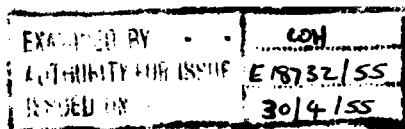


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HIGH CLOUD OVER SOUTHERN ENGLAND

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and P. GOLDSMITH



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HIGH CLOUD OVER SOUTHERN ENGLAND

By R. J. MURGATROYD, B.Sc.(Eng.) AND P. GOLDSMITH

Summary.—Data are presented of the frequencies of occurrence of high cloud over southern England, diurnal and seasonal variations, types of high cloud, heights and temperatures of bases and tops, thickness, visibility, and humidity in its vicinity. These data are based on surface observations and six years' high-level ascents by aircraft of the Meteorological Research Flight. The relation between the persistence of condensation trails and the presence of high cloud is discussed. Finally some mechanisms are suggested for the formation of high cloud over the British Isles.

Introduction.—Although high cloud, when visible from the ground, is reported in all synoptic observations and is plotted on synoptic charts, very little is known of its physical characteristics and the conditions under which it occurs. In the past cirrus cloud has been regarded as of little practical importance compared with other types, but with the advent of regular flying at cirrus levels its importance is increasing. A study has therefore been made of the observations of high cloud taken during the high-level ascents made by the Meteorological Research Flight from 1949 to 1954. These ascents were made primarily for the purpose of measuring temperature and humidity up to about 40,000 ft. with cloud observations as a secondary consideration. Details of the measurements of temperature and humidity made up to 1951 are summarized in *Geophysical Memoirs* No. 881*. In 1952 particular attention was given to the high-cloud observations during the flights made by Goldsmith, and this led to some of the conclusions given below which were also found to be consistent with the earlier observations. In addition to these flight observations use has also been made of ground observations made at the meteorological stations located at South Farnborough (Hampshire), Shawbury (Shropshire) and West Raynham (Norfolk). A preliminary study has also been carried out of the relationship between some of the high-cloud observations and the surface and upper-level synoptic charts for the same period.

Information derived from surface observations.—Surface observations of high cloud possess severe limitations. It is frequently impossible to see high cloud owing to the presence of lower cloud or fog, and observations at night are very difficult indeed. Haze layers in the atmosphere also have an effect. It has been noticed frequently during the flights that the amount of cirrus visible increases as the aircraft ascends, and it may sometimes even happen that there are eight oktas (eighths) of thin cirrus present when none is visible from the ground. As the aircraft ascends above a thick surface haze top this increase is often sudden. In addition the sun's elevation appears to be an important factor in the visual recognition of the cirrus from the surface. Nevertheless a survey of surface data on cirrus is of interest and is given below.

In Fig. 1 mean frequencies throughout the day of surface observations of high cloud are shown for each month for the period 1944–52 at South Farnborough. A comparison of the daylight observations of high cloud at South Farnborough, Shawbury and West Raynham for the years 1950–51 is given in the top part of Fig. 2, and a similar diagram for daylight observations at South Farnborough for the longer period 1944–52, in the bottom part of Fig. 2.

* The index numbers refer to the bibliography on p. 19.

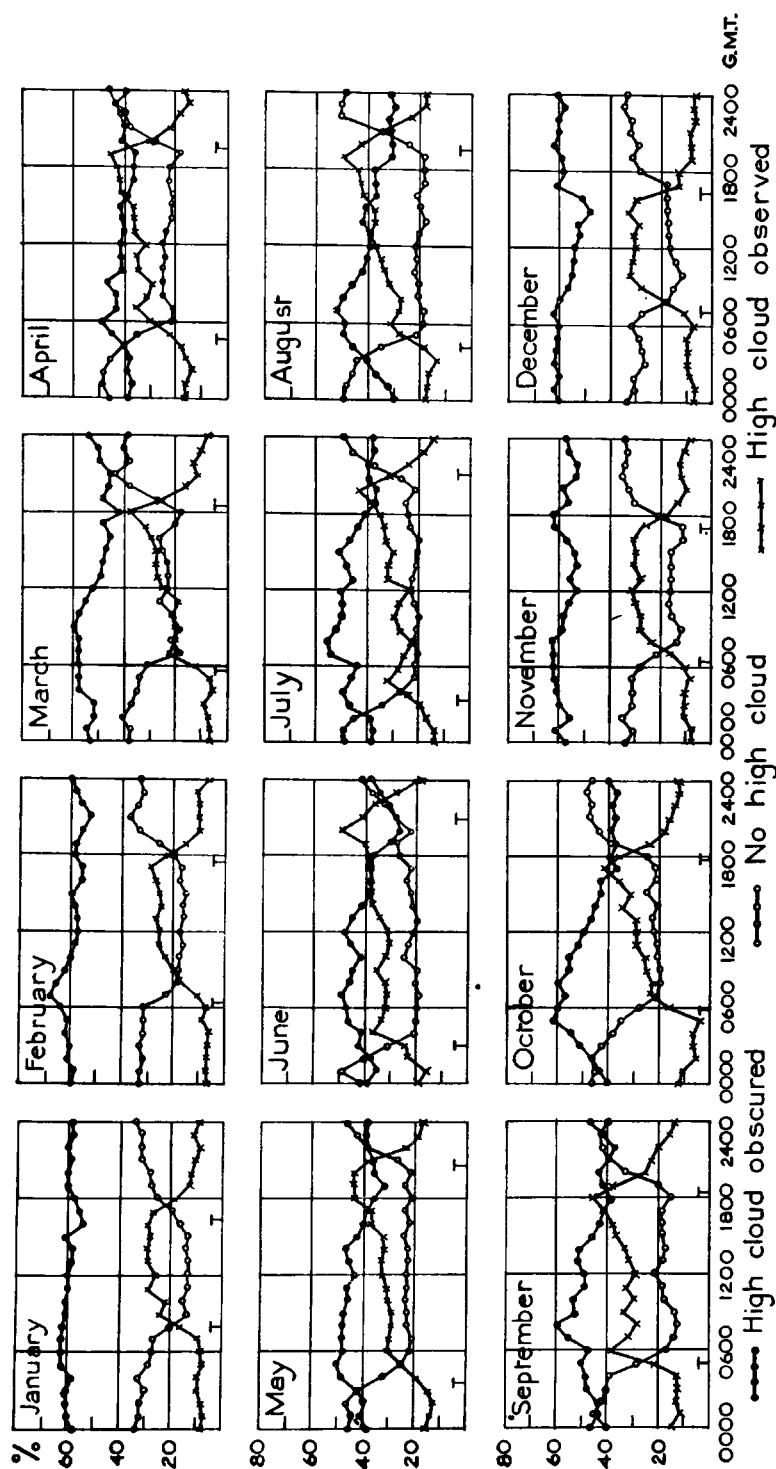


FIG. 1.—MEAN MONTHLY FREQUENCIES OF SURFACE OBSERVATIONS OF HIGH CLOUD THROUGHOUT THE DAY, SOUTH FARNBOROUGH 1944-52

T denotes the approximate times of twilight

Considering Fig. 1 it is seen that

(i) The observations all have a pronounced diurnal variation. During daylight hours high cloud is reported on an average for about 30 per cent. of the time and during the night for 15 per cent. of the time.

(ii) During the winter months the "high cloud observed" curve rises during the morning twilight period, reaches its maximum within an hour or so, remains fairly constant throughout the day, and then falls again at dusk.

(iii) During the other seasons and particularly in summer, there is a peak shortly after dawn and a much larger peak around dusk. Between them there is an unsteady rise which is more pronounced in the afternoon.

(iv) The "high cloud obscured" curve usually has a maximum around the dawn period and a minimum around the dusk period which is less pronounced in winter. On an average the high cloud is obscured for about 60 per cent. of the time in winter and 45 per cent. in summer.

(v) Clear skies with no cirrus were reported for about 20 per cent. of the time in daylight and 40 per cent. at night.

It is difficult to decide to what extent these observations are representative of the actual amounts of high cloud present. The belief that the summer dusk and dawn peaks are a visual effect is supported by the lack of definite peaks in winter when the sun is always low. The large percentage of cases when high cloud is obscured makes it difficult to ascribe any frequency to the periods when it is in fact above the station.

Considering now Fig. 2 :

(i) The curves of observations of high cloud from the surface all show maxima in summer, when values of about 40 per cent. are reached. Values of about 25 per cent. are given for all months between October and May.

(ii) The "no high cloud" observations show maxima of about 25 per cent. in spring and early summer with minima of 15 per cent. in winter, with irregular fluctuations in the late summer and autumn.

(iii) The "high cloud obscured" curves show a maximum of about 60 per cent. in winter and a minimum of 40 per cent. in summer.

(iv) In Fig. 2 the curves for the three stations correspond extremely well. This would be expected as the scale of the synoptic types affecting southern England is in general larger than the area enclosed by these three stations. This is in agreement with the aircraft observations made by the Meteorological Research Flight, and also from examination of surface synoptic charts which indicate that cirrus sheets are frequently extensive and sometimes cover almost the whole of the British Isles.

(v) The overall ratios of high-cloud occasions to no-high-cloud occasions for the period for these stations are Shawbury 2.5, West Raynham 1.8, South Farnborough 1.4.

The possible explanations for this are that

(i) On the average cirrus is more likely in the west than in the east of southern England.

(ii) As Shawbury is near hills the differences may be the results of orographic lifting².

(iii) The observations may not be representative of the actual high-cloud distribution. For instance haze in the atmosphere may account for these differences.

Unfortunately no quantitative data are available on the effective obscuration of high cloud by haze at these stations so that little can be said about (iii) except that West Raynham, being down wind of the prevailing wind direction,

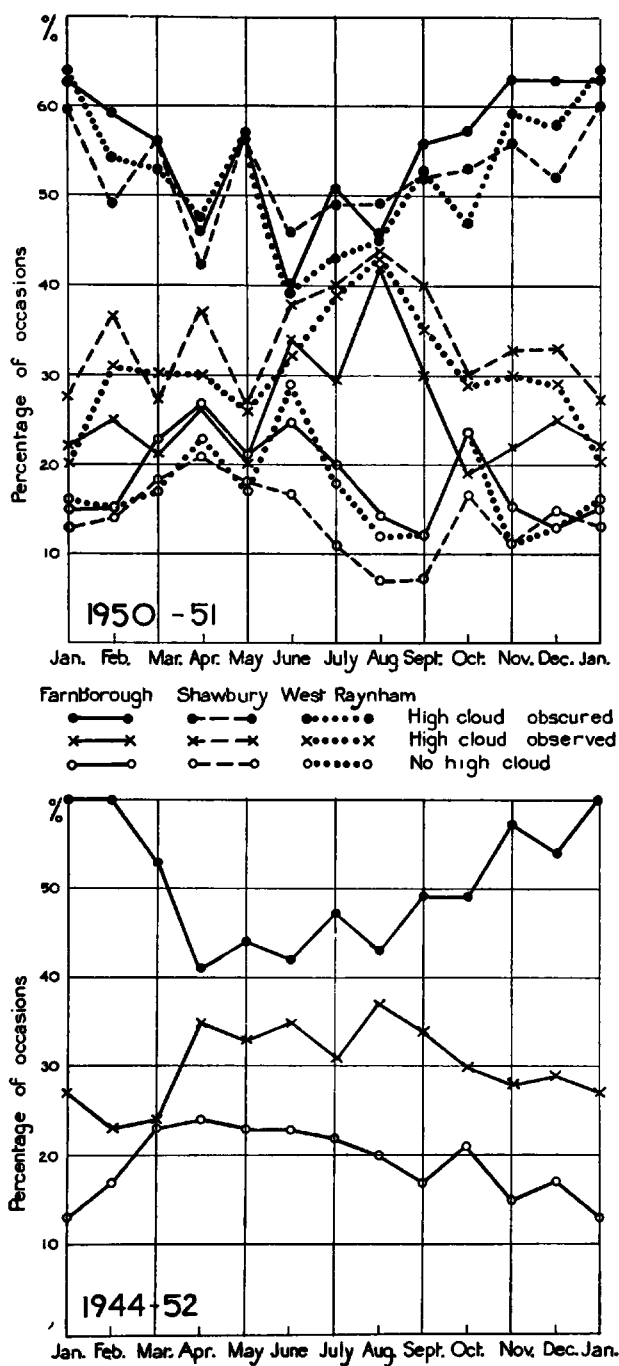


FIG. 2.—MEAN FREQUENCY OF DAY-TIME SURFACE OBSERVATIONS OF HIGH CLOUD AT SOUTH FARNBOROUGH, SHAWBURY AND WEST RAYNHAM FOR 1950-51 AND AT SOUTH FARNBOROUGH FOR 1944-52

over the industrial Midlands has probably suffered most from this effect. The question of when orographic cirrus can form and the likelihood of cirrus being more frequent in western than in eastern districts of the country is discussed on p. 17, from which it is concluded that both these explanations could contribute in part to the high cirrus frequencies at Shawbury.

During this work a study was also made of the frequency of the various types of high cloud which were reported over the same period at these stations and the results are given in Table I.

TABLE I—FREQUENCY OF SURFACE REPORTS OF HIGH CLOUD TYPES

Code No.	Description	Frequency of type reported			Mean
		South Farnborough	Shawbury	West Raynham	
		<i>per cent.</i>			
1	Cirrus filaments scattered not increasing	22	16	30	23
2	Cirrus dense patches usually not increasing	38	32	30	33
3	Cirrus anvil type associated with cumulonimbus	11	12	8	10
4	Cirrus often hook-shaped, increasing and thickening	1	1	1	1
5	Cirrus and cirrostratus often in bands increasing below 45° ..	2	7	4	4
6	Cirrus and cirrostratus often in bands increasing above 45° ..	8	9	9	9
7	Cirrostratus covering whole sky ..	4	6	6	5
8	Cirrostratus not increasing, not 8 oktas	10	10	9	10
9	Mainly cirrocumulus	5	6	2	4

Code numbers 1 and 2 are evidently reported with great frequency and code number 4 hardly at all. Code numbers 5, 7 and 9 are also very infrequently reported.

Information derived from aircraft observations.—To an observer flying in cirrus the cloud appears as a white haze. The density varies considerably and is usually greatest when the high cloud is a continuation of medium cloud. Frequently the observer is not certain whether he is in cloud or not and the isolated tufts or patches (code numbers 1 and 2) are not as common as Table I would suggest. Frequently the high cloud exists in widespread sheets, and these patches often appear to be local increases of cloud density. The base of the cloud is usually very ill defined, and it often has streaks falling from it but the tops can be recognized more easily, and frequently it appears that the cloud is more dense near its tops than near its base. A wave-like structure is frequently seen in the tops. Streaks have occasionally been seen coming out of the tops of the cloud but they were comparatively small and short-lived.

Frequency of occurrence.—The aircraft observations 1949–54 were as follows :

	No. of occasions	Percentage
High cloud in the immediate vicinity	135	47
High cloud visible in the distance	81	28
No high cloud observed	74	25
Total	290	100

There is no reason to suppose that these observations are selective in any way, so it appears that for about 50 per cent. of the time in daylight there is high cloud above any station in southern England, and that for only 25 per cent. of the time are there large areas completely clear of cirrus cloud.

If these observations are subdivided into seasons, Table II is obtained.

TABLE II—SEASONAL OBSERVATIONS OF HIGH CLOUD FROM AIRCRAFT

			Cirrus	Distant cirrus	No cirrus	No. of occasions
			<i>per cent.</i>			
Winter	..	..	64	9	27	55
Spring	..	..	31	29	40	87
Summer	..	..	49	37	14	84
Autumn	..	..	47	31	22	64

Unfortunately the number of winter and autumn cases are less than those of the other seasons. It appears from Table II that the frequency of high cloud is somewhat lower in spring than in the other seasons, but more observations are required on this point to establish it with certainty.

Height of cloud base.—It has been mentioned above that the base of high cloud is very indefinite and during an ascent into it the observer notes three successive stages: (i) definitely in clear air below cloud, (ii) in a region of doubt, "Is the aircraft in cloud or not?", (iii) now definitely in cloud. The region of doubt may in some cases extend through several thousand feet.

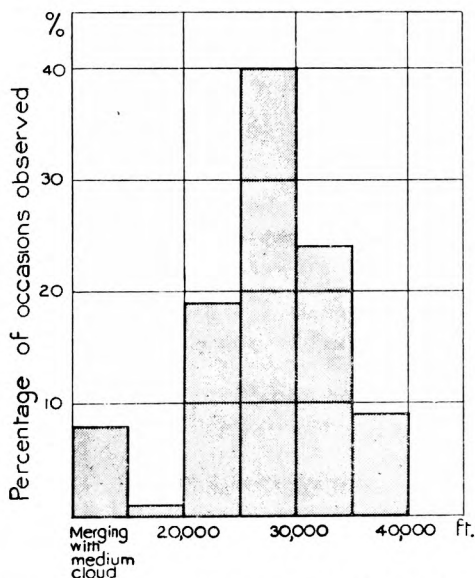


FIG. 3—FREQUENCY DISTRIBUTION OF THE HEIGHT OF THE CIRRUS BASE
Total number of observations = 63

A frequency distribution of heights of the base of the high cloud at stage (iii) is given in Fig. 3; these values may therefore be somewhat on the high side but are correct for all practical purposes. Heights were observed to the nearest thousand feet.

It can be seen that the base of high cloud is most frequently between 25,000 and 30,000 ft., and that it is usually somewhere between 20,000 and 40,000 ft. It is shown below that this cloud is almost always in the troposphere. However, there have been occasional reports of cirrus in the stratosphere. A height of 46,500 ft. has been reported by Farquharson³ and on a few occasions Meteorological Research Flight aircraft with a ceiling of about 40,000 ft. have failed to reach the base of cirrus seen during an ascent. As these observations are of particular interest they are listed in Table III, together with some other observations of cloud in the stratosphere made by other aircraft based at South Farnborough. Some of them have been discussed by Jacobs⁴ who suggests that they may have been dust clouds.

TABLE III—REPORTS OF CIRRUS IN THE STRATOSPHERE

Date	Time	Type of aircraft	Height of tropopause	Maximum height of aircraft	Estimated height of cloud base	Description of cloud
1953	G.M.T.			<i>feet</i>		
May 4	1500	Mosquito	39,000	35,000	..	Some cirrostratus well above 35,000 ft. may be in the stratosphere
May 5	1000	Mosquito	38,000	+1,000	45,000	Thick dense extensive cirrostratus
July 1	1600	{ Valiant Canberra Meteor }	38,000	..	..	Cumulonimbus top at 42,000 ft.
July 27	1400	Meteor	28,000	40,000	..	Some cirrus above 40,000 ft. at about 30 miles west of South Farnborough
July 29	1200	Canberra	34,000	42,000	..	A small amount of cirrus or condensation trail above to the north of South Farnborough
July 30	1500	Mosquito	35,000	38,000	45,000	A layer of thin cirrostratus to the south-west of South Farnborough
August 7	1500	Mosquito	36,000	39,000	45,000	Thin cirrostratus thickening

Height of cloud tops.—On most of the occasions examined the high cloud appeared to extend to the region of the tropopause. In view of the variability of tropopause height it was therefore attempted to relate high-cloud tops to tropopause level. This has been done in Fig. 4.

It appears that the tops of the high cloud are most frequently less than about 2,000 ft. from the tropopause. It is not known to what extent this conclusion is determined by the nature of the definition of the tropopause, but in practice it appears that the first definite decrease in the lapse rate in the tropopause region determines the tops of the cloud. A few cases have been reported when the tops apparently extend into the lowest 2,000 ft. of the stratosphere. On other occasions the tops may be as much as 11,000 ft. below the tropopause. In these cases the cloud is often patchy in contrast to the usual widespread effect and resembles patchy altostratus in appearance and density.

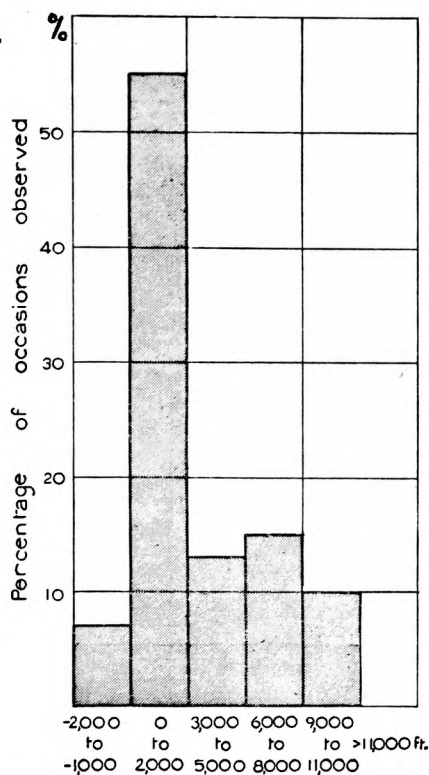


FIG. 4—FREQUENCY DISTRIBUTION OF THE DIFFERENCE BETWEEN THE HEIGHT OF THE TROPOPAUSE AND THE HEIGHT OF THE CIRRUS CLOUD TOPS

Total number of observations = 78

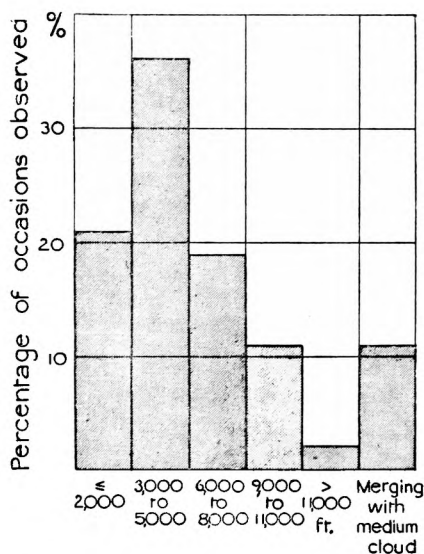


FIG. 5—FREQUENCY DISTRIBUTION OF THE THICKNESS OF HIGH CLOUD

Total number of observations = 63

Cloud thickness.—A frequency distribution of cloud thicknesses is given in Fig. 5. High-cloud layers most frequently have a thickness between 3,000 and 5,000 ft. but thicknesses up to 12,000 ft. have been observed. Sometimes they merge with the medium cloud. When the thickness is great there is a tendency for several layers to form, but it is difficult to decide whether in fact clear lanes exist with cirrus above and below, or alternatively there is merely a stratification of cloud density.

Relation between the height of the defined tropopause and the base and thickness of cirrus cloud.—Fig. 6 shows the heights of base and top of cirrus cloud plotted against the height of the tropopause. Although the number of observations for each of these heights is small and their scatter is large, an attempt has been made to draw lines of mean base and top levels for each tropopause height. The following tentative conclusions are drawn from these lines :—

(i) The mean tops appear to reach the tropopause for heights up to 30,000 ft. but at higher levels they progressively become relatively lower until at 40,000 ft. they are on average about 4,000 ft. below the tropopause. It is considered that this happens because as the tropopause height increases so does the chance of an abrupt slackening of the lapse rate in the high troposphere become greater resulting in the limitation of the cirrus tops.

(ii) The mean bases tend to be at a constant thickness below the tropopause up to a tropopause height of 30,000 ft. At higher levels however the mean base appears always to be in the region of 30,000 ft. Consequently, on the average mean cloud thickness with tropopause levels below 30,000 ft. is about 4,000 ft., and it progressively increases to 7,000 ft. with a tropopause level of 40,000 ft.

It must be emphasized that the above conclusions refer only to mean values. Individual cases, as can be seen from the scatter of the points on the diagrams, may differ widely from them.

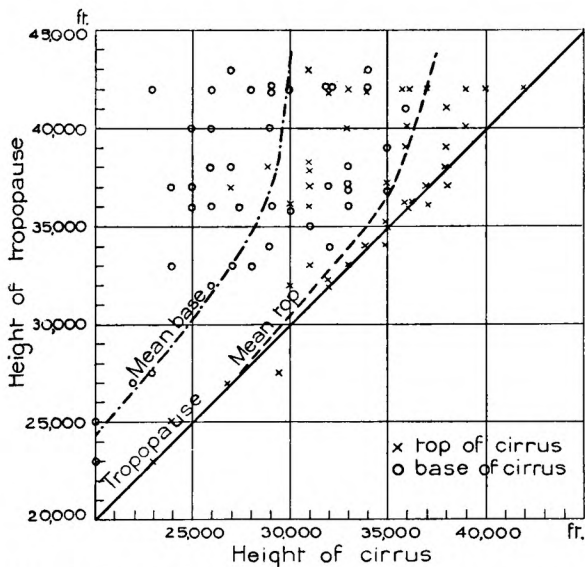


FIG. 6—RELATION BETWEEN THE HEIGHT OF THE TROPOPAUSE AND THE HEIGHTS OF THE BASE AND TOPS OF HIGH CLOUD

Temperature of base and tops.—A frequency distribution of temperature of the base of high cloud is given in Fig. 7. The most frequent values are from -40° to -50° F. but measurements have been made within the range -10° to -80° F.

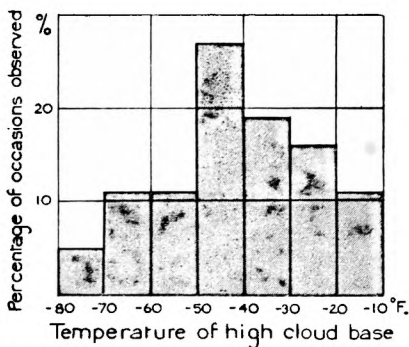


FIG. 7—FREQUENCY DISTRIBUTION OF THE TEMPERATURE OF THE BASE OF CIRRUS CLOUD

Total number of observations = 63

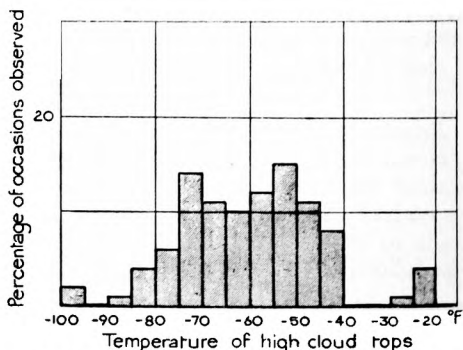


FIG. 8—FREQUENCY DISTRIBUTION OF THE TEMPERATURE OF THE TOPS OF CIRRUS CLOUD

Total number of observations = 81

The corresponding frequency distribution of cloud-top temperatures is given in Fig. 8. This distribution is rather flat between temperatures of -40° and -80° F. but a few values have been measured between -20° and -30° F. and down to -100° F. The lack of temperatures between -30° and -40° F. is interesting and suggests that the few values between -20° and -30° F. belong to another distribution—the low cirrus which is very similar to medium cloud.

Humidity in and around high cloud.—A frequency distribution of depression of frost point relative to air temperature as measured with the visual pressurized Dobson-Brewer hygrometer during the periods when high clouds were reported is given in Fig. 9. The values used in each case were the minimum depression of frost point within or near the cirrus layer, the readings being taken at 1,000-ft. intervals. It has previously been thought that at very low values of frost points the uncertainty of measurement was only about 4° F., and the accuracy somewhat better in cirrus cloud. Recent flights with automatic hygrometers at cirrus levels, however, have shown that short-period fluctuations in the frost point of 5° to 10° F. within distances of less than a mile are common. It is impossible to measure these fluctuations with the visual type of instrument which only gives a mean value over a distance of several miles.

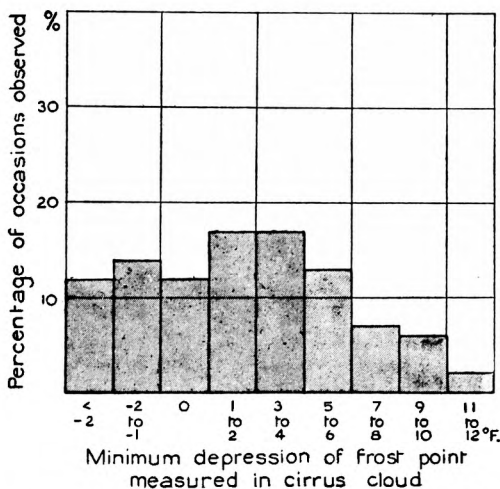


FIG. 9—FREQUENCY DISTRIBUTION OF HUMIDITY IN HIGH CLOUD IN TERMS OF DEPRESSION OF FROST POINT

Total number of observations = 86

The air temperature can probably be measured to about 1° F. at these levels. Hence it appears from the measurements with the visual hygrometer that in the immediate neighbourhood and even within cirrus cloud the air is not always saturated with respect to ice, but that on an average there is a frost-point depression of about 3° F. (about 80 per cent. relative humidity) and that lower values of relative humidity are common. According to Ludlam⁵ saturation with respect to water, i.e. considerable supersaturation with respect to ice, is necessary for cirrus cloud formation, but not of course for its continued existence, once formed.

It has also been noted that it is possible to form condensation trails in an atmosphere 60 to 80 per cent. saturated with respect to ice, and unless cirrus

cloud is present these trails almost invariably disappear within minutes. Furthermore it appears likely on theoretical grounds that ice crystals of the size measured in cirrus cloud would evaporate within times of this order in an atmosphere only partially saturated. Hence there is a difficulty in explaining why cirrus cloud should persist at all if these conditions were constant. The fluctuations revealed by the automatic hygrometer may be sufficient to provide regions of supersaturation. Further data are required before these comparatively low mean values of humidity can be reconciled with the long period of persistence of the cirrus cloud sheets as a whole.

Vertical distribution of humidity with relation to high cloud—the moist layer.—When high cloud is up wind in direction the distribution of frost points with height usually exhibits the characteristic form shown in Fig. 10 (a). This example was selected from the "cirrus in the distance" cases, and shows a rapid increase of humidity at 28,000 ft. with a moist layer persisting to 32,000 ft., the height of the tropopause. This moist layer becomes more pronounced as the distance from the cirrus is decreased until, when cirrus is present near the aircraft, the sounding takes the form of the example in Fig. 10 (b). The moist layer is not always easy to trace, and within it the depression of the frost point relative to the dry-bulb temperature may be as much as 15–20° F. This depression, however, quickly decreases as the cloud approaches. When no cirrus is observed the sounding frequently takes the form shown in Fig. 10 (c). A network of ascents giving this type of information would thus be invaluable to a forecaster who is required to give detailed information on high cloud.

It is necessary at this stage to qualify the above remarks because of the different ways in which cirrus cloud may be formed. This is discussed further in a subsequent section. It appears that most occasions of high cloud arise when a ridge of warm air recently over the Atlantic is brought over the British Isles at cirrus levels. Other occasions however are associated with cold pools or strong convection and the moist layer is not then evident.

Regarding the moist layer as potential cirrus cloud and plotting all the bases and tops relative to the tropopause Fig. 11 was obtained. The tops of the moist layer tend to coincide with the tropopause when it is low but are usually somewhat below the tropopause when it is high. Mean moist-layer bases tend to have the same distribution with height as the cirrus bases shown in Fig. 6, and never exceed 30,000 ft. Consequently mean thickness also increases with height.

As the mean base is about 30,000 ft. and its extreme value rarely below 24,000 ft. its temperature is generally between -25° and -45° F. Similarly the tops are rarely below 30,000 ft. where the temperature is usually about -45° F.

Visibility through high cloud.—No quantitative observations of visibility in cirrus are recorded, but the following details are based on experience of flying in high cloud.

High cloud usually limits the visibility from air to ground, but only when the high cloud is a continuation of medium cloud is it likely that the surface will be completely obscured. Normally the ground (or low cloud) is still visible for several miles ahead when the aircraft is flying in high cloud; indeed sometimes the cloud is so thin that its presence makes little or no difference to vertical visibility. However, vertical visibility is often more limited when the aircraft is above the high cloud. This effect is similar to that of surface haze; when flying just above surface haze the ground is often more indistinct than when actually in the haze layer.

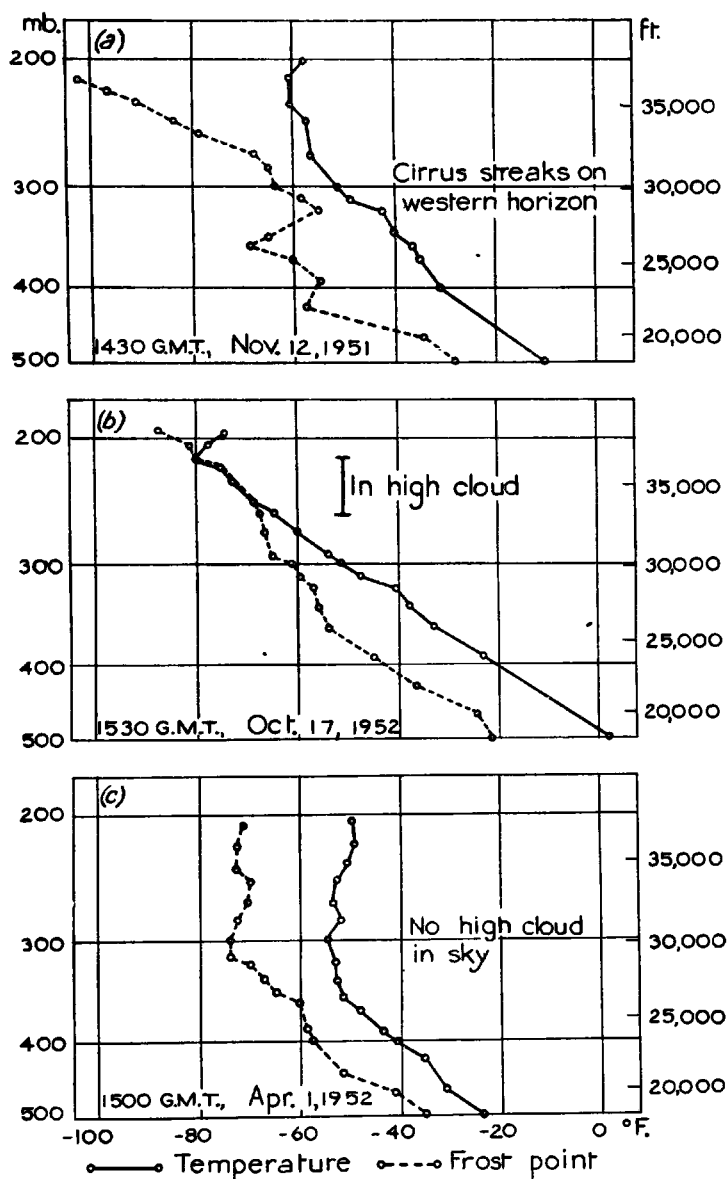


FIG. 10—AIRCRAFT SOUNDINGS ILLUSTRATING THE "MOIST-LAYER" EFFECT

The horizontal visibility in high cloud is a more difficult factor to estimate, but when aircraft of the Meteorological Research Flight have been flying in formation in high cloud, although the horizontal visibility was observed to be more limited than in clear air, this limitation was not serious and no difficulty was experienced.

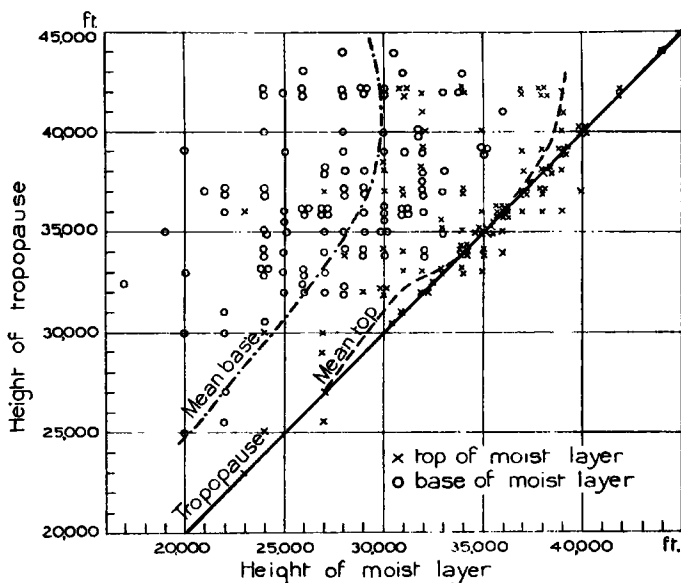


FIG. 11—RELATION BETWEEN THE HEIGHT OF THE TROPOPAUSE AND THE HEIGHTS OF THE BASE AND TOP OF THE MOIST LAYER

Forecasting high cloud.—At present a forecaster has not many tools which help him to forecast the probable occurrence of high cloud. It is apparent from daily examination of synoptic charts that the presence of a front is neither a necessary nor a sufficient criterion to use. High cloud frequently occurs without being associated with fronts, and on the other hand surface fronts need not extend to cirrus levels.

It is the purpose of this section to suggest other factors which can usefully be taken into consideration when it is necessary to provide a forecast of high cloud.

The general character of the weather at any point in the lower troposphere is determined by the nature of the air masses involved and the fronts which occur at their boundaries. It is not easy to extend the idea of air mass to cirrus levels, but it is usually possible to gain an idea of the recent history of the air there by studying the 300-mb. contour charts. Thus to some extent it can be determined whether the air over the British Isles at 300 mb. has recently been over polar, Atlantic or continental regions, although of course border-line cases are frequent. It would perhaps be more profitable theoretically to discuss the air characteristics at this level in terms of the position of the long-wave pattern with relation to the area involved, but this may not be easy in practice as shorter wave phenomena no doubt would be important as regards cloud formation.

It is considered that air over southern England at 300 mb. which has had a recent polar history is in general more likely to be free of cirrus than air with a recent Atlantic history. This conclusion is supported by a short study of high-cloud frequency with respect to wind direction at cirrus levels, and an examination of the moisture content at these levels with respect to the recent history of the air. These will now be described in turn.

Relation between high-cloud occurrence and the wind direction at 300 mb.—Over the two years 1950–51 all surface observations from South Farnborough of sky obscured, no high cloud and high cloud observed have been counted for

winds in the eight sectors of the compass. The wind directions used were the generally prevailing directions given by the Larkhill ascents between about 20,000 ft. and the tropopause. As the ascents were 6-hourly and the cloud observations hourly the wind direction was assumed to remain in a given octant for the 3 hr. preceding and following the ascent.

The results are given in Table IV which shows the percentage of occasions for each octant in which the sky was obscured, no high cloud was seen and high cloud was observed respectively.

TABLE IV—RELATION BETWEEN HIGH-CLOUD OBSERVATIONS AND PREVAILING WIND DIRECTION IN THE UPPER TROPOSPHERE

	Wind direction							
	0° to 49°	50° to 99°	100° to 139°	140° to 189°	190° to 229°	230° to 279°	280° to 319°	320° to 359°
	<i>per cent.</i>							
Sky obscured	51	64	59	62	55	52	49	52
No high cloud	39	32	34	22	20	23	27	32
High cloud	10	4	7	16	25	25	24	16
Ratio $\frac{\text{high cloud}}{\text{no high cloud}}$	0.3	0.1	0.2	0.7	1.3	1.1	0.9	0.5

From this table it appears that the percentage of occasions of high cloud is greatest when the wind is in the S.-W. (190–279°) sectors and least in the NE.-E. (50–99°) sectors. The percentages of no high cloud exhibit the reverse trend.

Considering the ratio of high cloud to no high cloud it is seen that the westerly winds are more likely to produce cirrus. It may be noted also that as easterly winds which are mainly continental in track are unlikely to produce high cloud it is very improbable that nuclei of continental origin are of any importance as regards the production of cirrus cloud over southern England.

Recent history of the air at cirrus levels and moisture available.—From the high-level ascents made by the Meteorological Research Flight and the relevant 300-mb. contour charts it appears that air at cirrus levels, which can be associated with contours extending over large areas of the Atlantic, usually has the requisite moisture content. Out of the 126 occasions found having a moist layer 106 were in air with a recent Atlantic track, 12 with a recent track over polar regions and 2 with a continental track. There were 9 Atlantic, 12 polar and 2 continental occasions with no moist layer. In addition there were about 30 occasions with very low tropopause or cold pools, whilst a number of ascents had to be rejected from this study for lack of data. Air streams of recent polar and continental history frequently do not have sufficient moisture at these levels. Hence on this account most cirrus is likely to be associated with air of recent Atlantic history.

Other factors influencing the formation of high clouds.—Although it is thought that the recent history of the air exerts a considerable influence on its potentiality to form high cloud, other factors which may tend to produce the lifting necessary to bring about condensation must receive full consideration

when producing a forecast. A complete list of these factors has not been produced, but those which appeared most important from a short study of synoptic cases for the British Isles in 1952 are as follows :

- (i) Presence of a jet stream over the area
- (ii) Warm advection at cirrus levels
- (iii) Cold pools at cirrus levels
- (iv) Cirrus formation from tops of cumulonimbus clouds
- (v) Orographic lifting.

No doubt this list could be extended, and the relative importance of the various factors assessed by means of a comprehensive synoptic study, but this is beyond the scope of the present paper. In general any situation which results in upward motion of the air between the 500-mb. and 300-mb. levels should be regarded as one likely to produce high cloud.

Short notes are given below about each of these factors in turn.

It has been noticed that the axis of a jet stream frequently coincides roughly with the edge of a high-cloud sheet. For this purpose the jet-stream speed need not be of the order of 100 kt. but merely a wind-speed maximum of 50 kt. or so. On the cold side there is usually little high cloud while on the warm side high cloud is often extensive. This has also been described by Murray⁶ in a report giving an analysis of jet-stream flights made by the Meteorological Research Flight, and by Sawyer and Ilett⁷ in a paper describing a statistical examination of cloud distribution near the jet stream. Schaefer⁸ has also associated the occurrence of high cloud with the jet stream over the United States. In our experience the rough boundary of the areas of cloud and no cloud at the jet-stream axis is most well marked with jet streams containing a considerable northerly component, cirrus then often being present over the western and not over the eastern districts of the British Isles.

The classical concept of warm fronts has always included cirrus cloud well ahead of the surface front and in fact it has been found that high cloud can often be associated with surface fronts up to 1,000 miles away. Between the 500-mb. and 300-mb. levels this situation usually shows advection of a warm ridge. The nature of the mechanism by which the necessary cooling for condensation occurs with this warm advection is not fully understood. It was formerly thought to be due to general up-slope motion on the frontal surface, but this picture is complicated by the presence of the jet stream which is so often present in the upper troposphere near the junction of air masses, and it is now thought by some authorities that frontal surfaces in fact do not usually extend up to cirrus levels. If the cirrus formation is related to warm advection in this way when warm surface fronts are present, there appears to be no *prima facie* reason why it should not occur when they are absent, provided that the situation in the 500–300-mb. layer is broadly similar. A short study of synoptic cases suggested that this is almost always so and warm-front cirrus formation may be regarded as a particular case of cloud produced by warm advection in the upper troposphere. In the cases where the connexion was not obvious it appeared that the cloud was usually ahead of the main warm advection area. Cold advection and areas of no high cloud appear to be similarly related. There is considerable support for this idea in general in the results of the M.I.T. Pressure Change Project⁹ which shows that there is a strong correlation between the sign of the vertical motion and the sign of the temperature advection at 700 mb. and above, warm-air advection being positively correlated with ascending air and conversely. It is also shown by Craddock¹⁰ that changes in the thickness of the 1000–700-mb. layer and the 700–500-mb. layer caused by advection are largely offset by those caused by dynamic heating or cooling

by non-adiabatic processes. This compensation was found to be more complete in the higher layer. If this conclusion can be extended to the 500–300-mb. layer it appears quite feasible that warm advection there can be associated with a process resulting in dynamic or other cooling, and hence a tendency for high cloud to form. Thermal advection in connexion with cirrus formation is also discussed in "The cirrus forecasting problem"¹¹. Another promising suggestion, given by French and Johannessen¹², is that the vorticity advection in the layers below the tropopause will be indicative of the vertical motions in the upper tropopause and hence might form a basis for forecasting high clouds.

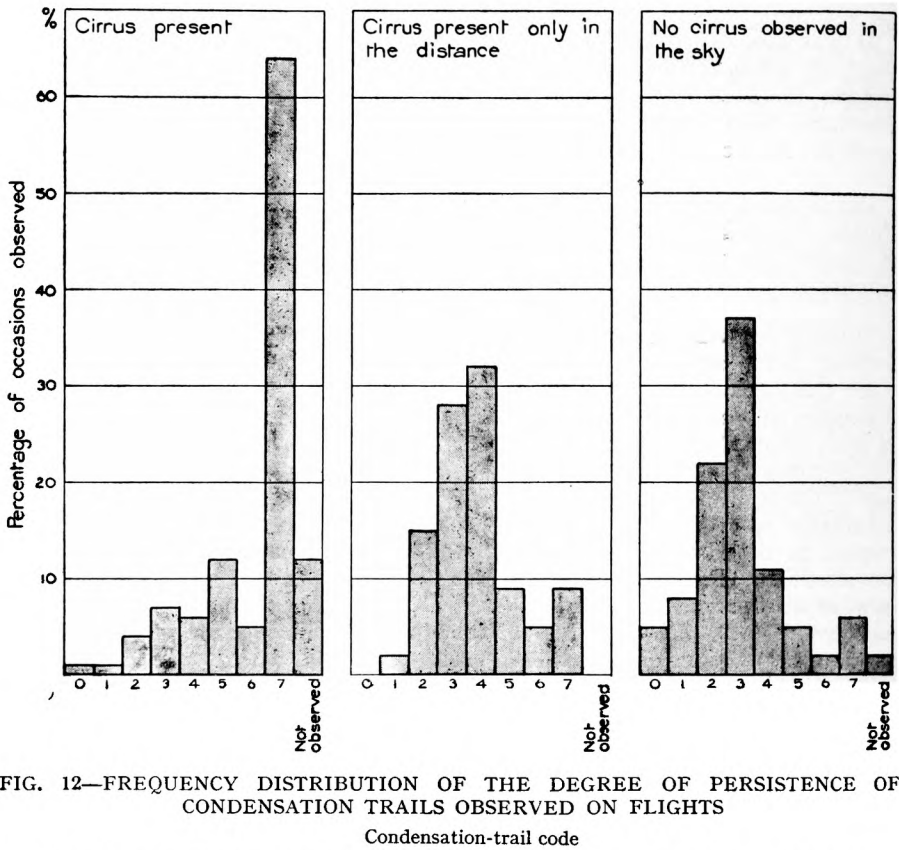
It was also noted that cold pools and deep troughs on the 500–300-mb. chart are often accompanied by large areas of high cloud. In the case of the troughs the high cloud is generally to the east and south-east and is often associated with warm advection round the south of the trough. With cold pools the high cloud is often more widespread.

Cirrus cloud may of course often be formed from the tops of cumulonimbus clouds. In such a situation it is often patchy and localized. The cirrus found in conjunction with cold fronts is frequently of this type and is usually not extensive.

Orographic lifting has also been suggested by Ludlam² as a mechanism for forming cirrus cloud. It can be demonstrated, however, that the conditions when this can occur are somewhat limited. From *Geophysical Memoirs* No. 88 it appears that on the average, i.e. whether cirrus is present or not, the depression of frost point with respect to temperature at cirrus levels is about 10–12° F. Fig. 9 shows a mode of 2° or 3° F. depression in and around cirrus cloud. Therefore a temperature decrease of 8° or 9° F. due to orographic lifting to reach saturation with respect to ice is usually necessary. For saturation with respect to liquid water the cooling would have to be about another 6° F., i.e. about 15° F. in all. With adiabatic conditions of lifting, therefore, an upward displacement of about 3,000 ft. on the average, and often considerably more would be required to produce cirrus by the orographic mechanism. In general it is thought that a lift of 1,000–2,000 ft. would only be exceeded infrequently, although there is little information on this point. Moreover the air at cirrus levels would have to be almost saturated with respect to ice for it to be effective in producing cloud. It is considered therefore that this mechanism would be effective only on the occasions when there is a moist layer, i.e. usually in air of recent Atlantic track, and either on the warm side of a jet stream, in the vicinity of a cold pool or ahead of a warm front or other warm advection. The effect of orographic lifting would then be most evident in cases where high cloud would be expected from these other considerations, and would usually either advance its onset or produce local thickening in the cirrus layer. All the cases discussed by Ludlam² can be explained on these grounds.

Although the above factors are helpful in assessing the likelihood of high-cloud occurrence there are many synoptic situations when they cannot be used. Occasions with no jet stream or cold pool and thickness lines parallel with the wind directions or contours are difficult to assess, as also are those associated with small thickness gradients or with concentric contours and thickness lines. Occurrence of high cloud in inverted situations with contour or thickness highs to the north of the British Isles is often difficult to explain by the above factors. A further study, preferably on a statistical basis, of the occurrence of high cloud with relation to these and other synoptic factors will be necessary before high-cloud forecasting can be achieved with confidence in these latter situations,

Persistency of condensation trails.—Condensation trails are usually formed at high-cloud levels, and they may be regarded as a form of high cloud. Their process of formation is of course an artificial one, but once they are formed their behaviour is governed by the same processes as for natural cloud. Thus if atmospheric conditions are such that cirrus cloud is present condensation trails at the same level might be expected to be persistent. Furthermore if the moisture content of the air is large the trails are likely to be longer and of greater duration than if it is small.



Observations made whilst aircraft is making a rate 1 turn. (1 complete turn takes 2 min.)

Code No.

- 1 = Just visible
- 2 = Plain, no sign of curve
- 3 = Curvature just visible
- 4 = Curvature plainly visible

Code No.

- 5 = Curvature visible through 90°
- 6 = Curvature visible through more than 90°
- 7 = Trails very persistent

These considerations have been examined with respect to the condensation trails and clouds observed on the high-level ascents and the results are presented in Fig. 12. Frequency distributions of the persistence of condensation trails on occasions of cirrus, distant cirrus, and no cirrus are given. The diagrams illustrate the following points :

- (i) When cirrus cloud is present very persistent condensation trails are common. The frequency of 60 per cent. given for condensation trails

Type 7 (very persistent) does not take account of the occasions when cirrus is present at levels lower than those at which it is possible for the condensation trails to form from considerations of the relative positions of the temperature sounding and the immunity line on the tephigram.

(ii) When distant cirrus or no cirrus is reported very persistent condensation trails are rare (less than 10 per cent.).

(iii) The mode for the diagram with no cirrus present is Type 3 condensation trails, and that for the diagram with distant cirrus, Type 4, the latter being the longer. It has been shown above that distant cirrus is usually associated with a moist layer, and therefore it appears that the length of non-persistent trail is a function of the humidity.

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