M.O. 584g

AIR MINISTRY

METEOROLOGICAL OFFICE

Geophysical Memoirs No. 99

(SEVENTH NUMBER, VOLUME XII)

TORNADOES IN ENGLAND MAY 21, 1950

BY

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1957

Decimal Index
551.515.3(42)

Geophys. Mem., London,
12, No. 99, 1957

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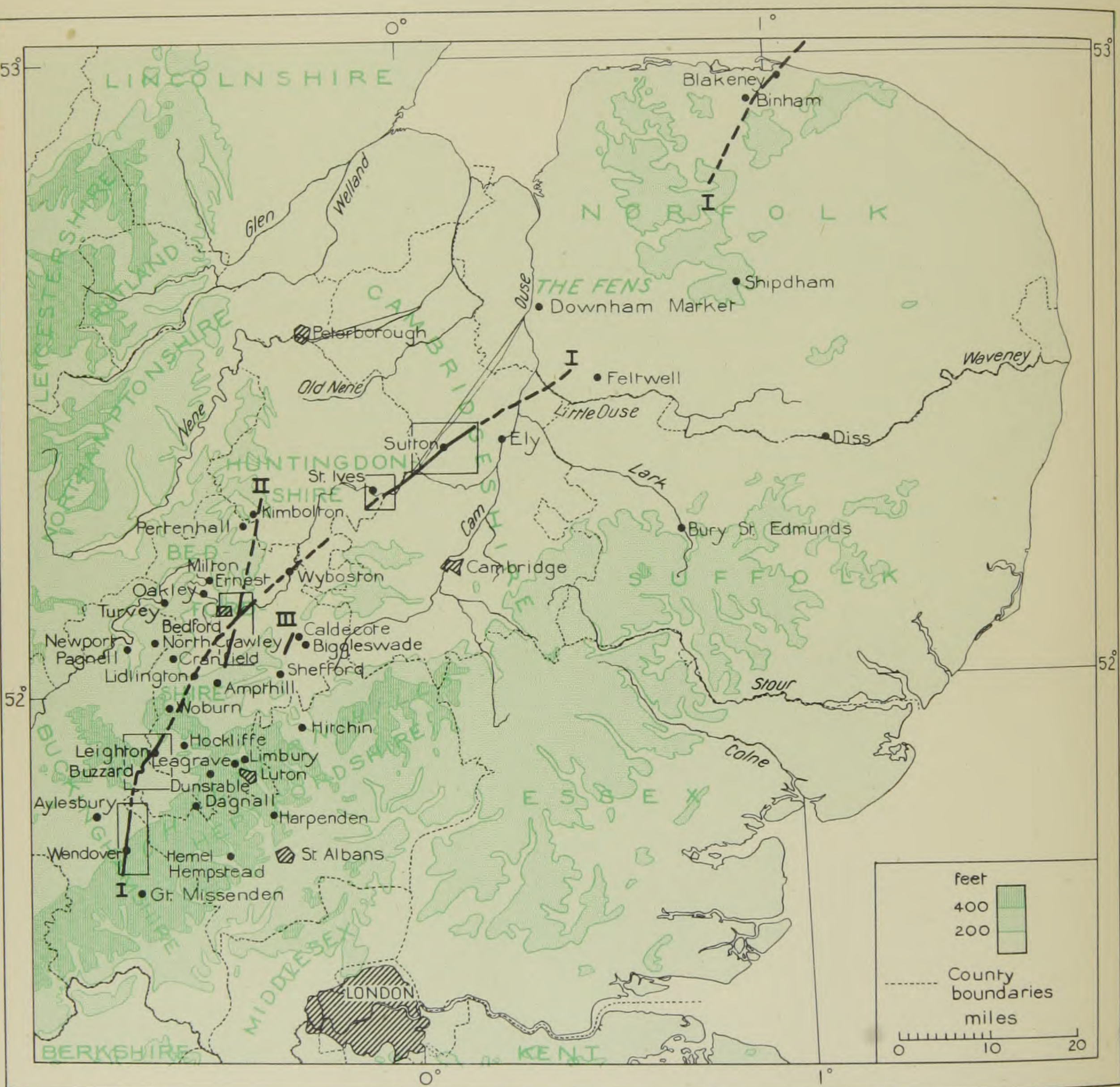

TORNADO TRACKS, EASTERN ENGLAND, MAY 21, 1950

The small rectangles show the positions of the larger-scale maps in Figs. 1-3

C.B.H. 27983 - Wt. 2517 - Dd. BM/4088 - 625 - 6/57

TORNADOES IN ENGLAND
MAY 21, 1950

SUMMARY

Close examination of the trails of devastation left by the main tornado and two subsidiaries over south-eastern and eastern England on May 21, 1950, reveals a good deal of detail about their behaviour through many successive pulses of activity. Estimates of the magnitude of the greatest wind speeds, shear and suction effects (pressure reduction) are derived ; the extreme winds probably exceeded, and perhaps considerably exceeded, 100 kt. at certain brief phases of the activity of the main tornado, but speeds of this order were only attained over a width of a few feet, sometimes only a foot or two. The more characteristic types of damage produced by a tornado are due to the twisting effect of the enormous horizontal gradient of wind speed (shear), capable of twisting off the main trunks of full-grown trees, and by the strong local reduction of pressure which together with the strong vertical current may burst roofs and house-walls and carry the debris over considerable distances.

These particular English tornadoes were clearly attributable to a complex of factors : they occurred (as is usual) in a severe thunderstorm, but the evidence shows that the instability cannot have attained the extreme values possible in England nor have extended through the greatest depth of the atmosphere ever occurring here. A low condensation level contributed to great potential instability in the lower layers, so that strong vertical currents could be formed near the ground in spite of only moderate to rather low afternoon temperatures. Close study of the terrain over which the tornadoes passed in relation to the main surface wind currents on May 21, 1950, suggests that a vital initial twisting impulse was supplied by a sudden local increase of the surface north-easterly wind immediately in front of the tornado cloud advancing from south-south-west, just as it came clear of various obstacles such as various north-east–south-west ridges of hills with small cross valleys in which there was little or no wind. This was the setting where each of the main bursts of activity began.

Smaller obstacles on the ground, such as dense coppices and conglomerations of buildings, also obviously affected the behaviour of the tornado (causing it to lose energy, wander up to a couple of hundred yards aside of its track or break up) though they themselves sustained considerable damage.

Study of the incidence of tornadoes in England over many years emphasizes the importance of an existing initial shear, presented either within the wind streams themselves (e.g. near sharp fronts or in intensely cyclonic situations) or caused by the local topography. Great instability and high moisture content are also important ; there is however a sufficient liability to tornadoes over eastern England for it to be not essential for any one of these factors to attain extreme values.

In the case of May 21, 1950, both frontal and topographical shears seem to have been present, though not in very pronounced degree, and the frontal situation, which could be followed in some detail, proved interestingly fluid in a manner associated with intense convection and local modification of air masses by heavy rainfall.

A deduced pressure profile through these tornadoes is presented, and some more theoretical discussion shows how samples of the wide variety of velocity profiles occurring may be constructed.

§ 1—INTRODUCTION

Tornadoes formed in the thunderstorms over Buckinghamshire, Bedfordshire, and neighbouring parts of the Chiltern Hills in the late afternoon of May 21, 1950, and advanced along tracks to the north or north-east, striking at intervals to do material damage estimated at over £50,000. Judged by this standard only a small proportion of the tornadoes reported in the United States are more severe*.

* For instance, in 1949 out of a record total of 290 tornadoes in the United States only 8 did over $1,000,000 damage and 34 over $100,000 (approximately £400,000 and £40,000 respectively).

Damage was heaviest in the Buckinghamshire town of Linslade (see Fig. 1), where some 50 houses were unroofed and a brick-built bakery demolished, the official estimates of losses suffered in Linslade alone totalling £25,000 (see Plate II). In the open country full-grown trees were felled and others had their tops twisted off, farm buildings were shattered, and lighter structures such as chicken-coops and Nissen huts were carried away and destroyed. Sheets of corrugated iron were carried as far as half a mile. Telephone lines and wireless and television aerials were broken. Next to the Linslade—Leighton Buzzard area, the places worst hit were Wendover and Aston Clinton, Buckinghamshire, the outskirts of Bedford, and Sutton near Ely (see Plate II).

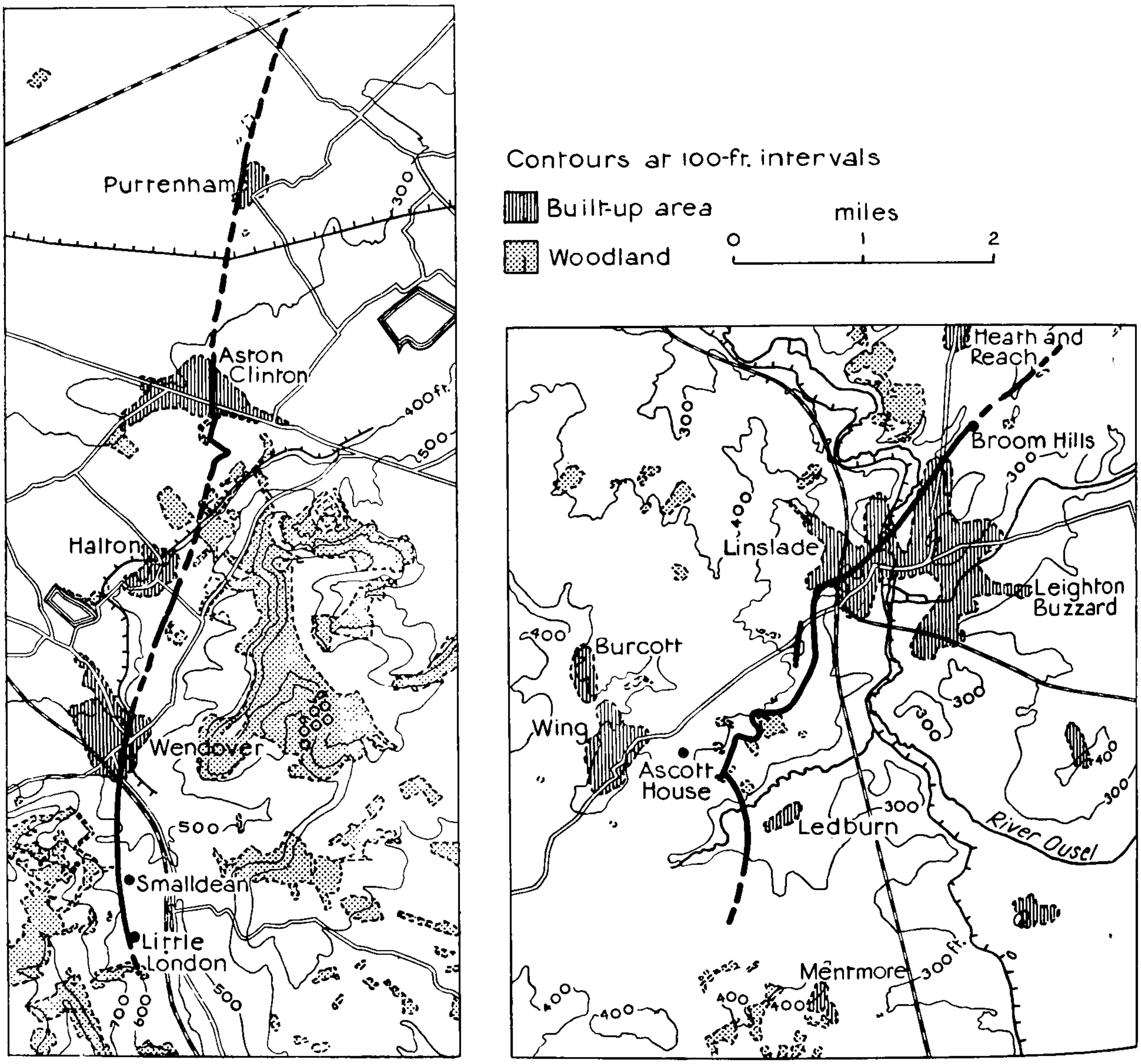

FIG. 1—TORNADO TRACKS THROUGH THE WENDOVER AND LINSLADE AREAS

The 65-mile track of the one tornado from south of Wendover to the fens near Ely ranks amongst the longest which have occurred in Europe, only the four longest quoted by Wegener[1*] having exceeded this. All the longer tracks are intermittent as this one was, since tornadoes habitually lift off the ground from time to time. The longest track in Europe quoted by Wegener was 300 miles, the shortest a fifth of a mile.

Conditions appear to have been nearly suitable for tornado formation over a wide area on the day in question, similar incipient cloud phenomena having been seen by many observers between Buckinghamshire and the East Anglian coast. Altogether three tornadoes left trails of damage on the ground ; one of these was short-lived and another travelled mainly over open country—the great bulk of the damage was done by the remaining one.

Because of the somewhat exceptional nature of such occurrences in this country and the proximity of these tornadoes to the Central Forecasting Office at Dunstable, it was decided to investigate and document this case fully. Two investigators, Mr. H. H. Lamb and Mr. J. Simmonds, spent several days going over the tracks of the tornadoes on the ground and taking reports from eye-witnesses. In addition much help was received from the local authorities and public utilities affected, as well as from the police and post-office personnel ; also from the fire services, the R.A.F. station at Halton, the British Electricity Authority, the Eastern Counties Omnibus Company and from many private persons who had suffered considerable loss.

In one respect even the areas afflicted were remarkably fortunate ; for there was no loss of life from the tornadoes, and few animals other than poultry were killed. This may be partly attributed to the heaviness of the rain which drove men and beasts to shelter.

There were four deaths from the accompanying thunderstorms, two from lightning and two from indirect causes. Lightning also interrupted electricity supplies in several counties. Four or five cattle are known to have been killed, mostly by lightning, though two were hit by flying sheets of corrugated iron carried by the tornado. Over 500 chickens were killed, and doubtless many wild birds.

The heights attained by the heads of the thunderclouds were probably not extreme, falling short of the occasional values of over 40,000 ft., which have been recorded over east and south-east England by radar observation. On May 21, 1950, over the region in question, the tropopause was at 32,000–35,000 ft. ; the biggest cumulonimbi must have grown to about this level. On the other hand the main seat of vigorous convective activity appeared to extend to lower levels than is usual in severe thunderstorms in England, and the exceptional shear between cloud motions at different levels and in different parts of the cloud base was remarkable to all observers. This, together with the rising wind, the unusual darkness underneath the cloud and the roar of the tornado, worked together in such a threatening manner as to frighten animals away from the immediate path of the tornado and drive men indoors.

The falls of rain and hail were of exceptional intensity. Flooding was extensive in Bedfordshire, Buckinghamshire, Northamptonshire, and the Fen counties, and blocked many roads ; run-off also caused damage to soil and crops on sloping land. Traffic on the Great North Road was interrupted by floods in Huntingdonshire ; the Bedford–Northampton road was blocked by more than a foot of hail at Oakley, Bedfordshire, and elsewhere by floods.

Hailstones broke windows, shattered greenhouses, damaged vegetable crops and fruit blossom and killed poultry. The largest individual hailstones fell close to the track of the main tornado at Ascott House near Linslade, and at North Crawley near Bedford (see Plate III). Examination in both instances revealed irregular masses of ice consisting of several hailstones frozen together, measuring altogether 6–6½ in. in circumference and weighing about 4 oz. In many parts of Bedfordshire flattish, almost leaf-shaped, hailstones were reported, consisting of

* The index numbers refer to the bibliography on p. 36.

up to 20 or 30 small hailstones frozen together into pieces of ice 1–1½ in. in diameter and ¼–½ in. thick. The more or less spherical hailstones were mostly ¾ in. or so in diameter, consisting of three to five concentric shells of ice around a spherical core of clear ice, and more often flattened or dimpled on one side. The unusual shapes suggested some unusual character even in the detailed air motions within the cloud, and might perhaps be explained in terms of much horizontal eddy motion and spinning accompanying the severe vertical currents.

§ 2—TRACKS AND BEHAVIOUR OF THE TORNADOES

There is some likelihood that all the tornadoes observed on May 21, 1950, had their origins near the north-west face of the Chiltern Hills. Incipient circulations in the cloud base were seen by several observers near the mouths of the Dagnall–Hemel Hempstead, Dunstable–St. Albans and Luton–Harpenden valleys between 1430 and 1630 G.M.T. The main tornado was first seen in the Missenden–Wendover valley a few minutes before 1600 G.M.T., uprooting an occasional tree and lifting the roof of a cowshed along a narrow trail proceeding north on the western side of the valley ; at the mouth of the valley its energy suddenly increased, and the trail of destruction widened to 50 yd. or so.

All three tornadoes passed through successive stages of regeneration, when the circulation developed down to ground level, followed by gradual weakening and decay, and eventually lifting off the ground again, until some fresh burst of energy occurred. Successive regenerations often took place at about 5-min. intervals. In several instances the regenerations were sudden and accompanied by sudden renewal or widening of the trail of damage.

Nearly all the main bursts of energy, especially the more sudden ones, took place either immediately to the north of a ridge of hills or just on the crest, notably at points where the surface north-easterly winds ahead of the advancing whirl would suddenly increase in strength. At Bedford a more gradual regeneration took place over flat land. The brief outburst at Puttenham (Fig. 1) was also over flat land. Over the south-facing slopes of ridges and over tightly grown coppices and avenues of trees situated across their paths, the tornadoes tended to break up.

Evidence of the effect of ground barriers on the path and progress of the tornadoes was found at many points, particularly where hill slopes and dense coppices or woodland caused the path to zig-zag, though never departing by more than some 400 yd. from its general line.

The topographical and ground effects were evidently secondary to the main controls in the free air. All the tornadoes at their outset travelled on parallel tracks orientated 15–20° east of north, in agreement with the direction and at about a half to three quarters of the speed of the observed winds at the 700–600-mb. levels (approximately 10,000–14,000 ft.), where there is some reason to suppose that the up-currents may have had their maximum vertical speed*. The main tornado, which formed further west than the others, travelled on this track at 20–25 kt. in its earlier stages ; the more easterly tornadoes advanced at only 10–15 kt. In its beginnings in the Missenden valley the main tornado travelled nearly due north in line with the valley, but soon came over the lower ground near Wendover and proceeded in the direction 15–20° east of north. This system seems not only to have been the most violent of the tornadoes formed on that day but to have had the longest history. Moreover, an outer cyclonic circulation gradually developed over a widening area around it over a radius of more than 50 miles over eastern England on the evening of the 21st, establishing light westerly winds on its southern side. This circulation was probably continuous with that of a small depression which travelled north-north-east over

* This supposition seems reasonable in the light of figures given by Sheppard[2] for mean conditions and making an allowance of the order of 4,000–5,000 ft. for the visual impression of maximum cloud development at a rather lower level than usual on this occasion.

the North Sea next day to the Skagerrak and reached Sweden on the 23rd. Light thunderstorms were observed over the North Sea and in southernmost Norway on the 22nd but nothing more ; there were, however, very few reports from ships at sea that day. Over eastern England from about Bedford onwards, after the tornado had been in existence for an hour, its track (and that of the broader cyclonic circulation developing around it) was in line with the (total) thermal wind of the 1000–500-mb. layer towards a direction of 45–50° east of north, and its speed of advance increased to 30–35 kt. on this track across East Anglia.

The track of one of the subsidiary tornadoes crossed the path of the main one near Bedford, intersecting it at an angle of 20–30°, and passing some 8–10 miles ahead of the main tornado on a track towards north-north-east. No coalescence took place ; the paths proceeded to diverge again, each continuing along its own line. The smaller tornado faded out a few miles farther on, though its line continued as far as Peterborough to be marked by the progress of a specially severe thunderstorm with a distinct maximum incidence of rainfall, hail and lightning effects.

The effects of the tornadoes may be listed as :

(i) suction effects, causing leeward walls and windows to blow out because of the pronounced lowering of pressure and extremely localized pressure gradients

(ii) lifting effects, associated with the strong vertical current at the centre

(iii) twisting effects, associated with the shear (or pronounced horizontal gradients of wind speed), capable of twisting off tree trunks over 2 ft. thick, and in one place at least 34–36 in. in diameter, at points up to 10 or 20 yd. from the core (see Plate IV)

(iv) battering effects, due to the tremendous horizontal speed of the wind, capable of felling full-grown elm trees not quite in full leaf up to 30 or 40 yd. from the core of the tornado*.

The battering effects were in all cases greatest in association with the southerly or south-westerly current immediately to the east of the track of the tornado, corresponding to the general current in the free air with which the system was advancing. If we suppose this general current of 15–25 kt. superimposed upon the circulation of the tornado, then the maximum southerly or south-westerly wind would be 30–50 kt. stronger than the maximum northerly or north-easterly wind on its other side. Only at Halton was the northerly current of the weaker side of the main tornado strong enough to leave grass and nettles battered down. This occurred nowhere else ; but at Wendover, Linslade, Bedford and Sutton, trees were felled all around the fringe of the tornado, which suggests that the southerly wind near the tornado at these places must have reached at least 100 kt. On the other hand, all the main strikes were marked by a trail of grass and undergrowth in the damaged woodlands beaten down towards the north-east, and in many places the only trees felled lay in this direction. This is mentioned as a common feature of American tornadoes by De Courcy Ward[3].

Over much of their length the trails of damage, limited to twisting and lifting, were only 5–7 yd. wide ; but at their widest the two most vigorous tornadoes reached 50–80 yd. in width, with battering also in evidence. Solid objects are believed to have been raised to 100–300 ft. above ground level before being dropped and strewn over a width of some 200 yd. Flat objects were carried a distance of up to half a mile and tree tops 200–400 yd.

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* According to the Forestry Commission records elms are amongst the most easily blown trees in Great Britain, and of course the fact that they were nearly in full leaf added to the danger. Most trees, elms included, stand up to gales of 50–60 kt. if the soil is dry, as it probably was on this occasion until shortly after the passage of the tornado. Trees in normally sheltered positions might however go over more easily. This seems to indicate 60 kt. as a minimum estimate of the wind on the fringe of the tornado where trees were uprooted and felled. Nearer the centre, where at times considerably greater speeds may have occurred in areas of narrow cross-section, the twisting effects and consequences of the great pressure differences were more in evidence.

Main tornado.—The beginnings of the main tornado left a narrow trail of damage in the Missenden valley from Little London and Smalldean farms to the point where the valley opens towards the Vale of Aylesbury immediately above Wendover (see Fig. 1). Here destruction on a much bigger scale began and the trail suddenly broadened. This was the beginning of the 12-mile stretch over which the worst havoc was wrought.

In a meadow beside the London road entering Wendover many full-grown trees (elms and walnuts) were felled and left lying in all directions over a width of 50 yd. or so, whilst neighbouring roofs had a few tiles lifted or swept off. The trail narrowed once more as it passed over Wendover town, lifting the tiled roofs of old buildings, and after raising a column of water from the old canal the tornado proceeded northwards for about a mile in less violent form.

The trail began again at Halton R.A.F. camp where the heavy roof of the power station was lifted and beaten nettles and battered trees left evidence of the full counter-clockwise rotation of the storm. Here the tornado was watched by many observers (see Plate I), and described as like a giant palm tree with its stem consisting of a not entirely opaque cloud and with a broader base at which objects were sucked in and passed up the stem to fan out higher up, probably at a height of 100–300 ft. At many points along its track, however, the upper part throwing out the objects was hidden in the main cloud base. The column was seen to break up as it passed over a close avenue of chestnut trees across its path, and the evidence suggests that a ground whirl somewhat separate from the upper part of the column continued over the next 300 yd. or so.

This tornado passed through seven or eight distinct regenerations within 40 min. between Wendover and the Leighton Buzzard area, each marked more or less by a sudden broadening of the trail on the ground, and followed by a gradual weakening recorded by narrowing and eventual disappearance of the trail.

Approaching Aston Clinton the revolving cloud was at first seen 200 ft. clear of the ground, but soon lowered to the down-hill slope and began to damage trees and buildings. Up to this point the path of the tornado had been very nearly straight. It now performed several zig-zags, apparently affected by the configuration of the densely grown coppices encountered, but never going more than about 200 yd. on either side of the main axis of its progress. Damage was severe at Aston Clinton but the trail narrow. The revolving storm eased and lifted clear of the ground once or twice more, passing lightly over open land between Aston Clinton and Puttenham and over the Mentmore estates, but lowering to strike heavily at big farm buildings in Puttenham and later, about 4 miles farther on, in Ledburn.

At Puttenham the north-eastern end of a well built byre of brick was tumbled down and outwards. A large Dutch barn supported on 6-in. iron girders with wide flanges was twisted up and the bales of hay tossed out. A nearby Nissen hut was destroyed, and its floor left spiked 50 ft. above the ground on the topmost branches of a neighbouring tree. The trail, however, passed from these buildings at the southern end of Puttenham into the fields west of the hamlet, and soon narrowed and faded out, to appear next in the tree tops beside the road near Ledburn (Fig. 1).

On the upward slopes of the Ascott estates and Wing ridge the tornado pursued a very zig-zag and even circuitous course, felling big trees, plucking the topmost boughs and branches out of coppices and lifting vehicles in the farmyards. A distant observer's report suggests the tornado was broken up into three or four twisting columns at this point, probably not all of them causing damage. An irregular, but nearly continuous, narrow trail of damage to trees and isolated buildings was found on the eastern part of the Ascott estates, whilst Burcott near Wing, nearly two miles to the north-west, felt the effect of one of the lesser twisting columns with a complete reversal of wind estimated at Beaufort force 6 about the same time. On the down-hill slope just south of Linslade two parallel tracks of damage left large trees broken and felled.

The separate columns were then seen to unite and advance north-east upon Linslade, where damage to buildings and property was heaviest. In the built-up area it was impossible to distinguish the direct damage due to wind and suction from that caused by falling objects, but in a field just south of Linslade trees were felled over a width of 50 yd. This was the widest development of the intense vortex, and some objects were carried as much as half a mile in this area.

Most of the houses in two streets, Old Road and New Road, Linslade, were either unroofed or had their roofs badly damaged ; and yard premises between the two streets were demolished (see Plate II). A heavier roof was carried away near the railway station, and cars parked in the station yard as well as an occupied horse-box were lifted and thrown about. From this point north-east the trail narrowed again, and objects were deposited in and near the river. The whirl lifted off the ground more than once in the Leighton Buzzard area, but lowered at odd points along its path to strike buildings near the Heath and Reach roads as well as orchards and greenhouses.

After passing Broom Hills Farm, where two cows were killed, the tornado was seen to lift off the ground and break up momentarily, only to re-form and lower towards Shenley Hill nurseries, Heath. Here apple and pear trees were uprooted, and cold frames were lifted and carried over the greenhouses but dropped undamaged. The trail disappeared in the open pastureland, and no further damage was done by the tornado for several miles. Its path continued, however, to be marked by particularly heavy rainfall, thunder and lightning, and the twisting cloud column was seen at various points.

The tornado passed over Woburn Park in this way, but was partially regenerated just north of the hill over Lidlington where the doors of a house at the foot of the hill were blown open and things carried out of the rooms into the garden.

Run-off following the heavy rain removed the top soil from sloping fields near Lidlington. There were various hearsay reports of minor damage to trees in this area, but the funnel cloud was seen moving away north-east over the valley well above ground level.

The next strike was at Harrowden Road on the southern edge of Bedford (Fig. 2), where tiles were lifted from roofs, apple trees uprooted, and garden walls overturned. Television aerials suffered. The violence of the whirlwind at the ground seems to have increased gradually to a maximum at Fenlake where big trees suffered severely over a width of about 20 yd. ; some were carried across the River Ouse and others blocked the river. Near this point another tornado had passed north across the track about half an hour earlier, giving a severe squall but not causing any breakages on the actual path of the main tornado still some ten miles away.

Willow trees along both banks of the Ouse from Fenlake to near Castle Mills Lock were felled by the main tornado, but its energy was slackening and at this point it lifted off the ground once more. The funnel cloud of this tornado was largely obscured by the extreme darkness accompanying the thundercloud at this point, many observers in the Bedford area describing it as darker underneath the cloud than they had ever known in the hours of daylight before. Only one or two people near Bedford reported having seen the twisting cloud column. The Cardington anemometer $1\frac{1}{2}$ miles south-east of the track was much less affected than by the subsidiary tornado which passed a good deal closer.

The main tornado continued on its track north-east undergoing several further phases of regeneration, followed by splitting up or withdrawal into the main cloud base. Its activity appears to have been weakening on the whole as evening drew on, but two or three of the regenerations led to damage at the ground.

At Wyboston on the Great North Road (see frontispiece) a few tiles were removed from the roof of the little Methodist chapel. There is no knowledge of any further damage or effects at the ground for the next 15 miles north-east of Wyboston, over rather higher country divided by winding valleys.

The track of the tornado reached the Fenland just south-east of St. Ives, and the beginnings of a major revival seem to have set in (see Fig. 2). Parts of Holywell and Needingworth had a severe squall, trees having their branches blown upward in characteristic manner underneath the revolving cloud although none were reported damaged. The wild birds were much disturbed. This particular pulse of energy seems to have faded out towards Earith, but beyond Earith (Fig. 3) over the fen lying east of the New Bedford River the funnel cloud was seen working downwards again and beginning to stir the soil. Soon there was vegetation swirling around at its base. On the hill at Sutton a number of houses and the church on the main street received some damage. Immediately on and over the crest of the ridge destruction became severe.

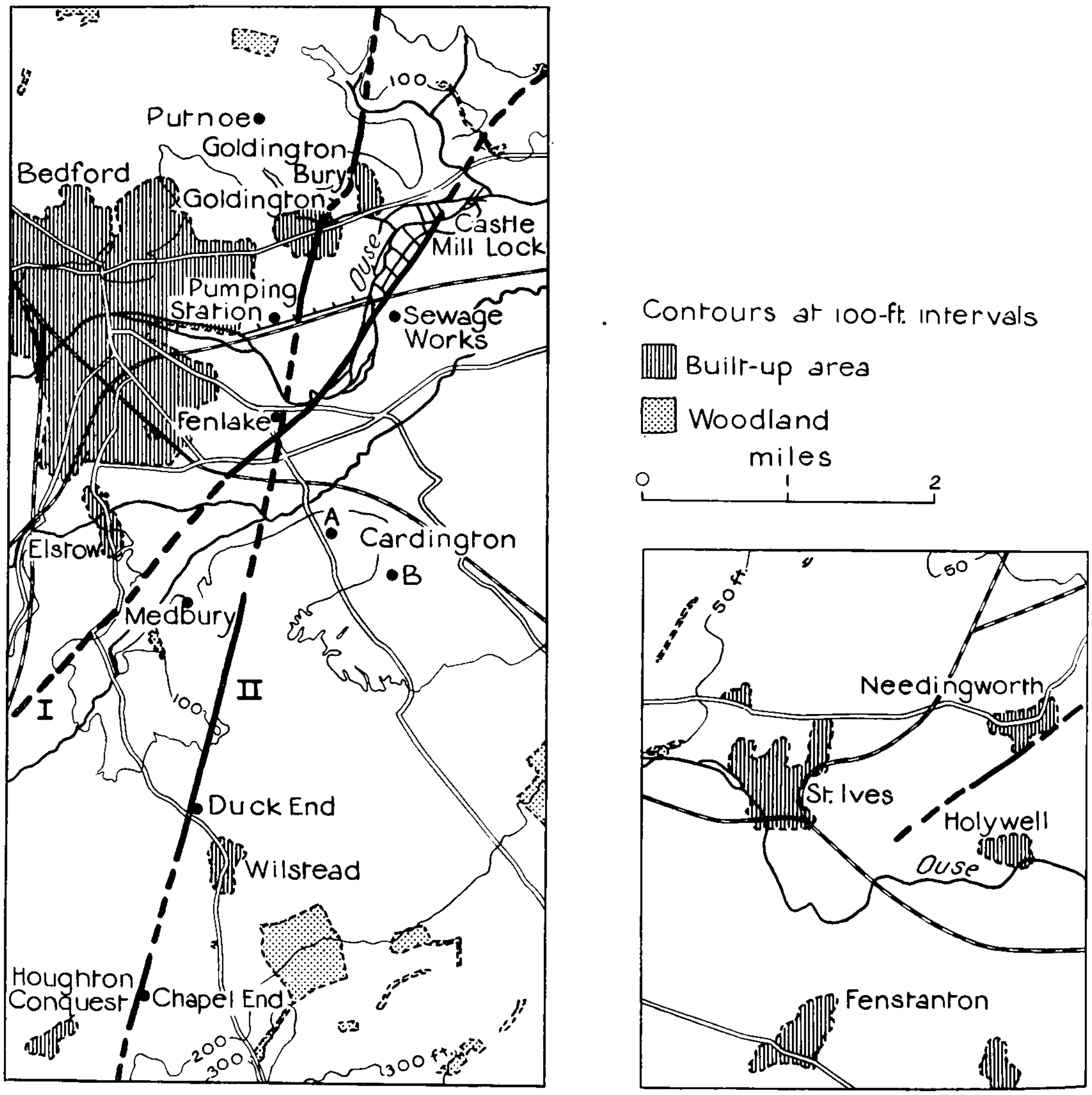


FIG. 2—TORNADO TRACKS THROUGH THE BEDFORD AND ST. IVES AREAS

A = Anemometer site at Cardington B = Barograph site at Cardington

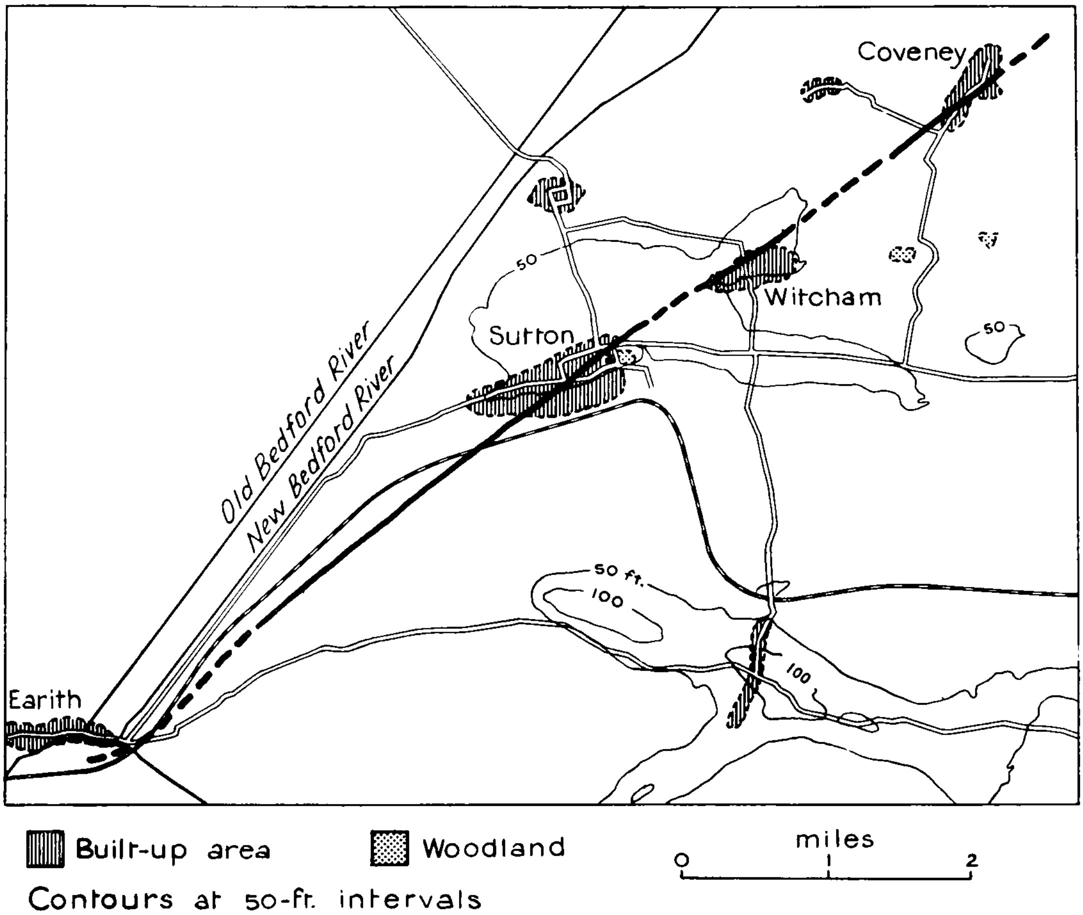


FIG. 3—TORNADO TRACK THROUGH THE SUTTON AND COVENEY AREAS, MAY 21, 1950

Roofs were lifted and the north-east end wall of a house was blown out ; an orchard was uprooted and a gap 10–20 yd. wide torn in a wood, full-grown oak trees being uprooted and twisted off where their trunks were a yard thick (see Plate IV). The main road was blocked by trees and a double-decker bus in the open was overturned by the wind. The driver watched the trees ahead being twisted off and their tops carried towards him before the wind took his bus.

For a mile the effect was less severe, but fresh destruction occurred in the small valley at Witcham and at Coveney. North-east of this valley the trail disappeared, and the progress of the cloud system could only be established with the aid of eye-witness reports, culled from local newspapers as well as from the trained observers at aerodromes in East Anglia.

The aerodrome at Feltwell lay directly in the path of the cloud system, which passed over with dozens of twisting vortices in its base but probably at their lowest 1,000–1,500 ft. above ground level. Similar phenomena were seen about the same time, but in rather less pronounced form as far east as places in Norfolk and Suffolk between Bury St. Edmunds and Diss. The funnel cloud formed again, however, and was seen from Shipdham, Binham and last of all over the sea off Blakeney, where the twisting column withdrew into the main cloud base as it moved away from the land towards the north-east. No damage was reported from these places.

Few accurate observations of the time of occurrence of the tornado were to be had. The following times have been counterchecked and are considered reliable to within a few minutes :—

	G.M.T.		G.M.T.
Wendover	1600	Bedford south ..	1705–1710
Halton	1606	Sutton, Ely ..	1830
Aston Clinton ..	1610	Feltwell	1900
Linslade	1630	Blakeney	2000
Heath and Reach, Broom Hills Road	1635–1640		

Subsidiary tornadoes.—Another tornado trail marked by severe damage to trees was found on a line from Wilstead, passing just east of Bedford, to Goldington. This tornado passed across the track of the main one advancing from Leighton Buzzard, and was causing destruction at Wilstead about the same time as Linslade was being hit. It travelled more slowly than the main tornado, probably at about 12 kt., and kept to a track 15–20° east of north throughout. It may have developed from the sluggish cyclonic circulation seen in the base of the thunderstorm cloud near Dunstable about 1530 G.M.T.

The first activity of this tornado seems to have been at Chapel End Farm near Houghton Conquest, where it passed as a narrow column between two ancient barns only 3 yd. or so apart without raising more than two or three ridge-tiles off the roof of one of them, but lifted a 10–15 ft. column of water from the duckpond between the barns.

There was a major burst of activity at Duck End Farm, Wilstead, where big trees were broken and felled over a width of 20 yd. or more and £200–£300 damage was done, though the track missed all the buildings.

This tornado passed mostly over open land, frightening animals and breaking a few trees on Medbury Farm, Elstow, where it passed about half a mile west of the Cardington anemometer. At this point its activity was weakening and the trail on the ground disappeared for nearly two miles. It passed close to the Bedford Sewage Pumping Station and began to damage houses and roofs in the southern part of Goldington, though not severely. It passed lightly over Goldington village but lowered again to strike severely and damage trees just north of Goldington Bury. Horses on the neighbouring Putnoe Farm were frightened by the sudden wind and ran for safety to the farmhouse, over half a mile from the track. The tornado cloud was seen to withdraw again into the main cloud base, and the trail on the ground was lost at this point.

Numerous observers in and around Bedford had seen the funnel cloud, and got the impression that it somehow returned to strike again in the main tornado a little afterwards. The sky was then so dark that nothing of the cloud form could be distinguished. Points between Cardington and Goldington felt the effects of the two tornadoes which were both seen by a few observers.

The trail of damage caused by the subsidiary tornado from near Houghton Conquest to Goldington was six miles long, and in this distance it underwent at least two major regenerations and subsequent decay. That this tornado cloud continued on its track north of Goldington with further regenerations seems to be indicated by a later observation of the swirling cloud at Kimbolton, and, perhaps, by damage to roofs and telephone lines in Paston Lane, Peterborough. The damage to roofs at Peterborough was accompanied by a lightning-stroke, and may be entirely attributable to this, although a hole 8 ft. × 5 ft. was left and the time of the occurrence would correspond to a steady advance of the tornado cloud from its first appearance at Dunstable and its passage over the eastern outskirts of Bedford.

The line of this supposed track was also marked by a distinct maximum of rainfall and other storm activity.

The most reliable times of occurrence of this tornado appear to be :—

	G.M.T.		G.M.T.
Dunstable area ..	1530	Goldington ..	1640
Wilstead	1625	Kimbolton	1730
Near Cardington anemometer ..	1632	Peterborough ..	1830

Yet another tornado was seen at Caldecote near Biggleswade, Bedfordshire, about 1730 G.M.T. travelling in a direction approximately 20° east of north. This may be tentatively connected with earlier squalls of gale force in the Leagrave–Limbury area of Luton and incipient tornado-cloud phenomena, although no damage was reported in the Luton area. At Caldecote corrugated iron roofs were lifted from sheds, an 8 in. branch torn off an apple tree and dropped on a car a few yards further on, and tiles removed from the roof of the Methodist Church. The trail was nowhere more than 5 yd. wide and less than ¼ mile long, damage being on a much smaller scale than with the other two tornadoes.

Similar small tornadoes and trails of minor damage over a couple of hundred yards or so must occur more often than reports are received, and in open country would often pass unnoticed.

§ 3—ACCOMPANYING WEATHER PHENOMENA

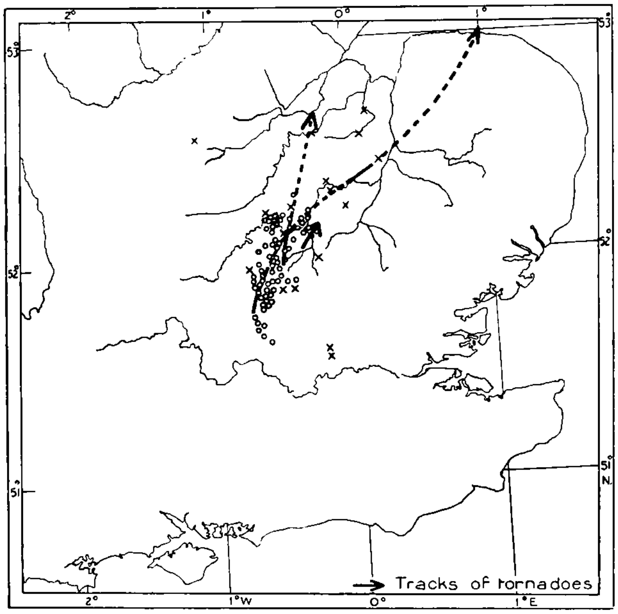
As may be seen from Fig. 4 the tornado tracks show a very close association with the incidence of the most severe lightning, hail, rainfall and flooding on May 21, 1950. This should be expected with phenomena which are all related to the most severe up-currents occurring. (Compare Figs. 13 and 14 showing the geographical distribution of frequency of tornadoes and thunderstorms in the British Isles, from which it is equally clear that these are allied phenomena.)

Lightning.—From 1400 G.M.T. onwards the " sferic " apparatus recorded flashes in too great numbers to be plotted in an area 30–50 miles in diameter, at first located between the Isle of Wight and Salisbury Plain, and reaching the Hertfordshire hills and Bedfordshire–Huntingdonshire plain (basin of the Great Ouse) by 1800 G.M.T. As early as 1200 G.M.T. a region of great " sferic " activity was noted on a north–south line in mid-Channel between Cap Gris Nez and Portland Bill. There was a suggestion of discontinuity in the motion of the main concentration of " sferic " (development of a new cell ?) between 1500 and 1600 G.M.T. ; the original group of flashes which had moved almost due north from the English Channel to Salisbury Plain between 1200 and 1500 G.M.T. seems to have been replaced at 1600 G.M.T. by a new locus of still more severe activity some 40–50 miles north-east over the Chiltern Hills and the Vale of Aylesbury, close to the main tornado which appeared about the same time. This was rather more than half way from Salisbury Plain to another (smaller) previous " sferic " concentration over the Hertfordshire hills.

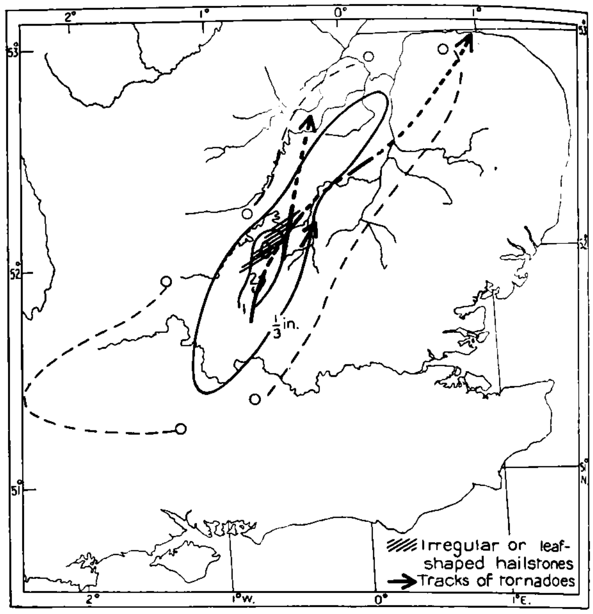
Because the " sferic " flashes were so prolific, the best map that can be given of the incidence of lightning is that shown in Fig. 4(*a*), based on reported interruptions to the high-voltage distribution lines of the Eastern Electricity Board and damage to buildings known to have been caused by lightning. In addition two people were killed and several hurt by lightning about 1700 G.M.T. in the open at Houghton Conquest, Bedfordshire, some 6 miles south of the position of the main tornado at the time, and a bullock was killed a few miles away, also within the main concentration of lightning strokes shown on Fig. 4(*a*). Altogether over 80 incidents affecting the electricity supplies occurred in this storm. The great majority of the severe flashes were within 7–10 miles of the tornadoes and distributed more or less evenly around them*. The

* There is some reason for suspecting an extension south of the centre however (see p. 16) associated with the clearing front (see p. 29) advancing from west to east in the wake of the main tornado.

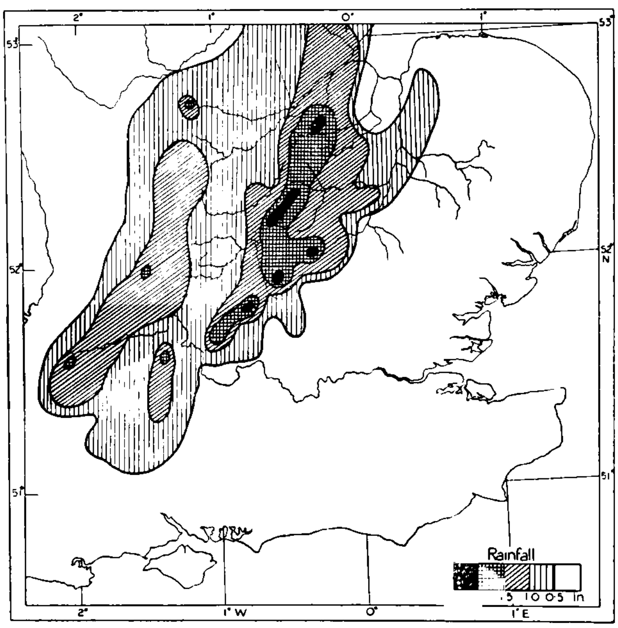
closest concentrations of severe flashes almost coincided with the tornado tracks, except in a small area near Oakley, just north-west of Bedford, and travelled with the tornadoes.



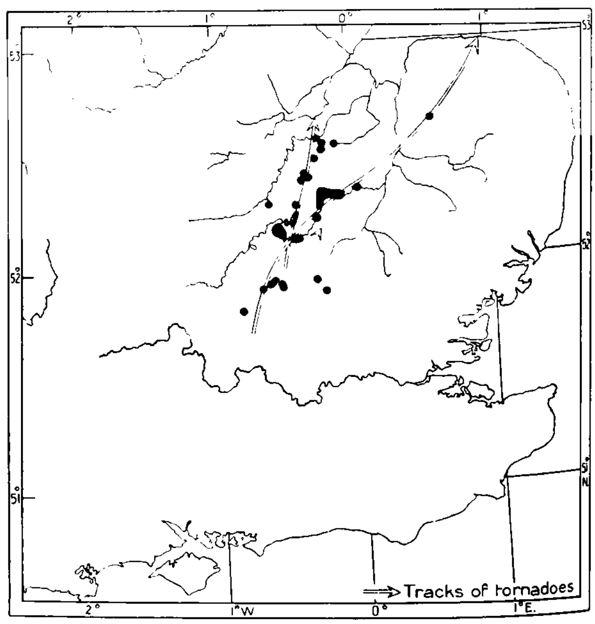
(*a*) Lightning strokes between 1500 and 1800 G.M.T. Interruption of high-voltage lines of the Eastern Electricity Board are shown by circles, other damage by lightning by crosses



(*b*) Isopleths of hailstone size. The approximate limits of the area over which hail fell are indicated by the 0-in. line (broken)



(*c*) Rainfall during the 24 hr. from 0900, May 21, 1950



(*d*) Areas affected by severe flooding

FIG. 4—DISTRIBUTION OF WEATHER PHENOMENA DURING AND AFTER THE TORNADOES

Hail.—The distribution of large hail (Fig. 4(*b*)) followed the track of the main tornado only slightly less closely. The largest stones of all fell on the track itself at Ascott Farm near Leighton Buzzard, and within about 3 miles of the track at North Crawley near Newport Pagnell about the time of the tornado's passage or within a few minutes afterwards. At these points however the stones were rather few in number. Elsewhere in the area shown in Fig. 4 (*b*) much larger quantities of hail fell, the maximum diameter according to the map being also a rough measure of the prevailing size of the great majority of hailstones which fell in each area during the main storm about the time of the tornado or soon after. The axis of the area over which large hail fell shows a slight, but unmistakable, displacement to the left of the track of the main tornado, amounting to 2–3 miles in the southern districts in Buckinghamshire and Bedfordshire and increasing to 10–12 miles in the Fenland. Displacement of the tornado to the right of the accompanying hailstorm is a common, but not invariable, characteristic of cyclonically rotating tornadoes[4]. Such a displacement must be taken to mean that the location of the most severe vertical currents at the level of hail production is not quite coincident with that of the strongest vertical current in the lowest layers. The axis of the funnel cloud sometimes reveals a slope which could be connected with this displacement. Evidence on this point is lacking in the present instance. The photograph (Plate I) was taken in the area where hailstorm and tornado were closest together ; the camera is believed to have been pointing almost west and the funnel cloud appears as an almost vertical projection from the main cloud base.

The largest quantities of hail, where the accumulated depths were measured, seem to have been more erratically distributed. By far the greatest depths seem to have been found 4–8 miles north-west of the track of the main tornado near Bedford ; on the main road at Oakley hail accumulated to a depth of over 18 in.—presumably in drifts—and there were unconfirmed reports of a depth of 3 ft. being reached at Turvey. The roads were blocked for some hours. Elsewhere the depth of hail was seldom more than a few inches, but Dunstable had drifts up to 6 in. deep and Hitchin also reported considerable drifts ; at both these places the abrupt hill slopes may have had an important effect on the air motion.

Rainfall.—The rainfall map for the 24 hr. between 0900 G.M.T. on the 21st and 0900 G.M.T. on the 22nd, prepared in the British Climatological Branch of the Meteorological Office, shows two main regions of maximum amounts both elongated from about south-west to north-east in line with the winds in the upper troposphere. The more westerly maximum follows roughly the line of the Cotswold ridge from near Bath to the English Midlands and is a common feature on days of convection rainfall. The main maxima on May 21, 1950 lie however along another line further east, where large amounts are less common, and are close to the tornado tracks of that day. Over 2 in. of rain fell in five areas :

(i) about Aylesbury, 5 miles west of the main tornado ;

(ii) at Hockliffe, near Leighton Buzzard, within 2 miles east of the track ;

(iii) at Shefford, between the tracks of the two main tornadoes and that of the Caldecote tornado ;

(iv) between Turvey and Kimbolton, 5–8 miles west of the Wilstead–Goldington tornado ;

(v) in Peterborough on the extrapolated track of the last-named tornado.

There was no systematic displacement of the heaviest rainfall to one side or the other of the tornado tracks. Slight influences of local geography and the occurrence of other storms during the day introduce erratic elements. Everywhere in south and east England had some rain. Also some of the hail may have been lost by bouncing out of the gauges : it seems likely that the region (iv) just north-west and north of Bedford had the heaviest falls of all, and it was here that a torrent of flood-water caused one death (on gently sloping ground near Pertenhall, Kimbolton). This region lay a little to the left of the path of the nearest tornado. In spite of these difficulties of interpretation the most striking feature of the map is the closeness of the heaviest rainfall maxima to the tornado tracks.

Much of the rainfall and some of the more abundant hail and lightning were associated with the line of the clearing front, i.e. the cold front which brought the final clearance, which advanced from west to east after the passage of the tornadoes. All these phenomena must therefore have been more concentrated south of the main tornado than north of it at any given moment.

The most interesting rainfall record received is that for Dunstable, 5 miles south-east of the track of the main tornado. Part of this record is reproduced in Fig. 5 ; it is to be noted that the clock was between 10 and 15 min. fast at 1600 to 1800 G.M.T. Around 1720 G.M.T. 0·39 in. (10 mm.) of rain fell in 10 min. This, the heaviest rainfall at Dunstable, accompanied the clearing front ; the main tornado was already 15–20 miles away to the north-north-east. Little or no rain fell at Dunstable at 1630 G.M.T. when the tornado was nearest.

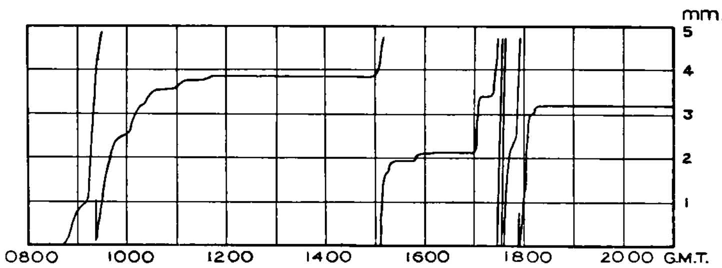


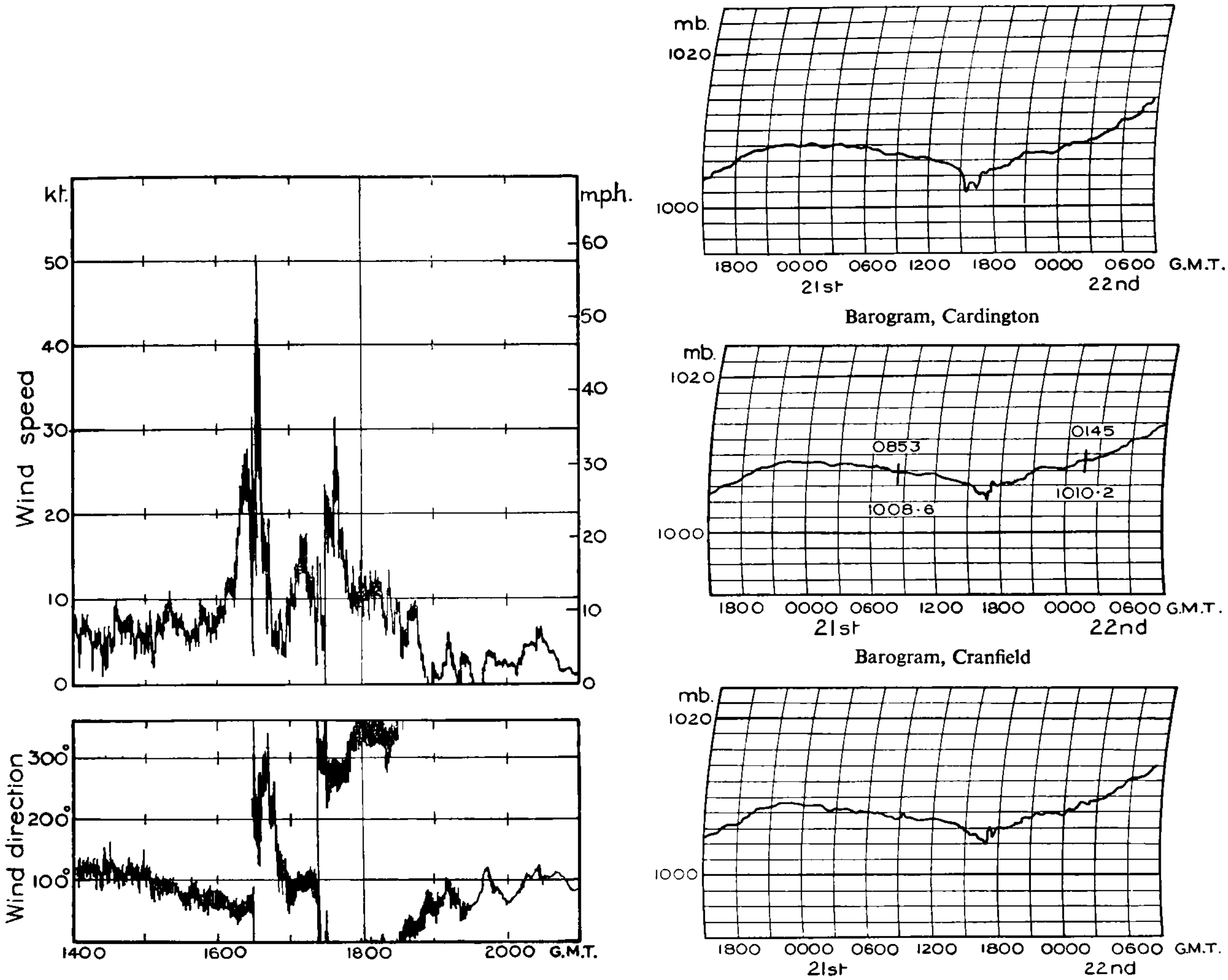
FIG. 5—HYETOGRAM, DUNSTABLE, MAY 21, 1950

Flooding.—As might be expected, the map of severe flooding reports (Fig. 4(*d*)) repeats the principal features of the rainfall distribution in eastern England. Flood reports follow the course of the Goldington subsidiary tornado over the relatively high ground between Bedford and the Soke of Peterborough. Otherwise flooding was worst in the Ouse and Nene valleys near the tornado tracks and in the vale of Aylesbury.

§ 4—WINDS AND ATMOSPHERIC PRESSURE IN THE NEIGHBOURHOOD OF THE TORNADOES

No instrument records from the immediate path of the tornadoes have come to light. Barographs over most of the storm area recorded abrupt rises of pressure of 2–3 mb. about the time of passage of the clearing front. The records from Cardington (52° 07′ N. 0° 25′ W.), Cranfield (52° 04′ N. 0° 37′ W.), and Dunstable (51° 53′ N. 0° 33′ W.), however, are worthy of closer attention (see Fig. 6). All these stations were within about five miles of the main tornado, and Cardington was affected by one of the subsidiaries as well.

The Cardington instruments were within 1½ miles east and south-east of the tracks of both the main tornado and the Wilstead–Goldington subsidiary. The latter passed just ½ mile west of the anemometer at 1632 G.M.T. giving a squall with a maximum gust of 51 kt. and a mean strength of 40 kt. for some minutes. The barograph in the meteorological hut was just a mile from the track of this tornado, and recorded a sharp drop and recovery of about 1½ mb. superimposed on the general downward trend. The main tornado passed ¾ mile north-west of the anemometer about 1710 G.M.T. and raised the pen to only 17 kt. The main tornado did more damage than the subsidiary in the area closest to Cardington where their paths crossed,



Anemogram, Cardington

Barogram, Cranfield

Barogram, Dunstable

FIG. 6—AUTOGRAPHIC RECORDS COVERING THE TIME OF PASSAGE OF THE TORNADO

yet because it was $\frac{1}{4}$ mile further away the maximum wind recorded by the anemometer was only one third as strong. The barograph $1\frac{1}{4}$ miles from the track shows no obvious trace of the main tornado, although its time corresponds closely with the minimum of the general trend of pressure during the day. More pronounced variations occur on the traces of both instruments about 1730 to 1740 G.M.T. in association with the hailstorm and clearing front, when the temperature dropped 10° F. ; pressure fell nearly 1 mb. again and remained low for some minutes, and there was a gust of 32 kt.

Cranfield lies about 3 miles north-west of the track of the main tornado at Lidlington, and this barograph record helps to check the time of passage of the tornado, which is marked by a very brief dip of the pen, amounting to 1 mb., about the time of the minimum of the general trend of the pressure curve. The effect can be seen here of the tornado in the midst of a region of rather weak general cyclogenesis. The further rise of pressure by about 1·5 mb. some 20 min. after the passage of the tornado seems to coincide with the onset of the heavy rain and hail associated with the clearing front.

The Dunstable record shows pressure falling throughout the afternoon to a minimum (slightly below 1004 mb.) about the time when the main tornado passed 5 miles north-west of the station, then an abrupt rise of about 2 mb. followed by a brief drop of 1 mb. accompanying the passage of the hailstorm and clearing front. There are no other pronounced irregularities; the weak cyclonic circulations seen near Dunstable during the afternoon have left no mark upon the trace.

Pressure profile.—These three stations' barographs can be used to construct a reasonable pressure profile through the subsidiary tornado about 1630 to 1640 G.M.T. when it was in the Bedford area. The resulting curve, which may be regarded as an approximation to the actual pressure profile at 1630 G.M.T. along a line from south or south-south-west through the centre (i.e. more or less in the line of its path) is shown in Fig. 7, and gives a rough idea of the local pressure gradients existing. The 1630 G.M.T. values of pressure at Dunstable, Cranfield, and Cardington, respectively 15 miles, 8 miles, and 1 mile away, have been used together with the Cardington values 20 min. before and afterwards, when the tornado is considered to have been about 5 miles away. The curve shows pressure falling from 1005 mb. 8–10 miles from the centre to 1002 mb. 1 mile away; beyond 10 miles there was a reversed gradient under the influence of the main tornado at that time over Linslade (5 miles from Dunstable). On the other side of the centre the curve constructed from the Cardington pressures also comes under the influence of the approaching main tornado; it might therefore more reasonably be taken to represent the profile along a line from the centre towards the west.

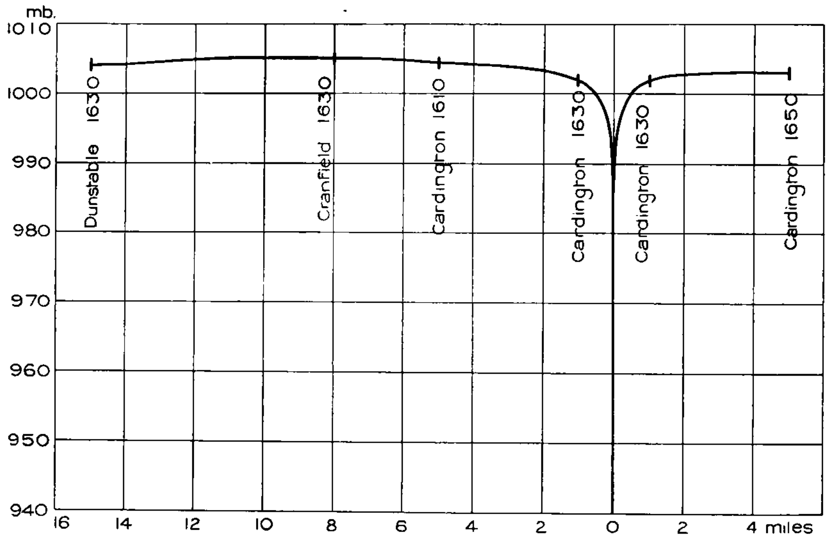


FIG. 7—DEDUCED PRESSURE PROFILE THROUGH THE WILSTEAD SUBSIDIARY TORNADO 1630–1640 G.M.T., May 21, 1950

The pressure profile within a mile of the centre of the tornado has been constructed from other considerations. The observed humidities and heights of lowest cloud (nowhere below 600 ft. except in the tornado funnel), always irregular in thunderstorm conditions, indicate that a pressure fall of at least 20 mb., and more likely 20–30 mb., would have been required to produce condensation by adiabatic cooling. Pressure must have fallen by fully this amount in the twisting cloud column wherever this touched the lower ground (see also the paper by Båth[5] where this approach to the problem is used). The height of the water column raised from the duck pond between two barns at Chapel End Farm, Houghton Conquest, which provided an usunually good yardstick for gauging its height, certainly reached 10 ft. (perhaps rather more) as an unbroken

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THE MAIN TORNADO APPROACHING THE R.A.F. STATION AT HALTON

The rotating funnel cloud was just lowering to the earth when the picture was taken and within the next few minutes a heavy roof in its path was lifted

Reproduced by courtesy of the Leighton Buzzard Observer

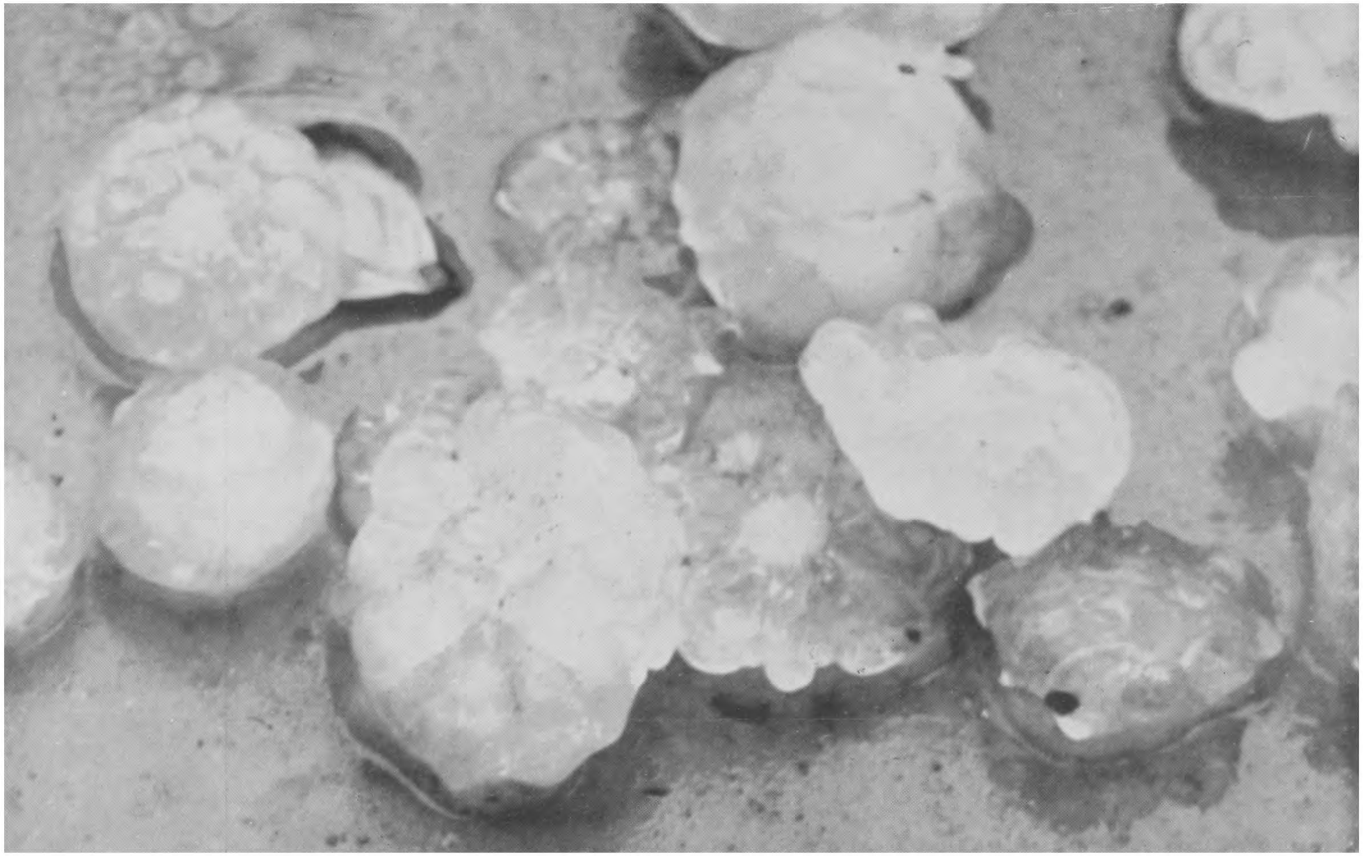
SCENES OF HAVOC AT LINSLADE

Reproduced by courtesy of Starr and Rignall, Ely

OVERTURNED BUS AT SUTTON, ELY

The bus fell on grass and only one headlamp and one window were damaged

Plate III



Reproduced by courtesy of F. Greenaway

HAILSTONES AT NORTH CRAWLEY, NEAR NEWPORT PAGNELL, BUCKS
(Actual size)

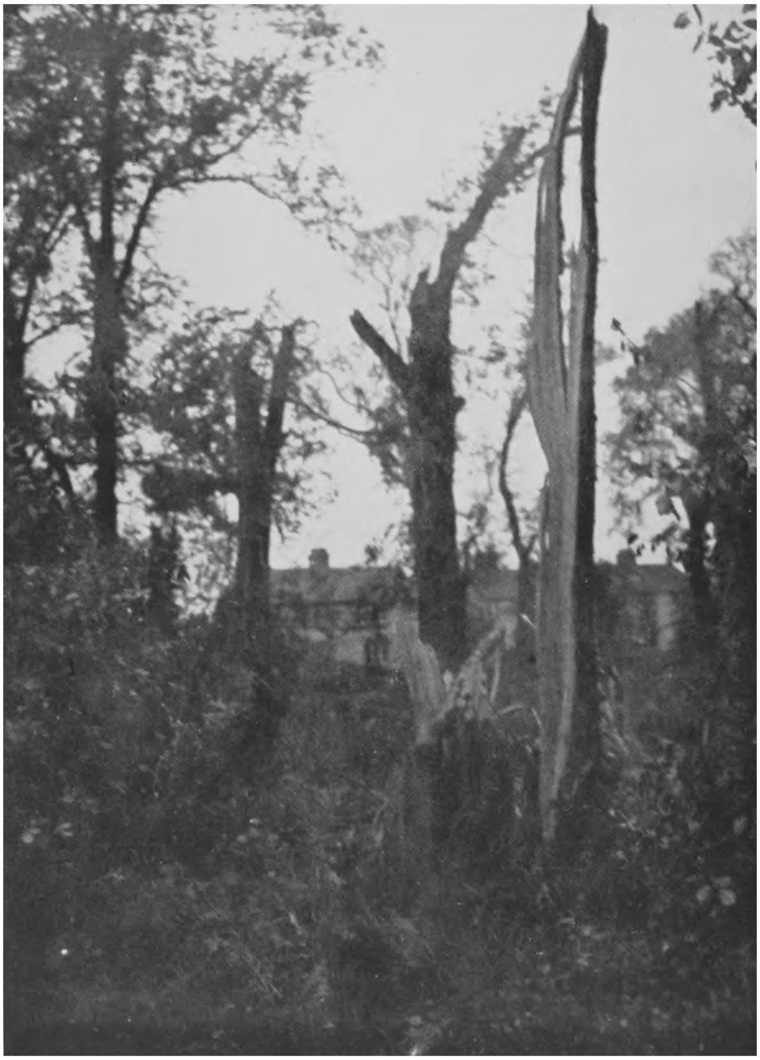


Photo by H. H. Lamb

TORN AND BROKEN TREES AT SUTTON, ELY

The trunk in the foreground was 34 in. in diameter column. If the height of the unbroken column is accepted as a rough-and-ready water barometer measuring the difference of pressure between the centre and its surroundings, the indication is that over a narrow centre, in this case not more than 1–3 ft. across, pressure may have fallen 300–500 mb. although within the next yard or two the drop is only 20–30 mb. below the surroundings. It must be seldom that the unbroken water column can be subjected to anything approaching accurate observation, but the present case and drawings by careful observers on ships at sea (see the paper by Wegener[1], p. 137) and various other reports[6] lend weight to estimates of this order. In estimating the height of the column care must be taken to distinguish the unbroken column from the spray and severed portions and there would be a likelihood of some over-estimate if the water were raised only momentarily and, following the quick upward acceleration, overshot the equilibrium position ; wavy, ragged portions of the top of the column should certainly not be included in the estimates.

The pressure profile in Fig. 7 has therefore been drawn to indicate a pressure drop of 30 mb. to 975 mb. within 20 yd. of the centre, and suggests a fall of still greater order in the actual centre. This profile is an attempted representation of one of the most intense phases of development of the centre, exemplified at least momentarily in the case of this tornado at Goldington Bury and Wilstead and in the case of the main tornado at Wendover, Aston Clinton, Linslade, Bedford and Sutton. The centres underwent constant changes of intensity and, no doubt, of detailed profile from minute to minute. Where the cloud funnel only just reached the ground, the greatest lowering of pressure would be only of the order of 20 mb. ; and where the funnel lifted off the ground, the pressure differences were certainly less, except in so far as very localized differences of humidity might affect the issue.

Wind speeds.—Consideration of the pressure profile and its variations from minute to minute suggests that

(i) the pressure changes may be too short-lived for any close approach to gradient-wind conditions to be reached—in any case these conditions could not be expected to apply fully where horizontal inflow is supplying a violent vertical current ;

(ii) the actual maximum wind velocities will be of brief duration, comparable to gusts and squalls, but possibly of very large order ;

(iii) the maximum winds must occur in zones or rings of extremely narrow width, to be measured in feet or possibly in inches ;

(iv) the most extreme wind velocities which might be measured are therefore likely to be of less practical importance than the extreme horizontal gradients of velocity (shear) involved.

Fig. 7 can be used to derive estimates of the theoretical (gradient) winds in the tornado, taking account of the pressure differences and curvature of the air trajectories (regarded as equal to that of the isobars) but not of friction. It is important to remember, however, that the profile shown in the figure can only represent the real profile in very generalized form, especially near the centre of the tornado. Gradients are in reality changing from minute to minute, and even the location of maximum gradient and strongest wind with respect to the centre is subject to evident changes.

Table I sets forth the appropriate values of gradient wind speed for the pressure gradients indicated at various distances from the centre in Fig. 7. The values have been computed for latitude 52° N., pressure about 1,000 mb. and temperature 50° F. The cyclostrophic term is dominant with these small radii of curvature, and in the central regions its effect varies greatly according to the precise distance of the steepest pressure gradients from the centre. But for the cyclostrophic effect gradient winds of the order of 1,000 kt. would be required. In studying this point the following form (given by Petterssen[7]) of the gradient wind equation, applicable to cyclonic curvature, is useful :

$$v_{gr} = \tfrac{1}{2}\lambda r \left\{ \sqrt{\left(1 + \frac{4v_{gs}}{\lambda r}\right)} - 1 \right\},$$

where v_{gr} is the gradient wind velocity and v_{gs} is the geostrophic wind velocity, r is the radius of path curvature and λ is the Coriolis parameter ($2\omega \sin \phi$) whose value is $0{\cdot}411$ hr. $^{-1}$ in 52° N.

TABLE I—GRADIENT WIND SPEED AT VARIOUS DISTANCES FROM THE TORNADO CENTRE

Distance from centre (regarded as equal to radius of path)	Pressure gradient from Fig. 7	Gradient wind speed
miles	mb./mile	kt.
8–10	0	0
$1\frac{1}{2}$	1	22
$\frac{3}{4}$	4	31
$\frac{1}{2}$	10	40

These figures, perhaps surprisingly, show that the observed winds are of the same order as the gradient wind, and would indeed exceed the latter were it not that the pressure gradients on a line east of the centre must be assumed to be rather greater than those in any other direction, owing to the observed asymmetry of wind effects around the tornado centre and the general translation of the system towards the north-north-east (see p.7). The strongest wind at Cardington around 1630 G.M.T. was appropriately a SSW. wind on the east side of the centre and, according to our reckoning, might therefore be 15–25 kt. stronger than the rotational velocity at the same distance from the centre.

Within half a mile of the centre of the tornado much bigger pressure gradients may occur, amounting perhaps to $1{\cdot}5 \times 10^6$ mb./mile, if our assumption of a drop of the order of 300 mb. within a foot or two around the periphery of the waterspout or at times within the funnel cloud is correct. This extreme pressure gradient might correspond to gradient wind velocities from 25 to 250 kt. according to whether the gradient were located within a foot of the centre of rotation or 15–20 yd. away.

From these calculations it seems fair to assume that :

(i) Winds of the order of 200 kt. near the tornado centre (as suggested by Shaw[8] and others) are an extreme condition, only likely to be attained during moments of particularly intense development of the whirl associated with a particular profile showing the maximum speed at a distance of some yards from the centre. At the centre the horizontal component speed may decrease to zero, but of course the vertical component must be very great.

(ii) For winds of this order (200 kt.) to occur near the tornado centre a pressure drop of several hundred millibars in the central regions, as suggested by the waterspout observations, must be assumed.

(iii) The evidence of winds of great strength shows that the " gradient-wind values " are approached and represent a reasonable first approximation to the actual (surface) winds, when a vector component corresponding to the translation of the system as a whole is added.

Closer observation, if such were possible, might well establish that the gradient wind value is somewhat exceeded, if the vertical current is to be regarded as the primary phenomenon and the high speeds of the surface wind in the rotating system as required to feed the vertical current, whilst the pressure distribution adjusts itself to what is occurring. Already the discovery that the surface wind approximates to the gradient values in spite of friction suggests this conclusion.

Further observation of other tornadoes might also be able to establish whether phases indeed occur in which the maximum speeds are to be found some yards from the centre ; for if so the twisting effects should change from clockwise to counter-clockwise sense on either side of the zone of greatest speed, having the same sense as that of the whirl itself between the speed maximum and the centre.

The strongest winds of which any numerical estimate can be formed in the case of the present tornadoes were :

(i) From the evidence of uprooted and beaten down trees all around the main tornado in its phases of maximum violence at Wendover, Linslade, Fenlake (just south-east of Bedford) and Sutton, the southerly or south-westerly wind on the right of the advancing centre must have reached, or somewhat exceeded, 100 kt. at these points (see p.7).

(ii) About two thirds of a mile before reaching the climax of its development, in the Bedford area at Fenlake the south-westerly wind of the main tornado blew down a brick-built garden wall of no great age across its path. Using empirical figures given by Wegener[1] for the lateral pressure necessary to overturn an exposed wall of this description, the horizontal wind speed v in m./sec. normal to the wall required to exert this pressure is given by

$$v = \frac{100d}{h}\sqrt{3(1+h)}\ ,$$

where d is the thickness and h the height of the wall in metres. Taking the appropriate values for the wall in question ($d = 0{\cdot}25$, $h = 1{\cdot}75$) $v = 41$ m./sec. (80 kt.). This is, of course, a minimum value. The wall was in fact blown down over a length of several yards. It seems safe to assume that the maximum horizontal speed in the tornado somewhat exceeded 80 kt. even at this stage of its development.

Form of the velocity profile.—From our observations of the tornadoes of May 21, 1950, it has been possible to construct a crude pressure profile (Fig. 7) through the Wilstead–Goldington tornado at one stage of its development near Bedford. The few available observations and reasonably reliable estimates of horizontal wind velocity, admittedly not contemporaneous but apparently characteristic of the most violent phases of this and the main tornado, have been found to be of the same order of magnitude as the " gradient wind " in a rotating system of the size observed. It would be interesting, however, to establish within rough limits, the actual form of the velocity profile through the tornado.

Wegener[1] assumes that " solid " rotation occurs in the core of the tornado between the centre and the maximum speed ring—i.e. the speed v at radius r, neglecting any component due to the translation of the system, follows the law

$$v = c\,r, \qquad \ldots\ldots(1)$$

where c is a constant. In the outer portion of the tornado Wegener assumes a similar law to hold

$$v = c_0\, r^k, \qquad \ldots\ldots(2)$$

where k is negative and c_0 is some other constant, related to c of equation (1) by the continuity of velocity at the maximum velocity ring, where $v = V$. Since $V = ca = c_0\, a^k$, where a is the radius of the maximum velocity ring,

$$c_0 = ca^{1-k}. \qquad \ldots\ldots(3)$$

Wegener believes that k approximates to —1 (irrotational flow) in old, mature tornadoes.

There seems to be no method of checking the hypothesis of solid rotation in the inner core of the tornado on account of its small size and the complete lack of evidence as to wind velocities between the centre and the velocity maximum. If, however, likely values for v are inserted in equation (2) between the maximum velocity ring and the outer limits of the tornado to which the observations apply (e.g. 100 kt. at 10 yd. (10 m.) radius, 25 kt. at 1,000 yd. (1 km.) and 10 kt. at 10,000 yd. (10 km.)), k should be about $-\frac{1}{3}$. This is in sharp contrast with Wegener's suggestion of large negative values for k in the outer portion, especially in young tornadoes, and appears to mean that in the cases considered here the wind speed fell off outwards much more slowly than Wegener assumes.

On the other hand, the figures used do not give a strictly constant value of c_0 in the equation ; and, although the figures are necessarily rough estimates, it is doubtful whether the constancy of c_0 is in fact maintained or whether so simple a law as that suggested by equation (2) holds in real tornadoes.

The same criticism is plainly applicable to the results one obtains by combining equations (1) and (2) with the gradient wind equation

$$\frac{1}{\rho}\frac{dp}{dr} = \lambda v + \frac{v^2}{r}, \qquad \ldots\ldots(4)$$

where friction and other extraneous forces are neglected (ρ being the air density and λ the Coriolis parameter), since neither law can be supposed to hold exactly. Wegener ignores the geostrophic term and uses only the cyclostrophic wind, which in the innermost regions of the tornado becomes 500–1,000 times as great as the geostrophic term.

The expression derived for the pressure profile in the core of the tornado by combining equations (1) and (4) is

$$p - p_c = \frac{\rho c}{2}(\lambda + c)\, r^2, \qquad \ldots\ldots(5)$$

where p is the pressure at radius r, and p_c is the pressure at the centre. This cannot give a simple, parabolic form of pressure profile, when the air density varies as it must with the considerable pressure differences occurring. The corresponding expression giving the maximum speed V in terms of the pressure drop between the maximum velocity ring and the centre is

$$P - p_c = \frac{\rho V^2}{2}\left(1 + \frac{\lambda}{c}\right). \qquad \ldots\ldots(6)$$

This indicates that the maximum speed V will be greater the larger the pressure drop in the core of the tornado and the lower the air density, a conclusion which is probably not affected by variations of c or the crudity of our assumptions. So long as c is reasonably constant, the maximum velocity should be greater the greater the dimensions of the core (radius of the maximum velocity ring).

As regards the outer part of the tornado, the integrated form of the equation derived by combining expressions (2) and (4) namely

$$p = \frac{\rho c_0 \lambda}{k+1} r^{k+1} + \frac{\rho c_0^{\,2}}{2k} r^{2k} + \text{constant} \qquad \ldots\ldots(7)$$

gives an infinite pressure at $r = \infty$ when k is between 0 and -1. From this it is clear that the law $v = cr^k$ cannot in any case hold beyond some limited radius outside the maximum velocity ring with the values of k found here. Equation (7) would not be valid if $k = -1$.

Unfortunately there are not enough reliable wind speeds from these tornadoes to establish the distribution of velocities fully at any stage. It appears however that the maximum velocities were probably attained at those points where the maximum velocity ring had its biggest radius (Wendover, Halton, Linslade, Bedford and Sutton). A reasonable first approximation to the rotational velocities in the outer portion of the tornadoes might be obtained by applying the gradient-wind equation to pressure profiles similar to that given in Fig. 7 or by taking $k = -\frac{1}{3}$ in equation (2) and using a figure of 5–6 × 10^4 cm.-sec. or about 600 ft.-sec. units for the constant c_0. To the rotational velocity must be added a component representing the translation of the system as a whole to arrive at the actual velocity observed. During the history of any tornado an almost limitless variety of velocity profiles may occur with different values of pressure drop in the centre and changing radius of the maximum velocity ring.

§ 5—GENERAL WEATHER SITUATION ON MAY 21, 1950, IN WHICH THE TORNADOES FORMED

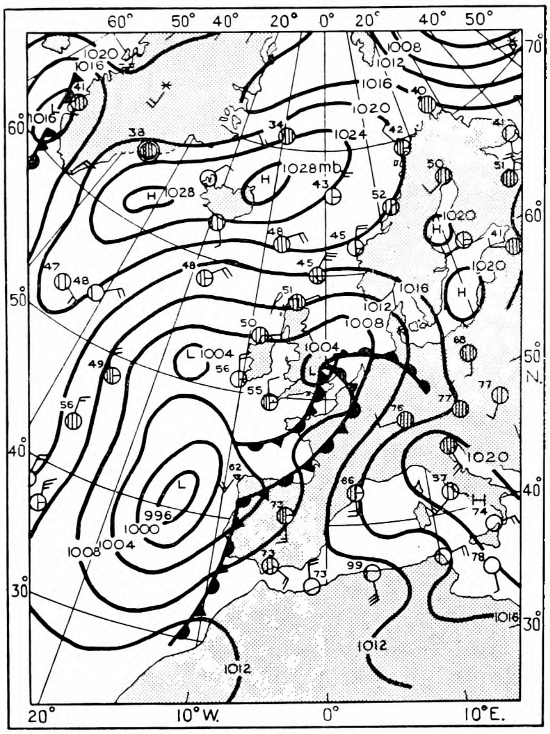
The synoptic situation is illustrated by Fig. 8, giving (*a*) the sea-level analysis for midday of the day before the occurrence and (*b*) for immediately before and (*c*) soon after the tornadoes appeared. Fig. 9 is a 700-mb. contour chart for the afternoon of May 21. The positions in which the three tornadoes actually formed are shown as nearly as possible by dots on Fig. 8 (*b*). Because the analysis is complex and rather difficult and because the positions in which the tornadoes formed show no immediately obvious association with the frontal structure, the maps have been carefully re-analysed, and the situation is further illustrated by a vertical cross-section (Fig. 10), by the Larkhill tephigram (Fig. 11), and by the isochrones in Fig. 12.

It is interesting to observe how little time before the occurrence the charts first showed any signs of the tornado disturbance. At 1500 G.M.T. only a slight trough appears over the area just north-east of the tip of the warm sector. Many tornadoes never appear on the charts at all ; but the zones of excessive convergence and shear may be detected. On the present occasion the remarkable convergence of the cloud motions feeding into the lower levels of the cumulonimbi constituted a readily visible threat in many parts of the area affected from 1400 G.M.T. onwards.

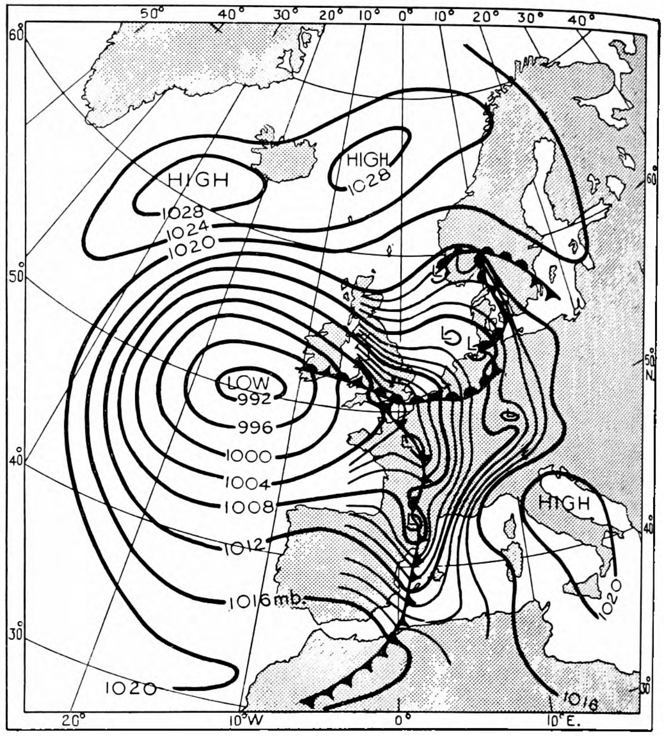
The chart analysis may none the less afford an instructive illustration of the general meteorological circumstances in which the tornadoes formed, helping us to recognize the elements of a tornado situation. In America it has been found that only warm sectors of unstable tropical air from the Gulf of Mexico produce tornadoes and therewith an overwhelming predominance of tornado tracks from south or south-west is noted in the United States[9]. In Europe the situations giving rise to tornadoes are more various, but usually (though not always) involve unstable, warm and moist southerly or south-westerly air streams. The present case was probably typical in that respect, and also shows a good deal of broad similarity with the situation which gave rise to one of the two other worst tornadoes of the past 88 years in this country[10].

Over the week-end of May 20–21, 1950, the southern half of the British Isles and North Sea lay in a broadly frontogenetic col area, maintaining a frontal zone and generally strong thermal gradient from southern Britain to central Sweden. In spite of this the frontal structure was not simple, partly because it was subject to a continual modifying influence, namely strong convection, associated with the vertical instability of both the principal air masses, especially in the afternoons, which produced a situation in which much mixing must have been going on. The various individual frontal lines within the broad frontal zone were always liable to be obliterated and replaced by a new effective boundary between the same air masses within a hundred miles or so.

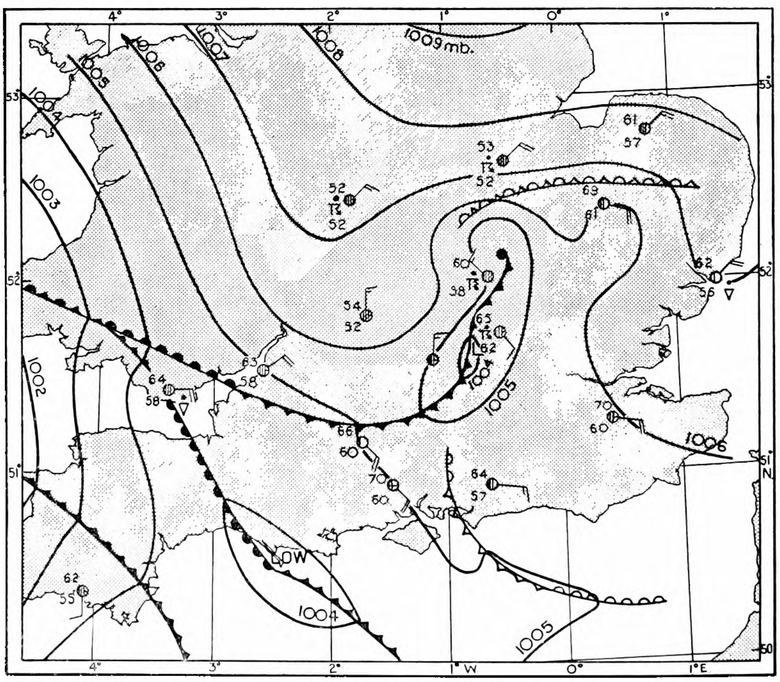
The colder of the two main air masses existed only as a shallow layer in the lowest levels over the tornado area ; its upper limit is marked by the frontal surface A on Fig. 10. It had come in from the north-east and east, after more or less stagnating over the North Sea where its moisture content was increased. The warm air mass overrunning was unstable African tropical air which seems to have come in about 30 hr. from Tunisia across the Mediterranean, over the



(*a*) 1200 G.M.T., May 20, 1950



(*b*) 1500 G.M.T., May 21, 1950



(*c*) 1700 G.M.T., May 21, 1950

FIG. 8—SEA-LEVEL SYNOPTIC CHARTS, MAY 20–21, 1950

The areas where the three tornadoes formed shortly afterwards are shown by three small dots on the chart for 1500 G.M.T. The main tornado centre is shown by a large dot on the chart for 1700 G.M.T.

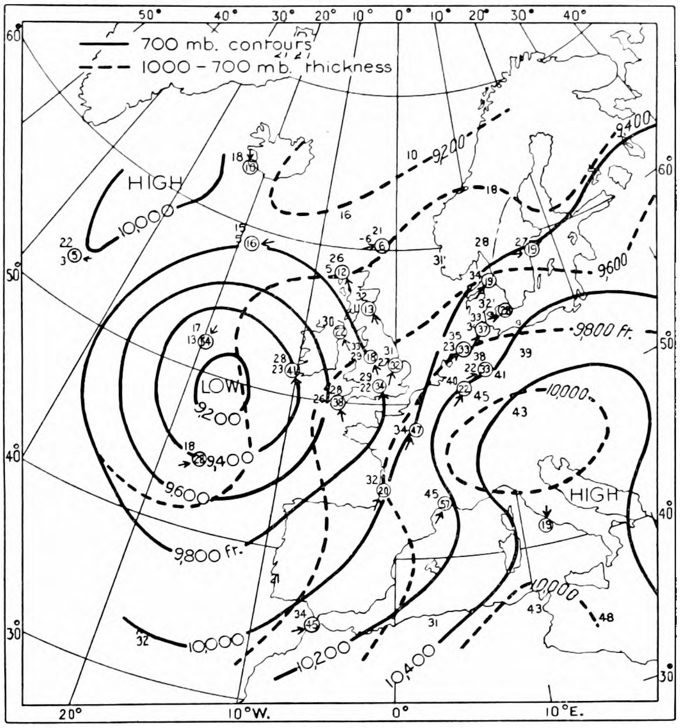


FIG. 9—700-MB. CONTOUR CHART, 1500 G.M.T., MAY 21, 1950

The figure inside each station circle gives the speed in knots of the 700-mb. wind whose direction is given by the arrow ; the upper figure is the air temperature and the lower figure the dew point, at 700 mb. in degrees Fahrenheit

Pyrenees and then the Atlantic coastal lowlands of France, to southern England. Moisture is acquired by such air streams over the Mediterranean and by evaporation over France, with much vertical exchange by convective activity both before and after crossing the Spanish mountains.

The situation seems also to have been somewhat cyclogenetic over England, lying in a diffluent region east of a major trough in the upper westerlies (Fig. 9) and close to the main thermal belt between England and Scandinavia.

On the 20th a small warm-sector depression broke away from the major stationary cyclone west of Portugal and passed north-east across England from Dorset to Lincolnshire (Fig. 8 (*a*)), later crossing the North Sea and declining as it approached Norway. In the middle of the day and afternoon weak thermal lows developed over Lincolnshire and over the hilly districts of Devon, Wales and southern Ireland. At the same time the main depression gradually moved north, preceded by the building of a minor ridge over southern England, where the trailing occlusion of the small break-away depression weakened and became hard to follow. The country remained however largely cloud-covered.

The distribution of wet-bulb potential temperature revealed by the vertical section (Fig. 10) shows that the upper frontal surface (marked B in the figure) of the occlusion survived until the 21st. The first thunderstorms on the 21st broke out about 0700 G.M.T. along an east–west line from the North Downs near London to Salisbury Plain and were probably associated with this front. These storms moved gradually north, reaching the Chiltern Hills and Oxford about 0900 G.M.T. and thereafter becoming more severe and widespread until the original line was lost.

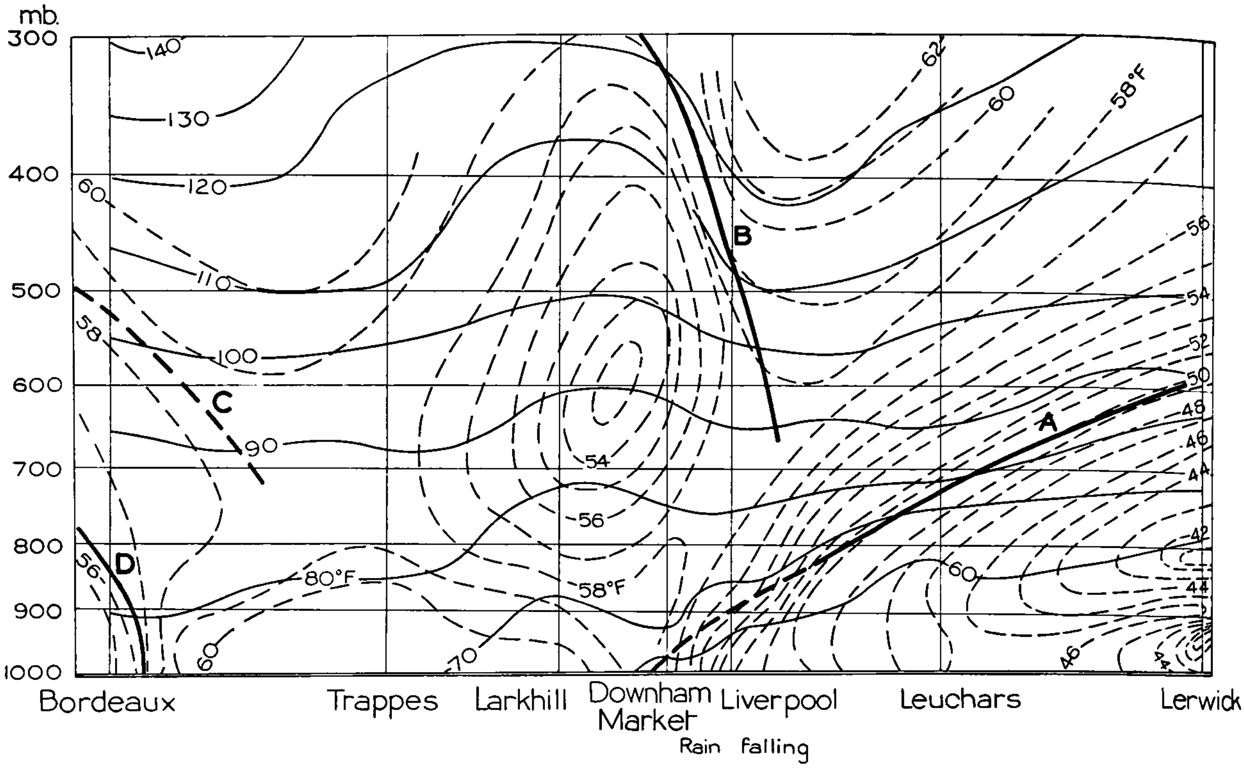


FIG. 10—VERTICAL CROSS-SECTION, 1400–1500 G.M.T., MAY 21, 1950

Full lines are potential temperature, broken lines wet-bulb potential temperature. Fronts and surfaces of discontinuity are shown by bold lines

They gave rain at Dunstable soon after 0900 G.M.T. and this rainfall enters into the rainfall distribution on the 21st discussed in connexion with Fig. 4 (*c*) (§ 3). The frontal line at the ground was also largely obliterated, but a short section of it appears over East Anglia on Fig. 8 (*c*) acting effectively as a warm front and it may be considered as an extension to ground level of the surface marked A on Fig. 10.

The general pressure gradient over the country was stronger on the 21st than the 20th, the main depression having moved north to near 50° N. 15° W. (Figs. 8 (*b*) and 8 (*c*)). It was only over eastern England nearest the col over the North Sea that any independent low comparable to the thermal (convection) lows of the day before could develop, appearing first about 1400 G.M.T. as a local trough between Cambridge and London—a small feature seen only on the largest-scale maps, but associated with intensified thundery activity, especially over the Hertfordshire hills.

Meanwhile another warm sector, seen over Portugal on the 20th in Fig. 8 (*a*), was approaching from the south. As often happens in similar synoptic situations, troughing of the isobars early became noticeable within this warm sector over north-east Spain on the 20th, probably due to lee effect and thermal factors (convection). By the afternoon of the 21st (Fig. 8 (*b*)) many troughs and minor cyclonic circulations had developed within the warm sector over France and Germany and on both fronts, and might be regarded as a characteristic of the air stream. By destroying the even alignment of the fronts these circulations made the analysis more difficult. The original cold front from the Atlantic, however, advanced fairly regularly (see Fig. 12) and at slightly over gradient speed until after 1500 G.M.T. on the 21st, when it began to be replaced by a secondary cold front some 50 miles in its rear.

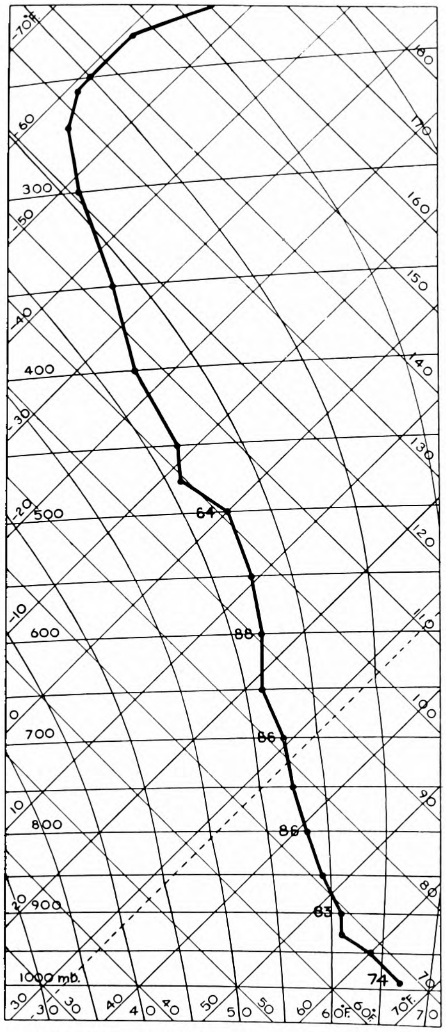


FIG. 11—TEPHIGRAM OF UPPER AIR TEMPERATURE, LARKHILL, 1500 G.M.T., MAY 21, 1950

Humidity is indicated by dark figures

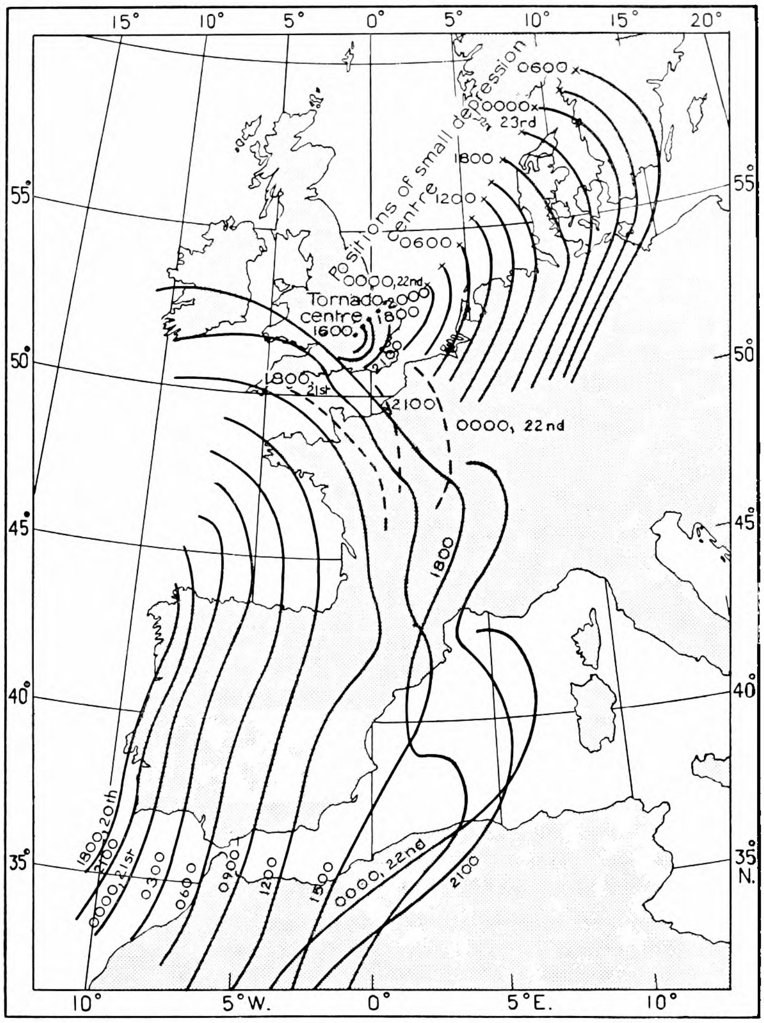


FIG. 12—ISOCHRONES SHOWING THE ADVANCE OF THE ATLANTIC COLD FRONT AND OF THE COLD FRONT GENERATED BY THE MAIN TORNADO

The passage of these fronts over northern France and the Channel Islands, where both warm and cold fronts were preceded by thunderstorms and accompanied by wind veers, can be easily established from the successive hourly observations, but the analysis becomes more difficult as they approach the British Isles. The cold front trails along the isobars and the warm front becomes weak, being only faintly discernible at the surface in the first part of the afternoon when it was quite destroyed by surface heating of the shallow underlying air mass over south-east England. Temperatures reached 68° to 72° F. between Kent and Salisbury Plain, where Larkhill was probably within the warm-sector air mass for a short time about 1400–1500 G.M.T. (Fig. 11). Nor can this warm front be identified on the north–south vertical section (Fig. 10) for that time, although cooler surface air remained everywhere north of the front at points west of Larkhill and north of the Chiltern Hills, where maximum temperatures were several degrees lower, thanks partly to the considerable cloud cover in the already mentioned local thundery trough. These modifications are thought to be fully attributable to the great convectional mixing and the influence of the pattern of surface heating.

Part of the warm front may have survived rather longer over the English Channel farther east. Immediately before the appearance of the tornadoes the effective northern boundary of the warm-sector air mass was therefore made up of the western portion of the original warm front and farther east a more diffuse boundary near the Chiltern Hills, passing therefore south of Downham Market, and then fading out completely in the convectional mixing going on and becoming replaced by the front marked A on Fig. 10, already referred to.

The cold front advancing east over France is also not well shown by Fig. 10 (on which it is marked D), since its line nearly coincides with that of the vertical section. As regards identification on the surface weather maps, lower dew-points occurred some distance behind the front over Cornwall, Devon, and Brittany, but nearer the front high dew-points resulting from precipitation and evaporation from the wet ground confuse the analysis as so often in thundery situations. In these circumstances the most reliable evidence of frontal positions is commonly afforded by the wind-field and by eye observation of the alignments of the main cloud structure, and it is on this basis (supported by the successive isochrones of the cold front represented in Fig. 12) that the surface analysis presented in Figs. 8 (*b*) and 8 (*c*) is substantiated. For example, Mr. F. H. Dight of the Meteorological Office noted two distinct phases, now presumed to be storms formed in the air overrunning the warm-front surface and at the nose of the cold front respectively, in the storm development near the tip of the warm sector passing over Trowbridge, Wiltshire, in the afternoon of May 21 :

> The first storm moved up from south-east (approximately)....and had all the characteristics of those pre-frontal storms moving up slowly in continental air....The storm was a relatively high-level one with frequent cloud-to-cloud lightning flashes....I saw very few flashes to earth at this stage.
>
> There followed a lull of 15–20 min. and it seemed that the storm had passed....I was a little startled to see further trouble coming up from south-south-west. This time the cloud was well down ; the lightning discharges were practically all direct to earth....They [the flashes] were all across the line of advance of the storm. Hail occurred....A man and five oxen in the neighbourhood were affected by one strike....one of the runways at Lyneham airfield was struck....probably at the time of a total power failure at 1515 G.M.T.
>
> Within half an hour the storm had passed to north-north-east and the sky cleared to about three oktas of shallow stratocumulus patches moving up from west of south, the clearance being well established (at Trowbridge) by 1500 G.M.T. Within an hour typical cumulus heads were moving up still from west of south, to dissipate during the early evening....It would seem unquestionable that the second storm accompanied the passage of a cold front....

Mr. Dight's diagnosis was supported by details of the wind veers at all levels.

Several distinct foci of thunderstorm development on that afternoon have been identified:

(i) in the local pressure trough over the Hertfordshire hills

(ii) in the warm-sector air mass overrunning the decadent warm-front surface

(iii) accompanying the Atlantic cold front, which had reached Wiltshire by 1500 G.M.T.

It is a moot point how far the storms of group (ii) may have been a product of convergence in the upper air ahead of the Atlantic cold front. This group of storms travelled with the upper winds defined by Fig. 9 about the 10,000–15,000-ft. level, whilst the other groups remained in association with the features of the sea-level analysis named in (i) and (iii) above.

The tornadoes broke out within about 50 miles north-east of the tip of this warm sector within an hour of the passage of the cold front across central Wiltshire. They were thus associated with the thunderstorms of group (ii) and like these storms proceeded to travel with the winds at 10,000–15,000 ft. (see Table II).

TABLE II—OBSERVED UPPER WINDS

Time of ascent	Pressure level	Observed upper winds				Tornado area. Vector mean of Larkhill and Downham Market upper winds	
		Larkhill		Downham Market			
G.M.T.	mb.	°true	kt.	°true	kt.	°true	kt.
1400	500	213	25	200	32	207	28
(before	700	168	34	201	32	185	33
tornado)	850	133	19	194	25	172	21
	950	123	15	155	15	139	14
2000	500	185	36	192	31	189	33
(after	700	194	25	205	30	201	27
tornado)	850	205	21	228	30	216	25
	950	228	12	277	20	259	15

It is also evident that the clearing front, swept forward towards the south-east and later towards the east by the growing cyclonic circulation around the main tornado, cannot from its timing have been initially continuous with the Atlantic cold front (see the isochrones in Fig. 12), but must rather have been created from the western part of the former warm front which became forced back by the new circulation and from the general diffuse air-mass boundary existing in the tornado region. The actual line of the new cold front may have been determined by the heavy hail which followed the tornado. The new clearing front was essentially created out of the old air-mass boundary between the same principal air masses : on the one hand, the cool North Sea air originally drawn from the north-east and now locally cutting in from the north and on the other hand continental air of African origin. Next day it seems to have become joined up over the Low Countries with the cold front of the Atlantic air still advancing east.

Two further significant points bearing upon the origins of the tornado remain to be mentioned.

The thunderstorms of group (ii), formed in the advancing warm sector aloft, reached their maximum severity, measured by rainfall, hail and lightning effects as well as by the occurrence of the tornadoes in them, where they came nearest to the pre-existing trough over eastern England. This trough notably increased the shear between the surface easterly current, which was progressively backed to north between Buckinghamshire and the Wash during the afternoon, and the overrunning warm air advancing from the south. It might also be presumed to distort any surviving traces of the warm-front surface in the lower levels, increasing the convergence and aggravating the thunderstorms thereabouts. This warm-front surface probably existed in some form quite low over the Chiltern Hills, and the surface northerly current beneath it would come abruptly into play about the northern face of the Chilterns and in the valley mouths facing north. These were the conditions when the tornadoes broke out.

Moreover, since the surface temperatures were not very high (e.g. maxima 64°–65° F. in the tornado area) and the tropopause (32,000–35,000 ft.) limited, the growth of the cumulonimbus at a distinctly lower level than sometimes occurs over this part of England in thundery weather, the causes of the tornadoes and severe storms of May 21, 1950, involve more than vertical instability alone. This suggests that the horizontal wind-field with its patterns of shear and convergence, determined by the intricate frontal situation and by the topography, played a vital role in enabling the vertical currents to build downwards and be fed in the ground layer by the rotating system of converging winds. Each of the main bursts of activity of these tornadoes occurred at some point where the tornado cloud, advancing from the south to south-west over some topographical feature, would encounter a fresh twisting impulse in the lower layers from the north-easterly breeze over the low-lying country north of the barrier : it seems reasonable to presume that this impulse played an important part in starting off the spinning column essential to the establishing of organized vertical motion near the ground.

§ 6—INCIDENCE OF TORNADOES

The fifty-odd destructive tornadoes in the British Isles from 1868 to 1950 noted in the *Meteorological Magazine* or in the publications of the Royal Meteorological Society are listed in Appendix I. Wegener[1] gives a list of about 250 European tornadoes from various sources; the list includes occurrences from the year 1456 to 1913, but it can make no pretence of being a full list and in fact the number of British tornadoes included in it is small—those prior to 1868 are included in Appendix I. It names 166 tornadoes in Europe between the years 1800 and 1899, and 192 between 1814 and 1913. Statistics of the occurrence of tornadoes in the United States of America show much greater numbers [11, 12]; in the record year of 1949 alone there were 290, and they took altogether 213 human lives; these American figures include, however, tornadoes which did no damage.

A more reasonable comparision between tornado frequencies in different regions can be obtained by converting the figures to numbers falling within a given unit of area. Fig. 13 shows the number of destructive tornadoes falling within $\frac{1}{2}°$ latitude squares (approximately 1,200 sq. miles) in the British Isles between 1868 and 1950; tornadoes are seen to have been most numerous in the eastern lowlands of England and the chief river basins, those of the Thames, Bedfordshire Ouse and Cam, the Fenland, the Severn valley, and the Yorkshire rivers. Comparison with similar terrains in Ireland suggests that proximity to the continent weights the distribution. One cannot however be quite sure that the figures are entirely free from bias according to the population density and corresponding probabilities of the occurrences being observed and reported. The pattern is strikingly similar to the pattern of thunderstorm frequency in days a year (average of 20–30 yr. up to 1933) shown in Fig. 14 taken from Marshall[13].

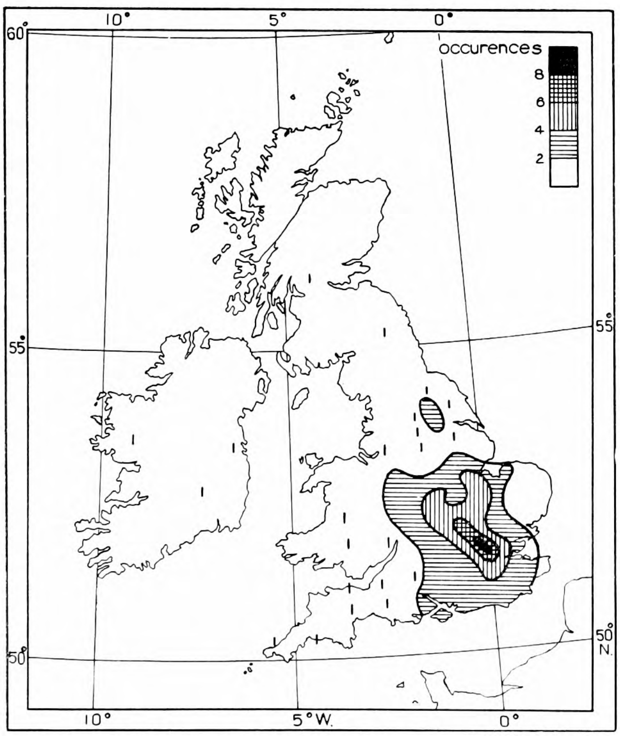


FIG. 13—DISTRIBUTION OF DESTRUCTIVE TORNADOES IN THE BRITISH ISLES, 1868–1950

The frequency is that of occurrences within $\frac{1}{2}°$ latitude squares (approximately 1,200 sq. miles)

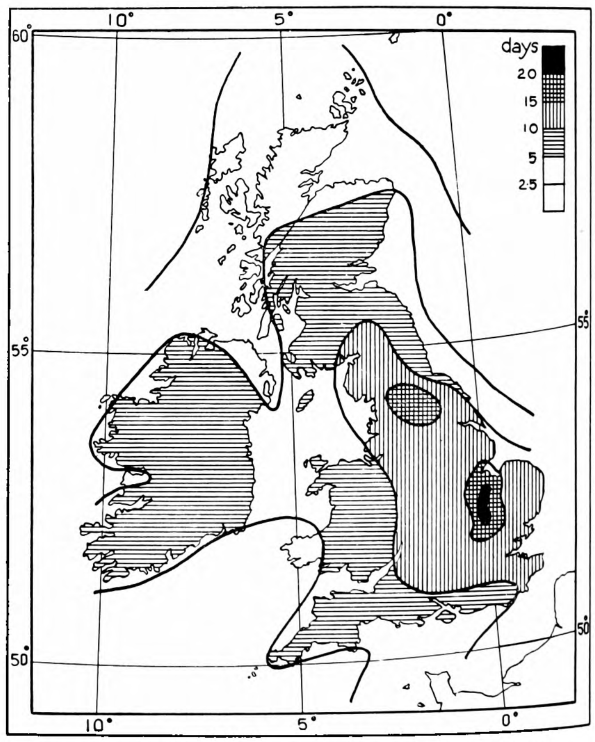
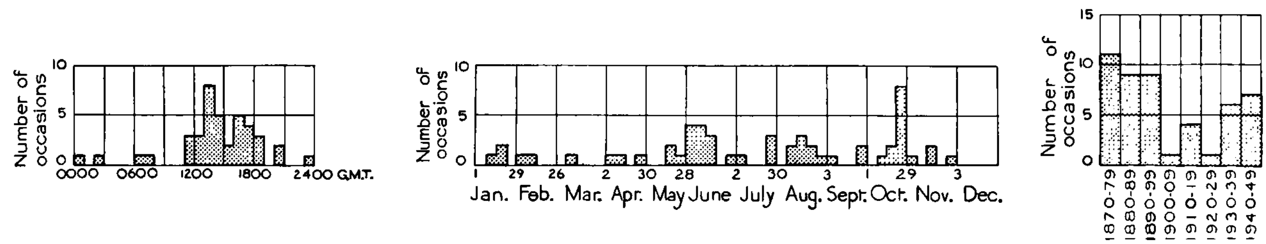


FIG. 14—MEAN ANNUAL NUMBER OF DAYS WITH THUNDER

Converting the figures given by Fig. 13 to yearly occurrences per 10,000 Km.^{2} (3,860 sq. miles) for comparison with continental figures, we find that the lower Thames Valley and Chiltern Hills, the district worst affected by tornadoes in the British Isles, shows a frequency of about 0·5 destructive tornadoes per 10,000 Km.^{2} a year. Koschmieder[4] gives the frequency in Holland as 2·5 tornadoes per 10,000 Km.^{2} a year and a figure of 1·25 for the Lake of Geneva, both taken over long periods of years ; it is not however stated that these continental figures are limited to destructive tornadoes. Brown and Roberts's[11] figures for the United States, not limited to destructive cases, yield a mean frequency of 0·56 yearly per 10,000 Km.^{2} for the States of Kansas and Iowa which are the States of highest tornado frequency. Much greater frequencies occur however in the worst afflicted localities in these States. The large number of tornadoes occurring in the United States is distributed fairly widely, especially in the broad Mississippi-Missouri basin and over the Great Plains east of the 20-in. annual rainfall line (i.e. in regions getting over 20-in. of rain in the normal year). Tornadoes are also well known in Australia and parts of Africa[8, 14]. It is clear however from these figures that parts of Europe including the great river basins and the eastern English lowlands rank among the regions of relatively high tornado-frequency.

By contrast tornadoes are notably rare in Scotland and Norway and in the mountainous parts of the United States. Their frequency falls off also even over the lesser uplands between the river valleys, although the case of the Chiltern Hills suggests that topographical features may be of importance as a trigger in setting off a tornado. The same suggestion is apparent in Wegener's maps of tornado distribution in France and Germany, showing concentrations along the rivers Seine, Rhône, Garonne, Rhine, Weser, Elbe, and Oder with maxima both towards the river mouths and at the edge of the Pyrenees, Alps and Erzgebirge.



Diurnal incidence | Annual trend | Secular variation

FIG. 15—FREQUENCY OF DESTRUCTIVE TORNADOES IN THE BRITISH ISLES, 1868–1950

The number of occasions refers to total occurrences between 1868 and 1950

The distribution of the English destructive tornadoes listed in the Appendix with respect to time of day, time of the year, and by ten-year periods since 1870 is given in Fig. 15. The diurnal variation shows simply the expected maximum in the afternoon corresponding to maximum instability : the peak of a smoothed curve would be approximately between 13 h. and 14 h. (local time ≏ G.M.T.). Cases of occurrence at night and in the early morning are, however, not unknown. The annual distribution shows that tornadoes may occur at any time of the year. Some of the winter occurrences were in the districts farthest inland, e.g. Banbury, Oxfordshire, on November 30, 1872, and Birmingham on February 4, 1946, so that these are no mere maritime phenomena. On the other hand the main peaks of frequency, each accounting for about 20 per cent. of the total, are (*a*) between mid May and the June solstice, the time of the onset of the European summer monsoon and its preliminary waves of cool air from west and north breaking into the continent, (*b*) between the last week of July and late August, the time of maximum frequency of summer thunderstorms and depressions centred over the British Isles, and (*c*) in late October, the sharpest concentration of all with 15 per cent. of the total in the one week October 23–29, associated with the most marked cyclonic singularity of the year[15].

The secular variation shows a decided minimum frequency of tornadoes in the British Isles stretching over the years 1900–29, much greater frequency in the years up to 1899 and again more recently, the renewed increase becoming noticeable first about 1934. The 35 years in which tornadoes became rare in this country coincide with the period in which the oceanic westerly type of weather is believed to have been exceptionally prevalent ; the pressure gradient between Eskdalemuir (55° 19′ N., 3° 12′ W.) and Lerwick (60° 09′ N., 1° 08′ W.) had a mean value of 3·3 mb. for the 30 years 1903–32 (extremes of the annual mean 5·0 and 1·1 mb.) and a mean value of 2·6 mb. for the 15 years 1933–47 (extremes 4·5 and 0·7 mb.)[16]. No good correlations between the frequency of destructive tornadoes and the average circulation index values in particular years have, however, been obtained. The reasons for this are probably (*a*) sampling errors introduced by the small numbers of destructive tornadoes, and (*b*) dependence of the phenomenon on the occurrence and frequency of particular circulation patterns rather than on the mean of a whole year. The decadal frequency of tornadoes in the United States (Fig. 16) shows a similar 30-year period in which tornadoes became quite rare in the United States*, but the minimum is centred about ten years earlier than in the British Isles.

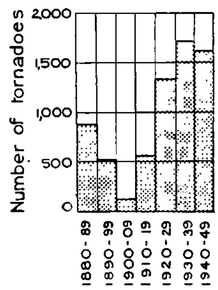


FIG. 16—FREQUENCY OF TORNADOES IN THE UNITED STATES[11, 12]

Attempts to correlate the secular variation of tornado frequencies with annual values of the solar constant and with the Zürich sunspot number have not yielded any result. Relationship to changes in the overall gradient of sea-surface temperature between the tropical and subpolar Atlantic, which must affect the incidence of all convection phenomena, appears more likely. It is moreover likely that the most intense, thundery fronts and frontal zones occur in years when the general zonal circulation is relatively weak and the effects of continentality can develop to a greater degree than at other times.

Decadal averages of air and sea temperatures between 60° and 70° N. in the north-eastern Atlantic, given by P. R. Brown[17], showed a general warming up of the order of 1° to 2° C. in the annual mean, especially in the eastern part, from the late nineteenth century to the 1930s followed by falls of up to 1° C. in the 1940s. Figures for the tropical Atlantic between 0° and 20° N. in preparation in the Marine Division of the Meteorological Office show apparently independent changes : the temperatures fell by up to 1° C. from the 1880s to a broad period of minimum temperature centred around the 1910–19 decade, followed by a greater rise since 1930. The overall difference in the annual mean sea temperatures between 20° and 60° N. in mid-Atlantic had in consequence a minimum value (about 15° C. in 30° W.) lasting broadly from 1900 to 1930, and was about 7 per cent. to 10 per cent. greater in the 1880s and again since 1940. The period of minimum latitudinal gradient of ocean-surface temperature thus corresponds very well with the years of minimum frequency of both tornadoes and tropical hurricanes in the North Atlantic and may be found to mark a general minimum in the manifestations of vertical instability and of intense frontal phenomena.

* Average number of tornadoes a year in the United States was 39 in 1890–1919 and 156 in 1920–49.

Finally, the listed occasions of destructive tornadoes in the British Isles have been studied in relation to the meteorological situations in which they occurred, using the series of daily weather maps for the British Isles since 1868 in the research library at Dunstable ; 56 per cent. clearly occurred at, or close to, a front ; of these about half were at cold fronts and a further quarter in the tip of a warm sector ; of the remaining 44 per cent. it is probable that a considerable number were either associated with fronts which are not obvious on the early maps or, as in the case of May 21, 1950, were related in more subtle ways to the frontal structure. Nearly all examples occurred with generally cyclonic curvature of the isobars over the tornado region ; 88 per cent. were obviously so, 6 per cent. straight isobars with suggestion of slight cyclonic curvature, 6 per cent. indeterminate or doubtful ; 31 per cent. occurred within a hundred miles of a depression centre, for the most part small secondary depressions. All the winter tornadoes (November–March inclusive) occurred during widespread gales ; 50 per cent. of the October cases were accompanied by general gales ; the corresponding percentages for the other months were quite low.

The significance of gales is presumably the likelihood of considerable local concentrations of shear and vorticity developing either at a front or under the influence of topography. In the seasons of the year when extreme thermal (vertical) instability is not easily attained tornadoes evidently require greater stress in the horizontal wind-field for their release. The few tornadoes which occurred at night also accompanied general gales.

§ 7—CONCLUSIONS

The essential features of a tornado are the development of the great vertical up-current, such as is ordinarily found only in the middle and upper troposphere in thunderstorm clouds, right down to ground level where it is fed by horizontal convergence from high-velocity winds in a rotating system of which it forms the axis. The lifting and twisting effects, the battering caused by the extreme wind velocities, and the disruptive effect of the extremely localized pressure differences make it the most violent of atmospheric phenomena.

Conditions favourable, and probably in some degree necessary, for the formation of tornadoes appear to be the following :

(i) Vertical instability.

(ii) High moisture content extending to low levels.

(iii) Cyclonic curvature of the isobars and air-tracks, and/or cyclonic shear in the horizontal wind-field usually at or near a front associated with considerable cyclonic vorticity.

(iv) A topographical trigger, acting through sudden local acceleration (release from barrier) of one of the air streams in the lower levels.

Vertical instability is needed for the development of the strong vertical current, first at fairly high levels. Its importance is amply shown by the association of tornadoes with thunderstorms and in the similarity of their diurnal and geographical distributions.

High moisture content extending to low levels increases the instability effect by release of latent heat of condensation in the rising air. Additional vertical acceleration starts at the condensation level, and development of the strong vertical current into the lowest layers is assisted if the condensation level is low. This factor shows itself in the relatively greater frequency of tornadoes near broad rivers, river-mouths and in the Fenland.

Cyclonic curvature and cyclonic shear help to build up the initial rotary impulse and encourage the development of suitable vertical currents. Their significance is clear from the associations with cyclonic situations and times of the year when cyclonic situations are most frequent, with fronts and with warm-sector tips.

Topography. Some topographical effect is suggested by the frequency of tornadoes near the edge of ranges of mountains and hills, although they are uncommon (and can at times be observed to break up) over the high ground itself. Evidence of the formation of the tornadoes of May 21, 1950 and of several of the rejuvenations along their tracks suggest that local accelerations of the surface wind ahead of an advancing atmospheric system once some barrier is passed may play an important part. The lee side of the hills with respect to the air stream in which the vertical current is developed aloft seems to be the danger zone. On one occasion (August 21, 1889) a tornado occurred in Shropshire in an unstable north-westerly air stream with no apparent frontal complications coming over the mountains of Wales : it may be that the topography supplied entirely the local concentration of vorticity which more usually requires the presence of a front.

Discussion of these and suggested further conditions for tornado development. Of the factors listed, the most important is undoubtedly vertical instability. In not less than 70 per cent. of the listed examples of destructive tornadoes in this country an unstable, moist, warm air stream from points between south-east and west (overwhelmingly from the south-west quadrant) seems to have been concerned. Where the instability is sufficient the wind system of the tornado may be developed in a wind-field showing a total shear of only about 30 kt., sometimes between opposing currents neither of which is more than a moderate breeze. Where the instability is rather less, tornadoes may be produced by more extreme local concentrations of shear in the horizontal wind-field at the ground.

Apart from the foregoing readily observed or demonstrated factors involved in tornado formation, there is a theory, first suggested by Wegener[1] and more adequately expounded by Walker[18], that the vast energy of tornadoes is associated with the development of a vortex with horizontal axis in the upper atmosphere bending down to the ground at one end and acting as an enormous centrifugal pump. The vortex is assumed to lie in a roughly north-south direction and to be set spinning by the earth-rotation effect upon air moving towards a horizontal axis of convergence (such as a front), the orientation of which is roughly meridional. That rotation must start about a horizontal, meridional axis of convergence is every bit as necessary a consequence of the earth's rotation as the better known rotations set up about any vertical axes of convergence. The rotation of the horizontal vortex should be clockwise when viewed from its southern end, and the tornado at this end should rotate cyclonically. The horizontal vortex aloft would thus normally lie to the left of the tornado's path.

It is alleged that most funnel clouds lean to the left of the track of the tornado, and further that the heaviest rainfall and hail is displaced to the left of the track—i.e. to one's left if one faces in the direction towards which the tornado is travelling. Walker points out that the heaviest rainfall associated with the British tornado of October 27, 1913, occurred some 20–30 miles to the left of the track, with maxima opposite three of the four points of severest tornado violence. He also names three cases in America where furniture and parts of buildings were carried 8–15 miles in a more or less northerly direction ; however it is not clear from his account whether these objects were really carried off to one side or along the tracks of the tornadoes in question. (The objects were probably mostly of wood.) Koschmieder[3] has been able to quote occasions where the sense of rotation, direction of transport of lifted objects, etc., conflicts with the Wegener–Walker theory, although apparently the greater number of tornadoes do conform.

On the whole the evidence suggests that the axes of these English tornadoes on May 21, 1950, showed an inclination to the left (i.e. towards the north-west aloft), which varied between 45° and 90° measured from horizontal but approached 90° (i.e. vertical) over much or most of their course. This being so, it appears likely that the most violent up-current in these cases was that in the axis of convergence and not generally the rotation about a horizontal eddy at some distance to the left of the tornado, as suggested by Walker.

Walker is of the opinion that only rotation in a horizontal-axis eddy could give up-currents strong enough to support hailstones of 3–4-in. diameter ; but in the present instance the greatest diameter of hail was just over 2 in., so there is no necessary conflict with this contention of Walker's.

In the tornadoes of May 21, 1950, the displacement between heaviest rain or hail and the tornado was very slight, although to the north-west when it was observable. Particularly heavy rain fell at Aylesbury, 5 miles west of the violent outburst of the main tornado at Wendover. Also particularly heavy hail occurred at Wingrave about 5 miles west of Linslade, though only about a mile to the left of the nearest point on the tornado track. Observers' reports did not suggest any marked slant in the funnel cloud. There was a well marked maximum of rain and hail in the Milton Ernest–Turvey neighbourhood some 5 miles north-west of the violent tornado phenomena on the outskirts of Bedford. North Crawley, which was one of the two places reporting hailstones over 2 in. in diameter, also lay 3 or 4 miles to the north-west of the path of the main tornado, though the tornado was quiescent at this point ; moreover the quantity of hail was not particularly great. Elsewhere the heaviest rain and largest hail fell close to the tracks of these tornadoes, even on the actual path of the centre.

Objects carried by the English tornadoes of May 21, 1950 (a roof and various sheets of iron at Halton, a sheet of iron at Linslade and the branch of a tree at Caldecote) followed closely the path of the centre. Such lateral scattering of objects as occurred seldom went beyond a hundred yards from the centre, though mainly to the north-west of the track.

It must apparently be concluded that the rapid horizontal-axis eddy in the upper air is not essential to all tornadoes in the manner described by Walker, although it may very well be so to the most violent examples of all. In the case Walker quotes on October 27, 1913, the axis would have been nearly east–west and very far from the meridional orientation suggested. On May 21, 1950 horizontal vorticity aloft was present and may have played some part ; but there is much evidence to suggest that the main control was the vertical current at the centre, extending from the ground to the upper troposphere and affected by vertical instability, possibly by humidity variations and certainly by features of the horizontal wind-field and ground relief.

In a paper published since this account was written, Fawbush, Miller and Starrett[19] have attempted to formulate and give minimum values for the conditions accompanying tornadoes in the United States, as a guide to forecasters warning people in the danger zone. From investigation of a large number of synoptic situations in the United States, these authors found that the following set of conditions characterized an area of tornado development :

(i) A layer of moist air near the earth's surface must be surmounted by a deep layer of dry air. Provided the other criteria were satisfied, tornado development occurred where the upper dry tongue crossed the lower moist strip.

(ii) The horizontal moisture distribution within the moist layer must show a distinct maximum along a relatively narrow band with dew-points over 55° F.

(iii) The horizontal distribution of wind aloft must show maximum speed along a relatively narrow band at some level between 10,000 and 20,000 ft., the highest speed exceeding 35 kt.

(iv) The vertical projection of the axis of wind maximum must intersect the axis of the moisture ridge.

(v) The temperature distribution in the air column as a whole must correspond to conditional instability.

(vi) The moist layer must be subjected to appreciable lifting.

It was found that in the cases examined in the United States at least four of the six conditions were fulfilled 12 hr. before the outbreak of the storm, the remaining ones becoming satisfied by the time of the outbreak.

Examination of Figs. 8 (*c*) and 10 and of the observed upper winds, given in Table II on p.29 in this account, suggests that conditions on this tornado day in southern England largely resembled those set forth by these American authors. Only condition (i) seems to be in doubt; Fig. 10 hardly shows any deep layer of dry air aloft, although there was a distinct minimum of wet-bulb potential temperature about the 600-mb. level over the area where the tornadoes developed. The orientation of this upper dry tongue, corresponding to the origin suggested for it (p.26) and to its appearance in Fig. 10, was probably approximately east–west; the orientation of the moist tongue in the lower layers differed from this chiefly as a result of air-mass modification proceeding rapidly over the moisture sources presented by the various sea surfaces, etc., and the dew-points in the lowest layers were characteristically irregular, as they so often are near the irregular coastline of north-west Europe.

No good correlations have been obtained between the occurrence of tornadoes and annual values of circulation indices or of the solar constant or sunspot number. This may be because tornadoes are related to particular shorter-lived phases of these elements. The rarity of tornadoes during the most oceanic period of our climate (1900–29) and their tendency, like that of particular circulation patterns, to repeated appearance within a particular year remain as suggestions of sensitiveness to the operation of external factors which affect the general vertical stability and instability of the atmosphere.

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APPENDIX

DESTRUCTIVE TORNADOES IN THE BRITISH ISLES

The reports of tornadoes over the British Isles given below for 1558 to 1839 are taken mainly from Wegener[1] and are believed to have been corrected throughout to the Gregorian calendar introduced in 1752 and now in use.

Date		Place	Damage
early July	1558	Nottingham ..	houses and churches demolished, lives lost.
October 21,	1638	Widecombe, Devon	church destroyed, lives lost.
October 13,	1667	Welborne, Lincolnshire.	..
August	1672	Bedford ..	trees uprooted, cottages destroyed.
August 15,	1687	Hatfield, Yorkshire.	..
August 7,	1694	Topsham, near Exeter.	..
June 21,	1702 or 1703	Hatfield, Yorkshire.	..
May 20,	1729	Bexhill, Sussex	buildings and trees destroyed.
August	1741	Holkham, Norfolk.	..
September 15,	1749	Rutland ; Northamptonshire.	..
November 1,	1785	Nottingham ..	barns, cottages unroofed, trees torn up.
July 2,	1788	Fife Ness ; St. Abbs Head ; Firth of Forth.	..
July 18,	1792	Loch Leven, Fife.	..
June 27,	1817	Stratford, Tottenham, Hampstead.	..
•	1818	Sussex ; Kent.	..
March 7,	1818	Isle of Wight ..	..
June 24,	1822 or 1823	Scarborough ..	..
July 18,	1822	Athlone, West Meath, Ireland.	..
September 18,	1822	Rosneath, Dunbartonshire.	..
end of July	1839	Killiney, Dublin, Ireland.	..

APPENDIX—*contd.*

The reports of tornadoes over the British Isles given below for 1868 to 1950 are taken from the *Meteorological Magazine*, *Weather*, and the *Quarterly Journal of the Royal Meteorological Society*.

Date		Time	Place
		G.M.T.	
April 27,	1868	..	Tottenham, London
April 14,	1869	..	Sweethope, Northumberland
October 10,	1870	..	Devon ; Somerset ; Stratford-on-Avon ; North Wales ; Isle of Wight ; Middlesex
February 10,	1871	0300	Kilkenny, Ireland
July 25,	1872	1500	Wantage, Berkshire
November 30,	1872	1200	Banbury, Oxfordshire
June 13,	1875	1340	Baldock, Hertfordshire
September 28,	1876	0715	Cowes, Isle of Wight
April 4,	1877	..	Ware, Hertfordshire
June 9,	1878	morning	Fowey, Cornwall
June 26,	1878	1700	Long Lawford, Rugby, Warwickshire
October 24,	1878	1300	Walmer, Kent
late August,	1879	..	East Yorkshire
July 30,	1881	1700	Boston, Lincolnshire
August 9,	1881	0100	Watford, Hertfordshire
August 19,	1881	1500	Brigg, Lincolnshire
November 17,	1883	..	Yeovil, Somerset
August 31,	1884	1400	Ely, Cambridgeshire
June 14,	1886	..	Deal, Kent
October 23,	1886	1200	Galway, Ireland
September 6,	1887	1745	Manchester
August 21,	1889	1400	North Shropshire
March 8,	1890	1530	Fulford, Yorkshire
May 26,	1894	1200	Ludlow, Shropshire
May 26,	1894	1300	Leominster, Herefordshire
October 24,	1894	1530	King's Lynn, Norfolk
October 26,	1894	1930	Oakham, Rutland
August 10,	1895	1900	Rotherham, Yorkshire
June 9,	1896	1600	Bridgwater, Somerset
May 31,	1898	1615	Loughton, Essex
October 29,	1898	2120	Camberwell, London
October 1,	1899	1400	Winterslow, Wiltshire
June 1,	1908	2100	Bushy Park, Middlesex
October 27,	1913	evening	South Wales ; Shropshire
October 28,	1913	1720	Gloucester
October 26,	1916	..	Writtle, Essex
July 26,	1918	1800	Halstead, Essex
October 22,	1928	evening	London
June 15,	1931	1400	Birmingham
January 13,	1934	0800	Carbis Bay, Cornwall
June 6,	1934	1815	Laindon, Essex
August 17,	1934	1730	Horndon-on-the-Hill, Essex
July 7,	1938	1730	Chiltern Hills ; Little Gaddesden towards Leighton Buzzard
November 18,	1938	2350	Kirton, Lincolnshire
August 19,	1944	1740	Shandon, Dunbartonshire
January 18,	1945	1350	Whipsnade Zoo, Chiltern Hills
January 18,	1945	..	Aston Upthorpe, Berkshire
February 4,	1946	1245	Birmingham
May 31,	1946	1900	Ampleforth, Yorkshire
May 31,	1948	1430	Kell
October 20,	1949	1415	Shoeburyness, Essex
May 21,	1950	16–1900	Buckinghamshire ; Bedfordshire ; Huntingdonshire ; Cambridgeshire ; Hertfordshire
July 7,	1950	..	Crediton, Devon
August 24,	1950	..	Derbyshire

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