M.O. 584f

AIR MINISTRY

METEOROLOGICAL OFFICE

Geophysical Memoirs No. 98
(SIXTH NUMBER, VOLUME XII)

GLAZED FROST OF JANUARY 1940

BY
C. E. P. BROOKS, D.Sc. AND C. K. M. DOUGLAS, B.A.

LONDON: HER MAJESTY'S STATIONERY OFFICE
1956

Decimal Index
551.506.2(410) : 551.574.42

Geophys. Mem., London,
12, No. 98, 1956

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Frontispiece

A86859 Wt.3490 625 4/56 Gp.961 F. & C. Ltd

GLAZED FROST OF 1940

SUMMARY

The glazed frost which began on January 25 in Great Britain was probably unequalled for persistence and extent. In Part I its development is described and mapped day by day until it disappeared on February 4—the maps show also the areas of rain and snow, the frost forming a broad and fluctuating band between them. This is followed by "eye-witness" reports including accounts of the widespread damage. A collection of photographs completes this part.

Part II describes various synoptic developments which combined to produce the severe glazed frost. Two important rain belts came in from the west and were then held up by an increasingly cold south-easterly air stream in which there was a large cross-isobaric wind component. The departures from geostrophic motion are discussed in detail. The upper air soundings do not fit into any simple scheme. A rough cross-section diagram is included, but there were no temperature soundings within the belt of glazed frost. The period January 26–28 is considered in detail, and the following few days in outline. Illustrations include surface and upper air charts and tephigrams.

INTRODUCTION

The following memoir was prepared in 1940, while the memory of the occurrence was still fresh, but publication at that time was not practicable. The glazed frost was however of so unusual a character, probably unique in Great Britain, that even after the passage of 16 years it is desirable to put the events on record.

Part I, dealing with the climatological aspects, was compiled by C. E. P. Brooks from the climatological reports at the Meteorological Office, accounts by C. J. P. Cave and others, and the experiences of the staff of the Climatology and Instruments Branches, which at the time were stationed at Stonehouse, Gloucestershire, one of the areas most affected by the glazed frost. It is illustrated by a unique series of photographs. Part II, giving an account of the synoptic developments, was written by C. K. M. Douglas with the aid of the working charts and upper air data at the Central Forecasting Office, Dunstable.

PART I—DESCRIPTION OF THE OCCURRENCES OF GLAZED FROST

§ 1—DATES OF OCCURRENCE OF GLAZED FROST

The greater part of January 1940 was cold over most of the British Isles. During the first three weeks a number of observers recorded glazed frost but the very severe occurrences were not reported until near the end of the month. The most general period was about the 15th when eight stations reported glazed frost: Boston, Boston (North Sea Camp), Earls Colne, Doncaster, Mansfield, Peterborough, Bristol and Appleby. Glazed frost near the beginning of the month was reported at Cromer, Rotherham, Wakefield, Mansfield, Bristol, Appleby, Rhyl and Newton Abbot. The longest period was at Bristol (Ham Green Sanatorium) from January 10 to 17 inclusive. Doncaster (January 10–15), Wakefield (January 3–8), and Appleby (January 10–15) each recorded six days. These glazed frosts were not severe; no reports of damage caused by them were received. On the 25th began a connected series of occurrences which for persistence and extent are probably unequalled in our experience.

The first reports came from Cupar (Fifeshire), Arbroath (Forfarshire) and Bromyard (Herefordshire) on January 25 and Marlborough (Wiltshire) on the night of January 25–26. On the 26th reports of glazed frost were received from Cupar (Fifeshire), Bromyard (Herefordshire), Mansfield (Nottinghamshire) and Sparkhill, Birmingham (Warwickshire). On the same day, hail, soft hail or granular snow occurred at a number of stations in eastern England.

From January 27 to February 3 the occurrences were much more widespread. The maps, Fig. 1, have been compiled from the monthly records sent in by observers, from letters addressed to the Editor of the *Meteorological Magazine*, and from letters sent to Mr. C. J. P. Cave as a result of an article which he contributed to *The Times*, and which he kindly lent for the purposes of the inquiry. Each map shows, by shading, the areas where glazed frost occurred on the day in question and also areas of snow or rain without glazed frost. The maps have been drawn in broad outline; on any one day there may be isolated areas within the area of glazed frost which escaped. It is proposed to describe each map briefly in turn, and then to refer in greater detail to some of the phenomena described in the letters.

On January 27 snow was falling over the greater part of northern, eastern and central England, while in western and southern Wales, south-west England and a narrow strip along the south coast the precipitation took the form of rain. Between these two areas was a broad belt where most stations reported glazed frost, generally beginning about 1700 on the 27th. The belt extended from Bala (Merionethshire) nearly to the Severn, then from Cirencester (Gloucestershire) nearly to Reading (Berkshire), and again north, west and south of London. On the edges of the two latter areas the phenomena were generally described as slight. The time of commencement was often considerably earlier on high ground than in the valleys; thus, on the high ground near Stroud (Gloucestershire), the formation began about 1700 on the 27th, while at Bristol it was not noticed until 0430 on the 28th. An isolated occurrence at Cambridge (University Farm) was based on the report " walls covered with glazed sleet ". There was also a report of slight glazed frost at Sparkhill, Birmingham, and more severe glazing to the south-west, and an isolated report from the centre of the Isle of Wight. The tongue of rain extending north-eastwards along the lower Severn Valley is especially noticeable.

On January 28 the formation of glazed frost reached its maximum along a belt which was almost continuous from the coast of north Wales into Kent. The phenomenon seems to have been especially notable in Herefordshire and again in southern England from Bristol to Farnham (Surrey), and it even included the northern part of the Isle of Wight. It was slight at Birmingham but severe in the Lickey Hills to the south-west. The areas of snow and rain changed little except for the encroachments of the area of glazed frost.

During the next few days temperature remained low and the thick coatings of ice which had accumulated on the 28th remained unbroken in many places. It was not always possible to determine whether reports of glazed frost were due to this persistence or to new formations.

On January 29 however there was a new area in south-west England extending in a narrow belt from Hartland Point to Mount Batten, Plymouth, along the edge of the last remaining area of rainfall. In southern England also glazed frost was reported for the first time at Leckford and Calshot (Hampshire) and Porton (Wiltshire), while it increased in thickness at South Farnborough (Hampshire), Farnham (Surrey), and Bridgwater (Somerset). In the north-west the formation continued at West Kirby (Cheshire) and Bala (Merionethshire).

On January 30 the area of rain was limited to the south-western half of Cornwall, and reports of glazed frost had become still more scattered. New formations were reported from Barnstaple, Newton Abbot, Paignton and Teignmouth, all in Devonshire. At Exeter (Devonshire) a drizzle which froze on contact with the ground began at 2000, the thickness of ice being from one eighth to one quarter of an inch. From Taunton (Somerset) came a report of " glacial frost at night ". There were isolated reports of new formations at Mansfield (Nottinghamshire) and Greenwich, but the reports from two areas in Wales and from southern England between Bristol and Farnham probably refer mainly to the persistence of old ice.

January 31 showed a re-development. The rain area in south-west England was restricted to the extreme tip of Cornwall, but a new rain belt extended along the south coast of England from Dorset to the Thames Estuary and another from the southern half of Wales to Cambridge. A large area of new glazed-ice formation occurred in Lincolnshire, north-eastern Northamptonshire, northern Nottinghamshire, and southern Yorkshire. At Boston (Lincolnshire) the observer recorded " supercooled rain 0630 to 0850 ". At Cleethorpes (Lincolnshire) " rain at night freezing on settlement ". At Rotherham (Yorkshire) the glazed frost came in the afternoon, at Peterborough (Northamptonshire) in the morning. There was also a renewed formation at Sparkhill, Birmingham, and at Wrexham (Denbighshire). The formation disappeared from the neighbourhood of the coast in Hampshire and Sussex, but a narrow belt of new formation extended north-eastward from London into Essex, where there was a renewal of formation at Earls Colne. Glazed frost was also recorded for the first time at Cullompton (Devonshire) and at Garvagh (Co. Londonderry). On the other hand the glazed frost in the west Midlands was apparently a persistence from earlier formations.

On February 1 there were only a few remnants of earlier ice coats, except in the west Midlands where new formations occurred north-west of Birmingham and at Stonehouse (Gloucestershire).

On February 2 so far as can be determined no new ice was formed anywhere in Great Britain and only a very few scattered remnants were left. Over the greater part of England there were light falls of snow, but in the west, and over nearly all Wales the weather was fine ; only in the south was there a considerable area of rain.

On February 3 there was a sudden change. The rainfall area expanded considerably to include nearly all the south-western half of England and most of Wales. The old areas of glazed frost on the north coast of Wales and from Birmingham northwards remained, but in addition there were new formations in Gloucestershire (Bristol and Stroud), Wiltshire (Boscombe Down), Hampshire (South Farnborough), Kent (Biggin Hill and Lympne) London (Greenwich and Southgate), and an isolated record at Cambridge (University Farm). Most of these occurred in the morning and were mainly limited to the formation of ice on the ground. Hail was recorded at several stations in west Yorkshire.

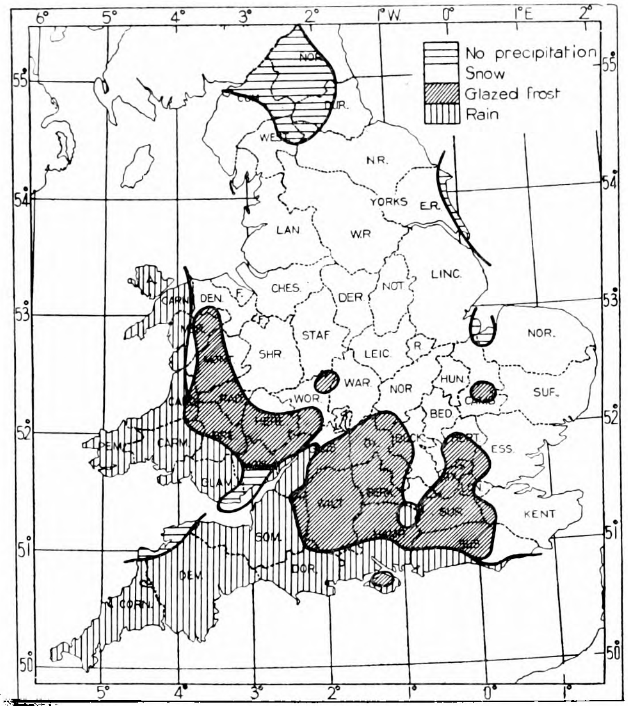
By February 4 the glazed frost had disappeared all over the country, but there were two isolated occurrences later in the month—on the 9th at Banbury (Oxfordshire) and in London (Greenwich and Southgate), and on the early morning of the 20th in Lincolnshire (Boston, North Sea Camp and Cranwell). At Banbury the thickness of ice reached ½ in.

§ 2—DETAILED DESCRIPTIONS

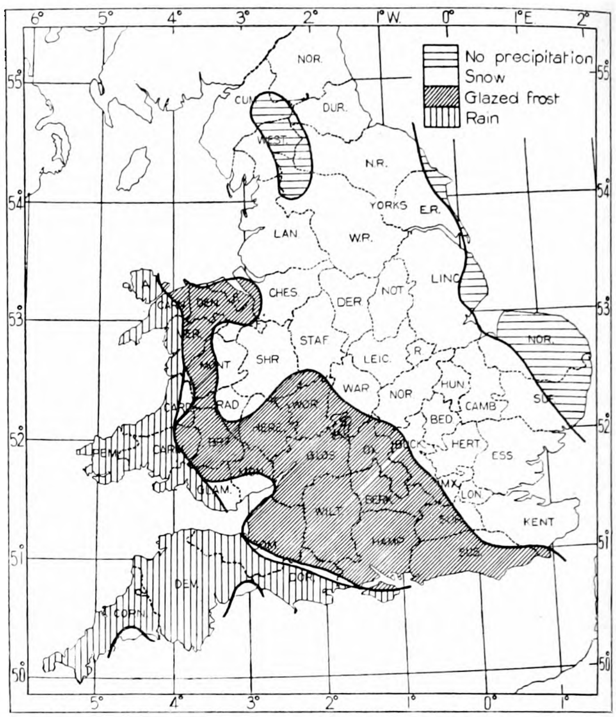
The following notes have been extracted or summarized mainly from letters addressed to the *Meteorological Magazine*, from a letter by Mr. C. J. P. Cave to *The Times*, and from correspondence elicited by that letter and kindly lent by Mr. Cave. For convenience they are grouped according to counties or groups of counties. Further details are given by Mr. Cave[1]*, and by Mr. W. I. Croome[2] of Bagendon, near Cirencester, in the *Quarterly Journal of the Royal Meteorological Society*.

Mr. R. A. S. Thwaites, in a letter forwarded by Mr. W. N. Lavis, states that in a journey by road from Wrexham to Southampton he saw little sign of damage to telephone circuits until

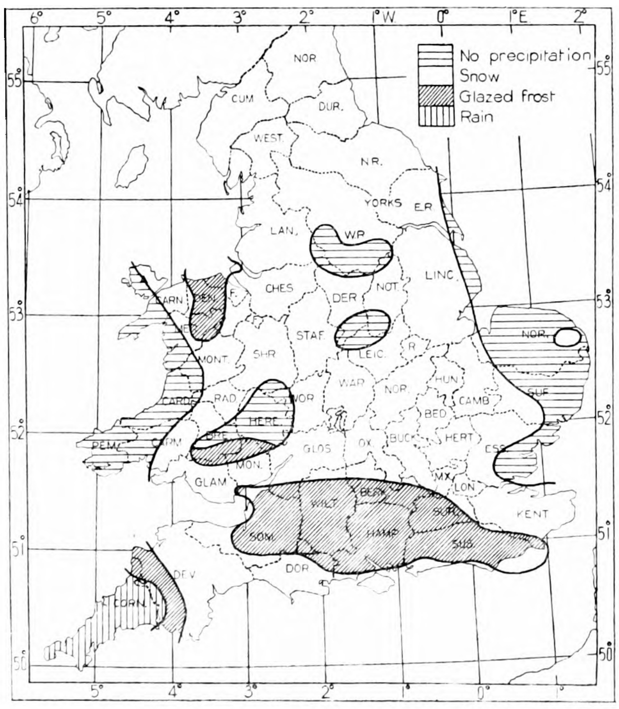
* The index numbers refer to the bibliography on p. 39.



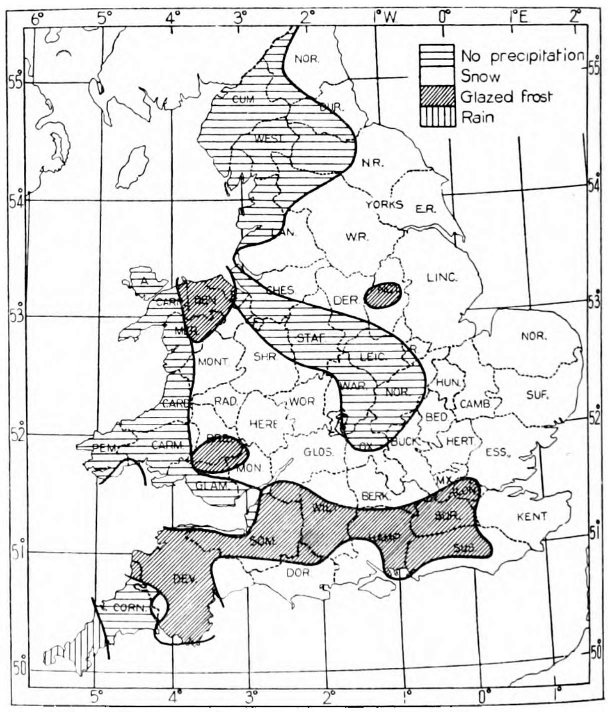
January 27, 1940



January 28, 1940

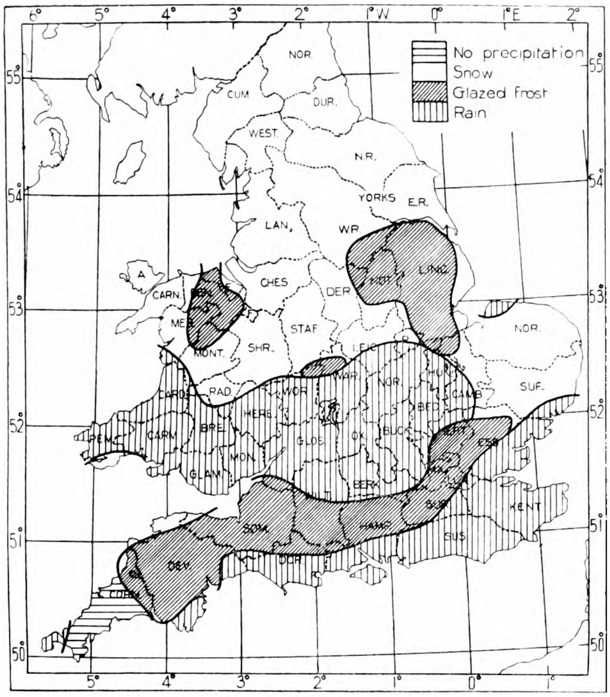


January 29, 1940

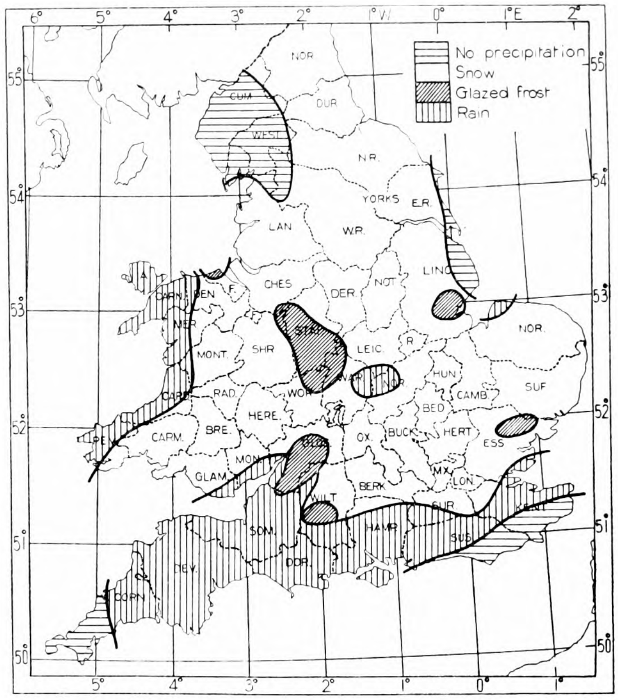


January 30, 1940

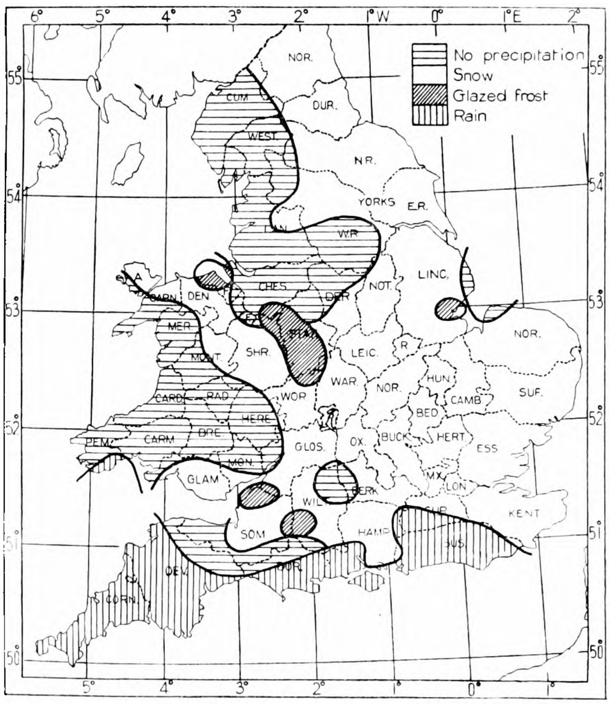
FIG. 1—OCCURRENCES OF GLAZED FROST IN



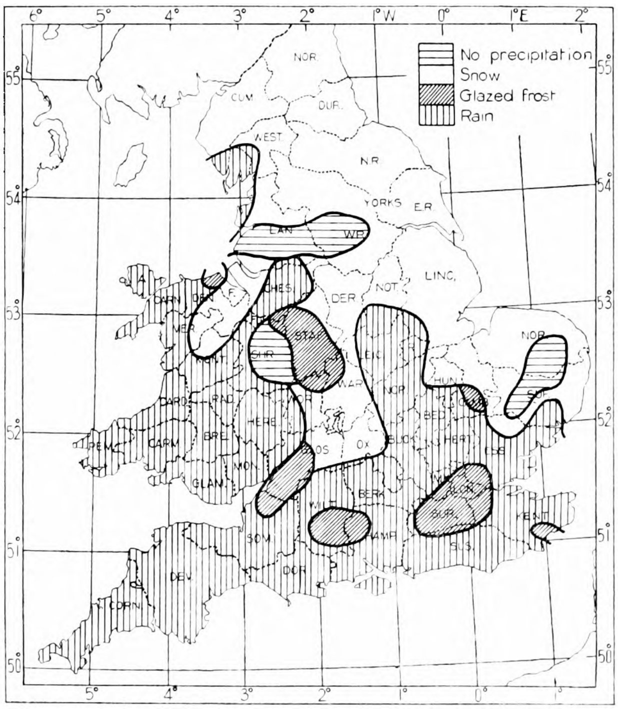
January 31, 1940



February 1, 1940



February 2, 1940



February 3, 1940

ENGLAND AND WALES, JANUARY 27–FEBRUARY 3, 1940 he reached Cheltenham ; from there to Salisbury there was not a single Post Office circuit intact and in many places for a mile on end no Post Office pole was left standing.

North and central Wales.—Mr. S. E. Ashmore described the phenomena near Bwlchgwyn, Minera (1 mile south-south-east of Bwlchgwyn) and Coedpoeth, mountain villages to the north-west of Wrexham. On January 26 heavy wet snow fell till the early afternoon. On the 27th drier snow fell ceaselessly ; this was followed by a period of sleet, rain and soft hail. During nearly the whole of the 28th the precipitation was nearly invisible, but each drop fell with a distinct sound on the snow, walls and other objects, and there it froze immediately. The air temperature was about 25°F. After this icing, further snow fell until the morning of the 29th. The snow had a hard surface crust strong enough to support the weight of pedestrians and, in many places, motor cars. Every twig had ice, often well over 2 in. thick, not surrounding the object centrally but adhering to the south-east (windward) side. Every small reed or stem sticking out of the snow had this ice on its south-east side. The only objects on which ice formed concentrically were those which had previously been horizontal, such as telegraph wires, which were encased by rough cylinders of ice in some cases " so thick that I could scarce encompass them with my two hands ". There were further light snowfalls, and after January 31 there was nearly continuous mist, accompanied on the 31st by glazed frost (rain above 32°F. falling on surfaces below that temperature) thus increasing still further the ice deposit. After this the mist gave rise to the formation of rime, still on the south-east side of objects, so that by February 3 it was common to see small stems less than $\frac{1}{8}$ in. thick supporting 5 in. of ice to one side—about $3\frac{1}{2}$ in. of clear ice and $1\frac{1}{2}$ in. of the copious feathery deposit of rime. The thaw began slowly on February 4, and by the end of that day, most of the ice had detached itself from its supports and fallen on to the snow beneath.

At West Kirby, Cheshire, a prolonged fall of " frozen rain " began at 1530 on January 27 and continued almost without interruption for over 30 hr. followed by a heavy fall of snow. This was apparently just outside the edge of the north-western area of glazed frost, the rain having frozen before reaching the ground.

At Bala, Merionethshire, moderate to heavy rain commenced at 1300 on the 27th and continued until about 0400 on the 28th. It was freezing as it fell after 1800 on the 27th. Mr. W. M. Walker described the thickness of ice as $\frac{1}{2}$–1 in. ; between Bala and Trawsfynydd in a stretch of about $2\frac{1}{2}$ miles every telegraph post was either broken or bent. There was intermittent rain on the 28th which again became ice as it fell. About 11 miles east of Bala the precipitation was in the form of snow, and there were deep drifts as the lower ground was reached in Denbighshire and Cheshire. Even up to 2,000 ft. there was no snow in the Bala district.

At Rhayader, Radnorshire, according to Mr. E. Vaughan, rain fell with a SE. wind from about 1500 on the 27th until the early hours on the 28th. After about 1700 on the 27th it changed to ice immediately on coming into contact with any object. On the morning of the 28th the ice was $\frac{3}{4}-1$ in. thick on the upper side of all twigs and rarely more than $\frac{1}{4}$ in. thick below. The grass minimum thermometer was put out at 1800 and read 28°F. on the morning of the 28th. It was encased in a mass of ice, and Mr. Vaughan suggests that 28°F. was the temperature of the falling rain. The ice covered everything from January 28 to February 3.

Similar conditions were general in Montgomeryshire, Radnorshire, Breconshire and the high ground of Cardiganshire but not near the sea. The ice was much thicker on the high ground than in the valleys. On the hills the rushes and coarse grass were covered with an average of 2 in. of ice. Ice was seen on the tail feathers of crows and pigeons, and a shepherd reported that he found a buzzard on the mountain with its feet frozen to the ground although it was still alive. Sheep which were lying down during the night were unable to rise until the ice had been broken round them. Mountain ponies on the Plynlimon moors were found dead encased in ice.

Herefordshire and Worcestershire.—At Ross-on-Wye Mr. F. J. Parsons recorded two glazed frosts. The first occurred on January 27–28. Rain fell on the evening of the 27th and began to freeze about 2200. On the 28th rain fell on and off most of the day interspersed with drizzle which froze as it fell. Footpaths and roads were alternately like sheets of glass or covered with a disintegrated mass of small pieces of ice. Icicles hung from the lower side of the grass minimum thermometer. The metalwork on top of the observatory tower was encrusted with a layer of clear ice $\frac{1}{8}$ – $\frac{1}{4}$ in. thick. The wind-vane pole was coated, chiefly on the windward side (east and north-east). In some parts the trees and telephone wires gave way. The second glazed frost occurred on February 3 when rain and drizzle froze and formed a layer of clear ice on the surface of the snow.

At Malvern according to Mr. R. Moreland the formation occurred on the night of January 27–28. The ice on a twig $\frac{3}{16}$ in. across reached a diameter of $1\frac{3}{8}$ in. mainly on the windward side with small pendant icicles. The telephone wires had icicles about $\frac{3}{4}$ in. apart.

Somerset and Devon.—The formation of glazed frost began appreciably later than to the north and east. At Stogursey near Bridgwater, Lord St. Audries wrote that rain continued almost without ceasing from midday on January 26 to 1000 on January 29. The rain began to freeze as it fell at about 2100 on the 28th, but at higher levels the phenomenon began about midday on the 28th. Great damage was done.

Near Exeter, according to Mr. W. N. Lavis, there was continuous fine rain and drizzle throughout January 28. On the 29th the rain was intermittent ; at 1400 frozen rain commenced to fall, followed by a fairly heavy fall of clear-ice cubes, rather like coarse granulated sugar, covering the ground in places. At 1500 the ice cubes gave place to snow ; for a short period both fell together. On the 30th some scattered snow fell early with wind from ENE. At 2000 the air temperature was 29°F. and slight drizzle was falling, which froze on contact with the ground ; this persisted until 2030, giving an ice coating on walls, fencing and trees of $\frac{1}{8}$ – $\frac{1}{4}$ in.

At Princetown, Dartmoor, there was no true formation of glazed frost but extensive formation of rime on trees, bushes and grass, telephone wires, etc. on the 29th and 30th.

Warwickshire.—Mr. C. K. M. Douglas reported that on January 27–28 there was little glazed frost in Birmingham, but a great deal on the Lickey Hills to the south-west, where a number of young pines 20–30 ft. high in a valley were snapped right off. On the hills exposed trees with more ice suffered less. On the 31st there was supercooled drizzle and more glazed frost in Birmingham than on the 27th. At Sparkhill the observer first noted glazed frost on the 26th. Twigs were appreciably ice-coated.

Gloucestershire.—At Stonehouse the formation of glazed frost began very early on the morning of January 28 and formed a coating of ice over 1 in. thick. On a section of telephone wire the cylinder of ice was almost $2\frac{1}{2}$ in. in diameter, and 130 times the weight of the wire alone. The ice was thickest on the windward or eastern side of exposed objects. Great damage was done to trees and telephone wires. There were further occurrences on February 1 and 3, the latter began at Woodchester ($2\frac{1}{2}$ miles south-west of Stroud) a few minutes before midnight on the 2nd.

On Painswick Hill, about 3 miles north-east of Stroud, at an elevation of 750 ft. Mr. R. H. Ellis states that on January 27 rain fell all the afternoon. About 1600 the temperature fell considerably and by 1700 the surface of the ground was covered by glazed frost. Soon afterwards rain fell heavily and froze on shrubs, trees, grass, etc., which were all heavily sheathed in ice by 2000.

At Bristol (Horfield) photographs by Mr. G. H. Brown on the morning of January 29 show deposits of clear ice with long icicles hanging from the bars of gates (Plate IV).

Mr. W. I. Croome reports that over large stretches of the Gloucestershire Cotswolds practically all telephone wires were brought down. Sir John Percival and Sir John Birchall weighed sections of telegraph wires and calculated that 23 wires between 2 posts carried a total weight of just over $11\frac{1}{4}$ tons of ice. Under this weight the posts snapped like match sticks. Among the trees ash, birch, oak and sycamore suffered most, especially birch; some beeches with only one side exposed to the driving supercooled rain split down the middle under the weight of ice. A small spray of beech twigs weighing $3\frac{1}{2}$ oz. carried 3 lb. $4\frac{1}{2}$ oz. of ice. On February 3 the ice began to melt, and on the 4th there were floods 4–5 ft. deep in the valley at Bagendon near Cirencester. The church was flooded to the top of the pews.

Wiltshire and Dorset.—A series of excellent photographs by the Royal Air Force taken at Hullavington (Wiltshire) show heavy formation of hard clear ice on the windward side of vegetation. Horizontal edges show numerous fine pendant icicles. Wire netting of diamond mesh was not completely filled up by ice (Plate II).

Full details for Marlborough were supplied to Mr. C. J. P. Cave by Mr. L. G. Peirson and members of the Marlborough College Natural History Society. A small ice storm with very noticeable " ticking " occurred on the night of January 25–26. Each drop of rain as it fell made a " tick " or " click ", even if it came through the open window and fell on a cork carpet. Next morning the window-pane and sill and smooth paving stones were pimply with drops of ice. On January 27 there was a steady E. wind with considerable rain and fog. A slight ice storm began about 1900 but lasted only a short while. Early on the 28th there was 4 mm. (about $\frac{1}{8}$ in.) of ice. The great deposition of ice began about 1600. Trees started to break about 1800 and breaking continued until after midnight by which time most of the damage was done. No appreciable amount of ice formed after dawn on the 29th. On horizontal wires and twigs the deposit was uniform and cylindrical with occasional small pendants. On vertical wires and twigs the deposit was almost entirely on the east side. On the higher ground telephone wires reached a diameter of $1\frac{5}{8}$ in.; on the east side of vertical posts the thickness of ice was just under 2 in., and on flat surfaces $1\frac{1}{2}$in. In the valley the deposit on flat surfaces was $\frac{9}{16}$ in. thick, and stems of grass became about $\frac{5}{8}$ in. in diameter. Wire netting of moderate mesh became a solid wall of ice; mackintoshes and capes froze to the shape of the wearer and umbrellas once opened could not be closed.

In west Wiltshire, Dr. E. R. Gunther[3] describes the glazed frost as beginning to form in the early morning of January 28. Ice formed roughly elliptical fingers on the exposed and upper sides of supports, which occupied a position near the periphery in the longer axis. Around telegraph wires the ice was, however, circular (about $\frac{3}{4}$ in. in diameter), which suggests that the wires had undergone torsion. Icicles hung from some of the trees and from the eaves of buildings but were not a conspicuous feature.

At Savernake Mr. R. C. B. Gardner found the ice deposit to be over 2 in. in diameter on twigs of ash and well over 1 in. on telephone wires. In Savernake Forest 10 additional kilns were installed to make charcoal entirely from the thousands of tons of branches broken from beech, ash and oak trees by the ice.

At Zeals, Wiltshire, according to Mr. A. O. Dyer, the ice on telephone wires had a diameter of $\frac{3}{4}$ in. At Gillingham, Dorset, on the 29th, his umbrella became a solid sheet of thin ice with heavy icicles depending from the ribs.

At Swanage, Dorset, on the 29th the observer reported frozen rain 1240–1530 changed to hard snow blizzard.

Oxfordshire.—At Sibford Ferris, 6 miles south-west of Banbury, there was, according to Mr. J. Lamb, little damage in the valley at 600 ft., but 1 mile away at 800 ft. the ice coating was much thicker, due to the stronger wind.

At Henley-on-Thames Mr. R. Michaelis states that as the liquid rain touched one's hat or coat or the road it froze and bounced off in little icicles.

Hampshire.—A number of letters testify to the intensity of the phenomenon in Hampshire. A letter from Mr. C. J. P. Cave published in *The Times* for February 13, 1940 and an account in the *Quarterly Journal of the Royal Meteorological Society*[1] give full accounts of the phenomena at Petersfield. Temperature fell steadily from 40°F. at midnight on January 26 to 29°F. at 0900 on the 28th. On the evening of the 27th very fine rain, hardly more than mist, began to fall and before 1800 there was a very fine coating of ice on exposed surfaces. By this time the air temperature was just above 31°F. The ice formation seems to have gone on all night, and by the morning of the 28th it was ½ in. thick on the thermometer screen. The precipitation continued all day, and by the morning of the 29th the coating on the screen was about 1 in. thick. Telephone wires were encased in ice over 1 in. in diameter. Blades of grass carried cylinders of ice about 1 in. across but mostly on the windward side ; the ice was perfectly transparent and the grass could be seen inside.

At Micheldever Mr. J. F. Nixon records that on the morning of January 28 rain fell with an air temperature of 28°F. and froze as it struck the windows. Between 0800 and 1000 on the 29th the temperature had fallen to 24°F. and the rain froze to ice droplets in the air. By 1100 the precipitation had turned to snow. He also saw some pheasants which were unable to fly because their wings had become glued. On the coast at Portsmouth the rain did not turn to glazed frost until 1700 on the 28th.

At Andover Major G. W. Quin Smith recorded that wire netting was converted into a smooth sheet of ice. The telephone wires on Ashdown Ridge were covered with cylinders of ice about 2 inches in diameter. In the woods a rabbit was killed by a piece of ice from a small hornbeam. Enormous damage was done to woods. Falling branches broke up on striking the ground; eight fractures were counted in the main branch of a large beech.

At Liss Mr. B. Schaffter saw icicles formed on the telephone wires ; the wires afterwards twisted with the weight of ice so that the spikes stood upwards. Icicles 2 in. long formed regularly on the power wires at Petersfield and on the points of twigs near Havant.

At East Meon near Petersfield Mr. W. Manning described icicles on overhead wires, 3 in. long and 2 in. apart. Telephone wires carried symmetrical cylinders of ice about 1 in. in diameter, but on thicker wires transverse to the wind the deposit was almost entirely on the windward (east) side.

At South Farnborough the ice coating was ¼ in. thick on the morning of January 28 (thicker on surfaces exposed to the wind, which was E. force 3–4. By the evening the thickness had increased to ½ or ¾ in. Temperatures were between 28° and 32°F. and icicles 6 ft. or more in length were formed. Snow fell heavily on the 29th, but on the evening of the 30th slight drizzle fell and produced a little more ice on snow-free surfaces.

Surrey and Sussex.—The effect of the glazed frost on transport was especially disastrous over the area served by the electric trains of the Southern Railway. In some extracts from the *Southern Railway Magazine*[4], kindly supplied by Mr. W. N. Lavis, it is stated that telegraph wires of about ¼ in. diameter were coated with cylinders of ice nearly 3 in. in diameter. The 4 ft. 6 in. diamond-mesh fencing had in some districts been converted into a wall of ice 5 in. thick, with the wire fencing encased in the middle.

The thickness of ice appears to have been distributed rather irregularly ; at Farnham, Surrey, stems 4⅛ in. in diameter carried ice cylinders of 1½ in. At East Grinstead, Sussex, Mr. I. D. Margary gave the thickness of the coating, on fences etc. as only $\frac{1}{16}$ in. At Eastbourne (Sussex) the railings, flagstaffs, etc. along the sea front were coated with ice only on the seaward (south-east) side.

Buckinghamshire.—In the northern Chilterns an ice storm lasted a few hours on January 26, doing extensive damage to trees and shrubs but not to telegraph or telephone wires. This district suffered severely from snow, however, as described by Mr. E. L. Hawke[5]. A blizzard set in on January 27 and continued until the 29th, the wind on the 29th reaching Beaufort force 7 or 8 (9 in gusts). The snow formed great drifts in the northern parts of the Chilterns.

Eastern England.—The occurrences of glazed frost here were local and apparently nowhere very severe.

§ 3—TEMPERATURE

Fig. 2 shows the distribution of maximum temperature on January 27. Isotherms are drawn for every 5°F. and a broken line for 32°F. A large part of England south of 54°N. had a maximum temperature of between 30° and 32°F., but in the south-west there was a rapid rise to above 50°. Between January 28 and 30 there was a slow general fall of temperature. The warm area retreated towards the south-west and its boundary became less marked, while over most of the remainder of the country, apart from coastal districts, the temperature failed to reach 30°F. The distribution of maximum temperature on January 30 is shown in Fig. 3.

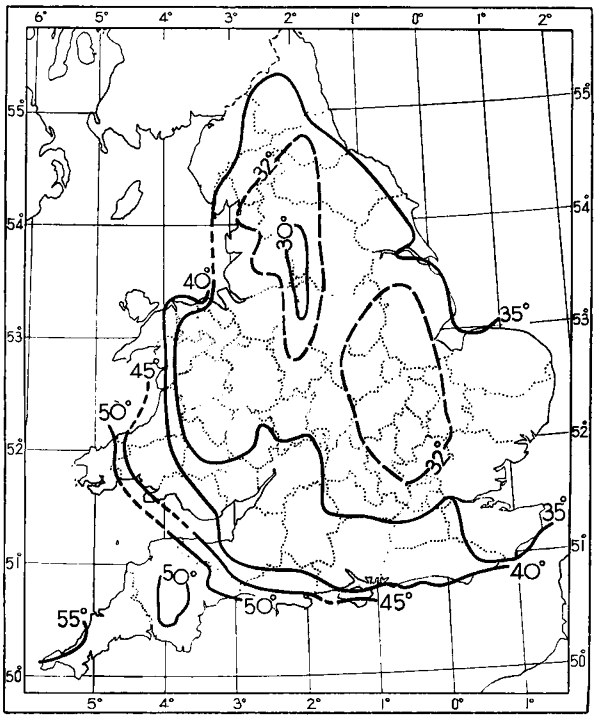


FIG. 2—MAXIMUM TEMPERATURE, ENGLAND AND WALES, JANUARY 27, 1940

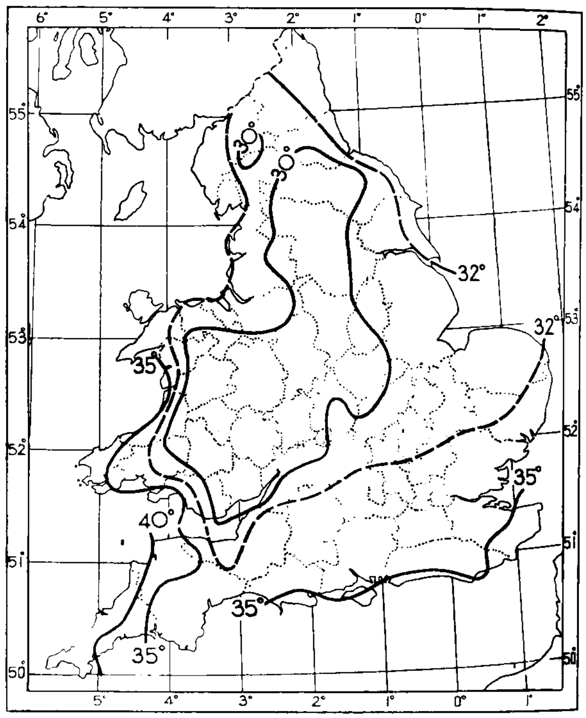


FIG. 3—MAXIMUM TEMPERATURE, ENGLAND AND WALES, JANUARY 30, 1940

The variations of temperature at Ross-on-Wye (Herefordshire) are shown in Fig. 4.

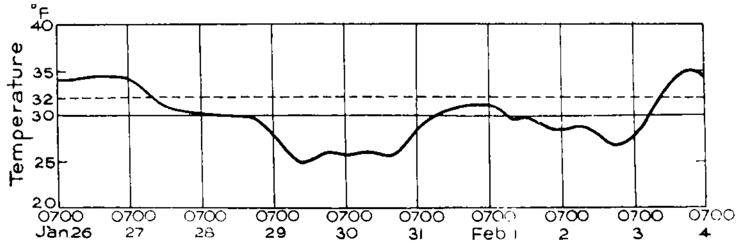
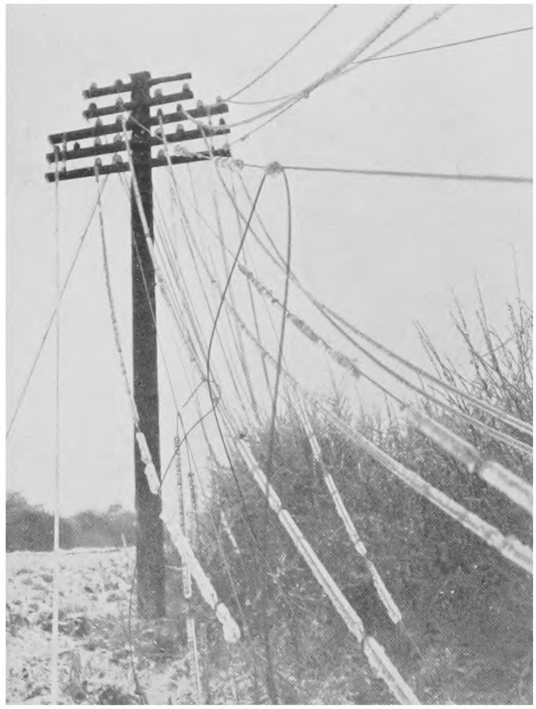


FIG. 4—TEMPERATURE AT ROSS-ON-WYE, JANUARY 26 TO FEBRUARY 4, 1940

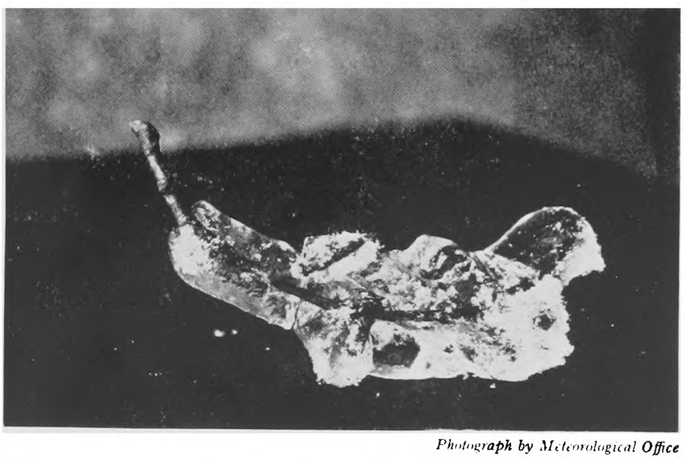
Photograph by R.A.F.

Ice formation on grass, Hullavington, Wiltshire, January 30, 1940



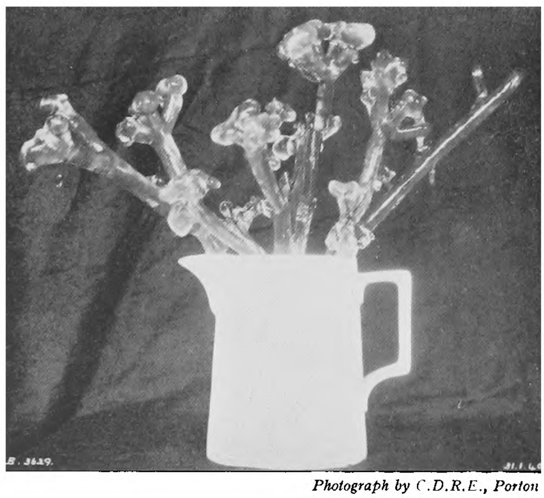
Photograph by R.A.F.

Close-up of telephone wires, Hullavington, Wiltshire



Photograph by Meteorological Office

Twig, Stonehouse, Gloucestershire, January 29, 1940

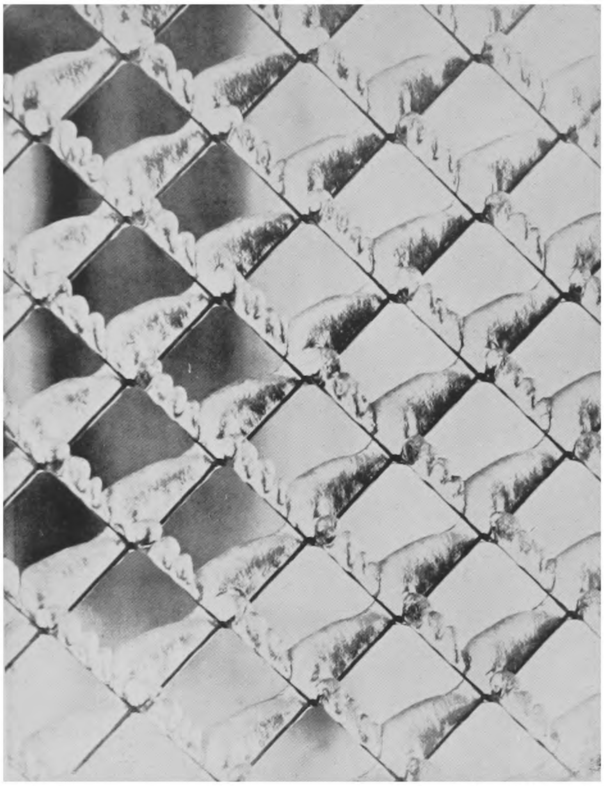


Photograph by C.D.R.E., Porton

Twigs, Porton, Wiltshire, January 29, 1940

SMOOTH CLEAR ICE OF UNIFORM THICKNESS

Plate II

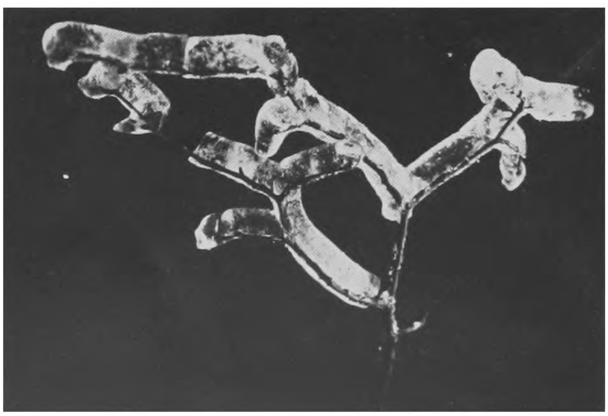


Photograph by R.A.F.

Close-up of wire netting, Hullavington, Wiltshire, January 30, 1940

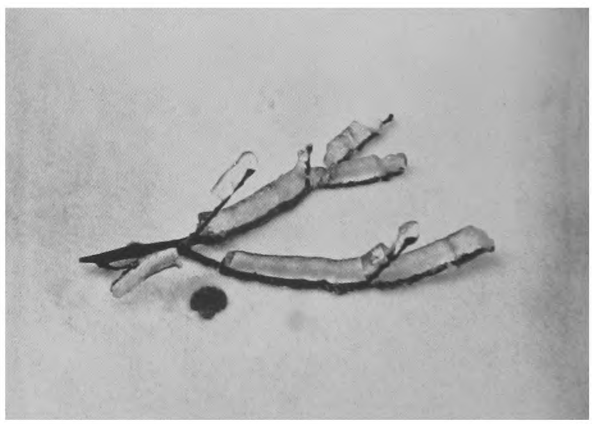
Photograph by R.A.F.

Sapling, Hullavington, Wiltshire.



Photograph by Meteorological Office

Twig, Stonehouse, Gloucestershire, January 29, 1940



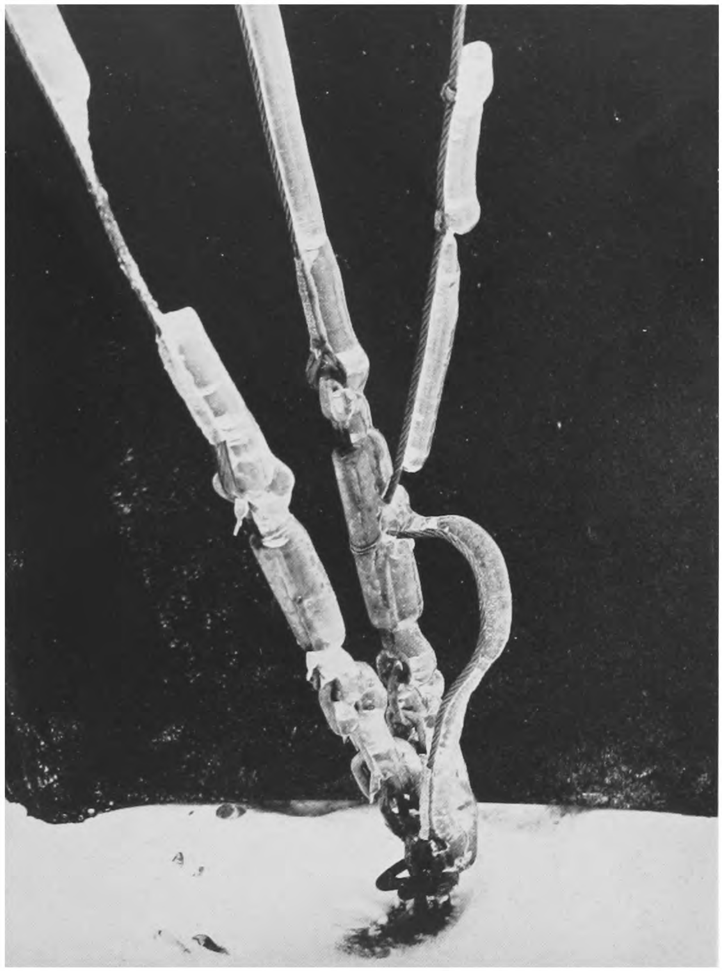
Photograph by R.A.E.

Twig, South Farnborough, Hampshire, January 28, 1940

SMOOTH CLEAR ICE ON THE WINDWARD SIDE

Photograph by Meteorological Office

Shrub, Stonehouse, Gloucestershire, January 29, 1940



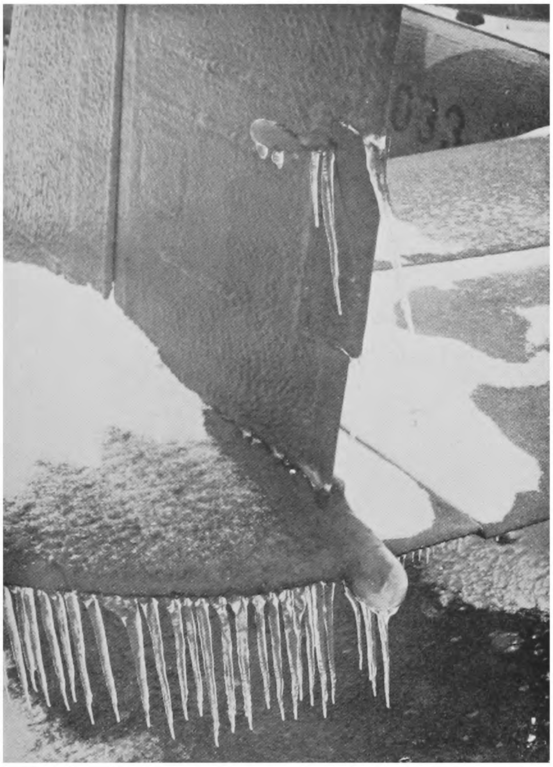
Photograph by R.A.F.

Cables, Harwell, Berkshire, January 29, 1940

Reproduced by courtesy of the late I.A.C. Campbell

Sapling, Wellington College, Berkshire

SMOOTH CLEAR ICE ON THE WINDWARD SIDE

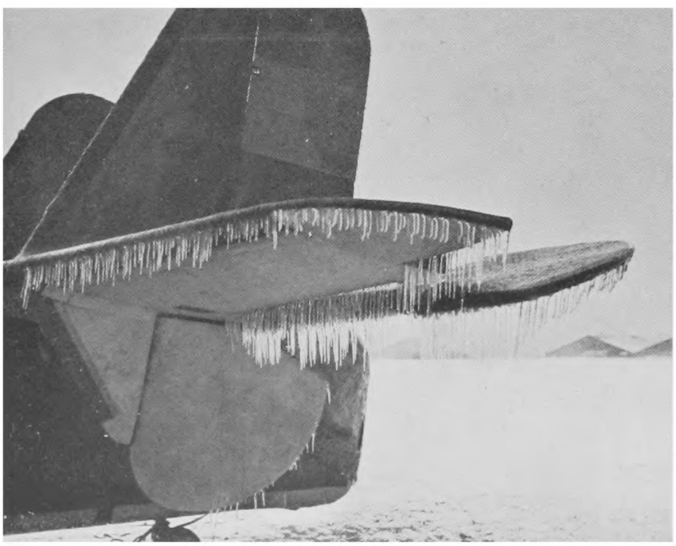


Photograph by R.A.F.

Aircraft tailplane, South Farnborough, Hampshire, January 29, 1940

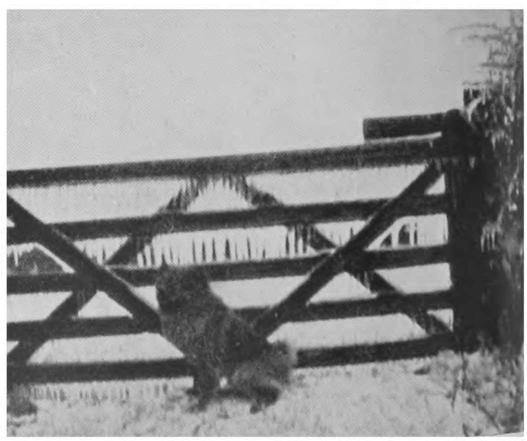
Photograph by R.A.F.

Fire bell, Hullavington, Wiltshire



Photograph by R.A.F.

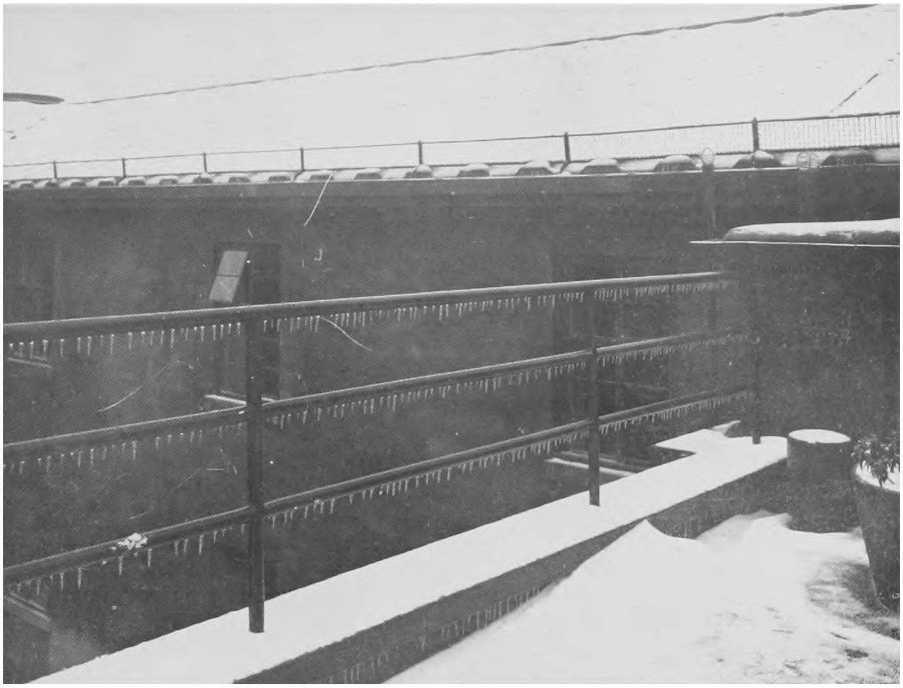
Aircraft tailplane, South Farnborough, Hampshire, January 29, 1940



Reproduced by courtesy of G. H. Brown

Wooden gate, Horfield (Bristol), Gloucestershire, January 29, 1940

SMOOTH CLEAR ICE FORMING LONG ICICLES

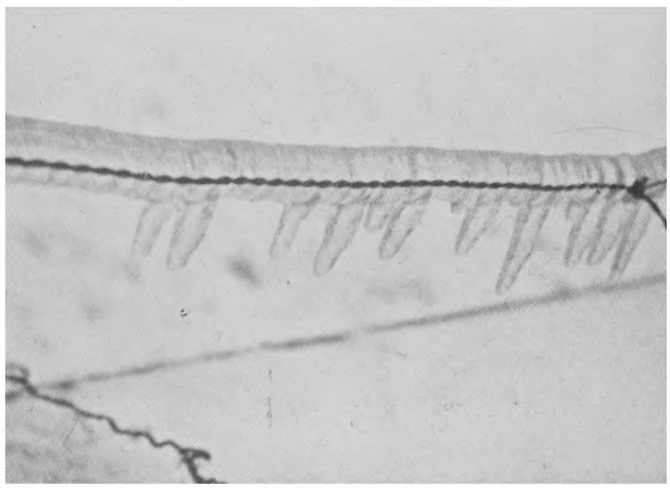


Reproduced by courtesy of the Bristol Aeroplane Co. Ltd

Roof railing, Filton (Bristol), Gloucestershire, January 28, 1940

Photograph by Meteorological Office

Shrub, Stonehouse, Gloucestershire, January 29, 1940



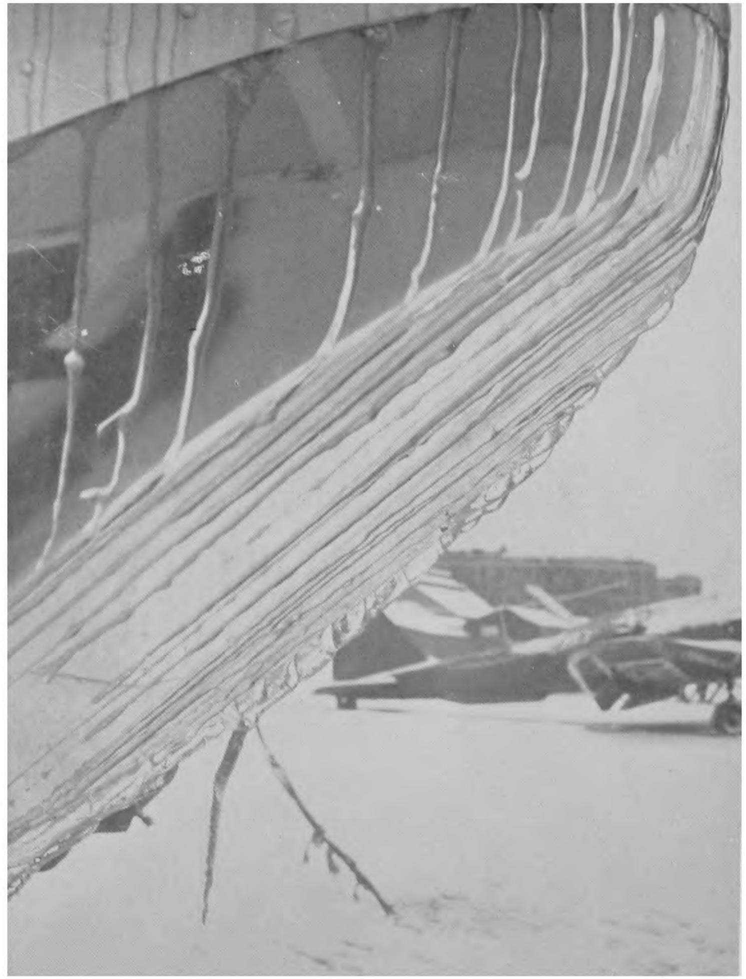
Reproduced by courtesy of the late Sqdn.-Ldr J. M. Donaldson

Wire cable, Filton (Bristol), Gloucestershire, January 29, 1940

SMOOTH CLEAR ICE FORMING LONG ICICLES

Photograph by R.A.E.

Ice on aircraft, January 29, 1940



Photograph by R.A.E.

Ice on aircraft, January 29, 1940

ROUGH ICE AND CLEAR ICE ON AIRCRAFT

Reproduced by courtesy of R. A. S. Thwaites

Close-up of electric cable, near Wrexham

Reproduced by courtesy of R. A S. Thwaites

Pylon, near Wrexham

Reproduced by courtesy of R. A. S. Thwaites

General view of electric cable, near Wrexham

ROUGH OPAQUE ICE

Plate VIII

Photograph by R.A.F.

Young trees bent by weight of ice, Harwell, Berkshire, January 29, 1940

Photograph by R.A.F.

Sapling bent by weight of ice, Hullavington, Wiltshire

Photograph by R.A.F.

General view, Chippenham Road, near Hullavington, Wiltshire

TYPES OF DAMAGE CAUSED BY THE GLAZED FROST

Photograph by Meteorological Office

Damaged trees on the Minchinhampton Rd., Cowcombe Hill, Gloucestershire, January 29, 1940

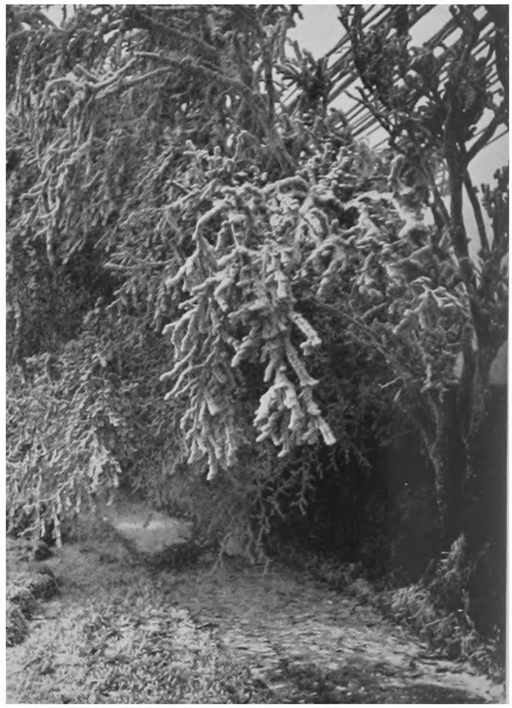
Reproduced by courtesy of Sir Graham Sutton

Tree broken by the weight of ice, Porton, Wiltshire, January 29, 1940

TYPES OF DAMAGE CAUSED BY THE GLAZED FROST

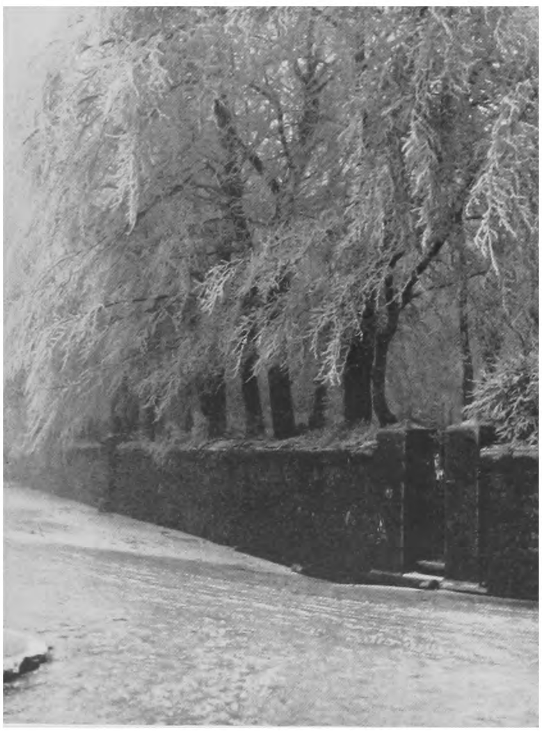
Reproduced by courtesy of J. Hyde

First day rime forming, January 29, 1940



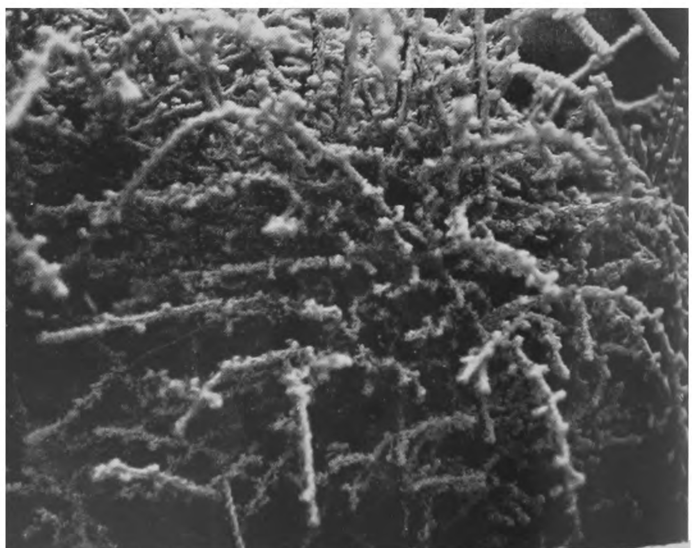
Reproduced by courtesy of J. Hyde

Rime, January 30, 1940



Reproduced by courtesy of J. Hyde

Rime, January 30, 1940



Reproduced by courtesy of J. Hyde

Close-up of bushes, January 30, 1940

RIME, PRINCETOWN, DEVONSHIRE

§ 4—PHOTOGRAPHS

The photographs of glazed frost shown in Plates I–X fall into four groups, but the distinction between the groups is not of great importance.

The first group (Plate I) shows the ice evenly distributed round the object. The twig from Stonehouse is a remarkably good example, being almost exactly central in a thick tube of ice. This is probably due to there being enough residual water after the initial freezing of the drop to be blown to leeward before it froze. Some telephone wires were also found to be the centres of symmetrical cylinders of ice, but in these cases the ice may have been deposited on the upper windward side until the wire rotated under the weight. That this actually happened is shown by an observation of icicles which pointed upwards, owing to a subsequent rotation of the wire.

The second group (Plates II–III) shows clear hard ice deposited on the windward side of the object (twig, wire netting) or on the upper surface (branches). This suggests that the supercooled raindrops froze immediately they struck the object and that there was not sufficient residual water to be blown or flow to the other side. This was probably only possible if the drops were very small.

Examples of icicles are shown in Plates IV and V. This represents a further stage, in which there was a good deal of flow. The tailplane at South Farnborough is typical of many. The long icicles on a plant near a pipe at Stonehouse are probably due to the warmth of the building. The diameter of the wire cable at Filton was 2·5 mm. while the average thickness of the glazed frost on it was 15 mm.

Plates VIII and IX represent five examples of the effect of the weight of ice. The upper photograph on Plate IX shows a row of trees along the Minchinhampton Road near Cowcombe Hill, Stroud, Gloucestershire, with some branches bent down to the ground and others broken off; in some cases the drooping branches were frozen to the ground by the glaze, and were not released until the thaw; on the leeward side the branches seen through the gap were practically free of ice. The lower photograph on Plate VIII is typical of many miles of telegraph line in southern and south-western England. The wires had been dragged down, stretched or broken by the weight of tons of ice. In this example no poles were snapped off or pulled out of the ground, but the nearest one to the camera is leaning at a perilous angle.

Other photographs accompany articles published in the *Meteorological Magazine*[6].

PART II—SYNOPTIC ASPECTS

§ 5—SEQUENCE OF SYNOPTIC DEVELOPMENTS

The great ice storm at the close of January 1940 and the exceptionally heavy snowfall over a larger area to the north-eastward, extending to Scotland, was preceded by a long spell of severe weather; cold easterly or northerly winds had prevailed in alternating spells with only short intervals since December 11, 1939. Frost began in the south on December 22, and from December 27 onwards till early February the only important break was from January 6 to 8. The frost was at times very severe and the ground was frozen to a considerable depth.

The ice storm was a glazed frost due to supercooled rain, and not merely rain frozen by a cold ground, but the fact that the air received no appreciable heat from the ground during its westward flow, in spite of the brief thaw just before the ice storm, was a contributory factor in keeping its temperature just below freezing point. A severe ice storm is very rare in Great Britain, although the type of pressure distribution shown on the accompanying charts is relatively frequent. When there is warm air over cold air, heat is imparted to the cold air from above by turbulence and radiation, and exceptional conditions are required to keep the temperature of the surface air below the freezing point. The severe cold on the Continent and the low temperature of the intervening sea (which can be inferred) were important factors on this occasion. The abnormal amount of ice deposited was due to the slow movement of the front, to the large amount of rainfall associated with the convergence to the front, to Atlantic fronts which amalgamated with the main front, and to the high water content of the tropical air, at least in its lower regions.

Between January 22 and 24 a ridge of high pressure moved south-east across the British Isles ; the very cold weather gave place to SSW. winds, and temperature rose generally to between 38° and 42°F. on the 25th, but slight night frost continued in most areas and the ground was not appreciably thawed. Returning polar air which had been warmed, first off the south-west coasts of the British Isles and then over the North Sea, had penetrated to the south Baltic, and even on January 26 when the wind had recently changed to E. in southern Scandinavia, temperature was not really low in that area. The source of the cold air which reached the British Isles at the beginning of the ice storm was over and to the east of the Low Countries and north-east France.

The dominant feature of the pressure distribution during the period was the Scandinavian anticyclone, but on the 26th this was a new feature on the map. From the 14th to the 23rd pressure had been highest over north-east Greenland. As this anticyclone declined, a small fragment of it drifted away south-eastwards to Scandinavia where it developed again. Pressure at its centre was 1020 mb. just north of the Faeroes on the 24th, 1028 mb. off Norway on the 25th, 1036 mb. over Scandinavia on the 26th, and finally 1040 mb. over the same area on the evening of the 28th, when the highest pressure was attained.

The other major feature was the low pressure on the Atlantic from the 23rd onwards, with an extensive warm current to the west and south-west of the British Isles, consisting alternately of tropical air from south-west of the Azores and of very old polar air which had swept round from the west side of the Atlantic and had penetrated almost as far south as the Azores before advancing north-eastwards to our south-west coasts. The cold front on the 26th marked the arrival of old polar air of this type, and temperature at Valentia fell from 52° to 48°F. between 0100 and 0700, while the dew point fell from 51° to 44°F. In persistently mild south-westerly weather all the fronts are of this type and are of great dynamical importance, the temperature changes being much larger up aloft than at the surface. On this occasion the indirect effect of this front on the pressure changes and the accompanying weather was very important, even though the change of surface temperature was confined to the south-west coasts and was small in comparison with the difference between the continental and Atlantic air masses. The warm front shown over Ireland on the synoptic chart for 0700 on the 26th had first given rain in Ireland on January 23, with 0·85 in. at Valentia in the 24 hr. ending 0700 on the 24th, and had subsequently moved very slowly. The rain ahead of it diminished, and by 0700 on the 26th there was only slight rain at a few widely scattered places, including London. There was a layer of cloud over Mildenhall from 4,000 to 12,000 ft. and a diffuse surface of discontinuity with its base at 5,100 ft. (see tephigram for the morning of the 26th). The cold front had caused a renewal of the heavy rainfall in Ireland, and Valentia had 1·18 in. in the 24 hr. ending at 0700 on the 26th. It was this belt of rain which advanced eastward on the 26th and started the period of heavy precipitation over most of the British Isles. Temperature on the 26th was above freezing point almost everywhere, and precipitation took the form of rain, wet snow, or pellets of frozen rain. There was little true glazed frost on that day, as it was not cold enough near sea level in the areas which had rain, but E. L. Hawke[5] reported it from the northern Chilterns.

The synoptic chart for 1300 January 26 shows that the cold front quickly cut through the narrow strip of warm air and became an occlusion which at low levels was of pronounced warm-front type but higher up was of cold-front type. Over Aldergrove there was a pronounced fall of temperature above about 4,000 ft. between 0715 and 1245 on the 26th, while at Mildenhall there was a slight fall above 8,000 ft. between 0715 and 1300 on the 26th, and also a fall above

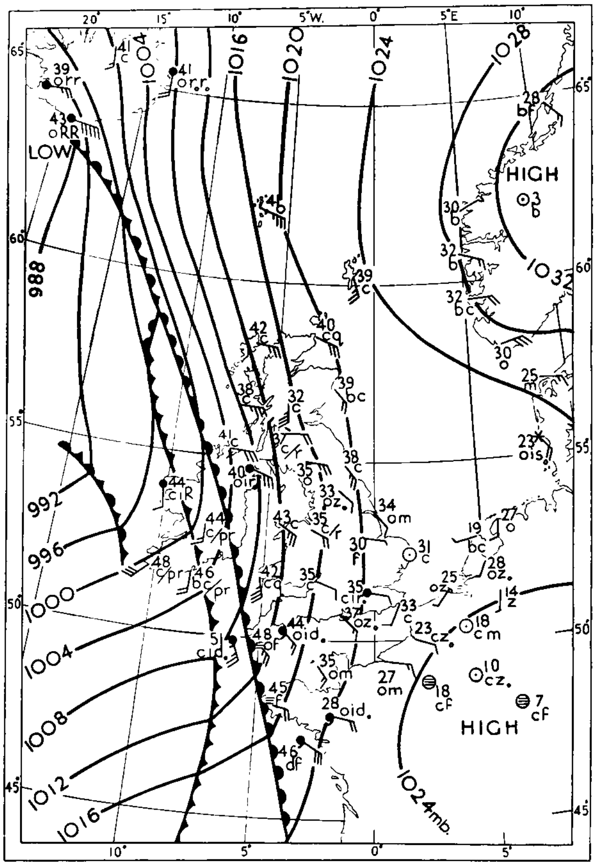
4,700 ft. between 1300 on the 26th and 0700 on the 27th, though high up it did not fall nearly so low as it did at Aldergrove on the 26th (see tephigrams for the 26th and 27th). The occlusion did not reach Mildenhall, and the changes must be interpreted in terms of continuous fields of temperatures up above rather than in terms of a surface of discontinuity. The matter is discussed more fully in the section dealing with the upper air.

Hail was reported on the 26th from several places in the Midlands and east and south-east England ; this was not true hail but rain frozen after falling through an inversion. Possibly the rain was of a slightly sleety type, with a few crystals still in the drops, and so froze immediately on reaching the freezing layer. At Mildenhall there was no actual thaw layer above about 2,700 ft., but judging from the 1300 temperature at that station it is probable that further westwards and southwards there was a thaw layer somewhere between 4,500 and 6,000 ft., and a freezing layer between (about) 2,700 and 4,500 ft. At Birmingham slight rain turned to heavy frozen rain, and this was soon followed by a heavy but brief fall of wet snow which lay to a depth of some 2 in. The thaw layer above the inversion was evidently soon eliminated, and, considering that at Aldergrove at 1300 the freezing level was as high as 6,000 ft., this is unlikely to have been due directly to the upper cold front, but rather to the cooling effect of the heavy snow falling into the layer from above. Heavy precipitation soon cools the air to the wet-bulb temperature previously existing, and during the melting of snow as it falls there is further cooling. The barograph showed a brief rise at the onset of the heavy precipitation, followed by a fall. The rise might have been due to the cooling of the air by the precipitation, resembling that in a heavy shower. The fact that the precipitation ahead of the occlusion took the form of a narrow but heavy band was probably due to its cold-front nature high up. The precipitation was probably developed above the upper freezing level (about 6,000 ft.), from cloud extending up to a great height. The warm-front surface low down was doubtless important, but the precipitation at that time was not typical of a warm front. The band of precipitation went on ahead of the surface front, as is clearly shown in the 1800 chart on the 26th when there was a belt free of precipitation (though with much fog) about 130 miles wide ahead of the front, south of Sealand and Cranwell and extending 100 miles into France.

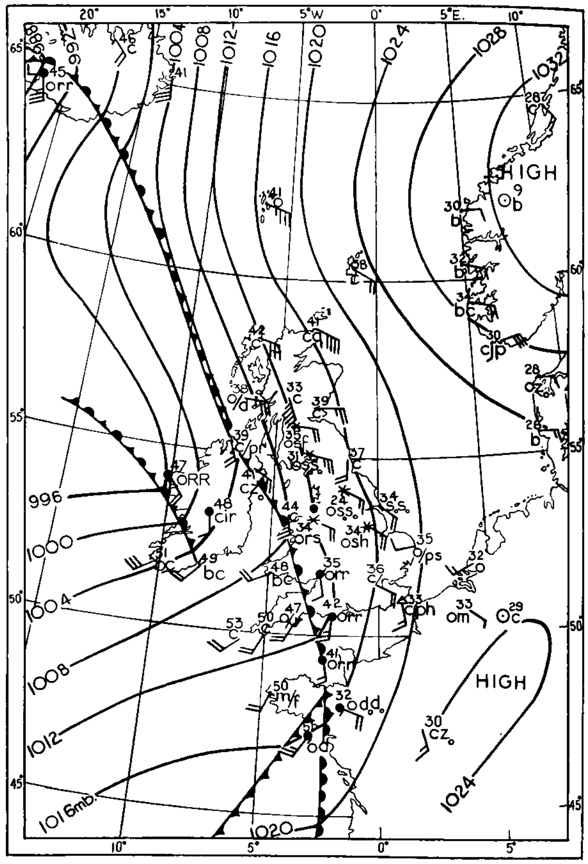
A movement of the rain and the isallobaric low ahead of a surface front is not uncommon. Even when the temperature contrast is quite large, rain does not readily develop again at the front, and when it is renewed it is often due to a new rain belt overtaking the surface front. On the present occasion a new rain belt did approach from the south-west, but rain had previously been renewed ahead of the main surface front.

The new warm front shown on the charts for 1800 on the 26th and 0100 and 0700 on the 27th was associated with a replacement of the old polar air by tropical air. It was probably originally joined to the previous cold front, but it was no longer possible to trace the connexion. The new warm front gave 0·91 in. of rain in the night at Pembroke and 0·62 in. at Portland Bill, both on the warm side of the main front, and subsequently this new rain area amalgamated with the old one and contributed to the heavy precipitation which followed.

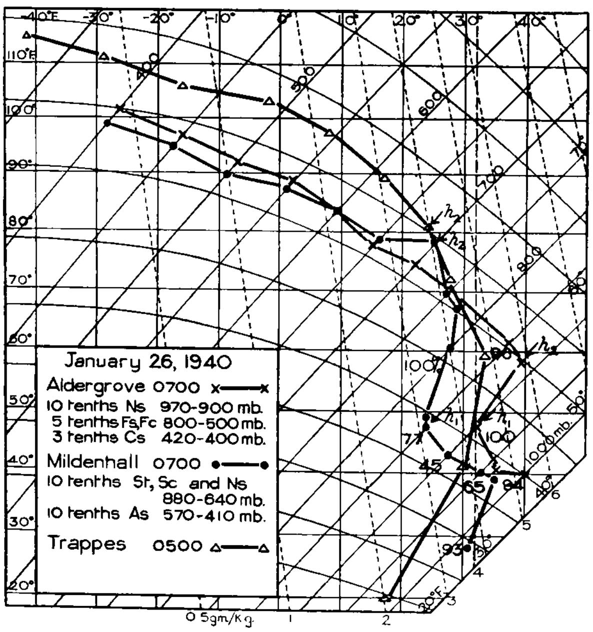
The phenomenon of a warm front overtaking an occlusion may appear strange, but it should be recognized that the label attached to a particular front involves its past history in addition to its present structure, and that in some marginal cases there is inevitably an arbitrary element. The fact that the main front became occluded on the 26th was a very important factor, and it was therefore necessary to call it an occlusion for a time, but since it had a pronounced warm-front character at low levels it would soon have been changed to a warm front if it had continued to advance, independently of the weaker warm front overtaking it. Since it actually moved back towards the south-west, in the opposite direction to the geostrophic wind across it, it had to be called a cold front. The belt of precipitation north-east of it was wide, as with other fronts of this type which form a special class. Once the two fronts amalgamated there was a very pronounced front separating tropical air from continental air.



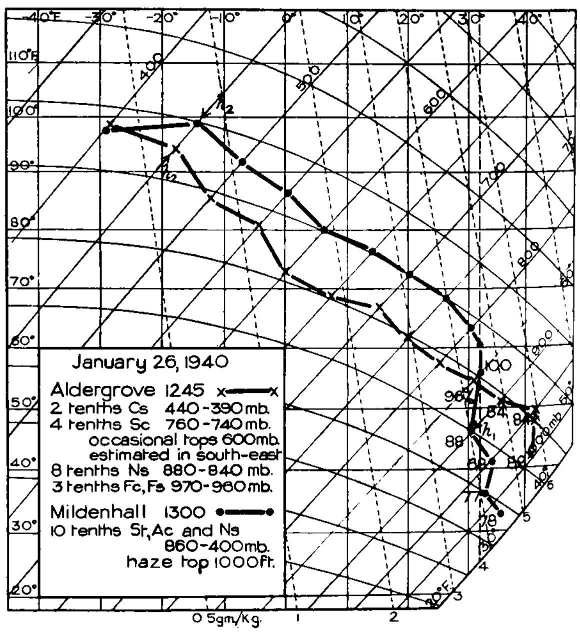
SYNOPTIC CHART, 0700, JANUARY 26, 1940



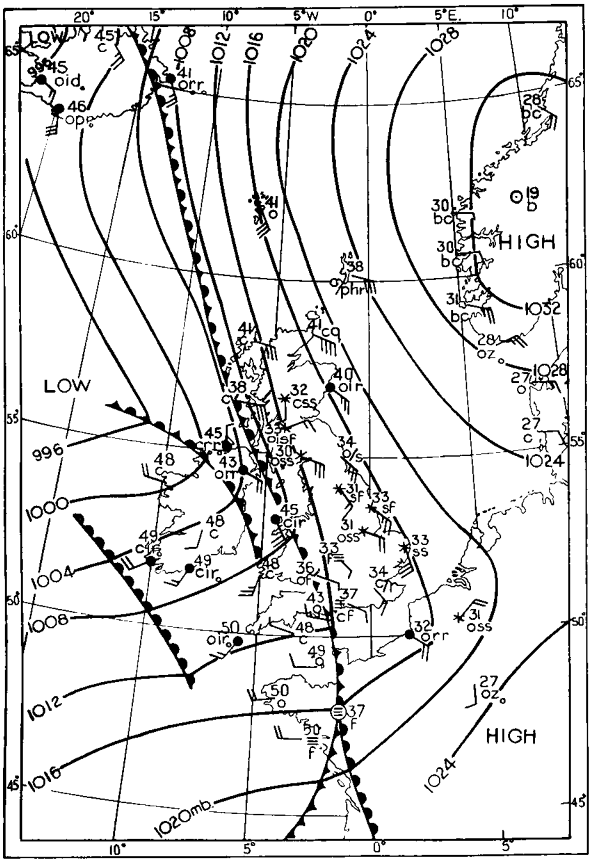
SYNOPTIC CHART, 1300, JANUARY 26, 1940



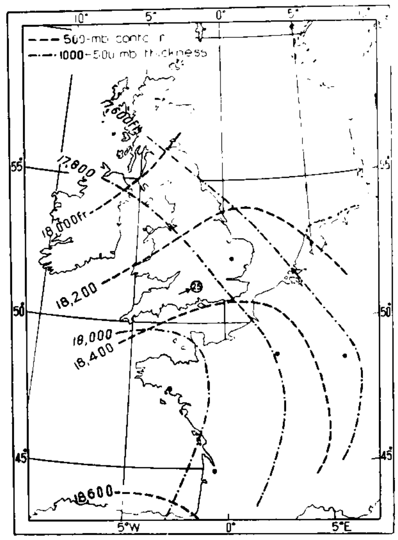
TEPHIGRAM



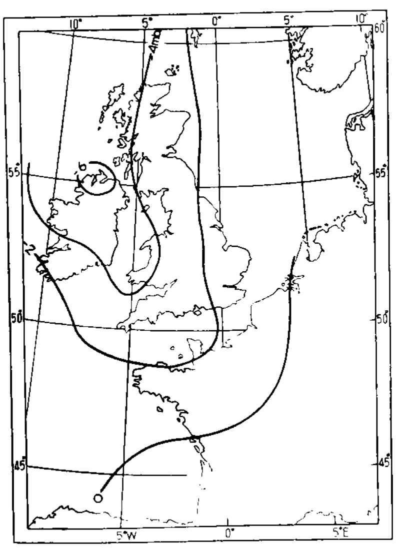
TEPHIGRAM



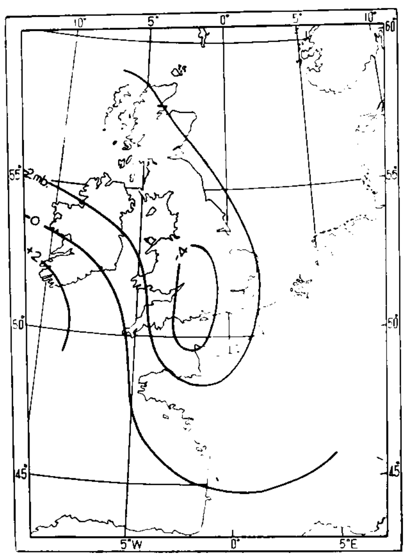
SYNOPTIC CHART, 1800, JANUARY 26, 1940



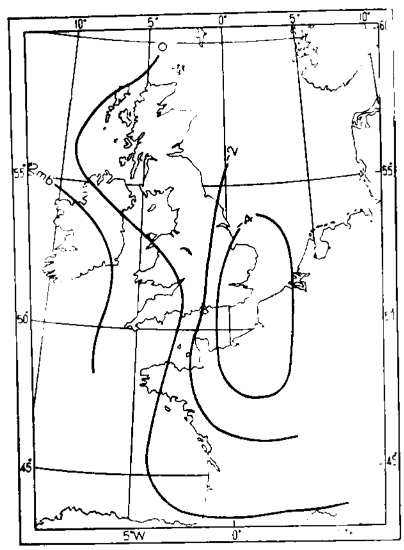
UPPER AIR CHART, 0700, JANUARY 26, 1940



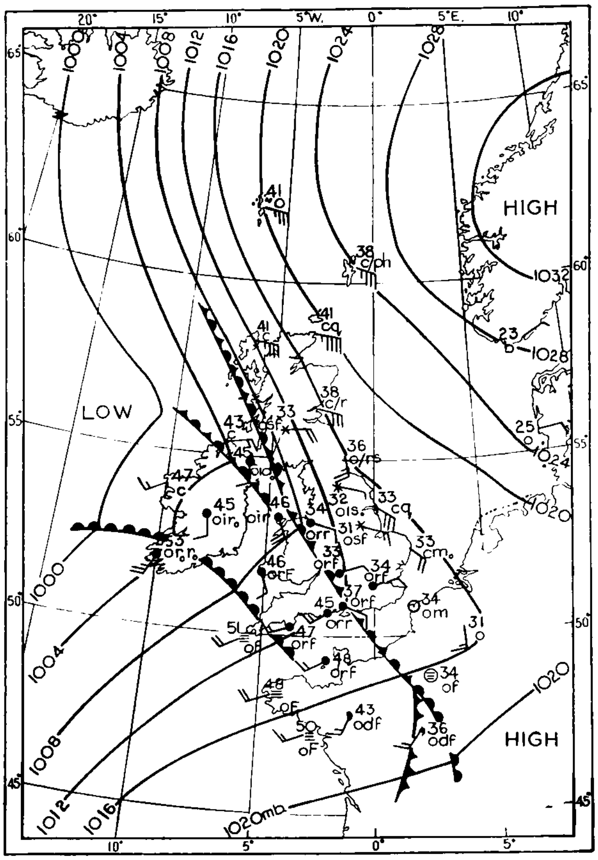
PRESSURE CHANGES,
0100-0700, JANUARY 26, 1940



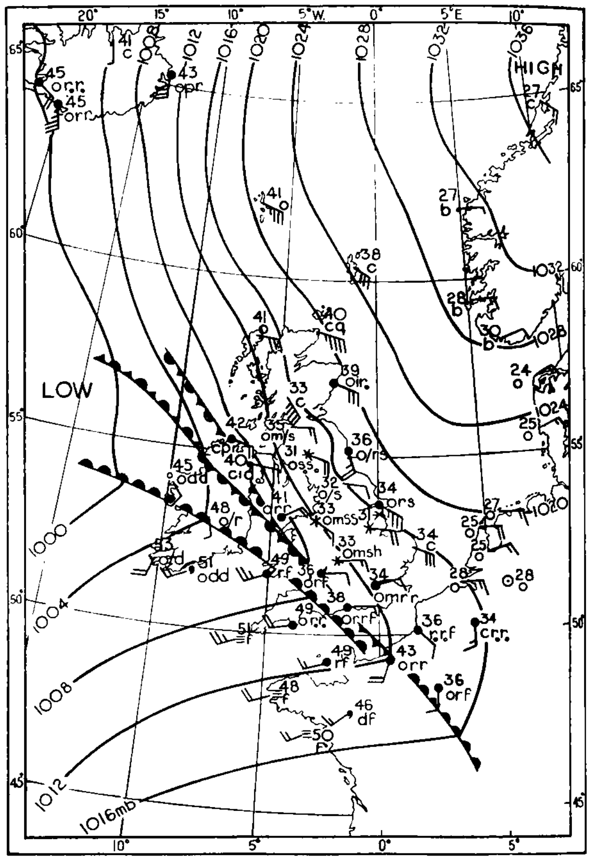
PRESSURE CHANGES,
0700-1300, JANUARY 26, 1940



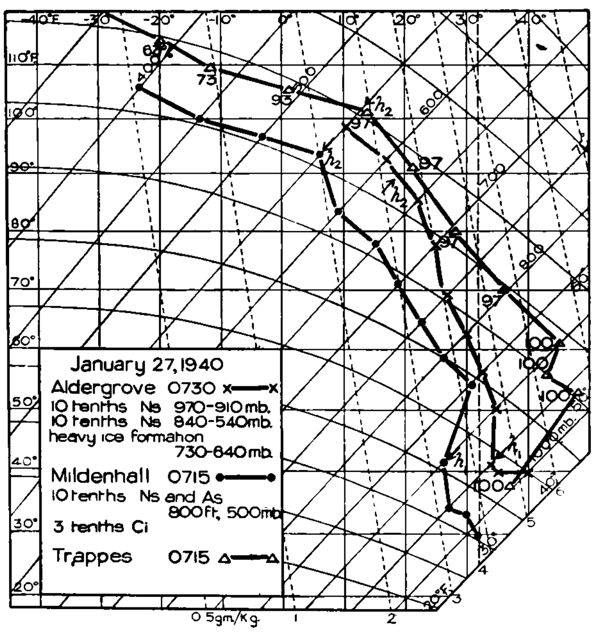
PRESSURE CHANGES,
1300-1900, JANUARY 26, 1940



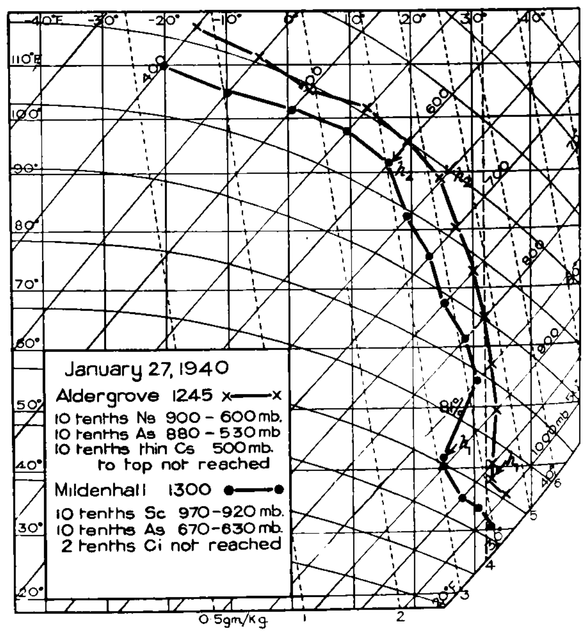
SYNOPTIC CHART, 0100, JANUARY 27, 1940



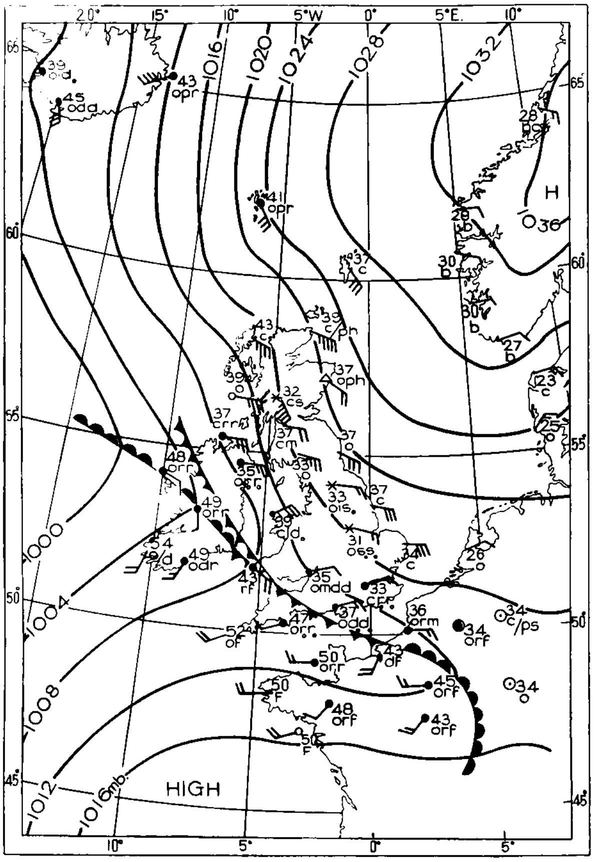
SYNOPTIC CHART, 0700, JANUARY 27, 1940



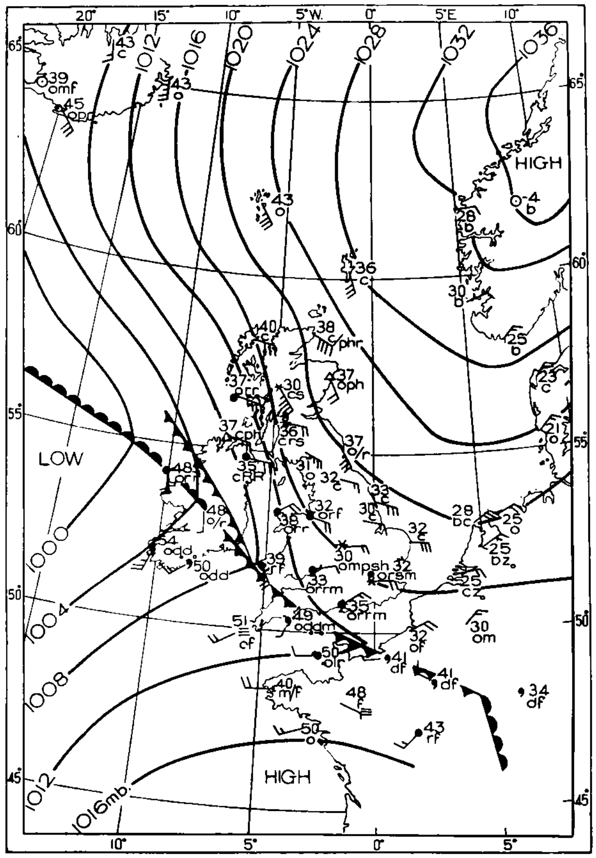
TEPHIGRAM



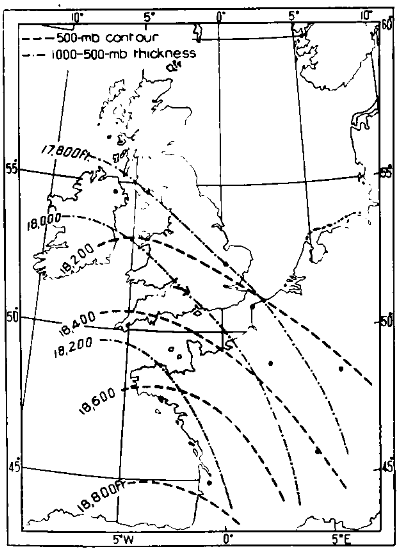
TEPHIGRAM



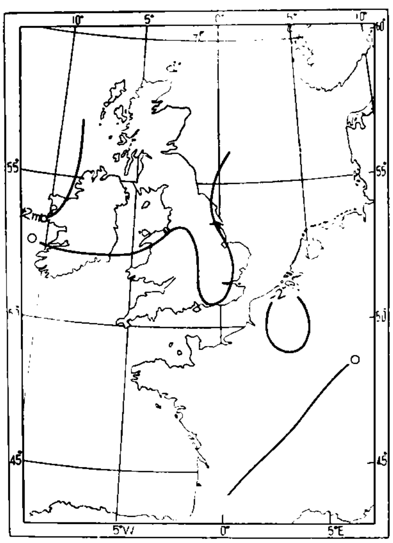
SYNOPTIC CHART, 1300, JANUARY 27, 1940



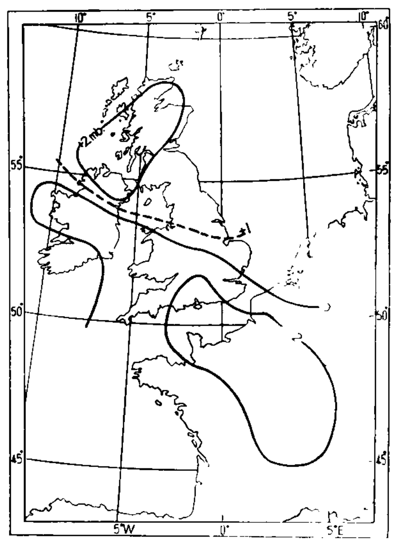
SYNOPTIC CHART, 1800, JANUARY 27, 1940



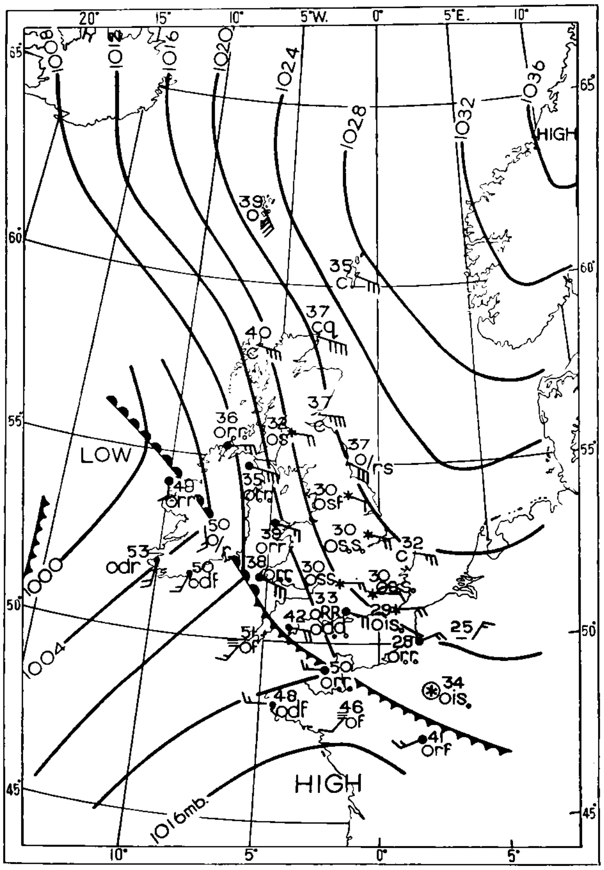
UPPER AIR CHART,
0700, JANUARY 27, 1940



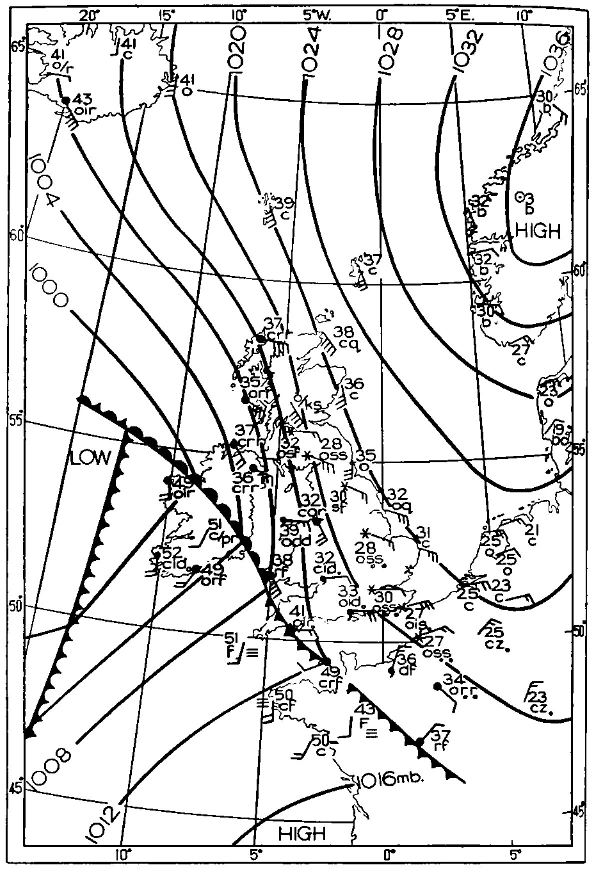
PRESSURE CHANGES,
1900, JANUARY 26–0100, JANUARY 27, 1940



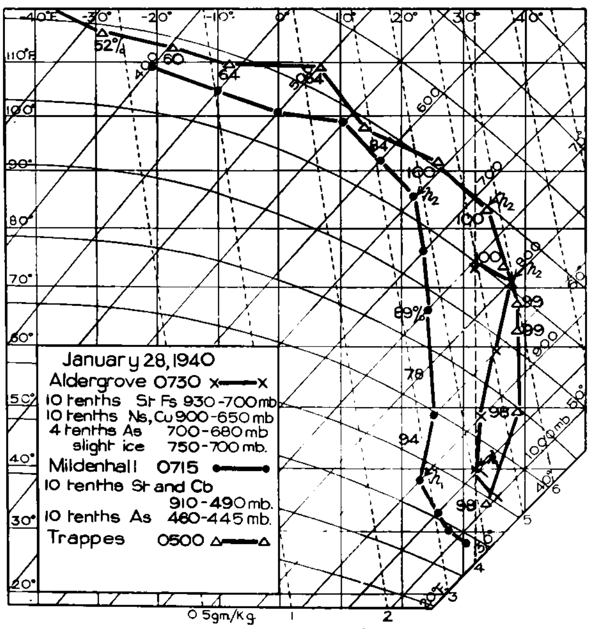
PRESSURE CHANGES,
0100–0700, JANUARY 27, 1940



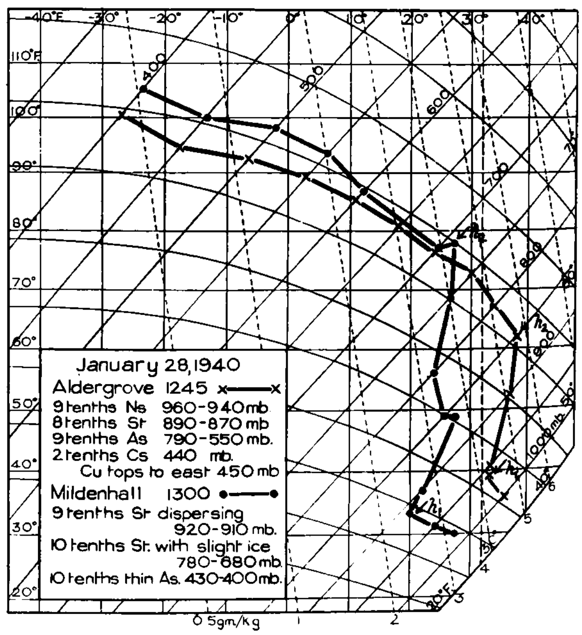
SYNOPTIC CHART, 0100, JANUARY 28, 1940



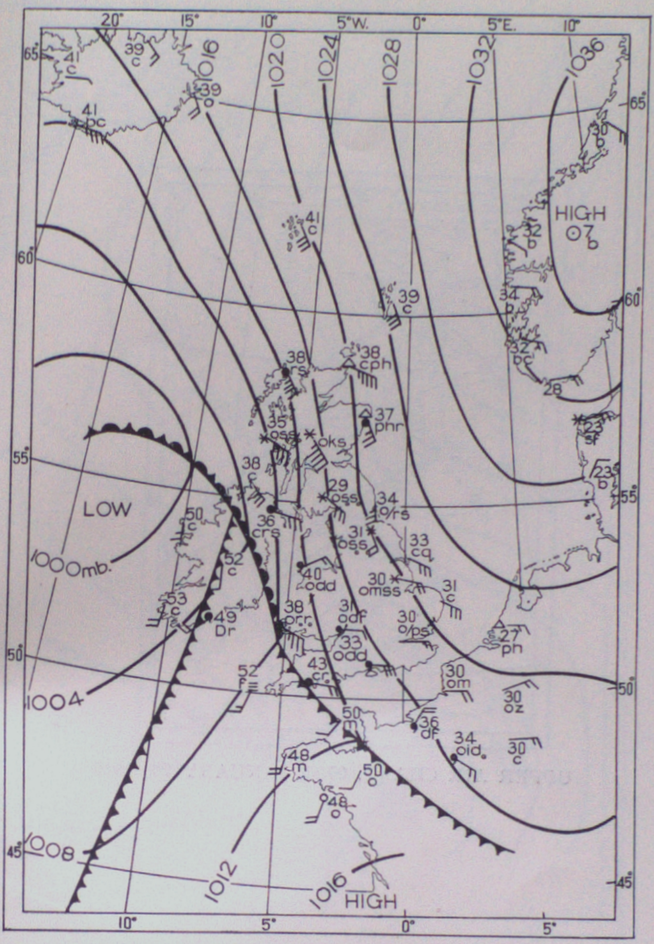
SYNOPTIC CHART, 0700, JANUARY 28, 1940



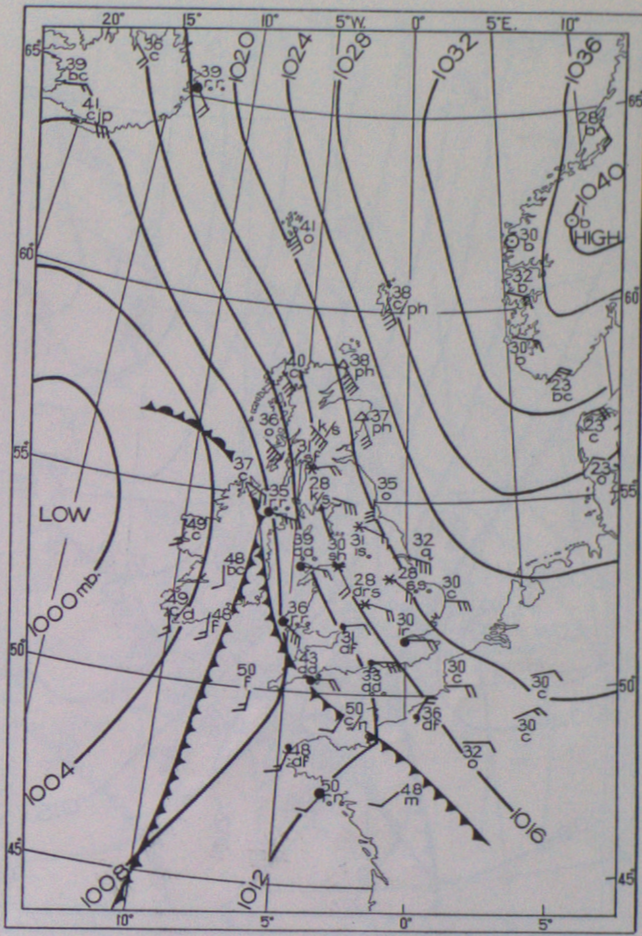
TEPHIGRAM



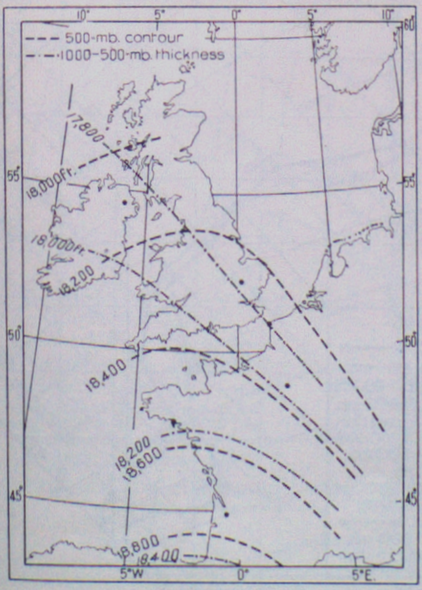
TEPHIGRAM



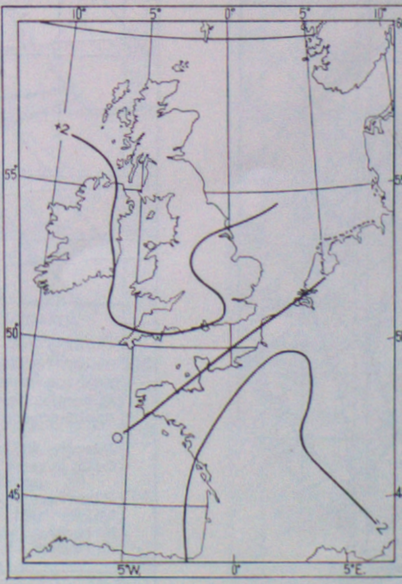
SYNOPTIC CHART, 1300, JANUARY 28, 1940



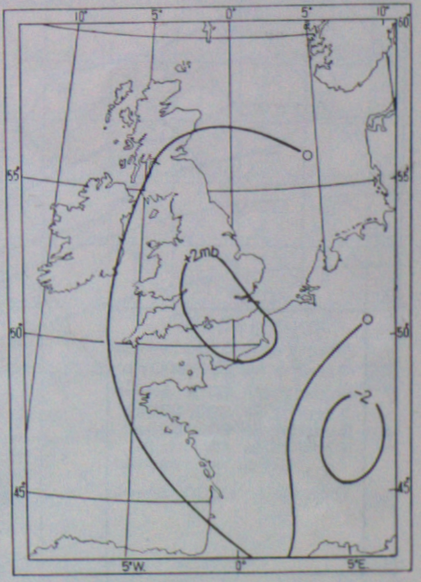
SYNOPTIC CHART, 1800, JANUARY 28, 1940



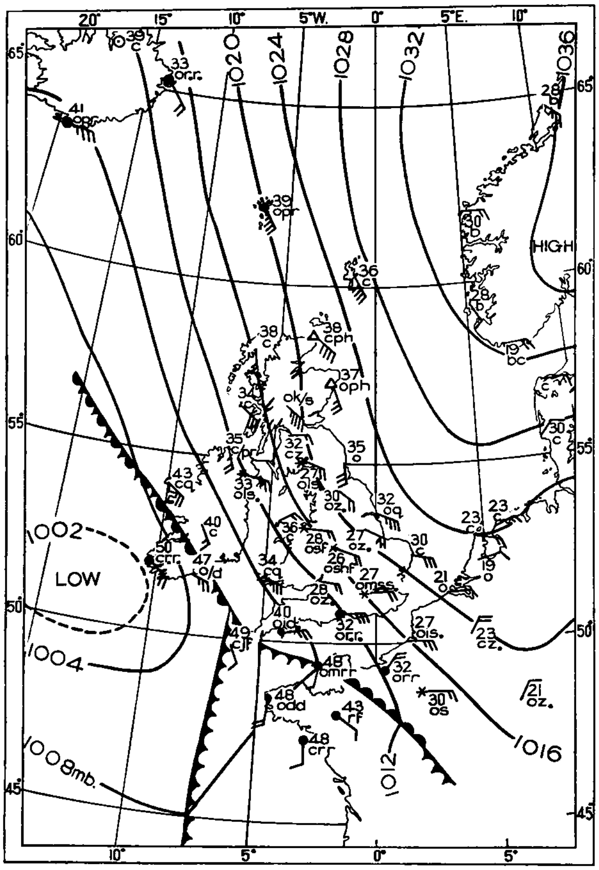
UPPER AIR CHART,
0700, JANUARY 28, 1940



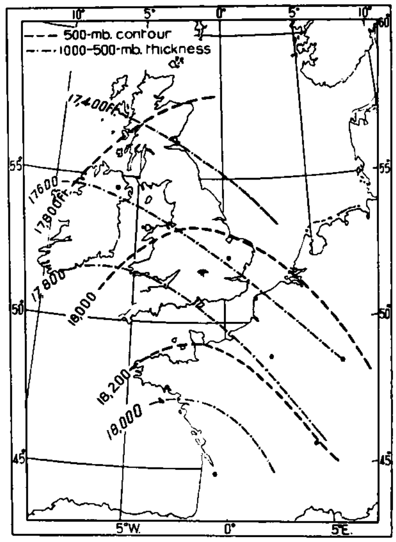
PRESSURE CHANGES,
0700–1300, JANUARY 27, 1940



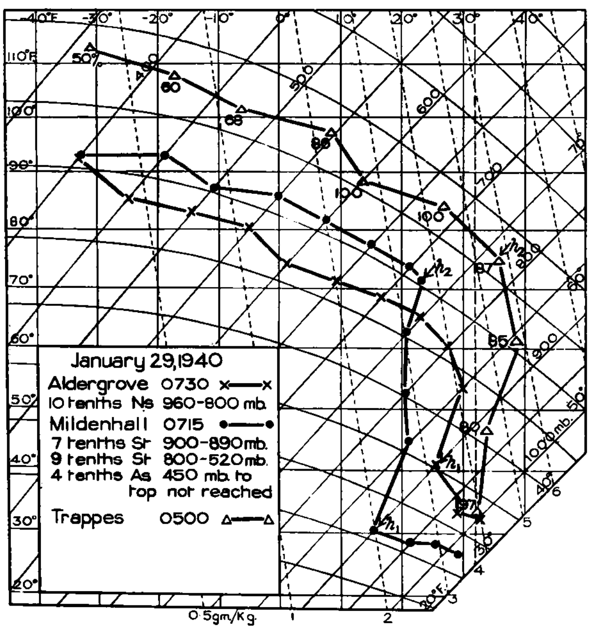
PRESSURE CHANGES,
1300–1900, JANUARY 27, 1940



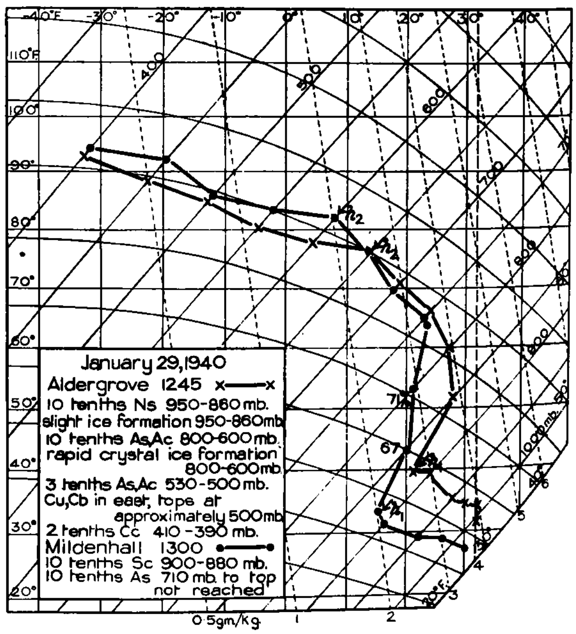
SYNOPTIC CHART, 0700, JANUARY 29, 1940



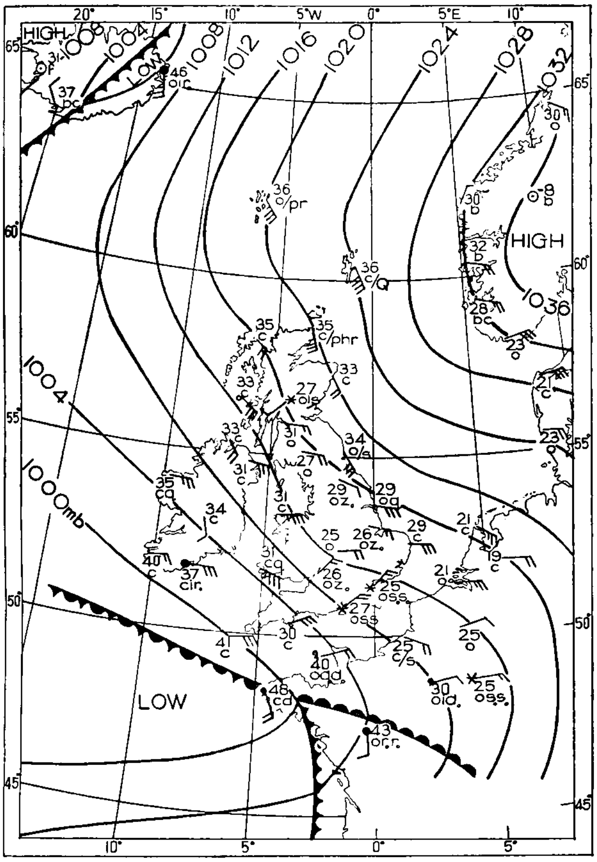
UPPER AIR CHART, 0700, JANUARY 29, 1940



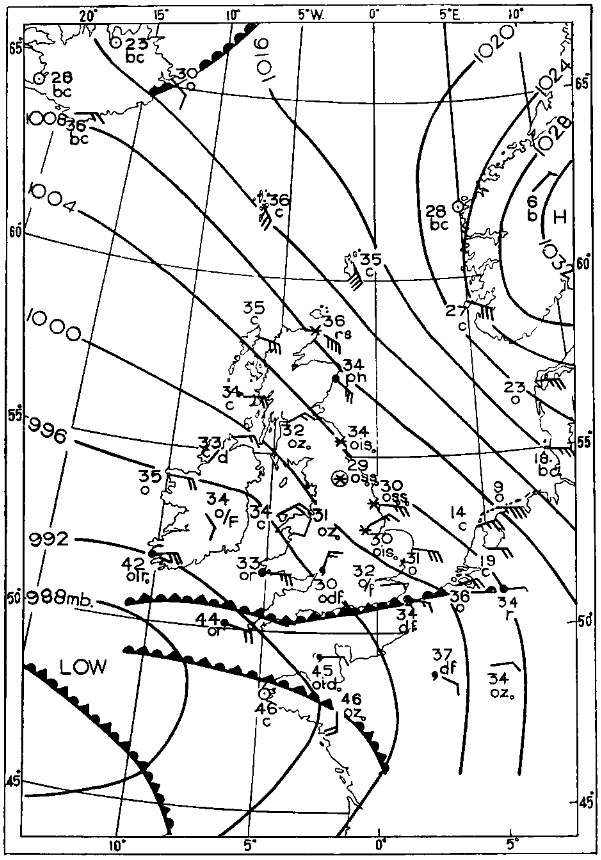
TEPHIGRAM



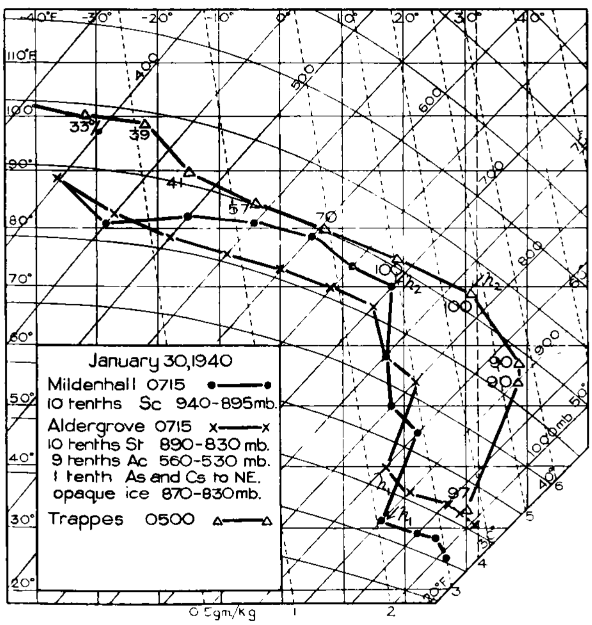
TEPHIGRAM



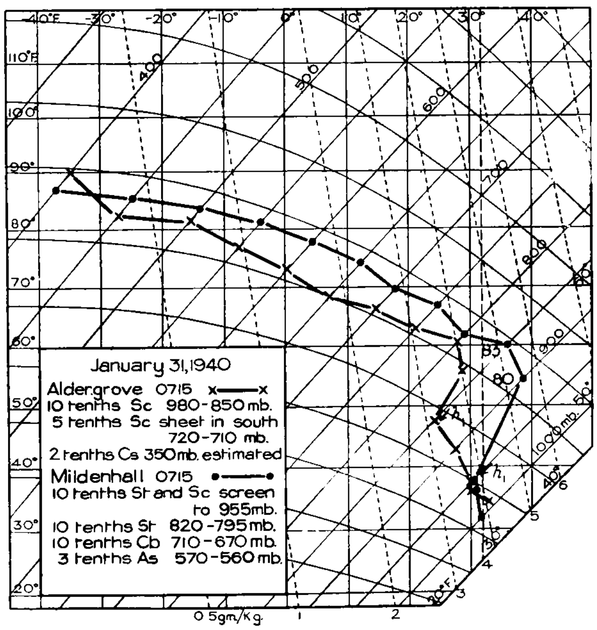
SYNOPTIC CHART, 0700, JANUARY 30, 1940



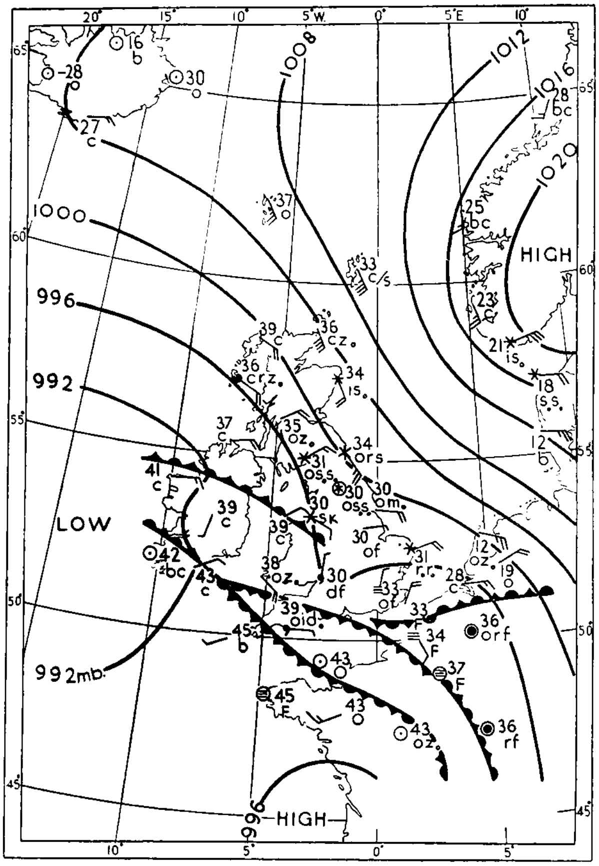
SYNOPTIC CHART, 0700, JANUARY 31, 1940



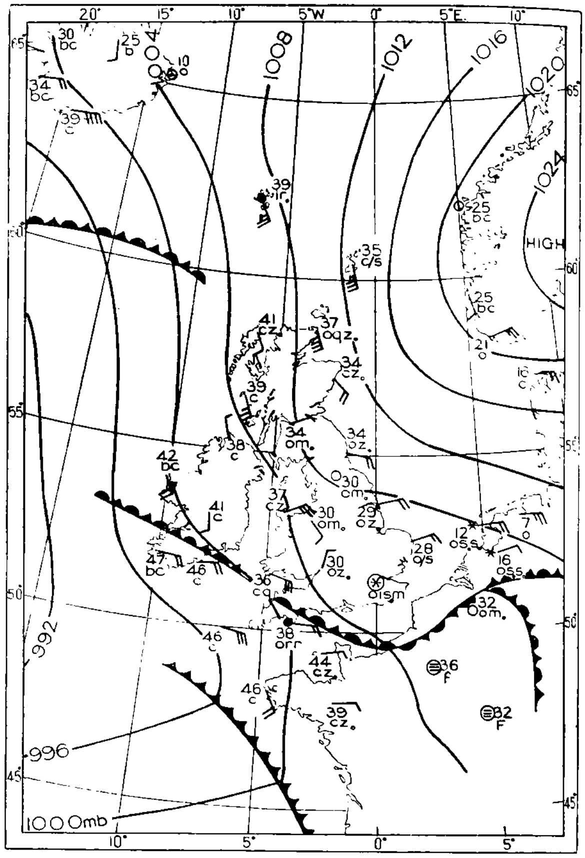
TEPHIGRAM



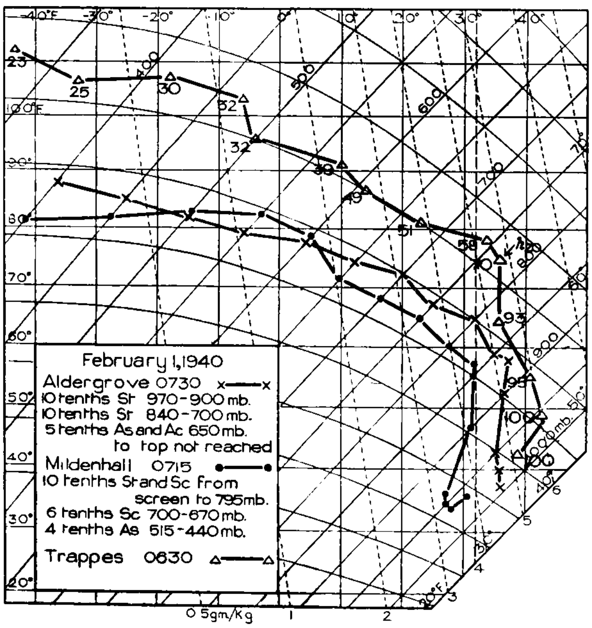
TEPHIGRAM



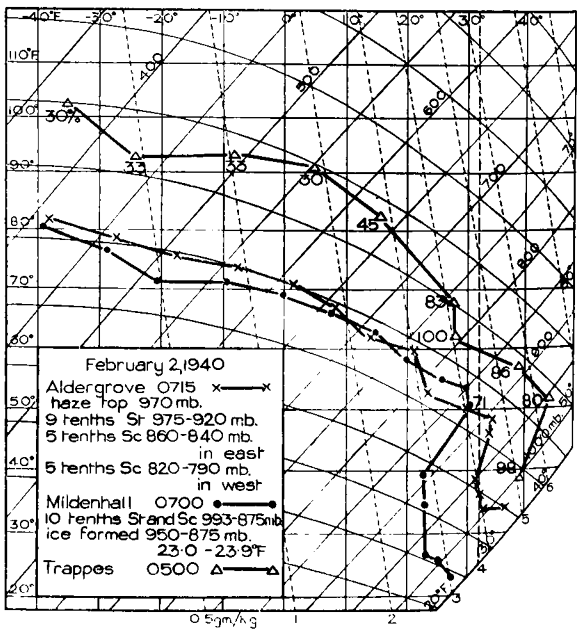
SYNOPTIC CHART, 0700, FEBRUARY 1, 1940



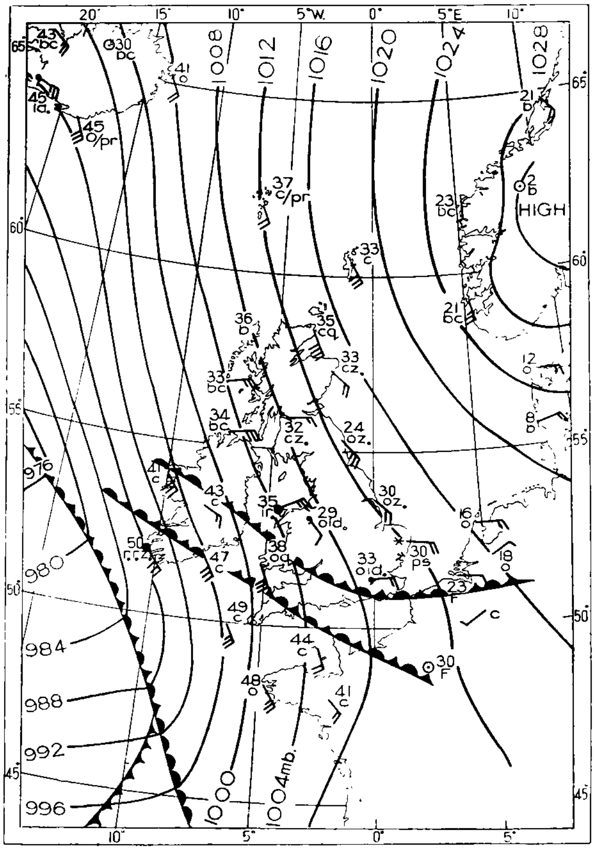
SYNOPTIC CHART, 0700, FEBRUARY 2, 1940



TEPHIGRAM



TEPHIGRAM



SYNOPTIC CHART, 0700, FEBRUARY 3, 1940

The occlusion made considerable progress on the 26th, and it looked as if it would cross southern England and take up a position from Scotland to Belgium, which is quite a common one when there is a Scandinavian anticyclone, especially with another anticyclone over Spain. The development which actually took place was undoubtedly due to the fact that the tropical air became occluded and that the big fall of pressure over the British Isles was followed by a rise. The progress which the front, and still more the first band of precipitation, made on the 26th was probably due to movements aloft associated with the upper cold front, which are further discussed later.

It is notorious that after a cold spell in winter the surface cold air is not easily displaced from a land area, but if the air aloft is warm enough there is a thaw nevertheless. During the thaws of January 6–7 and February 4–8, 1940, a large area in the east and Midlands was covered by a cold fog, practically continuous at a number of places. A fog and slight thaw had begun over a very large area on the evening of January 26, and it was only the cutting back of the cold air across the isobars that made possible a return of wintry weather. The front started to return against the pressure gradient early on the 27th and continued to do so until the 30th. This development raises questions of great scientific interest, and is discussed in a separate section, following the general description of the remainder of the period.

The remaining synoptic charts to the end of the month show the gradual retreat of the front and the falling temperature, associated with the arrival of still colder continental air, probably coming from the heart of Russia round the Scandinavian anticyclone. At 0700 on the 27th rain was falling over a wide belt on both sides of the complex frontal system ; the width on the north-east side of the main front was greater in the south than in the north, the difference being due to the steeper slope of the frontal surface in the north and perhaps partly to the horizontal temperature gradient in the warm air, with its associated upper wind structure.

There was snow over a large area in the Midlands, east and north. Assuming that the rain on the north-east coast north of Spurn Head was of local origin, the greatest width of the belt of precipitation on the north-east side of the front was 200 miles at Spurn Head. The fact that it was snowing at Cranwell and Mildenhall indicates that the sleet at Spurn Head was probably part of the main area of precipitation.

There is no evidence on the chart that glazed frost had started by 0700, and temperature was generally just above freezing point in the rain area, but by evening temperature had fallen and the glazed frost began. Temperature at 0700 was just below freezing point from Mildenhall to Catterick, and this air moved west with no diurnal rise of temperature, owing to the snow and thick clouds. The air from the Yarmouth area (temperature 34°F. at 0700) cooled as it moved inland, but this was to be expected in the zone of snowfall, since the wet-bulb temperature at Yarmouth at 0700 was 31°F. An effect of elevation may have existed in the early stage of the glazed frost. Where the glazed frost occurred there must have been an appreciable thickness of air with a temperature below freezing point, probably with a normal lapse rate ; the wind was too strong for a surface inversion to be in the least probable. Close to the front temperature was above freezing, the cold air being probably too shallow to retain a really low temperature. In crossing the Irish Sea the surface air was warmed to a temperature above the freezing point, and if glazed frost occurred anywhere in Ireland it must have been on the hills. The upper air soundings at both Aldergrove and Mildenhall were all outside the glazed-frost area.

On January 29 and 30 the maximum temperature was as low as 27°F. at a number of places, but there was still a considerable thaw belt near the front. During the glazed frost the width of the belt of precipitation varied considerably. It diminished during the 27th but increased again in the night and was fully 250 miles wide at 0700 on the 28th. Over England as a whole the largest falls of precipitation took place during three successive nights 26th–27th to 28th–29th. The nocturnal excess was much more than can be accounted for by the longer time intervals between 1800 and 0700, but may have been accidental.

There were alternations of glazed frost and snow in some areas. Early on the 28th on the Lickey Hills, 10 miles south-west of Birmingham, dry snow fell on top of ice and some deep drifts were formed, but further heavy glazed frost occurred on the following night, even though the front was retreating slowly, and then more snow. At Birmingham itself there was very little glazed frost, but deep snow, so that the boundary between snow and glazed frost was sharply defined. Quite a small margin of temperature would make all the difference, and from the discussion of upper air conditions given later it is clear that several factors were operating, and that from a forecasting standpoint the question is one of extreme difficulty.

By the 29th the front had retreated to west Cornwall, and by 1300 had passed west of Scilly. The belt of glazed frost between the thaw area and the snow area had become extremely narrow. At Exeter there was a fall of ice pellets followed by snow. The intensity of the precipitation decreased on the 29th and remained slight for a considerable period afterwards, which was fortunate in view of the fact that the glazed-frost conditions spread back over a wide area on the 31st, though in the extreme south there was a thaw on that day. The Mildenhall observations on the 31st showed a thaw layer above a freezing layer for the first time during the period, and it was only the lightness of the precipitation that prevented severe glazed frost. The front had again become occluded and poorly defined. Other occlusions further south were interfering with the convergence, which appears to have been slight over England in spite of the fall of pressure.

The thaw on the 31st extended over the whole of France, Belgium and southern Holland. A remarkably large temperature contrast developed over Holland, and the front was held up there in spite of the considerable southerly geostrophic wind across it. Next day the cold air cut back again in southern England, and by 0700 the thaw layer above Mildenhall had entirely disappeared.

The original occlusion became impossible to follow over England after the 31st, but at Holyhead there was a decrease of wind and a rise of pressure as the front passed over up aloft, and over Aldergrove temperatures fell at high levels. The second and third occlusions amalgamated, and with colder air coming back over England a fairly sharp front was again formed. On February 2 and 3 the synoptic charts show that this advanced north with other fronts behind it, and the thaw set in accompanied by widespread dense fog on the 4th and for some days afterwards, and by much flooding.

§ 6—DEPARTURES FROM GEOSTROPHIC MOTION

One of the chief points of scientific interest arising from this investigation is the marked difference, maintained over a considerable period, between the actual motion of the front and the motion it would have had if this had been determined by the component of geostrophic wind at right angles to it. The latter is a purely theoretical quantity but is useful for analytical purposes. Table I gives the approximate speed of the front, averaged over the period of 5, 6 or 7 hr.

TABLE I—SPEED OF MAIN FRONT COMPARED WITH THE THEORETICAL MOTIONS BASED ON THE COMPONENT OF GEOSTROPHIC WIND AT RIGHT-ANGLES TO IT. JANUARY 26–30, 1940

Speeds averaged over periods of 5, 6, or 7 hr. ending at times given in the first column.
+ sign indicates motion to the east or north-east.

	FRANCE			SOUTH-WEST ENGLAND			IRELAND		
	Actual motion	Geostrophic motion	Difference	Actual motion	Geostrophic motion	Difference	Actual motion	Geostrophic motion	Difference
G.M.T.	*miles per hour*								
January 26									
0700	+10	+20	−10	+ 3	+23	−20	0	+15	−15
1300	+12	+22	−10	+17	+27	−10	+10	+20	−10
1800	+12	+22	−10	+14	+23	− 9	+ 8	+16	− 8
January 27									
0100	+14	+22	− 8	+ 4	+20	−16	− 1	+11	−12
0700	+12	+23	−11	0	+28	−28	−10	+ 7	−17
1300	+12	+23	−11	− 5	+15	−20	− 3	+12	−15
1800	− 2	+10	−12	− 5	+14	−19	− 2	+16	−18
January 28									
0100	− 4	0	− 4	− 4	+15	−19	0	+17	−17
0700	− 5	0	− 5	− 3	+17	−20	0	+21	−21
1300	− 3	0	− 3	0	+20	−20	+ 1	+21	−20
1800	− 4	+ 2	− 6	0	+20	−20	+ 4	+15	−11
January 29									
0100	0	+ 7	− 7	0	+16	−16	− 7	+ 5	−12
0700	0	+10	−10	− 4	+13	−17	−12	0	−12
1300	+ 2	+ 9	− 7	− 4	+13	−17	− 9	0	− 9
1800	− 2	+ 9	−11	− 5	+12	−17	−10	0	−10
January 30									
0100	0	+15	−15	− 4	+ 9	−13	..	..	..
0700	+ 3	+22	−19	− 4	+ 9	−13	..	..	..
1300	+ 8	+25	−17	0	+12	−12	..	.	..
1800	+ 8	+22	−14	+ 5	+15	−10	..	..	..
Mean	..	..	−10	..	..	−17	..	..	−14

ending at the times given in the left-hand column and considered positive when directed towards the north-east ; the speed corresponding to geostrophic motion, which was always positive ; and the difference between them, which was always negative, i.e. directed towards the south-west. Three portions of the front were chosen, about 300 miles apart, covering altogether 600 miles of the front. The first was in France (initially in the Bay of Biscay), the second over south or south-west England and later in the English Channel between Lizard and Brest, and the third in Ireland, roughly on a line from Aldergrove to Valentia. Owing to limitations of measurement individual figures are liable to error, but the average of the difference over some days, which was as high as 19 m.p.h. in south-west England from the 26th to the 29th and 17 m.p.h. from the 26th to the 30th, is substantially correct. These high values cannot be explained in terms of isallobars and their influence on wind. The figures in the difference column for south-west England average 17 m.p.h. for the five days, 26th–30th. The average value of the "isallobaric" effect during that period can most readily be found by measuring the geostrophic wind in the cold air close to the appropriate part of the front at the beginning and end of the period. Actually it backed from S. to SE. with no appreciable change of speed, and the mean "ageostrophic wind"* corresponding to this change is small and practically parallel to the front, so that this factor contributed nothing to the average of the difference columns. A much larger contribution was supplied by the acceleration along the stream-lines. In this particular case, when the isallobaric effect was negligible, this was the same on the average as the acceleration along the path of the air, which, since it represents one component of the acceleration of an air mass, seems to have more physical reality than either the isallobaric effect or the acceleration along the stream-lines.

A small mass of cold air in contact with a well defined front remains in contact with it, and its motion consists of that of the front itself, together with a motion along the front. Since the ageostrophic wind is at right angles to the acceleration, the component of ageostrophic wind at right angles to the front depends only on the component of acceleration parallel to the front. A front can only move at right angles to itself at any given point, and unless the orientation of the front is changing very rapidly, only the motion of the air along the front need be taken into account in measuring the acceleration parallel to the front. In the period under review, and in most frontal situations especially in winter, the pilot-balloon data (see Table II) are quite insufficient to give the acceleration, but a first approximation to the required quantity can be obtained by measuring the component of geostrophic wind parallel to the front in the cold air at different points close to the front, and this method was used in constructing Table III, taking the same portions of the front as for Table I.

The quantity G_s is the component of geostrophic wind parallel to the front (measured to the nearest 5 or 10 m.p.h.), and the change with time, in the time interval (5, 6 or 7 hr.) ending at the time given, is a measure of the "isallobaric" effect. The corresponding ageostrophic wind is directed at right angles to the front, of magnitude $2 \cdot 3\ \partial G_s/\partial t$, and is towards the front when $\partial G_s/\partial t$ is positive (Brunt and Douglas[7]). The expression $G_s\, \partial G_s/\partial s$ is based on the difference of speed at a given time between two points on the front 300 miles apart, the value of G_s being taken as the mean of that at the two points.

Columns under the heading $G_s \partial G_s/\partial s$, the mean of the two sections of the front, give a rough measure of its value in south and south-west England, though no very high accuracy can be claimed for individual figures. The corresponding ageostrophic wind is again obtained by multiplying by $2 \cdot 3$, and in all except the two small negative cases it was directed towards the front, from the cold side to the warm.

The penultimate column gives the ageostrophic wind over south-west England due to the combined effect of the two factors, i.e. to the acceleration along the path of the air, the two terms being simply added together to give a sufficiently good approximation. The last column gives the ageostrophic motion of the front, taken from Table I. The average of the latter is

* A term introduced by C. S. Durst to denote the vector difference between the actual and geostrophic winds.

TABLE II—PILOT-BALLOON OBSERVATIONS, JANUARY 26–30, 1940

January 26

Height above M.S.L.		Biggin Hill 0000		Calshot 0600		Duxford 0600		Manston 0600		Mildenhall 0600		South Farnborough 0600		Biggin Hill 0900		Henley 0900		Shoreham 0900	
		°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.
Geostrophic wind		190	20	190	38	185	30	190	30	190	20	180	38	180	38	180	38	180	38
m.	ft.																		
2,500	8,000	230	15			(1,600 m.)		(1,900 m.)		(1,900 m.)									
2,000	6,500	200	15			230	9	190	16	200	20			(1,300 m.)		(1,200 m.)		(1,100 m.)	
1,500	5,000	200	12			220	16	190	12	160	12			230	18	200	24	200	30
1,000	3,000	200	12	170	25	180	19	190	16	200	12	190	34	190	33	210	30	190	30
500	1,500	190	24	190	22	170	12	200	16	200	12	170	28	170	30	200	24	170	24
Surface		170	9	160	16	170	6	190	6	130	6	120	9	130	15	170	9	170	12

January 26

Height above M.S.L.		Northolt 1000		Upwood 1000		North Weald 1200		St. Eval 1200		Croydon 1300		Pembroke 1500	
		°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.
Geostrophic wind		180	38	180	38	180	40	240	35	180	40		
m.	ft.												
2,500	8,000					(1,600 m.)							
2,000	6,500	(1,400 m.)				240	22	260	37	(1,200 m.)		(1,200 m.)	
1,500	5,000	210	28			220	19	250	47	210	31	240	28
1,000	3,000	200	40	180	31	190	25	250	34	200	31	240	28
500	1,500	170	22	150	37	160	34	260	34	160	34	240	34
Surface		140	12	130	6	140	12	230	16	140	16	190	9

January 27

Height above M.S.L.		Hemswell 1500	
		°	m.p.h.
Geostrophic wind		135	35
m.	ft.		
		(1,200 m.)	
1,000	3,500	110	25
500	1,500	110	37
Surface		..	..

January 28

Height above M.S.L.		Shoeburyness 1100		Bircham Newton 2100	
		°	m.p.h.	°	m.p.h.
Geostrophic wind		140	35	140	35
m.	ft.				
2,000	6,500			100	22
1,500	5,000			120	16
1,000	3,000	110	19	120	34
500	1,500	100	31	120	40
Surface		100	16	100	16

January 29

Height above M.S.L.		Mildenhall 0000		Marham 0400		Driffield 0800		Honnington 0900		Penrhos 0900	
		°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.
Geostrophic wind		135	40	135	40	140	35	135	40	135	40
m.	ft.			(1,100 m.)							
1,500	5,000	(800 m.)		130	40	(700 m.)		(800 m.)		(700 m.)	
1,000	3,000	120	56	130	46	130	34	120	47	120	22
500	1,500	120	43	110	40	120	34	110	43	110	31
Surface		110	19	110	25	130	22	90	12	80	25

January 29

Height above M.S.L.		Finningley 1000		Wittering 1000		Hemswell 1100		Marham 1100		Waddington 1100		Cranfield 1200		Feltwell 1200		St. Eval 1400		Wattisham 1400	
		°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.
Geostrophic wind		140	35	135	40	140	35	135	35	140	35	130	45	125	35	130	30	125	35
m.	ft.																		
2,500	8,000															220	9		
2,000	6,500			(1,100 m.)												220	6		
1,500	5,000			120	43	(700 m.)						(700 m.)				170	6	(1,100 m.)	
1,000	3,000			120	40	120	37			110	43	100	40	(600 m.)		130	3	110	37
500	1,500	120	34	120	43	120	37	110	34	110	40	100	34	110	34	170	16	110	34
Surface		120	16	110	16	100	22	100	1	90	22	90	19	90	19	110	22	110	25

January 29

Height above M.S.L.		Bircham Newton 1500		Dishforth 1500		Lympne 1500		Manchester 1500		Mildenhall 1600		Wittering 1600		Marham 1700		Thornaby 2100	
		°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.
Geostrophic wind		130	35	140	35	125	35	140	45	130	35	140	35	130	35	130	30
m.	ft.																
1,500	5,000	(800 m.)						(700 m.)		(700 m.)				(700 m.)		(900 m.)	
1,000	3,000	110	34	120	34	110	25	110	43	110	40	120	50	110	31	120	25
500	1,500	100	34	120	34	90	40	100	40	110	28	110	37	100	37	120	25
Surface		110	12	120	16	80	31	110	22	100	16	110	16	90	19	120	9

January 30

Height above M.S.L.		Mildenhall 0600		Exeter 0800		Digby 0900		Bristol 1100		Digby 1200		Marham 1200		Digby 1500	
		°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.	°	m.p.h.
Geostrophic wind		110	30	130	60	115	30	120	40	120	30	135	30	120	30
m.	ft.														
1,500	5,000	(800 m.)				(700 m.)				(800 m.)		(600 m.)		(600 m.)	
1,000	3,000	90	34	(200 m.)		100	34			100	34	110	28	100	37
500	1,500	90	34	70	22	100	31	80	28	100	37	100	31	100	28
Surface		90	19	70	16	90	12	50	19	100	16	90	19	100	16

When the balloon failed to reach the standard height at which the wind velocity is given, the actual height reached is given in brackets just above the value of the wind velocity.

TABLE III—COMPARISON OF CALCULATED AGEOSTROPHIC MOTION OF FRONT WITH MEASURED AGEOSTROPHIC MOTION, JANUARY 26–30, 1940

G_s = approximate geostrophic wind component parallel to the front, measured over France (column 1), over south-west England (column 2), and over Ireland (column 3).

$\partial G_s/\partial t$ = partial acceleration due to variation of time of wind component parallel to the front, measured over France (column 4), over south-west England (column 5), and over Ireland (column 6).

$G_s \partial G_s/\partial s$ = partial acceleration due to variation with distance along front, measured between France and south-west England (column 7), between south-west England and Ireland (column 8), and the mean of these two (column 9).

DG_s/Dt = total acceleration of wind component parallel to the front over south-west England (sum of columns 5 and 9).

	G_s			$\frac{\partial G_s}{\partial t}$			$G_s\frac{\partial G_s}{\partial s}$			$\frac{DG_s}{Dt}$	Ageostrophic wind Calculated*	Observed
	1	2	3	4	5	6	7	8	9	10	11	12
G.M.T.	*miles per hour*			*miles per hour per hour*							*miles per hour*	
January 26												
0100	15	40	60	..	..	..	+2·3	+3·3	+2·8	..	..	..
0700	25	50	70	+1·7	+1·7	+1·7	+2·7	+4·0	+3·3	+5·0	+11	+20
1300	30	50	70	+2·5	0·0	0·0	+2·7	+4·0	+3·3	+3·3	+ 8	+10
1800	10	25	75	−4·0	−5·0	+0·8	+0·9	+8·3	+4·6	−0·4	− 1	+ 9
January 27												
0100	10	25	50	0·0	0·0	−3·6	+0·9	+3·2	+2·1	+2·1	+ 5	+16
0700	15	50	55	+0·8	+4·2	+0·8	+3·7	+0·7	+2·2	+6·4	+14	+28
1300	20	40	50	+0·8	−1·7	−0·8	+2·0	+1·5	+1·7	0·0	0	+20
1800	25	50	60	+1·0	+2·0	+2·0	+3·1	+1·8	+2·5	+4·5	+10	+19
January 28												
0100	20	40	50	−0·7	−1·4	−1·4	+2·0	+1·5	+1·7	+0·3	+ 1	+19
0700	20	40	50	0·0	0·0	0·0	+2·0	+1·5	+1·7	+1·7	+ 4	+20
1300	25	40	60	+0·8	0·0	+1·7	+1·6	+3·3	+2·5	+2·5	+ 6	+20
1800	20	35	70	−1·0	−1·0	+2·0	+1·4	+6·1	+3·7	+2·7	+ 6	+20
January 29												
0100	25	40	50	+0·7	+0·7	−2·9	+1·6	+1·5	+1·5	+2·2	+ 5	+16
0700	30	35	40	+0·8	−0·8	−1·7	+0·5	+0·6	+0·5	−0·3	− 1	+17
1300	30	35	40	0·0	0·0	0·0	+0·5	+0·6	+0·5	+0·5	+ 1	+17
1800	30	35	40	0·0	0·0	0·0	+0·5	+0·6	+0·5	+0·5	+ 1	+17
January 30												
0100	15	45	40	−2·1	+1·7	0·0	+3·0	−0·7	+1·1	+2·8	+ 6	+13
0700	15	40	35	0·0	−0·8	−0·8	+2·3	−0·7	+0·8	0·0	0	+13
1300	25	40	40	+1·7	0·0	+0·8	+1·6	0·0	+0·8	+0·8	+ 2	+12
1800	30	40	40	+3·0	0·0	0·0	+1·2	0·0	+0·6	+0·6	+ 1	+10
Mean											+4·2	+16·6
Correlation coefficient ..												0·54

* Calculated ageostrophic wind = 2·3 × DG_s/Dt.

much higher than the average of the calculated value, showing that one or more other important factors were operating. The correlation coefficient between the individual figures in the two right-hand columns is 0·54, with a probable error of 0·11, which is reasonable when one considers the difficulties of measurement, and shows that there is some physical basis for the theory, though it is of little use from a forecasting point of view. As already mentioned, the isallobaric term contributed nothing on the average for the five days, but it was important during the critical period on January 26 and 27. The sharp fall of G_s between 1300 and 1800 on the 26th was associated with the movement of the isallobaric low to a position some distance ahead of the front (see pressure change chart for 1300–1800 on the 26th) soon after occlusion, and this helped the front forward. Between 0100 and 0700 on the 27th this was reversed, owing to an isallobaric low having moved southward to France while an isallobaric high had moved across the front (see pressure change chart for 0100–0700 on the 27th) with its centre over Scotland and an extension to the Wash area : the front was retarded in a very marked manner.

The mean numerical value of $\partial G_s/\partial t$ in south-west England, taken without regard to sign, is 1·1, while that of $G_s\,\partial G_s/\partial s$, based on the third column of Table II, is 1·9. There is no appreciable correlation between the two sets of figures.

Table II gives all available pilot-balloon data from England, Wales and Ireland from the 26th to the 30th, and the geostrophic winds for purposes of comparison. On the 26th the observations were numerous but the results rather irregular. The only definite feature in the morning was that the velocity was below the geostrophic value. At midday the direction was backed 20° from the geostrophic at 1,500 ft. at Croydon and North Weald, but higher up the wind was veered from the surface geostrophic direction under the influence of a " thermal " wind, i.e. a change with height of the geostrophic wind itself. Observations were scarce on the 27th and 28th, but more numerous on the 29th and 30th. The directions were rather consistently backed from the geostrophic up to about 3,000 ft., which was usually the highest level reached. The velocities were rather irregular, and at some places in the east were rather above the geostrophic value, as one would expect from the curvature of the isobars, but this had almost no effect on the motion towards the front. An average of 27 observations in the Midlands and east of England from the 27th to the 30th gives a difference of 23° between the observed and geostrophic wind at 1,500 ft., with a mean speed of 35 m.p.h., giving an ageostrophic wind of 14 m.p.h., nearly at right angles to the front, and the mean ageostrophic motion of the front for the same period (see Table I) was 17 m.p.h.

The pilot-balloon records from the west also mostly showed a considerable ageostrophic wind towards the front, but they are too few to give a reliable numerical measure of it. The Larkhill observation of the 27th showed a sharp wind discontinuity between 1,500 and 3,000 ft. on the 27th, but from the 28th to the 30th the ice prevented the ascent from being carried out. The Larkhill ascents up to February 3 are given in Table IV for the sake of their general interest.

Sixteen pilot-balloon observations at 3,300 ft. (including a few to 2,500–3,000 ft. only) showed winds inclined at an average angle of 20° to the geostrophic value, with an average speed of 37 m.p.h., giving a mean ageostrophic wind of 13 m.p.h. The same 16 observations gave a mean ageostrophic wind of 15 m.p.h. at 1,500 ft. The slight difference may be attributed to the effect of surface friction, and the really outstanding feature is the maintenance of a large ageostrophic wind right up to 3,000 ft.

At almost all warm fronts, and also at retrograde fronts of the type considered here, surface friction gives a component of ageostrophic wind directed towards the front which is greatest at the ground and should vanish at about 2,000 ft. If this were the only factor producing an ageostrophic wind, it is clear that the angle of slope of the frontal surface would be markedly decreased below 2,000 ft., especially below 1,000 ft., and this would smooth the discontinuity in the isobaric field, and in extreme cases displace the main bend in the isobars well forward from

TABLE IV—LARKHILL RADIO PILOTS

January 26, 1940 0400 G.M.T.			January 27, 1940 0700 G.M.T.			Januray 31, 1940 1400 G.M.T.			February 1, 1940 1100 G.M.T.			February 2, 1940 1200 G.M.T.			February 3, 1940 1100 G.M.T.		
Height	Wind Direction	Wind Speed	Height	Wind Direction	Wind Speed	Height	Wind Direction	Wind Speed	Height	Wind Direction	Wind Speed	Height	Wind Direction	Wind Speed	Height	Wind Direction	Wind Speed
ft.	°	m.p.h.	ft.	°	m.p.h.	ft.	°	m.p.h.	ft.	°	m.p.h.	ft.	°	m.p.h.	ft.	°	m.p.h.
38,000	260	44				35,400	280	44	35,800	230	22	37,700	240	12	34,300	270	75
33,400	220	40				33,100	280	28	..	..	..	..	..	..	..	..	..
..	..	..				32,800	290	28	32,800	220	22	32,800	250	34	..	..	..
29,500	220	31				29,500	290	28	29,200	230	22	28,800	240	31	29,500	270	53
25,900	230	50				26,100	240	25	26,100	210	22	25,600	240	31	25,900	270	44
22,900	230	22				22,800	230	25	23,000	220	19	22,600	230	19	22,600	260	44
20,200	250	22				19,700	240	25	19,700	260	19	20,000	240	16	20,000	260	37
17,700	250	37				..	..	..	..	..	..	17,400	240	22	17,400	260	22
15,400	260	19				16,400	240	12	16,400	240	16	15,100	250	19	15,100	220	19
13,400	220	37	13,100	290	40	13,100	210	6	13,100	260	16	13,100	250	16	13,100	160	22
11,500	250	28	11,200	290	50	..	..	..	11,500	290	12	11,200	250	16	11,200	190	28
9,500	250	25	9,500	280	34	9,800	160	19	9,800	..	..	9,200	250	12	9,200	190	28
7,900	230	25	7,500	280	28	8,200	130	22	8,200	..	..	7,500	240	12	7,500	190	22
6,200	270	25	5,900	280	40	6,600	130	12	6,600	..	..	5,900	230	12	5,900	180	28
4,600	230	28	4,600	290	31	4,900	290	9	4,900	..	..	4,300	200	9	4,300	170	25
3,280	180	34	2,900	260	25	3,280	120	16	3,300	..	..	2,900	130	19	2,900	150	..
1,640	150	25	1,640	150	19	1,640	130	19	1,640	..	..	1,640	100	12	1,640	160	22

the main discontinuity of surface temperature. This is sometimes observed at warm fronts, but in the case under discussion, as with other retrograde fronts of that type, the discontinuity remained sharp, and the pressure gradient in the cold air was large within 20 or 30 miles of the front. In the reconstruction of the vertical cross-section given in Fig. 5 the frontal surface is given a constant slope, and this fits in with the glazed frost much better than a slope with marked flattening near sea level would have done. The problem is thus to explain the ageostrophic wind at 2,000–3,000 ft. or more, which is roughly as great as that produced by friction at ground level.

It has already been seen that the acceleration of the horizontal motion of the air was insufficient to explain such a large ageostrophic wind. Durst and Sutcliffe[8,9] have shown that mass vertical movement in a region of horizontal temperature gradient produces an acceleration and therefore an ageostrophic wind. In this case the persistence of low clouds was incompatible with much subsidence over the British Isles. Further east there must have been subsidence large enough to feed the observed ageostrophic wind, and its magnitude depends on the width of the belt of subsiding air, which is unknown. There is no evidence of a large horizontal temperature gradient at the level of about 1,500–3,000 ft. in this area.

The remaining possibility seems to be a frictional influence due to the frontal surface itself and acting in the free air, where marked wind shearing can set up some turbulence even when the lapse rate is stable. The frontal surface is a region of very marked wind shearing, and assuming that some turbulence is developed the transfer of momentum becomes very large. The principle is general, but can be explained most readily in the case of a warm front orientated from north to south. In the transitional layer the north component of wind increases rapidly upwards, owing to the warm air to the west, and turbulence carries north–south momentum downwards. This in itself does not affect the motion of the front, but the balance between the deflecting force of the earth's rotation and the pressure gradient is upset, and there is movement of the cold air towards the front, which retards its advance. If a steady state is attained, the ageostrophic wind (or that part of it due to friction) is at right angles to the net flux of momentum into the layer and of magnitude $(K\partial^2 v/\partial z^2)/2\omega\sin\phi$ where K is the coefficient of eddy diffusivity, v the wind component parallel to the front, z the height, and $\omega\sin\phi$ the horizontal component of the earth's rotation.

In Appendix II of Brunt and Douglas's Memoir[7] an attempt was made to examine the frictional effect in the case of a pilot-balloon ascent which penetrated a frontal surface over Eskdalemuir, and the results look plausible if it is assumed that turbulence decreases upwards. The figures in the right-hand column of the table at the foot of p. 49 of that Memoir give a theoretical ageostrophic wind (taking $K = 10^5$ cm.^{2}/sec.) blowing towards the front of 16 m.p.h. (7·5 m./sec.) at a height of 2,000 ft. (600 m.) above the station, or 2,760 ft. (842 m.) above mean sea level. This agreed well with the actual ageostrophic wind at that level, but since other factors were acting simultaneously it is probable that K was really somewhat less. Since the value of K at frontal surfaces in the free air is not known, the magnitude of the frictional effect must at present remain conjectural, but it probably should be taken into account at all heights. The relatively thick transitional layers normally observed are perhaps evidence of frictional smoothing, but in order to prove it one would need to show that the discontinuity would have been sharp in the absence of friction.

After January 30 the front over the English Channel and southern England became diffuse, and its exact position is difficult to determine, but over the Low Countries there was a pronounced front on January 31 and February 1 which remained almost stationary in spite of a geostrophic wind of not less than 30 m.p.h. tending to push it northwards. This implies an even larger departure from geostrophic balance than anything shown in Table I.

The pressure change charts show the south-east movement of isallobars of 6-hr. pressure changes. There was an isallobaric gradient helping the ageostrophic motion of the front on the morning of the 27th, but the most important effect of the pressure changes was the change of geostrophic wind itself.

No wholly satisfactory explanation of the ageostrophic motion can be given at present. A shallow cold layer is unlikely in itself to be a dominant influence, but the shallow cold air over the British Isles was only the boundary of a great mass of cold air over Europe, which must have extended to a great height. The predominance of northerly wind components in the upper troposphere in January is evidence of that. An extensive deep mass of cold air is not readily displaced, or warmed by subsidence, and so long as it exists there is always a risk of it spreading westward if favourable conditions arise. When there is a cold easterly current over Europe the mountain barriers of the Alps and Norway increase the chance of the cold air reaching England, but this line of argument would not have helped in predicting the developments of January 26–27. When the front reversed its motion on the night of the 26th–27th, the air just east of it had come northwards from France and had previously been stagnant after arriving from the north a few days earlier. The air from the heart of the Continent followed later.

§ 7—UPPER AIR CONDITIONS

The available observations of upper air temperature from the British Isles and north France are plotted on the tephigrams on pp. 16–24. The point which strikes the eye is the enormous depth of the transitional layer with nearly isothermal conditions, more especially at 1300 on the 27th and 28th, and also at Mildenhall on the morning of the 29th. The maximum depth of almost isothermal air was at Mildenhall at 0700 on the 28th, when it extended from 3,200 to 11,600 ft. (900–650 mb.). A frontal surface is often smoothed over a layer 5,000 ft. or more thick, represented by a layer with a lapse rate below the saturated adiabatic. During precipitation the air is normally saturated, and the wet-bulb potential temperature increases with height in the transitional layer. When the temperature discontinuity is unusually large, there is obviously more chance of finding an isothermal layer or an inversion instead of merely a stable layer. In the present case the depth of the transitional layer was increased by the presence of polar maritime air between the continental and tropical air masses, as described in § 5. All the polar maritime air had left the ground by about 1300 on the 27th, but as it must have ascended over the continental air, there is nothing surprising in finding it for a longer period up aloft. The depth of the transitional layer decreased between the 28th and 29th and still more afterwards. The wet-bulb temperature at the surface in the polar maritime air was about 45°F. and bearing in mind the fact that the wet-bulb potential temperature is a conservative property during ascent, it appears that the air in the middle of the transitional layer from the 27th to the 29th probably consisted of this air mass. It did not occupy the whole transitional layer, since there is always much smoothing at a frontal surface.

A definite discontinuity of lapse rate persisted at the base of the transitional layer, marked as h_1 on the tephigrams, and Table V gives the values of the heights of h_1, the distance, d_1, of the front, and the ratio d_1/h_1. It can be seen that there is much irregularity about these figures, partly owing to the lack of autographic records in the upper air ascents. Regular observations are only made at 50-mb. intervals in the aeroplane ascents, and, although inversions are often noted at intermediate pressures, this is not always so, and the bases of inversions as reported show an undue preponderance of pressures which are multiples of 50 mb. In any case it is very difficult to observe the base or top of an inversion accurately with eye readings only. Thus the figures for d_1/h_1 are not really accurate to two significant figures. There are also genuine casual irregularities in the height of an inversion, which sometimes varies by a few hundred feet between the ascent and descent of an aeroplane. The large rise in d_1/h_1 at Aldergrove between 0700 and 1300 on the 27th was due to colder air from the east forming a new discontinuity lower down, as can be seen from an inspection of the tephigrams. Though no importance can be attached to some of the variations of the angle of slope, certain main conclusions can be drawn. The slope was considerably steeper at Aldergrove than at Mildenhall, especially at first, which fits in with

TABLE V—SLOPE OF UPPER BOUNDARY OF COLD AIR AND LOWER BOUNDARY OF WARM AIR, JANUARY 26–FEBRUARY 1, 1940

	Upper boundary of cold air						Lower boundary of warm air					
	Mildenhall			Aldergrove			Mildenhall			Aldergrove		
	Distance of front d_1	Height of base of transition layer h_1	Inverse of slope of front d_1/h_1	Distance of front d_1	Height of base of transition layer h_1	Inverse of slope of front d_1/h_1	Distance of the nearest tropical air d_2	Height of top of transition layer h_2	Inverse of slope of front d_2/h_2	Distance of the nearest tropical air d_2	Height of top of transition layer h_2	Inverse of slope of front d_2/h_2
G.M.T.	miles	miles		miles	miles		miles	miles		miles	miles	
January 26												
0700	280	0·91	310	70	0·56	130	280	1·87	150	70	0·61	115
1300	180	0·61	290	10	..	..	300	3·96	76	440	3·87	114
January 27												
0700	130	0·59	220	40	0·30	130	160	2·98	53	130	2·37	55
1300	150	0·62	240	60	0·23	250	150	2·59	58	110	2·19	50
January 28												
0700	220	0·62	350	70	0·30	230	220	2·20	100	90	1·15	78
1300	220	0·56	420	60	0·27	230	220	1·90	116	60	0·85	71
January 29												
0700	220	0·60	370	170	0·58	290	220	1·70	149	270	..	..
1300	220	0·67	330	220	0·65	340	220	2·56	86	320	2·18	147
January 30												
0700	300	0·62	480	350	0·93	380	300	1·79	167	..	..	..
1300	250	0·55	460	320	0·89	360	250	1·14	219	..	..	..
January 31												
0700	100	0·27	370	280	0·80	350	..	..	..	..	..	..
1300	100	0·25	400	220	0·63	350	..	..	..	..	..	..
February 1												
0700	120	0·28	430	..	..	..	..	..	..	..	..	..
1300	120	0·24	500	..	..	..	..	..	..	..	..	..

the larger wind discontinuity at Aldergrove, associated with a steeper pressure gradient in the cold air. At both places the angle of slope decreased considerably after the 27th, probably in association with a sharpening of the temperature discontinuity close to the front.

The upper limit of the transitional layer was less clearly defined than the lower limit. The lapse rate in the upper parts of the curves tended to approximate to the saturated adiabatic rate, but the actual saturated adiabatic line varied from 60°F. near Paris* on the 27th and 28th and at Aldergrove on the 28th, to below 50°F. at Mildenhall and Aldergrove later. By February 2, the curves at these two places were on or just above the 45°F. saturated adiabatic, and the air could then be classed as mild polar maritime. When the curves were on or about the 50°F. line the air was intermediate and could be classified as either warm polar maritime or as " cold tropical " (Bjerknes and Palmén[10]). The best label to use is entirely a matter of opinion, since the air at high levels generally travels fast on an undulating trajectory.

Under these circumstances it is impossible to fix the upper limit of the intermediate air merely in terms of wet-bulb potential temperature, and indeed any criterion is to some extent arbitrary. It is clearly best when possible to take a salient point on the curve, but such points require great caution in their interpretation, as they can be produced in various ways. The genuine tropical air had been cooled over the sea surface before it started to ascend, and probably some of the salient points represented the limit of this cooling rather than an air-mass boundary, but such difficulties are unavoidable. The procedure adopted was to mark certain salient points as h_2 on the curves, so that the evidence can be judged by the reader, and to include their values in Table V for what they are worth, so long as the upper mass could reasonably be regarded as tropical or semitropical. The distance d_2 in the table is the distance of the nearest tropical air at ground level from the place of observation, which was not in all cases the same as the distance d_1 of the main front. The ratio d_2/h_2 gives the average angle of slope of the tropical air, but the slope is unlikely to have been uniform when the main front was occluded. In other cases one would expect some approach to a uniform angle of slope, as this has been fairly frequently observed in the past. The angle was by no means constant along the front. It was steepest on the 27th, when the transitional zone had its greatest thickness. The sudden increase of angle at 1300 on the 29th at Mildenhall has probably no meaning except as an illustration of the unsatisfactory nature of using salient points on the curve to find the frontal surface, but as already mentioned any other criterion would appear to be arbitrary, involving an element of personal choice. Another peculiar curve is that at Paris on the 27th. The main front was only 30 miles from Paris but there was an enormous transitional layer and the upper salient point was at a height of nearly three miles. The second warm front was probably somewhere to the rear of the main front, but it is impossible to place it accurately on the sea-level chart.

The sequence of upper air changes in relation to the synoptic charts has been referred to already in § 5. The influence of the upper cold front associated with the occlusion process on the 26th is clearly seen on the tephigrams at Aldergrove, and to a lesser extent at Mildenhall on that day, and also at Mildenhall between 900 and 800 mb. at 0700 on the 27th. The new warm front had notable effects over Aldergrove by 0700 on the 27th and also at high levels over Mildenhall, and by 1300 its influence was great over both places. A fall of temperature had begun high up by 1300 on the 28th and continued till the 30th. It was associated with the renewed occlusion of the warm air, but can only be explained in terms of temperature gradients and not in terms of surfaces of discontinuity. It extended to the east of the occlusion and over the remains of the warm sector.

The observations of humidity are limited by the fact that wet-bulb readings are unreliable at temperatures below freezing. During the precipitation at 0700 on the 27th the cloud was of immense thickness, extending at Mildenhall from 8,000 to 18,000 ft. without a break When the

* The tephigrams for January 29–31 show that the Paris readings were probably slightly high.

belt of precipitation moved away westward a relatively dry layer appeared between the layer cloud under the inversion and the other clouds higher up. The relative humidities shown on the tephigrams may be higher than the true values, but cannot be appreciably lower. The low humidities at low levels at Mildenhall on the 26th were noteworthy.

The Paris radio-sondes carried a hygrograph on most of the ascents, of which the readings (apart from lag) are fairly reliable low down, but are more doubtful at high levels, where temperature and moisture content are both low. They all showed a thick layer of saturated or very damp air, with drier air above about 18,000 ft., and somewhat lower down near the end of the period. Even if the instrument is not really dependable high up, it appears probable that the fall of humidity was real, although perhaps not quantitatively accurate, and the top of the saturated air was at much the same level as the top of the cloud at Mildenhall. The rainfall from the 27th to the 29th was larger at Paris than at Mildenhall, owing to the proximity of the front, but it was not so large as in the belt of heavy precipitation in England. Dry air at high levels over warm-front cloud was noted in certain cases by Hewson[11] who also found independent evidence of divergence of the air rising up the warm-front surface, or, in other words, of a decrease with height of the vertical motion over a given point on or just above the frontal surface or transitional layer. In the present instance the thickness of the transitional layer complicated the whole question, and it is clear that some of the precipitation must have been produced by ascent of the transitional air, to a greater extent than at the average front. Sometimes the frontal cloud is thicker than it was at Mildenhall or Aldergrove on this occasion.

Fig. 5 is an attempt to construct a vertical section, showing the temperature distribution at 0700 on the 28th, from the front to Mildenhall, the only place in Great Britain where there were any observations of upper air temperature. Above 11,500 ft. (650-mb. pressure level, see the tephigram for the morning of the 28th) the lapse rate over Mildenhall was roughly the saturated adiabatic, near the 55°F. wet-bulb potential temperature curve on the tephigram ; this may be taken as representative of the warm air, so that the lapse rate in the warm air can be taken along

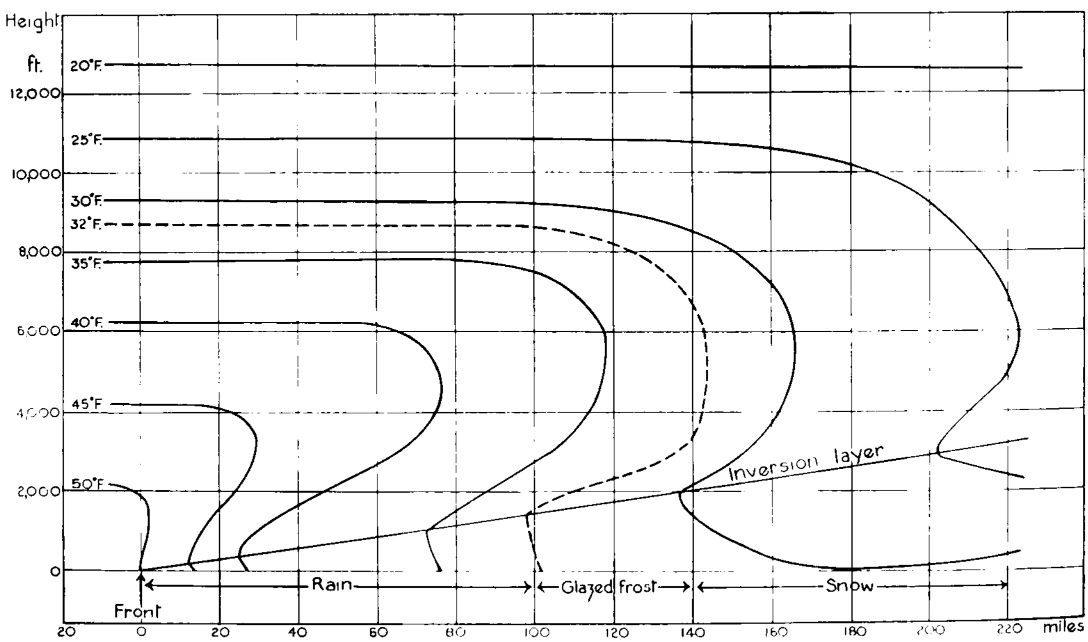


FIG. 5—ESTIMATED VERTICAL CROSS-SECTION FROM MILDENHALL TO FRONT AT 0700, JANUARY 28, 1940

that line except for the effect of surface cooling (mostly on the sea) indicated by the observed surface temperatures. The inversion at the top of the very cold continental air, which is an approximation only, is drawn as a uniformly sloping boundary, solely because there is no reason to draw it in any other way. The only other known facts bearing directly on the upper air temperature are the distribution of rain, glazed frost, and snow, in zones roughly 100, 40 and 80 miles wide, and the fact that the upper air soundings on other days during the period all showed a transitional layer of considerable thickness. The diagram is based on these facts together with general considerations of symmetry. The point that stands out is the thickness of the thaw layer in comparison with that of the freezing layer lower down. The sharp wind discontinuity observed at Larkhill on the previous morning, January 27, may indicate a sharper inversion in the glazed-frost area on the 28th but this would thicken the thaw layer still more. The isotherm of 32°F. can only have extended very slightly to the north-east of the glazed-frost belt, and the effect of falling snow, which would become soft just to the south-west of the 32°F. isotherm, would tend to make the temperature rather uniform, i.e. to make the 32°F. isotherm nearly vertical. Slight horizontal fluctuations of this isotherm would lead to alternations of snow and glazed frost, and this happened to the south-west of Birmingham and probably in some other areas, though the front was receding slowly all the time. Factors tending to make a nearly isothermal layer were the presence of an intermediate air mass (see § 5), the normal smoothing processes of turbulence and radiation, and probably to some extent the precipitation. The complex structure and the absence of a single sloping surface of discontinuity separating only two air masses presents difficulties from the point of view of forecasting. The exact line of separation between the snow and glazed frost would have been very difficult to predict in this case even with a good and extensive network of upper air stations.

On the upper air charts the broken lines are contours of the height of the 500-mb. surface above sea level, and the dot-dash lines contours of the height of the 500-mb. surface above the 1000-mb. surface, which is proportional to the mean temperature of the column of air. The places with observations are shown by the dots. Over France there were radio-soundings of temperature at several places, and over the British Isles there were aeroplane soundings at Mildenhall and Aldergrove, and also wind observations by radio-pilot at Larkhill on the 26th (which needed smoothing), and on the 27th up to 13,000 ft. Over most of France there was a gradient for NW. winds throughout the period, and judging from the normal structure when temperature is low on the Continent this NW. wind probably extended to areas east and north-east of that covered by the observations. As described in § 5, a large fall of upper air temperature occurred over Aldergrove on the 26th, and since the main cyclonic centre was far out on the Atlantic, there is no doubt that the cold air producing this fall of temperature was part of a large mass of cold air to the north-west. The dominant feature of the upper air structure was thus a warm wedge extending northwards from Spain, though there must have been a subsidiary wedge over the warm sector then approaching from the south-west. By the 27th this warm air had reached the south-west of the British Isles and the upper wind over Larkhill had veered to WNW. A cold front had reached the Azores, and observations on a ship to the north-west of the Azores and at land stations (including Greenland) suggest that the point of occlusion was at about 56°N. 22°W., and that there was a deep occluded centre with pressure below 980 mb. near 47°N. 36°W., which was moving slowly north-east. The older depression to the south-west of Iceland had probably no longer a separate centre, and it is clear that there had been a northward recession of the cold air mass. Since the warm current was south-westerly with a cold front approaching from the west, it is certain that the general upper structure over the British Isles was still a wedge extending north from Spain. It was really an amalgamation of two wedges, but in the small area with actual observations it is impossible to trace the remains of the trough between them.

On the morning of the 28th observations were scanty in the British Isles, with no radio-wind observation from Larkhill and the Aldergrove ascent only up to 750 mb., but there cannot have been a large change, though the wedge may have moved slightly east. By evening the temperature in the warm air aloft had fallen somewhat at Aldergrove, and by the 29th there had been a fall over a large area extending as far as Bordeaux, which was still in the warm air at sea level, the point of occlusion being just north of Scilly. The Atlantic depression had moved to about 50°N. 15°W. and filled to about 998 mb.; and the upper cold trough was probably little if at all west of 15°W.

A comparison between the upper air and pressure-change charts shows that in the north-west of the British Isles the isallobaric systems were moving south-east in an area just west of the crest of the wedge at 500 mb., but the thickness lines, giving the distribution of the mean temperature of the column of air, show a wedge further west than that shown by the 500-mb. contours. Sutcliffe's theory[12] of the influence of upper winds on the movement of pressure systems (obviously also of isallobaric systems) emphasizes the thermal wind as the steering agency, but it would be unwise to deduce much from a single period when the upper air information was still scanty.

§ 8—GENERAL CONCLUSIONS

(revised 1946)

Like other abnormal meteorological phenomena, the glazed frost was due to an exceptional combination of factors unlikely to recur over a long period. Whether glazed frost on this scale occurs over a comparable area in the British Isles as often as once in a century is a question for historical climatologists to answer if they can. The fact that somewhat similar situations may give little or no glazed frost suggests a negative answer. The most unusual features were the long duration in one area and the continuation of the cold weather afterwards.

The large ageostrophic motion of the front played an essential part, both in pushing the front slowly south-west and in producing the marked undercutting of the cold air which is necessary for the formation of glazed frost. (A geostrophic wind system provides no mechanism for undercutting, though it can obviously move an already existing surface of discontinuity.) Another important point was the thickness of the thaw layer, probably as much as 6,000 ft., near the south-west boundary of the glazed-frost belt. If the thaw layer is thin it can easily be cooled down virtually to freezing point by snow falling into it from above. This case was unsuitable for quantitative treatment, and even with upper air information on the 1946 scale the difficulties of quantitative methods are great, owing to the number of factors operating and the absence of ideal surfaces of discontinuity.

On this occasion rainfall exceeded 0·8 in. in 12 hr. in some areas, but the average was less, and some of it must have been due to ascent below the upper freezing level. A snowfall giving equivalent rainfall of 0·04 in./hr. is quite usual, and the melting of this would cool a layer of air 3,300 ft. thick with a density 1,000 gm./m.^{3} by 0·54°F./hr. Ascent of the stable transitional air would reduce the temperature at a fixed level, and to counteract the two cooling factors only advection can be operative. Taken relative to the front, this advection is associated with the upsliding, and with considerable precipitation it is of the order of 10–15 m.p.h. With the horizontal temperature gradients of the general magnitude observed in this case, this gives a rise of 0·2–0·4°F./hr., rather below the rate of cooling of a layer 3,300 ft. deep by snowfall of the magnitude mentioned above. This is probably one reason for the rarity of prolonged glazed frost. Another reason is the fact that the shallow cold air near the front tends to be warmed by mixing with warmer air above.

Glazed frost of a few hours' duration followed by a thaw is comparatively common. Three examples have occurred over a large area in the Midlands and east of England since 1940, namely January 18–19, 1941; January 10, 1943; and January 30, 1945; all ahead of warm fronts or warm occlusions in returning polar air from France. The second case was in a mild winter. There have also been examples of supercooled drizzle with no thaw layer above. During one such period at Dunstable on January 5–6, 1941, the drizzle alternated with dry snowflakes of moderate size. Though supercooled drizzle can occur without a thaw layer, there is no reason to doubt that real supercooled rain requires a substantial thaw layer.

The severe spell early in 1942 provided examples of the failure of glazed frost to develop on any considerable scale, even when the general situation seems favourable. From January 15 to February 2 inclusive, the mean temperature difference between Yarmouth and Scilly was 16°F., and often exceeded 20°F., compared with an average of 6°F. During the heavy snowfall of January 19 temperature was lower in eastern and Midland districts than it was on January 26–28, 1940. The front was sharp with a narrow transitional belt from snow to sleet and then rain, and this happened again on February 1–2. The Larkhill observations never showed quite the right conditions for glazed frost, though the difference between the actual conditions and those required for glazed frost amounted to a few degrees only. During snowfall at Larkhill at 2000 G.M.T. on January 19 there was a stable layer from the ground to 6,200 ft., temperature falling from 32° to 29°F Wind shear was large, with a vector change of 39 m.p.h. (35 kt.) from 3,160 to 6,230 ft., and, according to Richardson's criterion, turbulence must have been set up and have smoothed out the inversion, thus destroying the chance of glazed frost.

The lack of definition of the top of the transitional layer, shown in Table V, is a common phenomenon, and is not confined to cases with more than two air masses. The base of the transitional layer is more often well defined, but by no means always. Subsidence in the cold air frequently brings the temperature and wind discontinuity below the air-mass discontinuity, which is shown by the wet-bulb potential temperature and is not necessarily sharp. The ideal surface of discontinuity is rare, and is not a possible basis for the use of quantitative methods, at all events for forecasting glazed frost.

BIBLIOGRAPHY

1. CAVE, C. J. P. ; The ice storm of January 27–29, 1940. *Quart. J. R. met. Soc., London,* **66**, 1940, p. 143.
2. CROOME, W. I. ; Account of the formation of ice on vegetation at Bagendon, near Cirencester, Glos. *Quart. J. R. met. Soc., London,* **66**, 1940, p. 150.
3. GUNTHER, E. R. ; Unusual ice formation in Wiltshire. *Nature, London,* **145**, 1940, p.428.
4. *Southern Railway Magazine, London,* **18**, No. 207, 1940.
5. HAWKE, E. L. ; The snow-storm and drifts of January 26–29, 1940, in the northern Chilterns. *Quart. J. R. met. Soc., London,* **66**, 1940, p. 152.
6. London, Meteorological Office. The glazed frost of January, 1940. *Met. Mag., London,* **75**, 1940, p. 12 and p. 21.
7. BRUNT, D. and DOUGLAS, C. K. M. ; The modification of the strophic balance for changing pressure distribution, and its effect on rainfall. *Mem. R. met. Soc., London,* **3**, No. 22, 1928.
8. DURST, C. S. and SUTCLIFFE, R. C. ; The importance of vertical motion in the development of tropical revolving storms. *Quart. J. R. met. Soc., London,* **64**, 1938, p. 75.
9. DURST, C. S. and SUTCLIFFE, R. C. ; The effect of vertical motion on the " geostrophic departure " of the wind. *Quart. J. R. met. Soc., London,* **64**, 1938, p. 240.
10. BJERKNES, J. and PALMÉN, E. ; Investigations of selected European cyclones by means of serial ascents. Case 4 : February 15–17, 1935. *Geofys. Publ., Oslo,* **12**, No. 2, 1937.
11. HEWSON, E. W. ; The application of wet-bulb potential temperatures to air mass analysis. II The ascent of air at warm fronts. *Quart. J. R. met. Soc., London,* **63**, 1937, p. 7.
12. SUTCLIFFE, R. C. ; Cyclonic and anticyclonic development. *Quart. J. R. met. Soc., London,* **65**, 1939, p. 50.

(3770) Wt 3490/BM 4200 K5 5/56 Hw.