intensity as the precipitation areas moved toward the coasts of Devon and South Wales (section  $y_4y_4$ ). In contrast, the radar echo intensities in the sections over western and central Ireland do not seem to have been radically different from one another. This does not imply that the surface rainfall was the same in sections  $y_1y_1$  and  $y_2y_2$ , for the Shannon radar would not have detected low-level growth in section  $y_2y_2$  due to intervening hills.

The persistence, and the pronounced orographic modulation of the intensity, of a warm sector MPA is shown clearly in Fig 8, which depicts the total surface rainfall during the passage of the short band of MPAs labelled D in Fig 7. The increase in rainfall over central Ireland may have been slightly larger than is indicated as most of the gauges there



are on low ground. Nevertheless, the rainfall minimum extending from SE Ireland to Pembroke is clearly evident, as is the rapid increase in rainfall over south Wales, the Bristol Channel and Devon. Altogether this MPA was trackable for a period of 6 h as it travelled from western Ireland to south-east England.

- (e) The nature and amount of rain associated with the MPAs compared with the warm frontal rain

Figs 9(a) and 9(b) show the distributions of total rainfall from the relatively uniform warm frontal rain and the warm sector MPAs, respectively, based mainly on the charts from 40 autographic raingauges in Ireland and about 200 over England and Wales. In order to improve the analysis over Ireland, where the network of recording gauges does not reveal the orographic complexity, the percentages of the total system rainfall which could be attributed to the warm front and warm sector were plotted for each autographic site, a field of percentages was drawn and this field was applied to the network of daily measurements. The division between the rainfall produced in the warm sector and that attributable to the warm front has taken account of those MPAs which remained easily identifiable as they began to overrun the SWF. This has been done by drawing a line parallel to the SWF and located just ahead of the MPA labelled C in Fig 6. That a change in the character of the surface rainfall did occur near this line is indicated by the rainfall records from the four sites in mid-Wales reproduced in Fig 10. The continuous warm frontal rain clearly changed to a more intermittent type around midday with the arrival of MPAs associated with middle-level PI.

The warm sector MPAs contributed on average about 35% of the total system rainfall (over 50% in parts of southern Ireland and southern England which had been in a rain-shadow during the passage of the warm frontal rain area) but they contributed only 10-20% over the west coast of Ireland and Wales.



We estimate that in the warm sector 2 to 5 mm of rain occurred on the west coast of Ireland, 1 to 3 mm on the east coast of Ireland, and 2 to 4 mm on the west coast of Wales. Hence there is no strong evidence to show that the rainshadow which existed at short ranges to the lee of the Irish hills extended as far as the coast of Wales. There was, however a rapid invigoration of the MPAs as they approached high ground, such that the warm sector made a substantial contribution to the system rainfall on the hills both as a magnitude and as a percentage. Thus, for example, the total system rainfall of 18 mm on the west coast of Wales at Aberporth (Site 1 in Fig 2) was distributed between the warm front, warm sector and cold front in the ratios 12 : 4 : 2, whereas 30 km inland amongst the hills at Lampeter (Site 2 in Fig 2) the total rainfall of 40 mm was distributed in the ratios 22 : 14 : 4, ie proportionately much more rain from the warm sector MPAs than at Aberporth.

Fig 10 shows that the same MPAs which crossed Aberporth could be identified 20 min later downwind at Lampeter, although with much increased intensity. However, on the higher ground of Moel Cynnedd the orographic enhancement of MPAs was sometimes such that the individual MPAs which earlier had crossed Penglais almost lost their identity. Once again, though, the relative importance of the warm sector MPAs was far greater inland, for whereas the 24 mm of rain on the coast at Penglais was distributed between the warm front, warm sector and cold front in the ratios 19 : 4 : 1, the 75 mm of rain which fell downwind at Moel Cynnedd was divided in the ratios 38 : 31 : 6.

### 3 APPLICATION TO SHORT-PERIOD FORECASTING

The fact that more rain tends to fall in the broad area of continuous rain ahead of the warm front than from the mesoscale precipitation areas (MPAs) in the warm sector might at first appear to reduce the significance of the present study. However, it is easier to forecast the broad-scale frontal rain using current numerical and subjective techniques than it is to handle the potentially unstable regions characterised by weak large-scale convergence which give rise to the MPAs in warm sectors. For some forecasting



purposes a general statement in terms of there being a likelihood of intermittent rain would provide adequate guidance. But there are users of forecasts, such as Water Authorities, for whom the duration and amount of rain following a period of heavy warm frontal rain may be of great concern. This is especially so for Authorities whose catchments extend into the hilly western areas because, as shown in this study, although MPAs give relatively little rain over low land, the MPAs are strongly modulated by topography and can give heavy falls of rain over high land.

It is encouraging from a forecasting point of view that the MPAs which travelled from western Ireland to southern England remained as recognisable entities over a period of 6 hours. The MPAs could be followed for almost as long in the warm sector studied by Browning et al (1974). In both cases the limiting factor was the range covered by the radar network rather than the transformation of the MPAs. Given a better coverage of radars, mesoscale features such as these MPAs can be expected to become amenable to more precise short-period forecasting. Even so, a problem with the limited westward coverage provided by radars located on the mainland of England and Wales, is that there would in the present cases for example have been only about an hour's notification of the position and track of individual MPAs approaching the hills of Wales and southwest England. Another problem is that the MPAs, while over the sea, may travel in a skeletal form, producing very little rain. Thus the radars are liable to underestimate the rainfall which the MPAs later produce over the hills. The increase in the extent and intensity of rainfall over the hills probably arises not only from the normal orographic intensification due to increased uplift and rate of condensation, but also occasionally from an increase in the vigour of the middle-level convection over the hills.



It will be helpful for forecasting purposes to ensure there are very sensitive radars with good seaward horizons. They will then be able to detect the skeletal MPAs as far upwind as possible. However, the results in the present paper suggest that, for MPAs travelling from the west, the most promising method of anticipating the intensity of the rain from the MPAs when they reach the hills in England and Wales will be to observe their previous intensity as they cross the hills of Ireland. This idea has been carried a step further by Harrold (1975). He proposed that by running a fine-scale numerical model which takes into account the detailed local topography and comparing the predicted rainfall with the rainfall actually observed over the hills of Ireland, it should be possible to calculate an orographic rainfall efficiency factor which could then be applied to the rainfall predicted by the model over the Welsh hills when the same rainfall areas subsequently reach that region.

#### 4 CONCLUSIONS

Mesoscale areas of precipitation (MPAs) associated with potential instability at medium levels in the warm sectors of wintertime depressions have been observed to persist for many hours as they travelled 600 km from west to east across the British Isles. The MPAs, which were typically 20 to 50 km across (larger near hills), were too small to be resolved without the help of radar. They travelled much faster than the associated frontal system and some of them moved through the warm sector to merge with the more uniform area of warm frontal rain. The wind at 650 mb was a useful first approximation to their movement on the occasions studied, but the rapid identification of their location and motion by means of radar is necessary if their paths are to be accurately predicted.

The intensity of the rainfall from the MPAs was modulated strongly by topography; some of the MPAs produced barely a trace of rain at lowland sites while giving 30 min to 1 hr of heavy rain on suitably exposed hills



in Wales and Southwest England. Over the sea between Ireland and the mainland of England and Wales they appeared to travel in skeletal form, only to be invigorated upon encountering high land.

This scale of feature is likely to become more amenable to prediction when an operational radar network is established. With a network covering only the mainland of England and Wales, there would have been about three hours' notification of the existence and movement of the MPAs before they reached eastern England but only about one hour's advance warning over western areas. Thus it will be beneficial to incorporate radar data from Ireland into this network in order to extend the period over which detailed forecasts may be issued in situations of strong westerly flow. It is not yet clear to what extent the MPAs can be identified by satellite imagery alone but the use of frequent sequences of data from a geosynchronous satellite may prove to be helpful. Although we must not expect too much in the way of precise estimates of rainfall amounts for specific locations, the combination of radar and satellite data can be expected to lead to major improvements in the forecast timing of rainfall events for periods of a few hours ahead.

#### ACKNOWLEDGEMENTS

The authors are grateful to the following organisations and individuals for their contributions as listed: the Irish Meteorological Service for photographs from the weather radar at Shannon Airport, for daily raingauge totals, and for autographic raingauge charts; the Director of the Centre for Industrial Research and Consultancy, University of Dundee, for the supply of high resolution satellite imagery; the radiosonde teams at Aberporth, Aughton and Camborne for launching non-routine ascents; the technical staff of the Dee Weather Radar Project and of the Royal Signals and Radar Establishment, Malvern for data from the radars at Llandegla and



Defford respectively; the technical and radiosonde teams of the Met Office Radar Research Laboratory, Malvern, for radar and radiosonde data at Pembroke; numerous observers, local councils and river authorities for raingauge charts; the Agriculture and Hydrometeorology branch of the Met Office, Bracknell, for additional rainfall data; Dr W T Roach for helpful comments on the manuscript. Copyright © Controller HMSO, London, 1978.



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## FIGURE LEGENDS

- Fig 1 : Tracks of five MPAs observed with a network of three radars on 5 December 1972. Radar sites are indicated by D (Defford), G (Gower) and L (Llandegla). The inset shows the location of the five MPAs labelled A to E and of all other MPAs observed at 1747 GMT.
- Fig 2 : Locations of radars used on 12 February 1976: Defford (D), Llandegla (L), Pembroke (P) and Shannon (S). Circles show the effective coverage of this network. Lines specify location of the four t-y sections shown in Fig 7. Crosses indicate sites of raingauges used in Fig 10: Aberporth (1), Lampeter (2), Penglais (3) and Moel Cynnedd (4). The main hills are indicated by the solid contour at 300 m.
- Fig 3 : Surface analysis for 0900 GMT on 12 February 1976 and the nephanalysis at approximately 0936 GMT for orbit 5681 of the NOAA4 satellite. Dense stippling shows main areas of continuous Cirrostratus (Cs); lighter stippling shows cloudy areas (C) with tops mainly to medium levels but with patches or small bands of Cirrus above; areas labelled MCO were mainly covered by low cloud; areas of nil cloud or only scattered low cloud are indicated by MOP.
- Fig 4 : Stability and humidity analysis for the layer 800 to 600 mb at 1200 GMT on 12 February 1976. Differences in the  $\theta_w$  at 600 mb and 800 mb are shown by the contours at  $1^\circ\text{C}$  (thin line) and  $3^\circ\text{C}$  (thick line). Regions liable to potential instability (PI) are hatched. Maximum dew-point depression in the 800/600 mb layer is shown by the broken lines at  $7^\circ\text{C}$  and  $14^\circ\text{C}$ . Regions of dry air are emphasised by stippling. Solid triangles show upper-air stations which launched radiosondes between 1130 and 1230 GMT. Open triangles show the estimated location with respect to the frontal system of additional ascents launched at Pembroke and Camborne between 0800 and 1800.
- Fig 5 : Time-height section derived from radiosondes launched at Pembroke on 12 February 1976. Continuous lines show wet-bulb potential temperature ( $\theta_w$ ) in  $^\circ\text{C}$ . Broken lines show the 80% and 50% contours of relative humidity with respect to ice, the drier regions being emphasised by stippling. Vertical bars show layers of potential instability. Times of launch are indicated by balloon symbols at the foot of the diagram.
- Fig 6 : Hourly rainfall totals on 12 February 1976 plotted at three-hour intervals. Contours are drawn at 0.1 mm (dashed line), 0.5 mm (continuous line), 1.0 mm (single hatching), 2.0 mm (double hatching) and 4.0 mm (cross-hatching). Letter A indicates the main rainband associated with the warm front. Letters B to H indicate MPAs, some of which are shown in greater detail in Fig 7.



- Fig 7: Time sections of radar echoes crossing the four lines,  $y_1y_1$ ,  $y_2y_2$ ,  $y_3y_3$  and  $y_4y_4$ , shown in Fig 2. Time (GMT) is labelled at two-hour intervals along the middle of each section. Each strip is 150 km wide. The shaded and unshaded echoes correspond to rainfall intensities of approximately 2 and 0.5 mm h<sup>-1</sup> respectively, but take no account of orographic enhancement below the radar beam.
- Fig 8: Total rainfall associated with the band of MPAs identified as D in Fig 7 during its passage across Ireland, Wales and England. The outer limits of the MPA and its time of passage across each rainfall station were determined by radar but the amounts of rain were taken from the autographic charts after adjustment for any timing errors.
- Fig 9 Total rainfall associated with (a) the warm front and (b) the warm sector (excluding rain just ahead of cold front). Contours are drawn for 2 mm (dashed line), 5 mm (single hatching), 10 mm (double hatching), 20 mm and 30 mm (cross hatching and 40 mm (solid).
- Fig 10 Comparison of rainfall intensities for two pairs of raingauges located along the direction of travel of the rain areas on 12 February 1976. Each pair comprises a coastal and inland site (see locations in Fig 2). The histogram for Lampeter has been displaced by 20 min with respect to that for Aberporth, corresponding to the time of travel of MPAs between the two sites. Similarly there is a 10 min displacement between Moel Cynnedd and Penglais. The letters refer to the Rainband A and to the MPAs shown in Figs 6 and 7.



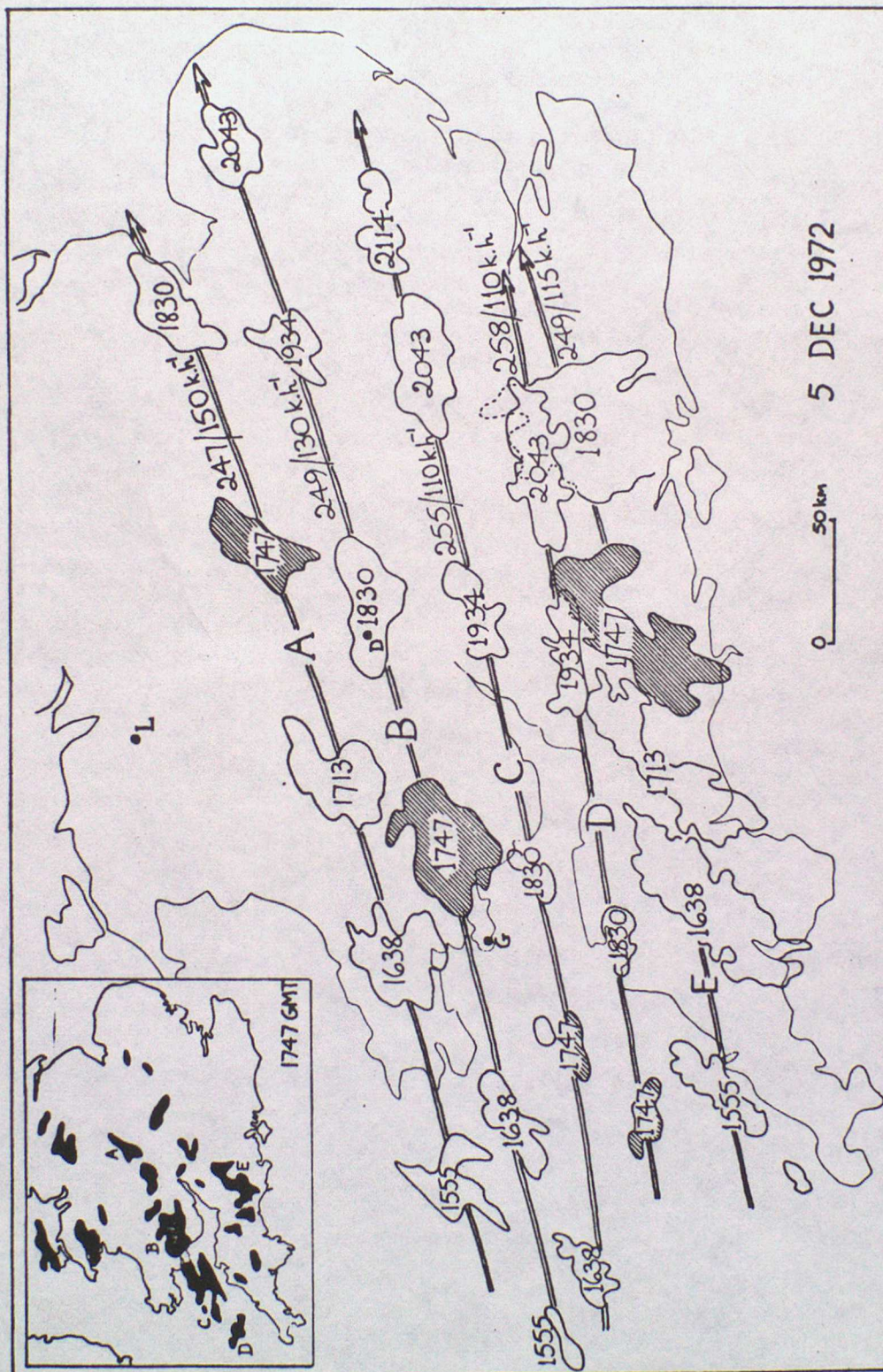


FIG 1



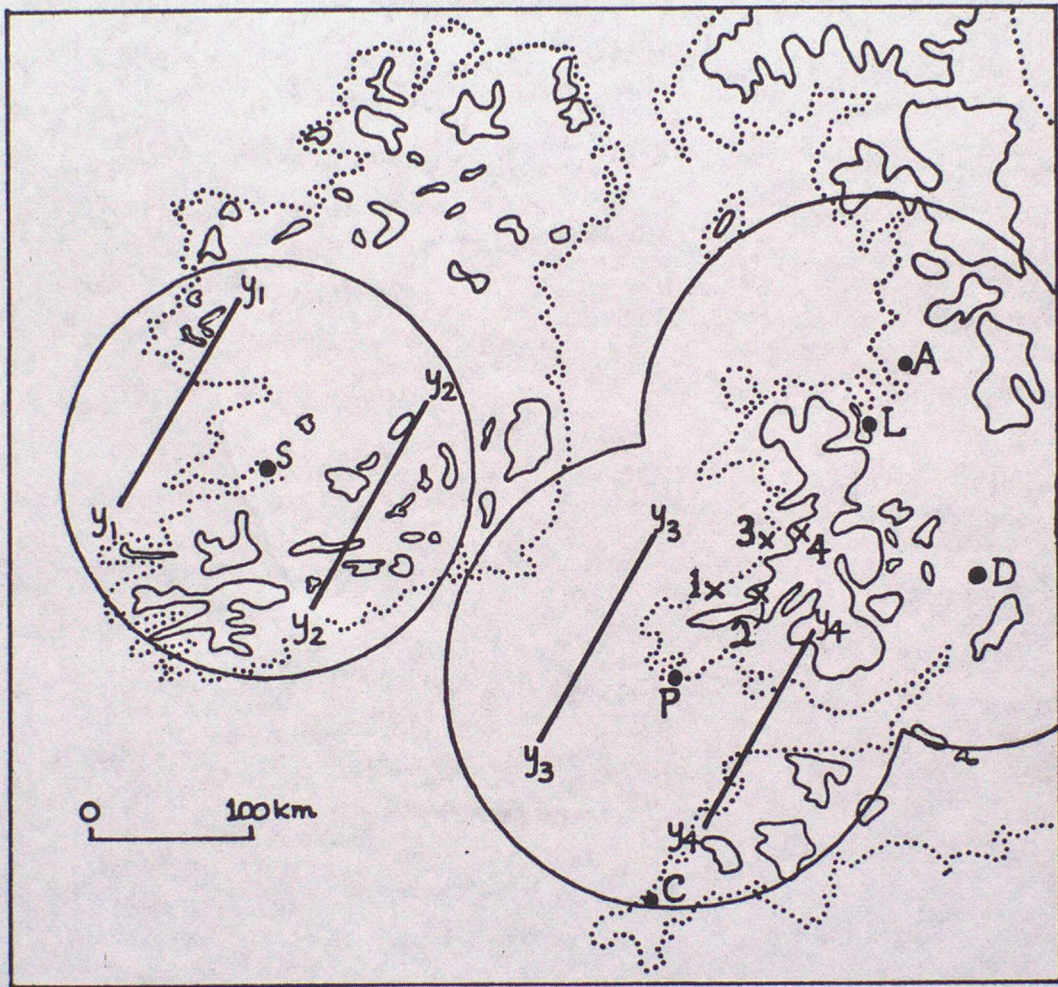
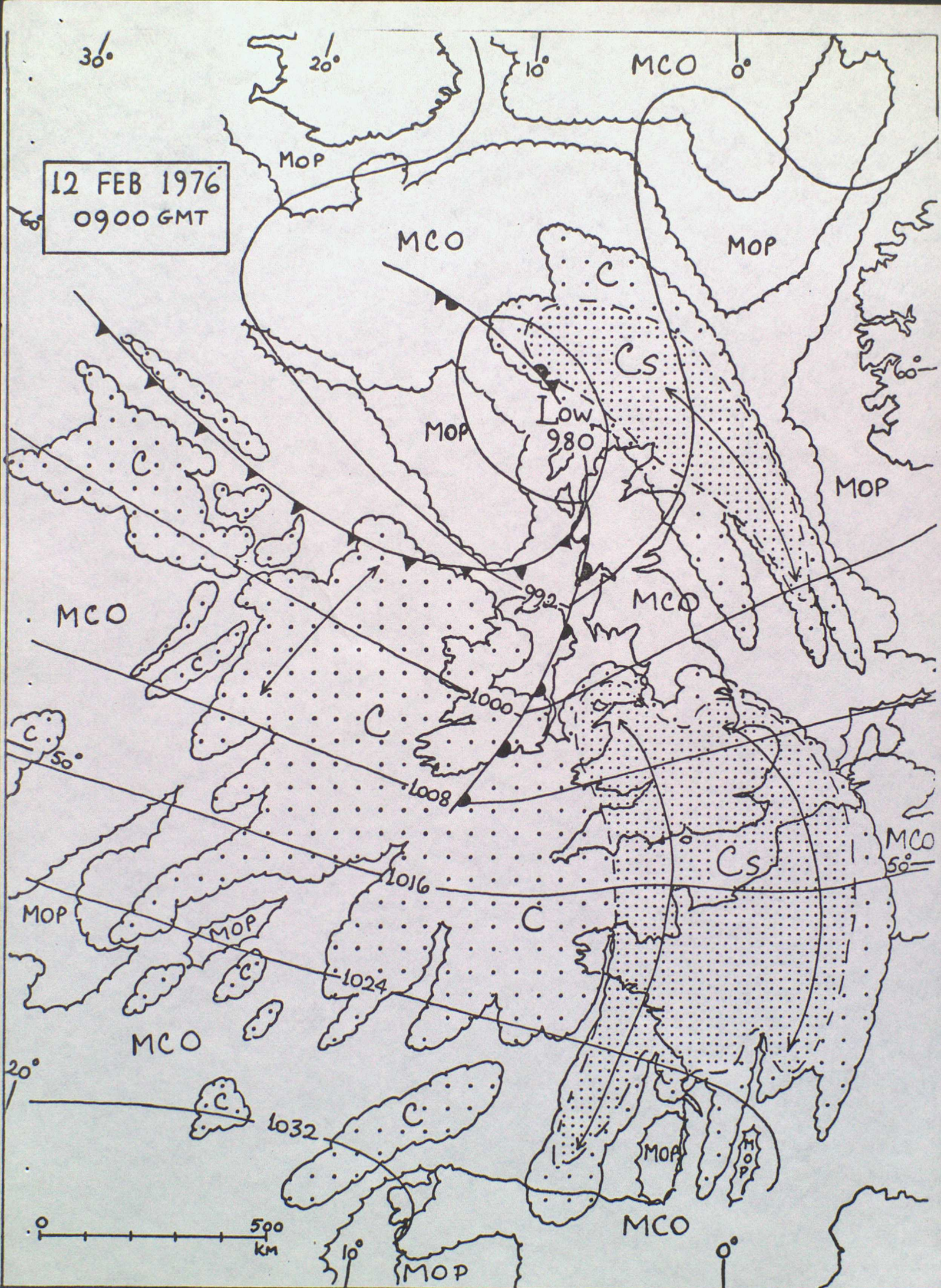


FIG 2







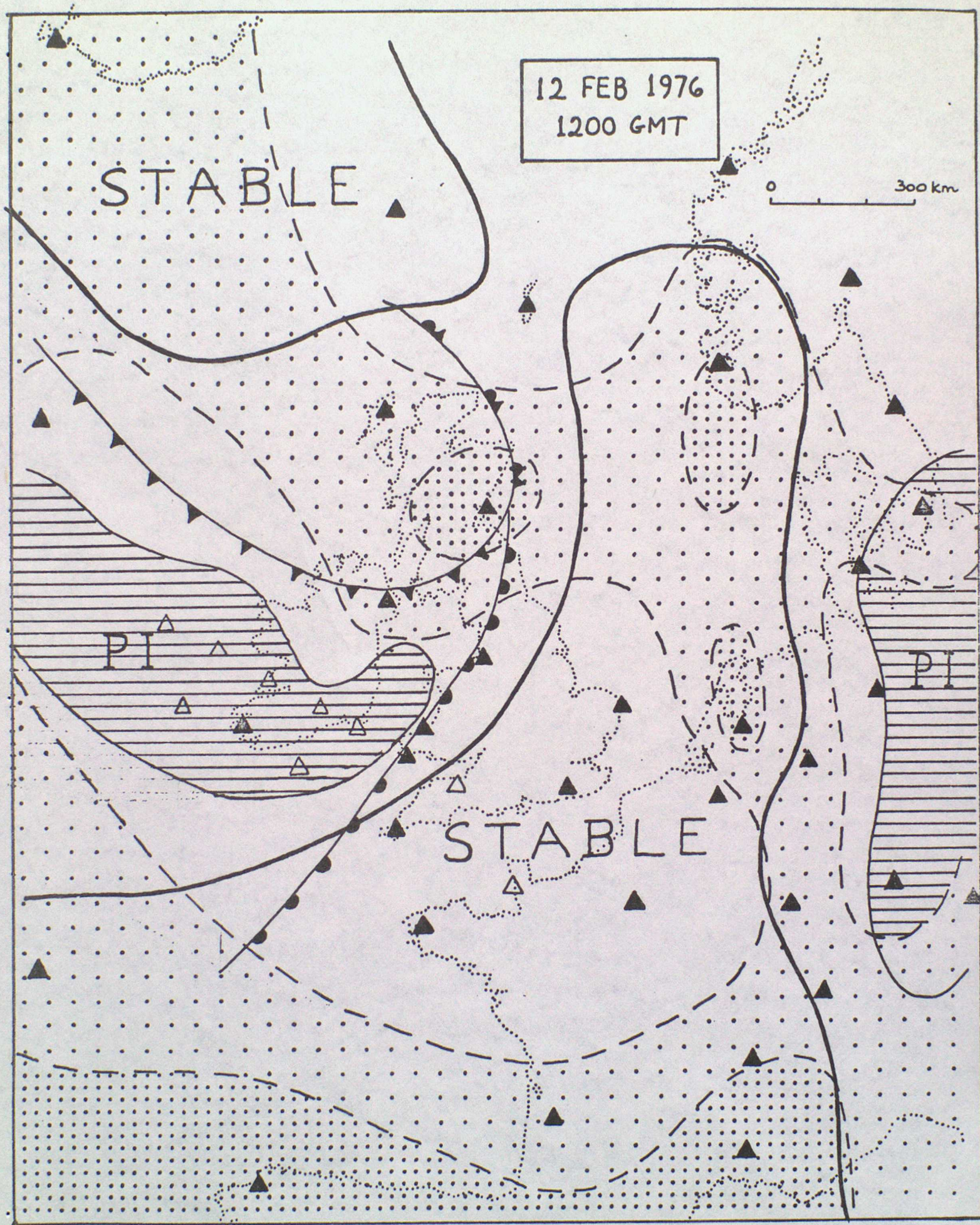


FIG 4



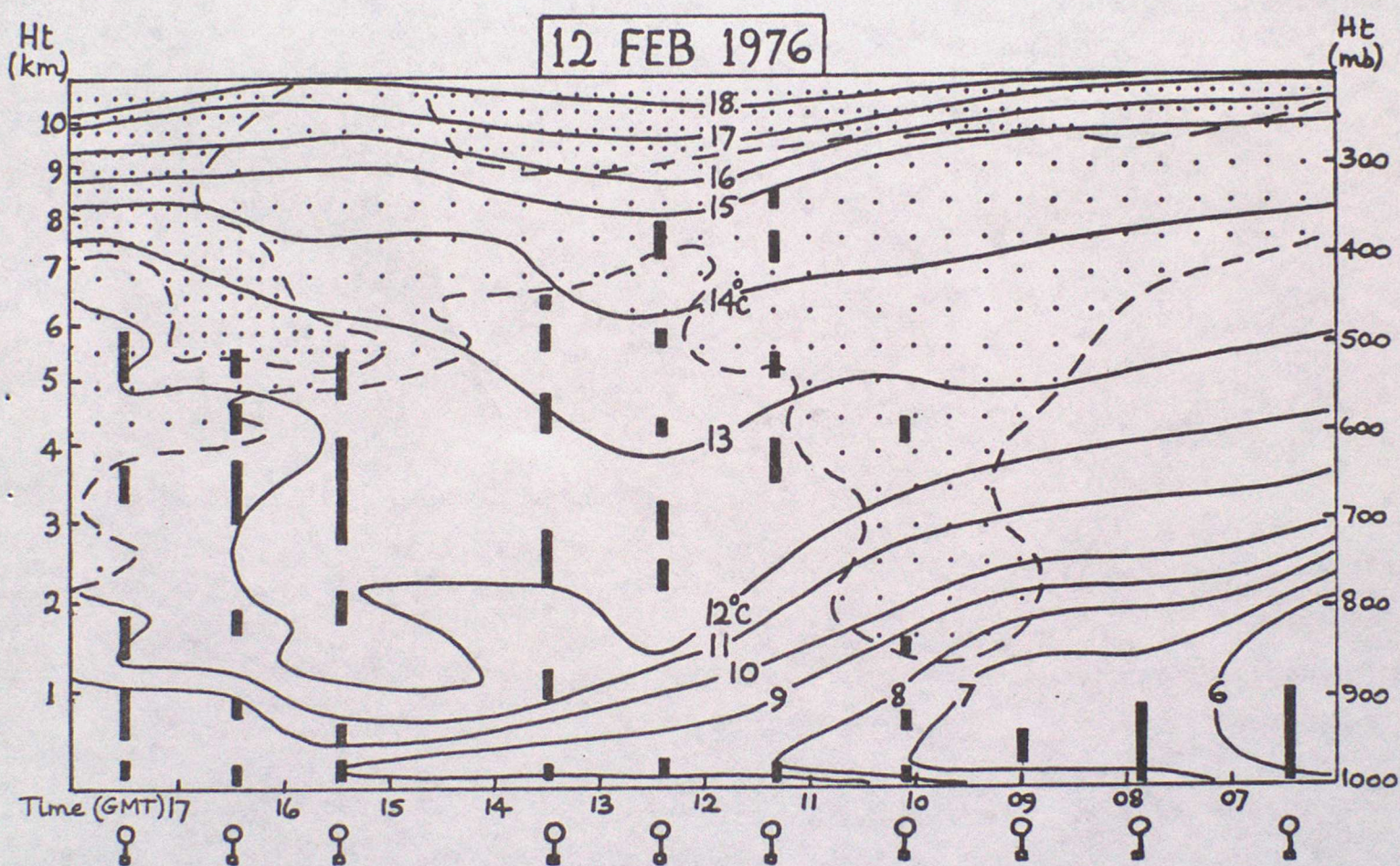


FIG 5



12 FEB 1976

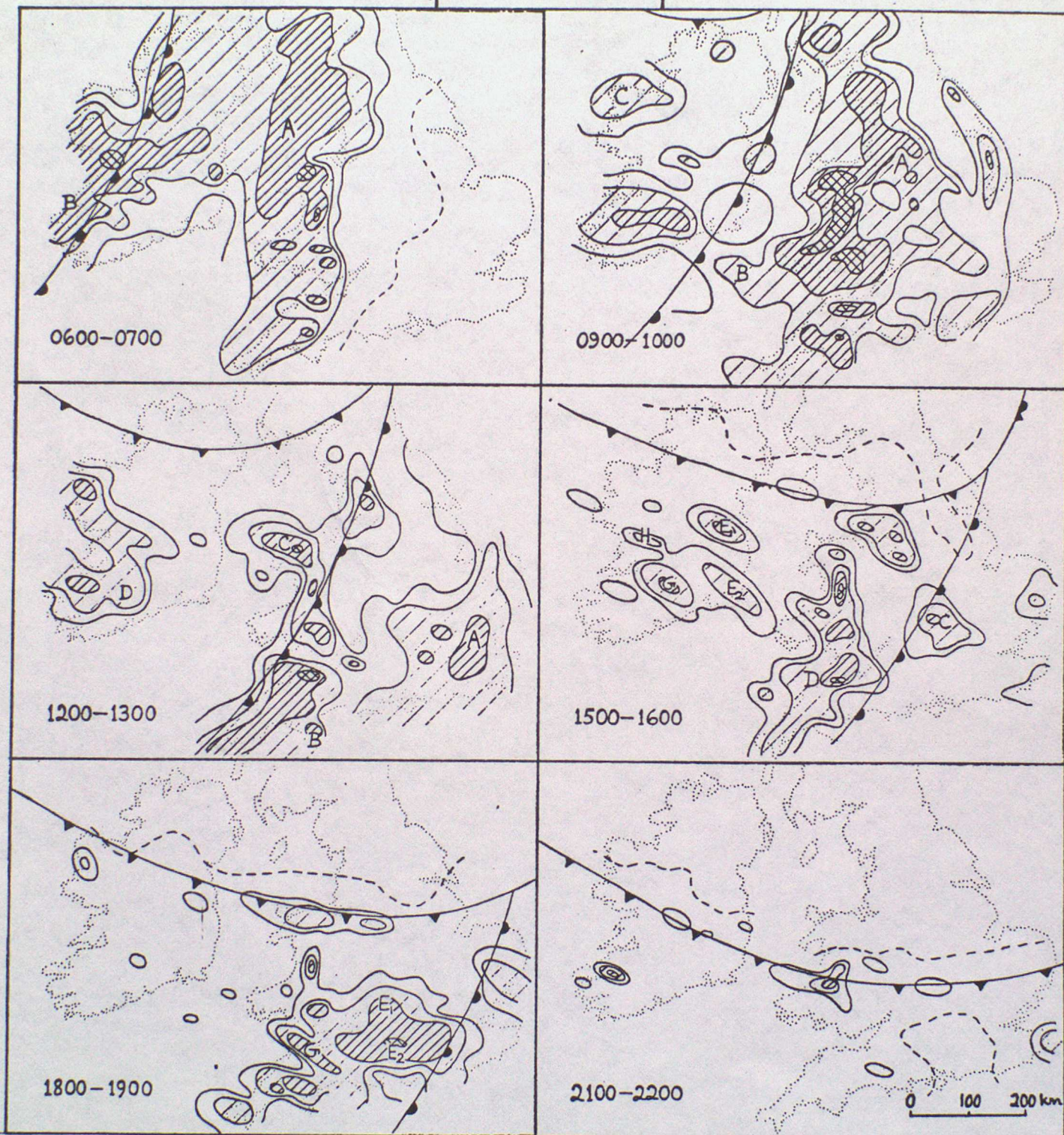
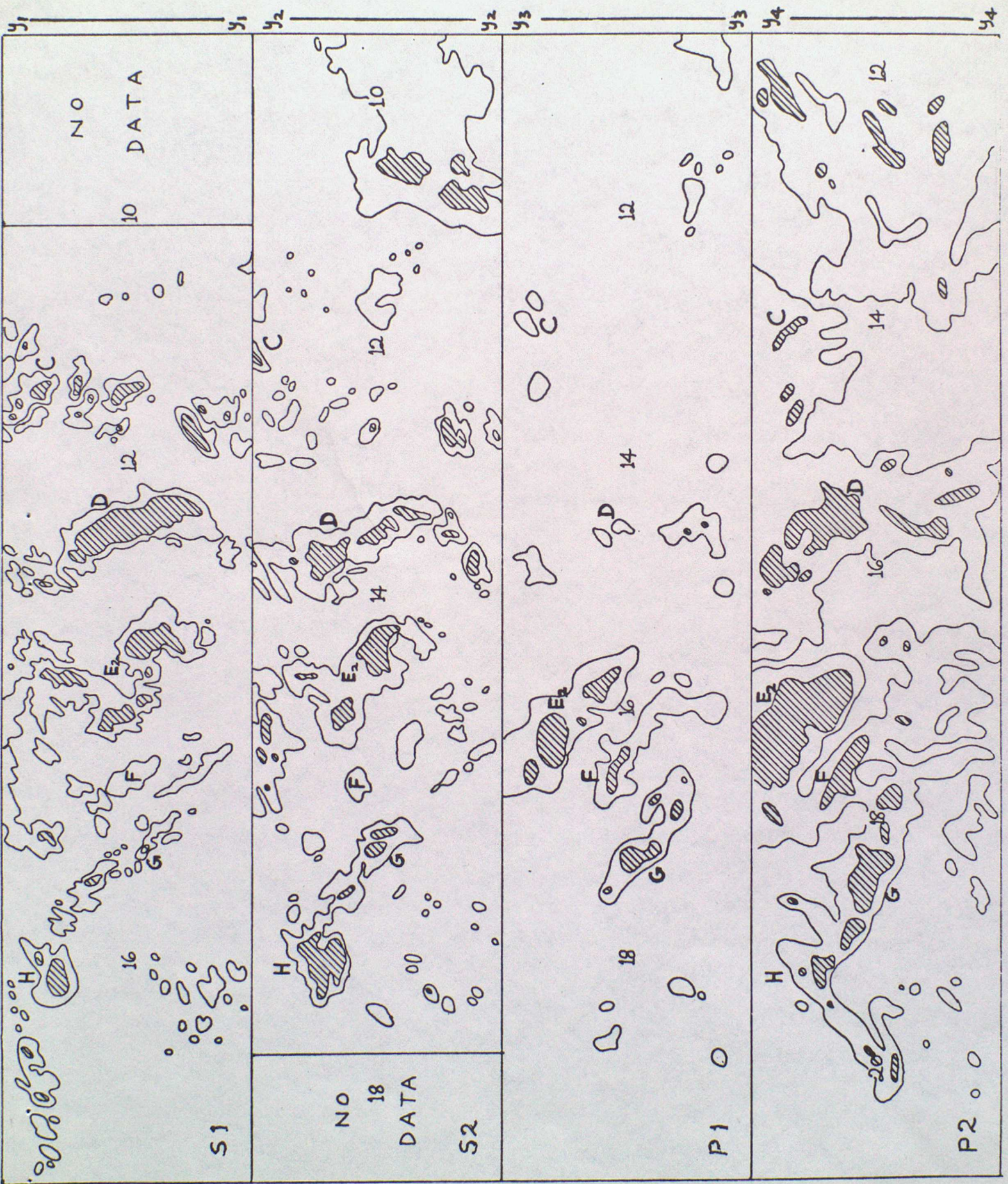


FIG 6



FIG-7





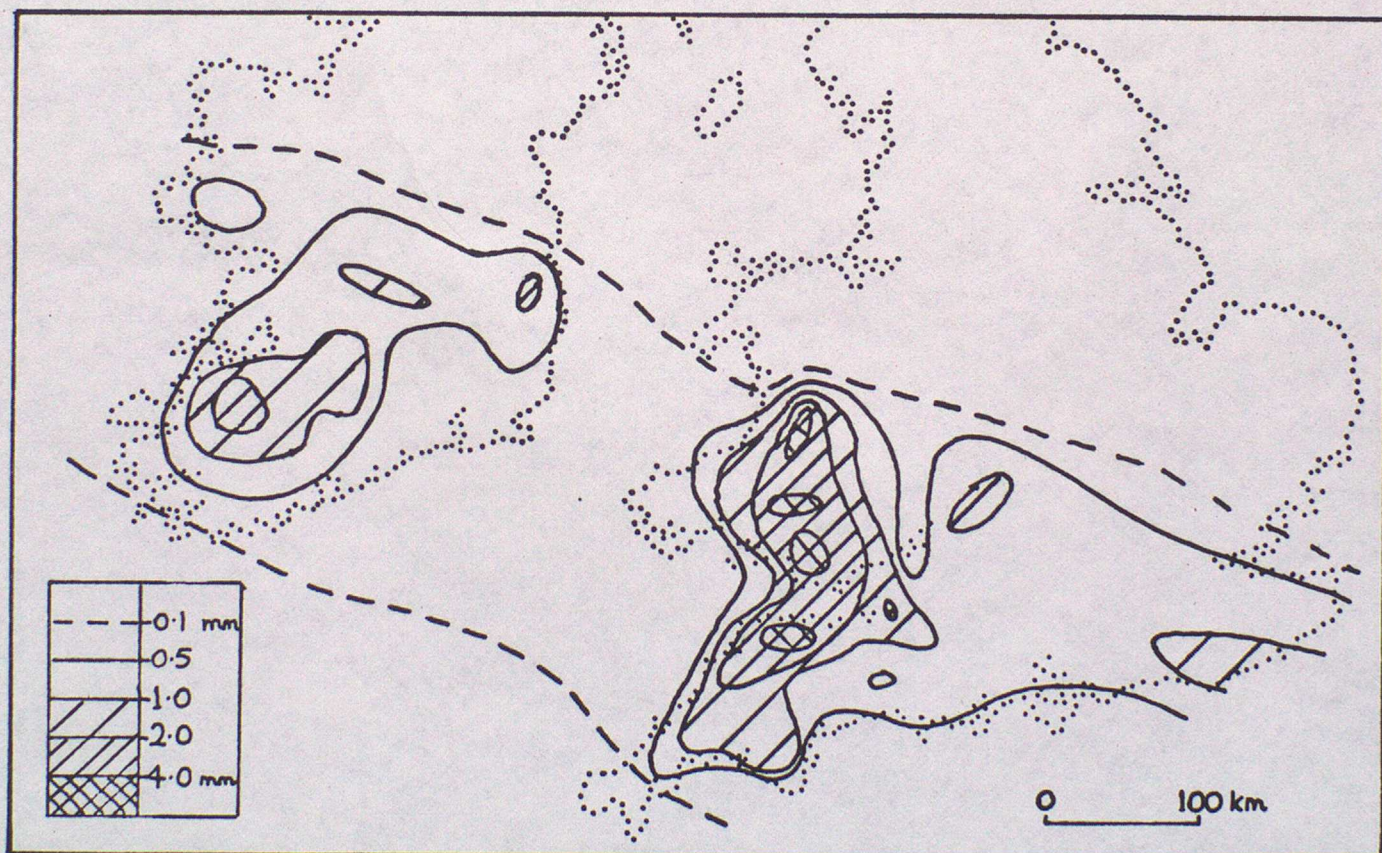


Fig 8



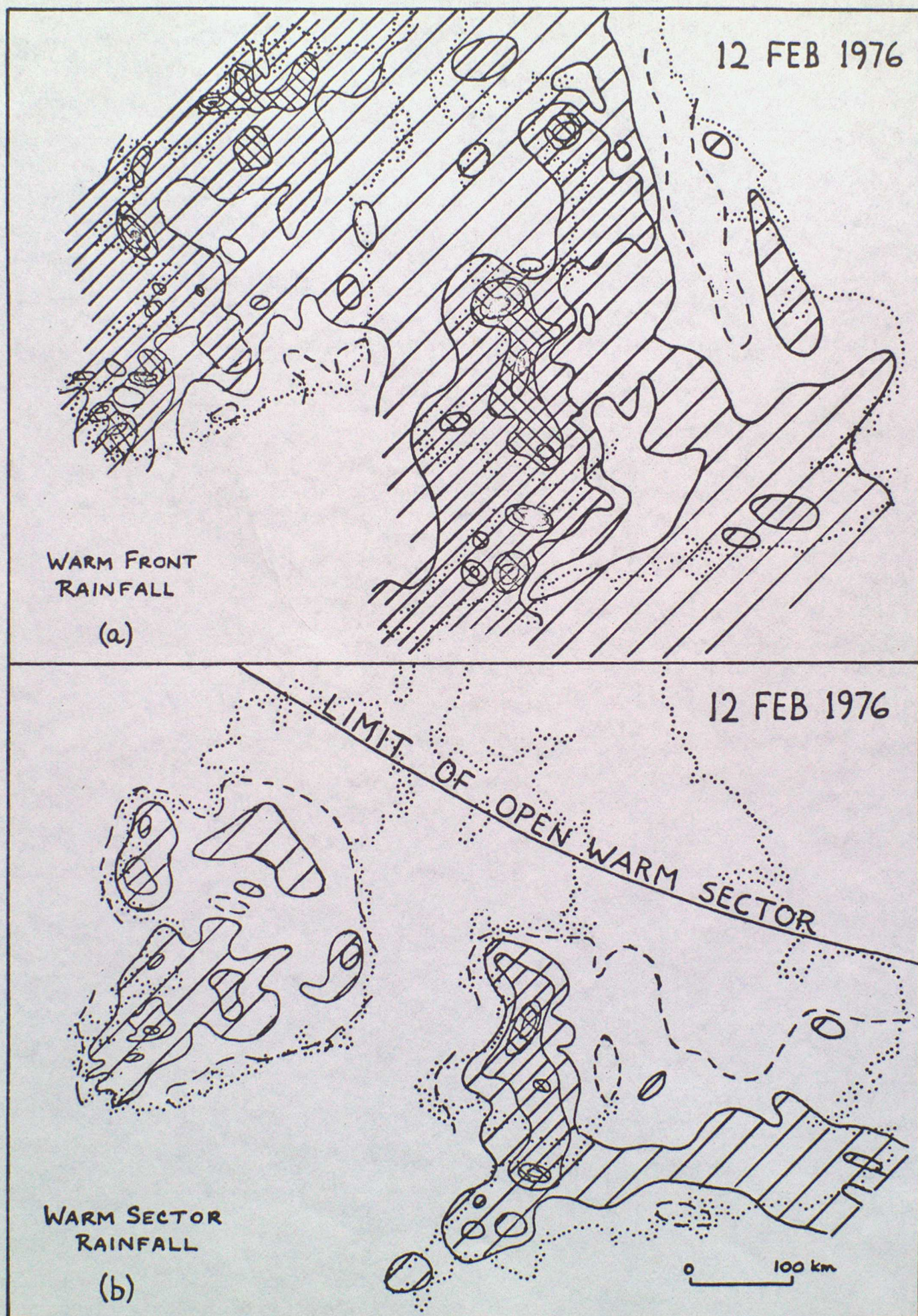
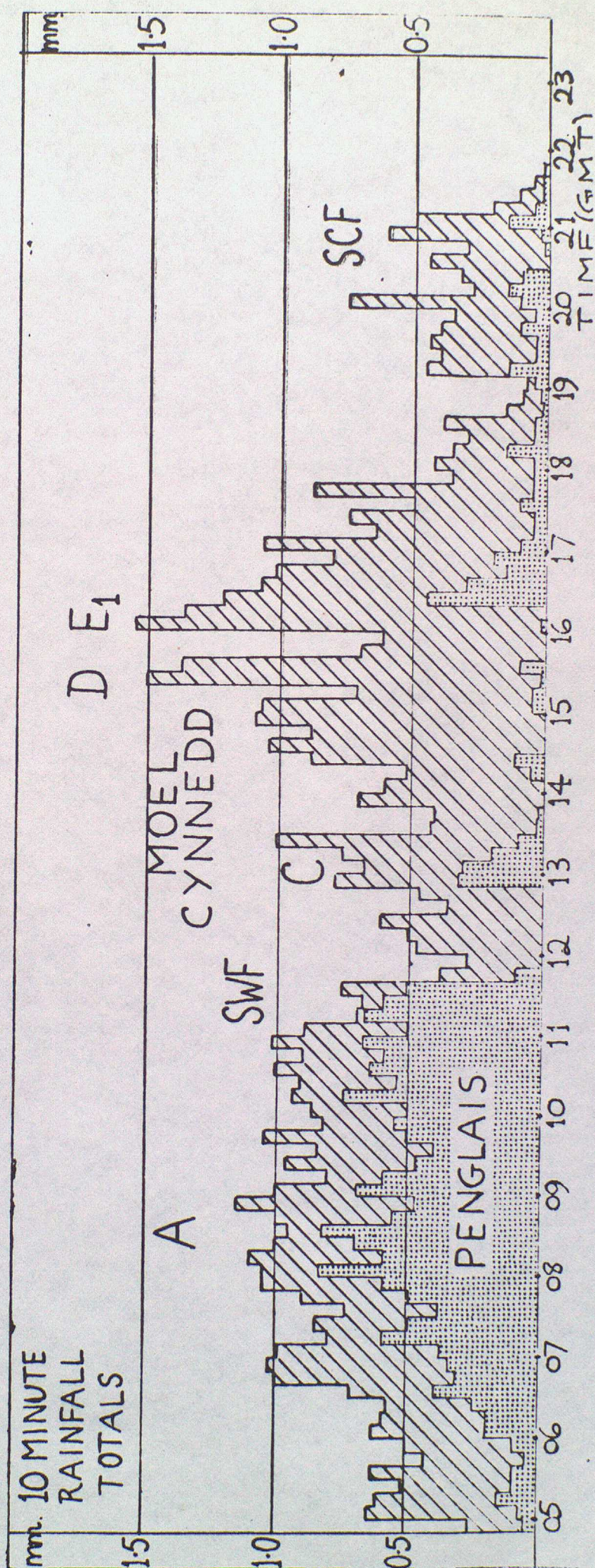
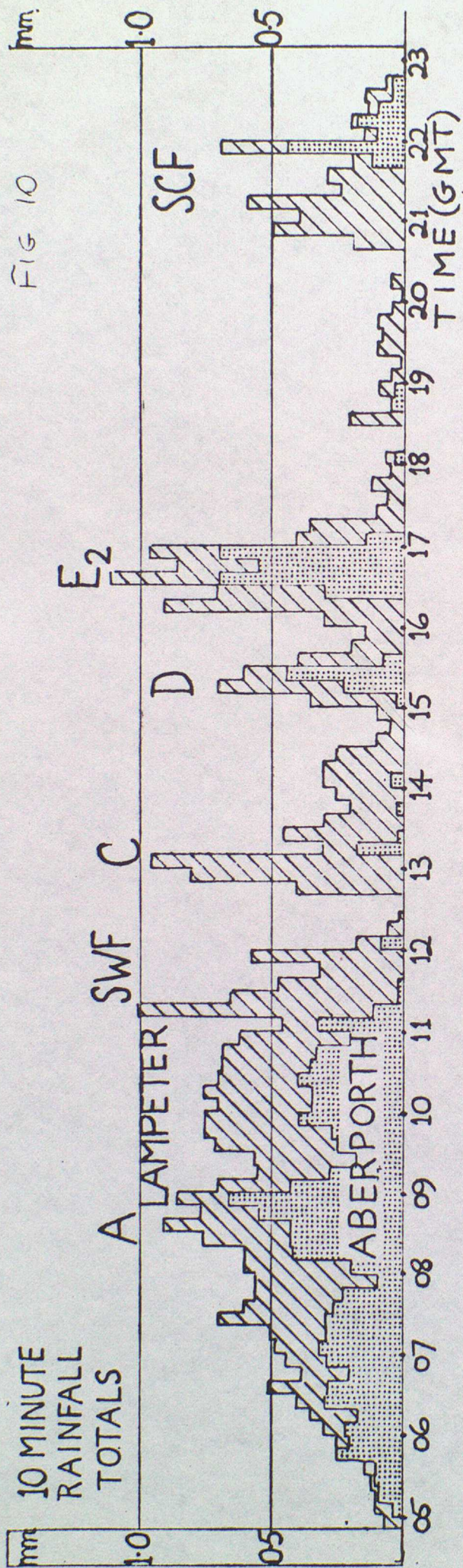


FIG 9



FIG 10





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