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Airflow in convective storms

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SUMMARY

Some known properties of travelling storms are used to infer a general model of the airflow within them, in which updraught and precipitation-maintained downdraught are fed persistently from opposite sides. Detailed radar and ground observations of a particular hailstorm are used to refine the model.

1. THE DURATION OF SHOWERS AND CONVECTIVE STORMS

The evolution of individual showers and thunderstorms can be studied with the help of radar. Usually in Europe precipitation echo is first seen to form at levels between 10,000 and 15,000 ft, and to extend downwards towards the ground at a speed comparable with the fallspeed of large raindrops (20 to 30 ft/sec). Occasionally the entire echo disappears within ten minutes, the precipitation evidently all reaching the ground or evaporating, but more commonly it quickly enlarges and intensifies; afterwards it can often be followed for an hour or two without great change, which is longer than the period required for air in a moderate convective updraught to move through the cloud or for the precipitation particles formed in it to reach the ground. Clearly there must then be a persistent updraught, and a continual renewal of precipitation by a process whose details seem to be beyond the capability of radars of conventional resolution to detect.

The persistence of the individual convective circulation is more strikingly exemplified in the severe travelling storm. It was established in the last century that the severe thunderstorm or hailstorm of middle latitudes travels over a long, nearly straight path during a period of up to about twelve hours. For example, Gibson wrote in 1863 ' In Europe hailstorms usually travel very rapidly in straight bands of great length but small breadth . . . . A hailstorm which fell on 13 July 1788 began in the morning in the south-west of France and reached Holland in a few hours, destroying a narrow line of country in its path.' Clayton in the U.S.A., Marriott (1892) in England, and Prohaska (1907) in Austria, studied thunderstorms and hailstorms and found a similar behaviour.

2. THE SPEED OF TRAVEL OF CONVECTIVE STORMS

Prohaska recognized that the severe storms typically occurred in the border regions between warm and cool air masses (cold front zones) where there is a marked variation of wind with height, and that they move with the velocity of a middle-level current, frequently opposed to the surface wind (in accord with the popular belief that thunderstorms ' come up against the wind '). In recent years it has been confirmed that the travelling speed of showers and storms is that of the wind at some level in the middle troposphere (see, e.g., Ligda and Mayhew 1954; Newton and Katz 1958) : moreover, in our experience on occasions of severe storms there is typically a strong wind shear, high wind speeds occurring in the upper troposphere (see also, e.g., Ramaswamy 1956, referring to Indian storms; Dessens 1960, and Newton 1960).

3. The air circulation in convective storms

The foregoing information implies that the convective storm contains a rather persistent circulation in which the potentially warm low-level air enters its forward (downshear) side. In the typical circumstance that the wind shear is almost uniform with height and the wind in the high troposphere has the same direction and a greater speed than the storm velocity, it is observed that the anvil cloud stretches in front of the storm, often for great distances. This implies that the potentially warm air also leaves the storm (in the high troposphere) on the forward side.

If we recognize that the potentially cold air present in the upper troposphere overtakes the storm from the rear, and can often be identified at the ground in the rain area and behind the storm (Normand 1946), we can visualize that the circulation contains also a downdraught derived from high levels and is organized as shown schematically in the vertical section of Fig. 1 (a).

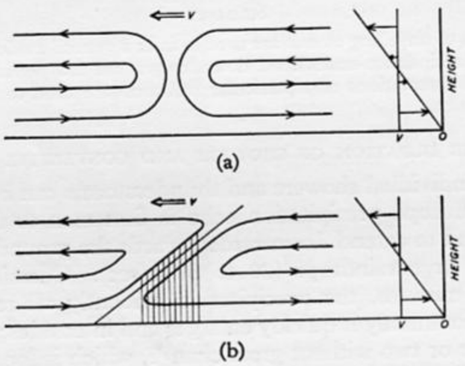

Figure 1. (a) Large and persistent convective disturbances travel at the speed *V* of the wind at some mid-tropospheric level. The figure shows schematically the kind of circulation implied in a vertical section along the direction of travel when the wind distribution relative to the disturbance is as shown on the right. (b) The airflow in (a) modified in order that condensed water may be precipitated from the updraught and evaporated in the downdraught.

At the ground behind the storm, the low wet-bulb potential temperatures often observed imply not only the descent of upper-level air but also the evaporation into it of a large amount of water. This can be derived only from that condensed in the updraught. It is therefore preferable to modify the circulation into a form such as that shown in Fig. 1 (b). Here the updraught is partly inclined over the downdraught, so that we can envisage the precipitation of condensed water into the downdraught.

The updraught is drawn separated from the downdraught by a sloping surface which near the ground can be identified with the well-known squall front which heralds the approach of the storm. The model now resembles those often drawn to represent an ordinary cold front : it differs from previous storm models mainly in that it implies that in the presence of wind shear the up- and down-draughts can be maintained continuously, without serious interference, from opposite sides of the storm. It represents a disturbance which is essentially an open system, working in an extensive environment which it inverts with a conversion of potential into kinetic energy.*

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* Normand emphasized the greater energy transformation which can occur in a cumulonimbus 'organized to take in potentially cool air at high levels as well as potentially warm air at the lower levels.' The invigoration of convection clouds often noticed after the onset of precipitation (e.g., Thorkelsson 1946; Craddock 1949; Ludlam and Saunders 1956; Howell 1960) and previously regarded as due to the release of latent heat during glaciation, can probably be attributed to the establishment of the cool downdraught and the organization of the convection.

Many storms have a duration which suggests that for a considerable part of their existence they contain a circulation of the kind shown in virtually a steady state. It is an interesting theoretical problem to show that such a flow pattern can be maintained by a distribution of heat sources and sinks plausibly representing the effects of vapour condensation in the updraught and precipitation evaporation in the downdraught. A preliminary treatment suggests that such a steady circulation can be demonstrated, although some important aspects of the behaviour of real storms have become apparent which cannot be represented in only the two dimensions of the model drawn above. The development of a theory accepting the storm as a three-dimensional disturbance, and eventually also embracing its development into a virtually steady state, is a formidable task. However, even the simple two-dimensional model may explain some familiar properties* not only

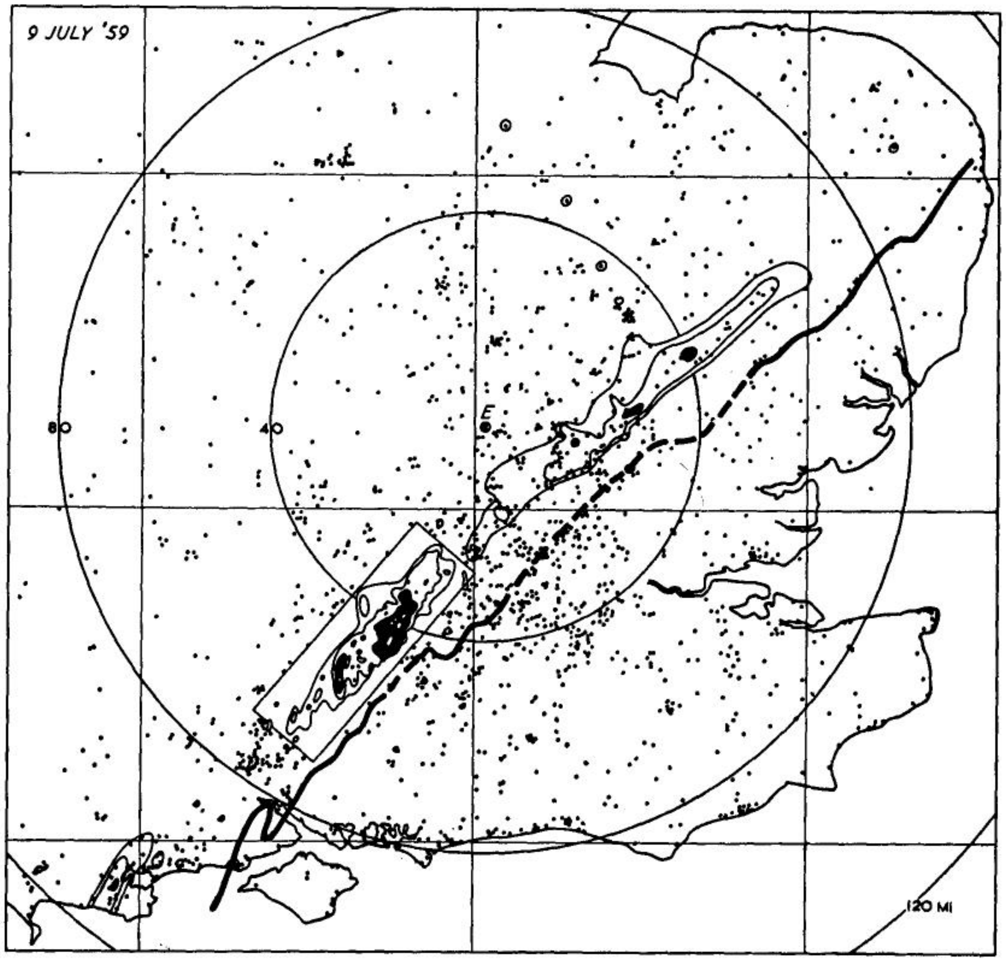

Figure 2. Distribution of hailstone size, 9 July 1959. The isopleths limit areas within which the maximum diameter exceeded $\frac{1}{4}$, $\frac{1}{2}$, 1 and $1\frac{5}{8}$ in., the area between the latter two isopleths being shown black. Observation-points (totalling 1,935) are indicated; 442 lie within the rectangle surrounding the most severely affected area. The thick line is the locus of the right flank of the main storm, determined from the PPI radar records. The range markers are concentric about the East Hill radar station (E).

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* One which at once comes to mind is the organized storm's independence of surface heating, the lifting near the squall front being sufficient to realise latent instability; others are the preference for the most severe storms to occur where there is marked wind shear and notable dryness, that is, low (wet-bulb) potential temperature, in the upper troposphere.

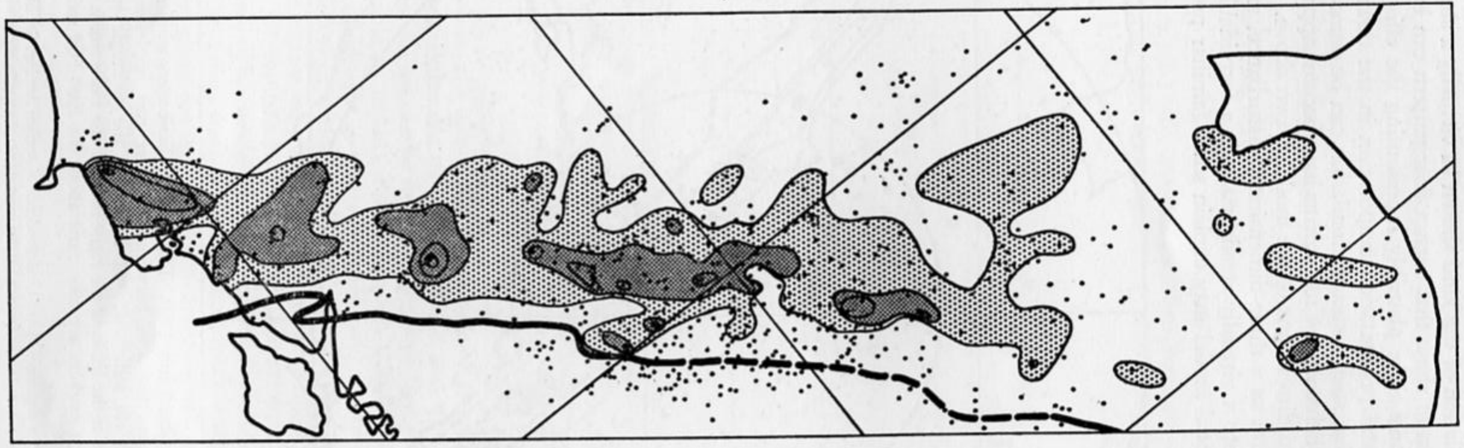

Figure 3. Smoothed rainfall pattern in the vicinity of the path of the main storm; isopleths are for ¼, ½, ¾ and 1 in. Areas with more than ¼ in. but less than ½ in. are lightly shaded; areas experiencing more than ½ in. are more heavily shaded. The positions of the rainfall observations are also indicated. The thick line represents the locus of the right flank of the main storm.

of storms but also of other disturbances in which precipitation develops in the presence of wind shear (for example, in ' stable ' air at warm and cold fronts, and in cirrus clouds).

The main purpose of this paper is to show how airflow of the kind envisaged can be deduced from the analysis of observations, including extensive radar data, of a particular severe hailstorm.*

4. THE WOKINGHAM HAILSTORM OF 9 JULY 1959

On the morning of 9 July 1959, a cold front extending from the central North Sea across SE. England and NW. France to Spain was moving slowly eastwards. In the frontal zone there was a strong horizontal temperature gradient (1°C/100 mi, or more) throughout practically the entire troposphere, and a corresponding SSW'ly thermal wind of 2 to 3 kt

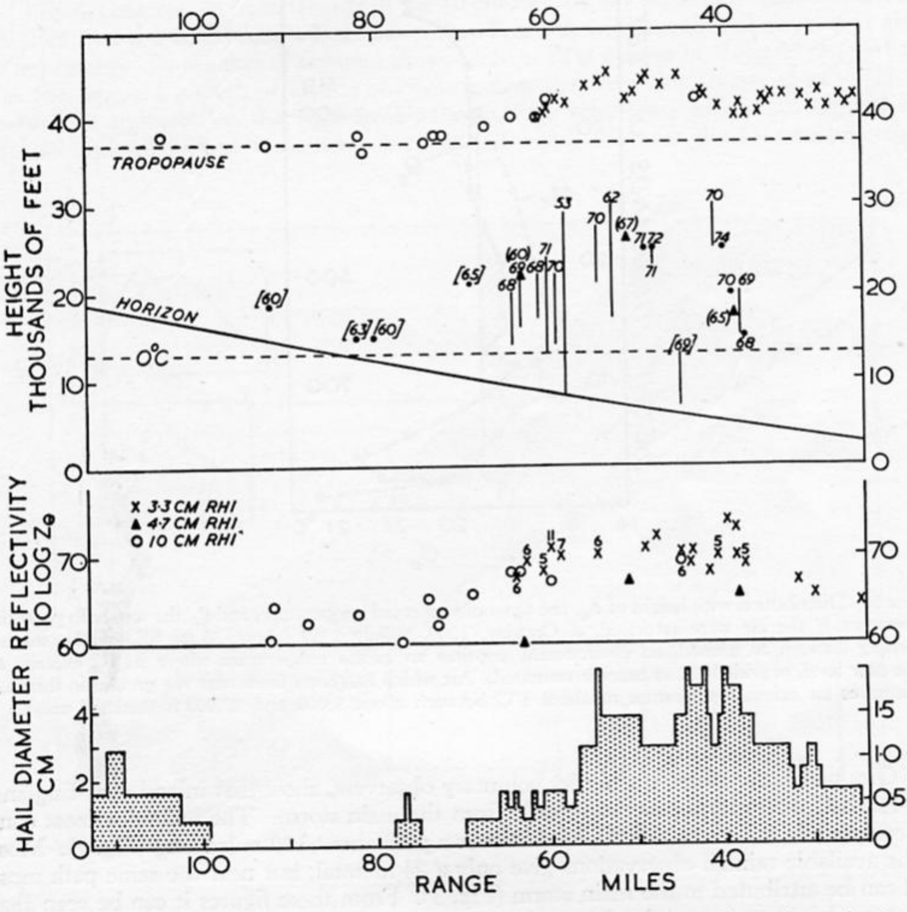

Figure 4. Peak echo heights, magnitudes and vertical extents of the most intense echoes observed at 3 wavelengths, and maximum hail diameter at the ground, all as a function of range from the East Hill radar station. Intensity is expressed as 10 log Z_e, (Z_e is the equivalent radar reflectivity in mm^6 m^{-3}) after correction for beam-width effects (on the assumption that the intense echo occupied a region extending 2 mi across the axis of the beam). Intensities are written alone or within curved or square brackets according to whether they were obtained from 3·3, 4·7 or 10 cm radars. Figures beside the crosses in the middle diagram show the vertical extent (in thousands of ft) of the strongest 3·3 cm echoes.

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* The observations are described and discussed more completely in a reference (Browning and Ludlam 1960) of limited distribution, copies of which are held in the Society's library.

in each height interval of 1,000 ft. Consequently although over SE. England along the path of the storm to be discussed the surface wind was NNE'ly about 15 kt, at 6,000 ft the wind had become SSW'ly and at greater heights it increased from the same direction, to reach 35 kt at 13,000 ft and a maximum of about 70 kt near the tropopause at 37,000 ft.

According to sferics observations the particular storm to be discussed developed over Brittany just before 0800 (BST). Subsequently it crossed the Channel and then travelled within the cold front zone across SE. England, under observation by five meteorological radars based at East Hill (near Dunstable). Six other individual storms came under radar survey during the course of the day, but none of these was as persistently intense as the main storm.

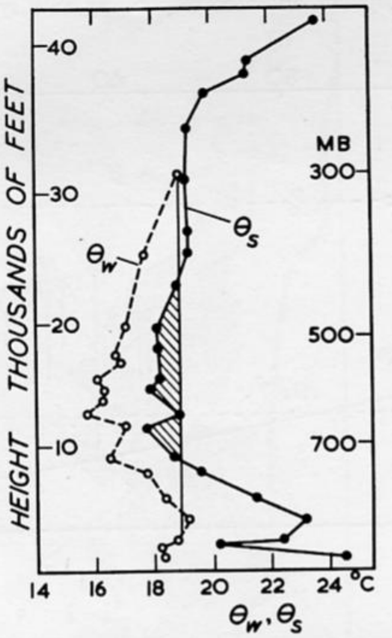

Figure 5. Distribution with height of θ_w, the wet-bulb potential temperature, and θ_s, the wet-bulb potential temperature if the air were saturated, at Crawley, 1200, 9 July 1959 (about 35 mi SE. of the storm). Air rising through an unmodified environment acquires an excess temperature where its θ_w exceeds θ_s at the new level, provided it has become saturated. Air which has risen from near the ground in this case acquires an excess temperature of about 1°C between about 9,000 and 23,000 ft (hatched area).

Ground observations, mainly by voluntary observers, show that inland over England hail reached the ground practically only from the main storm. The hail fell almost continuously while the storm moved at 35 kt over a path about 130 miles long (Fig. 2). Most of the available rainfall observations give only a 24 hr total, but near the same path most of it can be attributed to the main storm (Fig. 3). From these figures it can be seen that the storm became severe inland over southern England; during the period 1130 to 1240 it traversed the small rectangle drawn in Fig. 2 and produced hailstones of one inch or more in diameter and a rainfall of mostly rather more than half an inch. During the fall of the large hail the height of the radar-echo tops, and the height and intensity of the strongest echoes at the shorter wavelengths, reached consistently high values* (Fig. 4).

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[*] Echo intensity is specified as 10 log Z_e (Z_e is the equivalent radar reflectivity in mm^6 m^{-3}) and written alone, or within ordinary or square brackets according to whether it was obtained from 3·3, 4·7 or 10 cm radars.

The routine upper-air soundings made at the same time show that over SE. England the air in the lowest few thousand feet was stably stratified, but could become buoyant if lifted through an undisturbed environment to above about 10,000 ft. This is illustrated in Fig. 5, derived from the sounding made at Crawley, only 35 mi south-east of the storm. All the storms which occurred over England appeared in areas where there were extensive altocumulus clouds, and evidently began as showers from cumuliform developments amongst them (most formed to the south of the main storm, near its gust front).

5. CHARACTERISTICS OF RADAR ECHO FROM THE WOKINGHAM STORM

The characteristics and the modes of operation of the radars used to observe the storm are given in the Appendix.

Fig. 6, constructed from records of the 10 cm PPI display made at 3-minute intervals, indicates that the echo mass which was to produce the widespread hail developed after the appearance of a number of separate shower echoes all at a range of about 80 mi, perhaps after the repeated growth of clouds originating near the coast-line (range 95 mi). These new echoes appeared on the right flank of an intense echo mass which had crossed the Channel and which was responsible for the hail which fell near the Dorsetshire coast.

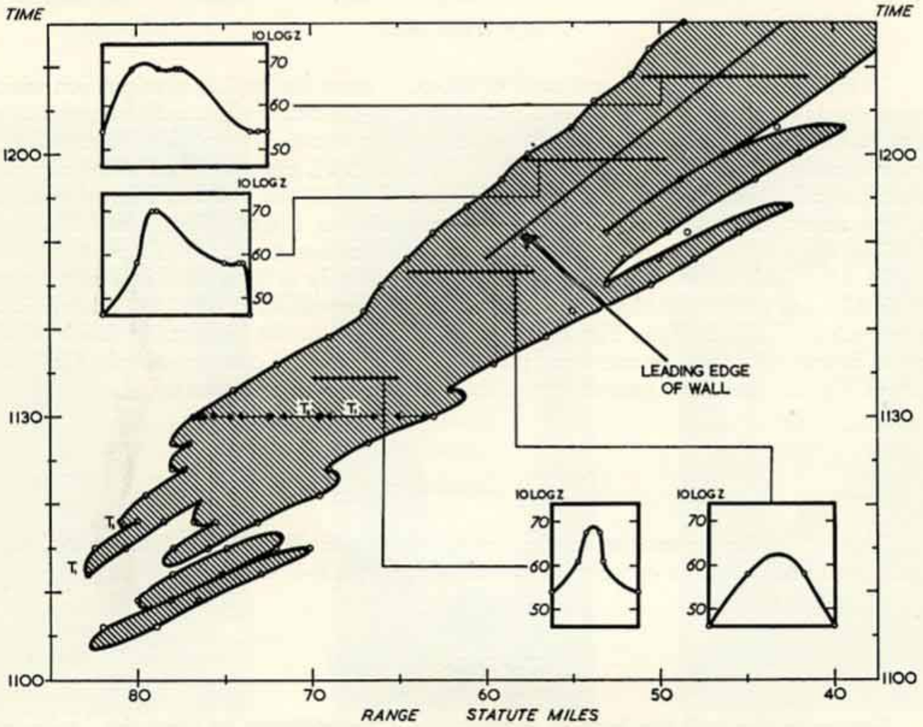

Figure 6. Range of the rear and leading edges of the echo within a section along 210° as a function of time (from full-gain 10 cm PPI photographs taken at 3-min intervals). Also shown is the position of the wall (from 3·3 cm RHI photographs). Profiles of intensity are given for the times 1134, 1147, 1159 and 1209; these were obtained from series of reduced-gain 10 cm PPI photographs.

The approximate positions of columns visible in a 10 cm RHI photograph at 1130 are shown (the two towers T_1 and T_2 of the series of photographs in Fig. 7 are identified). This diagram illustrates the transition at 1147, from an echo mass comprising small identifiable elements travelling at 50 kt to a single entity travelling at 35 kt. The transition is associated with the establishment of an extensive and persistently intense updraught.

At this time, before the intense phase, and also later, after the intense phase, the composition of the echo mass from smaller units was apparent also in RHI displays, which showed a succession of individual columnar echoes rising at the rear of the storm, each of which became the highest echo before moving to the forward side, subsiding and decaying (Fig. 7, Pl. IV).

With the onset of the intense phase the speed of advance of the rear edge of the PPI echo diminished from 50 to less than 35 kt, and it became impossible to discern any individual rising columns on the RHI display, although the echo tops gradually rose to reach a peak of 45,000 ft, 8,000 ft above the tropopause level. Throughout this phase the echo mass moved with a uniform velocity and without any marked variation in its character. Consequently it has been possible to construct representative vertical sections from the records of the 4·7 cm radar, which was used in a scanning cycle of period 12 min to explore the echo mass quantitatively. Fig. 9 shows such sections in the direction of advance of the storm; they resemble the instantaneous 3·3 cm RHI displays for this period (Fig. 8, Pl. V). Fig. 10 contains vertical sections across the direction of motion of the storm and illustrates the tendency for the precipitation carried ahead of the storm to fall towards its left flank (right of the diagram).

Throughout the intense phase the vertical sections have features which we call the 'wall,' the 'forward overhang' and the 'echo-free vault.'

(a) *The Wall*

In the central and right-hand parts of the echo mass the leading precipitation which approached the ground formed a 'wall' with a sharply-defined upright front face orientated perpendicularly to the direction of movement of the storm. It was first observed at a range of nearly 61 mi (RHI section for 1146·50 in Fig. 7), close to where the hail swath at the ground suddenly doubled in width (Fig. 2). By 1158 the wall had become as much as 7 mi across and rose above 13,000 ft over much of its extent (Figs. 9 and 10).

The steadiness of the echo structure during the intense phase is again demonstrated by Fig. 13, which shows that the wall advanced uniformly at 35 kt with its range always within 1½ mi of that of the highest echo top. (Before the wall formed at 1147 an individual top – such as T_1, T_2 or T_3 in Fig. 7 – could be identified as the highest for about 10 min before it was succeeded by another up to 5 mi farther away; consequently in the lower part of Fig. 13 there is a greater spread in the ranges of the highest tops).

(b) *The forward overhang*

This is the name given to echo which reached down to about 12,000 ft along the length of the wall and 1 to 3 or more miles ahead of it (Figs. 8-10).

(c) *The echo-free vault*

Nearer to the wall the base of the forward overhang rose to form the 'echo-free vault,' whose ceiling reached upwards to almost 15,000 ft close to the wall (the conventional laterally-compressed RHI display gives a poor impression of the horizontal extent of such a feature). It too extended for several miles across the storm : on the PPI presentation of the shallow-beam 4·7 cm radar which intersects the storm at heights between 12,000 and 15,000 ft the echo-free vault appears as an echo-free wedge or notch (Fig. 11 : the finger of echo ahead of the wedge represents the intersection with the tip of the forward overhang).

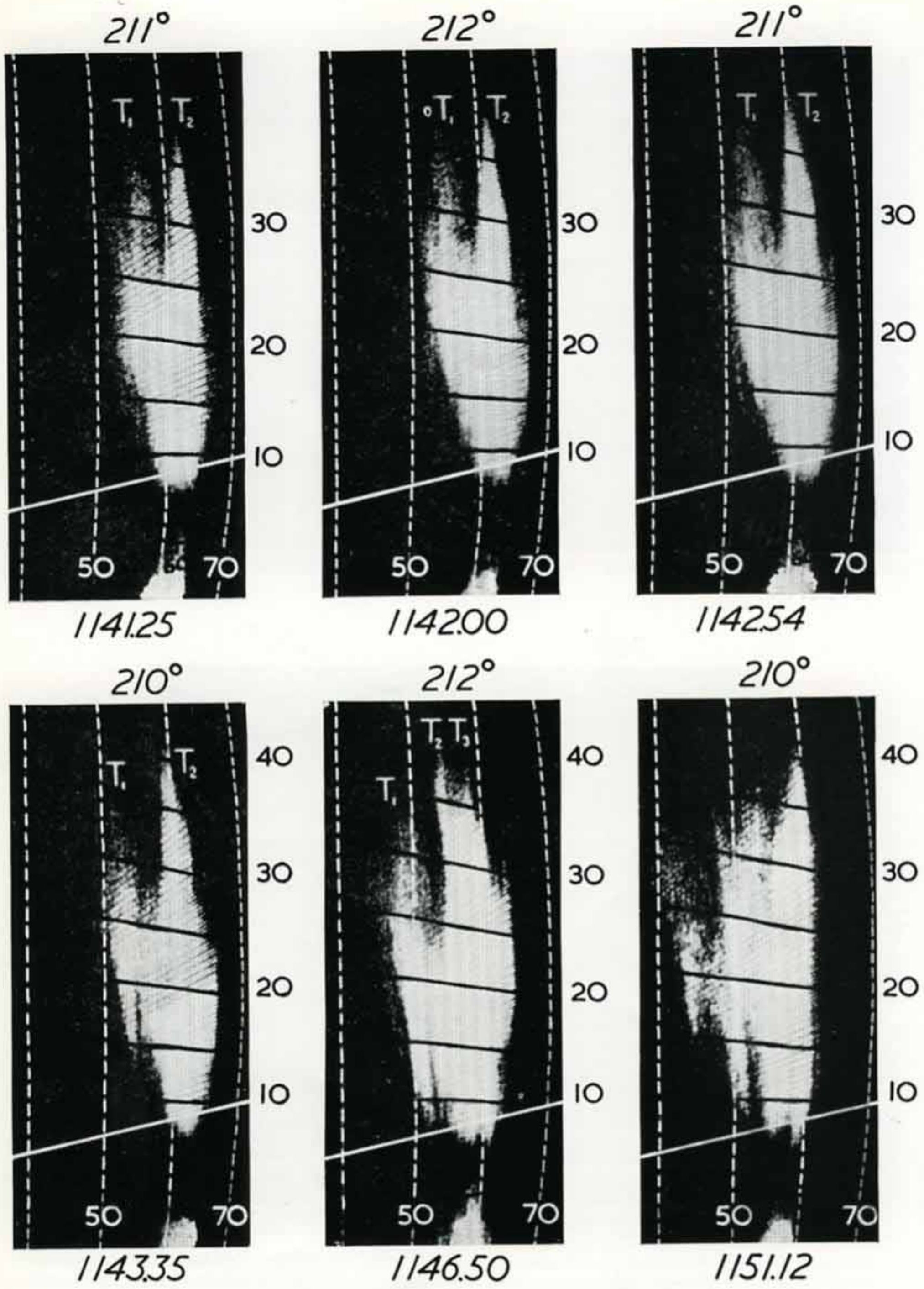

Figure 7. Full-gain 3·3 cm RHI photographs of the storm along its direction of travel, showing the growth and advance through the echo mass of two towers T_1 and T_2, and their eventual decay at the front of the storm as it approached the radar station. No such discrete towers occurred during the intense phase, after 1147, when the updraught became persistently intense and quasi-steady (c.f. Fig. 13). Height markers are at intervals of 5,000 ft and range markers at intervals of 10 mi. The radar horizon ($1\frac{1}{4}$°) is indicated in each photograph.

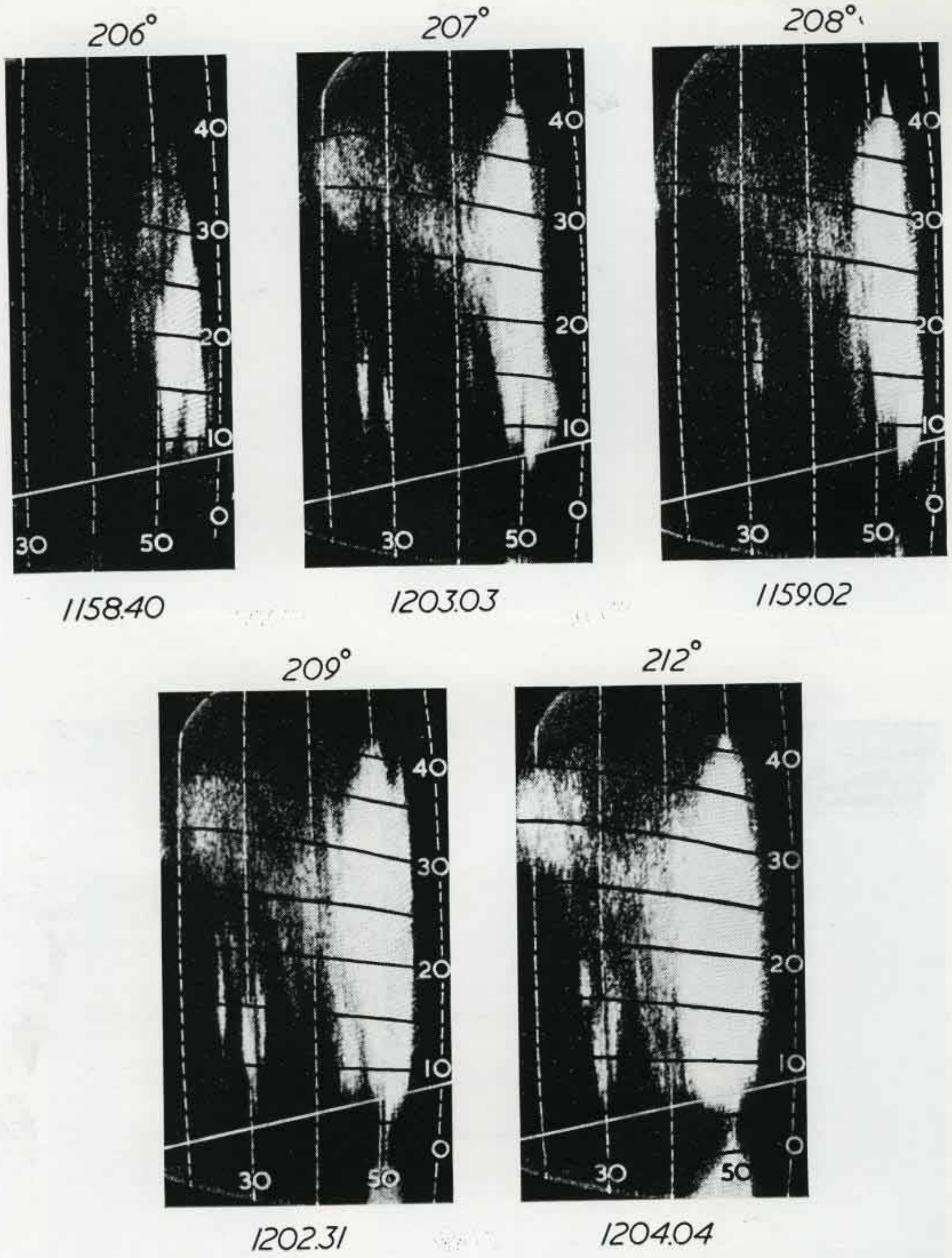

Figure 8. Full-gain 3·3 cm RHI photographs of different sections through the storm (approximately along its direction of travel) during the period to which Figs. 9-12 apply. Note the presence of the characteristic features indicative of the persistently intense and quasi-steady updraught – the forward overhang, and the wall with the highest top practically vertically above it (in the first 4 photographs), the echo-free vault (in the first two photographs), and the broader extent of the low-level echo in the left flank where precipitation reached the ground ahead of the wall (last photograph). The top in the centre photograph is at 45,000 ft and was the highest observed during the day. Height markers are at intervals of 5,000 ft, and range markers at intervals of 10 mi. The radar horizon ($1\frac{1}{4}°$) is indicated in each photograph.

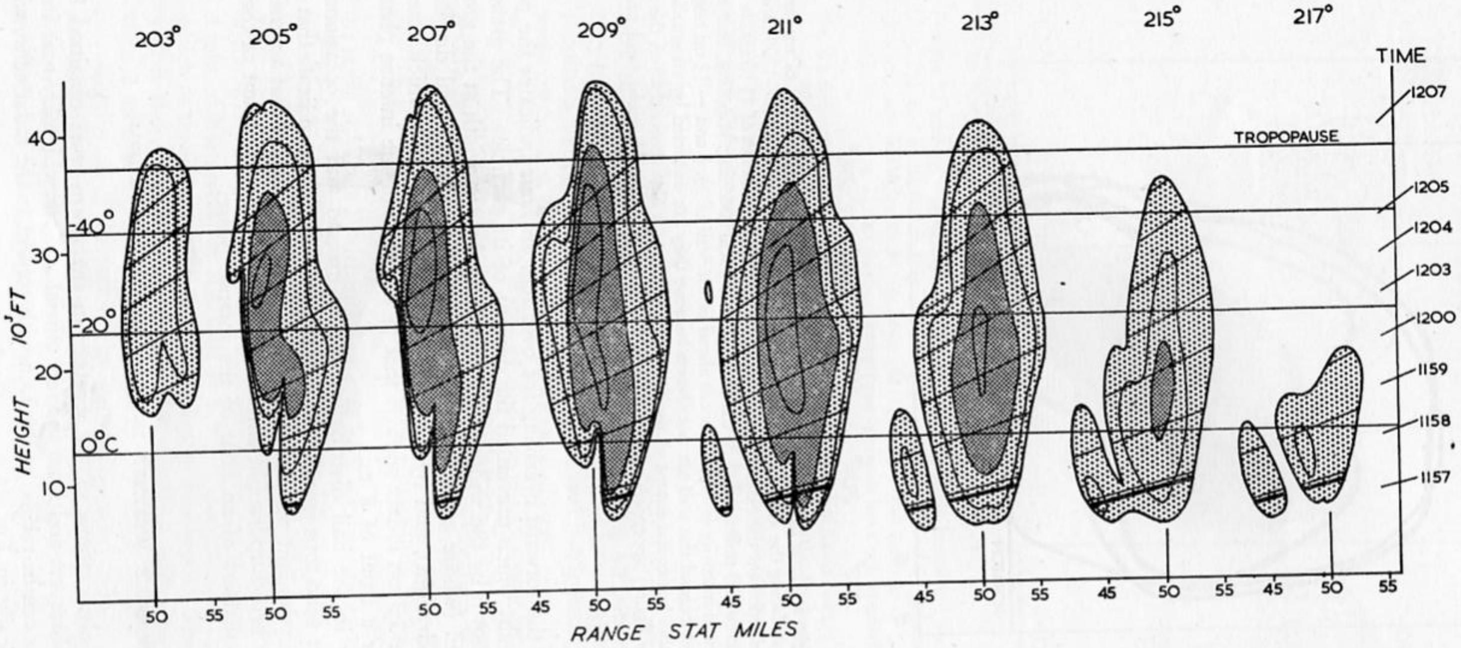

Figure 9. RHI sections at 2° intervals of azimuth through the storm (approximately along its direction of travel), for the period 1156 to 1208. They have been derived from 4·7 cm PPI photographs taken at a series of gain steps at successive elevations. The data from these photographs have been combined into a representation of the echo structure at 1202, by assuming that the storm as a whole moved uniformly along 210° at 35 knots. The radar horizon is shown as a thick line where it intersects each section. The contours refer to different gain steps, the intensities corresponding to which are (29), (38), (49) and (58) (strictly at only 50 miles range). No beam-width corrections have been applied to these values. Notice the presence of the wall, forward overhang and echo-free vault.

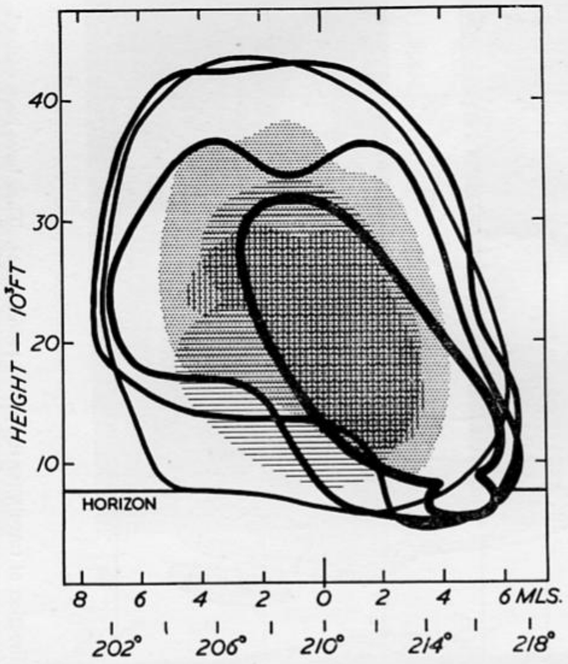

Figure 10. Distance-height sections through the storm at right-angles to its direction of movement (the reader can regard himself as facing the approaching storm), applicable to the period 1156-1208, and derived from Fig. 9. The contours represent the extent of echo of intensity (29) at distances of 4½ (thickest contour), 2½, ½ and — 1½ (thinnest contour) miles ahead of the wall. The vertical hatching, stippling, and horizontal hatching indicate the extent of intensity (49) at distances ahead of the wall of 2½, ½ and — 1½ mi respectively. Sections at greater distances behind the wall are not shown because they are distorted by attenuation. This figure shows the considerable horizontal extent of the forward overhang; it also shows that on the left front of the storm (right of the figure) appreciable precipitation fell below the radar horizon (and presumably reached the ground) more than 4 mi ahead of the wall.

The existence of the forward overhang for over half an hour indicates the presence of a persistent updraught which prevented the descent of its particles. The great width of the updraught is shown by the width of the overhang, by the width at the ground of the swath of large hail (whose great fallspeed prevents significant lateral displacement after fall from the updraught), and by the lateral extent of that echo which rose above tropopause level: the 3·3 cm radars showed that at the peak of the intense phase echo reached 43,000 ft over a front of 8 mi.

Some irregularity in the hail distribution at the ground and the occasional brief protrusion of columnar echo tops from the summits of the echo mass indicate that at least in its upper parts the updraught was not quite steady, but it is evident that a persistently strong and remarkably broad updraught entered the forward right quadrant of the storm throughout the three-quarters of an hour of the intense phase.

6. SURFACE WEATHER IN THE WOKINGHAM STORM

Accurately-timed observations of the weather in the storm were obtained from a number of voluntary observers and from the few official stations which lay near its path. From these the weather can be related to position with respect to the radar echo, with the result shown schematically in Fig. 14.

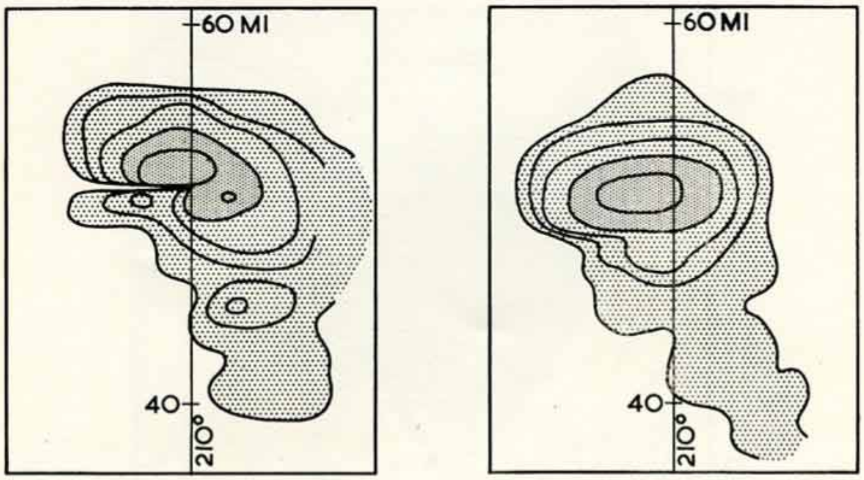

Figure 11

Figure 12

Figures 11 and 12. Intensity contours at 1202 in nearly horizontal sections through the storm at 13,500 ft (Fig. 11) and at 32,000 ft (Fig. 12) (heights refer strictly to 50 mi range), derived from the 4·7 cm data. Contours are for intensities (16), (29), (38), (49) and (58) (strictly only at 50 mi range). No correction for beam-width effects has been applied.

Fig. 11 demonstrates the extent of the wall and echo-free vault (which here appears as an echo-free notch). The echo just ahead of the echo-free vault lies in the lower part of the forward overhang.

Fig. 12 shows that the curtain of precipitation carried ahead (down-shear) of the storm is displaced by a wind possessing an appreciable component towards the left flank at high levels (from left to right in the figure).

This diagram has been constructed mainly from observations made at about 1250, after the intense phase of the storm, but when the observations were more plentiful; they have been supplemented by the study of autographic records. The density of synoptic reporting stations is indicated in the figure and is adequate to permit it to be drawn with some confidence, though it is by no means sufficient, even in combination with conventional autographic records, to reveal as much detail as could be desired.

A prominent feature is the well-known gust front which heralds the approach of the severe part of the storm, and where on this occasion the surface wind direction was suddenly almost reversed. Behind the front the surface wind generally increased while veering from SW'ly to NW'ly, reaching a maximum mean speed of 25 to 30 kt near the region of heaviest precipitation. In the intense phase there were probably gusts to over 50 kt (as at White Waltham), but even so it seems that the mean SW'ly component behind the gust front was substantially less than the speed of the storm.

As sometimes remarked before (Prohaska 1905), the largest hail fell on the right flank of the storm. Here the first precipitation experienced was large hail practically without any rain. Twenty timed observations showed that it began at the ground within 3 min of the arrival of the wall at 8,000 ft (determined from the records of the radars, which at these ranges could not see below this level). The intense echo close behind the wall is therefore to be associated with the large hail, which fell mostly for rather more than 5 min, to be succeeded by heavy rain for a similar period.

To the left of the path of the wall, precipitation falling ahead of the updraught arrived at the ground as rain : this subsequently intensified and near the storm centre it became mingled with small hail for a while. At the rear of the storm the rain diminished gradually, and before it ceased completely the sun shone, indicating the absence of the medium-level clouds which had spread over the sky well ahead of the storm. A few timed observations

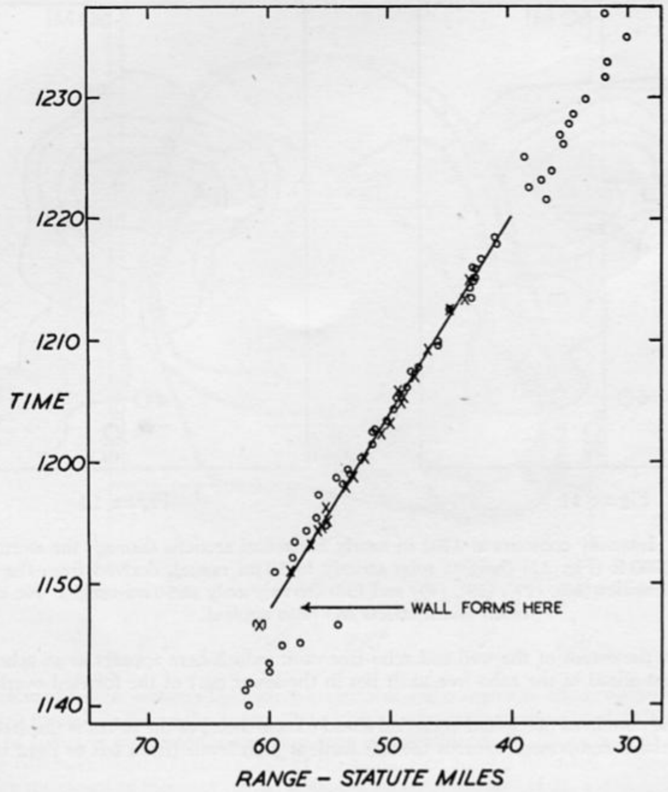

Figure 13. The crosses (through which the straight line is drawn) and the circles represent respectively the range of the wall and highest echo top, as observed by the 3·3 cm radars. Notice that the highest tops were found almost vertically above the wall (within $1\frac{1}{2}$ mi), but that their range was more variable both before its formation (during the period to which Fig. 7 is applicable), and after its disappearance.

show that the rain stopped a few miles behind the rear of the 10 cm echo (which suffers negligibly from attenuation), showing that in falling from above the radar horizon, it had been displaced rearwards by the low-level (relative) winds.

Behind the gust front the screen-level temperature and wet-bulb potential temperature θ_w fell, both reaching a minimum of about 14°C in and behind the region of heaviest rainfall. The soundings made at Crawley, Hemsby and Shoeburyness show that in the environment of the storm values of θ_w as low as 14 to 15°C occurred only at heights above 10,000 ft; because of the strong horizontal gradient of temperature and possibly also of θ_w in the frontal zone, it is not possible to be quite sure that in the path of the storm such values could not be found at rather lower levels, but the form of the isopleths of θ_w in the diagram and the strong divergence of the surface wind in and behind the rain area are consistent with the view that in the precipitation area the air near the ground had descended from these levels in a downdraught. Nearer the gust front θ_w was not so low and can be associated with air drawn through the precipitation area extending to the north-west of the storm, either from near the ground or from levels below 10,000 ft.

There was some tendency for the NNE'ly surface current ahead of the storm to be deflected southward near the gust front, but the near-discontinuity in the flow indicates that the current was lifted over the front. The main updraught was presumably derived from the potentially warm air initially at heights between about 1,500 and 8,500 ft; its position at the level of the cloud base was marked by a dark arch-cloud lying approximately

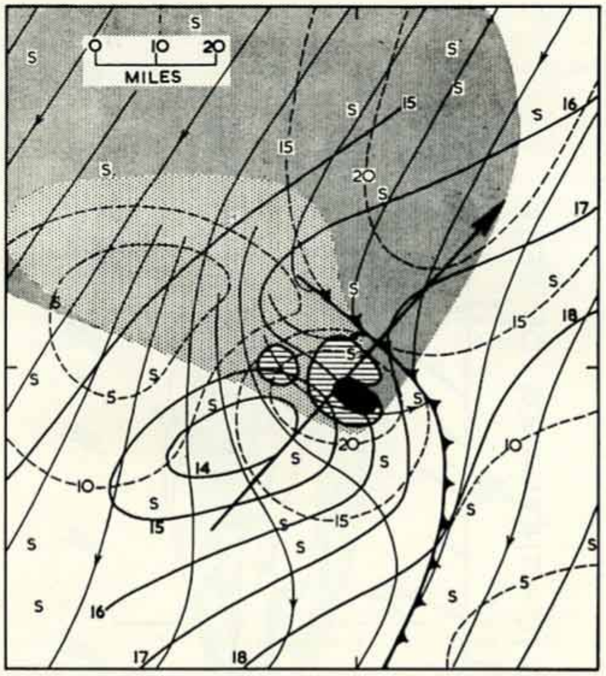

Figure 14. Surface weather associated with the storm. This diagram has been constructed mainly from observations made at about 1250, after the intense phase of the storm but when they were more plentiful (their distribution is shown by the letters ' S ').

The airflow near the surface is shown by thin lines (streamlines) and pecked lines (isotachs, labelled in kt). The gust-front is marked as a cold front. The thick lines are isopleths of screen-level wet-bulb potential temperature, θ_w, labelled in °C. The area overshadowed by the radar anvil ' cloud ' is represented by a fine stipple and that over which there is at least light rain at the ground is represented by a coarse stipple. Over the hatched areas the echo intensity Z_e exceeds 10^4 $\mathrm{mm}^6\,\mathrm{m}^{-3}$ and the surface rain is probably intense; in the small heavily-shaded area hail reaches the ground. The arrow shows the direction of movement of the storm.

above the position of the front at the ground. In a vertical section drawn along the predominant direction of the tropospheric winds (210°; the azimuth on which the RHI radars viewed the storm), the updraught thus entered the storm near the ground several miles ahead of the region where the fall of large hail and the highest echo tops indicated its presence in the high troposphere. Considering also that potentially cold air overtook the storm from the rear at heights above 13,000 ft and entered a downdraught in the precipitation area before flowing out of the rear of the storm near the ground, we see that all the observations are consistent with a flow in this section which is like that drawn in Fig. 1 (b). Study of some of the characteristics of the radar echoes allows the drawing of the updraught to be refined, as explained in the following section.

7. Derivation of the flow pattern in a vertical section through the Wokingham storm

Fig. 15 is a vertical section along 209° through the storm echo at about 1203 and shows the structure representative of the intense phase. The strongest echo occurred at a height of about 23,000 ft in a position (marked ' x ') about one mile ahead of the wall. Atlas and Ludlam (1960) have shown that here the magnitude and variation with wavelength of the echo intensity is consistent with the presence of hailstones with an almost uniform diameter of about 5 cm and with a dry surface. (Hailstones of this size reached the ground,

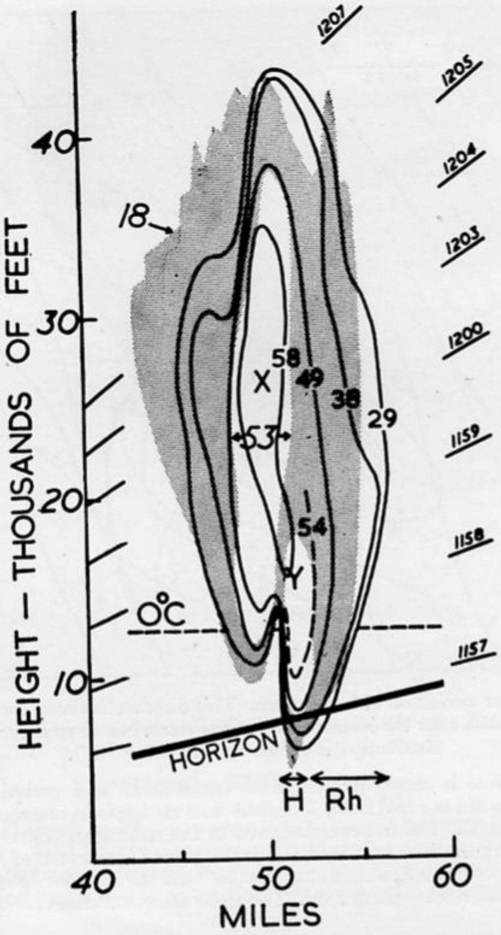

Figure 15. Range-height sections through the main storm along 209°. The stippled area denotes the region occupied by full-gain 3·3 cm echo at 1202·31 : in the unshaded region in its interior the intensity exceeded 53, according to a photograph on reduced gain at 1203·40.

The contours represent the intensity distribution in the corresponding vertical section derived from the 4·7 cm data for the period 1156-1208. Corrections for beam-width have not been applied to these values. All sections have been displaced in range at 35 kt along 210° to make them applicable to the time 1203.

but over areas only about 1 km across. This, and the embarrassingly high echo intensity after correction for attenuation which would otherwise be implied, shows that the region aloft containing such large hail was small). Atlas and Ludlam suggested that this large hail had become separated from smaller stones while falling ahead of the storm from the outflowing air of the updraught. Although at these heights the stones could have a dry surface while they were in cloud-free air, at some lower level it can be anticipated that melting would have produced a surface wetting and consequently a large decrease in echo intensity of the kind observed at the shorter wavelengths. That this decrease commenced well above the 0°C level (at 12,000 ft) can only indicate that the large stones had re-entered the updraught and were again accreting droplets in the wet-growth regime. Evidently it is possible to construct for this particular storm a more accurate outline of the form of the updraught in a vertical section than that sketched in Fig. 1 (b), not only by ensuring that it passes through the cloud-base level near the position of the surface gust front and through the region of the highest echo tops, but also that it skirts the position of maximum

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echo intensity. Further than this, when the distribution of updraught speed (or of speed along the streamlines of the updraught) is specified, it should be kinematically consistent and lead to calculated hailstone trajectories which accord with the presence of large hailstones in the position of maximum echo intensity and at the wall, and of smaller hailstones in the echo ahead of the storm at high levels and to the rear of the wall at low levels.

Other useful guidance is given by the form and intensity of the echo in the forward overhang. In Fig. 15, for example, the intensity contour (49) in the overhang, descends to a level between about 10,000 and 15,000 ft and then rises again towards the wall, the associated particles entering the updraught and being swept upwards again. Evidently at the tip of the overhang the updraught speed already somewhat exceeded the fallspeed of the re-entering particles. Assuming that they were dry and present in a spectrum similar to that* found by Jones (1960) in dense tropical anvil clouds, the diameter and fallspeed of the largest in this position can be estimated as several mm and about 35 ft/sec.

If the scattering was like that from dry spheres of ice, small compared with the wavelength,

$$
\begin{aligned}
Z_e &= 0{\cdot}21\ \Sigma\, N D^6 \\
&= 0{\cdot}21 \int_{D_0}^{D_1} 10^3\, D^3\, dD \\
&\approx 50\, D_1^{\,4},
\end{aligned}
$$

where D_1 is the diameter of the largest particles present. Accordingly this diameter is 6·3 mm where 10 log Z_e is (49). If the drag-coefficient is 0·6 (Macklin and Ludlam 1960) and the mean density 0·7 g/cm^3, the corresponding fallspeed is 35 ft/sec.

Because the dominant contribution to the echo is from the largest particles their size is not much affected by the particular form assumed for the spectrum. For example, if the particles are assumed alternatively to be of uniform size and present in a concentration of 1 g/m^3, the diameter is again found to be about 6 mm.

If the particles became wet on re-entering the updraught and scattered like liquid spheres, the diameter deduced falls to about 4 mm, but the estimated fallspeed (now assuming a mean density of 0·9 g/cm^3) is reduced only to about 33 ft/sec. The speed of the updraught in the neighbourhood of the forward overhang must therefore have been rather more than this. The general configuration of the updraught streamlines implies that here the horizontal component of motion towards the rear of the storm must have had an equal or slightly greater value and was therefore capable of tilting appreciably the trajectories of the largest hailstones which descend immediately behind the wall. The observed uprightness of the wall (within one-fifth of a mile over a height interval of at least one mile) indicates that in its vicinity the air had a relative horizontal speed (in the direction of motion of the storm) of not more than 20 ft/sec†, and thus that the lower boundary of the updraught should not be drawn to intersect the wall.

A vertical section showing a pattern of the airflow within the storm which is consistent with these considerations is given in Fig. 16. The form of this diagram has been influenced by the construction of streamlines drawn so as to imply constant mass fluxes in the up- and down-draughts, the magnitudes of which were set by the horizontal winds relative to the storm within the layers of potentially warm and cold air. They were subsequently adjusted slightly to be consistent with the position of fall and internal structure of a number of large hailstones collected from places affected by the storm in its intense phase, using theoretical estimates of the rate and density with which ice is deposited by accretion on growing stones. (This work will be reported separately. It places a severe limitation upon the slope of the streamlines in and below the region of most intense updraught, and requires that its speed reached about 100 ft/sec near the − 40°C level – the fallspeed of the largest stones at this height).

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[*] $N_D = 10^3/D^3$, where $N_D\, \delta D$ is the concentration (m^{-3}) of particles with diameter between D and $D + \delta D$ mm.

[†] The fallspeed of the largest hailstones near the ground was about 100 ft/sec, and if they were within the updraught, the speed relative to the ground would have been less.

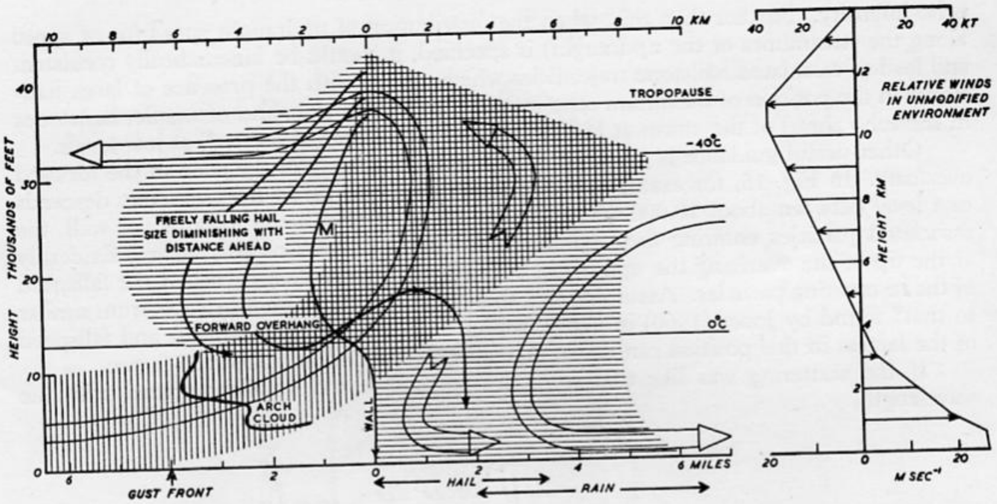

Figure 16. Vertical section through the centre of the storm along the direction of motion (from right to left of the diagram). The extent of the updraught is denoted by vertical hatching and that of echo whose intensity Z_e exceeds 10^3 $\mathrm{mm^6\,m^{-3}}$ is denoted by horizontal hatching. Some hailstone trajectories are indicated.

8. A THREE-DIMENSIONAL MODEL OF THE WOKINGHAM STORM

In the work on hailstone trajectories referred to in the last paragraph it was found possible to account for the rise of small hail in the updraught, its growth into large hail before arrival at the position of the strongest radar echo, and its subsequent fall to the ground just behind the wall. However, difficulties arose in accounting for the growth of small hail from cloud particles, and in explaining the duration of large hail at the ground and the great rearward extension of the radar echo. These difficulties indicated that particles and air entered the section from outside it, and that the mass fluxes in the draughts were augmented from outside it.

The streamlines of the wind near the ground (Fig. 14) show that the downdraught spread out towards the right flank of the storm. Immediately behind the gust front the wind had a mean relative speed away from the front. (This may be due to surface friction; the cold air a little distance above the ground probably advances with the storm velocity, intermittently descending to produce a new gust front and thus introducing some unsteadiness into the circulation). It seems that air at the front was replaced partly by descent from above, and partly by a flow from the left forward flank which cannot be represented in the vertical section. The sweep of the low-level air in the rear of the storm towards its right flank may be an effect of Coriolis and frictional forces, and seems to be associated with the formation of the gust front and generation of the updraught on this side only.

On the left flank of the storm precipitation fell into low-level air approaching the storm. This air could acquire buoyancy if lifted sufficiently, but can also be regarded as potentially cold if precipitated into, since it was unsaturated. The downdraught could, therefore, be fed from the left flank not only by middle-level air which overtook the storm, but also by air below 13,000 ft which entered from the front. Probably the downdraught flux was also augmented by a convergence in the middle and upper troposphere associated with increased wind components from the left flank.

It seems significant that the low-level potentially warm air approached the gust front with a component from the right, which was observed to increase near the front. The disposition of the echo at high levels (Fig. 12) shows that the updraught air also left the storm with a substantial component in the same direction. The updraught must, therefore, be envisaged as inclined upwards from the right as well as from the forward flank. The great rearward extent of the echo at high levels (ascertained from the 10 cm RHI records) can be attributed partly to the entry into the section of updraught which rose near the gust front (farther to the right of the storm) and partly to a rearward spreading of the updraught near the tropopause level. It appears that the total mass flux in the updraught was substantially increased over that given by the relative speed of approach of the potentially warm air in the winds of the undisturbed environment, by a low-level convergence associated with increased wind components from the right.

Accordingly there was an organized circulation not only in the section of Fig. 16, but also in the vertical plane through the storm at right-angles to it, and the storm had a noticeable component of motion towards the right. Its line of advance made an angle of nearly 15° with the predominant direction of the tropospheric winds; in this respect its behaviour is typical of severe storms (Newton 1960).

The gust front weakened, and presumably the cold air behind it became shallower, with increasing distance to the rear of the storm. Along its length the smooth arch cloud in front of the storm, where the updraught was strong and persistent, was probably replaced by a belt of cumuliform clouds where the weaker updraught broke into a succession of thermals. (Fujita and Byers (1960) have discussed the form of a cumulonimbus photographed by Cunningham (1960) on an occasion when the wind shear was remarkably similar to that in the environment of the Wokingham storm. Cunningham noted that there were no distinct turrets at the storm top, 'suggesting that it was characterized by a large region of fairly continuous upward velocity.' Fujita and Byers present diagrams and pictures which show a line of cumulus on the right rear flank of the storm whose tops become successively higher nearer the storm). Before and after the intense phase of the storm it was observed that intermittently echoes formed to the southwest of the right flank of the main echo mass, at first separated by a mile or two from it but then expanding and after some minutes becoming fused with it. This behaviour is interpreted as due to the formation of precipitation in the largest of the cumuliform clouds above the gust front near the right flank, followed by their invigoration and development into cumulonimbus which amalgamated with the main storm cloud. It is remarkable that during the intense phase the storm echo extended towards the right continuously, and not in this intermittent manner. A belt of cumuliform clouds extending along the gust front to the rear of a large cumulonimbus may be made more striking by the virtual absence of cumulus over a large neighbouring area where the cold air behind the front is deeper. An instantaneous view of the whole cloud system may give a false impression that the updraught approaches the storm from the rear: air in the cumuliform clouds which fails to rise above some mid-troposphere level (13,000 ft on the occasion of the Wokingham storm) is in a wind field which leads it away from the storm. Only that air which rises above this level in the larger cumuliform summits can approach the storm, and little or none of it may ever become incorporated into the strong updraught which rises at the storm front.

9. CONCLUSIONS

A tentative three-dimensional model of the airflow in the Wokingham storm is shown in Fig. 17. A model of this kind may be representative of the structure of the severe travelling storm of middle latitudes, but this can be established only by more detailed study of other examples. A similar but less well-organized and steady flow pattern may occur in many lesser storms and showers, but their smaller scale, intensity and persistence make it difficult to study them with radars of ordinary resolution.

Observations inside severe storms are hazardous to make and difficult to interpret, but the concentrated use of conventional ground-based techniques can be rewarding, and the addition of new methods of observation, such as those using a vertically-directed Doppler radar stationed beneath or flown over the storm, will accelerate progress.

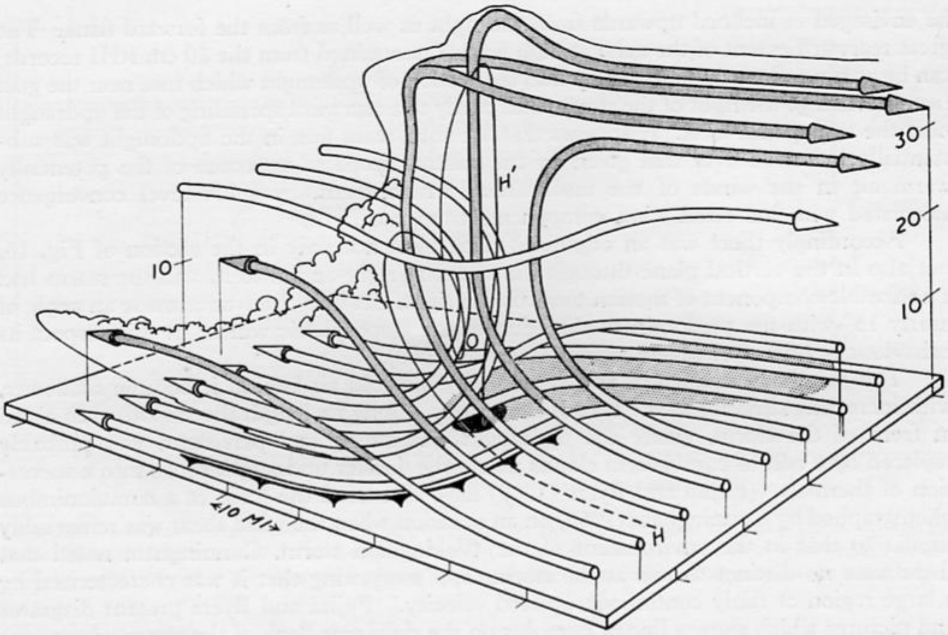

Figure 17. Three-dimensional model of the airflow within the Wokingham storm. Streamlines of air in which condensation has occurred are shaded.

The extent of hail and light rain at the surface are represented by dark and stippled shading respectively. The gust front is marked as a cold front and the belt of cumulus above it on the right flank of the storm is indicated schematically. Precipitation forms in the larger of these cumulus in air which enters the storm from a position near *H*; some of it is carried at levels above 13,000 ft forward and across relative to the storm, and falls to re-enter the strong updraught and form the forward overhang, near O. A small proportion of the particles rise to great heights and grow into large hailstones before again falling, forward of the strong updraught, near the position *H'*. Here their surfaces become dry and they produce a very intense 3·3 cm radar echo. Subsequently they traverse the updraught again before reaching the ground. The path HOH' can therefore be regarded as the trajectory of a particle which becomes a large hailstone.

The proposed model is likely to stimulate theoretical study of the severe storm by suggesting that, for a start, it can be regarded as a steady-state disturbance. Even an examination in only two dimensions may give some insight into the problem of what parameters control its intensity, velocity and persistence; on the other hand, important aspects such as its development and its capacity to produce extreme rainfall, large hail and tornadoes, will probably demand a more general treatment.

ACKNOWLEDGMENTS

We are pleased to thank the Director-General of the Meteorological Office for the provision of staff and facilities at the East Hill Radar Station, from which the observations were made. The research on severe storms of which this work has been a part, is also supported by the Geophysics Research Directorate, Air Force Cambridge Research Center of the Air Research and Development Command, United States Air Force. The British Rainfall Organization provided data from their observers, and we are grateful for the many painstaking records provided by a large number of voluntary hail observers. Personnel who contributed to the observational programme were Messrs. W. G. Harper (Officer in Charge), N. Coupe, A. Denham and J. Beimers of the Radar Station; Dr. David Atlas, Messrs. P. J. Harney and P. Petrocchi of the Geophysics Research Directorate, U.S.A.F.; Dr. and Mrs. S. C. Mossop of the South African Council for Scientific and Industrial Research, and Dr. W. C. Macklin of the University of Western Australia.

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Appendix

Characteristics and mode of operation of radars on 9 July 1959 at East Hill (51° 55′ N 00° 30′ W; National Grid Reference 52 (TL) 028 248)

Type	Wave-length cm	Beam-width, degrees		Max. display range (statute mi)	Sweep period sec	Mode of operation
		Horiz.	Vert.			
AN/TPS-10	3·3	2·0	0·7	70	1	Set A: manual following of echo column tops, to obtain their rate of rise. Set B: manual location of most intense echoes, and intensity measurement by reduction of gain.
MPS-4	4·7	4·0	0·8	140	12	Stepwise gain reduction during PPI sweeps at successive fixed elevations (complete cycle time 20 min)
A.M.E.S. Type 13	10 (RHI)	7½	1½	160	10	Manual search for maximum echo heights; intensity measurement by reduction of gain
Type 14	(PPI)	1¼	6 (centred at 2° elevation)	120	15	Automatic full gain photograph every 3 min; intermittent stepwise gain reduction

Records were made by photographing the displays, and have been analysed with the help of the written notes and tape-recorded comments of the radar operators.

occurrence of two parts in the w-spectrum in these particular observations may be related to an indeterminacy of the turbulent motion in a constant-stress layer. By this, I mean that details of the turbulent motion can change considerably from one kind of flow to another while preserving the same relations between vertical transport-rates and mean gradients. Examples of this are well known from laboratory studies.

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Airflow in convective storms

By K. A. BROWNING and F. H. LUDLAM

(Read 16 May 1962. See *Q.J.*, **88**, p. 117. Presented by Dr. F. H. Ludlam.)

Mr. J. S. Sawyer: I should like to draw attention to the fact that the slope of the up-current in Dr. Ludlam and Dr. Browning's model hailstorm is in the opposite direction to that in a simple cumulus cloud which is distorted by wind shear. It is not easy to visualize the transformation from a small growing cumulus to a well-organized hailstorm. Have the authors any ideas on this subject? Do they think that the transformation is an occasional accident or is it inevitable if the air stream structure is such as will support a large hailstorm?

Mr. C. E. Wallington: By far the majority of tornadoes which have been reported in this country have moved towards NE. Does the three-dimensional storm system you have discussed help to explain this observed tendency?

Mr. J. M. Craddock: When I was stationed in Malaya about 15 years ago, I spent some time observing and recording the development of cumulus cloud, making photographs of developing clouds at time intervals of three or five minutes, and adding a written description. Some of this work was reported in the *Quarterly Journal* – some is unpublished – but the general impression left by my observations agrees excellently with the model now put forward by Dr. Ludlam. I can confirm several features, such as the dome on the anvil, and cannot call to mind any important discrepancy.

Mr. W. G. Harper: Although, as Dr. Ludlam has said, self-propagating systems as severe as the Wokingham storm are very infrequent in the British Isles, for Europe as a whole they are a regular seasonal occurrence. I think we must take a 'Common Market' view of this because the speed of present-day aircraft is such that European flights are now almost local flights to us. There is practical importance in severe storm studies quite apart from their theoretical interest.

Capt. J. R. C. Young: One of the illustrations showed a classical photo of hail on the ground fallen from a cloud generated in a cold NW'ly air stream over Nebraska and you specifically mentioned the high cloud base as 14,000 ft., about 11,000 ft above the ground in this area. Over India in the 'pre-monsoon' storms, over the Persian gulf area, and over the South African plateau, to mention but a few places, much damage is done to property and sometimes specifically to aircraft and to life by storms having the common characteristic of the high cloud base, and with no lower structure visible. Do you consider this fact significant?

Dr. F. H. Ludlam (*in reply*): In reply to Mr. Sawyer, we have not studied the manner in which the organization of the air motion in cumulonimbus is established, but we believe that the backward lean of the updraught is pronounced only in the lower troposphere and develops by the intrusion forward of the downdraught. The paths of air particles rising in the updraught may at all times be forward relative to the ground, just as in cumulus convection, but the draught is continuously renewed at a position ahead to the storm, over the squall-front of the downdraught. We have the impression that if our criteria for instability were refined a little further we should find severe hailstorms almost always develop in favourable conditions, that is, that it is very rare for them to fail to develop for lack of some suitable 'triggering' process.

The paths of tornadoes lie approximately along the line of motion of the parent storms, and hence are roughly parallel to the orientation of the frontal zone in which they occur. In this country the prevalent orientation is from SW to NE, as Mr. Wallington says, on the forward side of cold troughs approaching slowly from W, but in other places it may be different: for example, in the central U.S.A. it is frequently from W to E, or even NW to SE. Captain Young remarks that hailstorms often have an abnormally high cloud base; we think that this may be associated simply with the intense heating which often precedes them well inland. Nearer coasts the cloud base may be very low, as in the Wokingham storm, so that a high cloud base does not seem to be an essential feature of the most intense storms.