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SOME FEATURES OF JET STREAMS AS SHOWN BY AIRCRAFT OBSERVATIONS

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SUMMARY

The results of an analysis of aircraft observations of temperature, frost point, cloud and turbulence near jet streams are presented; brief mention is also made of reports of condensation trails. It is shown from frost-point observations that between about 500 mb. and 200 mb. there is on the average a horizontal gradient of humidity across the jet stream, with the moister air on the high-pressure side. At about the level of the jet stream the average relative humidity with respect to ice is about 50 per cent. at 250–300 nautical miles on the right of the axis, looking down wind, and decreases to about 10 per cent. at the same distance on the left, but individual jet streams show considerable variability. The average humidity distribution indicates the existence of a relatively dry patch of air below the jet-stream axis in the vicinity of the frontal zone at about 500 mb.

Layer cloud, both medium and high, is a feature of the high-pressure side of the jet stream, although amounts vary from case to case; such cloud is rare at distances greater than about 100 nautical miles from the jet-stream axis on the low-pressure side. Layer cloud does not appear to occur above the level of the jet-stream axis. The average distribution of layer cloud and humidity is discussed in relation to the surface fronts and a dynamical model is suggested. The broad features of the accepted thermal structure of the upper troposphere and lower stratosphere near jet streams are confirmed. The occurrence of clear-air turbulence near jet streams agrees with the results put forward by Bannon.

§ 1.—INTRODUCTION

Twenty special flights were carried out by the Meteorological Research Flight, Farnborough, England, from May 1951 to August 1952 to investigate the atmospheric structure near jet streams. The central purpose of this paper is to present an analysis of the observations made on these flights. In addition a brief examination is made of some other data of the Meteorological Research Flight, namely the vertical ascents made during the three years 1949–51 within about 350 nautical miles of jet streams, and the observations from the horizontal grid flown in the stratosphere on August 19, 1948. However, unless otherwise mentioned, the statistics and discussions in this paper are generally concerned with the 20 flights made in 1951 and 1952.

On each of these 20 flights vertical grids were flown; the tracks of the horizontal legs (top leg being in reciprocal direction to bottom leg) were chosen to be approximately normal to the jet-stream axis. On the horizontal legs various instrumental and non-instrumental observations were made, generally every minute but every half-minute (at least for certain types of observation) on some of the earlier flights. Vertical climb and descent at the end points of the horizontal legs completed the grid; on the vertical legs observations were usually taken every 1,000 or 2,000 ft. During the climb of the aircraft from Farnborough to the level of the bottom leg, and also later, on returning to base, some observations were made at rather irregular height intervals; regular and frequent readings were not justified since the extra time consumed in levelling out the aircraft would have meant a shortening of the horizontal legs owing to the limited flight endurance of the aircraft (a Mosquito) and of the meteorological observer. The flights were made in the afternoon or occasionally in the late forenoon, and were usually of two or three hours' duration.

The jet streams were selected at the Central Forecasting Office, Dunstable, but in each case the flight plan was agreed in consultation with the Senior Meteorological Officer of the Research Flight. No rigid criteria were laid down as to what types, or what specific regions or features, of jet streams were to be investigated. However, the aircraft was not able to operate at a greater distance than some 200 nautical miles from Farnborough, so that it was necessary to select only those jet streams that were within a few hundred nautical miles of south-east England. During the period of the experiment the number of cases investigated was limited mainly by the availability of the aircraft; only some weak jet streams were deliberately not investigated after a few of this type had been examined. The specific regions explored were to a great extent determined by the position and orientation of the jet-stream axis relative to Farnborough, although there was freedom of choice of the levels of the horizontal legs. The length of each horizontal leg of the rectangular grid was usually 150–200 nautical miles; the bottom leg was at 400 or 350 mb. and the top leg between 300 and 200 mb. in most cases.

These investigational flights have produced an extremely close time-and-distance network of readings of various meteorological quantities. However, only limited regions of jet streams were explored on each flight. This has made some of the data difficult to interpret either statistically or specifically in relation to individual jet streams. Moreover, the observations did not include wind, so that wind variations, wind shears and other related phenomena cannot be discussed except by means of the routine synoptic wind reports. Nevertheless, the flight data have been very useful, not only in enabling a broad picture of the distribution of humidity and cloud to be obtained, but also in confirming certain other notions about the structure of the free atmosphere near jet streams. If clear-cut simple models of structure or behaviour of jet streams have not emanated from this study, it is less the result of any inadequacy of data or of the sample of jet streams but more the consequence of variety and complexity in nature.

§ 2.—FLIGHT OBSERVATIONS

The one observer on each flight was responsible for making observations of temperature, frost point, airspeed, cloud, turbulence and condensation trails. The methods of obtaining the observations, as well as their frequency and quality, are briefly commented upon below.

It should be emphasized that it was a difficult operation for the one observer to maintain a continuous record of all the items listed.

Temperature.—Temperature, which was reported to the nearest 1·0°F. on most flights but to 0·1°F. on some occasions, was obtained by means of a flat-plate electrical thermometer with an accuracy of about ±0·5°F. under the conditions of these flights. On the horizontal legs readings were taken generally every minute, but every half-minute on some of the early flights, and on the vertical legs every 1,000 or 2,000 ft.

Frost point.—Frost point was measured to the nearest 1·0°F. by means of a Dobson-Brewer frost-point hygrometer; the probable error of these observations is about ± 3·0°F. The aim was generally to observe frost point every minute. However, there were considerable breaks in the readings, caused partly by instrumental trouble and partly by the difficulty experienced by the observer in maintaining the frost-point records together with the other types of observations.

Cloud.—Visual observations of cloud below and above the aircraft were made at irregular intervals.

Turbulence.—The turbulence or " bumpiness " experienced on the flights was estimated and reported, normally every minute, on the scale, 0, 1, 1–2, 2, 2–3, 3, etc., one unit being roughly equivalent to $0{\cdot}1g$, where g is the acceleration due to gravity. The experienced observers of the Meteorological Research Flight consider that the probable error of these reports is about half a unit or $0{\cdot}05\,g$.

Condensation trails.—At convenient intervals notes were made of the occurrence and type of condensation trails on most of the flights. In straight flight it was not generally possible for the observer to see whether or not condensation trails were formed.

Airspeed.—The indicated airspeed of the aircraft was usually recorded every minute on the horizontal legs. The records of indicated airspeed show fluctuations of the type that has been discussed by Frith[1]*. However, these observations are not discussed in this paper, because it did not appear from inspection of the data in graphical form that there were any very significant correlations between the indicated-airspeed variations and changes of temperature or frost point or bumpiness, nor was it found possible to relate the indicated airspeed to synoptic features of the jet stream.

§ 3.—SYNOPTIC ASPECTS

At least one vertical cross-section along the flight path, i.e. approximately perpendicular to the jet-stream axis, was constructed from the routine aerological observations on each occasion. The cross-sections enabled the flight data to be related to various synoptic features.

Temperatures recorded by the aircraft were generally in fair agreement with values estimated from the cross-section. Perfect agreement cannot be expected since the observations on each flight

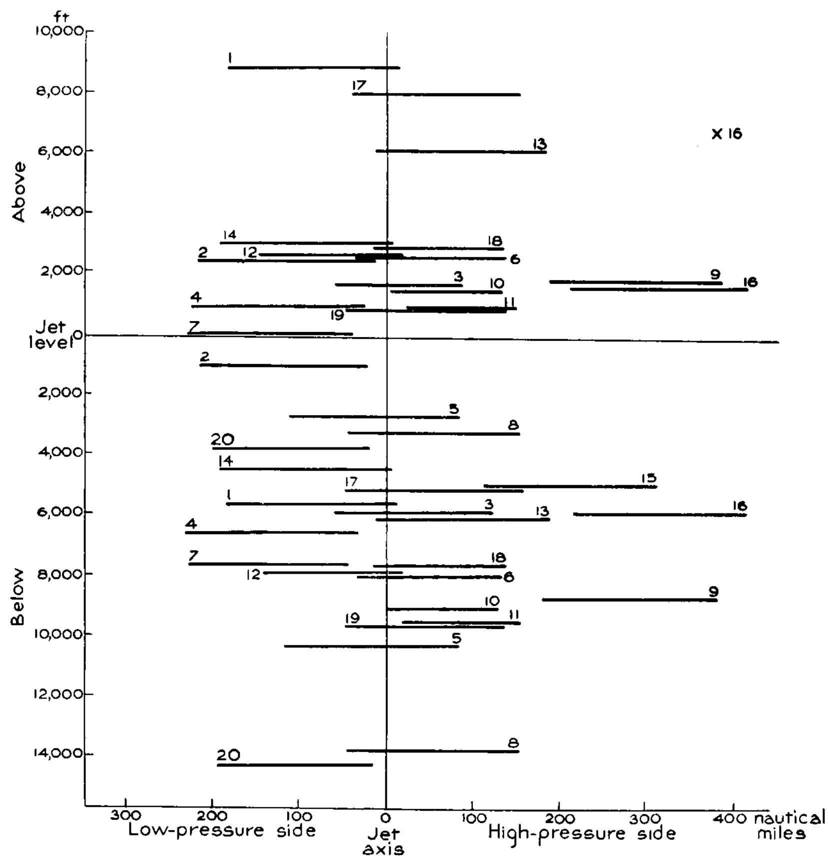


FIG. 1—POSITIONS OF HORIZONTAL LEGS OF FLIGHTS RELATIVE TO JET-STREAM AXIS
With flight 16, a minor jet-stream is marked x 16

*The index numbers refer to the bibliography on p. 25.

were necessarily taken at different times, nor were they exactly synchronous with the routine aerological reports. A comparison was made between mean temperatures over 50-nautical-mile distances on the horizontal legs and interpolated values from the relevant cross-sections to see whether any systematic difference existed. The average temperature difference (aircraft minus radio-sonde) was $-0{\cdot}2°$ F. in the troposphere (above 20,000 ft.), $1{\cdot}1°$ F. at the tropopause, and $1{\cdot}0°$ F. in the stratosphere. No allowance for these systematic instrumental differences was made in the analysis in this paper.

The dates of the flights, together with some other facts concerned with the individual jet streams, are listed in the Appendix. The positions of the horizontal legs of the various flights relative to the jet-stream axis are conveniently summarized in Fig. 1. The numbers against each leg indicate the relevant flight; only one leg is shown for flight 15 since the aircraft developed engine trouble and the flight was cut short on that occasion; on a few of the flights the bottom leg was actually flown in two parts. No part of any leg was at a greater distance than 250 nautical miles on the low-pressure side or 450 nautical miles on the high-pressure side of the jet-stream axis. Also, the horizontal legs were all flown within the region from about 14,000 ft. below to 9,000 ft. above the level of the jet axis.

The jet streams showed much diversity of type. The wind direction within the core of the jet stream in the region of the cross-section may be classified as follows: 9 cases at or between NW. and N., 7 from S.–SW., 2 from W., and 2 from NE. The wind speed at the jet-stream axis averaged 113 kt.; the lowest value was 70 kt. and the highest 150 kt. Some of the jet streams were rather small in longitudinal scale, others were on the scale of the long waves. The great majority of the jet streams were slow moving, with only small changes in intensity during the period from 12 hr. before to 12 hr. after the time of the flight; notable exceptions were jet stream 9 which moved quickly eastwards on December 3, 1951, and jet stream 5 which weakened rapidly on June 15, 1951 (the latter case was discussed by Murray[2]). The aircraft explored the central part of the jet stream in most cases; the entrance and exit regions were not investigated except perhaps on the occasion of flight 6 (near marked confluence in wind flow).

§ 4.—SOME THERMAL FEATURES

Temperature irregularities. The temperature readings on the horizontal legs of the flights made by the aircraft of the Meterological Research Flight invariably showed small-amplitude fluctuations over short time intervals. The magnitude of these effects may be measured by the standard deviation of the individual observations from a 9-min. running mean (over about 45 nautical miles), or by the root-mean-square temperature variation over 1-min. intervals. These two quantities were computed for the individual legs which were classified into the three categories: (i) leg entirely in the troposphere, (ii) leg partly in troposphere and partly in stratosphere, and (iii) leg entirely in stratosphere. All the observations pertaining to each of these three categories were combined, and the result is shown in Table I.

TABLE I—STANDARD DEVIATION OF INDIVIDUAL TEMPERATURE READINGS FROM 9-MIN. RUNNING MEAN AND ROOT-MEAN-SQUARE 1-MIN. TEMPERATURE VARIATION

Temperature run	Standard deviation from 9-min. running mean	Root-mean-square 1-min. variation
	°F.	°F.
(i) Entirely in troposphere (at or above 400 mb.) ..	0·55	0·70
(ii) Partly in troposphere and partly in stratosphere ..	0·81	0·98
(iii) Entirely in stratosphere	1·05	1·23

Table I shows quite clearly that the temperature irregularities are significantly greater in the stratosphere than in the upper troposphere. The same general trend is displayed in Fig. 2 which

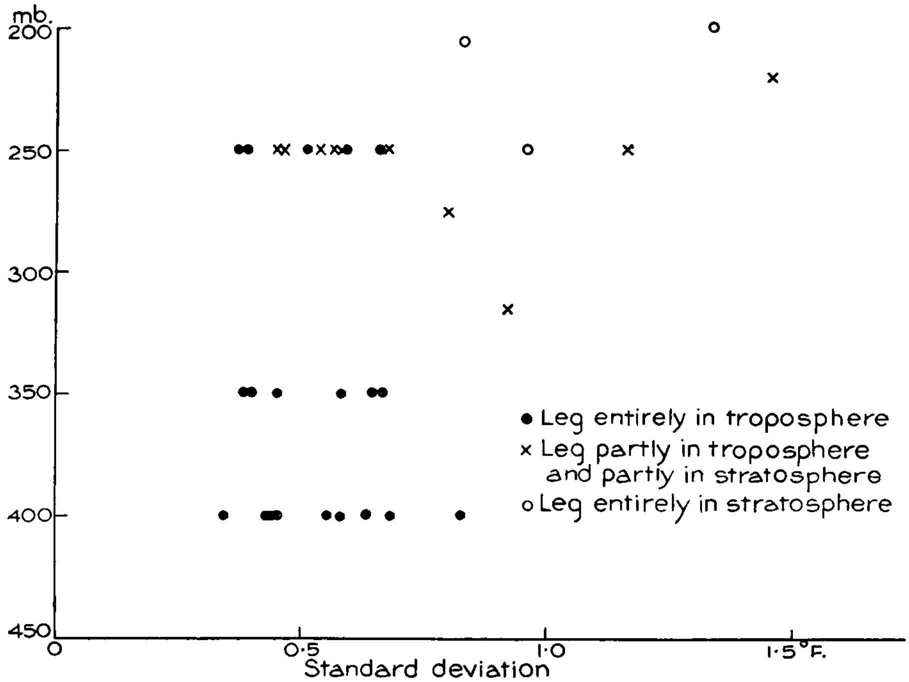


FIG. 2—STANDARD DEVIATION OF INDIVIDUAL TEMPERATURE OBSERVATIONS FROM 9-MIN. RUNNING MEANS FOR EACH HORIZONTAL LEG

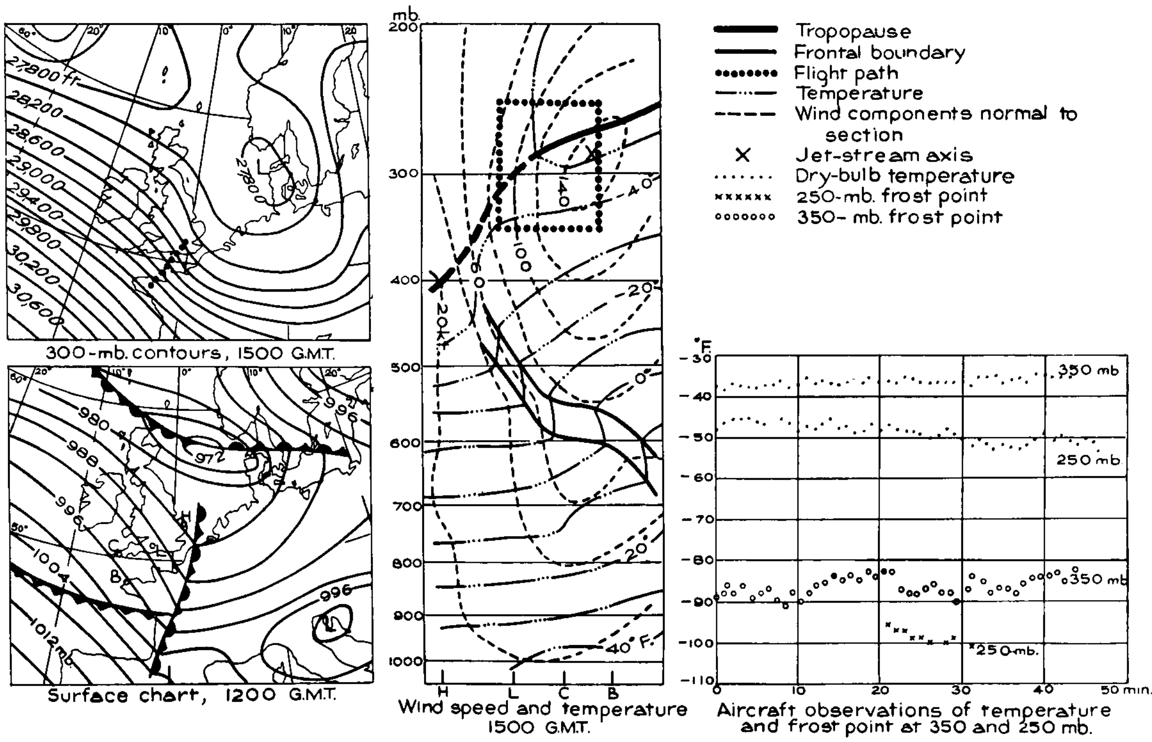


FIG. 3—SYNOPTIC SITUATION, FEBRUARY 1, 1952 (FLIGHT 14)

H = Hemsby, L = Larkhill, C = Camborne, B = Brest shows the standard deviations for the individual legs plotted against the pressure level of the leg. Examples of the temperature irregularities observed in the troposphere and in the stratosphere are shown in Fig. 3, which refers to the flight on February 1, 1952. Fig. 3 contains relevant surface, 300-mb. and cross-section charts which enable the general synoptic picture to be readily seen.

Frith[3] has already pointed out that temperature fluctuations of this type normally decrease in intensity with height in the troposphere and increase again on entering the stratosphere; the present series of observations gives an interesting confirmation of this fact which is not specially a feature of jet streams.

Temperature profiles near jet streams. The temperatures observed on the horizontal legs do not add much to existing ideas concerning the thermal structure of the upper troposphere and lower stratosphere in the vicinity of jet streams. The picture presented by the cross-sections constructed from routine upper air data was generally confirmed except in points of detail.

On each leg the temperature difference between the end points was noted, and the mean temperature gradient (in degrees Fahrenheit per 100 nautical miles) thereby computed. From the relevant sections estimates of the temperature gradients were also made. The mean absolute value of the temperature gradient based on all the legs was 3·0° F./100 nautical miles compared with a mean value of 3·5° F./100 nautical miles obtained from the sections. The mean value, irrespective of sign, of the difference of the magnitudes of the temperature gradients obtained by the two methods was 1·4° F./100 nautical miles. Furthermore, the direction of the over-all temperature gradient invariably agreed with that interpolated from the section. Thus the broad-scale picture given by the cross-section was generally confirmed.

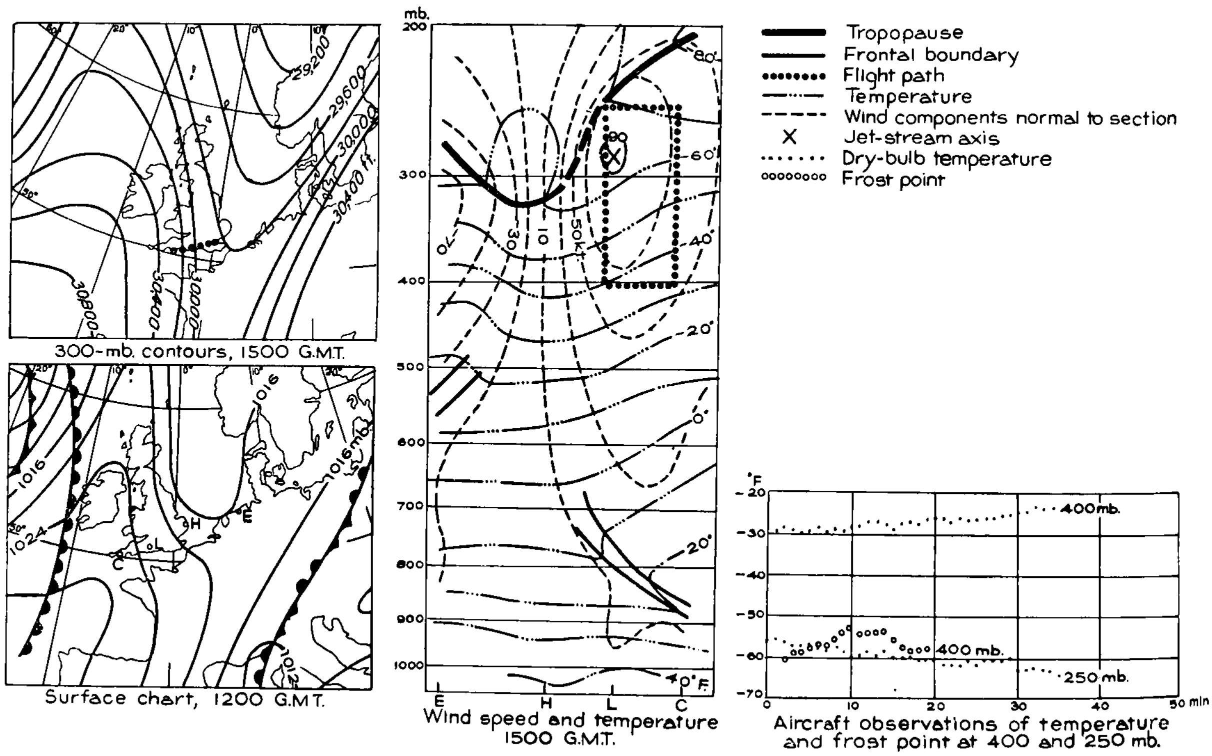


FIG. 4—SYNOPTIC SITUATION, APRIL 24, 1952 (FLIGHT 18)
E = Emden, H = Hemsby, L = Larkhill, C = Camborne

The broad tropospheric baroclinic zone, generally associated with jet streams and extending horizontally over several hundred miles, was not completely traversed on any one flight. Some part of 12 legs, i.e. bottom legs of flights 1, 3, 6, 8, 10, 12, 13, 14, 17, 18 and 19, and top leg of flight 8 (see Fig. 1 but note that trouble with the thermometer prevented the use of flight 5), was located vertically below the jet-stream axis. The readings obtained on these legs may be regarded as representative of conditions within the baroclinic zone in the upper part of the troposphere. The individual temperature gradients on these 12 legs varied from 1·0° F./100 nautical miles to 7·0° F./100 nautical miles with a mean value of 3·7° F./100 nautical miles. Not unexpectedly, the smaller temperature gradients tended to be associated with the weaker jet streams and with the flight legs nearer the level of the jet-stream axis. The temperature profile generally showed a fairly smooth trend with superimposed temperature fluctuations of the size mentioned on p. 6. A typical example is shown in Fig. 4 by the temperature profile oberved at 400 mb. on April 24, 1952. In passing, it will be noted that the temperature gradient on the leg at 250 mb. (above the level of the jet-stream axis but in the troposphere) was in the opposite sense to that at 400 mb.; such a reversal of the sign of the general tropospheric thermal gradient in the few thousand feet which often separates the jet-stream axis from the tropopause is frequently suggested on cross-section charts, and is of course a necessity if the upper flow is quasi-geostrophic.

Clearly defined frontal zones in the troposphere at or above 400 mb. were not generally indicated by the flight observations, although it should be remembered that most of the legs were not located in the region where fronts might be expected. The only well defined front was the cold front associated with the SSW. jet stream of June 18, 1951 (flight 6), of which the synoptic situation and temperature profile are shown in Fig. 5. The temperature profile at 400 mb. clearly shows the frontal boundary adjacent to the warm air within which the horizontal temperature gradient is smaller than suggested on the cross-section.

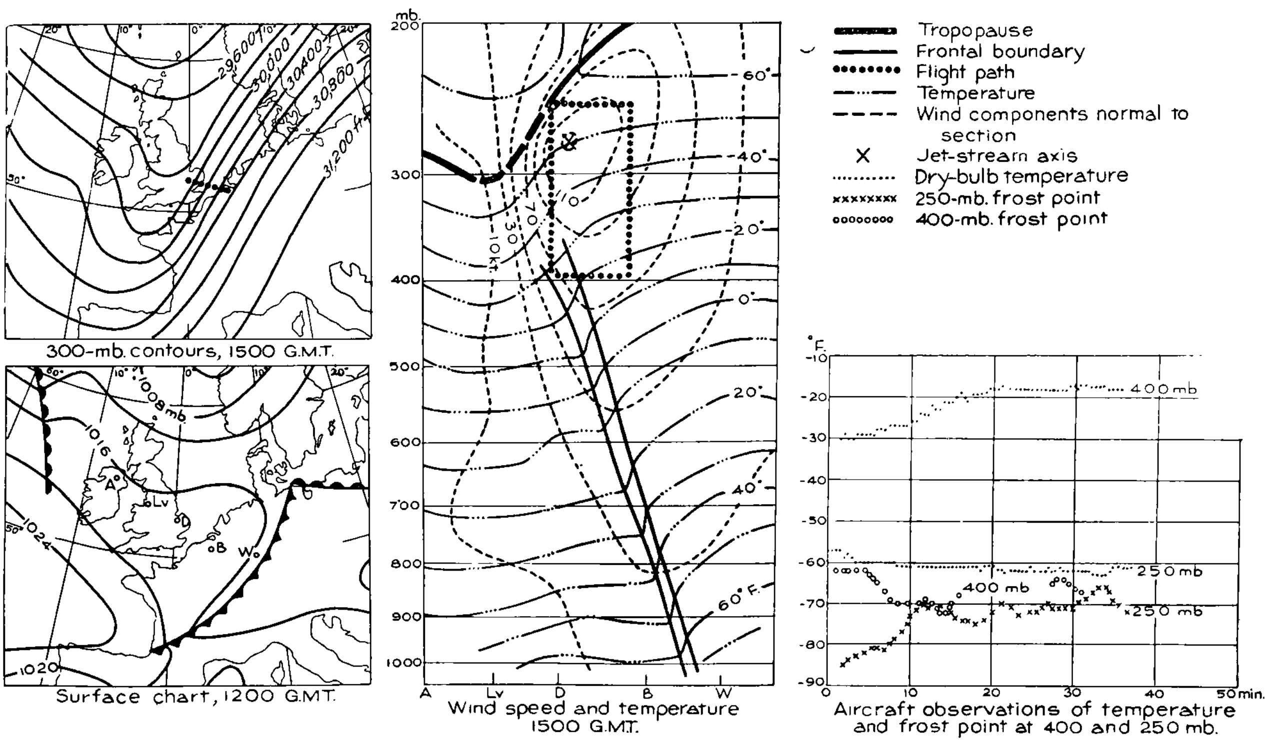


FIG. 5—SYNOPTIC SITUATION, JUNE 18, 1951 (FLIGHT 6)
A = Aldergrove, Lv = Liverpool, D = Downham Market, B = Brussels, W = Wiesbaden

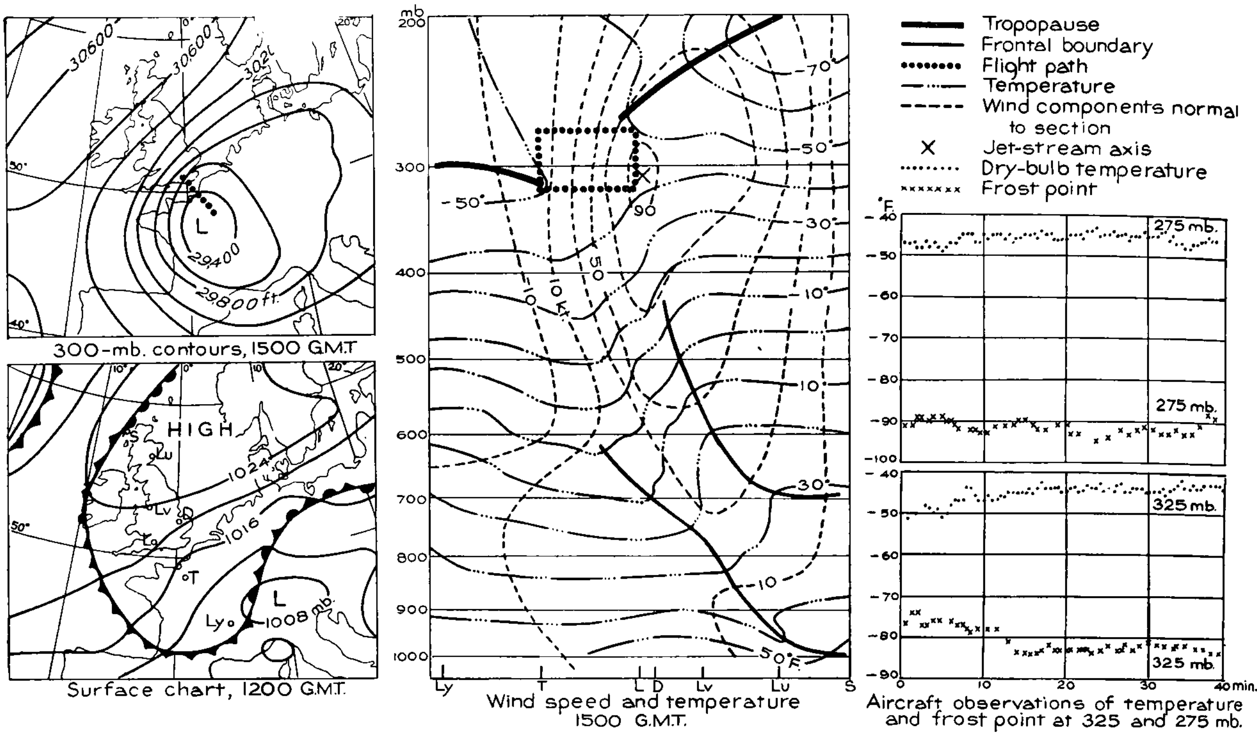


FIG. 6—SYNOPTIC SITUATION, MAY 17, 1951 (FLIGHT 2)
Ly = Lyons, T = Trappes, L = Larkhill, D = Downham Market, Lv = Liverpool, Lu = Leuchars, S = Stornoway

It might be expected that an aircraft investigation near the level of the jet-stream axis and on the low-pressure side would throw some light on the question of the continuity of the tropopause in that region. Flight 2 on May 17, 1951, was made with that end in view. The relevant synoptic charts and cross-section are shown in Fig. 6. The cross-section through the NE. jet stream suggested a definite break in the tropopause although the evidence was inconclusive. The temperature observations taken by the aircraft (see Fig. 6) confirmed that at this time there was no indication of a tropopause in the region examined. No other flight was quite so satisfactorily situated for the specific purpose of examining the nature of the tropopause just to the low-pressure side of the jet-stream axis, although several traversed the tropopause. In some cases the tropopause was drawn on the cross-section as continuous from the high-pressure to the low-pressure side of the jet stream, in others it was drawn as uncertain or discontinuous, but in none of these cases did the flight observations add any additional evidence to permit a definite or a contrary construction to be made. It might be mentioned, however, that the tropopause tended to be continuous with the weaker jet streams, and to be uncertain or discontinuous with the more intense ones.

Temperature pattern on horizontal grid flown on August 19, 1948. It is desirable to put on record the data obtained on a flight made between 1000 and 1200 G.M.T. on August 19, 1948. Readings were taken on level flight at 35,000 ft. over a roughly rectangular area relative to the air. This area was traversed six times along nearly parallel legs running south to north, each 53 nautical miles long and about 5·3 nautical miles apart. The first leg commenced at Farnborough and finished 53 nautical miles farther north, and each leg was 5·3 nautical miles west of the previous one relative to the air. On this occasion the air flow in the upper troposphere and lower stratosphere was west-north-westerly. The position of the jet-stream axis cannot be determined with any precision owing to lack of wind observations over France, but the observations over England indicated that the wind

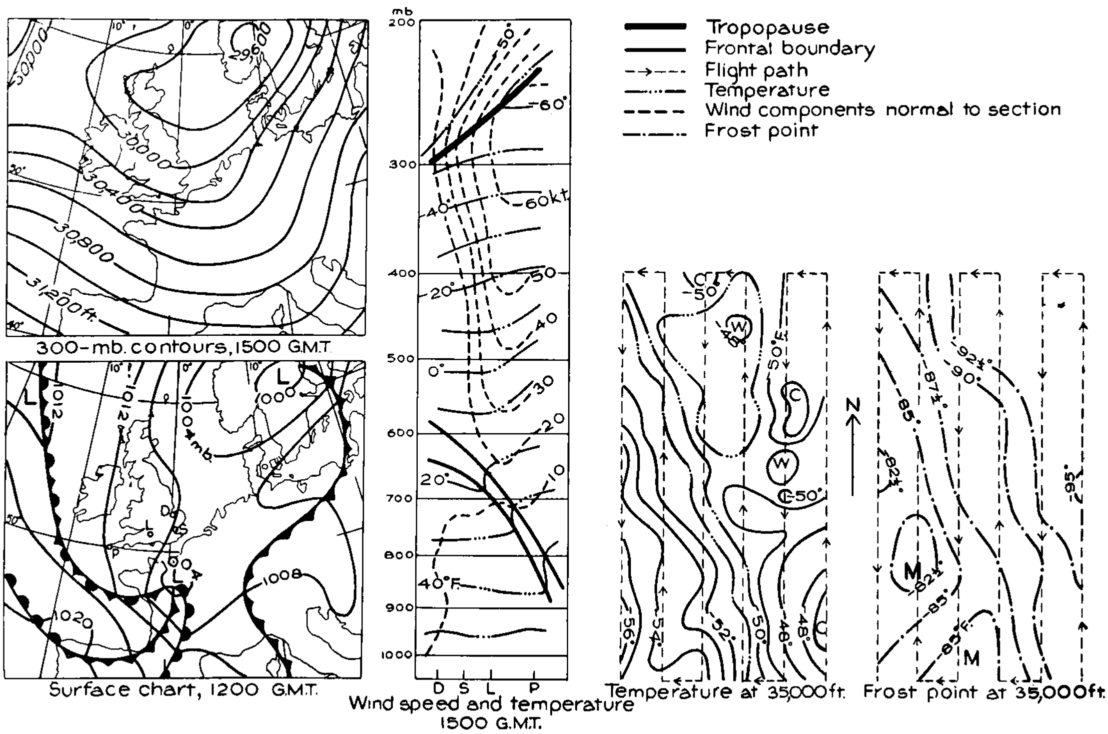


FIG. 7—SYNOPTIC SITUATION, AUGUST 19, 1948

The horizontal temperature and frost-point patterns were observed, as indicated, on six quasi-parallel legs in the stratosphere on the low-pressure side of a jet stream over south-east England between 1000 and 1200 G.M.T. The area covered by the flight extended 53 nautical miles from north to south and 26·5 nautical miles from east to west
D = Downham Market, S = Shoeburyness, L = Larkhill, P = Penzance
W = Warm centre, C = Cold centre, M = Moist centre

maximum was to the south of the area over which the flight was made. The flight data refer to an area relative to the air at 35,000 ft. in the lower stratosphere on the low-pressure side of the rather weak WNW. jet stream. The synoptic situation is illustrated in Fig. 7 together with the temperature and frost-point patterns; the horizontal temperature pattern is of course a plot of non-synchronous temperature readings relative to the air; because of the horizontal wind shear the plot should not be in the form of the rectangular grid shown, but it is difficult to construct the true air grid.

The temperature readings on the 53-nautical-mile legs were made every 2·7 nautical miles or so, and show irregularities of the type mentioned on p. 6. However, perhaps the main point of interest is the existence of quite a pronounced horizontal temperature gradient in a direction from north-east to south-west in the stratosphere, above and slightly on the low-pressure side of the jet-stream axis. The true direction of the temperature gradient is probably from north-north-east to south-south-west, but is distorted on the diagrammatic representation because of horizontal wind shear.

§ 5.—HUMIDITY DISTRIBUTION NEAR JET STREAMS

Frost-point observations on the 20 special flights.—Frost point was more variable than temperature. Over intervals of 2–5 min. (horizontal distances 10–25 nautical miles) fluctuations greater than 10° F. occurred on 11 legs, and greater than 20° F. on 2 legs. On 11 legs with fairly complete sets of readings at 1-min. intervals the root-mean-square 1-min. variations of frost point ranged from

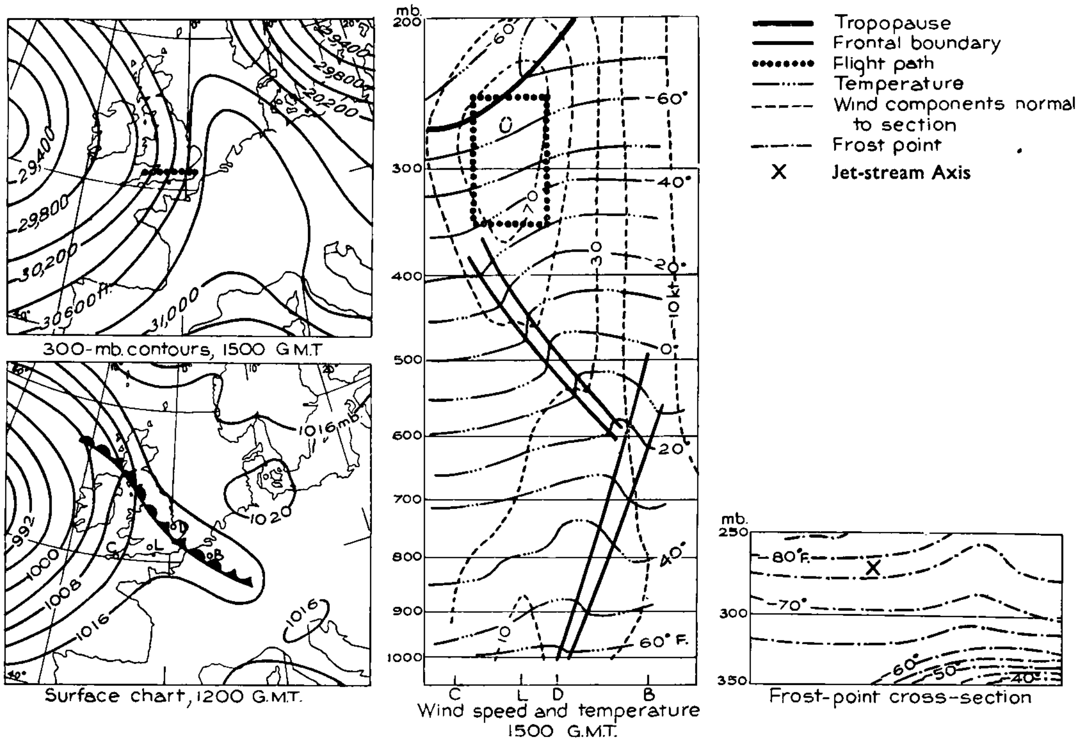


FIG. 8—SYNOPTIC SITUATION, MAY 24, 1951 (FLIGHT 3)
C = Camborne, L = Larkhill, D = Downham Market, B = Brussels

1·0° to 3·3° F.; these fluctuations tended to be rather greater for the legs entirely in the troposphere. Frost-point fluctuations of this type have already been studied by Frith[4], and are not particularly a feature of the atmosphere near jet streams.

Vertical frost-point sections were constructed in most cases for the grid region flown by the aircraft. The observations were not sufficient to show all the minor variations of frost point within the grid region but the broad picture was usually delineated. Two such frost-point sections are presented in Fig. 8 (flight 3 on May 24, 1951) and Fig. 9 (flight 12 on January 2, 1952). On 11 occasions (flights 2, 3, 4, 6, 10, 11, 12, 13, 14, 17 and 19) it was found possible, with the aid of these frost-point sections, to estimate the approximate values of temperature, frost point and frost-point depression (i.e. temperature minus frost point) at the jet-stream axis. The mean values were −60° F. for temperature, −79° F. for frost point and 19° F. for frost-point depression. The frost-point depression varied from about 0° F. (flight 12) to 43° F. (flight 14); although these figures are uncertain to within 5° F. at least, they do indicate the existence of great differences in humidity at the jet-stream axis from case to case; indeed it appears that the air in the core of the jet stream can be practically saturated or quite dry. However, it is noteworthy that there is an association between a high value of frost-point depression (i.e. low relative humidity) and high temperature in the core of the current. For example, the five jet streams (flights 2, 6, 14, 17 and 19) with relatively warm air at the position of the jet axis had a mean temperature of −50° F. and a mean frost-point depression of 32° F.; in contradistinction, the other six cases (flights 3, 4, 10, 11, 12, 13) averaged −68° F. for temperature and 9° F. for frost-point depression in the core of the current. The jet streams with a relatively moist core and those with a relatively dry core do not appear to have any particular seasonal preferences, nor to be related to broad synoptic features such as the forward side of a long-wave trough or ridge, nor to be connected with the direction of lateral motion of the axis; but the smallness of the sample makes it uncertain whether these results are truly representative of jet streams.

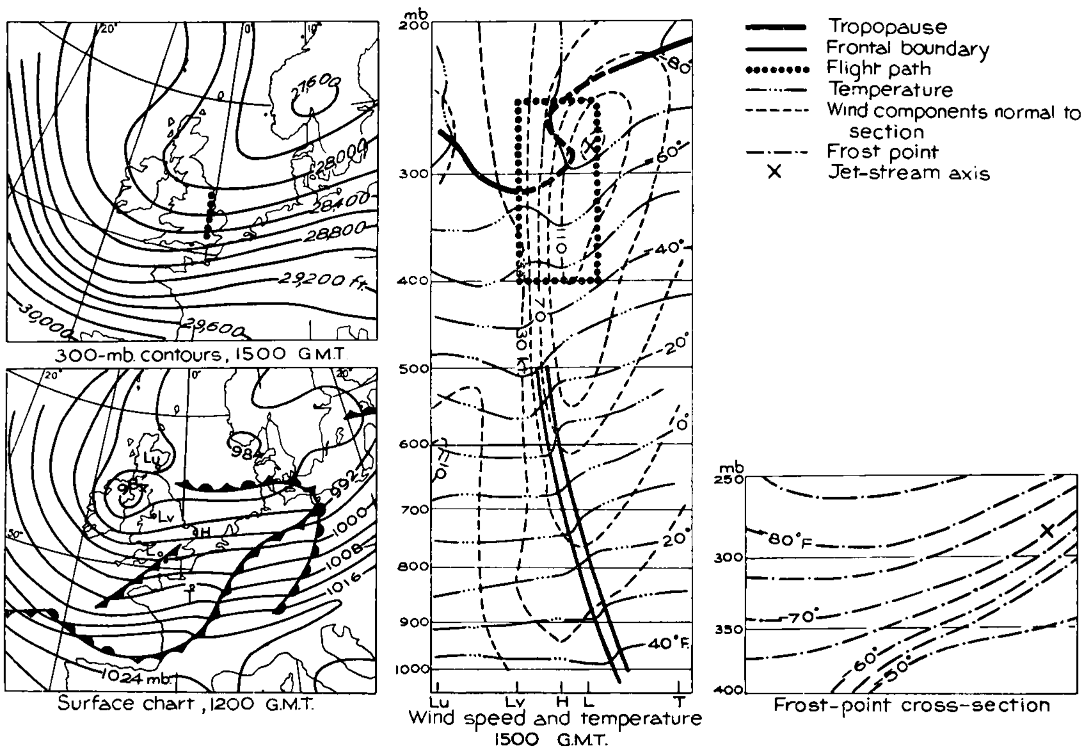


FIG. 9—SYNOPTIC SITUATION, JANUARY 2, 1952 (FLIGHT 12)
Lu = Leuchars, Lv = Liverpool, H = Hemsby, L = Larkhill, T = Trappes

The frost-point cross-sections in Figs. 8 and 9 indicate a horizontal gradient of frost point in the same direction as the pressure gradient. This type of frost-point distribution was suggested on many of the flights, despite the masking of the effect on some occasions by irregularities from the general trend or by missing observations. An example of a different frost-point distribution is shown in Fig. 6; the overall horizontal gradient of frost point along the leg at 275 mb. is practically zero, and along the leg at 325 mb. it is in the opposite sense to the horizontal pressure gradient. However, the fact that the region explored by the aircraft on individual occasions was always limited in extent and differed in position relative to the jet-stream axis, and that there were certain shortcomings of the frost-point observations, made it necessary to combine the data from the different flights in order to bring out the over-all features of the frost-point distribution. Various combinations of the data are discussed below.

In the first place it seems quite clear that there is normally a horizontal gradient of frost point from the troposphere to the stratosphere. Seven legs, which quite certainly traversed the tropopause, namely those at 250 mb. on flights 3, 4, 7, 12, 19 and 20 and at 220 mb. on flight 19, were employed in the construction of Fig. 10 which shows the mean horizontal variation of temperature and frost point relative to the tropopause values; the considerable difference in humidity between the stratosphere and the troposphere at the same level is obvious.

There were 18 legs (bottom and top legs of flights 3, 5, 6, 10, 12, 13, 17, and 19, and bottom legs of flights 8 and 14) with fairly complete frost-point readings, and on which the frost-point observation was available or could be estimated with confidence on each leg at the point vertically above or below the axis of the jet stream. The frost point was then obtained on each leg at positions 50 nautical miles apart on each side of the jet-stream axis, and hence the frost point relative to that at the point of intersection of the leg with the vertical through the jet-stream axis. The averages of these relative frost points at different distances for the legs above and below the level of the jet-stream axis

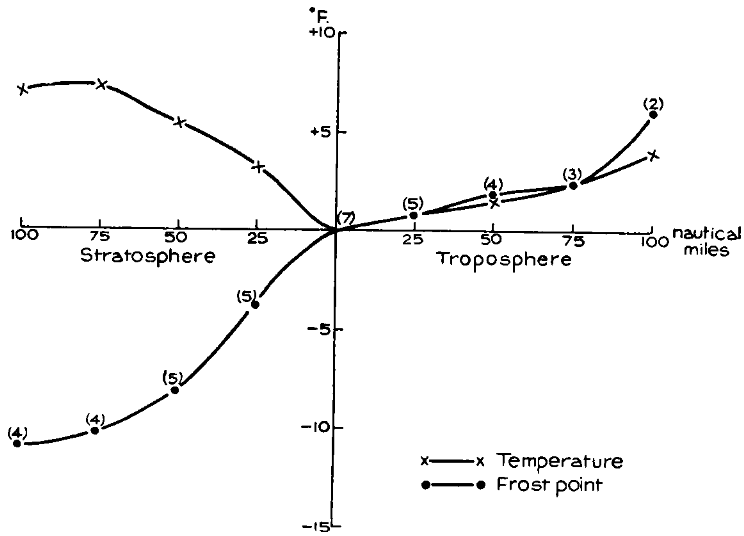
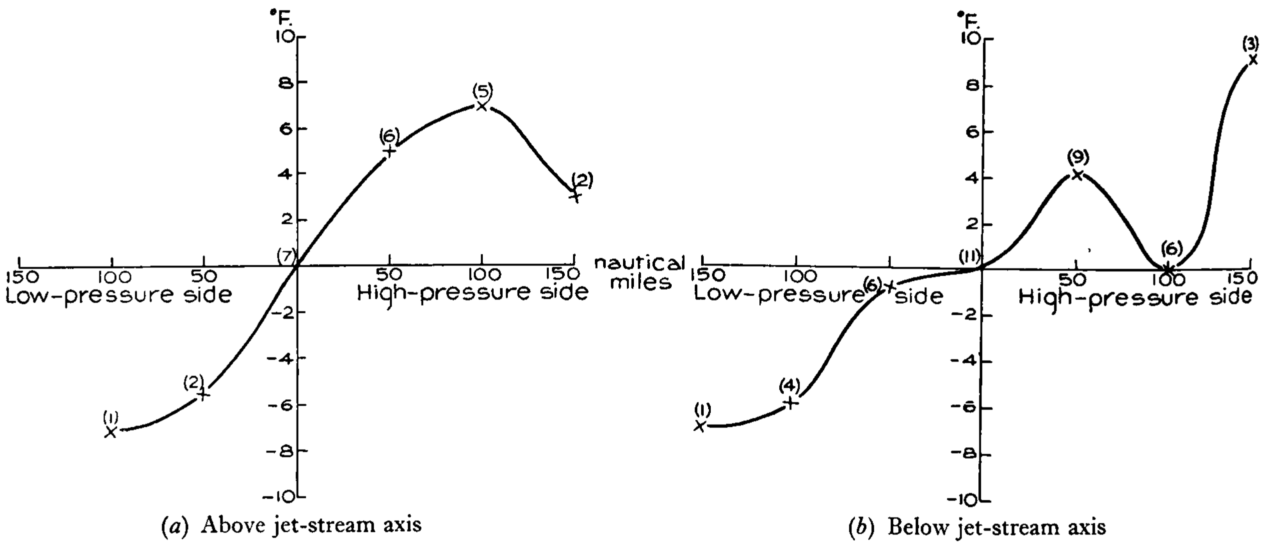


FIG. 10—MEAN TEMPERATURE AND FROSTPOINT RELATIVE TO THE VALUES AT THE TROPOPAUSE, BASED ON SEVEN HORIZONTAL TRAVERSES THROUGH THE TROPOPAUSE

Mean tropopause temperature = —64·4°F.
Mean tropopause frost point = —75·0°F.
The number of observations at various distances are in parentheses

are displayed in Fig. 11. The frost-point profile in Fig. 11(*a*) indicates a horizontal gradient of frost point across the jet stream in the same direction as the pressure gradient. Six of the 7 legs employed in obtaining Fig. 11(*a*) were either in the uppermost part of the troposphere or partly in the troposphere and partly in the stratosphere, and these 6 legs individually agreed with the mean profile; the remaining leg, that of flight 13, was entirely in the stratosphere and had frost points at 100 and 150 nautical miles on the high-pressure side some 10° F. lower than the values at the points 0 and 50 nautical miles. The average frost-point profile for the legs below the jet-stream axis, shown in



(*a*) Above jet-stream axis (*b*) Below jet-stream axis

FIG. 11—MEAN RELATIVE FROST-POINT DISTRIBUTION

The relative frost point is frost point minus that at the point of intersection of the horizontal leg with the vertical through the jet-stream axis. The number of observations comprising mean values at various distances are in parentheses

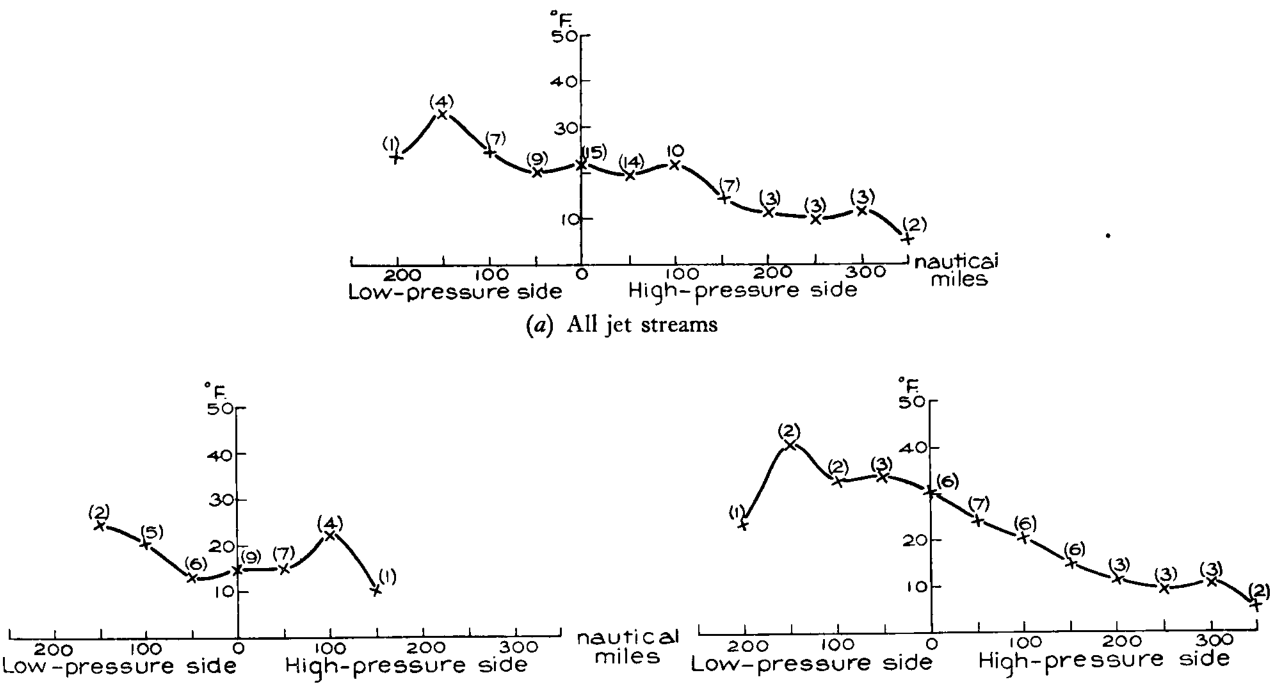
Fig. 11(*b*), is of the same type as that shown in Fig. 11(*a*), apart from the zero value at 100 nautical miles on the high-pressure side. Three of the 11 legs used in constructing Fig. 11(*b*) had frost-point gradients agreeing with the mean picture; the other 8 legs, taking a broad view, showed a similar over-all trend, but with frost-point irregularities so large as to give a contrary trend over substantial parts of each leg. Evidently there is a definite tendency for the air to be moister, as measured by higher frost points, in the region 100–200 nautical miles to the right, compared with the region 100–200 nautical miles to the left of the jet-stream axis, looking down wind. This type of humidity distribution appears to occur both above and below the level of the jet-stream axis. The profiles of temperature and frost point shown in Fig. 10 indicate that a substantial humidity gradient exists from the troposphere to the stratosphere at the same level, and this may account for much of the transverse humidity gradient shown in Fig. 11(*a*) for the legs above the axis of the jet stream.

In order to construct some kind of humidity profile across a larger extent of the jet stream, the frost-point depressions (i.e. temperature minus frost point) were obtained from all the legs which were flown entirely in the troposphere. Fig. 12(*a*) shows the mean picture of the depression of the frost point across the jet stream, based on 23 legs in the upper troposphere. The jet streams were subdivided into two groups:

(i) those which either were quasi-stationary on the forward side of a cold upper trough or moved normal to the axis in the direction from cold to warm troposphere

(ii) those which either were quasi-stationary on the forward side of a warm upper ridge or moved normal to the axis in the direction from warm to cold troposphere.

The mean profile of the frost-point depression obtained from the cases in group (i) is shown in Fig. 12(*b*), that from the cases in group (ii) in Fig. 12(*c*). The profile of Fig. 12(*b*) is unfortunately rather limited in extent, but it does not appear to be radically different from the profile of Fig. 12(*c*)



(*a*) All jet streams

(*b*) Jet streams approximately between S. and W.

(*c*) Jet streams approximately between NW. and NE.

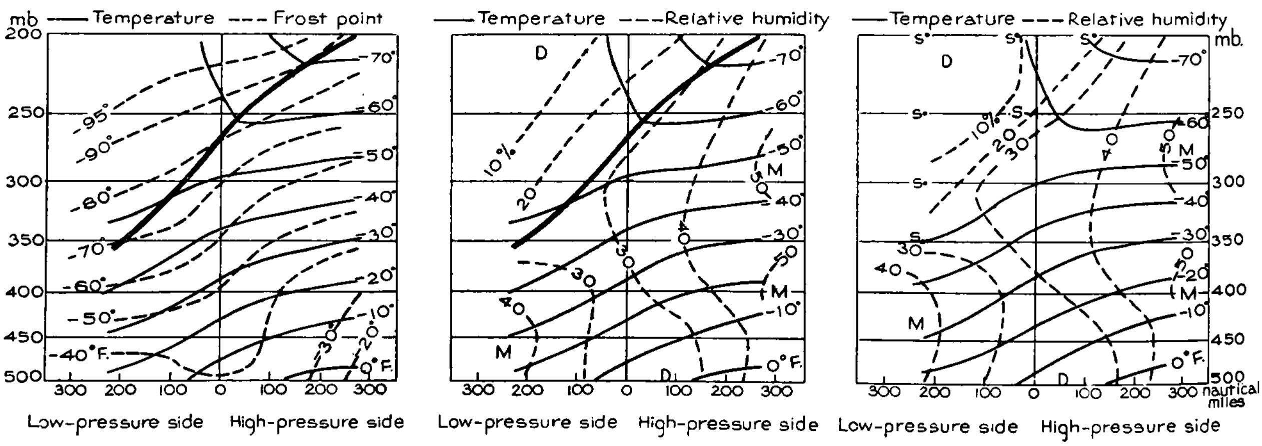
FIG. 12—PROFILES OF MEAN FROST-POINT DEPRESSION ACROSS JET STREAMS IN THE UPPER TROPOSPHERE

The number of observations at various distances from the jet-stream axis are shown in parentheses over a similar distance relative to the jet-stream axis. There is thus little or no evidence to suggest that the profile shown in Fig. 12(*a*), i.e. with a definite horizontal gradient of humidity in the upper troposphere across the jet stream from high to low pressure, is, or is not, greatly dependent upon the broad synoptic type of jet stream.

Confirmation of the tendency for a horizontal gradient of humidity across jet streams will be given in the following section by an analysis of independent data. The tropospheric humidity distribution will be shown in § 6 to fit in with the average distribution of layer cloud near jet streams. The significance of the humidity and cloud distribution in relation to vertical motion will also be discussed in § 6.

Mean humidity distribution obtained from vertical soundings made in 1949–51.—Those vertical soundings made by the Meteorological Research Flight during 1949–51 within 350 nautical miles of the axes of jet streams were examined. For this purpose a jet stream was taken as a wind maximum of at least 70 kt. on the 300-mb. charts constructed by the Central Forecasting Office. The soundings were divided according to their position relative to the jet-stream axis (as estimated on the 300-mb. chart); the four groups comprised observations within 175 nautical miles and within 175–350 nautical miles from, and on either side of, the jet-stream axis. Mean values of temperature, frost point and relative humidity with respect to ice were computed in each group for pressure levels at 50-mb. intervals from 500 mb. to 200 mb. Some soundings either stopped between 500 mb. and 200 mb. or had an incomplete set of frost-point readings. These were discarded from the analysis if less than 5 humidity observations (at 50-mb. intervals) were available; 8 soundings were thus rejected, but in only one of these cases were the frost-point observations missing because the aircraft was definitely in cloud (cirrostratus), and this flight took place some 260 nautical miles from the jet-stream axis on the high-pressure side. Altogether 56 vertical soundings were available for the analysis; on the low-pressure side there were 6 at 175–350 nautical miles and 16 at 0–175 nautical miles, on the high-pressure side 14 at 0–175 nautical miles and 20 at 175–350 nautical miles from the jet-stream axis.

In Fig. 13, diagram (*a*) is a composite cross-section (based on the 56 soundings) which shows the temperature and frost-point distribution; diagram (*b*) shows relative humidity with respect to



(*a*) Mean temperature and frost-point, making no distinction between stratospheric and tropospheric observations

(*b*) Mean temperature and relative humidity with respect to ice, making no distinction between stratospheric and tropospheric observations

(*c*) Mean temperature and relative humidity with respect to ice. Means based on stratospheric observations only are marked S; all other observations are in the troposphere

FIG. 13—MEAN CROSS-SECTIONS SHOWING THE HUMIDITY DISTRIBUTION NEAR A JET STREAM

D = Relatively dry region, M = Relatively moist region ice in place of frost point. The humidity pattern above 400 mb. could be a reflection of the preponderance of stratospheric observations on the low-pressure side of the jet-stream axis, and of tropospheric observations on the high-pressure side, for the air is drier in the stratosphere than in the troposphere at the same level, as has been illustrated in Fig. 10. The overlap between stratospheric and tropospheric observations occurred between 400 and 300 mb. in the group at 175–350 nautical miles from the axis on the low-pressure side, and between 250 and 200 mb. at 175–350 nautical miles from the axis on the high-pressure side. Another composite diagram—Fig. 13(*c*)—was constructed so as to emphasize the difference in humidity between stratospheric and tropospheric air. The top left part of Fig. 13(*c*) is based on mean values from individual soundings entirely in the stratosphere (marked S); the remainder of this figure refers to tropospheric conditions. The criterion for deciding that the points S were in the stratosphere was simply the existence of a majority of stratospheric observations at these points—the tropospheric observations at the same points being neglected in evaluating the mean temperature and humidity; a similar criterion was applied to the tropospheric points. Fig. 13(*c*) shows that the main part of the horizontal gradient of humidity which is indicated in the upper parts of Figs. 13(*a*) and 13(*b*) is concentrated near the tropopause.

There are clearly two main features of the average humidity distribution shown in Fig. 13:

(i) Above about 400 mb. the air tends to be relatively dry on the low-pressure side and relatively moist on the high-pressure side of the jet stream. The horizontal gradient of humidity is probably, in the main, a result of the fact that, at about the level of the wind maximum, the air on the low-pressure side is usually stratospheric, whereas on the high-pressure side it is tropospheric. Nevertheless, there appears to be a tendency for a horizontal humidity gradient also to exist in the upper troposphere; a similar feature has been noted in connexion with the analysis of the 20 special flights.

(ii) At or below about 500 mb. a relatively dry patch tends to occur roughly beneath the jet-stream axis. It is clear that this relatively dry patch has a close association with the frontal zone which usually intersects the 500-mb. surface directly beneath the jet-stream maximum. Sawyer[5] has confirmed the existence of a dry patch near many frontal zones; he suggests that its presence can be accounted for by the advection into the frontal zone of air which has been dried by subsidence at an earlier stage in a region external to the frontal zone.

Frost-point pattern on horizontal grid flown on August 19, 1948. The air-plot of the frost-point observations made on a horizontal flight in the stratosphere near a weak jet stream on August 19, 1948 is shown in the right-hand diagram of Fig. 7; the corresponding temperature observations have been discussed in § 4. This diagram is of interest in illustrating the fluctuations of frost point that occur in the stratosphere, and in showing the existence of a gradient of frost point in the stratospheric air associated with the jet stream.

§ 6.—CLOUD DISTRIBUTION NEAR JET STREAMS

The observations of cloud from the 20 special flights have enabled some broad features of the cloud distribution near the jet stream to be made fairly clear, although it was not found possible to present in any detail the cloud structure near individual jet streams, except occasionally over quite small regions.

Cloud was actually traversed on the horizontal legs rather infrequently, as is indicated by Table II which gives the percentage of the flying time in cloud of various types. The 39 legs shown in Fig. 1 occupied some 26½-hr. flying time.

Not only was no cloud traversed on any of the 16 legs which were located above the jet-stream axis, but only on 3 of these legs (flights 9, 10 and 16) were cirrus or cirrostratus patches observed above the aircraft. The cirrus type of cloud occurred at distances varying between about 30 and

TABLE II—DURATION OF FLIGHT IN CLOUD ON HORIZONTAL LEGS

	Position of horizontal legs relative to jet-stream axis		
	Above	Below	Above and below
	percentage of flying time		
Cirrostratus, cirrus, anvil cirrus	0	2·9	1·8
Nimbostratus, altostratus, altocumulus	0	3·6	2·2
All cloud	0	6·5	4·0

400 nautical miles from the jet-stream axis on the high-pressure side in the upper troposphere; no cloud was observed at or above the level of the jet-stream axis on the low-pressure side. It seems clear that the atmosphere above the jet-stream axis is generally cloudless, apart from occasional patches of cirrus or cirrostratus on the high-pressure side in the uppermost part of the troposphere.

Seven legs (flights 1, 3, 7, 9, 12, 13 and 16) traversed some cloud. The one report of cumulonimbus anvil occurred just over 200 nautical miles from the axis on the low-pressure side of jet stream 7, below which region a good deal of convection was taking place. The delicate cirrus which was traversed on flight 13 occurred practically vertically below the jet-stream axis. However, on the remaining five flights the aircraft traversed cloud of the layer type, i.e. nimbostratus, altostratus, altocumulus and cirrostratus, which occurred at distances from the jet-stream axis varying from about 70 nautical miles on the low-pressure side to 400 nautical miles on the high-pressure side. Flights 3 and 12 may be cited as illustrative examples; the synoptic situations of these are shown in Figs. 8 and 9. In each case layer cloud was encountered in the region beneath and to the high-pressure side of the axis of the jet stream.

On seven flights (numbers 2, 4, 5, 8, 11, 15 and 17) no cloud was observed at or above the bottom leg. In each case there was usually broken stratocumulus or cumulus below the aircraft, and on one or two occasions some local altocumulus. These seven jet streams differed considerably in both intensity and orientation. However, it is noteworthy that the region investigated extended from about 230 nautical miles on the low-pressure side to about 150 nautical miles on the high-pressure side of the jet-stream axis; in other words the legs were somewhat biased towards the low-pressure side of the jet-stream axis. Although the position of the region investigated almost certainly was associated with the nearly complete absence of medium and high cloud on these particular flights, it is also significant that in six of the cases no surface front accompanied the jet stream; the typical sloping baroclinic zone appeared linked in each of these six cases (all but number 5) with an inversion or very stable layer of the subsidence type in the lowest few thousand feet. The other jet stream at the time of flight 5 was rapidly weakening and was associated with a weak surface cold front; the sequence of events associated with this case has already been discussed by Murray[2].

In contrast with the seven flights with no cloud at or above 400–350 mb., the remaining thirteen flights reported some cloud at (seven flights) or above (six flights) the bottom leg. These thirteen flights ranged from nearly 250 nautical miles on the low-pressure side to just over 400 nautical miles on the high-pressure side of the jet-stream axis. Excluding the nimbostratus, altostratus and altocumulus cloud actually traversed and already discussed, all the cloud was ice-crystal type, i.e. cirrus or cirrostratus, or on one occasion combined with some cirrocumulus in addition; excluding also the cumulonimbus anvil cloud traversed at just over 200 nautical miles from the axis on the low-pressure side of the jet stream, the high cloud was observed from about 70 nautical miles on the low-pressure side to just over 400 nautical miles on the high-pressure side of the jet-stream axis, i.e. predominantly on the high-pressure side. The jet streams investigated by these thirteen flights cannot easily be placed into convenient synoptic pigeon-holes; they were situated on the forward side of both upper troughs and upper ridges; they were quasi-stationary or mobile; and they were diverse as regards intensity and synoptic size. However, the most notable synoptic feature associated with these particular jet streams was the existence of a surface front in all but one or two cases (e.g. no surface front on May 3, 1951), although more than half the fronts were quite weak in terms of rainfall activity.

Collating the observational evidence from the entire series of flights, it appears that the cloud in the atmosphere above about 400 mb. is predominantly on the high-pressure side of the jet-stream axis. More precisely, above 400 mb. it may be said that:

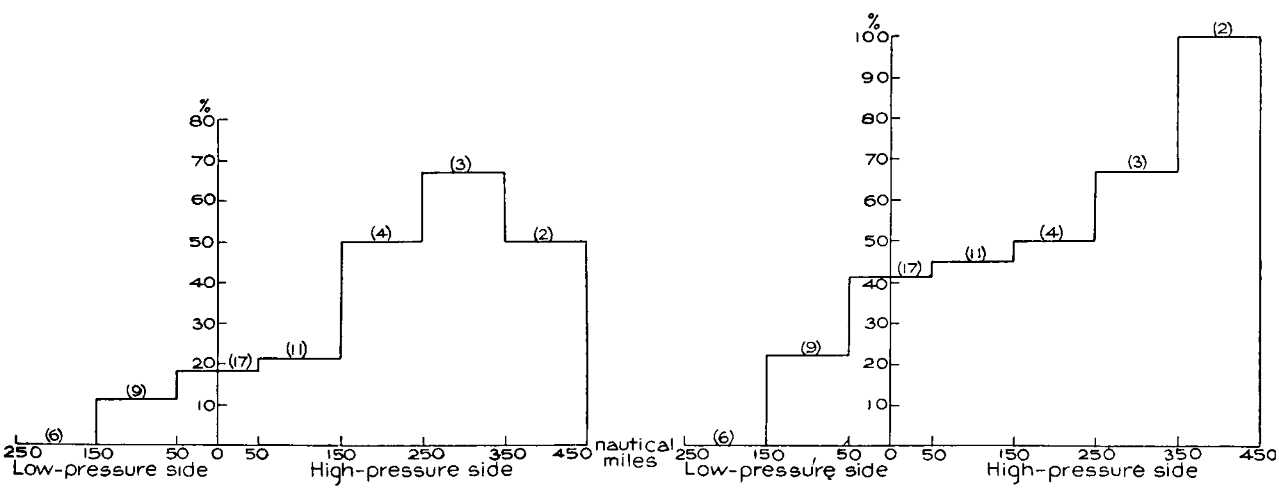
(i) generally no cloud (except occasionally cumulonimbus tops or anvils) occurs on the low-pressure side within the region between about 250 and 100 nautical miles from the jet-stream axis,

(ii) some cloud generally occurs on the high-pressure side between about 150 and 450 nautical miles from the jet-stream axis,

(iii) from about 100 nautical miles on the low-pressure side to about 150 nautical miles on the high-pressure side there may be nil or any amount of cloud.

So far the discussion has centred on the cloud distribution at or above 400 mb. On most of the flights some cloud was generally observed below the aircraft. As regards low cloud, it was predominantly cumulonimbus or cumulus or stratocumulus on the low-pressure side, and stratocumulus or nimbostratus on the high-pressure side of the jet-stream axis, but amounts were variable from case to case; such a distribution of low cloud was generally supported also by the surface synoptic observations, and is not unexpected. Medium cloud tended to be much more common when the region explored was on the high-pressure side of the jet-stream axis, as with cloud above 400 mb.

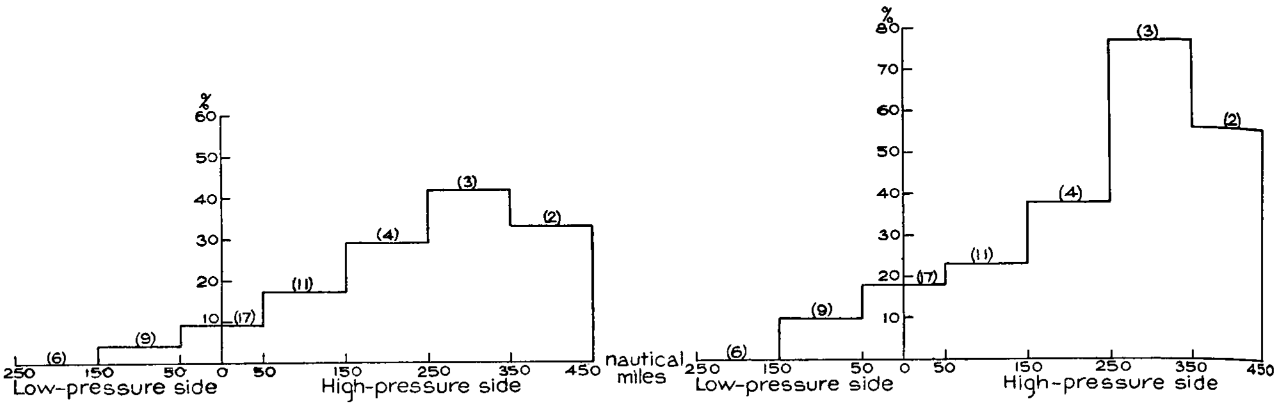
Quite clearly the distribution of layer cloud (excluding low cloud) near jet streams appears to be of most interest and to fit into a rough pattern. Therefore, it was decided to form composite pictures from all the aircraft observations of layer cloud, irrespective of whether the cloud was observed above or below (or at) the level of the flight, in order to bring out the main features of the cloud distribution. For this purpose the jet stream was divided into sectors of width 100 nautical miles as shown on the abscissae of Figs. 14 and 15. The fraction of each sector examined on each flight, and the incidence and extent of layer cloud were noted, and so it was possible for the overall distribution of layer cloud to be presented. Fig. 14 shows the percentage frequency of occurrence of layer cloud (whatever the amount) within the various sectors; histogram (*a*) is based on reports of nimbostratus, altrostratus and altocumulus only, whereas (*b*) also includes cirrostratus type. Fig. 15 presents the observational data rather differently: it shows for each sector the observed cloud amount expressed as a percentage of the maximum amount of cloud that would have been observed if the flights had reported layer cloud all the time, either above or below the grid track. Despite the



(*a*) Nimbostratus, altostratus and altocumulus (*b*) Nimbostratus, altostratus, altocumulus and cirrostratus

FIG. 14—PERCENTAGE FREQUENCY OF OCCURRENCE OF LAYER CLOUD IN THE VARIOUS SECTORS OF A JET STREAM

The figures in parentheses give the number of flights which investigated part or all of each sector



(*a*) Nimbostratus, altostratus and altocumulus (*b*) Nimbostratus, altostratus, altocumulus and cirrostratus

FIG. 15—PERCENTAGE OF TOTAL DISTANCE FLOWN WITH LAYER CLOUD ABOVE, AT OR BELOW THE AIRCRAFT IN THE VARIOUS SECTORS OF A JET STREAM

The figures in parentheses give the number of flights which investigated part or all of each sector

smallness of the sample upon which the histograms of Figs. 14 and 15 are based, all tell a consistent story. The placing of cloud observations on individual flights in their correct position relative to the jet-stream axis was uncertain in some degree; but there is no doubt of the reality of the overall distribution of layer cloud portrayed in Figs. 14 and 15. It is quite clear that layer cloud is mainly a feature of the high-pressure side of jet streams, although great variations in individual cases make one hesitant to say that the average picture is the typical model in any but broad respects.

Examination of the surface synoptic and the aircraft observations suggests that the jet streams with extensive layer cloud mainly on their high-pressure side are usually associated with a surface front which may be either active or rather inactive in terms of weather; such jet streams may be located on the forward side of either an upper trough or an upper ridge. Moreover, the jet streams with little or well broken layer cloud on their high-pressure side are normally either not associated with a front on the surface chart (a low-level subsidence inversion usually occurs where a front might be expected) or the front is very weak; these jet streams occur more frequently on the forward side of an upper ridge than on the forward side of an upper trough.

The distribution of layer cloud is in agreement with the type of humidity distribution discussed in § 5. The absence of fairly extensive layer cloud is not related in any simple way to general descending motion, although there is probably some positive correlation between the two factors. However, it is quite clear that, in order to produce such layer cloud, there must have been ascending motion of the air, although it may have ceased at the time or at the place of observation of the cloud. Thus the average distribution of layer cloud does not necessarily imply that the vertical circulation model is one in which there is general ascending motion over a more or less deep layer of the troposphere on the high-pressure side and subsidence on the low-pressure side; it does, however, suggest that such a vertical circulation model exists farther up stream, probably near the jet-stream-entrance region as has been suggested by Namias and Clapp[6]. Such a model of vertical motion would be consistent with horizontal divergence in the upper troposphere at about the level of the jet-stream axis roughly balanced by convergence below in the lower troposphere on the high-pressure side of the jet stream; high-level convergence with low-level divergence would then occur on the low-pressure side of the jet stream. The association between extensive layer cloud and an active surface front can then be explained if the convergence-divergence field is pronounced, since the low-level horizontal convergence, which is well known to have the effect of intensifying fronts, occurs on the high-pressure side of the jet stream in the lower troposphere where the surface front is normally located.

It is interesting in this connexion that flight 6 took place fairly near the jet-stream entrance (see Fig. 5), and that in this case there was much layer cloud on the high-pressure side of the axis as confirmed both by the aircraft and surface observations. None of the other flights was carried out in either a pronounced entrance or exit region.

§ 7.—TURBULENCE NEAR JET STREAMS

It is perhaps rather surprising that the twenty flights in the vicinity of jet streams experienced so little heavy turbulence. In about 26½ hr. flying on the horizontal legs shown in Fig. 1, when observations were generally made every minute, only once was a bump of intensity 0·4 g (the lower limit of heavy turbulence according to Bannon[7]) reported. Some statistics of the occurrence of bumps, based on one report every minute, are shown in Table III.

TABLE III—PERCENTAGE FREQUENCY OF OCCURENCE OF BUMPS IN THE NEIGHBOURHOOD OF 20 JET STREAMS

26½ hr. flying time. Heights between 400 and 200 mb.

Intensity of turbulence	$\geqslant 0{\cdot}1g$	$\geqslant 0{\cdot}2g$	$\geqslant 0{\cdot}3g$
Percentage frequency of occurrence	37·4	4·9	0·2

Slight bumps, i.e. of intensity less than 0·2 g, occurred roughly 33 per cent. of the time, but heavy bumps were extremely rare; even bumps of moderate intensity occurred less than 5 per cent. of the time.

Bannon[7] has pointed out that there is a fairly high association between the occurrence of pronounced clear-air turbulence and small values of the Richardson number R_i, and also large horizontal wind shears. The present series of observations offers an opportunity to test Bannon's ideas on independent data.

The positions of the legs on which no bumps or bumps of intensity 0·1 g (i.e. slight bumpiness) were reported are shown in Fig. 16 in relation to the jet-stream axis. It will be seen that there was some tendency for the legs with little or no bumpiness to be on the high-pressure side of the jet-stream axis. The minimum value of R_i (this suffers from the restriction that mean temperature lapse rates and vertical wind shears were measured over layers about 2,000 ft. thick) was estimated along each of the legs. The mean minimum R_i for all the legs was about 3·2, with individual minima ranging from about 0·5 to 7·6. Of the 14 legs 12 had an estimated minimum R_i greater than 1. At the extremity, on the low-pressure side of the jet stream, of each of the legs of flight 18 (synoptic situation shown in Fig. 4) R_i as measured was less than unity, but a displacement of the flight grid towards higher pressure by only 20 nautical miles relative to the cross-section would have increased R_i to a value greater than 1. The positions of the legs relative to the jet streams are uncertain to about this extent, since the flight and radio-sonde observations are not synchronous, and it is therefore possible that on this occasion R_i was greater than 1 everywhere along the legs. It seems, therefore, that the lack of bumpiness on the legs shown in Fig. 16 is not inconsistent with Richardson's criterion that turbulence tends to increase with R_i less than 1.

Maximum values of horizontal wind shear were also estimated for the legs shown in Fig. 16. Horizontal shear is equal to the space variation of wind speed normal to the wind direction modified by an effect arising from the curvature of the stream-line, and the latter effect is zero in straight flow. In the analysis the horizontal shear has been taken on the assumption of straight flow (i.e. zero curvature effect); for the non-synchronous nature of the flight data and widely spaced routine upper air data, and the fact that the flow appeared to be nearly straight in the region examined in most cases, made it scarcely possible to allow satisfactorily for the curvature effect. Thus, for various reasons, there is a good deal of uncertainty in the values given for the horizontal wind shears, but the errors of estimate are probably not sufficient to mask the general results. For the legs shown in Fig. 16 the estimated maximum cyclonic shear had a mean value about 25 kt./100 nautical miles, and varied from about 10 to 45 kt./100 nautical miles in individual legs; the estimated maximum anticyclonic shear had a mean of about 21 kt./100 nautical miles with individual variations from 10 to 38 kt./100 nautical miles. The two largest shears were cyclonic and occurred with flights 2 and 18. Flight 2 (see Fig. 6) was associated with a large R_i but flight 18, as has been mentioned, with R_i perhaps less than 1. In the latter case the horizontal shear might have been substantially less, for the same reason that R_i might have been larger than the computed value.

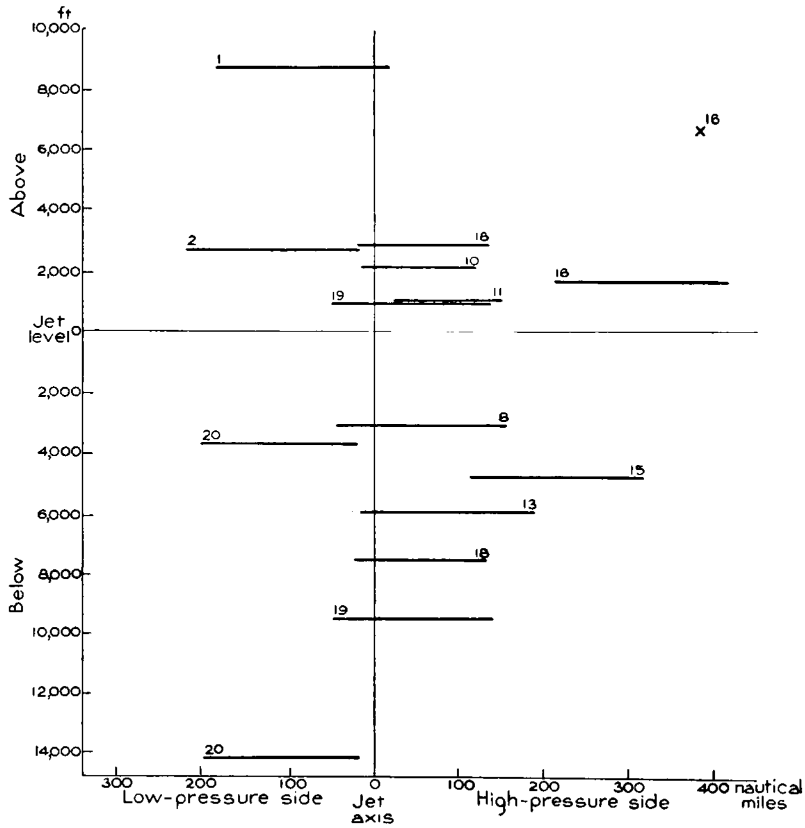


FIG. 16—POSITIONS OF LEGS RELATIVE TO JET-STREAM AXIS WITH LITTLE OR NO BUMPINESS (BUMPS NOT GREATER THAN 0·1g)

The figures against each leg refer to the flights concerned; with flight 16, a minor jet-stream axis is marked x 16

The nine regions (associated with five jet streams) with bumps greater than 0·2g (i.e. 0·25 to 0·4g) are shown in Fig. 17. Broadly speaking, the bumpy positions marked in Fig. 17 are complementary to those with little bumpiness shown in Fig. 16, although there is some overlapping. It is particularly noteworthy that the sector in the troposphere on the high-pressure side of the jet-stream axis is completely free of turbulence of the scale under consideration. Bannon[8] has found a similar distribution of severe bumps. All the bumps above the jet-stream axis occurred at or very near the tropopause. All but two groups occurred in clear air, including the most severe bumps (intensity 0·3 to 0·4 g) reported on the series of flights namely those of flight 7 at between 50 and 100 nautical miles from the axis on the low-pressure side; the other bumpy region (intensity 0·25 g) on flight 7 occurred in a cumulonimbus anvil, and the line of bumps (intensity 0·25 g) on flight 12 in nimbostratus cloud.

Minimum values of R_i in the vicinity of the bumpy regions were estimated for eight cases shown in Fig. 17 (the two adjacent bumpy regions of flight 7 were regarded as one). The mean value of R_i was about 1·2 with individual values ranging from about 0 to 4·2. The mean value of R_i in this case is significantly smaller than the mean minimum value of R_i estimated for the legs shown in Fig. 16. Furthermore in six out of the eight bumpy cases R_i was almost certainly less than 1. The isolated bump on the bottom leg of flight 12 and that on the top leg of flight 17 were probably associated with R_i greater than about 3, but in each case the bump was only of intensity 0·25 g. However, it is noteworthy that the bump on flight 12 was associated with a strong horizontal cyclonic wind shear of about 80 kt./100 nautical miles, and that the bump on flight 17 occurred at the tropopause.

The horizontal wind shears in the neighbourhood of the bumpy regions shown in Fig. 17 were all cyclonic except for an anticyclonic shear of about 10–15 kt./100 nautical miles in the case of the bump observed on flight 17. The cyclonic shears varied from at least about 20 to 80 kt./100 nautical miles from case to case with a mean value of about 40 kt./100 nautical miles; but in some cases much stronger shears occurred quite near the estimated position, which is uncertain to some extent, of the bumpy region, so that it is possible that, in fact, the cyclonic shears varied from about 30 to 90 kt./100 nautical miles with a mean value of about 55 kt./100 nautical miles. Thus, on the average, the

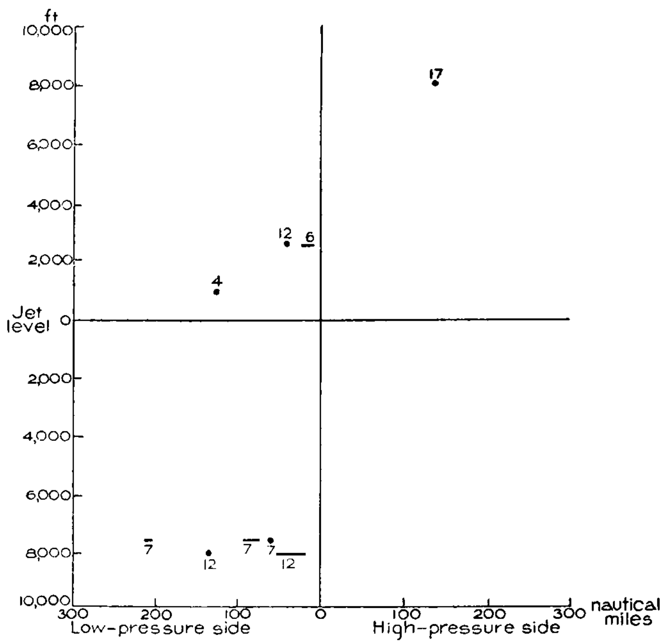


FIG. 17—POSITIONS OF BUMPS GREATER THAN 0·2g RELATIVE TO JET-STREAM AXIS

An isolated bump is shown as a dot, a line of bumps as a short line; the flight number is shown beside each bumpy region

cyclonic shears were considerably larger for the bumpy cases (mean value between 40 and 55 kt./100 nautical miles, say) than for the non-bumpy cases (mean value about 25 kt./100 nautical miles). It seems clear that there is some relationship between the occurrence of bumpiness and the strength of the horizontal shear, as has been suggested by Bannon[7]. The present investigation suggests, as a rough working rule for forecasting purposes, that turbulence of at least moderate intensity is probable when the horizontal wind shear is greater than about 45 kt./100 nautical miles, but may also occur with considerably lower values; shears of this intensity must almost certainly be cyclonic. With shears weaker than 45 kt./100 nautical miles it is probable that bumps occur with small values of R_i as has been stated by Bannon[7].

It is interesting to observe that the most bumpy region reported during the flights occurred in clear air on the bottom leg of flight 7 below the jet-stream axis, where R_i was small (less than 1) and the horizontal cyclonic shear was probably about 50 kt./100 nautical miles. Both conditions were suitable for the occurrence of turbulence. On the other hand the rather singular case of the bump on flight 17 is difficult to explain; it occurred near the tropopause where the horizontal anticyclonic shear and the vertical shear were apparently quite weak.

§ 8.—CONDENSATION TRAILS

Condensation trails occurred on 13 legs (top leg of flights 6, 8, 9, 10, 11, 12, 13, 14, 16, 17, 18, 20 and bottom leg of flight 13), did not occur on 2 legs (top leg of flight 19 and bottom leg of flight 14) and were not reported on the remaining 24 legs of the 20 special flights. It is possible that some ephemeral condensation trails formed and were not observed on these 24 legs, but it is at least fairly certain that no persistent trails formed. On vertical climbs and descents observations were made rather intermittently, but it is unlikely that persistent trails were missed.

The condensation trails invariably formed in regions where the air temperature was lower than the so-called immunity temperature[9]. However, there were many occasions when the observed temperature was lower than the immunity temperature but no trails were reported. Short and ephemeral condensation trails were reported on several occasions in the lowest few thousand feet of the stratosphere; for example, on the top leg of flight 14, which was entirely in the stratosphere, non-persistent condensation trails occurred just above the sloping tropopause but ceased on that part of the leg which was more than about 3,000 ft. above the tropopause. The frost-point depressions in regions where condensation trails were observed varied very widely, but there was a broad difference between the non-persistent and very persistent trails; the observed frost-point depressions ranged from 13° to 50° F. with non-persistent and from 1° to 26° F. with persistent condensation trails.

The observational facts given in the previous paragraph agree well with our knowledge of condensation trails which has recently been summarized in " Condensation trails from aircraft "[9]. None of these features is peculiar to the atmosphere in the vicinity of jet streams.

§ 9.—CONCLUSIONS

(1) The special flights near jet streams confirm that the thermal distribution as obtained by means of cross-sections constructed in a fairly close network of routine aerological stations is substantially correct. Although the flight data, for various reasons, were not always adequate to give definite information on the structure of the tropopause on the low-pressure side of the jet-stream axis, they do not disagree with the drawing of a continuous tropopause on some and a disruption of the tropopause surface on other cross-sections, indicating that both types of structure appear to occur in nature. The temperature observations also confirm that small-scale irregularities of about 1° F. occur in the lower stratosphere and near the tropopause, and significantly smaller fluctuations in the upper troposphere; but these are not specially features of the atmosphere near jet streams.

(2) There is on the average a horizontal gradient of humidity, in the same sense as the pressure gradient, across the jet stream in the region between about 500 mb. and 200 mb. The humidity of the air in the core of the jet stream varies considerably from case to case, but the average relative humidity with respect to ice at about the level of the jet stream is around 50 per cent. at 250–300 nautical miles from the axis on the high-pressure side and about 10 per cent. at a similar distance on the low-pressure side. Horizontal traverses of the tropopause demonstrate that the tropospheric air is moister than the stratospheric air at the same level, so that at least part of the horizontal humidity

gradient may be accounted for by the existence of a sloping tropopause. There is also evidence for the existence of a relatively dry patch of air in the vicinity of the frontal zone below the jet-stream axis; this dry feature of frontal zones has been noted by Sawyer[5].

(3) Cloud is variable from one jet stream to another, but there tends to be a broad pattern. The medium and high types of layer cloud predominate on the high-pressure side of the jet-stream axis, decrease in frequency of occurrence and in amount near the jet-stream axis, and are rare at a distance greater than about 100 nautical miles from the jet-stream axis on the low-pressure side. Layer clouds do not appear to occur above the level of the jet-stream axis, although occasionally patches of cirrus are observed in the uppermost part of the troposphere on the high-pressure side. The jet streams which have fairly extensive layer clouds on the high-pressure side are normally associated with surface fronts. Those jet streams with rather little layer cloud are generally associated with no surface front or a very weak one; such jet streams tend to be located on the forward side of an upper ridge. The average distribution of layer cloud suggests a vertical circulation model with ascending motion in the troposphere on the high-pressure side and descending motion on the low-pressure side, operating up stream probably in the jet-stream entrance region.

(4) On rather more than one third of the flying time near jet streams some turbulence was reported, but it was more than slight in intensity on only about 5 per cent. of the time. All but one of the moderate or severe bumps can be associated with small values of the Richardson number (usually less than 1) or large horizontal wind shears (cyclonic) or both factors together, thus confirming on independent data what has been said by Bannon[7].

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APPENDIX

A list is given below of the flights carried out by the Meteorological Research Flight, Farnborough, from May 1951 to August 1952 in connexion with the investigation of jet streams. Most of the flights were made in the afternoon, centred generally within an hour or so of the time of the routine aerological soundings; flights 10, 12, 16 and 20 took place some 2–3 hr. earlier. Flight 15 was terminated after completion of the bottom leg because of engine trouble. Failure of instruments resulted in the loss of observations on some flights; practically no temperatures were available on flight 5; frost points were missing for this reason over much or all of the top legs of flights 1, 7, 11, 14 and 18 and over shorter distances on several other legs. The jet-stream velocity given in the list below was obtained in each case from the wind maximum on the relevant cross-section.

Flight No.	Date	Bottom leg	Top leg	Jet-steam velocity	
		mb.	mb.		kt.
1	May 3, 1951	400	206	S.	70
2	May 17, 1951	325	275	NE.	100
3	May 24, 1951	350	250	S.–SSW.	90
4	May 30, 1951	350	250	ENE.	70
5	June 15, 1951	350	250	SW.	90
6	June 18, 1951	400	250	SSW.	130
7	July 11, 1951	350	250	SSW.	110
8	September 19, 1951	400	250	NW.–NNW.	100
9	December 3, 1951	400	250	NNW.–N.	110
10	December 10, 1951	400	250	NW.–NNW.	130
11	December 10, 1951	400	250	NW.–NNW.	130
12	January 2, 1952	400	250	W.	130
13	January 16, 1952	350	200	W.	90
14	February 1, 1952	350	250	WNW.–NW.	150
15	February 5, 1952	400	..	N.	140
16	March 21, 1952	350	250	NW.–NNW.	120
17	March 26, 1952	400	220	NNW.	80
18	April 24, 1952	400	250	NNW.	90
19	August 12, 1952	400	250	SW.	110
20	August 13, 1952	400	250	SW.	110

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