Met. O. 711c

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GALES IN YORKSHIRE IN FEBRUARY 1962

EDITED BY

C. J. M. AANENSEN, M.Sc.

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SUMMARY

Descriptions of the anemograph records for north-east England for 16 February 1962 show that a generally unexceptional gale in England produced exceptional winds to the lee of the Pennines. This is confirmed by a description of the damage to buildings in Sheffield and to trees in north-east England. A survey of the pressure and wind fields on both a synoptic and a meso-scale is followed by consideration of lee-wave phenomena. Calculation on a two-dimensional basis of the standing resonant lee-wave pattern gives an explanation of the gale. Similar calculation for 12 February 1962 also shows why a similar synoptic pattern on that occasion was not accompanied by severe gale damage.

On statistical grounds the gale of 16 February 1962 is placed tentatively in the 'once in 150 years' category.

§1—INTRODUCTION

The month of February 1962 will linger in the memory of many people in Great Britain, particularly those in north-east England and in Scotland, because of the exceptionally stormy period which began on the 11th. On that day a deep depression moving rapidly from near Iceland to southern Norway brought west to north-west gales to the whole of the northern half of the British Isles. These winds continued strong for about three days. Then, after a temporary abatement, another west to north-west storm of equal severity followed on the 15th and 16th; this storm too was caused by a depression moving across southern Norway. Both gales did very considerable damage to both property and trees, and though in many ways the two gales were similar their effects in certain areas of the West Riding of Yorkshire were markedly different. The damage caused by the earlier gale was widespread, but on the other hand, the later gale caused a remarkable amount of damage in the area of Sheffield and Leeds, more than half the houses there suffering damage of some kind or other. In Sheffield in particular, the amount and severity of the damage on the morning of the 16th was so great that emergency services had to be brought into action without delay to house homeless families, render damaged buildings safe and effect temporary repairs. It was indeed fortunate that this later gale was not accompanied by much precipitation and was followed by a dry period.

There is no doubt that neither of these two gales was exceptional over the country as a whole. On the other hand the effects of the second gale were catastrophic in the industrial West Riding, particularly in the immediate lee of the southern Pennines in an area which one might regard as sheltered from westerly gales. In view of this the staff of the Meteorological Office took immediate action to put on record the general effects of the wind and to investigate possible reasons why the scale of destruction had been of such great magnitude in the Sheffield area in particular.

The results of the investigation are presented in this Memoir which is the joint effort of a team of investigators. A broad survey of the damage to the City of Sheffield was undertaken by J. E. B. Raybould. J. G. Cottis visited a number of natural woods and plantations along the Pennines and collected much material about forestry damage, a summary of which is incorporated in this report. General information on the winds recorded in the northern part of England and an account of the synoptic situation is the work of C. J. M. Aanensen, whilst the more detailed analysis of the wind flow and pressure distribution over the area has been carried out by D. C. E. Jones. The climatological background has been filled in by H. C. Shellard who also investigated the probability of recurrence. The possibility of the combination of upwind topography and the vertical distribution of temperature and wind giving rise to marked lee waves in the Sheffield area has been investigated by G. A. Corby.

The authors are happy to acknowledge help received in this work from very many other sources, in particular from the City Engineer, Sheffield, the Forestry Commission, North-east England, and the managers of the various estates mentioned in the text. They are also pleased to record their appreciation of discussions with

Professor J. K. Page of the Department of Building Science at the University of Sheffield and of the co-operation of Professor A. Garnett and colleagues who have produced within the Department of Geography at Sheffield University a map of tree damage from photographs taken in an aerial survey by the Royal Air Force. The editor is pleased to be able to include this map in the present publication.

This Memoir deals primarily with the gale of 16 February 1962, but some details of the earlier gale of 11–12 February 1962 are also given since it has proved to be of considerable meteorological interest to compare them and it would be impossible to separate completely the effects of the two gales. The Memoir concludes with deductions regarding westerly gales in the so-called 'sheltered' lee of the Pennines.

Because of their immediate interest to a considerable section of the public the main findings of this investigation were given advance publicity in a summary published in *Nature*.[1]*

§2—ANEMOGRAPH RECORDS FOR 16 FEBRUARY 1962

Before proceeding to a discussion of the causes and effects of the gale it is desirable to put on record a brief description of some of the anemograph records that are available for northern England and the adjacent Midlands. Accordingly anemograph records from the following stations have been examined and are summarized below: South Shields, Fylingdales Moor, Sheffield, Manchester Airport, Manchester Weather Centre, Cranwell and Birmingham Airport (Elmdon). Wind directions are given throughout in degrees from true north and all times are GMT.

South Shields.—The anemometer was a pressure-tube anemograph having a fairly open coastal exposure, the vane being 57 feet above a pier and 73 feet above mean sea level. At this station a relative lull in the wind around 0040 on the 16th (when the wind was 255 degrees 12 knots) was followed by a fairly steady progressive increase until 0230 when gale force (34 knots) from 260 degrees was reached and a gust of 64 knots was registered. Gale force winds continued until about 0600 and during this period the maximum gust was 74 knots and there were 13 gusts over 60 knots. The wind had gradually veered during this period from 260 to 290 degrees. After 0600 the mean speed dropped to just below gale force except for short intervals around 1150 and 1445 when there were gusts of 59 and 66 knots respectively. The mean wind speed for about 10 minutes around 1445 was 45 knots. It decreased slowly after this and by 1800 was only 22 knots. During the morning the mean direction varied rather irregularly from 280 to 300 degrees; during the early afternoon it was mostly about 300 degrees. The wind direction showed no well marked sudden changes throughout the whole period.

Fylingdales Moor (*North Riding*).—An electrical cup anemograph at this station was sited on open moorland at 840 feet above mean sea level. Here there was a relative lull in the wind around 0235 on the 16th at which time the speed dropped to 17 knots and the direction showed a veer from 240 to 270 degrees. The wind speed then increased somewhat quickly, but irregularly, gale force being reached at intervals from 0300 to 0400 with a maximum gust of 60 knots (from 280 degrees). After 0400 the wind speed progressively increased until about 0515 when the mean speed reached 55 knots and a gust of 75 knots occurred; the direction at this time was 285 degrees. From then until the recording was interrupted at 1203 the mean speed varied between 40 and 55 knots. The maximum recorded gust was 83 knots and there were 36 gusts over 70 knots and 4 gusts over 80 knots (at 0655, 0733, 1155 and 1203). The wind direction showed a veer from 290 to 310 degrees around 0640 but otherwise was fairly constant. The recording was resumed at 1635 when the mean wind was 310 degrees 34 knots. Thereafter the wind continued to decrease very slowly.

Sheffield.—The instrument at Sheffield was a pressure-tube anemograph with the head some 30 feet above the roof of Weston Park Museum. Although the head was therefore 83 feet above ground level and 533 feet above mean sea level, the exposure to the west and north-west was a fairly normal one above the general level of roof tops. The ground rises slowly to the west of the site becoming level with the vane some 500 yards away and just exceeds 800 feet above mean sea level 1600 yards away. The traces for speed and direction are always wider than they would be for an open grass site because of the turbulence caused by the built-up area and in particular by the museum itself. The length of run of the tubing to the float chamber is thought not to have affected the maximum value of gusts to any great extent.

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* The index numbers refer to the bibliography on p.44.

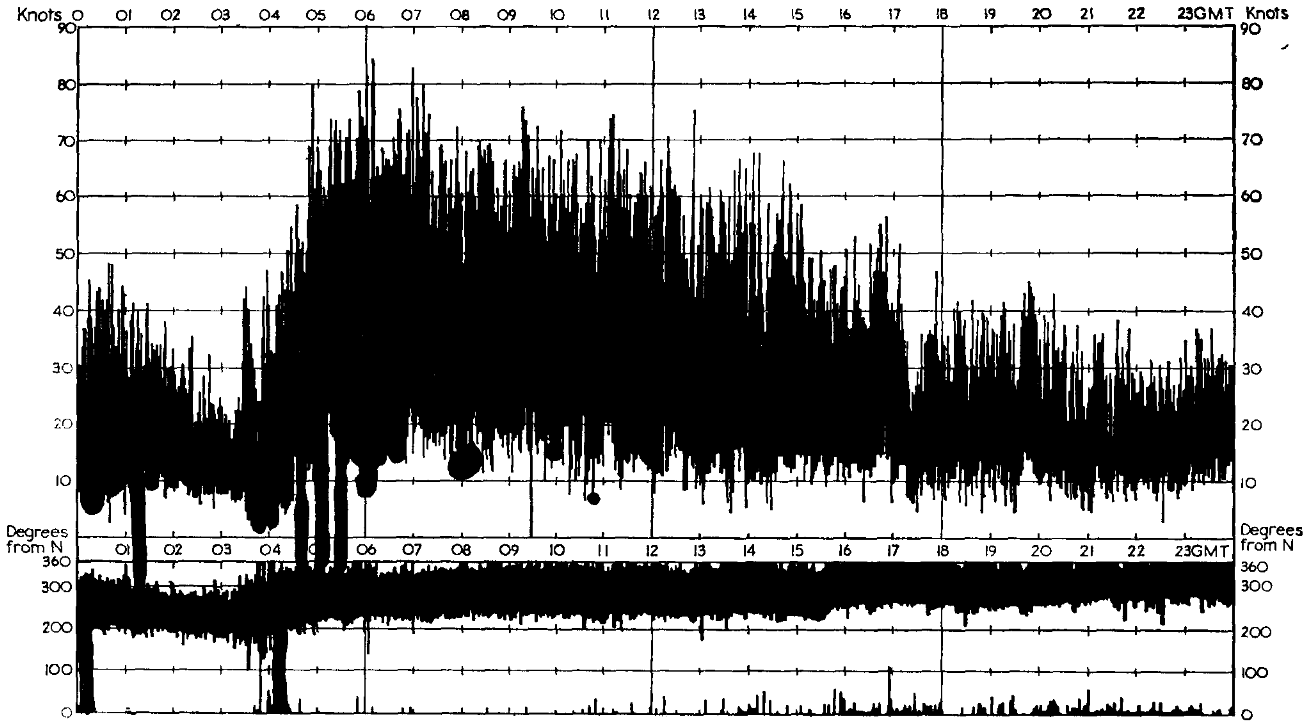

FIGURE 1—SHEFFIELD ANEMOGRAPH RECORD FOR 16 FEBRUARY 1962

Figure 1 is a reproduction of the Sheffield anemograph record throughout the 16th. It will be seen that the pre-gale lull occurred at Sheffield at about 0320 when the mean recorded wind was 14 knots from about 240 degrees. Then followed a fairly steady increase in the mean wind speed with a slow veer in direction until about 0540 when the mean was 280 degrees 40 knots. Gale force had been reached just before 0500 and frequent gusts over 60 knots occurred from 0450 onwards. The mean wind continued above gale force until 1230 from which time there was a gradual decrease reaching 25 knots by 1700. The wind slowly veered from 280 to 300 degrees during the morning and in the late afternoon there was a further slow veer to 310 degrees. During the period 0450 to 1300 there were at least 36 gusts of over 70 knots, and 6 gusts of 80 knots or over occurred between 0450 and 0710, the highest being 84 knots at approximately 0610. As far as can be judged from the record, the direction of these gusts was not substantially different from the mean wind direction (the trace shows a band width of approximately $\pm$ 60 degrees).

Manchester Airport.—The anemograph at the airport was a cup-driven electrical recorder with a good airfield exposure. The cups were 33 feet above ground and 261 feet above mean sea level. The wind record (see Figure 2) is of interest because it can be regarded as representative of the airflow on the windward side of the Pennines and hence may be compared with the Sheffield record made only 32 miles to the east but in the lee of the Pennines. The record shows the lull before the storm as occurring at 0130 when the mean wind was 240 degrees 18 knots. The wind then gradually increased, the mean reaching a maximum of 38 knots (from 270 degrees) by 0345. The increase was not regular but exhibited an irregular oscillation in speed from 0220. Consequently gale force was attained for a series of short periods after 0230 until about 0630. The wind direction was fairly constant at 270 degrees from 0345 until 0730 when there was a veer of 20 degrees over 10 minutes with a partial recovery in the next half hour. The mean wind speed dropped to 22 knots between 0830 and 0900 but increased again at 0920. The highest gust of all (56 knots) occurred at 0925 and the mean wind speed was again of gale force periodically from 1100 to 1500. The final decrease in the wind speed took place from 1700 onwards, though there was a spell at 2000 in which gust speeds reached a maximum of 50 knots. In all there were at least 22 gusts of 50 knots or over.

The anemograph record for Manchester Weather Centre is similar to that for Manchester Airport except that the traces are much wider. This can be expected since the exposure was a town one. The maximum recorded gust was 64 knots and there were in all at least 10 gusts of 60 knots or over.

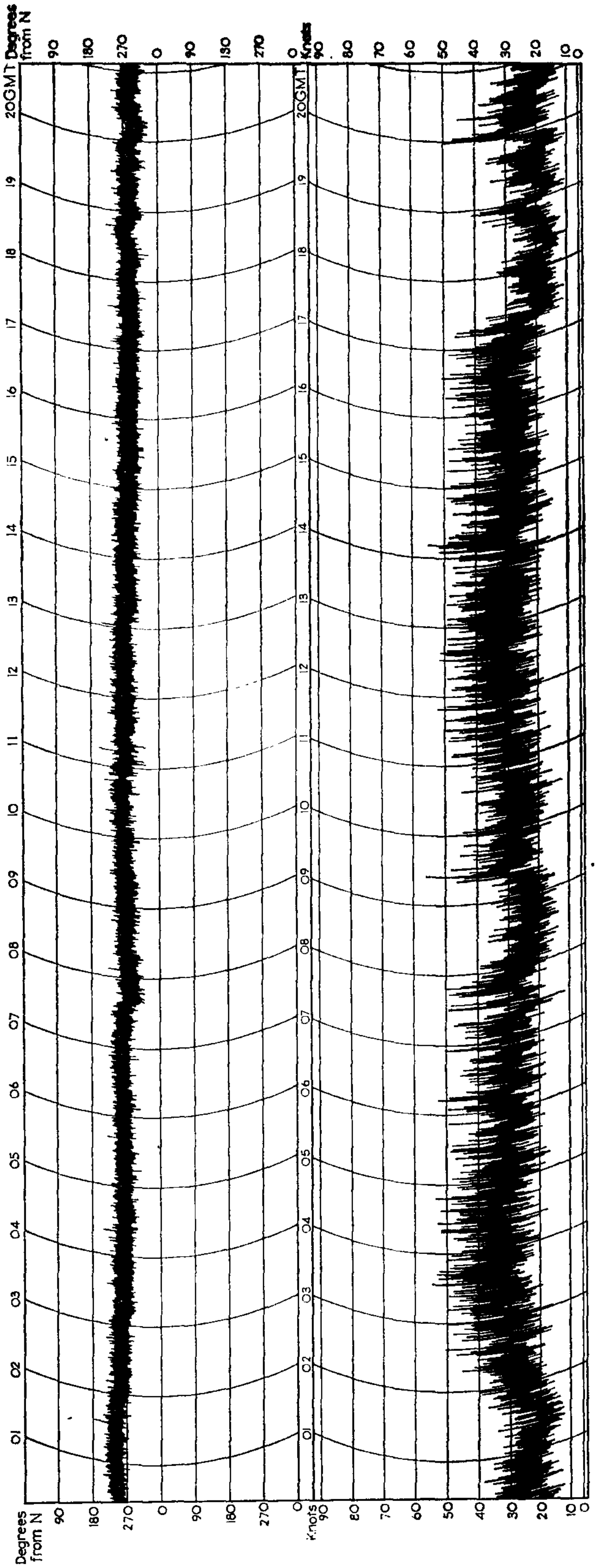

FIGURE 2—MANCHESTER AIRPORT ANEMOGRAPH RECORD FOR 16 FEBRUARY 1962

Cranwell (*Lincolnshire*).—The nearest downwind anemograph from Sheffield was at Cranwell 48 miles to the east-south-east and well away from the Pennines. Here there was a well exposed pressure-tube instrument with vane 47 feet above ground and 288 feet above mean sea level. The build-up of the wind speed from a mean value of about 20 knots took place from 2230 on the 15th. The mean speed reached gale force for a while about 0100 and 5 gusts of 50 to 53 knots were recorded between 0130 and 0410. The wind direction during this time showed a slow backing from 280 to 260 degrees. A slow veer of the wind took place from 0600 (270 degrees) to 0900 (310 degrees) and the mean speed again increased to gale force periodically from 0830 to 1830. The maximum gust was 64 knots (from 290 degrees) at 1435 and there were at least 20 gusts above 50 knots during this period. The wind then decreased very slowly during the late evening and night.

Birmingham Airport (*Elmdon*).—It will be seen later in this Memoir that the Pennines considerably distorted the airflow across the country. Birmingham is situated to the south of the major area of distortion and its wind record is of interest on account of this. The instrument was a cup-driven electrical anemograph, well exposed and with cups 30 feet above ground and 362 feet above mean sea level. Initially, the wind increased from 250 degrees 10 knots at 0150 on the 16th to about 30 knots at 0250. Gale force was reached periodically from 0335 to 0405, 0450 to 0610, 0650 to approximately 1100, 1740 to 1750, 1910 to 1920 and 2110 to 2130. Highest gusts were 55 knots at 0535, 63 knots at 0735, 65 knots at 1040, 57 knots at 1915 and 59 knots at 2125, and the highest mean wind speed was 46 knots. The wind direction was at first fairly steady, slowly varying during the night and early morning from 250 to 280 degrees, but at 0940 the mean wind veered 30 degrees in 10 minutes with a slow partial recovery afterwards. This veer occurred during a temporary slight lull in the mean wind speed. Thereafter the direction of the mean wind varied between 285 and 305 degrees. Between 1130 and 1515 there was a curious semi-regular repetition of the extreme veers with a period close to 9 minutes. Inspection of the maximum wind speeds at this time does not uphold this periodicity. On the other hand the peaks of wind speed occurred at approximately 90–100-minute intervals from 0530 to 1200 and the two squalls at about 1915 and 2130 were curiously prominent features of the speed trace (they were not apparent on the direction trace).

Other wind observations.—It is unfortunate that no other anemograph records were available in or near the West Riding to allow for a more detailed analysis of the wind flow. On the low ground to the east of Sheffield the nearest anemometer was at Royal Air Force Finningley (near Doncaster) where there was a well exposed cup anemometer and vane displaying on dials in the meteorological office. Readings of the mean wind over periods of about 15 seconds are taken at intervals and gusts are recorded by the observer as they happen to be noticed. According to the observer's meteorological register, the wind increased from 270 degrees 18 knots at 0554 to 300 degrees 35 knots at 0851. The wind continued strong to gale force until after 1654 and the maximum mean wind speed was 38 knots at about 1400. The maximum gust observed was 52 knots (at 1259) but there were many gusts over 45 knots between 0600 and 1700.

There were no anemometers for which records are available high up on the Pennines at the time of this gale but the following quotation from a letter written by Mr. Martyn Berry gives his experiences whilst attempting to walk on the hills above Edale Youth Hostel, to the south-east of the Peak.

> "Shortly before 10 a.m. I started up the spur above the Hostel. I soon found I had difficulty in moving and balancing. I had to use the lee of walls where possible. It took quite an effort to reach the plateau at about 1700–1800 feet. As soon as my head got above the plateau rim my eyes were filled with peat particles, and as soon as my body followed it was picked up and dumped in the heather. This was new: I had met extremely strong winds in Wales and on Ben Nevis, but nothing like this. . . After a bit I was able to make some progress along the plateau rim into the wind. Occasionally I was knocked over. After half an hour I had made 400–500 yards as far as the Ringing Roger outcrop, under which I sheltered. . . Putting one's head over the rim was equivalent to being punched in the face. On the spur down to Edale village a gust blew me over and I couldn't get up for about half a minute until it subsided."

It is evident that the gale on these slopes was exceptional and reference is made to this again in Section 11.

The wind observations at Watnall (near Nottingham) during the period of this gale are of very considerable interest and further reference is made to this later. Unfortunately there was no anemograph at Watnall, only a cup anemometer and in addition the site was by no means an ideal one; winds from the west usually appeared to be a little lighter than they should have been.

Winds were recorded hourly and Table I was compiled from the observer's record.

TABLE 1—SURFACE WIND AT WATNALL, 16 FEBRUARY 1962

Time *GMT*	Wind direction *degrees*	Wind speed *knots*
0600	260	18
0700	260	18
0800	280	24
0900	300	17
1000	280	10
1100	270	5
1200	300	15
1300	300	15
1400	300	15

Even if a considerable allowance is made for the sheltered exposure, it is still remarkable that the wind at 1000 and 1100 was as light as was observed. This phenomenon will be referred to later, when it will be seen that it was associated with a pressure trough to the lee of the Peak District.

From the above account it would appear that the general pattern of the gale was a fairly steady and rapid increase in wind soon after midnight, reaching gale force within two hours with a slow decrease setting in after midday. However, the general pattern was by no means universal throughout the country, certain localities having stronger and others much lighter winds. During the 'blow' the wind slowly veered from about 270 to 300 degrees. In the records examined there was no well marked veer or squall which could be followed through from one area to another.

§3—DAMAGE IN SHEFFIELD

The gale of 16 February 1962 caused widespread damage to property of all kinds in the Sheffield area, whilst other properties and woodlands in parts of the West Riding of Yorkshire, north Derbyshire and north-east England also suffered severely, but this section of the Memoir deals specifically with Sheffield where the concentration of damage to a built-up area was greatest.

Though local topography did not cause the gale it was without doubt a contributory factor to the severity of the damage due to the gale in the Sheffield area. The centre of Sheffield lies in a basin surrounded by hills, with the higher range of the Pennines to the west rising to 1200–1700 feet above mean sea level, and smaller hills to the north, south-east and south rising to 500–750 feet above mean sea level. The main centre of Sheffield lies between 120 and 300 feet above mean sea level, but the newer suburbs of the city have been built on the surrounding higher ground (see Figure 3). From the Pennines the rivers Don, Loxley, Rivelin, Porter Brook and Sheaf flow eastwards and together with the Meers Brook flowing northwards from high ground to the south, all converge and merge near the city centre, and then flow north-eastwards towards Rotherham as the main River Don. Thus the whole area surrounding the centre of the city, except that to the north-east, is very hilly with high spurs and escarpments interrupted by deep valleys. This configuration of the land presented many very exposed sites near the outer perimeter of the city where the full force of a westerly gale could be expected to be experienced and the wind speed in gusts would approach the gradient value. In addition, many of the valleys are orientated from west to east, and with the wind direction of this particular gale being westerly, wind speeds would be liable to increase locally by funnelling. Channelling of the wind at the lower altitudes, moreover, was not always confined to natural orographic features, since buildings and rows of houses with west–east alignment also created openings through which the wind was funnelled.

The effects of wind on buildings arise from the combination of external pressure on some parts, external suction on others, and, if there are openings, of internal pressure and suction. In certain places around the buildings, noticeably near roof ridges and along walls at corners where the mean wind direction approaches the tangential, the positive and negative pressures alternate in a rapid and random fashion in the eddying flow giving rise to severe turbulence and very considerable strain on the structure. Since the pressure of the wind

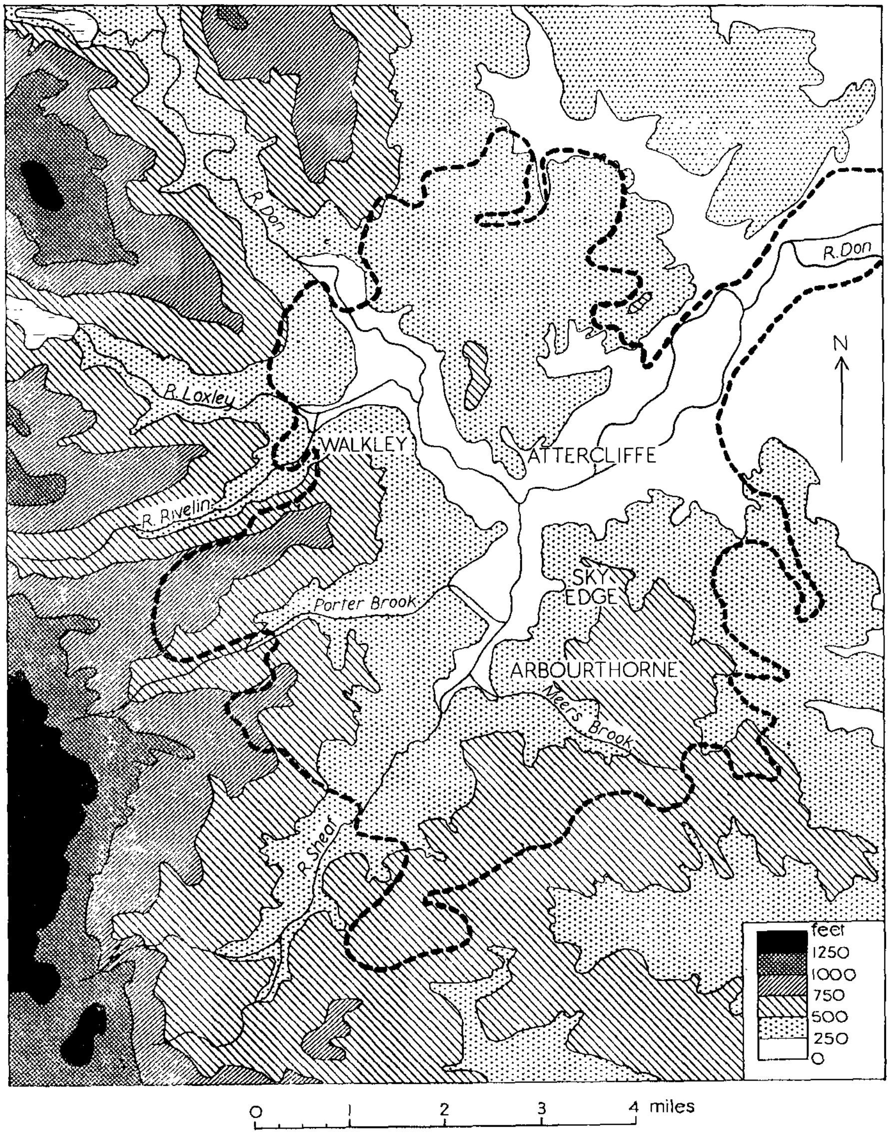

FIGURE 3—LOCAL TOPOGRAPHY OF THE SHEFFIELD AREA
---- boundary of built-up area.

varies as the square of the wind speed such effects increase very rapidly with increasing wind speed and above a certain speed, depending on the strength of the structure, damage is bound to occur. The parts of the buildings where the damage commences will depend on a variety of circumstances including the manner in which the mean wind is directed on the building and the age and condition of the building. Experience in the past has shown that roofs and chimneys are the most vulnerable and the gale at Sheffield corroborated this. This particular gale, however, did more than show the most vulnerable parts of the buildings since the scale of damage throughout the city was exceedingly heavy and very widespread. A tour of the area after the gale showed that the following generalizations could be made.

The initial damage to roofs appeared to be either loss of hip or ridge tiles presumably by direct lifting, the breaking of slates or tiles on lee slopes by lifting outwards, or the stripping of the roof near the gable end facing into the wind. Subsequent damage was caused by the wind entering under the roof and adding pressure from the inside to the suction effect on the outside of the roof and walls on the lee side of the buildings. Toppled chimney pots and bricks from the stacks also added to the holes in the roofs. It was noticed that when the wind blew along the roof, damage often occurred immediately to the lee of a chimney stack. Whether this was due to eddying or to vibration of the chimney is not known.

Damage to walls fell into two categories: direct blow-down because of insufficiently strong construction (poor mortar or single-brick walls), and stripping of the outer portions of cavity walls. In cases of the latter type of damage it would seem that internal pressure between the cavity walls must have been added to the suction effect on the outside. Similarly some plate-glass shop windows were blown out into the streets but there was no way of telling after the event whether this was due to suction alone or to suction plus positive pressure from the inside due to the wind having gained an entrance elsewhere into the building. There was no evidence at all to suggest any whirlwind, twisting or tornado-like motion of the wind. Some examples of typical damage showing these various features now follow.

(*i*) *Damage to roofs.*—Most of the minor damage throughout the city consisted of damage to roofs with several tiles or slates missing or broken. Some of this damage was caused by flying debris but the main cause was uplift due to the extremely high winds at roof-top level. The more serious cases of damage to roofs occurred when the initial fracture was the removal of the ridge or hip tiles. When this happened, the wind soon got underneath the roof and reinforced the uplift effect on the leeward side, so that the roof soon became stripped of its tiles and covering. On some of the new estates asbestos sheets, corrugated iron and copper sheeting had been used experimentally for roofing purposes and, where firmly fixed, withstood the gale very well. Instances occurred, however, of inadequate anchorage resulting in the loss of the whole or a large part of the roof.

(*ii*) *Damage to chimney stacks and chimney pots.*—Chimney stacks and chimney pots were particularly vulnerable to the wind. Evidence showed that some chimney stacks overturned about an edge of a weak joint at roof level, some falling in one mass and others crumbling as they overturned. In addition, many of the chimney stacks supported television aerials of the multi-array type which assisted in their overbalancing. Most of this type of damage was only moderate by itself, but in several instances it led to severe damage by the brickwork or chimney pot crashing through the roof and allowing the wind to cause further damage.

(*iii*) *Damage to buildings.*—Most of the damage occurred on the upper parts of buildings, where in the older property, walls were only of single-brick thickness. In some cases walls collapsed after the initial damage had been fractures to roofs or gable ends.

An instance of the outer wall being completely stripped from the inner wall was the house at the juncture of Hickmott Road and Neill Road, sited in the centre of Porter Brook valley (see Plate I and map in Figure 4). Extremely high winds must have struck across the corner of the house as a result of funnelling down the valley through the narrow ravine about a quarter of a mile upwind and thence along Neill Road.

Walls which had an outer covering of pebble-dash, cement, etc. came in for similar treatment and were in some cases completely stripped.

(*iv*) *Damage to walls and hoardings.*—There were several cases of walls and hoardings being battered to the ground by wind pressure. In all such cases the direction of the wind was perpendicular to the face of the wall or hoarding. Part of the wall outside Bramall Lane Cricket Ground on the Shoreham Street side was flattened in this way. The wall was about 12 feet high and of double-brick thickness with buttresses in places. The wind had a clear sweep across the open cricket ground on to the exposed wall. The latter eventually toppled over about an edge varying from six inches to two feet above ground level and fell almost intact with only a little crumbling of the upper portion of the wall. Examination of the wreckage suggested that there was considerable rocking motion of the wall before its final collapse. It is important to note that other walls to the cricket ground of similar age and construction, but less exposed, received little or no damage.

(*v*) *Damage to prefabricated houses.*—The single-storey prefabricated houses constructed just after the 1939–45 war were extensively damaged by the gale in the Arbourthorne and Sky Edge areas. Sixty-nine houses were finally damaged beyond repair. All the demolished prefabricated houses were sited to the south-east of Sheffield near the tops of slopes which faced west or north-west; thus they were completely exposed to the gale.

The process of disintegration was fairly simple and straightforward. The first failure occurred with the wind lifting and damaging the roof near the front porch entrance. Continued battering by the wind soon removed roof felting and the roof itself. Once this damage had been done the wind was free to blast away at the inner walls and complete disintegration soon followed. Impact with airborne debris added to the damage done directly by the wind.

On the Arbourthorne Estate the prefabricated houses (see Figure 5) are situated between 612 and 625 feet above mean sea level approximately 1½ miles south-east of the city centre. The vertical cross-section for almost a mile upwind indicates the open exposure. Detailed examination of the contour chart also reveals that a narrow valley known as Jervis Lum extends south-eastwards up the general slope and may have been responsible for a concentration of extremely high winds striking the Arbourthorne prefabs. Most damage was done in the Northern Avenue, Algar Road, Algar Drive and Errington Road areas. Plate II shows the damage done in Northern Avenue. It was observed that the prefabs in Algar Place, situated in a shallow saucer-like depression a few feet lower than Northern Avenue and Algar Drive, suffered far less damage. Prefabs a little further to the south, again where shelter is provided, were undamaged.

(*vi*) *Damage to cranes, pylons and scaffolding.*—This type of structure suffered damage mainly as a result of either toppling over or buckling. There were two specific instances of damage which are worth recording. The first was damage to the crane in use on the construction of the new Technical College at Sheffield. This was of the German cantilever type which is now in common use in this country on the construction of large buildings. This type of structure is obviously top-heavy and difficult to balance in anything more than moderate-force winds. It withstood the initial gusts, but as the gale built up to its peak it finally buckled and crashed, scattering bricks and scaffolding and tearing away part of the building under construction. The second instance was the buckling of the pylon carrying flood-lighting equipment at the Sheffield United Football Ground. This lighting tower was situated at the junction of St John's Street and Bramall Lane. St John's Street is orientated almost west–east and there is little doubt that the funnelling effect of the wind subjected this particular tower to extreme conditions and caused the buckling. The other three towers survived the gale without damage but these were well clear of other buildings and away from any channelling effects of the wind. Structural failure of the one pylon could not be attributed to corrosion or wear since the towers had only been erected three weeks earlier and failure was, therefore, a matter of design or strength of materials being inadequate to withstand such gale-force winds.

On the Sheffield Wednesday Football Ground the flood-lighting towers were not damaged. Here again the towers were well clear of other buildings and sited in the broad valley of the River Don at Hillsborough.

(*vii*) *Exposure.*—An example of the effect of open exposure on the prefabricated houses at Arbourthorne has already been given. Another typical example of serious damage to a normal dwelling house on an exposed site was that of a semi-detached house in Heavy Gate Road, Walkley (see Plate III and contour map in Figure 6). This case is of particular interest in that not only was the site in general exposed but there is reason to believe that local funnelling of the wind occurred between houses just upwind. In addition, the damage shown in the photograph occurred on the lee side of the house. The wind swept down the Loxley valley, increased owing to funnelling, crossed the Rivelin valley and impinged upon the ridge opposite. Heavy Gate Road, situated almost on the summit of this ridge, would therefore receive the full force of these concentrated winds. The first fracture of the building occurred at the leeward corner junction of roof and side and leeward walls and spread along the roof towards the gable end and down the side wall. As it spread, increasing pressure from inside would have assisted the suction effect from outside, larger portions breaking away (including the upper window frame) until eventually the whole of the upper wall from gable end to ground floor ceiling level had been removed.

Time sequence of damage.—Little or no damage occurred before 0300 GMT whilst between 0300 and 0500 only minor incidents were reported and these were mainly on the outskirts of the city. Most of the serious damage occurred between 0500 and 0730 with a peak around 0700. From 0730 onwards damage continued but the worst was over, although properties, structures and trees rendered unstable by the gale continued to fall throughout the morning.

Final analysis of damage.—The severity of the gale in the Sheffield area can be judged from the following final analysis of damage to dwellings:

(i) Number of buildings damaged beyond repair—98, including 69 prefabricated buildings.
(ii) Number of dwellings severely damaged with major repairs required—248.
(iii) Number of dwellings moderately damaged—34,200.
(iv) Number of dwellings with minor damage—66,954.
(v) Total number of dwellings damaged in one way or another—101,500.
(vi) Total number of dwellings in the area—161,000.

§4—TREE DAMAGE IN NORTH-EAST ENGLAND

The Forestry Commission, North-east England Conservancy, provided lists showing the damage by gales during February 1962 to wooded estates in Northumberland, Durham and each of the Yorkshire Ridings. The adopted classification of damage was deliberately simple, comprising nil (including slight in some cases), moderate, or severe, but no rigid definition was attempted for these terms. Any criterion based on percentage of trees fallen or broken would have been difficult to apply.

This schedule of damage was first transferred by plotting symbols on Ordnance Survey maps of the scale of four miles to the inch from which Figure 7 was prepared. It must be borne in mind that there are many woodlands, some of which are shown on the Ordnance Survey maps, which have not been included in this survey of damage, and that there are many areas devoid of trees which would have suffered severe damage had they in fact been wooded.

From Press reports and by interrogation of many on-the-spot observers it is known that each of the two gales (of 12 and 16 February 1962) contributed to the extensive damage but unfortunately observers were seldom able to apportion damage between the two gales, largely because these followed so quickly one upon the other. From Northumberland southwards to about the Leeds area the two gales seemed to be about equally damaging but from Barnsley to Sheffield and to the south of Sheffield there is no doubt that most damage was caused by the gale of Friday 16 February. (In the remainder of this section mention of 'gale damage', or 'gale' or 'gales' will imply reference to either or both of the gales of 11–12 and 16 February 1962 unless the gale is specified.)

Figure 7 shows that damage to woodlands occurred over very large areas in north-east England. There was much local variation in the amount of damage and in many places severe damage occurred in juxtaposition with no damage without there being any noteworthy differences of exposure, of tree species, or of root-holding characteristics. Nevertheless Figure 7 shows that the main area of severe tree damage lies in a narrow zone from near Sheffield, through Leeds, Harrogate and Ripon to Richmond, the zone probably ranging from about 8 to 15 miles in width over most of its length. Adjacent to and to the east of this zone of severe damage there is some evidence of a broken narrow zone in which damage was generally nil or slight, with a zone of more moderate damage further east. This pattern of damage supports to some extent the suggestion that standing waves probably developed to the lee of the Pennines (see Section 11); this would imply an alternation of zones of very strong winds with zones of relatively light winds, the zones being distorted because of the varying effects of topographical features.

Considerable tree damage occurred also over much of Durham and Northumberland, especially in the Tyne Gap and eastward of the Cheviot Hills. Much of the damage in the Tyne Gap was probably caused by channelling, the orientation of the Gap corresponding closely to the wind direction of each of the two gales. Figure 8 shows this area on a larger scale than Figure 7, using only the data obtained from the Forestry Commission, and offers a suggestion of alternation of zones of severe damage with zones of little or no damage.

As a matter of expediency it was impossible and indeed undesirable to visit or examine in detail all the places where severe damage had been reported. Instead a small number of estates were selected for study in as much detail as possible. The woodlands selected for these studies were:

(i) The Stang Plantation, Arkengarthdale,
(ii) The Washburn Afforestation, Blubberhouses, and
(iii) The Harewood Estate.

The positions of these are shown in Figure 7.

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PLATE I—STRIPPING OF OUTER WALL OF A CORNER HOUSE

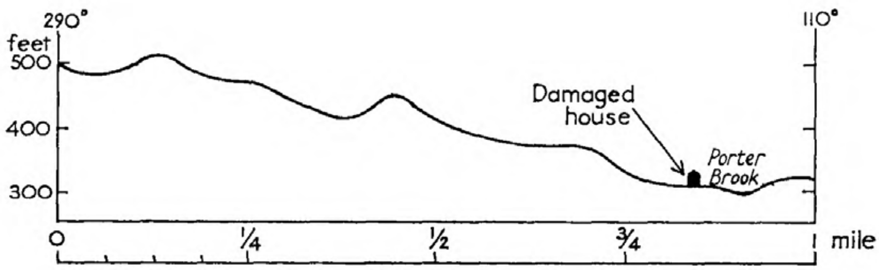

FIGURE 4 (*a*)—VERTICAL CROSS-SECTION ALONG GENERAL WIND DIRECTION (290 DEGREES) UPWIND OF DAMAGED HOUSE

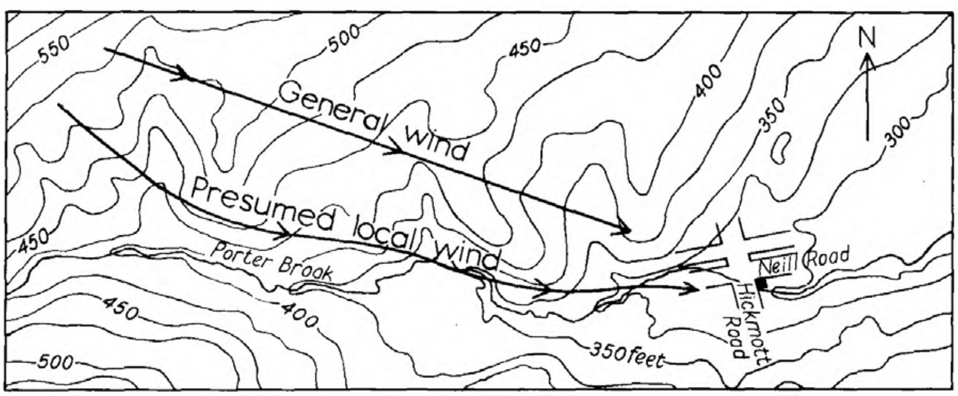

FIGURE 4 (*b*)—CONTOUR MAP (TO SAME SCALE) SHOWING PRESUMED LOCAL WIND FLOW

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PLATE II—DAMAGED PREFABS AT ARBOURTHORNE

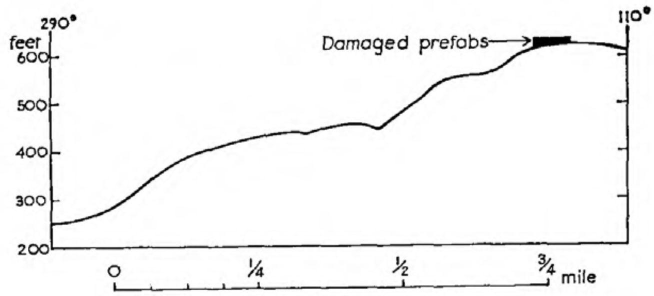

FIGURE 5 (*a*)—VERTICAL CROSS-SECTION ALONG GENERAL WIND DIRECTION (290 DEGREES) UPWIND OF ARBOURTHORNE PREFABS

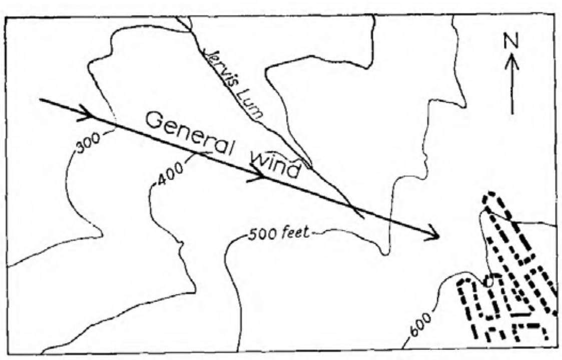

FIGURE 5 (*b*)—CONTOUR MAP (TO SAME SCALE) SHOWING AREA UPWIND OF ARBOURTHORNE PREFABS

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PLATE III—OPEN-EXPOSURE DAMAGE AT HEAVY GATE ROAD

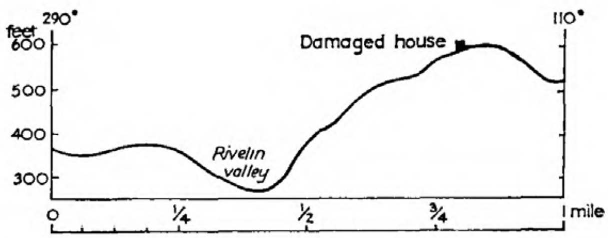

FIGURE 6 (*a*)—VERTICAL CROSS-SECTION ALONG GENERAL WIND DIRECTION (290 DEGREES) UPWIND OF HEAVY GATE ROAD

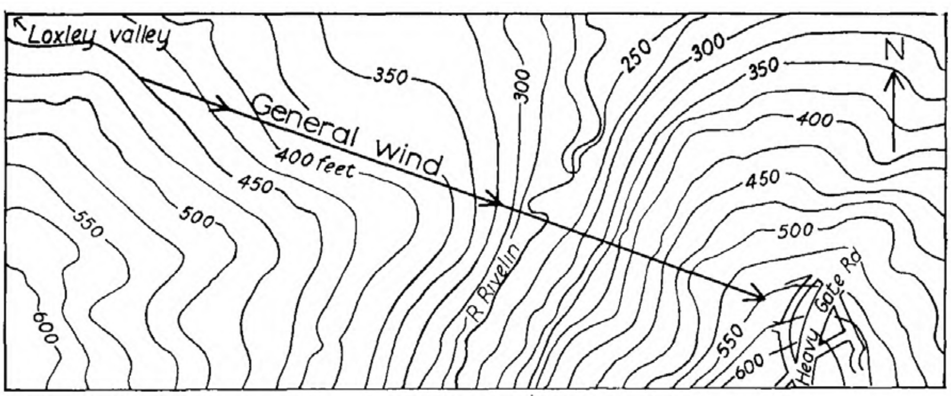

FIGURE 6 (*b*)—CONTOUR MAP SHOWING AREA UPWIND OF HEAVY GATE ROAD

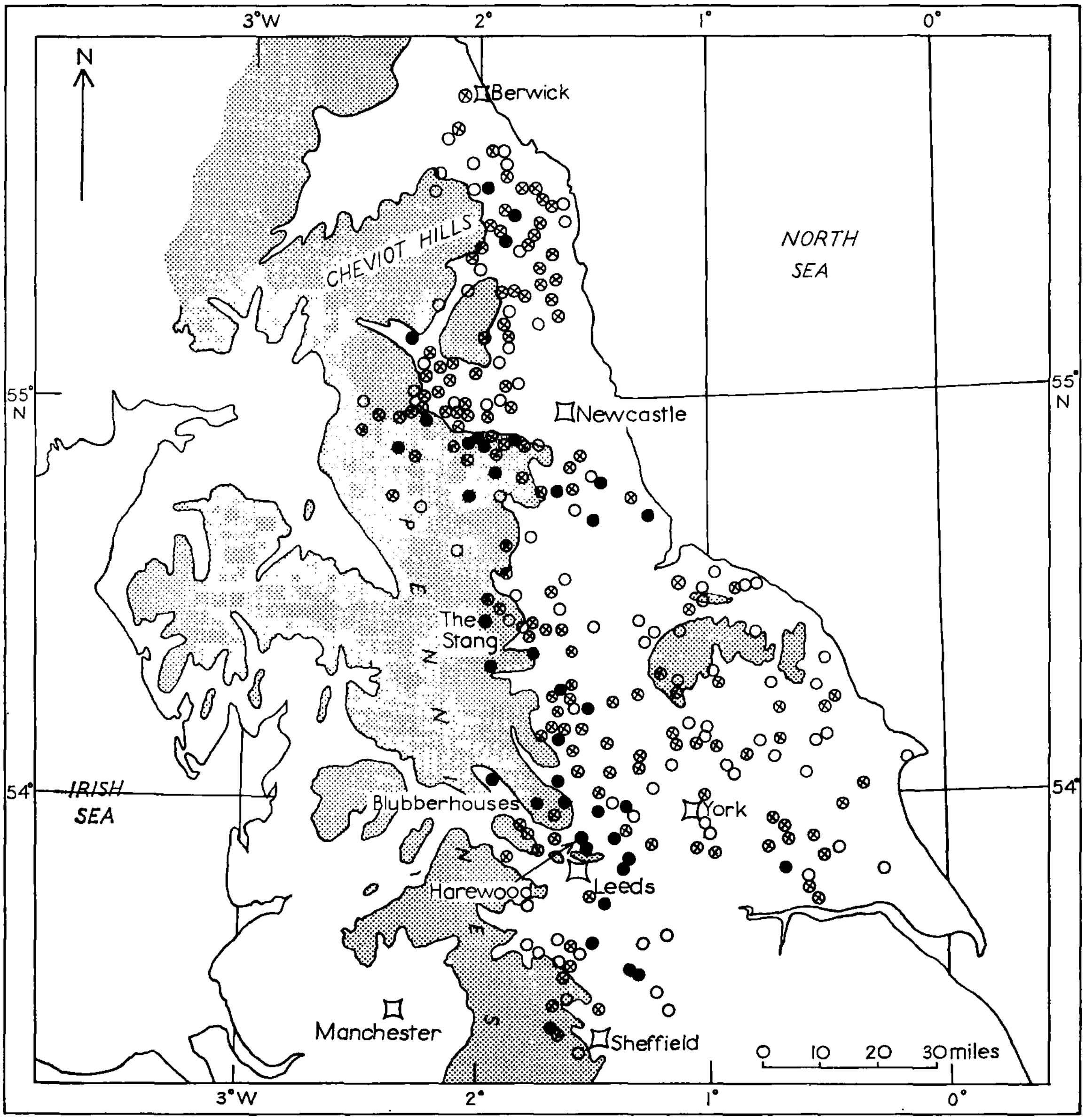

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FIGURE 7—TREE DAMAGE REPORTED BY FORESTRY COMMISSION, NORTH-EAST ENGLAND, IN FEBRUARY 1962
● severe ⊗ moderate O slight or nil Land over 200 metres (656 feet) above MSL is shaded.

Tree damage at the Stang Plantation, Arkengarthdale.—This plantation (see Figure 9) is just over two miles in east–west extent and one mile in north–south extent and slopes steadily down from about 1500 feet in the south and south-west to about 850 feet in the north-east. Land rises to over 1800 feet about one mile further to the south-west, but this higher ground is not afforested.

The main advantages of studying the effects of the gales in this plantation are that the trees are of one species (spruce), are of moderate age (mostly planted in 1934 or soon after) and are of moderate size (mostly 30–35 feet), that soil conditions are tolerably uniform over the area and that the forester was on the spot during both the gales. Spruce seldom has a tap-root, it is usually shallow rooted and top-heavy. The ground was very wet immediately prior to the gales and this of course made blowing down easier; in those places where most of the tree-fall started there was a thickish peat layer, sometimes amounting almost to a peat bog. Despite the wind being from the west, many trees fell towards the north-east, generally down the slope. The fringe trees

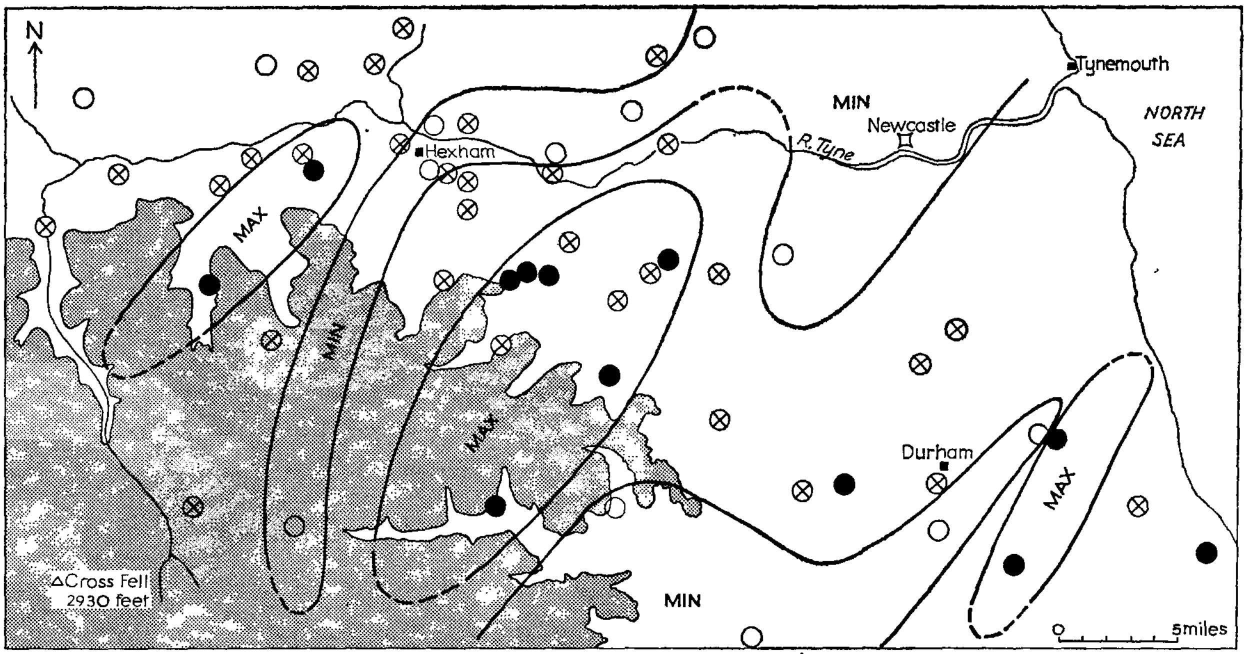

FIGURE 8—ENLARGED PORTION OF FIGURE 7 SHOWING TREE DAMAGE IN AND TO THE SOUTH OF THE TYNE VALLEY
● severe ⊗ moderate O slight or nil
Possible areas of maximum and minimum damage are outlined. Land over 1000 feet above MSL is shaded.

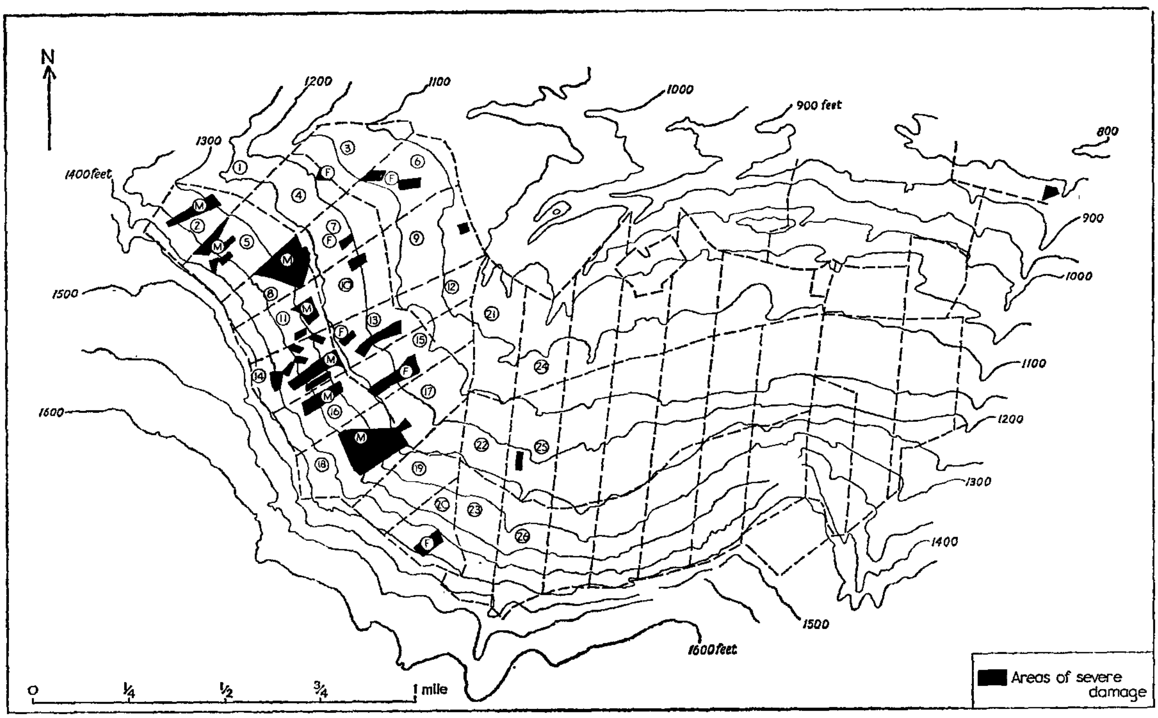

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FIGURE 9—TREE DAMAGE AT THE STANG PLANTATION, ARKENGARTHDALE, DUE TO THE GALES OF FEBRUARY 1962
– – – – rides separating compartments
M — damage done mainly by gale of Monday, 12 February
F — damage done mainly by gale of Friday, 16 February
Numbers in circles are those of compartments (omitted from the eastern half of the plantation since little or no damage occurred there, except for the small block of damage near the extreme north-east corner).

on the west and south-west boundary of compartments were well established; they usually stood firm but if they fell the inside trees had no protection.

Figure 9 shows the distribution of damage at the Stang marked simply as blocks where practically all trees were blown down. Minor damage is not indicated but compartments 3, 8, 11, 16, 17, 18 and 19 suffered serious scattered damage in addition to any block damage shown. The compartment boundaries have been shown chiefly in order to indicate the direction of the rides or cuttings.

The forester described the gale of Monday 12 February as "long and steady" while the gale of Friday 16 February was "very gusty". He said that the Friday gale gave him the impression of causing more damage *inside* compartments than the Monday gale, and that, in his 27 years experience on the plantation, these were the two worst gales. He thought the frequent strong winds in the previous autumn had paved the way for damage in February. In terms of trees brought down (not the total area affected), most damage was done on the 16th. One interesting feature was that the forester could smell burning during the height of Friday's gale—this was caused by trees rubbing one against another.

In compartment 14 it was particularly evident how damage by the wind had followed drains which had been cut down the slope and deepened after planting thus chopping the roots. The same feature was commonly seen in other compartments and explains the elongation of block damage (down the slope) in Figure 9. As is commonly observed in plantation, fringe trees were more sturdy and there were very few instances of such trees having fallen on the windward sides of compartments. On the western side of compartment 9, the sturdy well established fringe trees were not blown down whilst the trees immediately inside the compartment fell in directions ranging approximately from north-east to east-south-east. A small group of fringe trees was blown down, however, on the 'sheltered' side of compartment 2, three adjacent trees having fallen into the forest ride in directions of 90, 100 and 110 degrees. In compartment 8 about six acres were devastated by the gale on a better-drained site which was thinned before the blow, this thinning 'letting in the wind'. Compartment 18 suffered most and here the damage occurred on Monday 12 February, trees falling in very differing directions but the outer fringe was undamaged. Drains accounted for some damage.

Damage at the Stang Plantation was concentrated on the north-east facing slopes and this was noticeable in many other areas where severe or moderate tree damage occurred; the windward slopes often suffered less damage than the lee slopes.

It is unlikely that damage within any one block shown on Figure 9 occurred almost simultaneously as the result of a single gust of outstanding magnitude, and yet at the Stang as in many other places there were many swaths cut in the forest. Most likely, succeeding gusts added their quota of damage to that caused by the initial strong gust, gradually extending the swath downhill and downwind. The horizontal extent of the initial gust may perhaps be indicated roughly by the 'entry width' of the swath, although the damage of the two biggest blocks on Figure 9 (in compartments 8 and 18) may have been initiated by more than one particularly strong gust; ignoring these two blocks of damage the other swaths vary from about 25 to about 55 yards in entry width. Swaths about 50 yards wide were frequently seen in woods elsewhere.

The direction of a forest ride seems to exercise little or no control over the incidence of damage in its vicinity judging from the Stang, but the existence of a ride does seem to serve a useful purpose in helping to confine or limit block damage. For example, the damage in compartment 8 did not spread into compartment 7, and the damage in compartment 14 was not continued across the ride into compartment 13. These effects are due, perhaps partly perhaps largely, to the extra stability of fringe trees, and suggest the desirability of small compartments. Eight of the blocks of damage were over 200 yards long and three or four of these might have been longer had they not been stopped at a forest ride cutting roughly normal to the wind direction. Direction of tree-fall within each of the blocks varied considerably. As with damage examined elsewhere it proved impracticable to make many measurements at the Stang but it appeared that the majority of the fallen trees were affected by the direction of slope and fell towards the north-east.

Damage to Leeds Waterworks Afforestation Area near Blubberhouses.—On the Washburn Afforestation it was estimated that some 153 acres were so badly damaged that they would have to be clear-felled and replanted. Over the remainder of the area the number of trees severely damaged per acre varied from 30 to 120 although the younger plantations (up to about 30 years old) suffered very little. The official estimate was that roughly 62,000 trees were damaged, the volume being about 265,000 cubic feet; this includes trees which, although still standing, would be exposed after the others had been taken down and would most likely be blown down by the first high winds. Many of the trees were broken at various heights from ground level and much of the timber was thus shattered.

The most spectacular damage, amounting to the complete devastation over an area of 72 acres, was at Swinsty Moor (National Grid Reference 44 190535), where over 25,000 trees (151,000 cubic feet of timber) were blown down; these trees were about 56 years old and consisted of pines, larch and spruce. The site is in the lee of higher ground to the west which is thickly afforested and did not suffer very badly from the gale. An interesting additional feature is the existence of Round Hill, height 1341 feet, about 4 miles due west, which may have led to the intensification of wind strength in the Blubberhouses area. The profile of Round Hill, which has a smooth summit, may have been responsible for localizing the maximum wind speeds at Swinsty Moor, but further studies are necessary to ascertain if this was so.

At Ridge Bottom, a plantation of sitka spruce (shallower rooted than Scots pine), only about 75 trees were blown down on 12 February but about 21 acres were lost on the 16th. These spruce were planted in 1926–27 and had attained a height of 40 to 45 feet. Nearby, on roughly level ground with similar exposure, a stand of Japanese larch were scarcely damaged whilst another stand of spruce suffered almost complete destruction.

Tree damage on the Harewood Estate.—This estate, owned by the Earl of Harewood, lies midway between Leeds and Harrogate (see Figure 10). The main blocks of woodland lie to the south of the River Wharfe on undulating ground rising from the river valley and are mostly at 100 to 300 feet above sea level. The general slope of the ground is thus mostly down to the north, but considerable variations occur. It is however, important to note that Wharfedale lies west–east in this area for some 10 miles in the lee of Ilkley Moor (highest point 1321 feet above sea level) and that upper Wharfedale, lying approximately north-west to south-east communicates with the Skipton gap through the Pennines. It can therefore be expected that channelling of the winds down Wharfedale will cause westerly gales to be intensified and that the Harewood Estate might thus be subject to particularly strong winds. The soil on the estate is sandy loam on limestone hills.

The landscape woodland was planned in 1772. The belts of hardwood consist in the main of beech, oak and sycamore, much of it retained well past maturity because of its amenity value. The gale of 2 March 1956 blew down some 10,000 trees on the Harewood Estate in eight hours, including some 300–400 of the original beech on or near the skyline. Most of this damage was made good by planting in groups in the open spaces after wind-blown trees had been removed.

It is estimated that about 10,000 trees fell on the Harewood Estate as a result of the gale of 11–12 February 1962 and a similar number fell (or were badly damaged) in the gale of 16 February 1962, giving a total of about 217,000 cubic feet of timber affected. Figure 10 indicates the distribution of the damage to the trees.

About 85 per cent of the trees in the Grove, which is to the north of Harewood House, were blown down by the gales of February 1962. These trees had been retained for amenity value; many of them were about 200 years old with specimen trees planted at later dates. The Grove is at or near the top of an exposed west- or north-west-facing slope. About 150 feet down the slope to the west are shelter belts of lime, beech etc. (height about 60 feet) planted from 1933 onwards and these suffered little or no damage, although very exposed to westerly winds.

To the east of the Grove on the south side of Church Lane is a narrow belt of original 200-years-old timber of great amenity value which did not suffer extensively. Further north-east, Castle Plantation which contains much naturally regenerated sycamore suffered about 85 per cent damage (17 acres being virtually destroyed), while North Park containing some hardwood, but mainly conifer, lower down the slope to the north, escaped almost unscathed. It seems that the moderate damage in the narrow belt to the north of Church Lane and the extensive damage in Castle Plantation are attributable to the open exposure at the top of the north-facing slope.

Southward of Castle Plantation and skirting the main Harrogate–Leeds road (A 61) is Wall Side Plantation. Here severe damage occurred to some original hardwoods 200 years old and to uneven-aged, naturally regenerated hardwoods; many of the beech were long past their prime. Further severe damage occurred near the wall just on the lee side of a ridge rising to over 300 feet (east of Eller Fields) where the trees were originally 200-years-old beech with some Spanish chestnut and sycamore.

The Sugar Hills Plantation had suffered very badly from the gale of March 1956 and a large part suffered about 95 per cent damage from the gales of February 1962. This area is near the top of the north-facing ridge and quite exposed.

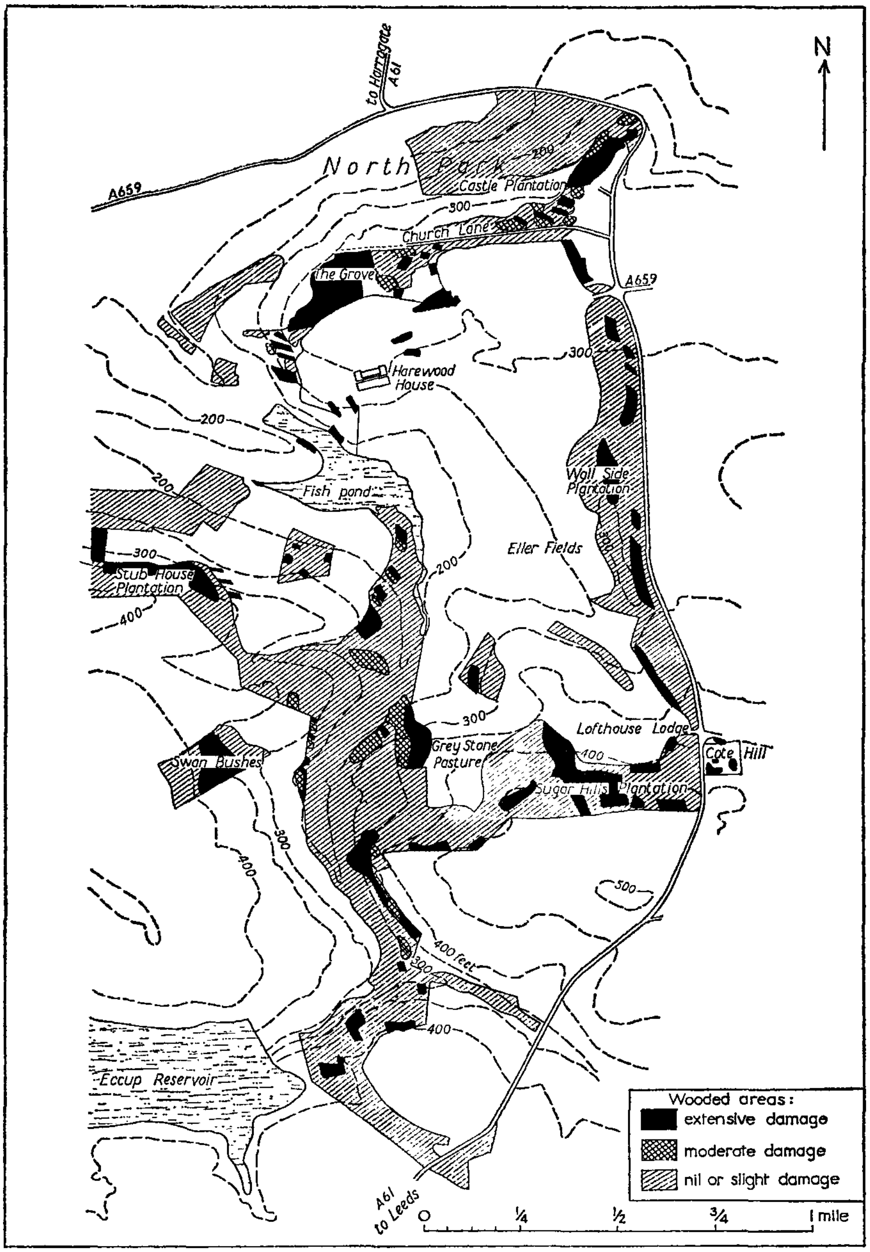

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FIGURE 10—TREE DAMAGE AT THE HAREWOOD ESTATE DUE TO THE GALES OF FEBRUARY 1962

Immediately west of Grey Stone Pasture the compartment lost about 95 per cent of its trees, although on the lee side of this particular woodland, one must regard the compartment as being exposed by virtue of its greater elevation. The central part of this wood, which suffered moderate damage, was planted in 1895 and consisted mostly of larch, spruce and pine, with heights often 65 to 80 feet. Further to the west the middle portion of Swan Bushes sustained total destruction. This block of severe damage occurred on a sheltered north-east-facing slope.

Further north at Stub House Plantation the 100 per cent damage was attributed by foresters to the thinning which had previously been carried out. The trees were sycamore, oak and beech, many of the latter being over 80 and some over 150 years old. As on Castle Plantation, exposure here was fairly open and some channelling of the wind probably occurred but it is noteworthy that damage was intensified on the upper part of the north-facing slope.

To face p. 15

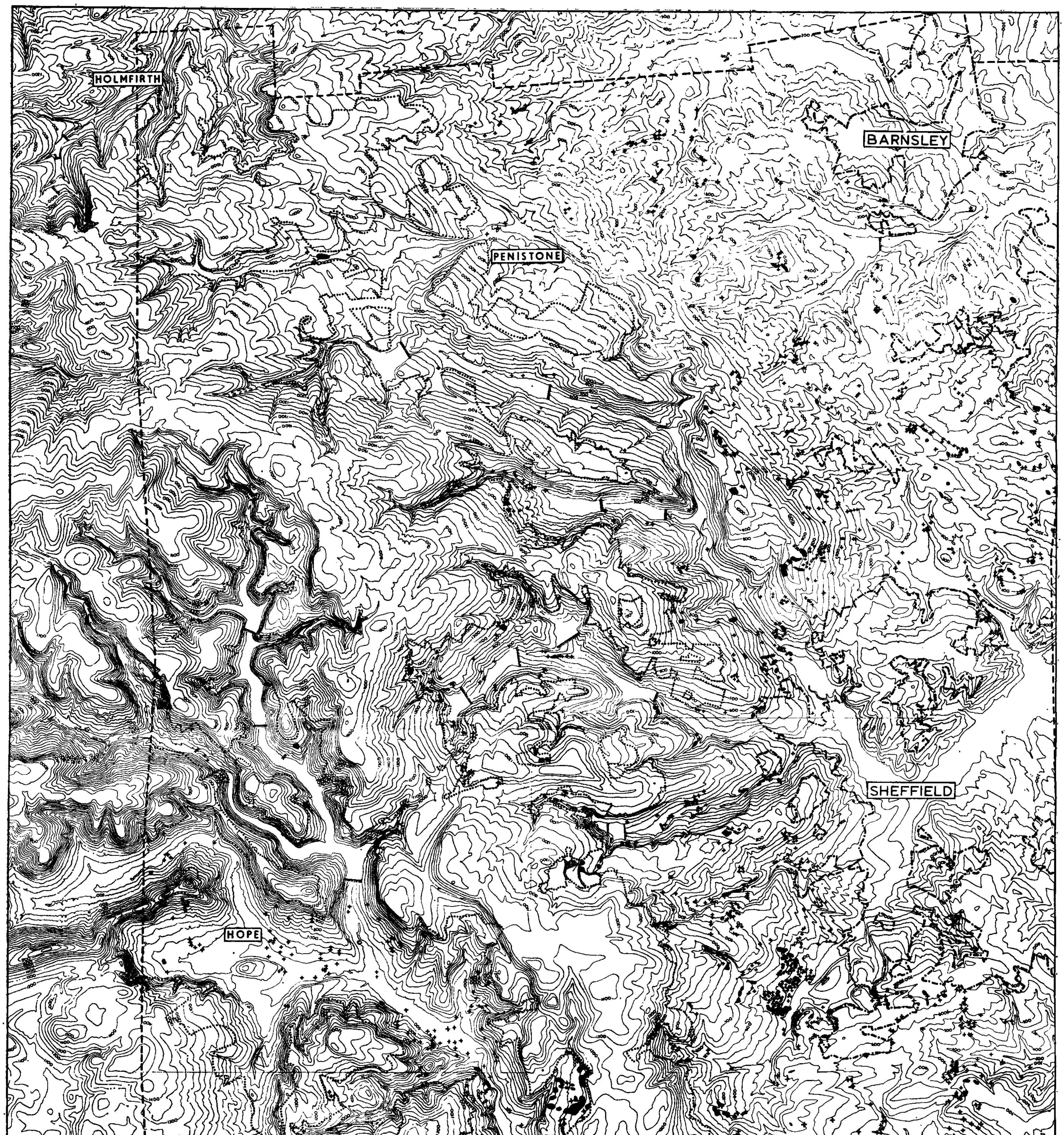


FIGURE 11—DISTRIBUTION OF TREE-FALL ASSESSED FROM AERIAL PHOTOGRAPHS TAKEN AFTER THE GALES OF FEBRUARY 1962

0 1 2 3 4 miles

reservoir dams
+ single tree-fall
areas of concentrated tree-fall
---- boundaries of photographical coverage
········ boundaries of treeless areas (moorland, etc)
-·-·-·- boundaries of urban areas (built-up, etc)

It will be seen from the above account that the damage at Harewood largely occurred in the more exposed areas near the tops of the hills particularly on north- or west-facing slopes. There is little doubt that the severe damage was aggravated by local channelling of the westerly gales down Wharfedale. Variability of damage on the estate was due largely to age, species, condition of trees and to forestry management, but local topography appears to have played an important part.

Aerial survey of tree-fall around Sheffield

Soon after the gale an attempt was made to obtain an aerial photographic survey of tree-fall in the district around Sheffield. It was felt that such a survey would be useful as a basic record and of interest and value to foresters and meteorologists. Accordingly photographic aircraft of the Royal Air Force made a number of attempts to photograph the area on a fairly large scale, but unfortunately unfavourable meteorological conditions, atmospheric pollution and other difficulties delayed the procurement of a complete and satisfactory stereoscopic cover until 15 March 1962. This cover was on a scale of 1:10,000 and was for an area of approximately 350 square miles extending from Barnsley and Holmfirth in the north to Chesterfield and Baslow in the south and from Tideswell and Castleton in the west to Handsworth and Wentworth in the east.

These photographs were stereoscopically examined at the Department of Geography of Sheffield University by Mr. G. M. Lewis of that department for evidence of fallen trees. In the ideal case of a large isolated example the photographic evidence was obvious. Smaller examples were more difficult to recognize. Such items as the cavity left by the uprooting, the on-edge root disk, the compression of the leafless crown, and the absence of a long shadow, were utilized to aid recognition. Fallen trees within closed-canopy woods were the most difficult to recognize except in those cases where a high proportion of the trees were down. The problem was greatest in coniferous plantations. It is estimated that over 95 per cent of the large isolated fallen trees were recognized and marked. For smaller isolated examples the proportion was probably 80 per cent and for individual trees in deciduous woods 60 per cent. For individual trees in coniferous plantations the percentage detected was probably far less. Areas of concentrated damage were of course easy to recognize and were outlined on the prints.

In addition, whenever the image of the fallen trunk was long and clear the direction of fall was measured in degrees from Grid North within estimated limits of error of $\pm$ 5 degrees. In areas of concentrated damage, selected trees were utilized and the angles recorded in a more or less random fashion around the perimeter of the devastated area.

The information derived in this manner was transferred in the first place on to Ordnance Survey 1:25,000-scale maps. In addition, the photographs were used to delimit approximately both rural and urban treeless areas. As the pattern of tree damage was diffused at this scale, a further plot of the positions of the fallen trees, without the direction of fall, was made on a background of ground contours at 50-foot vertical intervals on the scale 1:63,360, and this on a further reduced scale is reproduced as Figure 11.

Inspection of the tree-fall map shows that some tree-fall occurred in almost all areas where there were trees, and indicates that this area must have been subjected to a gale of quite unusual severity to cause such a concentration of tree-fall. It would appear that the area most affected lay in a belt north–south from about midway between Penistone and Barnsley to just east of Chesterfield, but this may be somewhat of an illusion because of the high proportion of coniferous plantations in the reservoir-filled valleys further west and because of the treeless areas on the highest ground.

An east–west belt of maximum damage can also be identified trending across country in roughly the latitude, and immediately to the south, of Sheffield and extending some distance west into north Derbyshire. Northward of this east–west zone there is evidence of conspicuously waning severity of tree damage, particularly on reaching the area between Holmfirth and Barnsley.

Viewed in detail, the map seems to supply interesting and widespread evidence not only of the high incidence of concentrated areas of heavy tree damage on leeward- (eastward-) facing rather than on windward-facing slopes, but also of the significance of narrow 'leeslope' valleys and valley heads, acting as funnels over the crest of the high land of the east-facing Pennine slopes, and again, within which tree damage was concentrated.

A detailed joint investigation area by area of the map evidence will be undertaken in the field with reference to the local meteorological, topographical, and ecological factors involved, and a fuller and more comprehensive interpretation of the map now awaits the completion of this further field work. When completed it will be published elsewhere or made available through the Department of Geography at Sheffield University.

§5—SYNOPTIC DEVELOPMENT

The gale of 16 February 1962 was caused by the strong pressure gradient between a depression moving from Iceland to the Baltic and an almost stationary anticyclone over the eastern North Atlantic. At midday on the 13th the anticyclone was centred at 45°N 25°W with a central pressure of 1045 millibars. For the next 36 hours the anticyclone was stationary, and then it began to extend eastwards until by midday on the 16th, whilst the centre was still at 45°N 25°W, an elongation existed towards and across northern Spain. At midday on the 13th a depression (central pressure 995 millibars) was situated between Labrador and southern Greenland. In the next 24 hours this depression deepened and moved northwards along the west coast of Greenland. The associated warm front which on the 13th lay eastwards approximately along the 58th parallel of latitude also moved northwards and during the 14th formed a wave depression between southern Greenland and Iceland. This depression deepened rapidly and moved steadily eastwards, reaching 67°N 5°W by midday on the 15th with a central pressure of 970 millibars. The warm front, which then lay to the south of this centre, moved across the British Isles from north-west to south-east during the day. The cold front extended in a south-westward direction from the centre to a wave south of Iceland and then further south-westwards. By 0000 GMT on the 16th the main centre was becoming complex (lowest pressure 954 millibars) and, moving east-south-east, was approaching the Norwegian coast. The wave on the cold front had run rapidly east-north-east along the front and was also approaching the Norwegian coast at about 63°N. The cold front at that time lay to the south-west and was only a few miles north-west of the Shetlands and Lewis. Thence it stretched west-south-westwards to the Atlantic. The cold front moved south-eastwards into Scotland at an average speed of 50 knots. The mean geostrophic wind at that time was 290 degrees 85 knots before the front and 300 degrees 80 knots behind the front; the component at right angles to the front was 70 knots.

By 0600 GMT (Figure 12) the depression with three separate centres was moving into Norway and a markedly strong pressure gradient extended from Kråkenes (position 62°02′N 4°59′E) with a pressure of 958 millibars, to the 1035-millibar isobar some 100 nautical miles south-west of the Scillies. The mean pressure gradient between these two points was 11·7 nautical miles per millibar (0·085 millibars per nautical mile) corresponding to a mean geostrophic wind over the 900 nautical miles of 60 knots. However, the average geostrophic wind at this time across Yorkshire and Lancashire was 70 knots and this increased to a maximum of 80 knots about 0900 GMT. The distribution of the pressure gradient across these two counties, however, was by no means regular, and hourly synoptic charts on a scale of 1 in 2 million showed from about 0300 GMT the formation of a lee trough in the West Riding, Nottinghamshire and Derbyshire. This trough intensified to the south-east of the Peak District until about 0900 GMT. As a result, the mean geostrophic wind in the industrial West Riding rose to about 100 knots. The direction of the isobars in this locality showed a considerable veer becoming almost northerly over the Peak District and for a short distance to the south-east, but the surface wind direction remained west to west-north-west and the airflow must therefore have been unbalanced. This local modification to the airflow persisted until about 1300 GMT. The formation of lee troughs is discussed in greater detail in Section 8 of this Memoir.

The cold front had moved southwards across Scotland and into northern England at an average speed of about 50 knots. At first, the frontal passage was fairly clearly marked by the change in both the weather and the barometric trace but by 0400 GMT these characteristics were becoming diffuse. The halt in the fall of pressure appeared to move ahead over England at a greater speed than the frontal weather change and could just about be traced into south-eastern England by 0800 GMT. The frontal weather on the other hand appeared to reach Yorkshire by 0600 GMT but could not be satisfactorily traced after that; it is likely that it passed through the Sheffield area towards 0700 GMT. A weak cold front could be placed in the Thames valley between 1100 and 1200 GMT and crossed the south-east coast of England about 1400 GMT. This could hardly have been the original cold front since if it had been the average speed of travel would only have been 30 knots, whereas the average component of the geostrophic wind at right angles to the front was 50 knots.

During the day of the 16th the centre of the main depression moved across Norway and central Sweden reaching the Swedish coast just north of Stockholm by 1800 GMT with a central pressure of 952 millibars. The anticyclone moved little during the day, the central pressure at 1800 GMT being 1044 millibars at about 46°N 20°W. The geostrophic wind over the West Riding gradually decreased until by 1800 GMT it was only 60 knots.

Reference has been made to the difficulty experienced in tracking the cold front across England, and vertical cross-sections were drawn from the available upper air data to elucidate this matter. No upper air data are

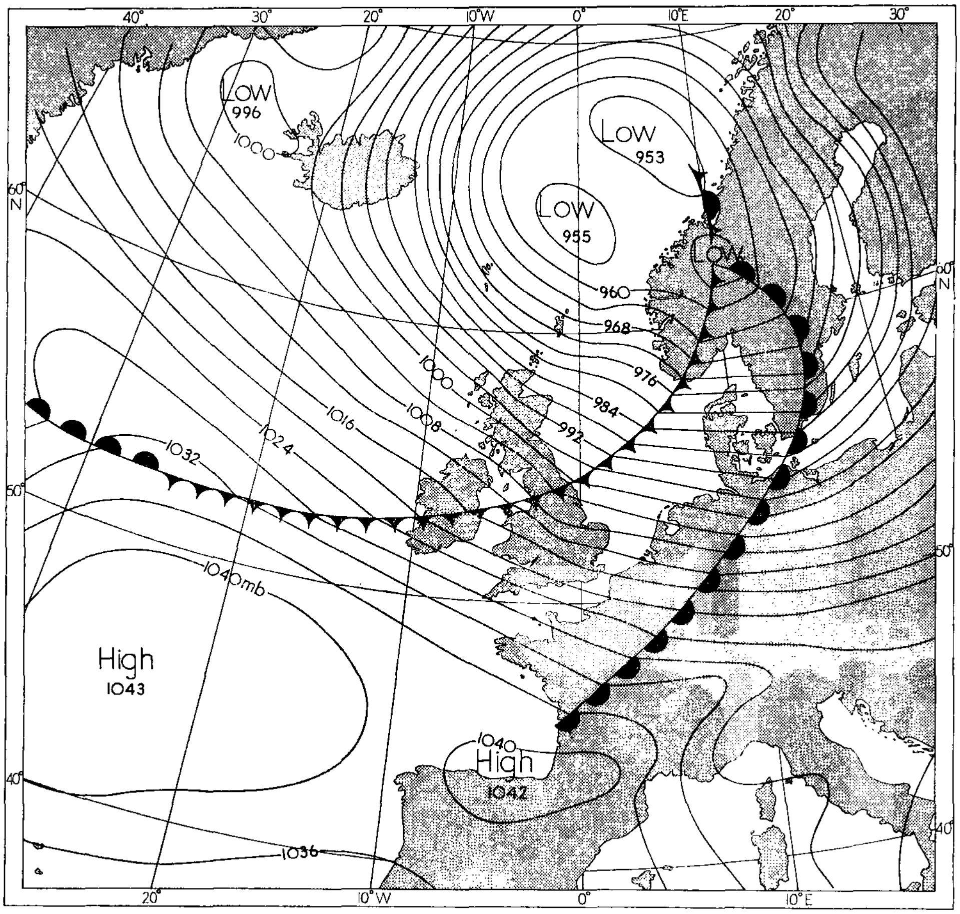


FIGURE 12—SURFACE SYNOPTIC CHART FOR 0600 GMT, 16 FEBRUARY 1962

available for the Sheffield area itself but radiosonde data are available from Aughton (near Liverpool) for 0000 and 1200 GMT, 16 February, and upper wind reports are also available for 0000, 0600 and 1200 GMT. The 0000 GMT tephigram is shown in Figure 13.

The vertical cross-section shown in Figure 14 is that for 0000 GMT on the 16th and lies fairly well along the direction of the wind flow and at an angle of about 65 degrees to the cold front. Figure 15 shows the cross-section for the same line at 1200 GMT. In each case the simplest construction of frontal and subsidence surfaces has been portrayed that will fit in with the facts having regard to continuity. It is seen from Figure 13 that at 0000 GMT there was an inversion over Lancashire of 4°C with base at 830 millibars and a shallow isothermal layer at about 520 millibars. Upwind at Aldergrove the inversion layer was at 850 millibars but from 920 to 850 millibars there was a layer in which the lapse rate was small. Thus it is deduced that from 0000 GMT onwards the inversion height over Lancashire and probably over the Pennines would lower only slightly, though underneath there would have been a region in which the lapse rate decreased. At midnight the cold front was quite well marked over the sea as it approached Ireland and the average slope of the front was about 1:135 up to 700 millibars. The front appeared to be normal and extended to the surface. By 1200 GMT there was no sign of a cold front extending to the surface. If the cold front had been moving at geostrophic speed it would by then have been over northern France but there was no trace of it in such a position on the surface map and the cross-section shows only a region of stable air above 850 millibars whose base is slowly lifting. Above it is the warm-sector air; below is the air which shows only a gradual transition to the cold air of the post-frontal region. Between Crawley and Aughton there is evidence of a weak frontal structure between about 900 and 700 millibars and it is presumably this structure which extended to the surface and was marked as a

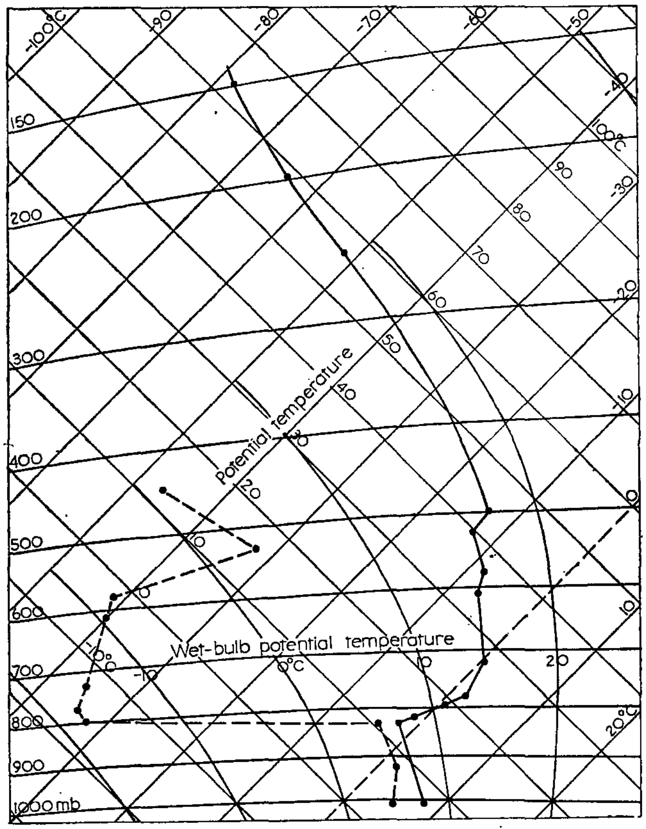


FIGURE 13—AUGHTON TEPHIGRAM FOR 0000 GMT, 16 FEBRUARY 1962
•——• dry-bulb temperature •- - -• dew-point temperature

cold front in later surface analyses. It thus appears that during the interval between 0000 and 1200 GMT the portion of the cold front below 850 millibars frontolysed. The mechanism by which this occurred is obscure. However, as will be seen later, the severity of the gales at Sheffield is thought to be partly due to the lee-wave effect and the persistence of the marked inversion at a relatively low height is therefore of interest. Had the cold front been a normal one the inversion would have risen fairly sharply after the cold-front passage and the period of severity of the storm at Sheffield would have been considerably lessened.

Examination of the wind field at upper levels brought to light some unusual conditions. Figures 16 and 17 are vertical cross-sections of the atmosphere some miles upwind of the West Riding. At 0000 GMT (Figure 16) there was a main jet core of about 150 knots in the region 300–350 millibars a little to the south-west of Lerwick. This core moved southwards to a position approximately over Shanwell at 1200 GMT (Figure 17). The distribution of shear around the core is by no means the regular sharp phenomenon so often described. Above this main core was another jet core of about 130 knots at about 180 millibars. This also moved southwards keeping its position relative to the main jet. In addition to these two cores there was a third jet of about 100 knots at about 650 millibars in the region of Shanwell at 0000 GMT which by midday had moved south-westwards to lie over Aldergrove at about 700 millibars. It was this third core which was in closest association with the gales in the north of England. It is noteworthy that the direction of wind at all levels was remarkably constant. This latter point is also brought out well in Figure 18 which shows a time-section of the Aughton winds. This shows the variation of wind with respect to time in the air to the west of the Sheffield area before its passage over the Pennines. The intensification of the wind in the lowest levels between midnight and 0600 GMT on the 16th is noticeable. This was presumably associated with the proximity of the lowest of the three jet cores and is due to the horizontal temperature gradient across the cold-front surface existing at medium levels.

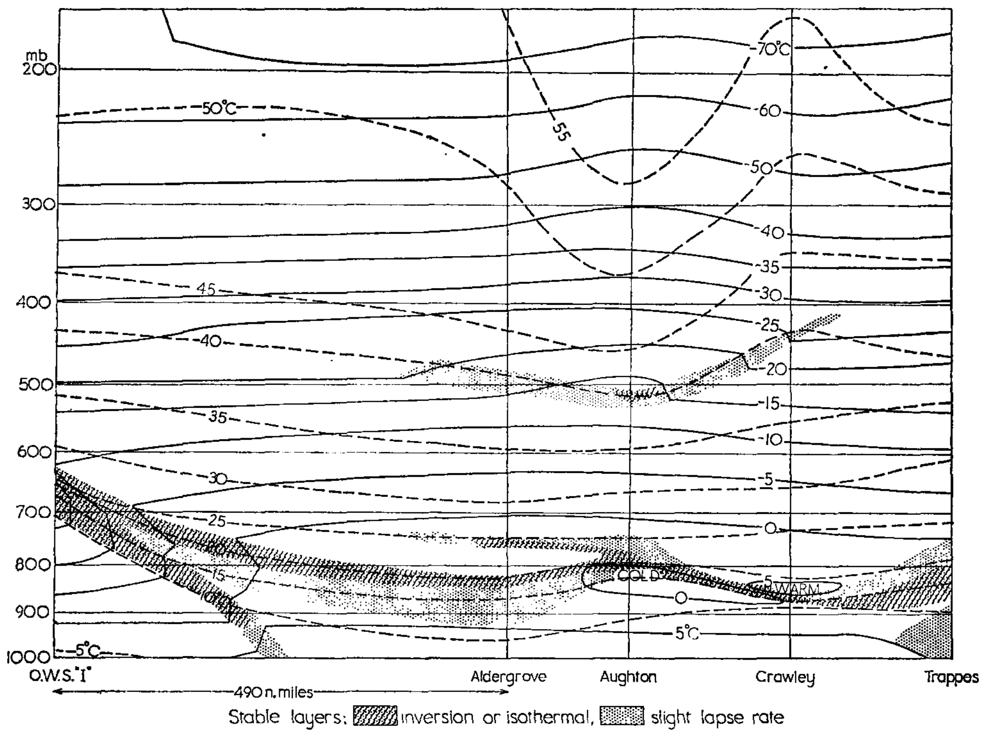


FIGURE 14—CROSS-SECTION OF TEMPERATURE AND POTENTIAL TEMPERATURE FOR 0000 GMT, 16 FEBRUARY 1962
Full lines are temperature isopleths, broken lines are potential temperature isopleths.
Mean bearing of cross-section 310°.

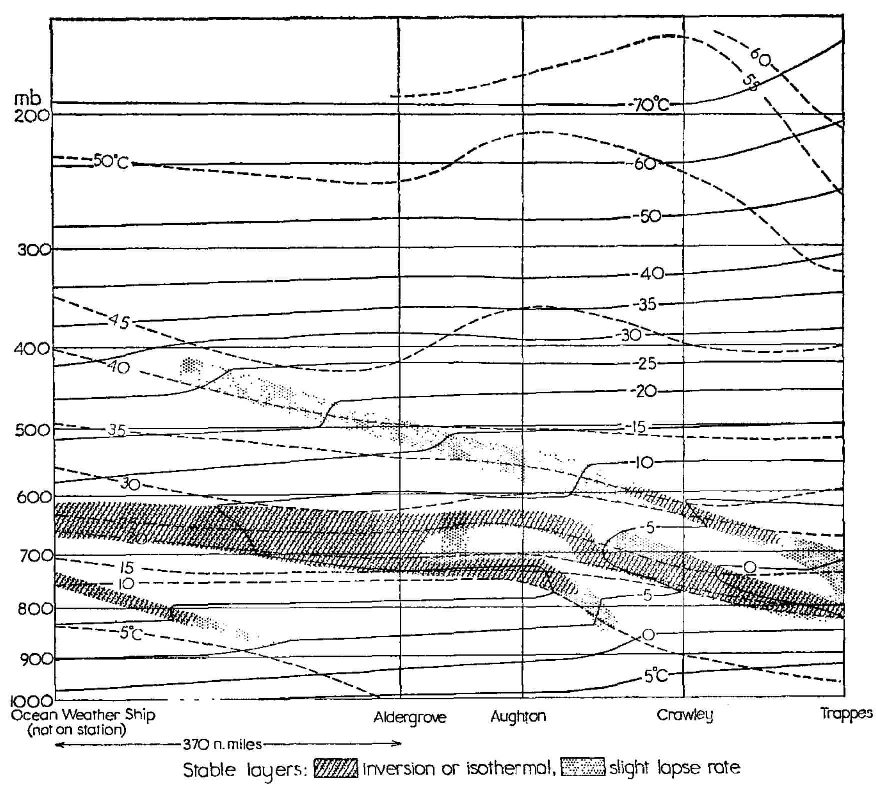


FIGURE 15—CROSS-SECTION OF TEMPERATURE AND POTENTIAL TEMPERATURE FOR 1200 GMT, 16 FEBRUARY 1962
Full lines are temperature isopleths, broken lines are potential temperature isopleths.
Mean bearing of cross-section 310°.

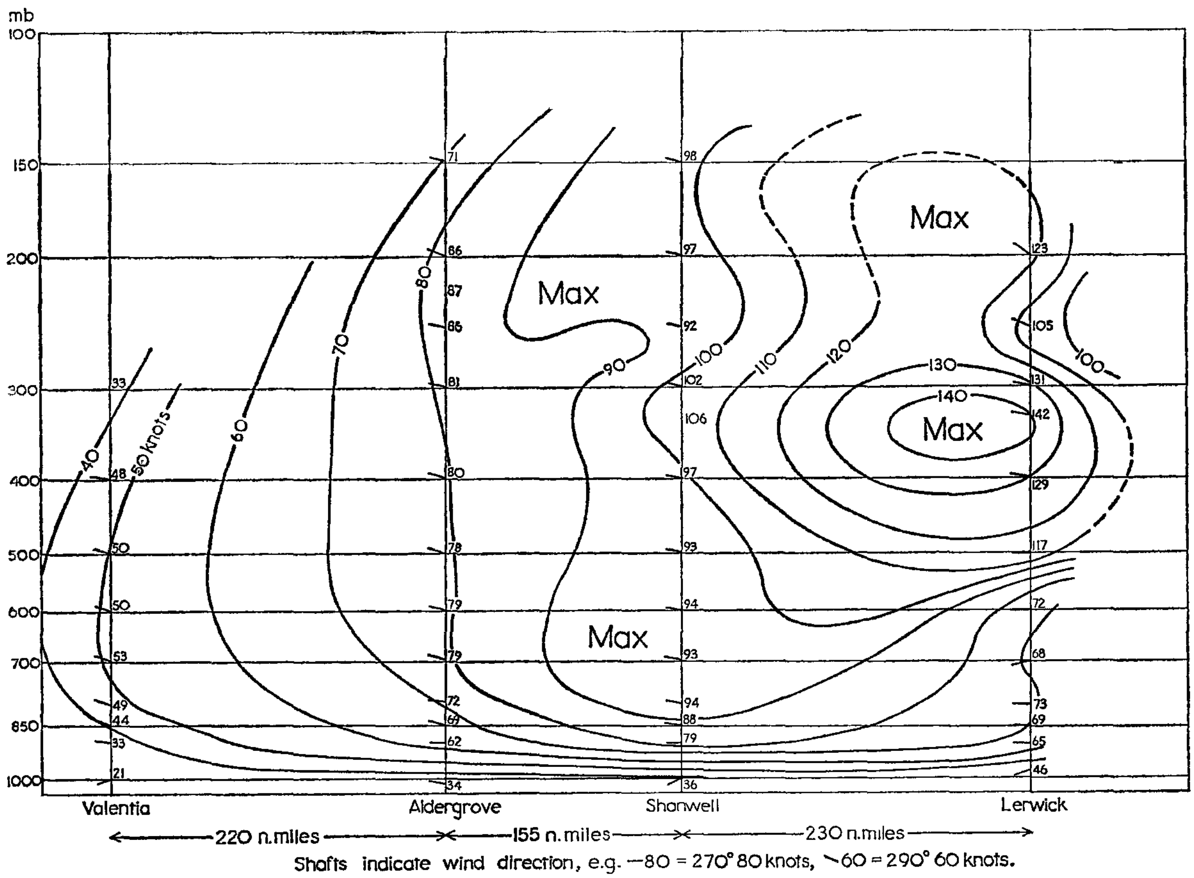


FIGURE 16—UPWIND CROSS-SECTION AT 0000 GMT, 16 FEBRUARY 1962
Approximate bearings of cross-section: Valentia to Shanwell 045°, Shanwell to Lerwick 012°.

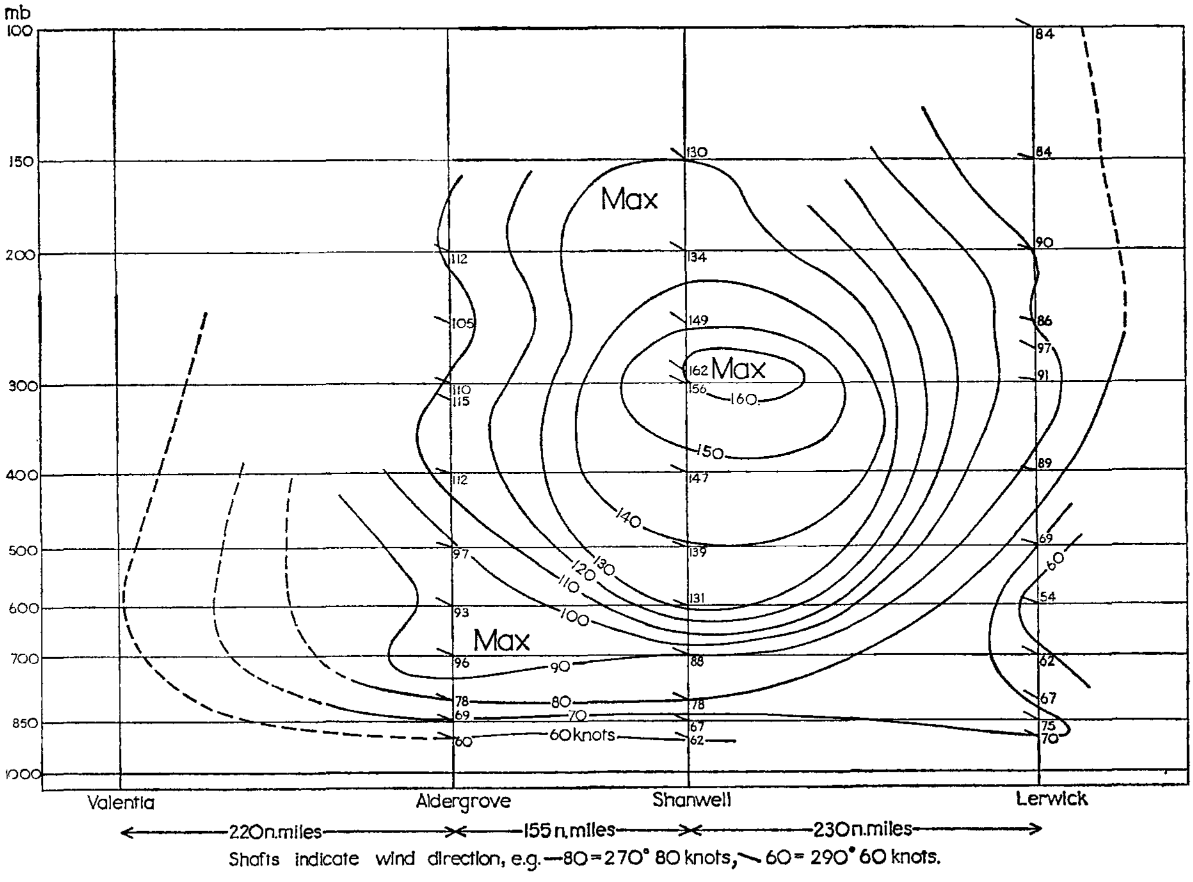


FIGURE 17—UPWIND CROSS-SECTION AT 0600 GMT, 16 FEBRUARY 1962
Approximate bearings of cross-section: Valentia to Shanwell 045°, Shanwell to Lerwick 012°.

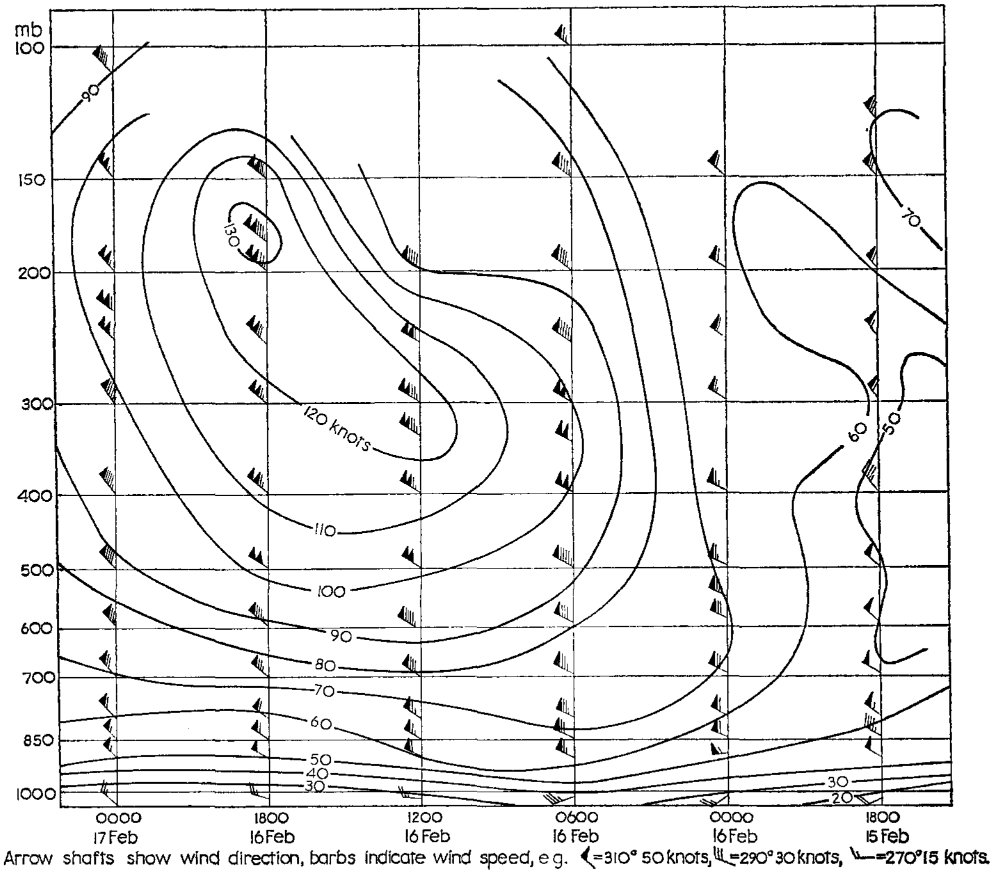


FIGURE 18—UPPER WINDS AT AUGHTON, 15–17 FEBRUARY 1962

§6—PREVIOUS GALE OF 12 FEBRUARY 1962

As has been stated the gale of 16 February 1962 was preceded by another gale during the night of 11–12 February 1962, and the synoptic situation was very similar in the two gales.

On the earlier occasion a depression had moved rapidly across the North Atlantic passing just south of Iceland and reached Stockholm by 1200 GMT on the 12th with a central pressure of 950 millibars whilst an anticyclone of 1046 millibars was centred at 45°N 25°W. The depression thus passed north of Scotland about 4 degrees latitude further south than in the case of the depression of the 16th. The relative movement of the associated cold front across the eastern Atlantic and Scotland was very similar to that of the 16th. In fact the surface charts for 0600 GMT on 12 February and 0300 GMT on 16 February are remarkably alike. On 12 February the mean geostrophic wind in northern England was 290 degrees 80 knots before the front and 300 degrees 60 knots behind the front with a component at right angles to the front of 40 knots, but the component was decreasing especially over the Irish Sea and Ireland. In this case the cold front could be followed on the surface chart fairly clearly though again it slowed up south of Durham rather more than would be expected from the geostrophic component across the front. Before the arrival of the cold front in northern England a marked lee trough developed east of the Pennines and extended from St Abb's Head to the Midlands (see Figure 25 and further discussion in Section 8). This trough was more marked in the northern counties than on the 16th (this may be partly because the upwind gradient wind direction was 280 degrees on this occasion compared with 290 to 300 degrees on the 16th). Although this lee trough did extend southwards to Derby, at no time was the southern portion distinct and prominent as on the 16th, and it disappeared with the passage of the cold front.

The following is a brief summary of the wind records for 12 February, and it will be seen that this gale was much more uniform over the northern part of England than that of the 16th though it was of about the same strength.

South Shields.—The highest 10-minute average wind speed was about 40 knots and the highest gust 63 knots (at approximately midnight). The direction was 265 degrees.

Fylingdales Moor.—The highest 10-minute average wind speed was 66 knots and the highest gust was over 92 knots (at 0405 GMT). There were at least 50 gusts over 80 knots. The direction was about 275 degrees but the recording is indistinct.

Sheffield.—The highest average wind was about 35 knots and the maximum gust was 69 knots (at 0210 GMT). The direction was 265 degrees.

Manchester Airport.—The highest average wind was about 260 degrees 38 knots and the maximum gust was 55 knots. The period of strongest winds was from 0820 to 1130 GMT, i.e. around the time of the passage of the cold-front region and did not start in the early hours as happened east of the Pennines.

Manchester Weather Centre.—The highest recorded gust was 70 knots (at 0935 GMT).

Cranwell.—The wind reached 230 degrees 34 knots with gusts of 52 knots by 0200 GMT. The highest winds occurred about two hours after the passage of the cold front, i.e. at about 1300 GMT with a 10-minute average of 280 degrees 36 knots and a gust of 56 knots.

Finningley.—The wind increased to gale force around 0300 GMT but the strongest winds came at 0600 and 0900 GMT with a mean of 280 degrees 45 knots and gusts to 65 knots.

Birmingham Airport.—The highest gust was 61 knots (at 0520 GMT) when the 10-minute average wind was 265 degrees 38 knots. Apart from a lull between 0600 and 0700 GMT the wind continued to blow around gale force until about 1400 GMT.

Watnall.—Watnall showed no abnormally light winds on this occasion. The highest observed mean wind was 270 degrees 34 knots and the highest observed gust was 58 knots. The period of strongest winds was from 0500 to about 1400 GMT.

The following comparison (Table II) of upper wind measurements at Aughton is of interest as on both 12 and 16 February the 0600 GMT sounding showed stronger winds in the lower layers than at 0000 or 1200 GMT.

TABLE II—UPPER WINDS AT AUGHTON AT 0600 GMT, 12 AND 16 FEBRUARY 1962

	Height (*millibars*)							
	Surface	900	850	800	700	600	500	400
	Wind direction/speed (*degrees/knots*)							
12 Feb.	250/35	270/73	280/78	290/83	290/99	290/99	280/97	290/107
16 Feb	250/35	280/67	290/68	290/75	290/76	290/81	290/93	290/99

It is seen that the winds on the 12th were slightly higher than those on the 16th but showed a backing of 10 degrees in the lower layers, but it seems a little doubtful if this alone could account for the difference in position of the lee troughs on the two occasions.

However, inspection of the upper air ascents for Aughton shows a conspicuous difference between the two days. Instead of the very dry subsided air above a marked inversion as on the 16th, there was on the 12th moist air throughout the troposphere with only small inversions at intervals (see Figure 19). Thus in the warm air at 0000 GMT there was only a 1°C inversion from 908 to 890 millibars and a 1°C inversion from 690 to 665 millibars; otherwise the dry-bulb temperature fairly closely followed the wet adiabatics. The cold air was moderately moist too and had a lapse rate only slightly more stable than the wet adiabatic. It thus seems that the difference in the airflow in the lee of the Pennines and in the Sheffield area in particular on the two occasions must be associated with the slight difference in wind direction and the marked difference in the temperature profile of the air in the lower troposphere. This point is dealt with later (p. 42).

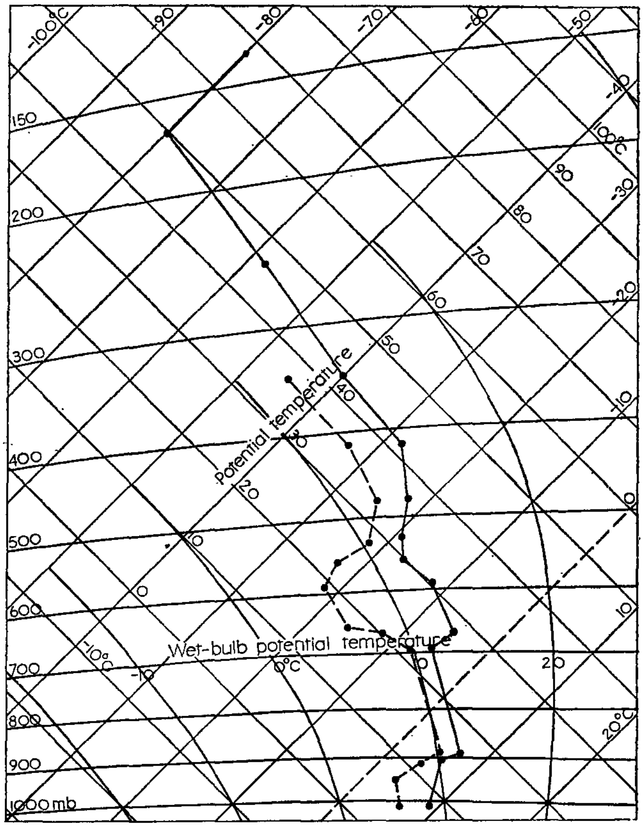


FIGURE 19—AUGHTON TEPHIGRAM FOR 0000 GMT, 12 FEBRUARY 1962
•——• dry-bulb temperature •- - -• dew-point temperature

§7—OTHER OCCASIONS OF STORM DAMAGE IN THE WEST RIDING

Fairly widespread and serious gale damage in the West Riding had also occurred on the following dates prior to February 1962:

1–2 March 1956 (between 1800 and 0600 GMT)

22 December 1894 (time of storm unknown).

On the first of these two occasions there were many features of the synoptic situation which were similar to the 1962 gales. During 1 and 2 March 1956 a deep depression moved rapidly from south Iceland to southern Sweden. At 0000 GMT on the 2nd it was situated near the Norwegian coast at about 62°N and the central pressure was 956 millibars. The associated cold front was through the English-Scottish border country and Northern Ireland and was moving south but decelerating. The anticyclone with a central pressure of 1041 millibars lay to the north-east of the Azores and had an eastern extension into the Bay of Biscay. The winds were again fairly constant in direction and increased upwards as may be seen from Table III.

TABLE III—UPPER WINDS AT LIVERPOOL AT 0200 GMT, 2 MARCH 1956

Height	Surface	900 m	850 mb	700 mb	600 mb	500 mb	400 mb
Wind direction/speed (*degrees/knots*)	260/27	280/63	290/68	300/86	290/97	290/104	290/104

The air mass was again stable with a well marked almost isothermal layer from 768 to 673 millibars (see Figure 20). At this time there was no anemometer at Sheffield but at the climatological station at Lindholme (seven miles east-north-east of Doncaster and some five miles north of Finningley) the observer, watching the dials

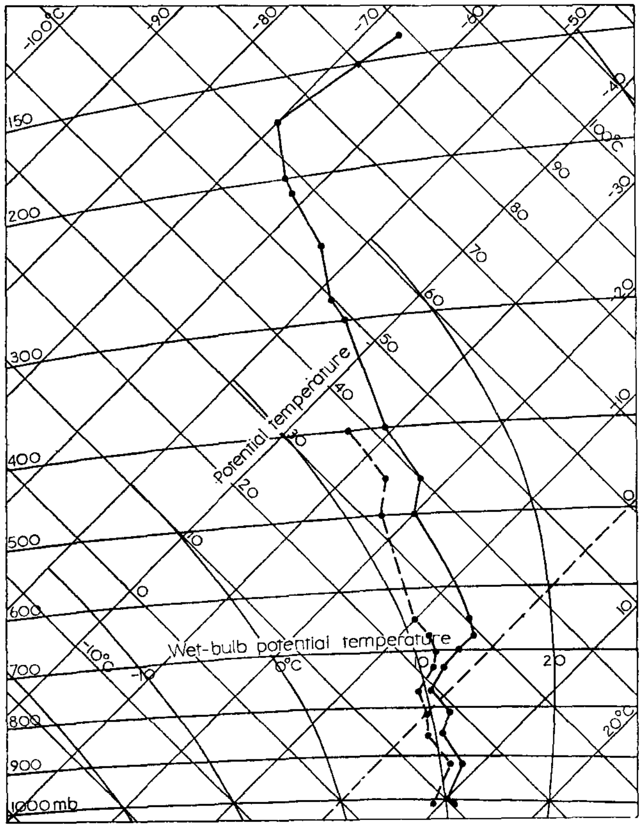


FIGURE 20—LIVERPOOL TEPHIGRAM FOR 0200 GMT, 2 MARCH 1956
•——• dry-bulb temperature •- - -• dew-point temperature

of a well exposed cup anemometer and wind vane, recorded a maximum mean wind of 280 degrees 45 knots at 0300 GMT. He also observed a maximum gust of 70 knots at 0217 GMT and noted down six gusts of over 60 knots between 2300 and 0500 GMT. The surface wind direction was 250 degrees before 0200 GMT and 270 to 280 degrees from 0200 GMT onwards. Examination of the routine hourly charts prepared at the Central Forecast Office showed that on this occasion too there was a distinct lee trough to the east of the Pennines and at 0400 GMT a meso-scale 'low' was between Nottingham and Sheffield.

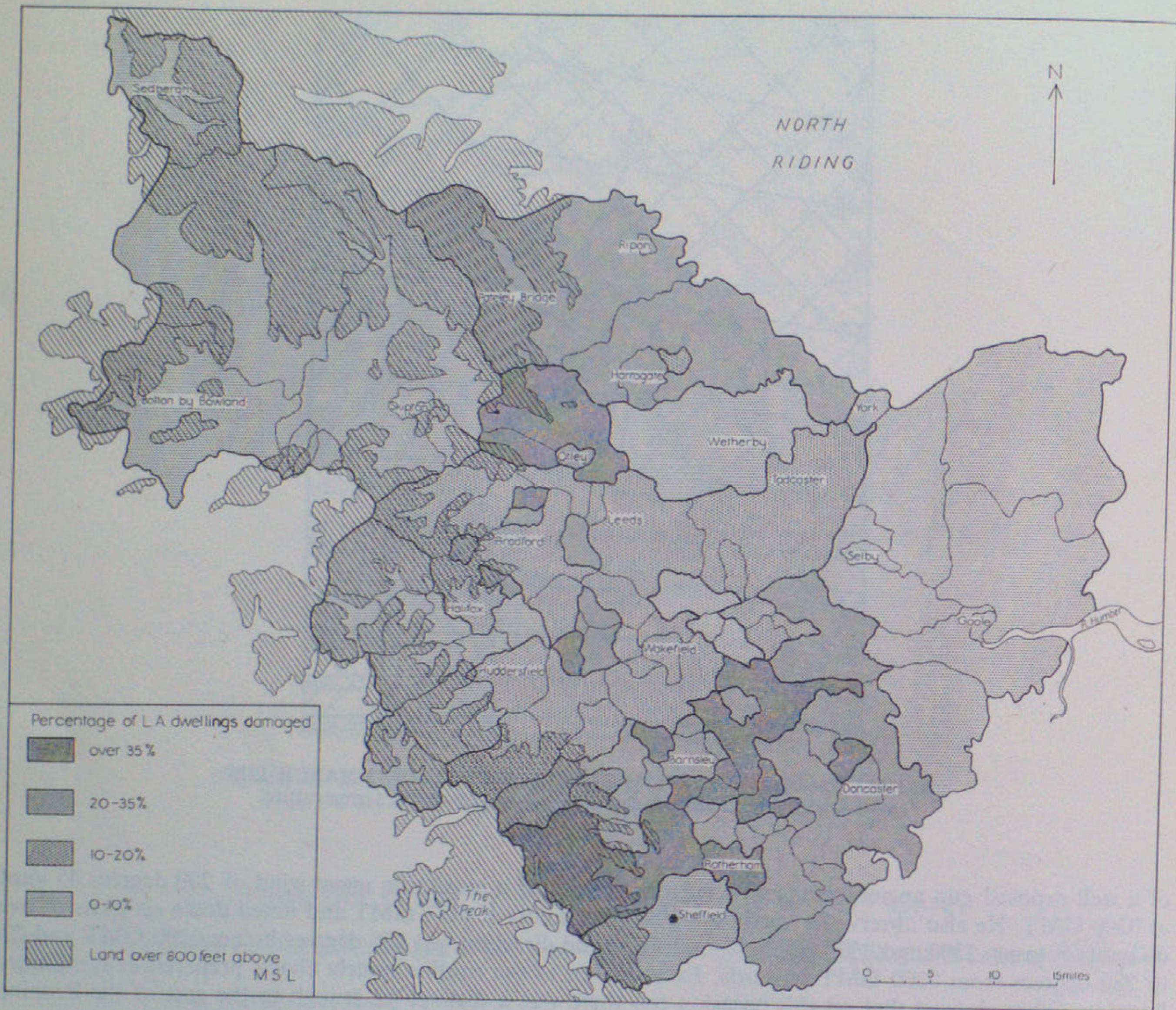
The distribution of damage was similar in many ways to that of February 1962. Figure 21 shows the distribution of damage to local-authority dwellings in most of Yorkshire. Again there is the north–south belt of damage parallel and close to the Pennines. It is also noticeable that the areas of maximum damage lie in two belts, to the lee of the Peak and the high ground in the north-west of Yorkshire.

Regarding the storm which affected Sheffield at the end of the last century, the only available information is the *Daily Weather Report** which in those days contained a surface chart for 0800 GMT daily. That for 0800 GMT on 22 December 1894 shows a deep depression off north-east Scotland which had moved to the south of Sweden by the following day. There was a very strong west-north-westerly gradient over the north of England and the following surface winds are recorded in the *Daily Weather Report.*

Shields (near Newcastle)	SW force 8	Loughborough	SW force 7
Spurn Head	WSW force 7	Liverpool	W force 10
York	W force 9	Holyhead	W force 10

This rather scanty information serves to show that the general synoptic situation was very similar to the other three occasions in recent times.

*Meteorological Office. *Daily Weather Report.* London, HMSO.



Reproduced by permission of the Ministry of Public Building and Works

FIGURE 21—SURVEY OF DAMAGE TO LOCAL-AUTHORITY DWELLINGS IN THE EAST AND WEST RIDINGS OF YORKSHIRE BY THE GALES OF 1–2 MARCH 1956

§8—MESO-ANALYSIS OF PRESSURE AND WIND FIELDS

Detailed examination of the hourly charts prepared from synoptic reports normally received at the Central Forecast Office showed that on 16 February 1962 there were some interesting pressure perturbations to the lee of the Pennines. A well defined trough developed about 0600 GMT and persisted for a while. There is some suggestion that a small depression developed in this trough but routine observations were sparse in the region of the Pennines and confirmation of a small closed system could not be obtained. However, at 0900 GMT daily, a number of observers at voluntary climatological stations make and record pressure observations, whilst all such observers make surface wind observations at this time. These observations from stations in the north of England together with pressure and wind observations from the normal synoptic reporting stations, were plotted on a large-scale map (10 miles to one inch).

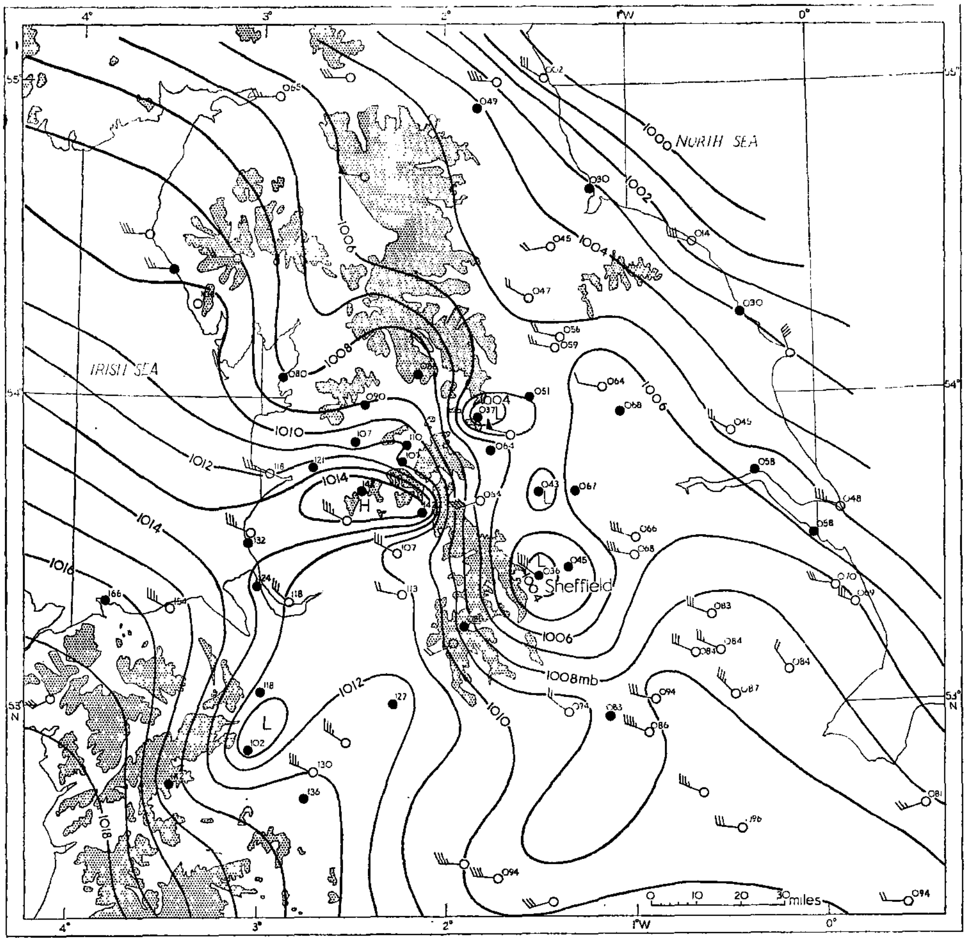


FIGURE 22—SURFACE PRESSURE CHART FOR 0900 GMT, 16 FEBRUARY 1962
o Meteorological Office stations, • other stations
Examples of pressure values: 094 = 1009·4 mb, 154 = 1015·4 mb. Land over 1000 feet above MSL is shaded.

The interesting features of this chart (Figure 22) are the following:

(i) A trough of low pressure extending north–south on the east side of the Pennines with three separate low-pressure centres over Sheffield, Dewsbury and Ilkley. (There was another small low-pressure centre over Flintshire to the east of the high ground in North Wales.)

(ii) A small centre of high pressure to the west of the Pennines between Bolton and Blackburn.

(iii) The extremely intense pressure gradient between the meso-high over Lancashire and the lee trough.

To the west of Huddersfield the pressure gradient was of the order of 1 millibar per 2 miles. For such a pressure gradient, the equilibrium geostrophic wind would have to be about 350 knots from a northerly direction. Obviously, since winds of this strength were not experienced, geostrophic balance was not reached probably because the individual air particles remained under the influence of this intense pressure gradient only for a very short time interval and were therefore moving under the influence of the large-scale general pressure gradient.

All the available synoptic reports were examined to see whether the meso-scale disturbances could be identified upwind from the Pennines but the result was negative; neither could any persistence or development of the disturbances be detected in an easterly direction on the routine hourly synoptic charts.

In order to study the fluctuations of pressure in detail, hourly pressure tendencies were calculated for all the regular hourly reporting stations in the British Isles for the period 0100 to 1300 GMT. These were plotted and these hourly charts show that there were considerable fluctuations to the lee of all high ground particularly the Pennines. In connexion with the Sheffield area, an isallobaric 'low' appeared over Yorkshire at 0200 GMT and quickly moved away eastwards. Another formed at 0400 GMT and persisted for an hour or two before disappearing from the charts and at 0700 GMT a third formed a little to the south of Sheffield. Although rather difficult to follow on account of the rapid changes taking place, this third isallobaric 'low' appears to have moved quickly towards the North Sea and was followed by an intense isallobaric 'high' on the 0900 GMT chart.

To get a clearer picture of the way in which the surface pressure fluctuated another two charts were constructed as follows:

(i) For each synoptic reporting station, the fall of pressure in the three hours before the passage of the trough was added to the rise in pressure that occurred in the three hours following its passage. The sum of the two was taken as a measure of the depth of the sharpness of the trough and Figure 23 shows the distribution of the parameter over the British Isles. In the south of the country the trough was rather shallow and the pressure changes were difficult to evaluate but they were certainly very small compared with changes in the north. That the trough intensified considerably to the east of the Pennines is clearly demonstrated by this chart and the trough started to fill up as it approached the east coast. Judging by the data available from the east of Yorkshire, Lincolnshire and Norfolk, it was still deeper than before it crossed the Pennines but whether the pressure

FIGURE 23—CHART SHOWING THE SUM OF (i) THE PRESSURE FALL IN THE THREE HOURS PRECEDING THE PASSAGE OF THE TROUGH ON 16 FEBRUARY 1962, AND (ii) THE PRESSURE RISE IN THE FOLLOWING THREE HOURS
Pressure is given in tenths of a millibar. Land over 1000 feet above MSL is shaded.

eventually recovered to its former value is impossible to determine because there are no observations available over the North Sea.

(ii) The hourly changes in the hourly pressure tendencies were calculated for each station for the period 0100 to 1300 GMT and the mean hourly pressure changes (regardless of whether each pressure change was negative or positive) were calculated and plotted (Figure 24). This chart shows that the variability of pressure was greater along a belt extending north–south on the lee side of the Pennines, the greatest variability being at Waddington about 50 miles downwind from Sheffield.

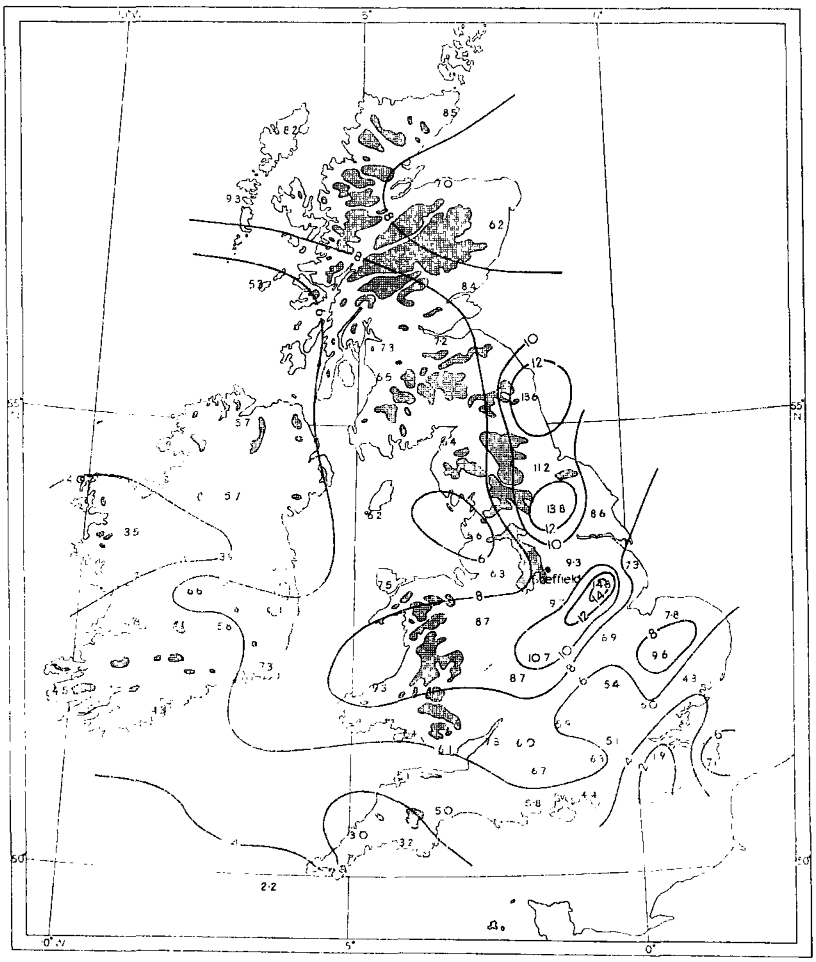


FIGURE 24—MEAN HOURLY CHANGES IN THE HOURLY PRESSURE TENDENCIES FOR THE PERIOD 0100–1300 GMT, 16 FEBRUARY 1962
Pressure changes are given in tenths of a millibar. Land over 1000 feet above MSL is shaded.

From the above evidence it appears likely that while the very strong winds lasted a trough persisted to the east of the Pennines (and probably to the east of high ground in North Wales and other places) and several 'meso-lows' formed in the trough. There is a suggestion from the isallobaric charts that some of the 'meso-lows' broke away occasionally from the trough and moved quickly eastwards but this point cannot be established conclusively on the data available.

For comparison, similar charts were drawn for the earlier gale of 12 February 1962. A convenient time when observations were available from several private observers was again 0900 GMT and these observations were plotted together with the information received from synoptic reporting stations (Figure 25). Although there were slightly fewer observations available on this occasion, it appears that the main meso-scale features of the chart are similar to those of Figure 22, namely, the ridge over Lancashire, the trough to the east of the

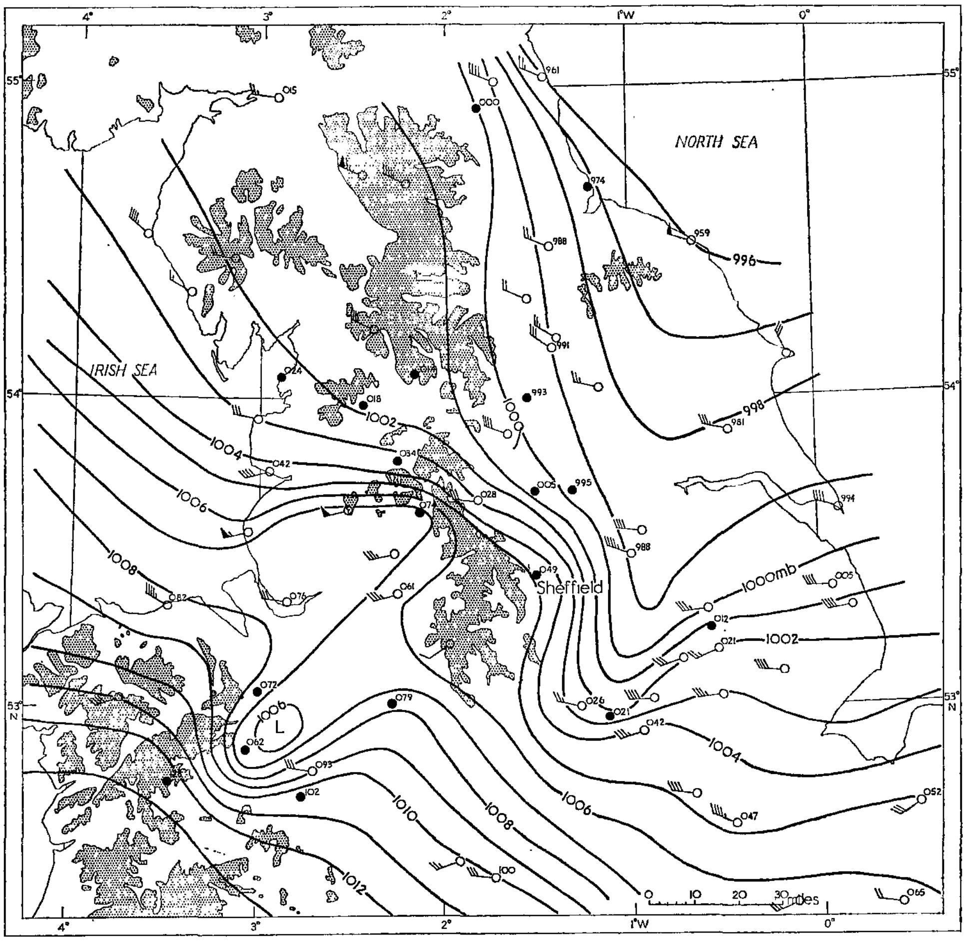


FIGURE 25—SURFACE PRESSURE CHART FOR 0900 GMT, 12 FEBRUARY 1962
o Meteorological Office stations, • other stations
Examples of pressure values: 093 = 1009·3 mb, 988 = 998·8 mb. Land over 1000 feet above MSL is shaded.

Pennines and the 'meso-low' over Flintshire. The lee trough was about 20 miles further east than on the previous occasion and there is no evidence of 'meso-lows' over the west of Yorkshire.

Charts of hourly tendencies show that isallobaric 'lows' formed *in situ* to the lee of high ground and moved away eastwards, the same process being repeated every two or three hours while the severe gales lasted.

To examine whether the troughs associated with the cold front underwent any changes in intensity the chart shown in Figure 26 was constructed in the same way as that shown in Figure 23. On this occasion the cold front became quasi-stationary from Wales to East Anglia with minor waves running along it and there were minor troughs crossing Scotland. Thus it was only possible to take into account stations in the north of England and the south of Scotland. Although not to such marked extent as on 16 February 1962 there is conclusive evidence that the trough became deeper immediately to the lee of the Pennines and then became shallower on approaching the east coast.

A chart showing the variability of pressure at individual stations on the 12th (Figure 27) was constructed in the same way as Figure 24. Maximum pressure fluctuations are shown in the Nottingham area, suggesting the existence of 'meso-lows' to the east of the Pennines as on the 16th.

A similar analysis was carried out for the gale of 1–2 March 1956. This gave very similar results.

From these analyses it is seen that on the last three occasions when damage was caused at Sheffield by severe gales, the synoptic situations had the following features in common:

FIGURE 26—CHART SHOWING THE SUM OF (i) THE PRESSURE FALL IN THE THREE HOURS PRECEDING THE PASSAGE OF THE TROUGH ON 12 FEBRUARY 1962, AND (ii) THE PRESSURE RISE IN THE FOLLOWING THREE HOURS
Pressure is given in tenths of a millibar. Land over 1000 feet above MSL is shaded.

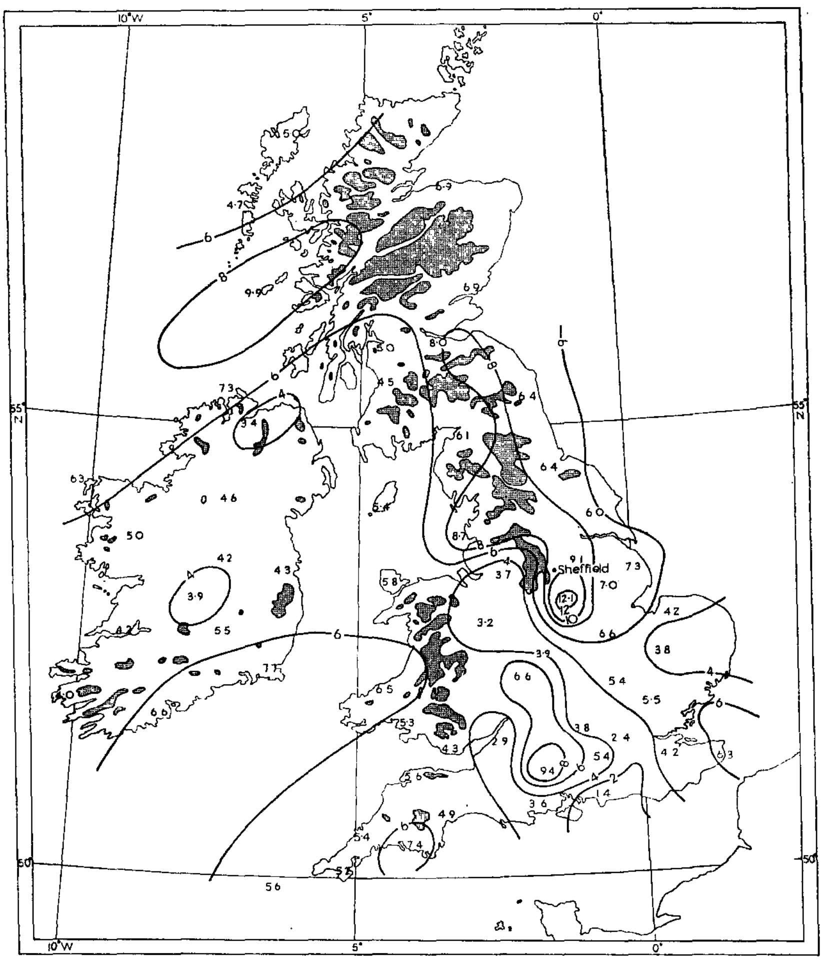


FIGURE 27—MEAN HOURLY CHANGES IN THE HOURLY PRESSURE TENDENCIES FOR THE PERIOD 0100–1300 GMT, 12 FEBRUARY 1962
Pressure changes are given in tenths of a millibar. Land over 1000 feet above MSL is shaded.

(i) A deep depression with a central pressure of 960 millibars or below between Iceland and southern Norway moved quickly eastwards. (This was also a feature of a gale which caused damage towards the end of the last century.)

(ii) A cold front associated with the deep depression moved south over the country but the air was stable ahead of the front and also behind it.

(iii) The wind at 2000 feet was between 280 and 300 degrees, 65–75 knots. The direction remained constant with height but the speed increased to more than 90 knots at 500 millibars.

(iv) The troughs associated with the cold fronts deepened considerably on the east side of the Pennines and 'meso-lows' formed in this trough. A study of the pressure fluctuations suggests that while the very strong winds lasted, the trough persisted to the lee of the Pennines and to the lee of other high ground (e.g. North Wales) and that some of the 'meso-lows' occasionally broke away from the trough and moved eastwards, then another 'meso-low' was formed and the process repeated itself.

§9—ANALYSIS OF REPORTED SURFACE WINDS ON 16 FEBRUARY 1962

Some details of surface wind speeds in the gale of 16 February 1962 in the north of England have already been given in Section 2. A spatial analysis of these and other reported surface winds on 16 February will now be considered to show the distribution of the maximum winds and an attempt will then follow to estimate the statistical probability of the recurrence of such a gale at Sheffield. Table IV summarizes the mean hourly winds and highest gusts at anemograph stations and shows the position and height details of each instrument. The highest speeds on record prior to 16 February 1962 and the approximate length of each record are also given to provide an indication of the severity of the gale. The table shows that although Sheffield recorded the highest gust speed, its highest mean hourly speed of 40 knots was comparable with those occurring on the Lancashire and Cheshire coasts and in the Isle of Man. Such speeds in an urban area well inland in England are noteworthy, particularly so in this case because the anemograph is somewhat sheltered to the west and north-west by rising ground.

Comparison of the maximum speeds on 16 February with the highest speeds on record, however, suggests that over northern England as a whole this gale was not particularly exceptional, especially west of the Pennines. In fact the most outstanding feature of this west to north-west gale was that while speeds west of the Pennines were not exceptional, major wind damage to structures and trees occurred in a relatively narrow belt in the lee of the Pennines, running approximately from Chesterfield to Leeds with appreciable damage further north also, as has already been described. To the east of this belt again recorded speeds were not exceptional in general.

These features are brought out in Figure 28, which shows the highest gust speeds in knots (reduced to 33 feet above the ground) recorded at all anemograph stations in the United Kingdom on 16 February 1962. It is often considered that in a gale the maximum gust gives reasonably good indication of the maximum gradient wind speed provided the wind flow is balanced, which, it has already been shown, was not the case over the Pennines. While it was fortunate that there was an anemograph in operation in Sheffield, undoubtedly the place which suffered most damage, it was unfortunate that this was the only such instrument operating in the West Riding of Yorkshire or the Vale of York. However, it has been possible to obtain a more detailed picture of the maximum gust speed distribution by making use of the highest gusts observed at those continuously manned meteorological stations in northern England which are equipped with cup-generator anemometers with indicating dials; these are underlined in Figure 28. It is of course possible that higher gusts could have occurred at some of these stations without being noted, but it is unlikely that any such gusts would have exceeded the highest actually observed by more than a few knots; the sound of the wind as it increases in a strong gust makes an experienced observer look automatically at the dials. The maximum gust values which are shown in brackets in Figure 28 relate to high-level stations and have therefore been ignored in drawing the isopleths. The gust of 103 knots (104 knots at 33 feet) recorded at Lowther Hill, Lanarkshire, 2412 feet above sea level, had previously been exceeded there in the gale of 12 February 1962 by a gust of 106 knots, the highest gust speed ever recorded in the United Kingdom at a station staffed by or co-operating with the Meteorological Office.

TABLE IV—MAXIMUM WIND SPEEDS AT ANEMOGRAPH STATIONS IN NORTHERN ENGLAND ON 16 FEBRUARY 1962

Station	Height of anemometer			Latitude	Longitude	Highest hourly mean wind			Highest gust			Highest on record		Length of record
	Above MSL	Above ground	Effective height	(north)	(west)	Speed	Direction	Time (hour ending)	Speed	Direction	Time	Hourly mean	Gust	
	feet	*feet*	*feet*			*knots*	*degrees*	*GMT*	*knots*	*degrees*	*GMT*	*knots*	*knots*	*years*
Point of Ayre	70	40	35	54° 25′	4° 22′	40	310	1600	64	310	1500	56	78	26
Ronaldsway	119	64	39	54 05	4 38	39	260	0100	63	310	2005	53	77	1
Durham	389	53	33	54 46	1 35	38	270	0700	73	280	1245	43	83	24
South Shields	73	57	44	55 00	1 26	37	265	0400	74	270	0515	56	76	28
Cranwell	288	47	47	53 02	0 30	35	290	1200	64	290	1440	45	96	30
Sheffield	533	83	35	53 23	1 29	**40**	280	0700	**84**	280	0610	30	70	3
Keele	706	50	40	53 00	2 16	29	300	1100	58	310	0830	34	75	9
Carlisle	137	42	42	54 56	2 57	32	230	0200	56	270	1215	35	59	1
Sellafield	83	39	35	54 25	3 30	28	290	1400	48	260	1310	44	76	12
Spadeadam	959	51	40	55 02	2 38	37	280	1300	60	240	0110	44	70	2
Moor House	1960	50	45	54 41	2 23	49	280	0600	74	290	0535	49	76	6
Fleetwood	112	50	31	53 55	3 03	41	280	1000	68	290	1300	53	79	34
Southport	59	41	33	53 40	2 59	41	270	0400	56	290	1325	61	79	48
Liverpool (Speke)	180	100	65	53 21	2 53	34	290	0600	61	280	0445	49	79	13
Manchester Weather Centre	268	147	55	53 29	2 15	31	250	0600	64	310	1805	36	70	2
Bidston	262	64	39	53 24	3 04	40	260	0300	64	260	0210	56	88	33
Manchester Airport	318	70	30	53 21	2 16	34	250	0400	56	280	0925	49	79	17

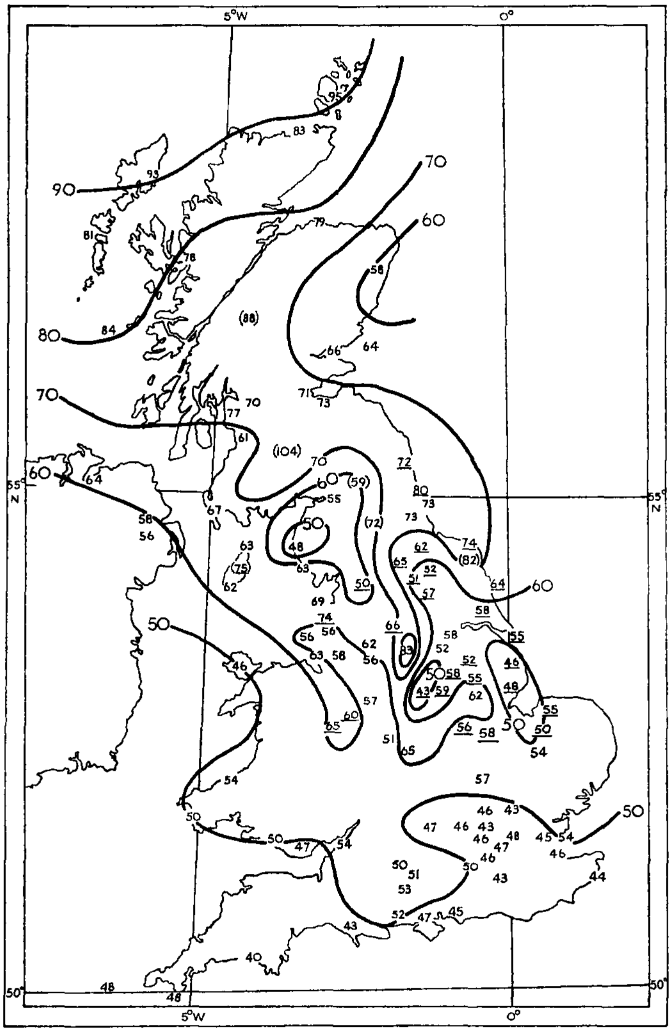


FIGURE 28—MAXIMUM GUST WIND SPEEDS (REDUCED TO 33 FEET ABOVE GROUND) FOR 16 FEBRUARY 1962
Wind speeds are given in knots. Bracketed values are from stations over 800 feet above MSL.
Underlined values are from cup-anemometer stations with indicating dials only.

Figure 28 suggests that the area in which gusts in excess of 70 knots occurred was probably a relatively narrow one running parallel to and east of the Pennines. It also indicates that there were two areas with much lower speeds further east, one roughly from Nottingham to Doncaster and the other over east Lincolnshire, with higher speeds separating them.

An attempt was made to prepare a similar chart of highest mean wind speeds, but this was not easy because the values obtained from stations with dial-indicating anemometers are less likely to be true maxima than in the case of gusts and because they are not comparable with the hourly means tabulated from anemograph records; they are estimated means over some unknown period of the order of a minute or less. It was decided that it would be more useful to examine the mean wind speeds reported at fixed hours to give an indication of the instantaneous wind picture at or near the time of strongest winds. The most suitable hour for this purpose seemed to be 0600 GMT and the resulting chart is shown in Figure 29. Unfortunately the number of stations reporting at 0600 GMT is limited and a further chart (Figure 30) was therefore prepared for 0900 GMT so that the speeds reported by voluntary climatological stations could be incorporated. Many of these stations estimate wind speed using the Beaufort scale but even so the majority of such estimates should not be in error by more than about 5 knots.

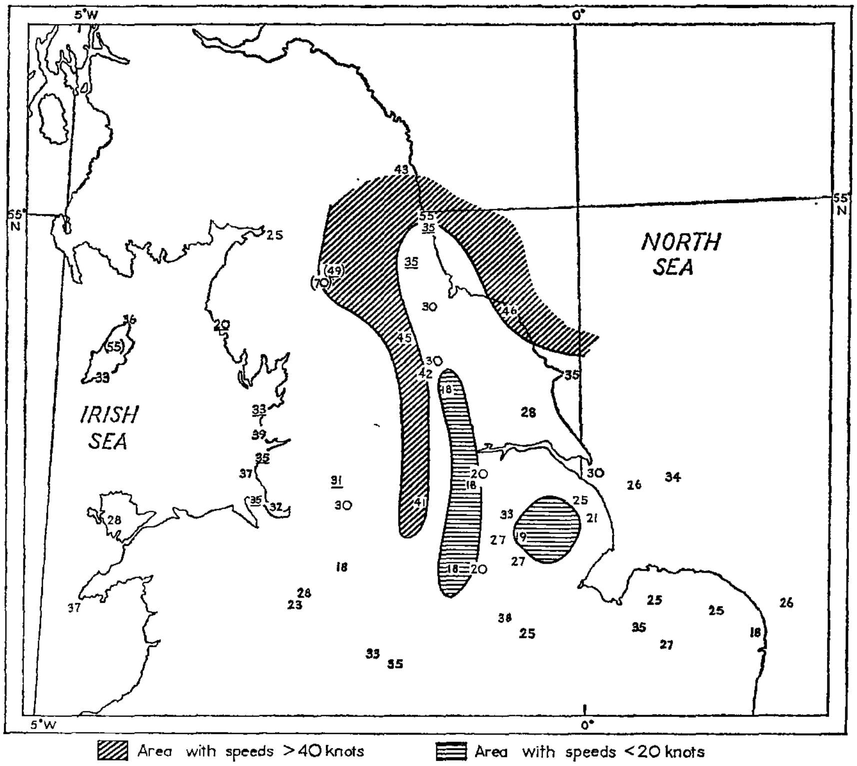


FIGURE 29—MEAN WIND SPEEDS AT 0600 GMT, 16 FEBRUARY 1962
Wind speeds are given in knots. Bracketed values are from stations over 800 feet above MSL.
Underlined values are mean speeds for the hour ending 0600 GMT from anemograph stations.

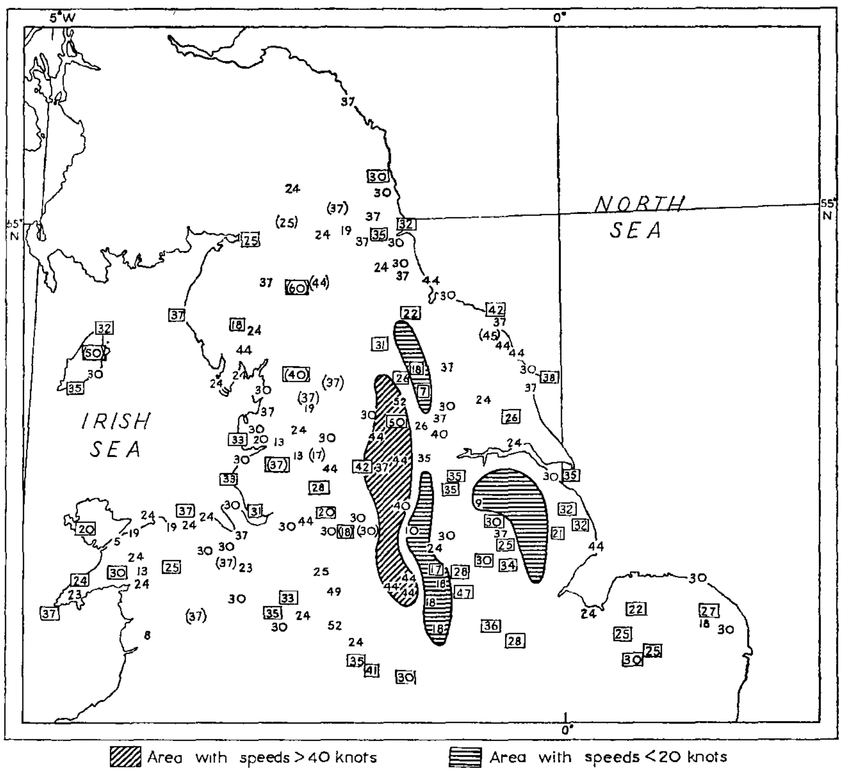


FIGURE 30—MEAN WIND SPEEDS AT 0900 GMT, 16 FEBRUARY 1962
Wind speeds are given in knots. Bracketed values are from stations over 800 feet above MSL.
Values in boxes are from Meteorological Office or auxiliary stations, others are from climatological stations.

In view of the obvious difficulties no attempt has been made to draw detailed isopleths on Figures 29 and 30 but areas with mean speeds greater than 40 knots and less than 20 knots have been shaded. These Figures both support Figure 28 in indicating a belt of maximum speeds parallel to and east of the Pennines. They indicate more strongly than Figure 28 a parallel belt of minimum speeds some 10–15 miles further east and then a further rise and fall in speeds further east again with a final rise towards the Lincolnshire coast. Such a state of affairs strongly suggests a system of lee waves set up by the Pennines and a discussion on the aspect is given in Section 11 of this Memoir.

§10—ASSESSMENT OF FREQUENCY OF RECURRENCE OF SUCH A GALE AT SHEFFIELD

As has already been stated, the gale was not exceptional west of the Pennines. Three low-level anemograph stations east of the Pennines recorded mean hourly wind speeds exceeding 36 knots and gusts exceeding 70 knots, viz. Sheffield, Durham and South Shields, and for the last two stations long-period records are available. These records show that the mean hourly speeds recorded on 16 February 1962 had previously been reached or exceeded in 17 years out of 28 at South Shields and in 9 years out of 24 at Durham, and that the maximum gusts recorded on 16 February 1962 had previously been reached or exceeded in 4 years out of 28 at South Shields and in 5 years out of 24 at Durham. Thus, judged by past records, the gale was certainly not exceptional in the Durham–Tyne area. In fact the only *recorded* wind speeds in northern England which appear to have been really exceptional were those at Sheffield. This again supports the idea that topographical features must have been a major factor in causing this localization of the area of violent winds. Owing to the short period of the Sheffield wind record, however, it is difficult to establish how exceptional they were. There have been a number of previous occasions when fairly widespread damage by wind has occurred in the Sheffield region, e.g. on 12 February 1962 (only four days prior to the occurrence under discussion), on 1–2 March 1956 and on 22 December 1894. Judged by the damage alone, the gale was probably the most severe since at least 1894, i.e. it must have been at least in the 'once in 50 years' category and probably in the 'once in 100 years' category. This is even making allowance for the fact that a lot of the damage on 16 February 1962 was either to very old property or to modern housing, both prefabricated and conventional, which had been erected in rather exposed positions where few, if any, buildings existed 50 or more years ago.

The Sheffield anemograph record dates from March 1958 only and is incomplete. There were no other anemographs in the area. The fact that the speeds recorded in Sheffield on 16 February 1962 were easily the highest since before 1958 is not by itself of much help in assessing the severity of the storm and the probable recurrence period of such wind speeds. Such an assessment can only be made in this case by comparing the short Sheffield record with those of the nearest long-period anemograph stations, for which the statistical distribution of extreme wind speeds has been computed.[2]

When the requisite minimum 10–15 years' data become available for Sheffield, it should of course be possible to make a more accurate estimate of the severity of this gale based on a straightforward statistical analysis of Sheffield wind records. At present an approximation can only be attempted in the following manner.

The nearest anemograph stations to Sheffield for which both recent and long-period records are available are Manchester Airport and Cranwell. Extreme wind speeds for all three stations, both mean hourly speeds and gusts, were compared for selected occasions and intervals within the period for which the records overlap. This gave average values for the ratios of the Sheffield extremes to those at each of the other stations. These ratios were then applied to the known linear equations of the extreme wind probability distributions for Manchester and Cranwell, based on their long-period records, to obtain approximate equations for Sheffield, from which estimates of the probable return periods for the extreme speeds recorded on 16 February 1962 were obtained.

It was found that the results obtained depended on the extreme speeds which were selected for comparison. Among the data tried were (i) extreme monthly speeds for all available months, (ii) extreme monthly speeds, omitting those months when the Sheffield maximum mean hourly speed was 16 knots or less, (iii) extreme daily speeds when the maximum mean hourly speed at Sheffield was 17 knots or more, and the maximum gust 40 knots or more, (iv) as (iii) but omitting days when the extremes at all three stations occurred more than

6 hours apart in time or more than 30 degrees apart in direction, (v) extreme daily speeds on days when the maximum mean hourly speeds exceeded 20 knots at all three stations and occurred within 6 hours and within 40 degrees.

For the extreme mean hourly speed the estimated return periods ranged from about 50 to 175 years based on comparison with Manchester Airport and from about 100 to 400 years based on comparison with Cranwell. For the maximum gust speed they ranged from about 20 to 50 years based on Manchester and from about 60 to 80 years based on Cranwell. It is considered that the best estimates that can be made, bearing in mind the lack of a really suitable comparison station and the limited period of data available, are about 150 years for the mean hourly speed and about 75 years for the gust.

The discrepancy between these two estimates may be partly explained by the fact that the ratio of the recorded maximum gust to the recorded maximum mean hourly speed on 16 February 1962 was 2·1 whereas on the average this ratio at Sheffield is nearly 2·4, i.e. the maximum gust was not as high as might have been expected. It seems reasonable to suppose that higher gusts than the one actually recorded did occur in the city area but happened not to affect the anemograph. If the mean wind speed recorded by the anemograph is accepted as the more reliable indicator of the severity of the storm then the storm can be regarded as falling in the 'once in 150 years' category. Maximum gusts of about 90 knots, instead of the recorded 84 knots, would be consistent with this return period.

§11—LARGE-SCALE TOPOGRAPHICAL EFFECTS

It is well known that the airflow in the neighbourhood of hills and mountains may be subject to organized deformations which reach a considerable magnitude on some occasions and there is now an extensive body of literature on the subject. A comprehensive review of the topic has been published by the World Meteorological Organization as Technical Note No. 34.[3] Much of the research has been stimulated by the need to ascertain the character of these disturbances from the point of view of their effect on aircraft and emphasis has thus largely been directed towards the properties of lee-wave phenomena in the free atmosphere. However, there is no doubt that important effects are also manifest at the surface near hills and mountains. In particular, large variations of surface wind occur in association with wave effects aloft and consideration of the pressure fields, the areas of maximum wind and damage has already shown them to be related to the Pennines. It is natural to inquire in what way the remarkable gale at Sheffield and other places in northern England on the morning of 16 February 1962 was associated with the topography of the region. The suspicion that lee-wave phenomena may have been the link is roused by the parallel belts of wind maxima and minima and is reinforced by the fact that Sheffield lies to the lee of the highest part of the southern Pennines, and it is known that when lee waves and other special phenomena are operating the most pronounced effects are normally to be found on the lee side of the high ground.

Thus when wind damage to trees occurs over mountainous terrain it is usually more widespread over the lee slopes than elsewhere; Manley[4] describes the exceedingly strong winds, force 9 or 10, which blow down the lee slopes of Crossfell in Cumberland when the 'helm bar', a lee-wave effect, occurs; Suzuki and Yabuki[5] have discussed the 'hiroto-kaze' or fierce lee-slope winds which sometimes do great damage to crops and houses in some localities of Japan whilst the windward slopes and open plains remain little affected; similar effects have been reported from many parts of the world. This tendency for the lee slopes to receive the strongest winds on occasions when lee waves occur is in accord with theoretical treatments of the airflow over hills and mountains. In the present section the available theory has been used to calculate the airflow across the Pennines on 16 February 1962.

Theory.—If the two-dimensional flow over a mountain ridge is represented by a stream function $\varphi\ (x, z)$ and the stream function is resolved into Fourier components so that

$$\varphi = \int_0^\infty \varphi_k(k,z)e^{ikx}dk$$

and if we write $\psi_k=(\rho/\rho_0)^{\frac{1}{2}}\varphi_k$ where ρ is the density at height z and ρ_0 the density at $z=0$, then the basic equation governing the flow is

$$\frac{\partial^2\psi_k}{\partial z^2}+(l^2-k^2)\psi_k=0 \quad \ldots (1)$$

where

$$l^2=\frac{g\beta}{U^2}-\frac{1}{U}\frac{\partial^2 U}{\partial z^2},$$

β is the static stability $\left(\frac{1}{\theta}\frac{\partial\theta}{\partial z}\right)$, θ is the potential temperature, U is the wind speed in the undisturbed airstream and z is the vertical co-ordinate.

For the lower boundary a convenient and simple mountain cross-section which has been widely used is

$$H(x)=h\left(1+\frac{x^2}{b^2}\right)^{-1}$$

$$=\text{real part of}\int_0^\infty hb\exp(-kb+ikx)\mathrm{d}k \quad \ldots (2)$$

Here h is the maximum height of the ridge and b is the so-called half-width parameter, viz. the value of x for which the height is half the maximum.

The main assumptions implicit in this formulation are as follows:

(i) The flow is laminar, steady, frictionless and adiabatic (condensation effects neglected).

(ii) The motion is two-dimensional with disturbances of small amplitude, allowing non-linear terms to be neglected.

(iii) The horizontal scale is small enough to allow neglect of the Coriolis force.

The theory leads to the following expression for the displacement ζ of the streamline at any height z

$$\zeta=\text{real part of}\left(\frac{\rho_0}{\rho}\right)^{\frac{1}{2}}\frac{U_0}{U}hb\int_0^\infty\frac{\mathrm{f}(z,k)}{\mathrm{f}(0,k)}\exp(-kb+ikx)\mathrm{d}k \quad \ldots (3)$$

where $\mathrm{f}(z,k)$ satisfies equation (1) and U_0 is the wind speed at the lower boundary ($z=0$) in the undisturbed airstream.

In order to determine the flow over the mountain ridge given by equation (2) we must solve for $f(z,k)$ and evaluate the integral in equation (3) for sufficient values of z and x to enable the streamlines to be plotted. The character of the result obtained is determined by the wind and stability structure of the airstream, viz. by the vertical profile of the parameter l^2. In simple cases, e.g. when l^2 is independent of z or when the airstream may be divided into two or three layers within each of which l^2 is constant, it is possible to exploit analytical approximations to the integral in equation (3); see for example Scorer.[6]

For the present purpose, however, it is desirable to take cognizance of the structure of the airstream in more detail and the procedure developed by Sawyer[7] is therefore used. In this method the airstream is specified by potential temperatures and wind speeds at one-kilometre intervals up to 16 kilometres, constant values being assumed above 16 kilometres. The integral in equation (3) is then evaluated numerically for various values of z and x by calculation on the electronic computer. The result gives the streamlines for the flow over the simple symmetrical ridge having the cross-section given by equation (2). To obtain the flow over the Pennines, the solutions obtained for a number of such elementary ridges are superposed. These ridges are so chosen that when their amplitude, phase and scale are superposed, they provide an approximation to the shape of the Pennines.

When the character of the airstream favours large-amplitude displacements it is possible for this direct application of the linearized theory to lead to streamlines which intersect the ground or each other. This is because the displacements are directly proportional to the height of the disturbing obstacle, so that if the obstacle is sufficiently high some of the low-level streamlines inevitably reach the ground. The difficulty may be avoided as follows. Equation (3) essentially gives ζ, the displacement, as a function of z, the undisturbed level i.e. $\zeta = F(z)$. If vertical profiles of ζ as computed from the linear theory are plotted, modified values, say ζ', which satisfy $\zeta' = F(z + \zeta')$ can be determined. Thus the computed displacements are associated with the displaced heights rather than with the undisturbed heights. This effectively avoids the intersection of streamlines when the amplitudes are large and the method, which is believed to make some approximate allowance for the non-linear terms, has been adopted in the present calculations. One effect of this method is that the effective cross-section of the terrain is not the same as that initially specified; the ground streamline becomes modified as well as those above. To achieve a given ground profile therefore requires considerable trial and error.

The airstream and terrain cross-section.—Information on the structure of the airstream was provided by the Aughton radiosonde and wind soundings for 0000 and 1200 GMT on 16 February 1962 supplemented by the 0600 GMT sounding giving winds only. An estimate was required of the undisturbed airstream at about the time of the onset of the severe winds at Sheffield, viz. 0500 GMT. The temperatures at Aughton for about 0400 GMT were therefore interpolated. In the calculations, the Pennines as a whole were regarded as an approximately north–south barrier and accordingly wind components from 270 degrees, interpolated for the same time, were used. The winds and temperatures so chosen are illustrated in Figure 31.

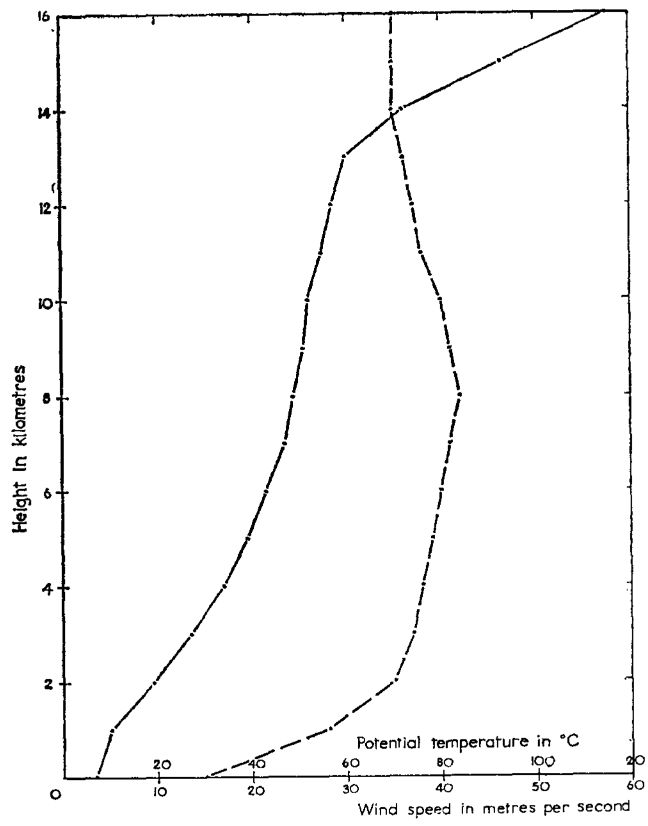


FIGURE 31—PROFILES OF POTENTIAL TEMPERATURE (θ) AND WIND SPEED (U) IN THE UNDISTURBED AIRSTREAM APPROPRIATE TO FLOW OVER THE PENNINES IN THE VICINITY OF SHEFFIELD AT ABOUT 0500 GMT, 16 FEBRUARY 1962
·——· potential temperature, ·— — —· wind speed

A cross-section of the topography in a west–east direction through Sheffield was derived by taking mean heights over a band about 2 miles wide from a half-inch Ordnance Survey map. During the course of the computation of the streamlines the main features of this cross-section were approximated to as closely as possible.

The profile of l^2.—The l^2 profile of the undisturbed airstream resulting from the estimated temperature and wind structure is given in Figure 32.

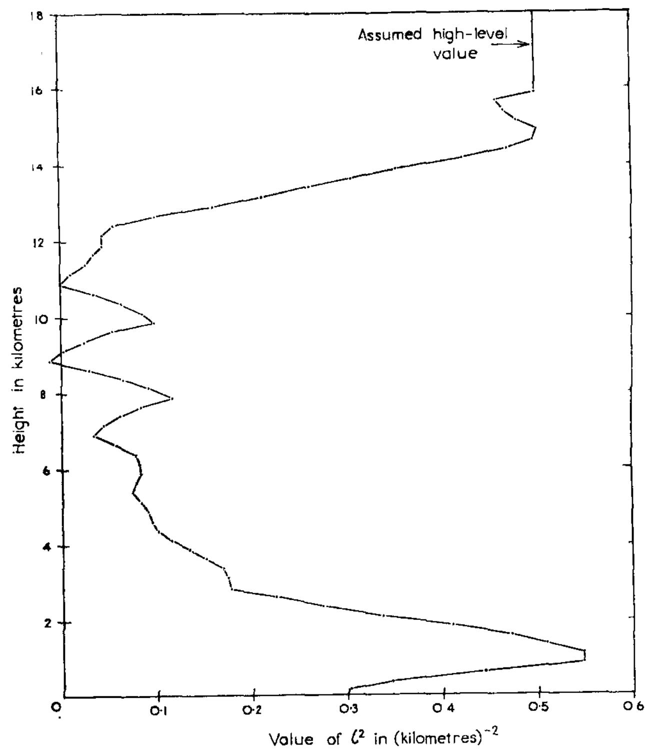


FIGURE 32—PROFILE OF l^2 BASED ON AUGHTON RADIOSONDE AND WIND DATA FOR 16 FEBRUARY 1962

A pronounced maximum is seen in the lower troposphere with much smaller values above, conditions which are known to favour the occurrence of lee waves, and indeed the calculations revealed the existence of one lee wavelength of 22·1 kilometres. This is unusually long; wavelengths for waves of the type which attain their maximum amplitude in the lower troposphere are more usually in the range 5 to 10 kilometres. The lee waves are rendered possible by the large values of l^2 in the lowest few kilometres, accompanied by the decrease above, and the very long wavelength in this case arises mainly because of the very small values of l^2 in the upper troposphere, these in turn being due to the very steep lapse rate and strong winds in those layers.

The occurrence of strong lee waves on 16 February 1962 was confirmed by Captain R. H. Ayres, the pilot of a B.K.S. Bristol Freighter aircraft which flew from Cambridge (1035 GMT) to Dublin (1355 GMT) on a track crossing the southern Pennines a little south of Sheffield. Because of the strong head winds the flight occupied 3 hours 20 minutes instead of the usual 2 hours. Although the aircraft was made to dive through the up-currents and climb at maximum power through the down-currents, the vertical currents were so strong (estimated 2000 feet per minute) that the pilot was unable to maintain his nominal height of 8000 feet and was obliged to inform Air Traffic Control of this. During these manoeuvres the aircraft's airspeed varied over the range 80 to 175 knots. Captain Ayres reported that the sky was covered with an impressive display of wave clouds.

Other observations of relevance included reports of wave clouds observed from the ground, together with two reports, from Carlisle and Manchester, of nacreous ('mother-of-pearl') clouds. The formation of the latter clouds would require, *inter alia*, a strong westerly component of wind up to at least 30 kilometres. These conditions are sometimes provided in the flow to the south of high-latitude depressions in winter and were satisfied on this occasion.

The computed streamlines for 16 *February* 1962.—The calculated streamlines across the Pennines are given in Figure 33 (*a*) where the vertical scale is exaggerated 16 times compared with the horizontal scale in order to depict the features of the flow more clearly.

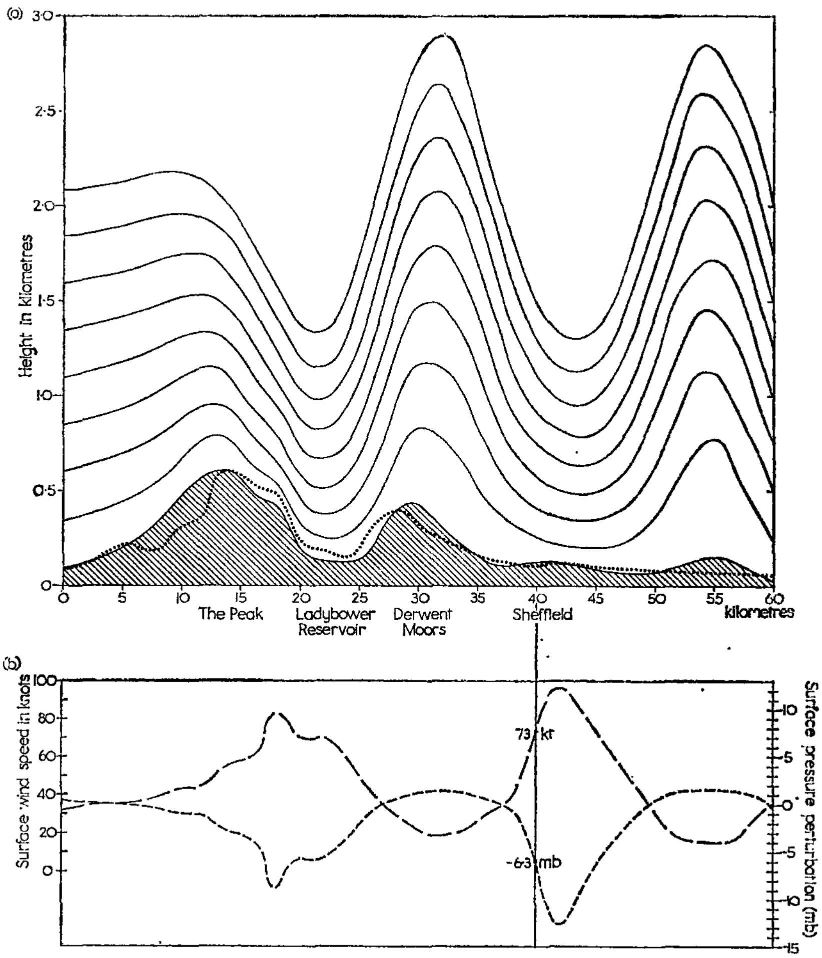


FIGURE 33—(*a*) CALCULATED STREAMLINES AND (*b*) SURFACE WIND SPEED AND PERTURBATION OF SURFACE PRESSURE FOR FLOW ACROSS THE PENNINES IN THE VICINITY OF SHEFFIELD, EARLY MORNING, 16 FEBRUARY 1962
———streamlines, — — — surface wind speed, - - - - surface pressure perturbation

In (*a*) the actual terrain is indicated by the dotted line while the terrain effective in the computation is represented by the shaded area.

It is seen that the theory predicts a powerful lee wave downwind of the Pennines. The wave has large amplitude partly because the structure of the airstream favours this, but also because in the spectrum making up the shape of the Pennines there is considerable power on a scale which suits the long wavelength of the airstream. It is also noteworthy that a large amplitude is attained very rapidly as one proceeds upwards from the surface; this, a direct consequence of the low height of the maximum of l^2, means that there is marked packing together of the streamlines below the troughs of the waves and opening out of the streamlines below the crests. In particular it appears that Sheffield was beneath the second wave trough downwind of the Peak and the degree of packing of the streamlines in that area implies that surface winds of 35 knots in the undisturbed stream would in the vicinity of Sheffield have been increased to 73 knots, with the wind falling to only 15 knots beneath the crest of the wave some 15 kilometres or so further downwind. The variation of surface wind speed along the cross-section is depicted in Figure 33 (*b*) together with the perturbation of surface pressure computed from Bernoulli's theorem. From this it is seen that the increase in wind at Sheffield should have been accompanied by a fall of 6·3 millibars in surface pressure.

From this diagram it can be seen that the lee slopes of the Peak district should also have been subject to a very high wind. It is of interest to note the remarks of Mr. Martyn Berry concerning his experiences whilst attempting hill walking above Edale (Section 2, p.5). With such complicated terrain it is of course not possible to identify the corresponding exact position on the simple cross-section.

The close similarity between the synoptic situations on 12 and 16 February 1962 prompts one to inquire what kind of flow pattern would be indicated by theory for the 12th when the damage at Sheffield, although considerable, was less severe than on the 16th. A similar computation of the streamlines was therefore carried out for the 12th and the results are given in Figure 34.

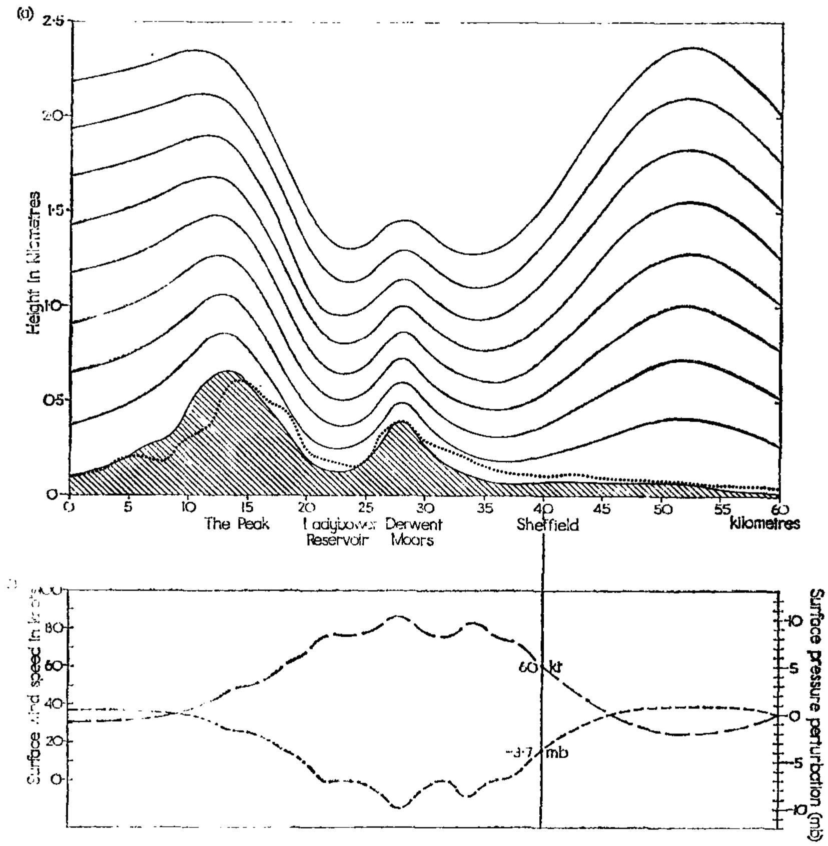


FIGURE 34—(*a*) CALCULATED STREAMLINES AND (*b*) SURFACE WIND SPEED AND PERTURBATION OF SURFACE PRESSURE FOR FLOW ACROSS THE PENNINES IN THE VICINITY OF SHEFFIELD, EARLY MORNING, 12 FEBRUARY 1962

———streamlines, — — — surface wind speed, - - - - surface pressure perturbation

In (*a*) the actual terrain is indicated by the dotted line while the terrain effective in the computation is represented by the shaded area.

Once again the structure of the airstream was favourable for a powerful lee-wave system with the lee wavelength having the exceptionally large value of 38 kilometres. This very long wavelength arose partly because the upper winds were rather stronger on 12 February than on 16 February and also because there was no pronounced inversion in the lower troposphere on the 12th so that the mean static stability of the troposphere was less. Because of the longer wavelength Sheffield did not lie beneath the trough of the second lee wave downwind of the Peak, as on the 16th, but somewhat downwind of the first trough. However, there is still a sufficient concentration of the low-level streamlines at Sheffield to suggest a substantial increase in surface wind speed and Figure 34 implies that wind speeds of 35 knots in the undisturbed stream would have been increased to about 60 knots at Sheffield.

The prediction of exceptionally strong winds in the Sheffield area on 16 February 1962 may appear to be a remarkable success for the theory of the airflow over the mountains. Indeed, Figure 33 probably gives a fair qualitative picture of the general character of the flow in the sense that powerful lee waves were almost certainly operating, with considerable local intensifications of wind speed. However, in view of the limitations and assumptions implicit in the theory, it may be somewhat fortuitous that a strong-wind zone is predicted precisely in the Sheffield area.

Firstly, the theory used is purely two-dimensional whereas in fact the Pennines do not constitute an infinite north–south barrier. In particular, there was probably some diversion of the flow around the southern end of the Pennines and, on a smaller scale, many three-dimensional deformations of the flow around individual peaks and through valleys, etc. Such variations, although probably reducing the amplitude of the overall lee-wave effect, would be accompanied by additional local intensifications of surface wind. Although the three-dimensional problem has received some attention, a technique adequate for useful calculation of the streamlines over realistic three-dimensional terrain does not yet exist.

Secondly, the theory assumes that the air is dry and all condensation effects, including the falling out of rain and the repercussions of this downstream, are excluded. One effect of general cloud would be that the static stability over a substantial depth of the troposphere might be neutral (zero l^2) and this would be expected to lengthen the lee wavelength.

In spite of these limitations, it is clear from the calculations that intensifications of surface wind in association with lee waves aloft can provide a perfectly feasible mechanism for the exceptional winds at Sheffield on 16 February. The limitations of the theory in no way invalidate this general conclusion.

§12—SUMMARY OF CONCLUSIONS

The gale of 16 February 1962 was not an outstanding gale when its effects over the country as a whole are considered. However it was noteworthy in that the wind speeds generally to the lee of the Pennines were comparable with those on the Lancashire and Cheshire coasts. In the latter areas there was little damage because buildings there are constructed to withstand gales of such magnitude, which are not infrequent in these coastal areas. To the lee of the Pennines however gales of such magnitude are infrequent and buildings are often constructed to a lighter scale. Consequently when such gales do occur the damage may be very great, as it was in the Sheffield–Leeds area.

The wind flow in towns is very complex and a study of the damage at Sheffield shows that both pressure and suction effects are important. Though these effects give rise to initial damage, much damage is due to flying debris, and it is often difficult after the event to discover what was the initial damage. Secondary damage often allowed the wind to create further damage to weakened structures. Considerable damage in Sheffield occurred amongst old property in the low-lying older districts but the property on the exposed hillsides of the newer suburbs also suffered badly. Local configurations of buildings and local contours of the ground no doubt imposed a pattern to some extent on the general damage caused by the gale.

Despite the very material and widespread damage to trees throughout north-east England on the lee slopes of the Pennines, it is only possible to use such damage as evidence towards the pattern of the gale in a very general way. This is because of the importance of such factors as local soil conditions, depth of root system, treatment of the roots during growth and the non-uniform woodland cover of the area. It is also quite difficult, if not impossible, to define damage to trees quantitatively. Nevertheless the broad analysis of tree damage gives strong support to the observation that the strongest winds were on the lee slopes of the Pennines and confined generally to a relatively narrow belt parallel to and close to the Pennines.

The analysis of the wind flow was made difficult by the lack of anemographs throughout the area, except fortunately in Sheffield itself. Meso-analysis of the pressure and wind observations for 0600 and 0900 GMT shows very prominent lee troughs with unbalanced flow over the hills and a small area of high pressure to windward. The mobile trough associated with the cold front deepened considerably immediately to the east of the Pennines with the formation of meso-depressions. The general picture is consistent with the view that lee-wave phenomena intensified the gale on the lee slopes. Charts of the maximum gusts and of the mean wind speeds show belts of maxima and minima parallel to the Pennines, strongly suggesting a system of lee waves.

Consideration of the temperature and wind structure in the upper air shows that according to modern theory lee waves were possible on 16 February. The outstanding features of the upper air were:

(i) a marked and persistent inversion at a low level, and

(ii) a constant wind direction (290 degrees) in the vertical with a marked increase in speed with height.

The complex topography of the Pennine Chain does not permit a three-dimensional analysis of the airflow but the somewhat simplified two-dimensional analysis presented in this Memoir shows clearly enough the probability of pronounced lee-wave flow resulting, in the Sheffield area, in a strong standing gravity wave of magnitude enhanced by the resonance caused by the two ranges of high ground west of the city. Despite the limitations of the theory, the calculations provide a perfectly feasible mechanism for the Sheffield gale.

Application of the theory to the observations of 12 February 1962, when the synoptic situation was very similar to that of the 16th but only small amounts of damage occurred in the Sheffield area, shows that the relatively minor differences in upper air temperature structure on this occasion resulted in a longer wavelength and less resonance effect. The calculation thus provides an explanation why there was no serious gale on this occasion despite the similarity of the synoptic pattern.

Comparison of the meteorological situations for other known occasions of westerly gales at Sheffield (1–2 March 1956 and 22 December 1894) shows strong similarities supporting the view that all were occasions of marked lee-wave effects. The lack of long-term anemograph records at Sheffield makes statistical assessment of the possibility of recurrence of a gale of the magnitude of that of 16 February 1962 very difficult. The best estimate that can be made at present puts this gale at Sheffield in the 'once in 150 years' category. However, the estimate is very tentative.

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