Meso-scale circulations and rainfall patterns in an occluding depression

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SUMMARY

Synoptic and meso-scale precipitation and airflow patterns in the occluding depression which passed over England and Wales on 8-9 March 1967 are analysed. Large-scale circulations are illustrated in terms of airflow relative to the synoptic system within the framework of surfaces of constant wet-bulb potential temperature (θw). Meso-scale precipitation and airflow configurations are inferred from a sequence of over 120 large-scale maps of 13-min precipitation amounts. There was no obvious 'conveyor belt' in the occluding depression, but the upward relative flow coincided closely with large rain areas of the warm front and the depression centre. Subsidence at the cold front and within the warm sector inhibited precipitation growth in those parts of the depression.

Large (200 × 50 km) and small (50 × 50 km) meso-scale rain areas were found in the depression. The latter resulted from clusters of generator cells, which formed in an area where potential instability was released by large-scale upward motion. The clusters moved with the winds at about 550 mb. The large meso-scale rain area lay at a small angle to the surface warm front and lasted for about three hours. Its size, location, and orientation were due to the movements of three small meso-scale systems within the relative flow at their generator level. The location and intensity of a small meso-scale rain area on the eastern flanks of the Pennines, together with the associated rainshadow to the west of the upland, were analysed with the aid of a modified lee-wave equation. Other small meso-scale precipitation areas were due to airflow over sub-synoptic deformations in the θw surfaces. All types fit into a two-tier scaling of meso-scale circulations in frontal zones.

1. INTRODUCTION

Within the last five years several studies of the meso-scale organization of airflow and precipitation in frontal zones have appeared in the literature. Most of these have been concerned with warm fronts, probably because meso-scale activity at cold fronts had been thoroughly investigated in the 1950s. Very few of the studies have concentrated on occlusions, the notable exceptions being the results of the Stormy Spring Experiment (Kreitzberg 1968; Kreitzberg and Brown 1970). This paper outlines the results of an investigation into the rainfall patterns of an occluding depression, concentrating on the synoptic and meso-scale circulations and comparing findings with previous work on frontal rainfall distributions.

2. DATA AND ANALYSIS

The types of data and methods of analysis employed in this study have already been outlined in a paper by Atkinson and Smithson (1972); they are listed only briefly here.

Synoptic conditions were analysed with the aid of teleprinter output, hourly surface charts and upper air information for the British Isles over the relevant period. Relative flows on isentropic surfaces, vertical cross-sections and analysis of the wind-field allowed the construction of a three-dimensional picture of synoptic-scale airflow in the system studied. The meso-scale precipitation areas were identified with the aid of data from nearly 350 autographic rain-gauges in England and Wales. Computer-mapping of approximately 13-min period amounts provided a valuable picture of the size and movement of such systems, a picture which was easier to interpret with the production of a cine-film of the one hundred and twenty maps.
It is perhaps relevant to note the comments of Benwell and Bushby (1970) to the effect that the denser the rain gauge network, the smaller the precipitation feature that will be ‘caught’ in the net. It follows that if gauges are sufficiently close (a few kilometres at most) and the sampling time is sufficiently short (one or two min), even individual clouds will leave their signatures on the autographic rainfall trace. This does not mean that the trace will not contain useful information on systems of larger spatial and temporal dimensions. On the contrary, it means that if one is basically interested in the meso-scale systems one has the problem of data-redundancy in such a situation. This opens up the whole field of

Figure 1. Surface synoptic maps during the passage of the system over the British Isles and map showing location of places mentioned in the text.
appreciation of scale in the atmosphere, a topic far beyond the scope of this paper. But the works of Eliassen, Sawyer and Smagorinsky (1960) and of Gandin, Mashkovich, Alaka and Lewis (1967) suggest that network density should be geared to the size of the system to be described: the majority of the literature in meso-meteorology, exemplified by Fujita, Newstein and Tepper (1956), Matsumoto and Akiyama (1969), Osawa and Ozaki (1960) and Abdullah (1953), suggests that a network with distances between gauges of 10–20 km is satisfactory for most meso-scale studies. Whilst the network of autographic raingauges in England and Wales is not ideal for meso-scale studies, its density compares favourably with non-experimental networks anywhere in the world. Certainly the results of the detailed investigations cited above are supported by the experience of the authors in producing over six hundred short-time-interval maps of frontal precipitation in England and Wales.

The occluding frontal system studied moved across England and Wales in the twenty-six hours starting 1500 GMT 8 March 1967. At the outset the warm and cold fronts of an active low pressure system to the west of northern France were quite separate and swept northward towards the British Isles (Fig. 1). The cold front initially moved at nearly twice the speed of the warm front, turned cyclonically quite rapidly and the depression began to occlude at about 0200 GMT, 9 March 1967. As the cold front was quite weak, the depression quickly took on the characteristics of a warm occlusion.

Analysis of the one hundred and twenty maps of rainfall over the twenty-six hour period of frontal passage confirmed patterns of precipitation and associated airflow on synoptic and meso-scales. The remainder of this paper analyses these two types of airflow and suggests ways in which the two scales interact, in the context of previously published work.

3. SYNOPIC BACKGROUND

The passage over England and Wales of the occluding system was characterized by two areas of precipitation separated by a widespread dry zone. Between 1500 GMT 8 March and 0900 GMT 9 March the warm front and associated rainfall moved from the Bay of Biscay to central England. A typical distribution of precipitation in this period is shown in Fig. 2(a). After 0900 GMT 9 March, as the warm occlusion began to stagnate over Wales and northern England, a drying out spread over most of southern and central England and northern and central Wales. The situation is typified by Fig. 2(b). After 1200 GMT 9 March, the second rain area, associated with the centre of the depression, moved towards 035° giving such heavy rain (Fig. 2(c)) that the map of the daily total reflected its passage (Fig. 2(d)).

Examination of the vertical thermodynamic structure of the depression and of airflow relative to the system provides a key to understanding the precipitation distribution briefly outlined above. A vertical section (Fig. 3) roughly perpendicular to the front, from Camborne to Shanwell, at 2330 GMT 8 March, shows notable inclination of the isentropes throughout the troposphere with some tightening of the lines between wet-bulb potential temperature values of 6°C and 9°C. Potential instability occurred between Camborne and Aughton at levels of 5–6 km and in a thin layer beneath the frontal surface. Warm, moist air lay to the south of the front, below the main area of potential instability. Green, Ludlam and McIlveen (1966) describe a method whereby relative streamlines may be constructed on isentropic surfaces within synoptic scale systems. They also make the point that if the system is in a steady state the streamlines may be treated as trajectories and this assumption has been widely used in previous work (e.g. Browning and Harrold 1969). Construction of the relative streamlines requires knowledge of the instantaneous system-velocity and this
Figure 2. Surface precipitation amounts within the period 1500 GMT 8 March 1967 and 1700 GMT 9 March 1967.
(a) Precipitation in the period 2159 GMT to 2212 GMT 8 March, showing abrupt northern limit.  (b) Precipitation in the period 1032 GMT to 1045 GMT 9 March showing the dry area associated with the cold front and the warm sector. The cold front marked here is as shown on the hourly charts of the Meteorological Office.  (c) Precipitation in the period 1553 GMT to 1606 GMT 9 March showing the dry area over the Welsh borderlands and heavy rainfall over the Midlands.  (d) Total precipitation for the period analysed, reflecting the high intensities shown in (c) and heavy falls in southern England behind the cold front.
was estimated to be 6 m s\(^{-1}\) from 160\(^\circ\) by inspection of the hourly charts. For most of the remaining analysis it was unnecessary to call upon the steady state assumption, except in Fig. 6 where the system velocity was used to plot the 0700 GMT Aberporth sounding on an 1130 GMT relative flow chart. In the application of isentropic relative flow analysis to an occluding system, it was felt that only streamline, and not trajectory flow, could justifiably be illustrated.

Relative flow maps were drawn for all isentropic surfaces between \(\theta_v = 5^\circ\)C and 14\(^\circ\)C, and Fig. 4, showing flow at 2330 GMT on the \(\theta_v = 9^\circ\)C surface, is representative of the motion over most of the well-defined frontal surface. The relative streamlines across the isobars of the \(\theta_v = 9^\circ\)C surface clearly show uplift, and suggest a magnitude of 6 cm s\(^{-1}\). Using Fulks’ (1935) method of estimating rainfall amounts, such an uplift over a depth of 5 km would give surface rainfalls of about 1 mm hr\(^{-1}\), a value found over much of southern England in the first rainfall period. A further check is provided by reversing the argument and employing Bannon’s (1948) method for estimating large-scale vertical currents from the rate of rainfall. Such a calculation gives value of 7 cm s\(^{-1}\) for the uplift speed.

Perhaps one of the most notable features of Fig. 2(a) is the abrupt northern limit of the rainfall over southern England. This could be due to cessation of uplift and associated production of precipitation or the evaporation of precipitation on its way to the surface or a combination of both. In arguing that evaporation is probably the cause of limits of this type, Harrold (1972) noted that they are usually approximately parallel to the surface front, regardless of the precipitation aloft. The current case is not quite parallel to the front, but it does concur with the more stringent requirements of Harrold’s hypothesis for evaporative trimming of the rainfall area. Harrold derived a relationship between the width of the precipitation area at the surface on the one hand and, on the other, the height of the
0°C level, the relative humidity of the sub-cloud layer, the slope of the cloud base, and the depth of the layer which produces the precipitation. Using data from Aughton for 2330 GMT 8 March, and taking an uplift-layer depth of 3 km, the relationship predicts a rain-area of about 300 km, a value very close to that actually observed (see Fig. 2(a)). Inspection of the relative flow on the $\theta_v = 13^\circ$C surface at 1800 GMT 8 March (Fig. 5) shows zero lift along a line parallel to, but further north than, the limit of rainfall on the ground. The evidence thus suggests that uplift did determine the orientation of the limit of rainfall in this particular case, but that evaporation caused the limit to be nearer to the surface front than would otherwise have been found in this first six to seven hours of the study period. By about 2200 GMT 8 March, the northern limit became less regular probably due to the increasing depth of uplift-layer as manifest in groups of convection cells. This is discussed in the next Section.

Throughout the early hours of 9 March the cold front began to occlude with the warm front and yet a marked drying-out of central England and Wales was evident between 0600 GMT and 1200 GMT 9 March. Fig. 6 shows the relative air flow on the $\theta_v = 9^\circ$C surface at 1130 GMT. The detailed structure on this Figure was identified with the aid of
Figure 5. Relative flow on the \( \theta_w = 13^\circ C \) surface (as defined by isobars) at 1800 GMT 8 March 1967, showing the locations of the limits of the precipitation area and of large-scale uplift of air over southern England. Temperature data for 1800 GMT inferred by linear interpolation between ascents at 1130 and 2330 GMT.

Figure 6. Relative flow on the \( \theta_w = 9^\circ C \) surface (as defined by isobars) at 1130 GMT 9 March 1967. The areas of uplift and sinking air correspond quite closely, particularly in the south-west, to the rainy and dry areas shown in Fig. 2(b).
soundings from Aberporth at 0700 GMT and 1130 GMT. Comparison with Fig. 2(b) shows a close correspondence of areas of uplift and sinking with areas of precipitation and drying out respectively. The cold front was of the keta-type with quite strong subsidence over much of its surface. There is little doubt that this subsidence caused the drying out found ahead of the surface cold front, and in the whole of the warm sector. The situation in the occluded part of the front is rather different. In this case, the cold front had ridden over the warm front with an associated bulging of the isentropes, well illustrated in Fig. 6. This deformation in the \( \theta_e = 9^\circ C \) surface meant that the generally downward progression of the northward-flowing air locally reversed, giving uplift over south-west England and south Wales. The correspondence with the rain-area at this time is most satisfactory, and in itself lends support to the independently derived isentropic analysis.

The rain area associated with the centre of the depression (Fig. 2(c)) gave some of the highest surface rates within the whole system. As the depression centre moved north-eastward, a steep rainfall gradient from zero values in the Welsh borderland to rates of 3 mm hr\(^{-1}\) over the Midlands became evident. Although no direct evidence exists, analogy with the rain areas in south Wales and south-west England outlined in the previous paragraph, suggests that a localized trough or pool in the mid-level isentropes would suffice to explain the phenomenon. In this case, a relative flow from the south-west would subside into the pool over the Welsh borderland and rise out of the pool over the Midlands, giving substantial precipitation. The existence of such a pool, on such a scale, associated with the centre of the depression is only hinted at on the 1130 GMT analysis, but the idea is supported by many studies of potential temperature fields in mid-latitude cyclones (e.g. Danielsen and McClain 1955).

4. MESO-SCALE CIRCULATIONS

The synoptic-scale patterns outlined above provide the background for the meso-scale rain areas and circulations which are the main objective of this work. Prior to the actual occlusion phase in the depression, three developments of meso-scale activity took place within the rain area associated with the warm front. The cold front, although comparatively weak, also provided meso-scale rain areas: and the rain area associated with the depression centre was itself of sub-synoptic proportions. The latter has been considered as fully as the data allow in the previous Section and will concern us no longer. The remainder of this Section is primarily concerned with the meso-scale circulations within the warm front.

The rain area associated with the warm front was heralded over south-east England at about 1500 GMT 8 March by rain cells of intensity of about 1 mm hr\(^{-1}\) moving from direction 210° with a speed of about 21 m s\(^{-1}\) (Fig. 7). The cells had horizontal dimensions of about 50 km and moved with the winds at about 500 mb. The winds at 1800 GMT (210° 23 m s\(^{-1}\)) suggest that the air in which these cells formed was probably sampled by the Bordeaux ascent for 1200 GMT 8 March. The relative flow charts show uplift between 700 mb and 500 mb, but at the latter level the lift was very small. In the previous Section it was shown that an uplift speed of 6 cm s\(^{-1}\) was typical of this part of the depression and consequently a lift of over one kilometre could have been expected in the six hours between 1200 and 1800 GMT. Although the air in the layer 620 to 500 mb on the Bordeaux ascent is potentially stable, such lifting would capitalize on the high humidities found there to give light precipitation. By 2100 GMT the small rain areas of intensity 1 mm hr\(^{-1}\) had coalesced into a general background rain, perhaps more representative of the stable layer in which it formed. Within this background rainfall, larger and more intense (2 mm hr\(^{-1}\) or more) cells were embedded, moving with the 500 mb wind from 210° at 23 m s\(^{-1}\). Such an increase in horizontal dimensions with intensity has been noted by Matsumoto and
Tsuneoka (1969) in their study of frontal meso-scale rain areas in Japan. The relative intensity of these systems which moved over south-east England between 2000 and 2300 GMT suggests a convective origin and Fig. 8 shows that uplift of air between 650 and 550 mb over Brest at 1800 GMT would release potential instability. Generator cells (Marshall 1953; Wexler and Atlas 1959) would develop at the 500 mb level and move with the wind. The spread and displacement of precipitation particles relative to the generators by the vertical wind shear of 0.8 m s\(^{-1}\) on the way to the ground would be negligible according to the work of Gunn and Marshall (1955), and so the movement of the surface rainfall cells reflects quite closely the movement of the generators. In summary, between 1700 and 2300 GMT 8 March, small meso-scale rain areas (about 50 km across), indicative of vertical air motion on the same scale, and with lifetimes of one to three hours moved with the 500 mb wind over south-east England. Within the context of the whole synoptic scale system, the meso-systems moved with the relative flow on the \(\theta_w = 12^\circ\)C and 13\(^\circ\)C surfaces, confirming the findings of Atkinson and Smithson (1972), though in this present case the relative flow is not parallel to the surface front over southern England. There is a suggestion in the maps of relative flow that parallel flow does exist over the North Sea, a substantial distance from the surface warm front at 1800 GMT. The lack of obvious similarity between the airflow on 26 June 1966 (the case considered in Atkinson and Smithson 1972) and the present case is probably partially due to the lack of parallelism between the orientation of the surface front at 1800 GMT (along line 120°–300°) and the orientation of the isobars on the majority of isentropic surfaces at that time (along line 70°–250°). It was only after 1700 GMT that the surface front rotated cyclonically to become located more conventionally with respect to the isentropic surfaces.

By 0130 GMT on 9 March another striking meso-scale feature had become evident as shown in Fig. 9. This rain area, with a general intensity of over 2 mm hr\(^{-1}\), was approximately 200 km long and 50 km wide and lay between the Severn Estuary and The Wash
for over three hours. Horizontal dimensions of this size have been recorded by Elliott and Hovind (1964), Kreitzberg and Brown (1970), Austin and Houze (1972), Atkinson and Smithson (1972), Browning, Hardman, Harrold and Pardoe (1973) and Harrold (1973). The duration is also in agreement with our earlier paper and with the work of Matsumoto and Akiyama (1969). Although the existence of such features is rapidly gaining acceptance, their origin is by no means clear in the literature. Elliott and Hovind (1964) suggest that the bands result from convection, and that their orientation is determined by that of the shear vector between the top of the convective layer and the adjacent layer above. This idea is treated sympathetically by Kreitzberg and Brown (1970) who suggest the existence of hyper-baroclinic 'leaves' within the frontal zone. Release of potential instability in these
zones is constrained into lines by the orientation of the shear vector in the convective layer. Whilst recognizing the above mechanism, Browning and Harrold (1969) also call attention to the possible effects of orography, suggesting that already established lines of convergence may 'lock-on' to a given upland area which then triggers convection to be accentuated in the convergence line downstream. No explanation is given for the existence of the convergence zones.

In all three works, the orientation of these large meso-scale features is attributed to thermal or actual winds. These hypotheses were tested on the present case but none offered a full explanation. Baroclinity did occur in a band stretching from Wales to the Thames estuary but the orientation of the shear vector within the zone paralleled the large-scale meso-scale rain area only in the 400-300 mb layer, where both lift and humidity are small.
However, the possibility that the baroclinity helps to release potential instability should not be ruled out. The location of the rain area relative to the mountains of south Wales strongly suggests an orographic effect, but, in fact, wind directions at all levels at this time (00–0300 GMT 9 March) are totally unsympathetic to this idea. A third possible cause of the release of potential instability, but not of the orientation of the resulting rain areas, is the existence of Kelvin-Helmholtz waves near the frontal surface. Browning (1971) has documented waves with amplitudes of up to 400 m and wave length of 1.5 km. Such waves require very strong vertical shear for their existence and thus tend to have a local and transient existence. In view of this, no clear relationship has been established between the occurrence of such waves and rainfall distributions at the ground, though the possibility of such a relationship cannot be ignored.

The limited success of earlier work in finding an explanation for the orientation of large meso-scale rain areas, if not their very existence, may lie in lack of adequate descriptive data. In the current project the data allowed a close inspection of the evolution of the rain area, and this suggests that the large meso-scale rain area comprised three small meso-scale rain areas which themselves resulted from meso-scale circulation systems moving with the wind at their generating level—a wind direction more normal than parallel to the orientation of the large meso-scale rain band.

The existence of generators, their location relative to synoptic systems and relationship to wind shear was thoroughly documented by Canadian meteorologists in the 1950's. The internal structure of cirrus generator cells has recently been observed by Heymsfield and Knollenberg (1972). The relationships between surface rainfall intensities and those aloft in the generators are, however, by no means clear. The roles of accretion, aggregation, coalescence, shattering, evaporation, melting and wind shear upon the ice crystal or raindrop spectrum, and therefore upon precipitation rates at both the surface and aloft, have been subject to marked disagreement in the literature. Earlier studies, such as those by Mason and Ramanadham (1954), Gunn and Marshall (1958), Wexler and Atlas (1958) and more recently Cornford (1966) suggested that the drop spectra in the low levels of clouds, at or below the 0°C level, are substantially modified by one or more of the processes mentioned above. In contrast, Rigby, Marshall and Hitchenfeld (1954) considered the effects of coalescence, accretion and evaporation to be negligible, a view partially supported by Caton (1966) for the case of accretion below the melting level. Even if the latter school of thought is believed it does not exclude the operation of relevant processes above the melting level, and indeed it is permissive of large production rates of precipitation-sized particles in generators at high levels. The resultant ice crystal spectrum, and, upon melting, rain drop spectrum, would, if the second school of thought is correct, be modified more by vertical wind shear above the freezing level than by any other process. These effects of wind shear upon precipitation have been examined by Gunn and Marshall (1955) on the assumption of little non-shear modification of the raindrop spectrum. Even if the spectrum is modified by factors other than wind shear, they are of the opinion that the velocity of rain areas on the ground is related to the velocity of the source of particles aloft (i.e. the generators). These concepts of generators, generator levels, and wind-shear effects are utilized and slightly extended in the following examination of the large meso-scale rain area in question.

The three small meso-scale rain areas which together form the large meso-scale rain band (Fig. 9), first appeared at 2230 GMT in locations shown in Fig. 10. The eastern one moved from 200° at 9 m s⁻¹ until it appeared to stagnate in the location shown in Fig. 10 at 0130 GMT. The middle rain area moved from 180° at 8 m s⁻¹ and the western one moved hardly at all from its location at 2230 GMT. It was suggested by Atkinson and Smithson (1972) and Browning and Harrold (1969) that rain areas of the size under consideration
here would be due to clusters of generator cells aloft. Observations of clusters of the required size have been made in another context by Langleben (1956) and Douglas, Gunn and Marshall (1957). In all three cases the velocity of the surface rain area was less than wind velocities for levels above 900 mb at Crawley at 2330 GMT 8 March. Any postulated generator clusters at levels above 900 mb must therefore move faster than their associated rain areas, yet must also be able to provide precipitation of the appropriate intensity to fall through a vertical wind shear ranging from 1 to 4 m s\(^{-1}\) km\(^{-1}\) to land in the observed location on the ground.

Precipitation particles with diameter about 1 mm and terminal velocity of about 1 m s\(^{-1}\) (figures supported by most of the relevant literature, summarized in Mason (1972)) would take about 90 min to fall from an altitude of 5-6 km and would be displaced 90–100 km relative to the original position of the generators on their arrival at the ground. Application of this argument to the three small meso-scale rain areas indicates plan positions of their sources at 2100 GMT as shown in Fig 10. In all three cases, and more particularly the two eastern ones, the velocity vectors of the rain areas at 2230 GMT and the associated generator clusters at 2100 GMT have origins 90–100 km apart, but by 0130 GMT they are virtually coincident in plan position. In the case of the eastern rain area, this requires a cluster velocity of 190° 20 m s\(^{-1}\), a value in very good agreement with the wind observation of 190° 19 m s\(^{-1}\) at 550 mb at 2230 GMT over Crawley. Similarly, the middle system requires a cluster velocity of 180° 19 m s\(^{-1}\) compared to an estimate from Crawley and Camborne ascents of 190° 20 m s\(^{-1}\). The western system moved more slowly than the other two but its direction was certainly compatible with the best estimates of wind direction over the area at about 2330 GMT. Within the three-hour evolution period of the large meso-scale rain area the intensity of precipitation in the three main small areas
increased by the order of 1 mm hr⁻¹. Thus, at a time when the generator clusters and
associated precipitation were moving into an area of stronger vertical wind shear (about
4 m s⁻¹ km⁻¹ in the Hemsby ascent) the surface precipitation rate increased slightly.
Gunn and Marshall (1955) show that, in the absence of other factors, shear tends to reduce
surface rates below those existing at generator level. Thus, if surface precipitation rates
increase in an area of greater shear, it is reasonable to conclude that the generators giving
rise to the precipitation had increased their production rate. Best's (1950) data suggest that
for the largest intensities shown in Fig. 10, a substantial proportion of the water would be
in drops of about 2 mm in diameter. Gunn and Marshall (1955) show that for a vertical
wind-speed shear of 4 m s⁻¹ km⁻¹ the displacement of particles of this size relative to its
associated generator cluster would be less than 10 km. Such considerations strongly suggest
a coincidence in plan position of generator cluster and surface rainfall area, as is noted at
0130 GMT on Fig. 10.

The above discussion carries two related implications; first, the generator clusters
evolve in time producing different precipitation rates as they move along the path suggested
in Fig. 10; secondly, there must be stagnation of the generator clusters in the locations
shown in Fig. 10 after 00 GMT on 9 March. The increased precipitation production would
result from the growth of the generators themselves in environments with differing degrees
of instability and differing efficiencies of triggering this instability. Certainly the surface
precipitation rate within the three small meso-scale areas decreases from the western one
to the eastern one, as does the degree of potential instability at the 550 mb level over the
same area. Yet the trigger for release of this instability – uplift on the θ_w = 13°C surface –
shows the reverse gradient, being at a maximum in the east and near zero over the Severn
Estuary. Such uplift is adequate to cause the generator clusters responsible for the two
easterly rain areas but not the westerly, most intense one. Inspection of the upper winds at

Figure 11. Relative flow on the θ_w = 13°C surface (as defined by isobars) at 2330 GMT 8 March 1967
showing the accordance between the northern limit of the large meso-scale rain area and the limit of uplift.
Crawley and Camborne for 2330 GMT reveals strong thermal winds and baroclinicity between 400 and 600 mb over the latter station but not the former. The origin of the westerly meso-scale rain area may lie in this baroclinicity, as suggested by Kreitzberg and Brown (1970). The stagnation of the generator clusters, which accounts for the locational stability of the large meso-scale rain area, appears to be due to the configuration of the relative flow on the $\theta_w = 13^\circ$C surface. The dashed line on Fig. 11 represents the northern limit of lift on this surface and its coincidence with the orientation of the large meso-scale rain areas is immediately apparent. As the generator clusters were dependent upon a supply of water for their existence, the absence of lift to release the potential instability and to allow sublimational heating further to increase their buoyancy meant their rapid demise. We conclude that the synoptic-scale relative flow determines the northward limit of the large meso-scale rain area and its locational stability despite the mobility of its constituent parts.

In summary, the large meso-scale rain area which lies virtually parallel to the surface warm front appears to be due to the synoptically controlled stagnation of three generator clusters which were themselves triggered in potential instability at the 550 mb level and, as they intensified, moved roughly normal to the surface front in the relative flow at the same level.

A third broad meso-scale rain area appeared over and slightly to the east of the south central Pennines between 0130 GMT and 0830 GMT 9 March (Fig. 12). Associated with this rain area was a similarly persistent dry area to the west of the Pennines. As winds were from the south-east or north-east throughout this period, it is clear that the fundamental causal factor operating here is the Pennine massif itself. Calculations suggest that the lifting of a near-surface layer of air 0.7 km thick over the Pennines would more than account for the increase of rainfall from a background level of about 1 mm hr$^{-1}$ to 2.5 mm hr$^{-1}$ as seen in Fig. 12. Any lift of other layers containing substantial amounts of water vapour would in the absence of sub-cloud evaporation provide an embarrassing excess of precipitation and would not be compatible with the pronounced dry area on the leeward side. The implication is that forced lift of significantly moist air was restricted to the lowest kilometre immediately above the Pennines. In the absence of observations to test this idea, use was made of the suggestion by Corby and Sawyer (1958) that by putting $k = 0$ in Eq. (1)

$$\frac{\partial^2 \psi}{\partial z^2} + (l^2 - k^2) \psi = 0 .$$  \hspace{1cm} (1)

(where $\psi$ is the departure of the stream function from its value in the undisturbed airstream $z$ is height

$$l^2 = \frac{g \beta}{u^2} - \frac{1}{u} \frac{\partial^2 u}{\partial z^2}$$  \hspace{1cm} (Scorer's parameter)

$u$ is undisturbed horizontal wind-speed
$g$ is gravity
$\beta = \frac{1}{\theta} \frac{\partial \theta}{\partial z}$ where $\theta$ is potential temperature

$k$ is wavelength of disturbance

the main features of flow over uplands such as the Pennines may be elucidated. Calculations based upon the upper air data from Aughton at 2330 GMT 8 March show slight lift (a few tens of metres) in the bottom 1.5 km, sinking of 2–300 m at the 3 km level over the summits of the Pennines, but a return of lift at and above the 5 km level (Fig. 13). Such a result
Figure 12 (a) Surface precipitation which fell in the period 0555 GMT to 0608 GMT, 9 March 1967, showing the intensification of precipitation over the southern Pennines and the dry area immediately to the west. The high values over eastern Wales probably reflect an orographic effect on the sub-warm frontal relative flow from the east. The dashed line shows the position of the cold front as suggested by cross-section analysis; the conventional symbol shows the position on the appropriate hourly chart. (b) Surface precipitation which fell in the period 0700 GMT to 0713 GMT, 9 March 1967, showing marked drying out in south Lancashire and north Cheshire and sub warm-frontal orographic precipitation over the central Welsh borderland and Midlands.
receives confirmation from Corby and Sawyer (1958) who hinted that in a statically stable airmass where $l^2$ is large descending air should be expected at no great height above the windward slope. In this situation, the local meso-scale rainfall maximum on the eastward flanks and summits of the Pennines is probably due to the addition to the background frontal rain of rainfall from forced lifting at low levels. At the same time, the orographically induced sinking between 2 and 5 km upstream and over the Pennines would reduce, if not extinguish, precipitation production in that air: so that on being advected to the leeward side of the obstacle it overran a ‘rained out’ lower 1–5 km layer of air – the net effect being the marked dry zone noted at the beginning of this Section.

The other major meso-scale rain areas observed in this occluding system were (a) associated with the cold front prior to its occlusion and (b) associated with the point of occlusion itself. The former (Fig. 12 (a)) was due to release of localized potential instability behind the front (Fig. 14) between 0400 and 0700 GMT on 9 March over central southern England and not ahead of the front as suggested by the operationally analysed hourly charts. The second rain area was closely related to the deformations in the isentropic surfaces over south-west England and Wales as considered in the Section on synoptic-scale airflow.

5. Conclusion

This study elucidates three types of meso-scale circulation within the occluding system:

(i) Those resulting from free atmosphere convection in areas of potential instability, viz: from 1800 GMT to 2200 GMT over south-east England and from 2200 GMT to 0300 GMT over central England in the warm front; from 0400 GMT to 0700 GMT over central south England behind the cold front.

(ii) Those resulting from orographic effects, notably from 0130 GMT to 0830 GMT over and to the west of the Pennines. Orographically induced precipitation in the sub-warm frontal
Figure 14. Vertical cross-section from Camborne to Hemsby at 0530 GMT 9 March 1967. Solid lines represent wet-bulb potential temperature (°C) and dashed lines dry-bulb temperature (°C). Temperature data inferred by linear interpolation between ascents at 2330/8 and 1130/9 March.

flow was also evident over the central Welsh mountains between 0600 GMT and 0700 GMT (Fig. 12 (b)).

(iii) Those resulting from sub-synoptic scale deformations in the isentropic surfaces, possibly leading to convection and thus overlapping with (i). This case is well exemplified between 0700 GMT and 1200 GMT.

All three categories readily fit into the two-tier system of meso-scale circulations already noted by Atkinson and Smithson (1972), Austin and Houze (1972) and Harrold (1973), but the majority are of small meso-scale size. This confirmation of previous work is gratifying, particularly in view of the comparatively complicated synoptic system investigated in this study. The size of the small meso-scale systems, their lifetime and their movement with the relative flow at about 550 mb all confirm the results of the previous study. It is the movements of these systems which are least well documented, and which are probably most complicated. In the study of 26 June 1966 the authors found that the systems moved essentially parallel to the warm front: in this case they moved virtually normal to the warm front. But in both cases they moved with the relative flow at about 550 mb, a conclusion not drawn by Browning and Harrold (1969) but implicitly recognized in a later paper by one of these authors (Harrold 1973).

Detailed analysis of movement also helps to clarify the relationship between the small and large meso-scale rain areas. Only one marked linear large meso-scale rain area was found and we have argued that its position, intensity and orientation are primarily due to
the movements of small meso-scale systems. Kreitzberg and Brown (1970) found several linear large meso-scale radar echoes in their analysis of an occlusion and attributed their orientation to the shear vector in the convective layer. Smaller systems were mentioned only in passing. Elliott and Hovind (1964), Browning et al. (1973) and Harrold (1973) also found linear, large meso-scale rain areas, but the origins suggested by the above authors do not appear to apply in the present case. Harrold (1973) accepted the four scale categories outlined by Atkinson and Smithson (1972) and constructed a model of synoptic-scale relative airflow compatible with rainfall distributions on all four scales. An important part of Harrold's model is the sweep of low level air from parallel to the cold front over the warm front, turning anticyclonically to parallel the surface warm front (called the 'conveyor belt' by Harrold). Browning et al. (1973) give typical dimensions of the conveyor belt as 200 km wide and 2 km deep, but Harrold (1973) points out that it is probably slightly narrower in occlusions. In the current case, if a flow had existed, it would have been clearly sampled by the Larkhill ascents in the early morning of 9 March. In fact there was no evidence for the existence of such relative flow in the streamlines. This may be due to the occlusion process as well as to relative paucity of data, but the analysis of the whole history of the cyclone suggests that the existence of the so-called 'conveyor-belt' in its 'classical' form may not be as widespread as suggested.

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