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CELLULAR STRUCTURE OF CONVECTIVE STORMS

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Abstract.—Seven convective storm areas crossed south-east England on 9 July 1959; radar data on these are presented to demonstrate a higher degree of organization within the more intense storms.

Introduction.—On 9 July 1959 seven convective storm areas crossed south-east England travelling at about 40 mi hr^{-1} in a north-easterly direction. One of them (storm 1 in the plates and figures accompanying this article) became very severe and produced widespread large hail, especially in the Wokingham area of Berkshire. Detailed radar and ground observations of this particular storm have been analysed in an earlier paper[1] so as to determine the nature of the associated airflow. Throughout its existence the radars showed that this storm consisted of a number of units or cells in various stages of development. Each of them had a lifetime (1–3 hr) which was small compared with the overall life of the storm (> 8 hr) but still long compared with that of the cells associated with ordinary showers (< 1 hr). For simplicity overt consideration of this cellular nature was avoided in the above reference. The purpose of the present paper is to expose the characteristic cellular behaviour of this, and another intense storm, and to contrast their organization with the chaotic behaviour of weaker storms occurring during the same day.

General behaviour and intensity of the storms.—For an outline of the synoptic situation on this occasion the reader is referred to section 4 of the paper already mentioned.[1] According to this reference the Wokingham storm developed over Brittany just before 0800 BST:† it subsequently crossed the Channel and travelled within a cold front zone across south-east England, where it came under radar surveillance from East Hill near Dunstable (Bedfordshire). The progress of this and six other individual storm areas was recorded by an AMES type 14/10 cm PPI (plan position indicator) radar and is illustrated by the plates between pages 356 and 357 which include photographs of the full-gain display at 15-minute intervals (apart from a break after 1300 caused by a power failure).

*Now at Weather Radar Field Station, Sudbury, Massachusetts.
†All times in this article are in British Summer Time (BST = GMT + 1).

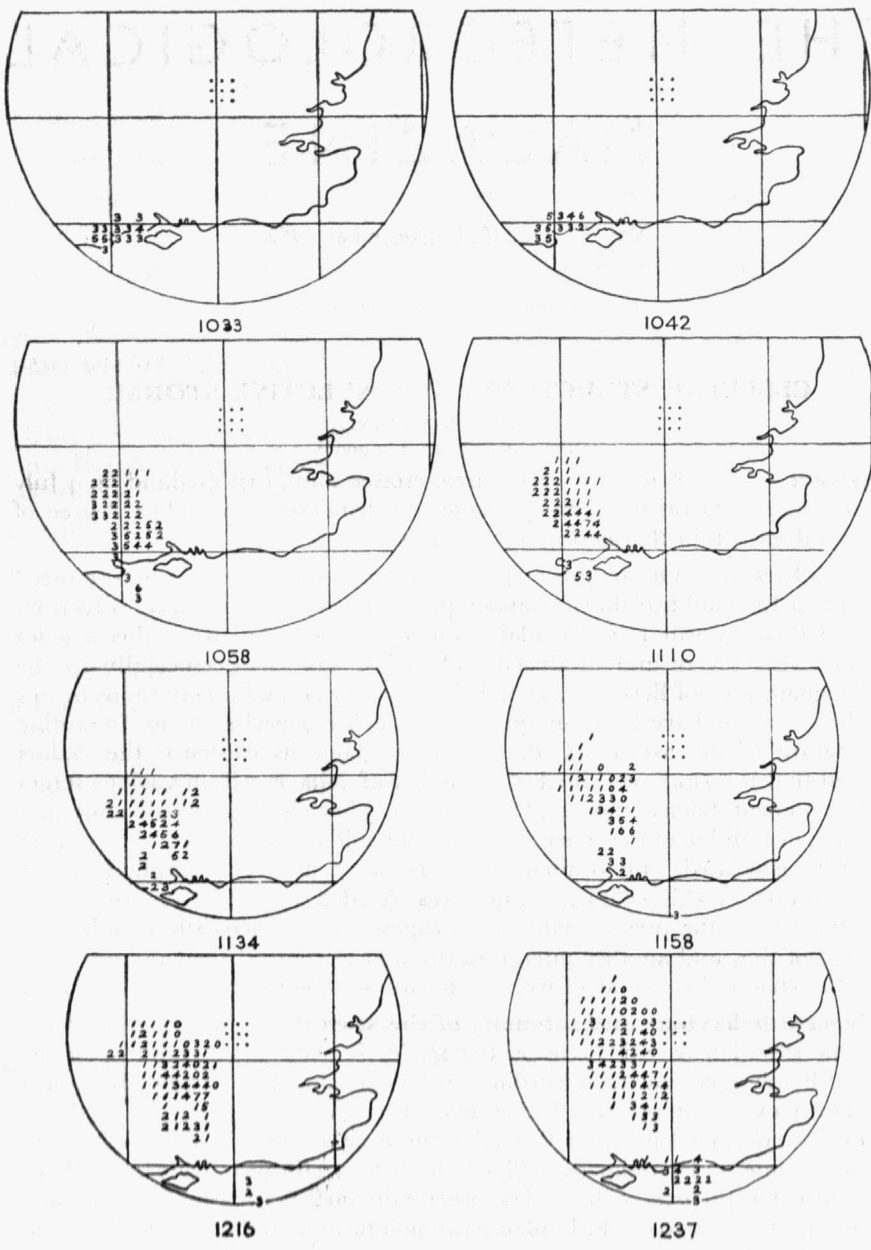

FIGURE I — THE HEIGHT-INTEGRATED ECHO-INTENSITY DISTRIBUTION OVER A REGION WITH THE EAST HILL RADAR STATION AS CENTRE, FROM 1033 TO 1646 BST.

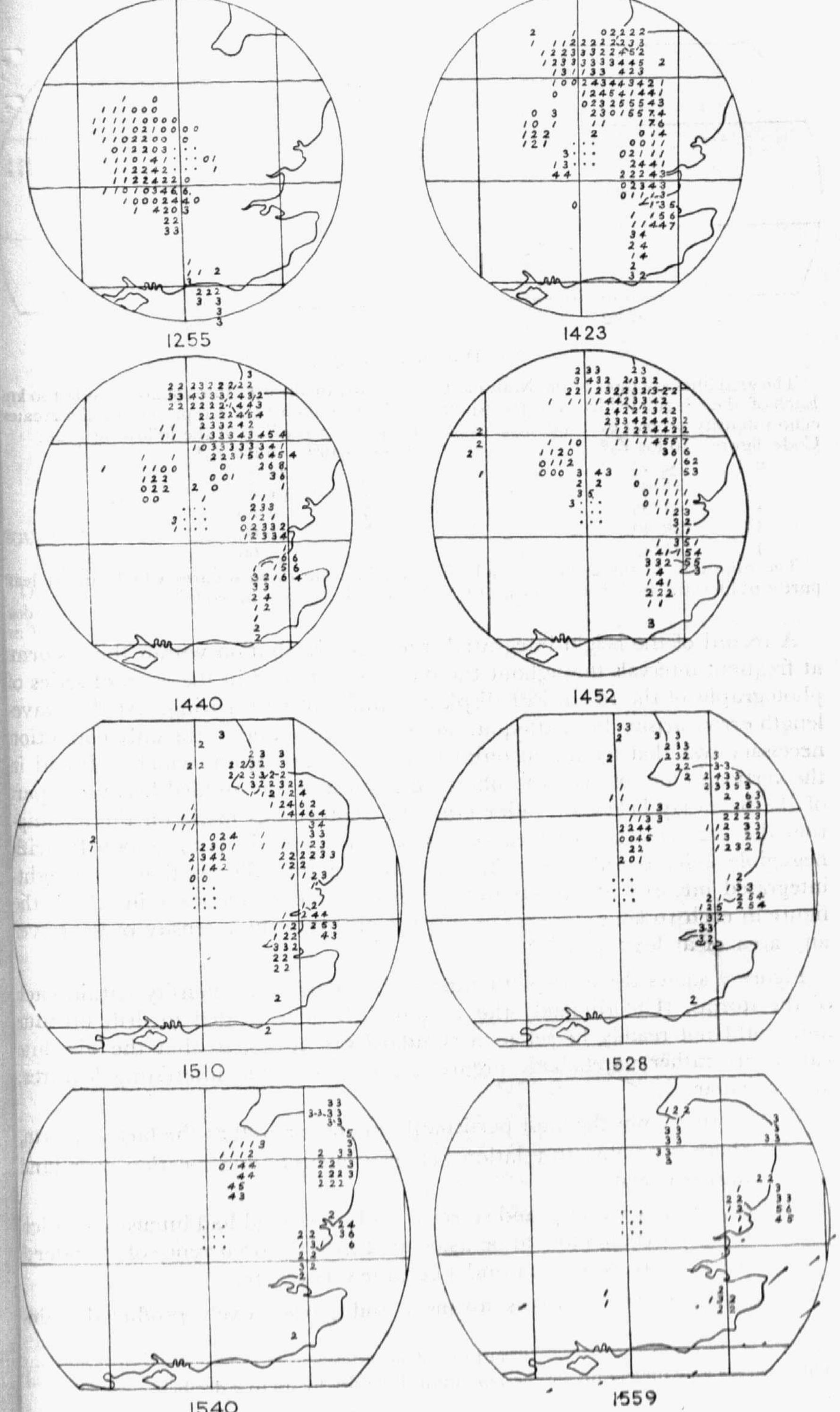

FIGURE I (*cont.*)

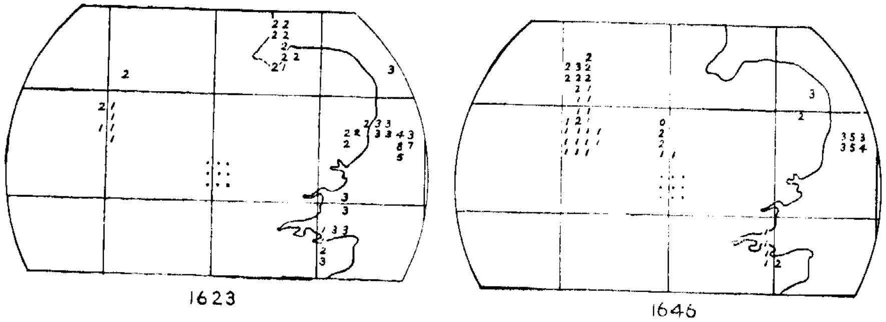

FIGURE 1 (*cont.*)

The grid lines are those of the National Grid and divide the area into squares of side 100 km. Each of these is subdivided into 100 squares, which contain figures representing the greatest echo intensity present over any area of at least 4 km² according to the following code:

Code figure	10 log Z_e*	Code figure	10 log Z_e*
0	$\leq$ 25	5	46–50
1	26–30	6	51–55
2	31–35	7	56–60
3	36–40	8	61–65
4	41–45	9	$\geq$ 66

The nine dots in the centre of each diagram indicate those squares which are at least partly obliterated by echoes from ground objects. (Times are in BST).

A record of the height-integrated intensity distribution within these storms at frequent intervals throughout the day was obtained in the form of series of photographs of the 10 cm PPI display at different gain settings. At this wavelength errors arising from attenuation are negligible and so the only correction necessary was that for the incomplete filling of the beam, which is broad in the vertical. One correction to observed intensities was applied because a part of the beam lay below the radar horizon; another was made on the assumption that strong echo occurred only from the ground up to 30,000 ft, with negligible echo outside these limits. The resulting distributions of height-integrated intensity at various times are displayed in Figure 1 in which the figure in each 10 km square represents the greatest echo intensity present over any area of at least 4 km².†

Figure 2 shows the trend with time of the maximum intensity within each of the storms. (Unfortunately the 10 cm PPI radar tended to drift off-tune and could not readily be set to a standard brightness, so that the absolute values are rather unreliable). Figure 2 illustrates some interesting features; in particular

(i) storm 1‡ was the most persistently intense as well as the largest storm,
(ii) there is no obvious relation between intensity and location over land and sea, and
(iii) storms 3, 5, 6 and 7, and storm 2 while over land had intensities which usually were too low to be associated with the occurrence of thunder:[2] by comparison storms 1 and 4 became very severe.

Figure 3 shows that, whereas storms 1 and 4 respectively produced wide-

*Z_e is the equivalent radar reflectivity in units of mm^6m^{-3}.
†These values may underestimate the maximum intensity by up to 5 decibels.
‡The Wokingham storm.

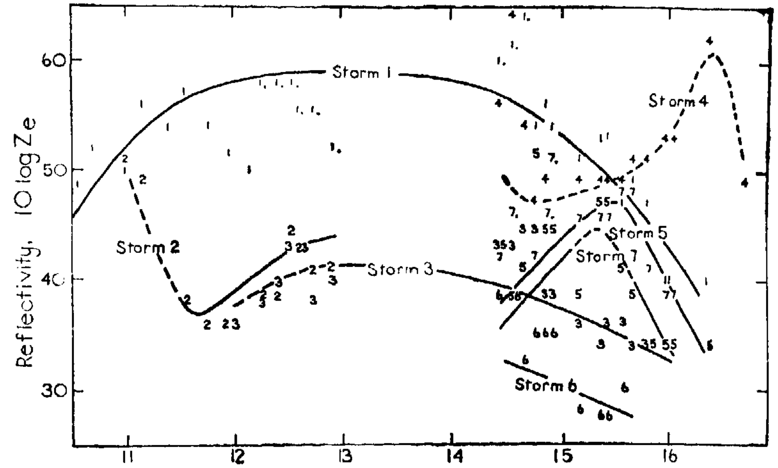

FIGURE 2 — THE TEMPORAL VARIATION OF THE MAXIMUM INTENSITY WITHIN EACH OF THE SEVEN STORMS AS DETERMINED BY THE 10 CM PPI RADAR

The individual measurements have smoothed curves drawn through them, which are dashed during periods when the storms were over the sea. Those values followed by a dot are liable to be under-estimated since they correspond to occasions when it was impossible to reduce gain sufficiently to remove the echo from the display. (Times are in BST.)

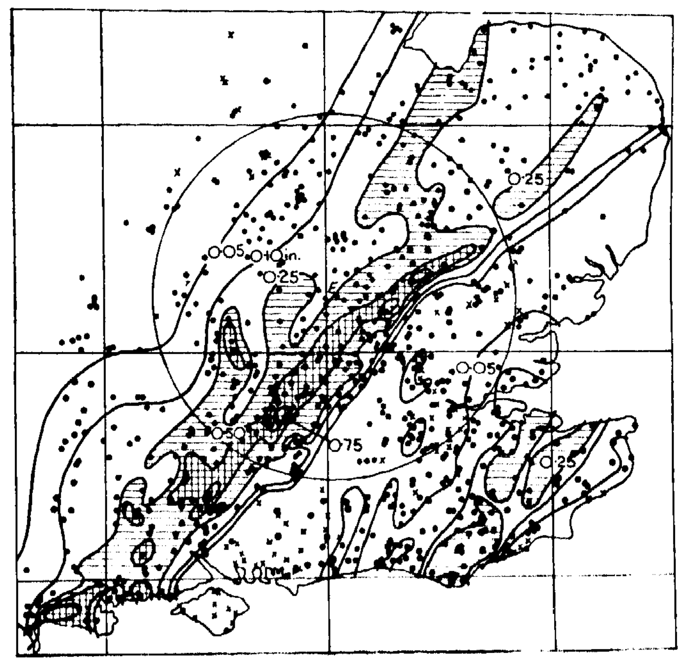

FIGURE 3 — DISTRIBUTION OF RAINFALL IN SOUTH-EAST ENGLAND ON 9 JULY 1959

The positions of 910 observations are indicated as dots or crosses according to whether or not measurable rainfall was reported. *E* denotes the location of the East Hill radar station. The circle marks a radius of 50 miles from East Hill.

spread rainfall totals exceeding 0.5 and 0.25 in., storm 3 produced few totals over 0.05 in. (Storms 2, 5, 6 and 7 probably made comparatively small contributions to these totals). Only storm 1 produced hail overland, giving a 130 × 5 mile swath roughly in association with the region of highest rainfall (see Figure 2 in Browning and Ludlam's paper[1]).

The motion of the storm cells.—Regions of radar echo corresponding to each of the seven storm areas portrayed in the plates between pages 356 and 357 are referred to as echo-masses. These varied in size from about 10 to 100 miles across and each comprised a number of distinguishable, but not necessarily completely detached, regions of higher intensity with diameters of the order of a few miles which are referred to as cells.* The velocity of travel of each echo-mass was determined not only by the translational velocity of the individual cells but also by their positions of formation and dissipation. In this respect there is found to be a notable difference between the behaviour of the two intense storms (1 and 4) and that of each of the others, as is now shown.

Storm 3 was the weakest of the seven: it developed off the Sussex coast

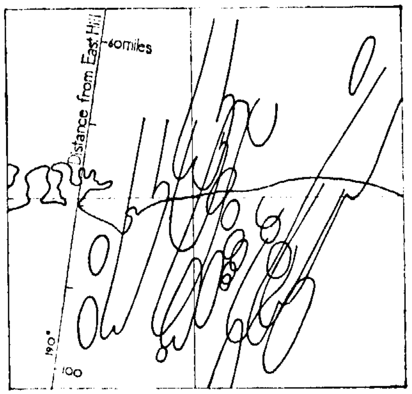

FIGURE 4 — PATHS OF CELLS COMPRISING THE GROUP CLASSIFIED AS STORM 3 DURING THE PERIOD 1150 TO 1300 BST AS THEY CROSSED THE SUSSEX SHORELINE

Note their short duration and lack of organization.

around midday as an irregular cluster of small weak cells. Figure 4 shows that these formed and dissipated in the unsystematic manner which is typical of feeble showers, the majority persisting for short periods only. The motion of the weaker cells (from about 195°) was along the wind direction in the medium levels: the more intense cells moved up to about 10° to the right of this.

The cells comprising storm 2 showed more organization (Figure 5). When the storm first came within range of the East Hill radars it was over the English Channel and consisted of a single intense cell travelling at 40 mi hr^{-1} from 209°: as it approached the south coast it weakened but further cells formed on both flanks, aligned approximately at right angles to their motion (from about 195°). The most intense cells occurred near the right-hand end of the line but none had an intensity within an order of magnitude of that of the first one.

The intense storms 1 and 4 were even more highly organized, the principal new development invariably occurring on the right flank. This is vividly demonstrated by Figure 6, which shows the path of their constituent cells. Like the preceding two diagrams, Figure 6 has been derived from the analysis

*Probably associated with single convective cells.

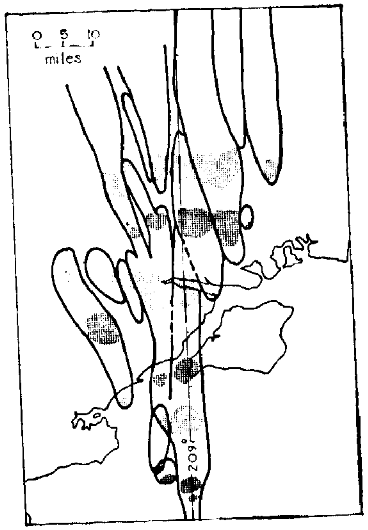

FIGURE 5 — PATHS OF CELLS COMPRISING STORM 2

Positions of the paths are indicated at times 1051, 1109, 1124, 1145, 1203 and 1218 BST (moving northwards).

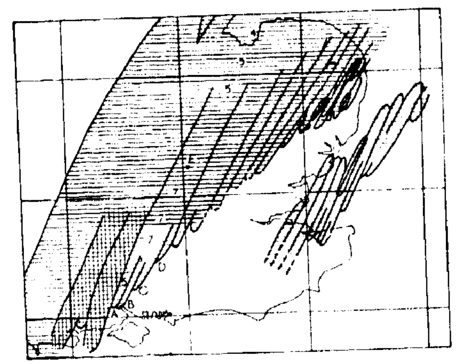

FIGURE 6 — PATHS OF CELLS COMPRISING STORMS 1 AND 4

The paths have been determined largely from the 10 cm PPI records. Boundaries between adjacent cells are terminated as soon as it becomes impossible to resolve them on any of the reduced-gain photographs. Numbers at intervals along the path of the largest cell indicate the trend in its maximum radar intensity according to the code in Figure 1. The two cross-hatched paths are of compact clusters of cells. Note especially the longevity of many of the cells and their systematic formation on the right flank of each echo-mass.

of photographs of the full-gain 10 cm PPI display taken at 3-minute intervals. However, in the case of Figure 6, because most of the cells could only be resolved by the radar at reduced gain, these data had to be supplemented by the frequent series of photographs of the display at different receiver gains. The gap in the 10 cm records caused by the failure of the mains electricity supply was filled in by data obtained using a 4.67 cm MPS-4 radar whose power was supplied by a petrol generator. Unfortunately this radar was operating with a poorer temporal and azimuthal resolution, so that parts of the cell paths derived therefrom (and drawn dashed in Figure 6) are less reliable.

The orientation of each path in Figure 6 lies within 5° of 210–030°. This is in good agreement with the wind direction of 214 ± 6° at all heights between 3000 and 30,000 ft recorded at Hemsby at 1200 (150 miles north-east of storm 1), but is veered a little from the wind direction at all medium levels at Crawley and Larkhill at this time. However, this need not necessarily imply a discrepancy between cell motion and the predominant direction of the large-scale geostrophic wind, as the sounding at Crawley and more particularly that at Larkhill were made fairly close to (and therefore may have been modified by) storm 1 during its intense phase. The Crawley sounding shows the wind veering with height throughout the medium levels, suggesting that the motion (from 195°) of the weaker cells comprising storms 2 and 3 was influenced more by the winds at lower levels than were the cells within storms 1 and 4.

The behaviour of cells within the intense storms.—The organization

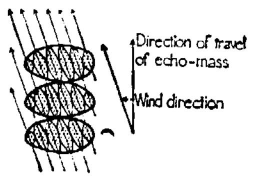

FIGURE 7 — SCHEMATIC DIAGRAM

This illustrates how the formation of new echoes at the right flank of an echo-mass and their eventual decay on the left flank causes the centroid of the echo-mass to travel to the right of the winds.

of storms 1 and 4 is illustrated schematically in Figure 7. It emphasizes the propagation of the centroid of the echo-mass to the right of the winds,* as has been observed by Newton and Katz.[8] Each constituent cell eventually became weak and diffuse so as to be indistinguishable from its forerunners on the left flank, its persistence determining the over-all size of the echo-mass.

In Figure 7 the cells are depicted as becoming elongated along the direction of the wind. Elongation along this direction occurred on this occasion because the wind direction was almost invariant with height, so that the shear vector also lay in this direction. This meant that the major component of the convective circulation occurred within a vertical section orientated parallel to the winds. Accordingly the updraught entered the cell at low levels at the downshear end and emerged at high levels at the upshear end before being accelerated downstream. This behaviour is demonstrated in Figure 6 of Browning and Ludlam's paper[1] which shows a series of radar photographs of vertical sections along the axis of a particular cell within storm 1: it portrays a succession of towers (roughly 3 mi in diameter) rising at the upshear end of the cell, each of which becomes the highest echo whilst moving in a downshear direction through the cell before subsiding and decaying at the downshear end. Although the presence of discrete towers implies an updraught which was essentially intermittent, nevertheless it must have been quite persistent, since this cell (and others like it) could be traced

*A similar process can be inferred where this deviation is evident, even though the resolution of the radar is inadequate to distinguish the freshly-formed parts of the echo, as in the case of the most intense cells in storms 2 and 3.

for over an hour, which is longer than the period required for air in a moderate convective updraught to move through the cell or for the precipitation particles formed therein to reach the ground.

Four of these cells (labelled A, B, C and D in Figure 6) became very intense soon after storm 1 came inland and they amalgamated to form a single large cell with horizontal dimensions of the order of 10 mi. This cell has been analysed in particular detail by Browning and Ludlam.[1] They show that it maintained a virtually steady structure throughout a 30-minute period, and employ certain characteristic features of this structure to evolve a three-dimensional model of the associated quasi-steady airflow, a feature of which is the reinforcement of the updraught flux by an inflow from the right flank. During the period prior to the development of new cells on its right flank this "supercell" was reaching the greatest heights and intensities of the day as well as producing the largest and most widespread hail. Although it declined somewhat after the development of new cells to its right, it persisted as a resolvable entity for more than two hours before decreasing in intensity to that of the diffuse decaying echo in which it was embedded.

In contrast with those cells forming during the more intense phases of storm 1, the cells appearing after about 1445 formed quite detached from the main body of the echo-mass, even at full-gain. Thereafter the rate of formation of new cells increased in inverse proportion to their intensity, size and persistence until the storm reached the North Sea, when regeneration ceased altogether.

Conclusions.—Although even small and comparatively weak cells often lasted for an hour, indicating the presence of a persistent (if intermittent) updraught, the larger more intense cells are most notable for their longevity. Indeed, one could still be identified more than three hours after its formation, continuing to be resolvable even after several new cells had developed to its right. This behaviour was responsible for the broad extent of storm 1, the echo-mass of which reached a width of 100 miles at one stage.

The storms which attained high radar intensities and which produced large rainfall totals were not only characterized by long-lived cells; they were also highly organized, propagating systematically to their right. This propagation generally occurred in the form of discrete cells which remained resolvable from their predecessors often for an hour or two. A notable exception occurred during the most intense phase of storm 1 when successive cells amalgamated within 30 minutes of detection to form a large and intense "supercell".

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FORMATION AND DISPERSAL OF FOG OVER THE FENS

By M. H. FREEMAN, O.B.E., M.Sc.

Introduction.—Forecasters in East Anglia have long been aware that the presence of the fens has an effect on the formation of fog in the area. At Waterbeach, for instance, it was asserted that fogs tend to form earlier and persist longer than in surrounding areas. The extent of the influence of the fens was not known accurately, so a detailed investigation was planned to seek further information on the formation and dispersal of fog over the fens and at the seven meteorological offices (Upwood, Wyton, Oakington, Waterbeach, Mildenhall, Marham and West Raynham) near the borders of the fens.

To this end the co-operation of about 50 voluntary observers (listed in the appendix on pp. 356–7) was obtained. Using the simple forms provided, they undertook to record, whenever practicable, the time at which visibility fell below or improved above the three limits 50, 200 and 1000 yards. Mr. W. B. Painting visited each observer to explain the project and assist in selecting suitable visibility objects and lights. Figure 1 shows a map of the region and indicates the approximate boundary of fen-land. It also shows the locations of the meteorological offices and the voluntary observing stations. The investigation related only to that part of the fens south of the Wash; no reports were obtained from the region to the north-west of Spalding.

The first phase of the investigation took place during the winter October 1959 to March 1960. A detailed analysis of the observations obtained was made by Mr. S. P. Peters, and in the light of his report it was decided to continue the investigation during the following winter 1960–61. A smaller number of strategically placed observers took part in this second phase; their locations are marked by small circles on Figure 1.

Analysis of the observations.—From the two winters 79 periods of fog were examined; a few occasions of patchy short-lived fog were ignored. For each selected period hourly charts on a scale of 1: 253,440 were plotted and lines indicating the boundaries of visibilities less than 50, 200 or 1000 yards were drawn. The standards of reporting achieved by the voluntary observers naturally varied, but it was usually possible to arrive at a coherent analysis of each situation. As would be expected the number of reports between 2300 and 0700 hours was small, and the formation of fog was less well documented than its dispersal. About half the observing stations were at schools, most of which were unable to report during holidays and at week-ends. Week-ends were also less well covered by Meteorological Office stations since Upwood, Oakington and Waterbeach were often closed then. Another, more or less inevitable difficulty was that voluntary observers could not maintain a continuous watch and their records merely showed the times at which the visibility had been observed to be below a certain limit. Also some occasions of fog were found to be missed so that absence of a fog report could not necessarily be taken as indicating that the visibility was greater than 1000 yards. Nevertheless sufficient reports were usually received to enable a worthwhile analysis to be made. The