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A STUDY OF WARM FRONTS

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A STUDY OF WARM FRONTS

By A. G. MATTHEWMAN, M.A.

Summary.—Some typical features of the structure of warm fronts with respect to temperature, humidity, wind and cloud are examined. An example of detailed analysis of a well marked warm front illustrates the large-scale and small-scale structures of the temperature, humidity and wind fields. The difficulties presented by the small-scale structure are discussed. The cloud structure is examined statistically in relation to the textbook models, and in relation to various parameters usually, or sometimes, available to the forecaster. The best correlation of frontal cloud here achieved is with the difference between the speed of the surface front and the actual wind component normal to the surface front at the upper surface of the frontal zone, but this correlation coefficient is only about 0·5.

Introduction.—The Norwegian concept of fronts is now over 30 years old, many detailed analyses of fronts have been published, and the standard textbooks show apparent agreement on many aspects. There still remain difficulties, however, of a fundamental nature—indeed there is no satisfactory definition of the term "front" which will cover its wide connotation in synoptic practice or ensure that two analysts will inevitably arrive at the same representation.

In the present note, the purpose is not to discuss fundamentals of definition or analysis, but merely from a study of the data to indicate some of the shortcomings of the conventional models, and some of the difficulties which confront the analyst and forecaster.

PART I

Analysis of the warm front affecting the British Isles, October 24–25, 1949.—From the analyses of many warm fronts this analysis of the warm front affecting the British Isles, October 24–25, 1949, is chosen to illustrate the present note because the front was in many ways typical: it was favourably placed with respect to the upper air data and it moved over 36 hr. without changing its orientation appreciably. Two almost parallel vertical cross-sections, each almost normal to the surface front, were available every 6 hr. over the period 0300 G.M.T. on the 24th to 1500 on the 25th. These two series of cross-sections passed respectively over or near to the following radio-sonde stations:—

(i) Ship 66°N. 2°E., Lerwick, Leuchars, Liverpool, Larkhill, Bordeaux, Gibraltar.

(ii) Jan Mayen, Thorshavn, Stornoway, Aldergrove, Camborne, Brest, Lisbon.

By no means all these stations reported wind, temperature, and humidity every 6 hr.; nevertheless a sufficient number of observations were available, particularly in the neighbourhood of the front, to obtain consistency in space and time. A selection of these cross-sections is shown in Figs. 4–8.

For comparison with the actual wind fields perpendicular to the cross-sections, additional cross-sections were constructed to show the corresponding geostrophic wind fields, based on the geostrophic winds at the surface as measured from the mean-sea-level isobars, and the thermal winds as measured from the gradient and slope of the isotherms in the vertical cross-sections. An example of a cross-section of the geostrophic wind field is shown in Fig. 9.

The surface synoptic situation is indicated in Figs. 1 and 2, which display the mean-sea-level isobars drawn at 4-mb. intervals, the reports of precipitation, and the main frontal zones (shown hatched between pecked lines). Minor frontal zones within the main warm sector are left unhatched. The chief emphasis of the analysis is on the main warm front in the area of the British Isles particularly along the line of the vertical cross-sections.

At 0300 on the 24th, a pronounced wave was centred north of the Azores on a frontal zone separating cold polar maritime air, with a relatively direct track, from warm polar maritime air which had passed for some time over much warmer sea. This frontal zone at the surface coincided with the main trough lines in the mean-sea-level isobars and carried the centre of the lowest pressure. South-east of the centre, a second frontal zone separated the warm polar maritime air from the tropical maritime air to the south. The temperature contrast across this second zone was feeble. Figs. 1 and 2 show the situation 12 and 24 hr. later when the wave was occluding and the centre was moving towards the Irish Sea. The occlusion process was accompanied by only minor and temporary deepening of the centre, by about 8 mb.

Larkhill soundings.—As the main warm front moved north, its effects could be clearly seen on the radio-soundings at Larkhill. Graphs of these soundings over the period 0900 on the 24th to 0300 on the 25th are shown in Fig. 3. In these graphs, along the vertical, pressure is taken as the basic variable, but actually the vertical co-ordinate is linear with respect to height in the international standard atmosphere. The dry-bulb temperature is shown by what Bleeker[1]* has called the "saturated potential temperature", namely the temperature at 1000 mb. on the saturated adiabatic curve through the observational plots of dry-bulb temperature on the tephigram. Humidity is shown by the depression of the wet-bulb potential temperature below the saturated potential temperature. The graph of saturated potential temperature, taken alongside the graph of humidity, gives by subtraction the wet-bulb potential temperature which is probably the best simple indicator of air-mass differences. It is to be noted that the form of the graph of saturated potential temperature with height preserves the form of the corresponding graph of ordinary dry-bulb temperature—in particular, rapid variations in the vertical gradients are preserved.

The vector wind is resolved into its components along the directions 160° and 250°. Marked by circles are the usual reported winds at 50-mb. intervals, which are based on 2- or 3-min. averages according as the corresponding 50-mb. pressure level falls or does not fall within 0·2 min. of the mid point of the successive 1-min. intervals at which the balloon is located. These circles have been joined by segments of full straight lines. In addition, some greater detail extracted from the original records is shown, in which the corresponding 1-min. averages are denoted by dots at the mid points of the 1-min. intervals. These crosses have been joined by straight segments of pecked lines.

The two sets of wind averages illustrate some of the intrinsic difficulties in dealing with observations of wind. Besides instrumental errors which, since the advent of radar, are considered to be in general very small—probably less than 2 or 3 kt. even up to a slant range of the order of 66,000 yd.—there are usually minor fluctuations of the order of 3 to 5 kt., which are probably of no interest except in the study of turbulence. If these errors and turbulent fluctuations are reduced by averaging over 2- or 3-min. instead of over 1-min. intervals, the vertical gradients are changed, together with the pressure levels at which discontinuities in the vertical gradients are located, as may be seen by comparing the graphs for the two sets of averages in, for example, Fig. 3.

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* The index numbers refer to the bibliography on p. 23.

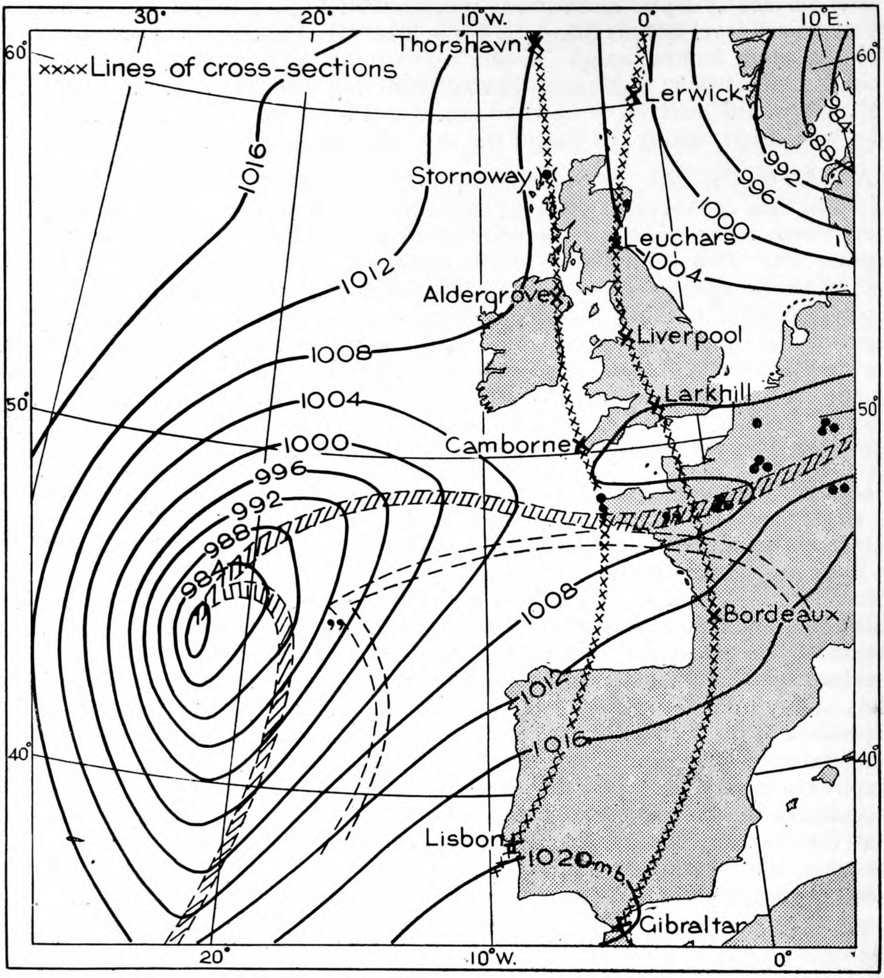


FIG. 1—SYNOPTIC CHART, 1500 G.M.T., OCTOBER 24, 1949

Main features of the soundings.—The graphs in Fig. 3 clearly indicate on a broad scale a warm air mass lying above a cold air mass, separated by a warm frontal zone of relatively small lapse-rate and associated with a relatively large increase of wind with height in the 250° component, which was nearly parallel to the surface front. In so far as the boundaries of the frontal zone are determined by rapid variations in the vertical gradients, the graphs also show that in detail there is considerable complexity, and sometimes considerable discrepancy between the pressure levels at which the frontal zone appears to be located according to the dry-bulb temperature, the wet-bulb potential temperature, and the wind curves on either set of averages.

It has already been remarked that the mode of averaging of the winds (and connecting of the points reported) may change the form of the corresponding graphs with respect to rapid variations in the vertical gradients. Subsequent work by Sawyer[2] has shown that small-scale turbulent fluctuations of temperature, together with errors of observation, may introduce into the graphs

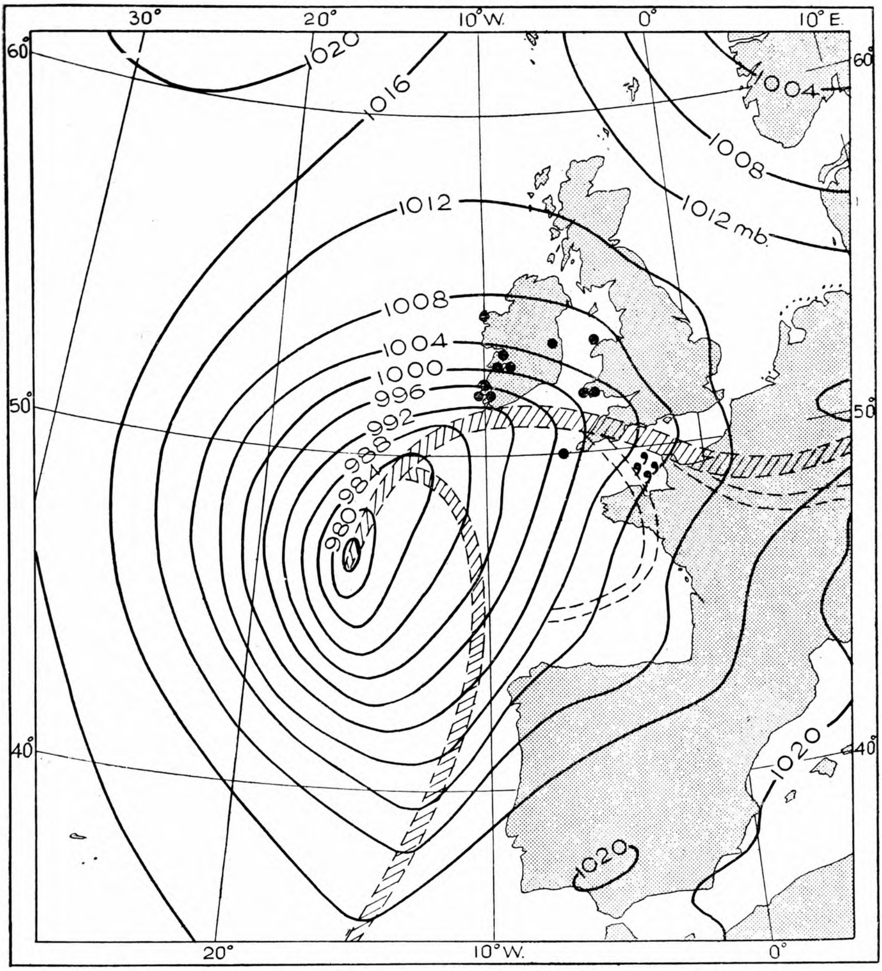
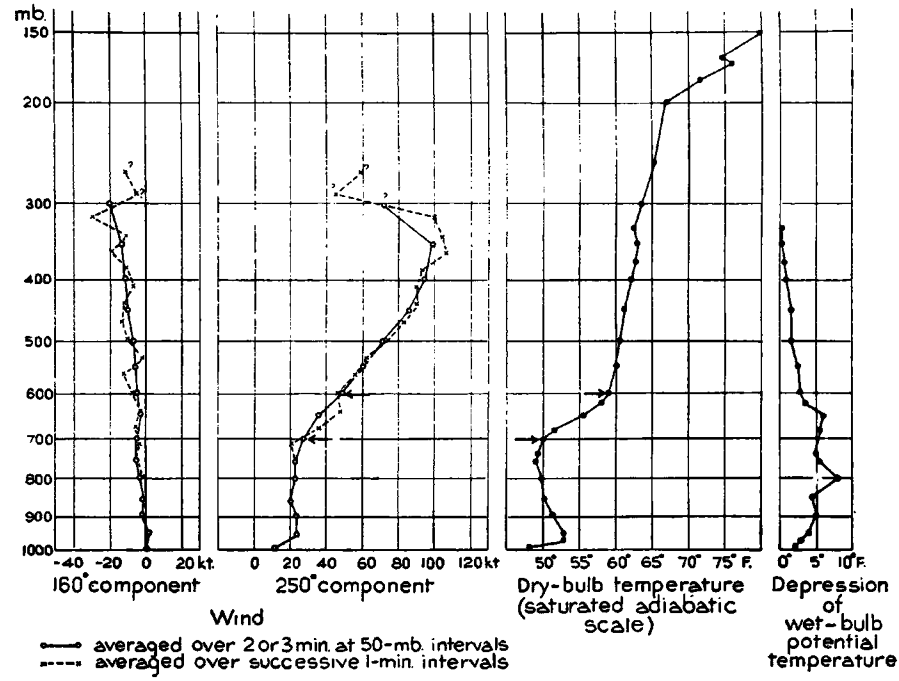


FIG. 2—SYNOPTIC CHART, 0300 G.M.T., OCTOBER 25, 1949

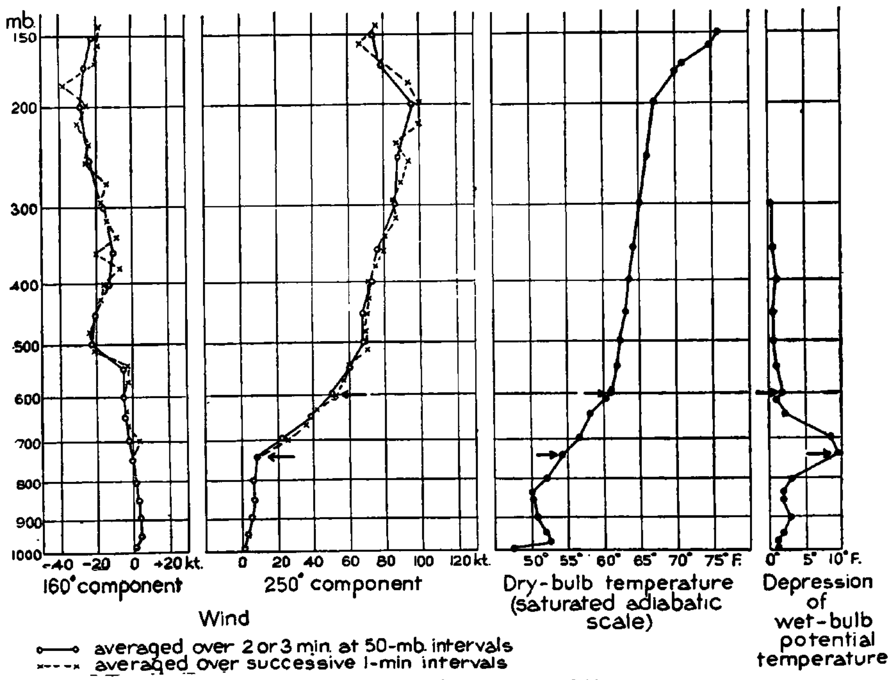
of reported radio-sonde temperatures spurious* discontinuities in the vertical gradients, may sharpen a gradual change of gradient into a discontinuity, and may somewhat shift the level at which a discontinuity in the gradient is located.

In some cases the discrepancies between the pressure levels at which the rapid changes in the vertical gradients occur in the graphs of dry-bulb temperature, wet-bulb potential temperature and wind component parallel to the front may be attributed to the fusion of an apparently subsided zone with the frontal zone itself (as for example at 2100 G.M.T., October 24, in Fig. 3) below the chosen lower boundary of the frontal zone. Here the zone of relatively strong wind shear corresponds more closely with the zone of relatively strong gradient of wet-bulb potential temperature than with the corresponding zone of temperature gradient. This may be seen by subtracting the humidity from the dry-bulb temperature readings at the relevant pressure levels. Whatever the cause of these discrepancies, their existence introduces an arbitrariness into the precise location of the frontal boundaries.

* Spurious, that is, for the identification of frontal boundaries on a synoptic scale.



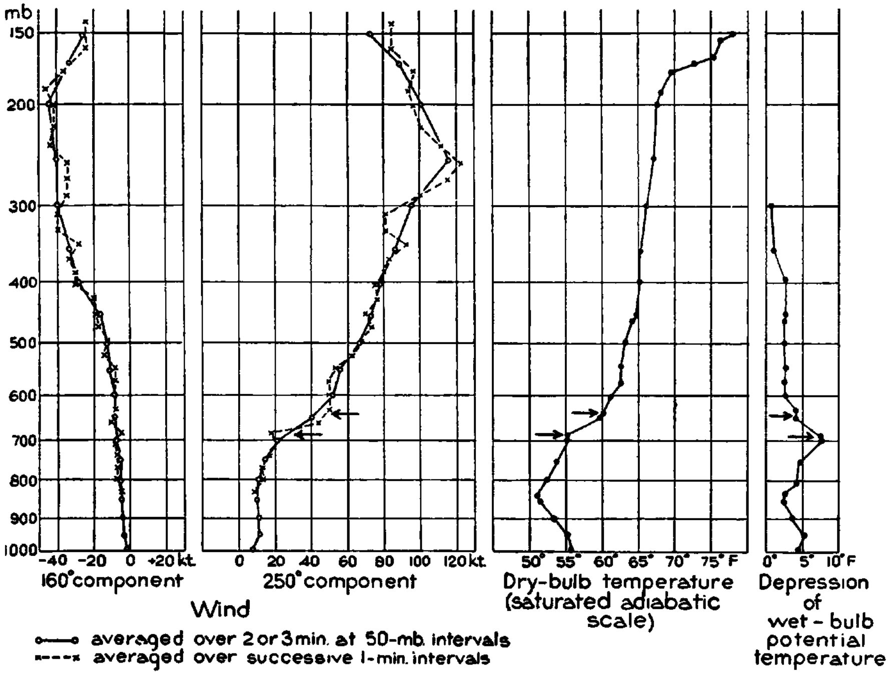
0900 G.M.T., October 24, 1949



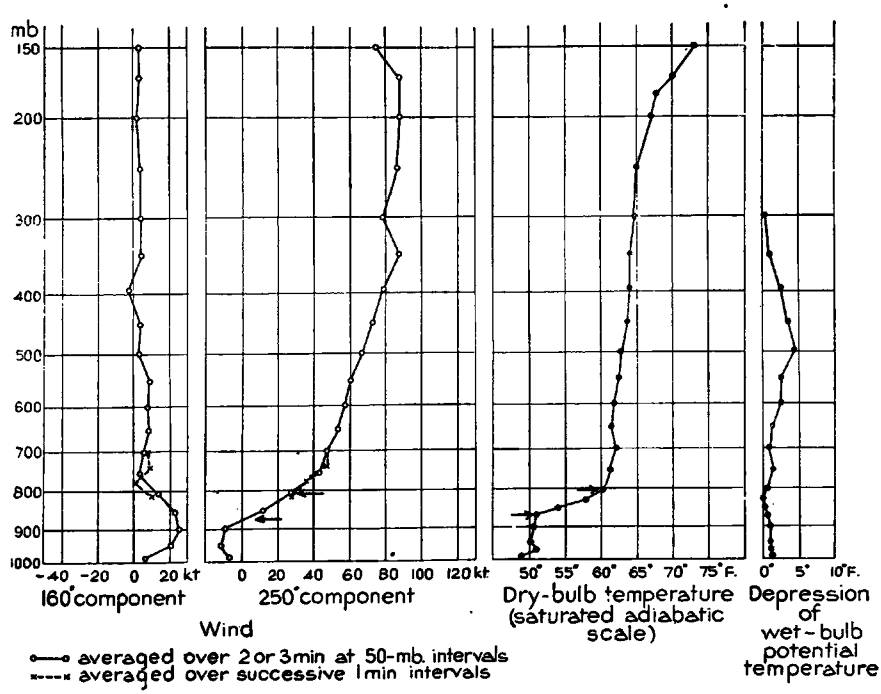
1500 G.M.T., October 24, 1949

FIG. 3—UPPER AIR DATA, LARKHILL

The arrows point to the upper and lower boundaries of the warm-front transitional zone



2100 G.M.T., October 24, 1949



0300 G.M.T., October 25, 1949

FIG. 3—UPPER AIR DATA, LARKHILL (*continued*)

The arrows point to the upper and lower boundaries of the warm-front transitional zone

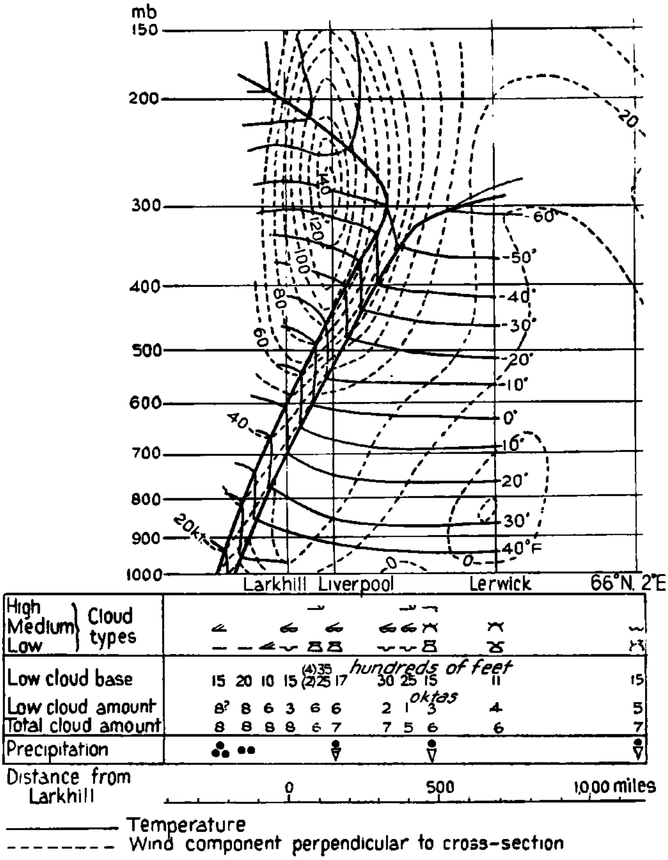


FIG. 4—VERTICAL CROSS-SECTION, 0900 G.M.T., OCTOBER 24, 1949

Vertical cross-sections.—Figs. 4–7 show vertical cross-sections through Larkhill at 6-hr. intervals from 0900 on the 24th to 0300 on the 25th. The vertical co-ordinate is again pressure on a scale linear with height in the international standard atmosphere. The tropopause above the warm air has been drawn continuous with the warm boundary of the frontal zone, and the tropopause above the cold air continuous with the cold boundary of the frontal zone. This is unconventional and uncertain.

Fig. 8 shows in a similar way a parallel vertical cross-section through Camborne at 1500 on the 24th for comparison with Fig. 5.

Below the cross-sections in Figs. 4–8 are shown the surface observations, cloud types in conventional symbols, total amount of cloud and amount of low cloud in oktas, the height of the base of the low cloud in hundreds of feet, and the present-weather precipitation. Also shown is a scale of distance from Larkhill (or Camborne).

Fig. 9 shows, on the vertical cross-section through Larkhill, the geostrophic component of wind normal to the cross-section, for comparison again with Fig. 5, and also the isopleths of pseudo wet-bulb potential temperature.

Main features of the cross-sections.—The isotherms in Figs. 4–8 exhibit a main frontal zone with small lapse-rate associated with strong baroclinity.

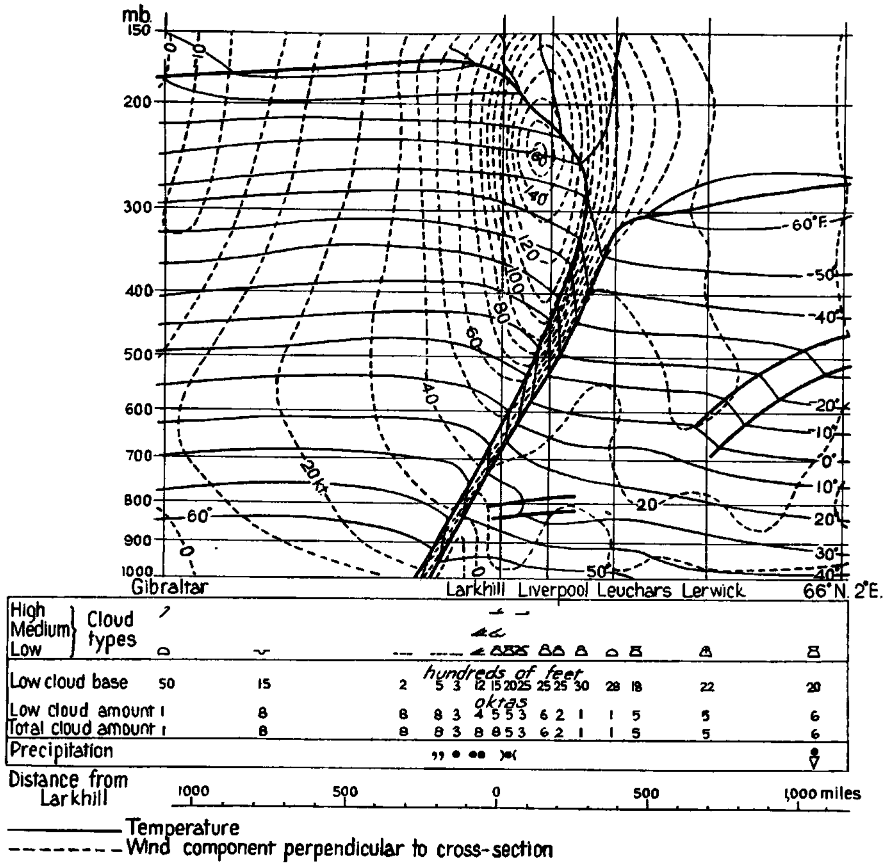


FIG. 5—VERTICAL CROSS-SECTION, 1500 G.M.T., OCTOBER 24, 1949

There is often fairly strong baroclinity in one or both of the surrounding air masses near the frontal zone. The boundaries of the zone are generally well defined, even at high levels in the troposphere, but are at times diffuse and somewhat arbitrary. There is some latitudinal fall of temperature northwards along the isobaric surfaces.

The isopleths of pseudo wet-bulb potential temperature in Fig. 9 exhibit the well known tendency to parallelism with and within the fontal zone up to 400 or 300 mb. The isopleths of geostrophic component normal to the cross-section in Fig. 9 exhibit a stong shear within the fontal zone associated with the strong baroclinity, and a well marked westerly jet stream within the warm air and just below the tropopause. There is a kind of easterly jet stream in the cold air ahead of the warm front near the ground.

The isopleths of actual wind component normal to the cross-sections in Figs. 4–8 exhibit a stong shear within the frontal zone, and a well marked jet stream agreeing fairly closely in probable location and probable central maximum value with the corresponding geostrophic jet stream. A second westerly jet stream begins to make its appearance above Larkhill in Fig. 7.

The behaviour of the westerly jet streams is summarized in Fig. 10. The main jet stream moved north rather faster than the surface warm front.

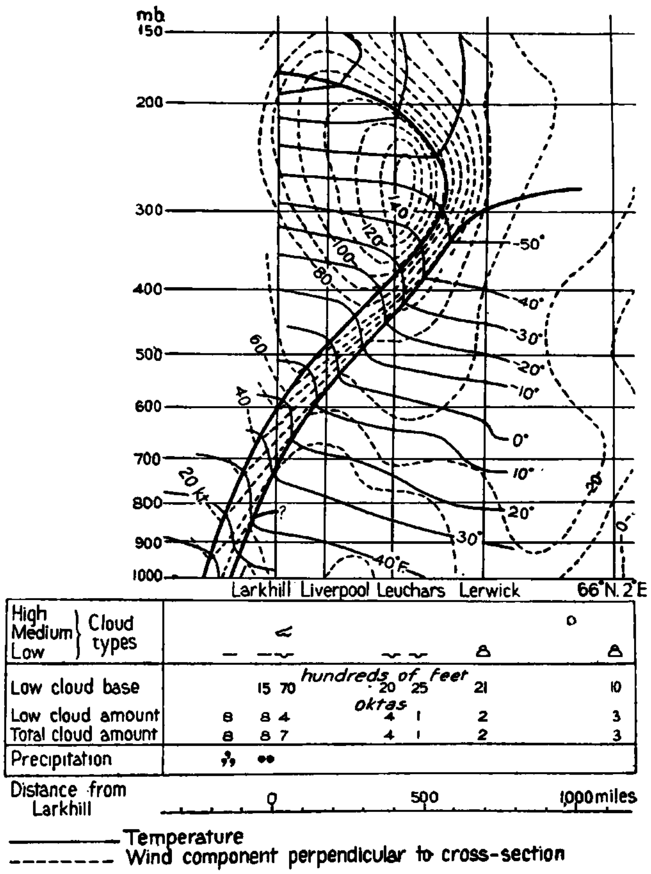


FIG. 6—VERTICAL CROSS-SECTION, 2100 G.M.T., OCTOBER 24, 1949

Comparison with various published studies of temperature and wind fields.—Nyberg[3] has indicated frontal zones extending into the stratosphere through breaks in the tropopause on either side. Berggren, Bolin and Rossby[4] have given an example (for February 12, 1948) of a frontal zone which was well marked and " seemed to extend into the lower stratosphere over the Shetlands ". The tropopause over the cold air is drawn continuous with the cold boundary of the frontal zone, and a trough in the isotherms extends northwards and downwards from the tropopause over the warm air towards the warm boundary of the warm front, but the tropopause is not drawn in this region. The associated zonal wind field shows a single jet stream, but with two troughs in the isopleths to the south and to the north.

In a similar way Palmén and Newton[5] show an average meridional structure based on 12 polar fronts, indicating upper boundaries of the frontal zone. Troughs in the isotherms are shown above the frontal zone without tropopauses. In this last example[5], the primary jet stream, just below 250 mb., is vertically above the front at about 500 mb. Durst and Davis[6] have shown an example of a jet stream vertically above a frontal zone at a much higher level than 500 mb. as in Figs. 6 and 7. Again, in the example given by Palmén and Newton[5] there is an indication of a minor secondary jet stream at a higher level (about 200 mb.) and 7° or 8° of latitude south of the primary jet stream.

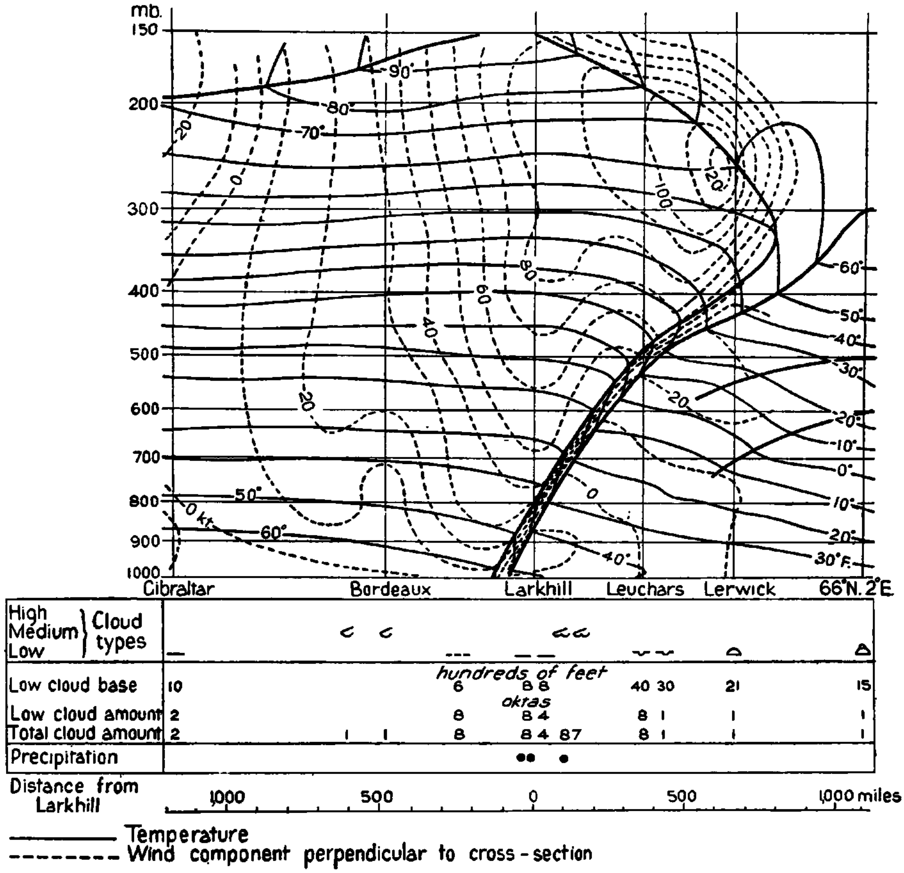


FIG. 7—VERTICAL CROSS-SECTION, 0300 G.M.T., OCTOBER 25, 1949

Cressman[7] has shown the existence of double jet streams, averaged over North America, in which the general tendency of the individual jet streams was to move south, but there is a northward movement of one jet stream from 50° to 57°N. over the two days March 27–29, 1948. The two jet streams were generally widely separated, but the separation varied from 22° to 8° latitude. This may be compared with Fig. 7 which shows the northward movement of the primary jet stream with, but rather faster than, the warm front, and the secondary jet stream about 10° south of the primary jet stream.

Phillips[8] has described an investigation into jet streams mainly over North America at 80° longitude, in which a double jet stream (January 23, 1948) is succeeded by a single jet stream associated with a well developed frontal zone (January 28, 1948), but later (February 3, 1948) the double jet structure is again apparent. The individual jets as they moved irregularly south showed an irregular increase in the potential temperature and an irregular decrease in the pressure at the centre of the jet stream. This may be contrasted with Fig. 10 which shows the centre of the main jet stream moving north at almost constant potential temperature and pressure.

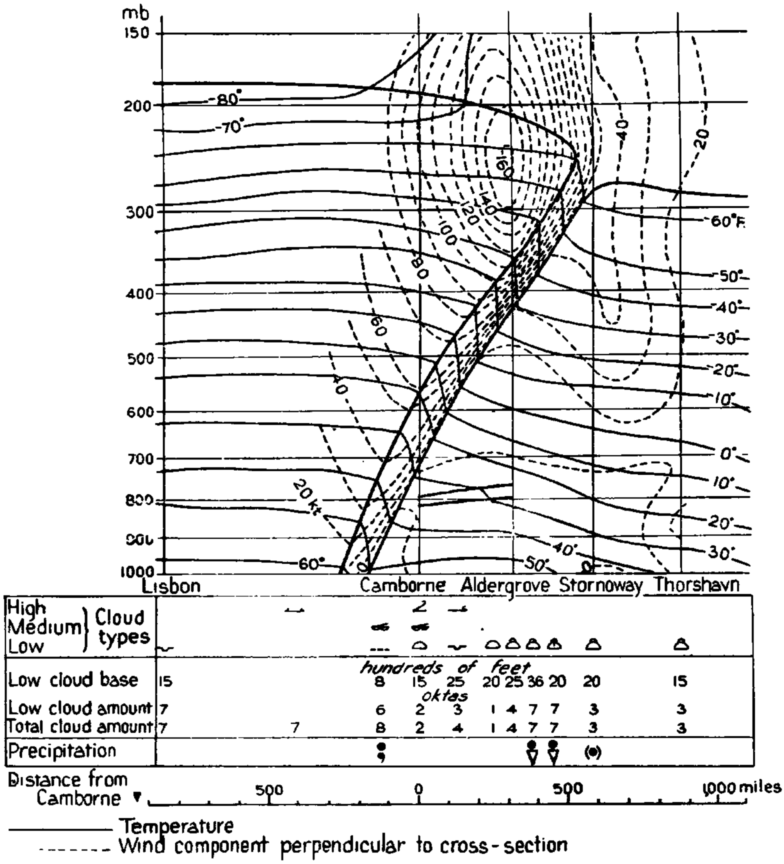


FIG. 8—VERTICAL CROSS-SECTION, 1500 G.M.T., OCTOBER 24, 1949

Precipitation and cloud structure.—Figs. 4–8 show, below the cross-sections, surface observations of cloud and precipitation. In the cold air well ahead of the warm front, there is convective cloud and some associated cirriform and altocumulus cloud, also some showers. The cross-sections show that towards the front, the convection was damped and the cloud became stratiform, with high and medium cloud increasing and thickening, and the low cloud base descending. Within about 200 miles of the front rain fell intermittently and, nearer to the front, continuously, but turned sometimes to drizzle just before the front was reached.

Surface observations of cloud, however, are usually, as in this case, inadequate for elucidating the complex details of cloud structure near fronts. Radiosondes, of course, do not report cloud, and the humidity observations are quite unreliable for indicating the existence and location of cloud. Aircraft observations are often lacking in important detail, unless specially directed to the reporting of the vertical distribution of cloud. During the Second World War, 1939–45, many flights were made over and near the British Isles, and over Europe, to determine in detail the cloud, temperature and humidity in the vertical, at frequent and regular times. These have provided the data for the statistics of frontal cloud which follow.

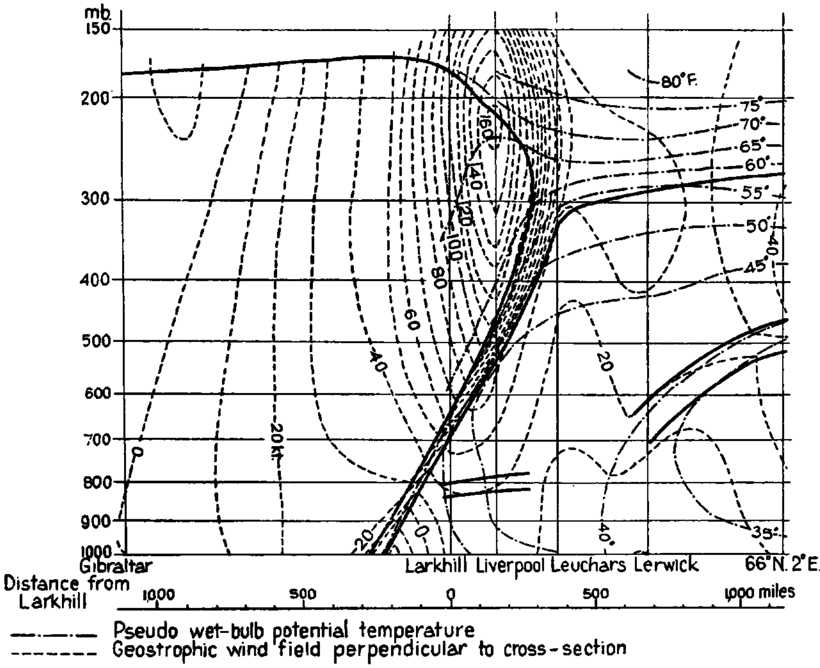


FIG. 9—VERTICAL CROSS-SECTION, 1500 G.M.T., OCTOBER 24, 1949

PART II

Data for the statistics of frontal cloud.—The British *Daily weather reports* over the period January 1–March 31, 1942 were examined for all analysed warm fronts, warm occlusions and quasi-stationary fronts near Bircham Newton. All cases were admitted for which the following conditions were satisfied :—

(i) The cold or transitional air could be identified near the ground over Bircham Newton.

(ii) The boundary of the warm air at Bircham Newton was below 400 mb.

(iii) A series of nearly simultaneous soundings was available roughly along a straight line normal to the surface front.

The German *Tägliche Wetterberichte* provided many data from aircraft ascents over western Europe. The times of the vertical cross-sections thus available were around 0700 and 1500. Wind soundings from Downham Market (near Bircham Newton) were also used.

Technique of the investigation of frontal cloud.—Simplified vertical cross-sections were prepared, with height in the international standard atmosphere as ordinate, showing the saturated potential temperature, the relative humidity if reported, and the location and amount of cloud as reported on the aircraft ascents. The cross-sections were analysed, except in one or two doubtful or peculiar cases, by indicating the boundaries of the frontal zones.

The wind soundings reported from Downham Market were plotted in the form of a time section with height in the international standard atmosphere as ordinate and time as abscissa. Isopleths of speed and direction were drawn to

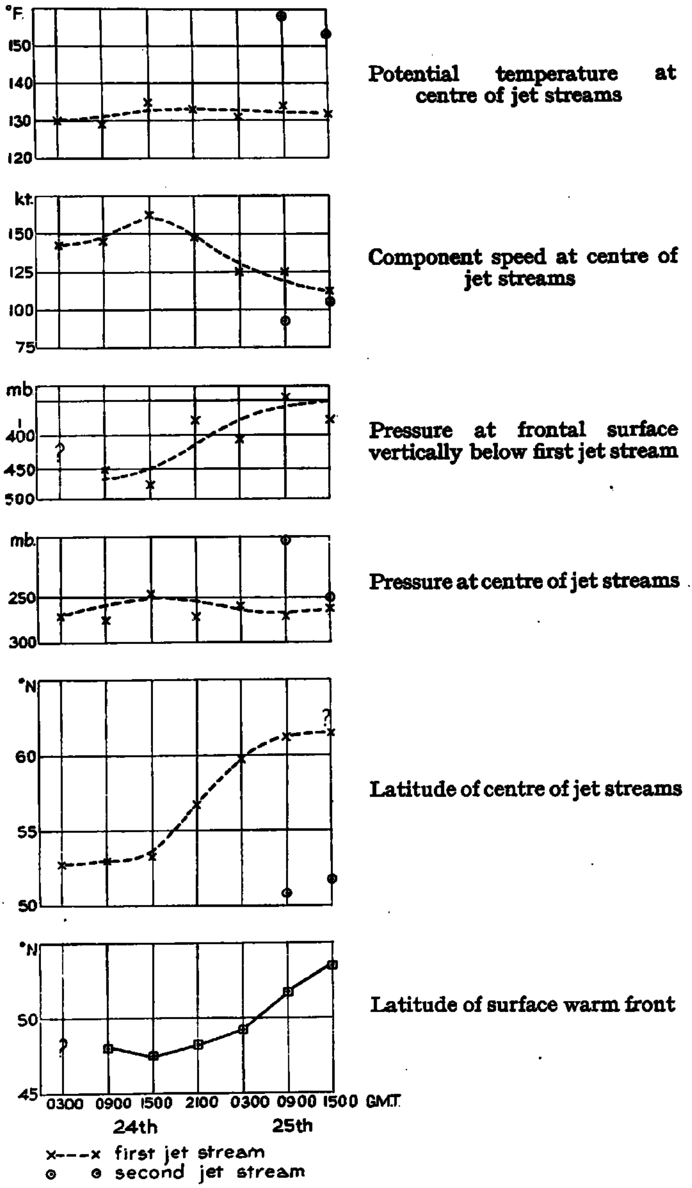


FIG. 10—BEHAVIOUR OF WESTERLY JET STREAMS IN RELATION TO THE WARM FRONT

obtain interpolated values of the wind at the levels of the boundaries of the frontal zone at the time of the relevant Bircham Newton aircraft sounding.

Uncertainties of the frontal analyses.—The frontal zones were analysed according to the classical model of a sloping zone of lesser lapse-rate bounded by more or less sudden changes to the larger and more or less steady lapse-rates in the air mass on either side, in conformity with the findings in the earlier sections of this paper. But, as discussed there in relation to the Larkhill soundings, the identification and location of the frontal boundaries may be arbitrary and uncertain. The analysis of the frontal cross-sections cannot therefore be regarded as entirely objective. Of the 55 vertical cross-sections 49 could be analysed in reasonable accord with the classical model. Confidence in the analysis was assessed as follows: 10 cases certain, 25 probable, and 14 doubtful.

In 1942 reports of humidity were irregular and of doubtful accuracy, but in general it was possible to avoid mis-identifying subsidence inversions as frontal zones.

The frontal analyses which were adopted deliberately avoided any complicated analyses into several frontal subzones unless the evidence for them seemed overwhelming. Nevertheless, in 12 cases, two frontal zones were considered probable. In some cases two or more surface fronts were shown on the surface charts, while not more than one frontal zone could be identified on the vertical soundings.

Modification of the warm, transitional and cold air masses, particularly near the ground or over the sea, gave some difficulty in deciding the most probable positions of the frontal zones on the surface charts; it was considered that in eight cases (five being of warm-occlusion type) the warm air did not reach the ground along the line of the cross-section; in an additional 18 cases there was also some uncertainty.

Classification of the frontal cloud.—For the purposes of classification, all cloud in the vertical column from the ground to 400 mb. (the limit of the Bircham Newton aircraft ascents) co-existing with one or more frontal zones was regarded as frontal cloud. The cloud was then classified into the following six classes:—

Class 1 .. No cloud.

Class 2 .. Cloud, apart from cirrus, cirrostratus or cirrocumulus, only below or near the base of the frontal zone(s).

Class 3 .. One or more thinnish layers of cloud above or near the top of the frontal zone(s). Here thinnish implies not more than 150 mb. deep.

Class 4 .. Thick cloud extending above the frontal zone(s), but with one or more lanes of clear air, at least 150 mb. deep, between the ground and 400 mb. Here thick implies more than 150 mb. deep.

Class 5 .. Continuous or almost continuous cloud extending from near the ground to near or above 400 mb., but with one or more layers or lanes of clear air not more than 150 mb. deep.

Class 6 .. Continuous cloud extending from near the ground to near or above 400 mb.

Since the number of cases in each of the classes 5 and 6 was small, for certain calculations of correlation coefficients, classes 5 and 6 were combined.

The frontal cloud having been classified according to the above definitions, relationships were sought between the classes and various synoptic parameters associated with the fronts.

Results.—*Relation of the cloud at Bircham Newton to the cloud at an adjacent sounding.*—Taking first the comparison with an adjacent sounding towards the warm side of the frontal zone, 6 cases were included in which the sounding on the warm side was entirely in warm air. A marked relation existed between the classes at the two soundings. Of the 23 cases for which the necessary data were available, only 4 cases showed a higher class number at Bircham Newton than the class number on the warm side, and 2 of these 4 were with the surface front between the soundings. Moreover in these 4 cases the class number at the warmer sounding was only less by 1 than the class number at Bircham Newton. Taking the comparison with an adjacent sounding on the colder side, 8 cases, the class number at Bircham Newton was in no case less than the class number on the cold side.

These relationships suggest both that the classification is meaningful, and that within the definitions of the various classes, the frontal cloud rarely decreased, and then only slightly, in the direction from the cold air towards the surface front. These relationships are of course in harmony with accepted ideas, but it is perhaps surprising that on these data the relationships were so good.

Relation of the cloud at Bircham Newton with the distance from Bircham Newton of the mid point of the frontal zone at the ground.—The tendency for the cloud class number to increase towards the front is also clear from Table I, in which the Bircham Newton soundings are enumerated in relation to class number and distance from the front.

TABLE I—NUMBER OF CASES OF SPECIFIED CLOUD STRUCTURES WITHIN STATED RANGES OF DISTANCE FROM THE SURFACE FRONT

Distance of Bircham Newton from surface front	Cloud class number*						
	1	2	3	4	5	6	All
miles	*number of cases*						
< 200	1	4	7	8	2	2	24
200–400	2	7	7	3	1	0	20
> 400	1	2	1	2	0	0	6

* In all the statistics which follow "cloud" refers to the cloud reported on Bircham Newton soundings.

Relation between the cloud and the slope of the warm boundary of the frontal zone.—The tangent of the angle of slope of the warm boundary of the frontal zone was measured in the vertical cross-sections, and multiplied by the secant of the angle between the direction of the surface front and the direction of the cross-section. This was considered to be the best practicable measure of the tangent of the angle of greatest slope of the warm boundary.

The mean value over all cases for the tangent of the angle of slope was $0{\cdot}005 = 1/200$.

The mean value of the slope in each class showed no clear trend with class, but varied between $0{\cdot}006$ in class 3 and $0{\cdot}003$ in class 1.

Relation of cloud with thickness (in terms of pressure) of the frontal zone.—The average over all cases of the thickness of the frontal zone was about 160 mb. The averages for each class showed no apparent relationship with class number, varying from 175 mb. in class 6 to 150 mb. in class 4—a small range. But the scatter in each class was large, e.g. in class 3 from 45 mb. to 450 mb.

Relation of location in the vertical of frontal cloud with the location of the frontal zone.—The elementary picture of a warm frontal zone with the medium cloud extending upwards from the warm boundary of the frontal zone was not well verified. Table II gives the percentage frequency with which cloud was present at various levels below, in, and above the frontal zone. The levels were taken at intervals of 2,000 ft. above the upper boundary, at intervals of 2,000 ft. below the lower boundary, and at three equally spaced points within the zone.

TABLE II—PERCENTAGE FREQUENCY OF OCCURRENCE OF CLOUD AT LEVELS SPECIFIED IN RELATION TO THE HEIGHT OF THE FRONTAL ZONE

Level		Frequency of cloud
		%
Above upper boundary of frontal zone	16,000 ft.	42
	14,000 ft.	46
	12,000 ft.	36
	10,000 ft.	38
	8,000 ft.	40
	6,000 ft.	36
	4,000 ft.	34
	2,000 ft.	36
Frontal zone	Upper boundary	28
	¾ depth of frontal zone above lower boundary	33
	Mid point	28
	¼ depth of frontal zone above lower boundary	41
	Lower boundary	33
Below lower boundary of frontal zone	2,000 ft.	32
	4,000 ft.	12
	6,000 ft.	0

It appears that cloud is equally likely at any level in or above the frontal zone and down to about 4,000 ft. below it. The chance of finding cloud at a specified level is about 1 in 3.

Relation of cloud with the temperature difference across the frontal zone (measured on the saturated adiabatic scale).—The saturated potential temperature of the warm air above the frontal zone was generally nearly constant or increased only slightly with height; in 40 per cent. of the cases the lapse-rate of the warm air was equal to the saturated adiabatic value, in 37 per cent. the lapse-rate was slightly less. The difference of saturated potential temperature from the cold to the warm air vertically across the frontal zone provided a measure of the thermal strength of the frontal zone. On average (over the 58 frontal zones) the saturated potential temperature difference was 11·3°F.

The means for each class separately ranged from 10·7°F. in class 4 to 13·3°F. in class 6. The mean in class 5, like the mean in class 6, was high, 13·0°F., but not much practical significance can be attached to the differences. The scatter in each class was large, e.g. in class 3 the values ranged from 3° to 25°F. The most that can be suggested is that a large temperature difference across a frontal zone may or may not imply much cloud, but that extensive cloud as in class 5 or 6 is unlikely to occur with small temperature contrasts. It must be recalled, however, that the season here studied was winter, and the conclusion may not necessarily be valid in summer, when vertical instability may be a factor in producing cloud at otherwise weak fronts.

Relation of cloud with the geostrophic wind shear in the horizontal across the front at the ground.—The geostrophic wind shear, i.e. the change in geostrophic component parallel to the front, was measured with a geostrophic wind scale on opposite sides of the front near Bircham Newton. The measurements were made on the surface charts, as drawn at the Central Forecasting Office, Dunstable, nearest the time of the Bircham Newton sounding. The results are shown in Table III.

TABLE III—RELATION OF FRONTAL CLOUD WITH SHEAR OF GEOSTROPHIC WIND ACROSS THE FRONT

		Cloud class number						All
		1	2	3	4	5	6	
Number of cases		3	10	19	10	3	3	48
		miles per hour						
Horizontal geostrophic wind shear at mean sea level	Mean ..	24	16	20	38	43	40	25·9
	Standard deviation	26	19	17	27	18	14	..

There is an increase in the means from class 2 to class 5, but the scatter is large in all classes. Part of this scatter is due to observational errors, to inaccuracies in the drawing of the mean-sea-level isobars, and in the estimation of the geostrophic speeds. It was thought that the errors might be reduced by taking in each case the average of the geostrophic shear on three successive charts, the chart nearest the time, the chart before, and the chart following. Time changes may be to some extent involved. The results showed, however, a distribution similar to that in Table III.

Relation of cloud to the time rate of increase of geostrophic wind shear in the horizontal across the front at the ground.—It might be considered that the poor relationship of cloud with temperature across the frontal zone and with geostrophic wind shear in the horizontal across the front at the ground were largely due to the property of a fluid to maintain equilibrium with a sloping discontinuity of density provided that the wind shear is appropriate. The next parameter to be tested was accordingly the time rate of change of geostrophic wind shear in the horizontal across the front at the ground. Forecasters often regard " troughing ", in the sense of increasing geostrophic shear, as related to the activity of the front.

The mode of measurement was first to draw the normal from Bircham Newton to the front on the surface chart nearest to the time of the Bircham Newton sounding, next to find the intersections of this normal with the front on the preceeding and following charts, and to measure the geostrophic wind shear across the front in each case. Dividing the difference by the time gave a measure of the troughing on the front. The *Daily weather reports* were used for this purpose. The results are shown in Table IV.

There is evidently no useful relationship. Partly this may be due to errors of observation, drawing, and measurement, but it is considered that one difficulty not overcome in this mode of measurement is that as the front advances along the normal, the measurements are made at points nearer to the tip of the warm sector ; the " troughing " may be masked by a weakening of the shear towards the tip of the warm sector. Another mode of measurement was tried, following the mean direction of the warm-sector isobars. This eliminated the large negative value in class 5 of Table IV. However, further study is necessary to devise a satisfactory parameter to express the forecaster's experience that " troughing " of a front implies dynamical activity.

TABLE IV—RELATION OF CLOUD WITH TIME RATE OF CHANGE OF GEOSTROPHIC WIND SHEAR

		Cloud class number						
		1	2	3	4	5	6	All
Number of cases		2	11	19	12	3	2	49
				miles per hour per hour				
Time rate of change of geostrophic wind shear in the horizontal across the front at the ground	Mean ..	−2·0	+0·2	−0·1	−0·4	−0·9	+1·0	−0·2
	Standard deviation	0·3	1·0	2·4	1·2	1·5	0·2	..

Relation of cloud with the actual wind shear in the vertical across the frontal zone.—The components of wind shear parallel to the front were computed from the serial graphs of wind speed and direction at Downham Market, near Bircham Newton; the orientation of the front was taken to be that of the surface front. The shear was measured from the lower to the upper boundary of the frontal zone as analysed on the cross-section. The results are shown in Table V.

TABLE V—RELATION OF CLOUD WITH VERTICAL WIND SHEAR

		Cloud class number						
		1	2	3	4	5	6	All
Number of cases		4	10	14	12	2	3	45
				miles per hour				
Actual wind shear in the vertical from the lower to the upper boundary of the frontal zone	Mean ..	4	11	18	17	21	20	15·4
	Standard deviation	8	20	16	18	18	15	..

There is a tendency for the mean in each class to increase with the class number. Combining classes 5 and 6, the correlation coefficient between the vertical shear and the class number is + 0·22.

Relation of cloud with the vertical change across the frontal zone of the actual wind component normal to the surface front.—It has been suggested by various writers, e.g. Parker[9], that the change with height of the wind component perpendicular to the direction of a surface front is a measure of the vertical velocity at the frontal zone.

If u and w denote the horizontal and vertical components respectively of wind at a frontal boundary in the vertical plane containing the line of greatest slope of the boundary, and if θ denotes the angle of slope of the boundary, then provided air does not cross the boundary

$$u = u_b + w \cot \theta, \qquad \text{.. .. .. (1)}$$

where u_b is the horizontal speed of the boundary.

If the upper and lower boundaries move at the same speed

$$u_2 - u_1 = w_2 \cot \theta_2 - w_1 \cot \theta_1, \qquad \text{.. .. .. (2)}$$

where the suffixes 1, 2 refer to the lower and upper boundaries respectively.

If it is assumed that $w_1 = 0$, i.e. the cold air moves horizontally with the lower frontal boundary,

$$u_2 - u_1 = w_2 \cot \theta_2.$$

In so far as the existence of cloud implies an upward vertical velocity at the time, $u_2 - u_1$ might thus be expected to be related with the class number of the frontal cloud. The results of such a comparison are shown in Table VI.

TABLE VI—RELATION OF FRONTAL CLOUD WITH THE VERTICAL WIND SHEAR NORMAL TO THE FRONT

		Cloud class number						
		1	2	3	4	5	6	All
Number of cases		4	10	14	12	2	3	45
		miles per hour						
Increase of the component of wind normal to the surface front from the lower to the upper boundary of the frontal zone	Mean ..	0	2	7	10	1	3	5·8
	Standard deviation	8	8	7	13	1	8	..

There is evidently some increase in the means of each class from class 1 to class 4, but the relation breaks down in classes 5 and 6. This break-down may be partly due to taking the 950-mb. wind as applying to the lower boundary when the frontal zone extends down to the ground. But it is evident that the scatter is large, and the correlation coefficient with class number (combining classes 5 and 6) is only + 0·19.

Relation of cloud with the difference between the speed of the surface front and the component of wind normal to the surface front at the upper boundary of the frontal zone.—Returning to equation (1) and assuming that $u_b = u_f$, the speed of the surface front, it follows that

$$u_2 - u_f = w_2 \cot \theta_2. \qquad \text{.. .. ..} \quad (3)$$

The speed of the front was taken as the average over about 12 hr. measured on the *Daily weather report* charts; u_2 was derived from the serial section of the wind at Downham Market, taking the direction normal to the orientation of the surface front. Table VII below gives the results of relating $u_2 - u_f$ to the class number of the frontal cloud.

TABLE VII—RELATION OF CLOUD WITH THE DIFFERENCE BETWEEN THE SPEED OF THE WARM AIR AND THE SPEED OF THE FRONT

		Cloud class number						
		1	2	3	4	5	6	All
Number of cases		4	9	15	11	2	3	44
		miles per hour						
Difference between the speed of the surface front and the component of wind normal to the surface front at the upper boundary of the frontal zone	Mean ..	−9	−7	+1	+5	+2	+10	1·4
	Standard deviation	4	14	6	16	15	10	..

The mean of $u_2 - u_f$ in each class tends to increase with increasing class number. Combining classes 5 and 6, the correlation coefficient between $u_2 - u_f$ and the class number is $+ 0 \cdot 42$.

Referring to equation (3) and multiplying each side by $\tan \theta_2$,

$$w_2 = (u_2 - u_f) \tan \theta_2.$$

The tangent of the angle of slope of each frontal surface had already been determined, as described above, and the product of $u_2 - u_f$ and $\tan \theta_2$ was accordingly calculated. The correlation coefficient between this product and the cloud class number (again combining classes 5 and 6) was $+ 0 \cdot 36$.

It was considered that the relations expressed in Table VII, though fairly good, might be improved by restriction to those cases for which the vertical shear was appreciable. The mean vertical shear across the frontal zones over all cases was 15·4 m.p.h. Restricting the cases to those for which the vertical shear was 8 m.p.h. or more, the comparison between $u_2 - u_f$ and the class number of the frontal cloud was repeated. The correlation coefficient was thereby significantly improved to $+ 0 \cdot 54$.

On repeating the comparison between $(u_2 - u_f) \tan \theta_2$ and the class number for vertical shear of 8 m.p.h. or more the correlation coefficient increased to $+ 0 \cdot 50$.

Relation of cloud with the difference between the speed of the surface front and the component of wind normal to the surface front at the lower boundary of the frontal zone.—Denoting elements referring to the lower boundary by the suffix $_1$ as before and with similar approximation in analogy with equation (3),

$$u_1 - u_f = w_1 \cot \theta_1. \qquad \ldots \ldots \ldots (4)$$

The results of relating $u_1 - u_f$ to the class number are shown in Table VIII.

TABLE VIII—RELATION OF CLOUD WITH DIFFERENCE BETWEEN THE SPEED OF THE COLD AIR AND THE SPEED OF THE FRONT

		Cloud class number						
		1	2	3	4	5	6	All
Number of cases		4	8	14	11	2	3	42
		miles per hour						
Difference between the speed of the surface front and the component of wind normal to the surface front at the lower boundary of the frontal zone	Mean ..	−9	−6	−7	−5	+1	+7	−5·1
	Standard deviation	8	12	10	10	13	4	..

There is a slightly irregular increase in the mean for each class with increasing class number, but the correlation coefficient between $u_1 - u_f$ and the class number is small, namely $+ 0 \cdot 25$.

It is interesting to compare this result with a comparison by Matthewman[10] (on entirely different data) between the component of wind at 900 mb. normal to a surface warm front and the speed of the surface warm front, restricting the cases to those in which the lower boundary of the frontal zone lay between 910 and 840 mb. The associated tephigram showed a well marked frontal zone of reduced lapse-rate, with the wet-bulb potential temperature increasing above the lower boundary. In 37 cases of this kind, the correlation coefficient between u_1 and u_f was very high, namely 0·85, with the mean value of $u_1 - u_f = -0{\cdot}4$ m.p.h.

The following interpretation of these results is tentatively suggested. Near the ground and up to 900 mb. the vertical speed of the cold air, w_1, is usually small, but above this height downward velocities commonly occur (see equation (4) and the predominantly negative mean values in Table VIII). It is probable, however, that the vertical velocities in the two air masses are positively correlated; thus when cloud amount is small the warm air is probably descending and the cold air descending more quickly, but, on the other hand, when there is extensive cloud both air masses are likely to be ascending, the cold air less quickly than the warm air. Thus the difference between the vertical velocities in the two air masses might have little correlation with the cloud structure in conformity with equation (2) and the low correlation found in Table VI.

Relation of cloud with the ageostrophic motion of the front.—It has been shown by Matthewman[10] that the speed of a warm front is determined by the speed of the cold air mass ahead of it at 900 mb., and that this speed is usually less than the normal component of geostrophic wind because the cold air is undergoing a pronounced acceleration. The warm air is usually less accelerated, and its motion is likely to be closer to the geostrophic speed, thus providing the conditions for it to rise over the slower-moving wedge of cold air. Thus it might be expected that the vertical motion at a warm front would be related to the excess of the geostrophic component, u_g, normal to the front over the speed of the front u_f. The relation between the frontal cloud structure and the value of $u_g - u_f$ has therefore been investigated with the results given in Table IX.

TABLE IX—RELATION OF CLOUD WITH THE AGEOSTROPHIC MOTION OF THE FRONT

		Cloud class number						
		1	2	3	4	5	6	All
Number of cases		1	8	17	9	3	3	41
		miles per hour						
Difference between the geostrophic component, u_g, normal to the surface front and the speed of the front u_f	Mean	6	7	7	8	14	6	7·4
	Standard deviation	..	7	10	9	10	12	..

Table IX shows no close relation between the ageostrophic motion and the cloud. This may be partly due to errors of measurement and estimation. However, there is some tendency for the mean ageostrophic component of the fronts to be greater for the larger cloud class numbers, but it is doubtful if this is statistically significant.

Practical applications.—The analysis of frontal zones continues to be one of the more or less important preliminaries to forecasting. While the present note verifies many of the properties of the conventional model of a warm frontal zone, it also shows that the boundaries of the zone may be more or less arbitrary. The conventional model of cloud is only partially substantiated, the location of the frontal cloud in relation to the frontal zone being particularly variable. The only promising relations between the extensiveness of frontal cloud (in the sense of the classification) and the various parameters so far tested, concern the associated actual wind field. The testing of the remaining parameters has perhaps fulfilled a purpose in emphasizing their unreliability.

Even the best correlation with class number here achieved, namely with the difference between the speed of the surface front and the actual wind component at the upper boundary of the zone directed normal to the surface front, is only of the order of 0·5, which is probably below the limit of usefulness in the sense of a definite forecasting rule. Nevertheless, relationships with no higher correlation have sometimes to be employed in some branches of forecasting, e.g. the correlation between actual and advected temperature changes investigated by Craddock[11]. The present relationships may thus be of some aid to the forecaster when nothing better is available.

Extension of the investigation to more cases is not likely to improve these findings, but refinement of technique and restriction to the better marked or less complex fronts would probably yield higher correlations which might prove to be of direct use to the forecaster.

The variability of the location of frontal cloud in relation to the frontal zone, the indication that extensive frontal cloud is associated with upward motion in both the cold and the warm air masses, and the low correlations between the cloud and parameters concerned with the frontal contrasts, together suggest that the cloud in frontal regions may be associated more closely with the general upward motion over a large volume of air, including the front, rather than with any specific up gliding at the frontal surface.

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