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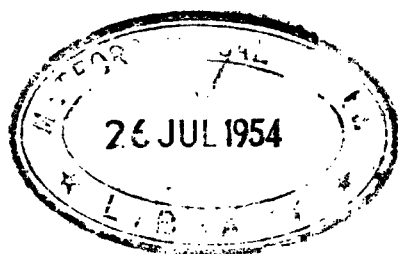
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CLASSIFICATION OF UPPER AIR
TEMPERATURE ACCORDING TO
TROPOPAUSE PRESSURE

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CLASSIFICATION OF UPPER AIR TEMPERATURE ACCORDING TO TROPOPAUSE PRESSURE

By J. K. BANNON, B.A.

Summary.—Upper air temperatures in the neighbourhood of the tropopause are best classified for some purposes according to tropopause pressure. Resulting from such a classification for 20-mb. ranges of tropopause pressure, mean temperatures at Larkhill are presented for standard pressure levels from 500 to 100 mb. for four months for a period of three years. The use of these mean temperatures for obtaining statistics of lapse rates and for the study of year-to-year temperature variations is discussed.

Introduction.—In temperate latitudes the level of the tropopause fluctuates through a large range of heights; over the British Isles it is usually between 20,000 and 50,000 ft. Levels within the range of occurrence of the tropopause will be in the troposphere on some occasions and in the stratosphere on others; statistics of temperature at such levels will thus include tropospheric and stratospheric features. For example the temperature frequency distribution at the 200-mb. level at Larkhill* is flat and in some months exhibits two maxima.

The level of the tropopause is related to temperature in the troposphere; thus Dines² found a correlation coefficient of $+0.79$ between the mean temperature from 1 to 9 Km. and the height of the tropopause (H_t), and Priestley³ a correlation of $+0.65$ between the temperature at 500 mb. and the height of the tropopause. Temperature in the lower stratosphere is also related to the height of the tropopause; though Dines² did not compute correlation coefficients for the stratosphere he says regarding the passage of a low-pressure area across Great Britain "As the barometer falls the temperature of the air column from 1 k. to 9 k. falls also, the value of H_t decreases, and the temperature of the upper air from 11 k. to 20 k. rises. As the depression moves away and the barometer rises, the lower air column rises in temperature, H_t increases, and the upper air column falls in temperature." It is well known that a low tropopause is associated with a warm lower stratosphere.

The mean temperature at a fixed level in the upper troposphere or lower stratosphere for a given period will then be a function of, among other things, the mean behaviour of the tropopause during the same period. For example, the mean temperature at Larkhill at the 150-mb. level for the month of January, 1948 was 12°F. warmer than for the same month in 1949; the corresponding mean tropopause pressures were 265 and 227 mb. respectively.

The variation of tropopause height is governed largely by advection, the horizontal transport of higher or lower tropopauses, and by vertical motion. Sawyer⁴ concludes that these two factors are equally important in the variation of tropopause height above a fixed point. Formation of a new tropopause at a different level by dynamical means, as opposed to motion of an existing surface, is another source of variability in tropopause height but is less important than the first two. Sawyer's findings are consistent, of course, with the classical correlations of Dines². Mean temperature in the troposphere is largely, though not entirely, governed by the source of the air or in other words by the type of air mass; the mean tropopause height in general increases towards the equator, and the advection of warmer air from the south will transport a higher tropopause with it. The correlation coefficient of $+0.79$ between mean temperature from 1 to 9 Km. and tropopause height is partly, probably largely, a result of advection. The close relation between pressure at 9 Km. and tropopause height (correlation coefficient $+0.84$) is probably mainly the result of vertical motion, though temperature (advection) effects will also be present; vertical motion in

* The index numbers refer to the bibliography on p. 20.

the upper troposphere and lower stratosphere is related to the depressions and anticyclones of temperate latitudes, subsidence occurring over the former and ascent over the latter^{5, 6}.

If upper air temperatures are classified according to tropopause height so that occasions of similar tropopause height are considered together, not only will statistics of upper air temperature so obtained be for stratosphere or troposphere separately and not for a mixture of the two régimes, but much of the variation associated with the variable height of the tropopause will be eliminated. Classification according to tropopause height was adopted for the discussion of humidity observations in the upper troposphere and lower stratosphere⁶. Temperatures at a fixed level and for a particular (small) range of tropopause height (or pressure) will still be affected by the two main causes of tropopause-height variation, namely advection and vertical motion, but the variations, so arising, will be smaller than the variations of temperature at a fixed level regardless of tropopause height. It may be possible to sift the temperatures further, after classification by tropopause height, so as to eliminate or at any rate to compensate for the effects of vertical motion, arriving at statistics which may be used, for example, for a comparison of year-to-year differences in temperature in the upper troposphere and lower stratosphere which will be free from the immediate effects of the predominant weather types of the particular years.

This classification and sifting process may be interpreted in the following way. If it is assumed that advection and vertical motion are the two main causes of temperature change in the upper air, then temperature may be considered a function of these two variables. Thus, symbolically,

$$T = F(A, V),$$

where T = temperature, A denotes advection and V , vertical motion. Similarly tropopause pressure, P_0 , is a function of advection and vertical motion and thus

$$P_0 = f(A, V).$$

If observations of T are classified according to P_0 , this is equivalent to picking out all values of T for which $f(A, V) = \text{constant}$, thus reducing the two degrees of freedom to one. If, after this classification, it is possible to classify further, for example by some relation between T and V , then the effects on T of both variables A and V will have been eliminated, remaining variations in T being attributable to other causes. This argument assumes, of course, that advection and vertical motion are the two main causes of variation in temperature and in tropopause pressure.

To demonstrate the possibilities of such a classification of upper air temperature according to tropopause height, the observations made at Larkhill in the years 1948, 1949, 1950 have been so classified for the four months January, April, July and October, and the results are displayed and discussed in the following sections.

Method of analysis.—The data consist of temperature observations made at Larkhill, four times daily with few exceptions, at approximately 0230, 0830, 1430 and 2030 G.M.T. for the months January, April, July and October of the years 1948, 1949 and 1950. Only those ascents which attained the level of 150 mb. (approximately 45,000 ft.) or higher were used. By means of Hollerith tabulating machines the observations were assembled in groups, each group having tropopause pressures within a 20-mb. range. Ranges were 179–160 mb., 159–140 mb., 139–120 mb., etc. Mean temperatures for each of the standard levels 500, 400, 300, 200, 150 and 100 mb. were computed for each group and for each of the four months. The standard deviations about the means were also evaluated.

The statistics assembled in this manner are subject to two sources of error :—

- (i) errors in the level of the tropopause as given in the record
- (ii) errors in the observations arising from instrumental deficiencies.

Regarding (i) the position of the tropopause is usually in little doubt from the observations, being marked by a sharp change of lapse rate to inversion or isothermal*.

On a minority of occasions, however, the tropopause is difficult to specify unless rigid definitions are followed. Sawyer⁴ says that for synoptic purposes it is best to analyse each case taking account of all adjacent observations and thus maintain continuity in space and time. For statistical purposes a rigid definition is, however, essential. The definitions of the tropopause at present in use in the Meteorological Office (see Sawyer⁴ or Bannon, Frith and Shellard⁶) are not entirely rigorous, but do make determination of the tropopause over the British Isles a simple matter on the great majority of occasions. However in 36 out of the total number of 1,436 ascents analysed here the tropopause, as specified, does not obey the present Meteorological Office definitions ; in each of these cases the lapse rate above the level named as the tropopause is greater than $1.1^{\circ}\text{F./1,000 ft.}$ and the true tropopause should be at a higher level. It is possible that there are other incorrectly placed tropopauses in the data which remain undetected, as temperatures are available on the Hollerith cards only at the standard pressure levels which are 6,000–8,000 ft. apart in the upper troposphere and lower stratosphere. For the purposes of this analysis, which is regarded as a demonstration only, these obvious errors in tropopause level have not been corrected. For this reason statistics for numbers of observations less than, say, 10, are in some cases liable to even greater errors than the number of observations would imply. It is possible also, especially on occasions of very low tropopause, that the tropopause obeying the definition and chosen for the classification of temperatures here, is not the physically significant level but a spurious tropopause arising from some local peculiarity. Such inaccuracies must be accepted in an analysis of this nature ; they provide a further reason for giving little weight to statistics from a small number of observations.

Instrumental inaccuracies, according to Harrison⁷, result in random errors distributed with probable errors of about 0.8°F. in the stratosphere and about 1.4°F. in the upper troposphere. These assessments neglect any errors which may be caused by direct solar radiation on the instrument ; it is not known exactly to what extent the observed diurnal variation of temperature in the lower stratosphere is due to such errors or to what extent it is real. However, for the purposes of comparing upper air temperatures observed with the same type of instruments any such errors may be neglected and the observed diurnal variation considered real, so long as statistics are corrected to allow for differences in numbers of day and night observations.

Mean temperature-pressure curves and variation about these curves.—After the data had been classified according to tropopause pressure, mean temperatures were calculated for each standard level for each tropopause-pressure range. The easiest way to demonstrate these means is by diagrams showing mean temperature-against-pressure curves for each tropopause category and for each season (Fig. 1). Mean tropopause temperatures are also given. Greater accuracy than can be obtained from the diagrams is probably not justified, because of the comparatively limited period covered by the statistics and because of inaccuracies in the data, as discussed above. The number of observations with very high or very low tropopause pressures was small, and some curves for such tropopause-pressure ranges have been omitted. The pressure scale in Fig. 1 is logarithmic and is approximately proportional to height.

* The tropopause is much more difficult to define in some tropical or subtropical regions.

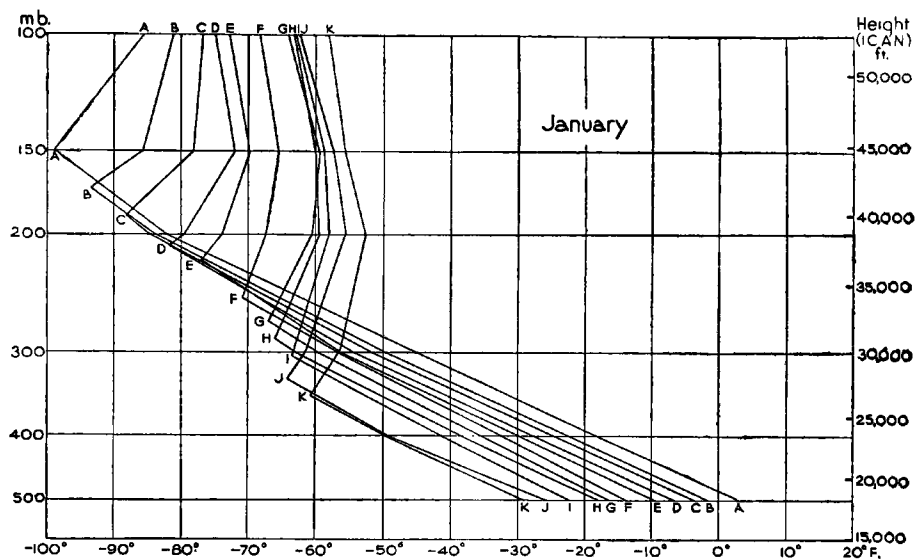
The orderliness of the curves in Fig. 1 is noteworthy, with few exceptions the mean curves in the stratosphere becoming steadily warmer with decreasing tropopause height (increasing tropopause pressure), and the reverse in the troposphere. This was to be expected, of course, at any rate in the troposphere where this feature of the curves is merely a pictorial representation of the Dines correlation between tropopause height and mean tropospheric temperature. The mean temperatures shown at the 100-mb. level are, in general, for fewer observations than at the other pressure levels; the numbers of observations are shown below the diagrams.

The distribution of temperatures at a fixed level is usually far from "normal"¹. Similarly the temperatures at a fixed level and for a particular range of tropopause pressures show a "flat" distribution about their mean. The diurnal variation of temperature as observed by the British-type radio-sonde would be expected, on the average, to account for a spread of the temperatures at the 100-mb. level of 5-6°F. in summer and 3-4°F. in winter (Kay⁸ and unpublished means in the Meteorological Office); at 300 mb. the corresponding figures would be of the order 3° and 1°F. respectively. Even allowing for this effect, the distribution of temperature at a particular level is much flatter than the "normal".

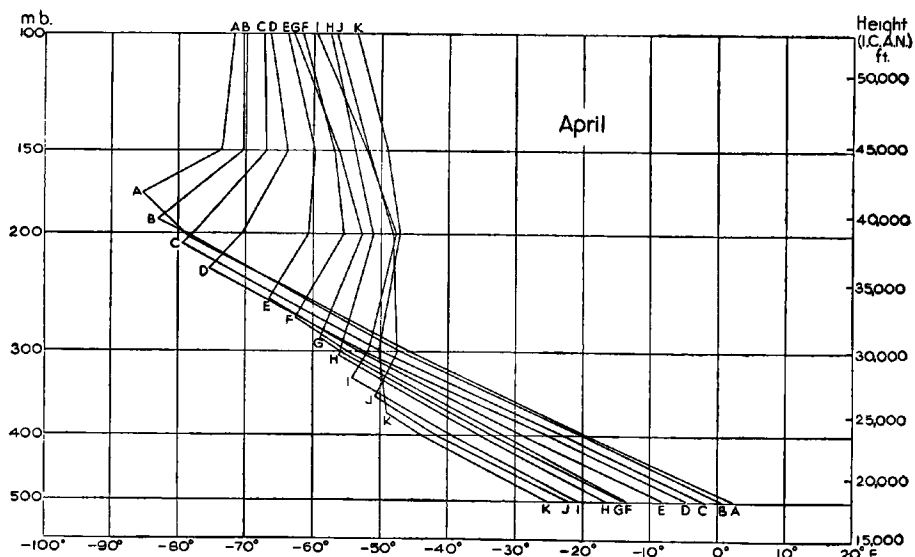
As would be expected, the variation of temperature about the mean at a fixed level is smaller when the observations are classified according to tropopause pressure than when all the observations are considered. Table I gives the standard deviations of temperature about the mean for various pressure levels for all observations at Larkhill in the period 1942-50 or 1942-51 for January, April, July and October, and, for comparison with these, means of the standard deviations of temperature for the various tropopause-pressure ranges are also given. The standard deviations vary considerably from tropopause range to tropopause range, in extreme cases approaching the standard deviation for all observations. This is partly the result of small numbers of observations in some tropopause categories. These mean standard deviations given in Table I are the means for all tropopause-pressure ranges containing 10 or more observations, and it is thought that they give the correct order of the reduction in variability which can be achieved by this classification. Very similar results are obtained by considering the reduction in the range of temperatures at a particular level by classifying according to tropopause pressure; the relative reduction in range is usually greatest at 200 or 150 mb., and the average ratio of the range in a particular tropopause category to the whole range of temperature at the same level is about 0.7.

In "Upper air data 1946-50, Part 1, Larkhill"¹ it is shown that the standard deviation of temperature varies with pressure in a regular manner, having maxima about 500 and 200 mb. (the former considerably smaller than the latter) and a minimum at 300 mb. A maximum of variability of temperature was also noted by Dines² at 6 Km. and a minimum at 10 Km., the variability increasing again at greater heights. Table I shows that classification with respect to tropopause pressure removes a great part of this variation with pressure of standard deviation of temperature, though there is still a slight tendency for a minimum to occur at 300 mb.

Also given in Table I are the standard deviations of temperature at 300 and 200 mb. according as these levels were in the troposphere or stratosphere respectively. The data used to compute these were those for 1948-50 used in deriving Fig. 1 and the entries according to tropopause pressure in Table I. These standard deviations were noted in the general analysis and are given here for interest, though they are irrelevant to the main argument of this paper. The fact that some of the standard deviations for the observations in the stratosphere

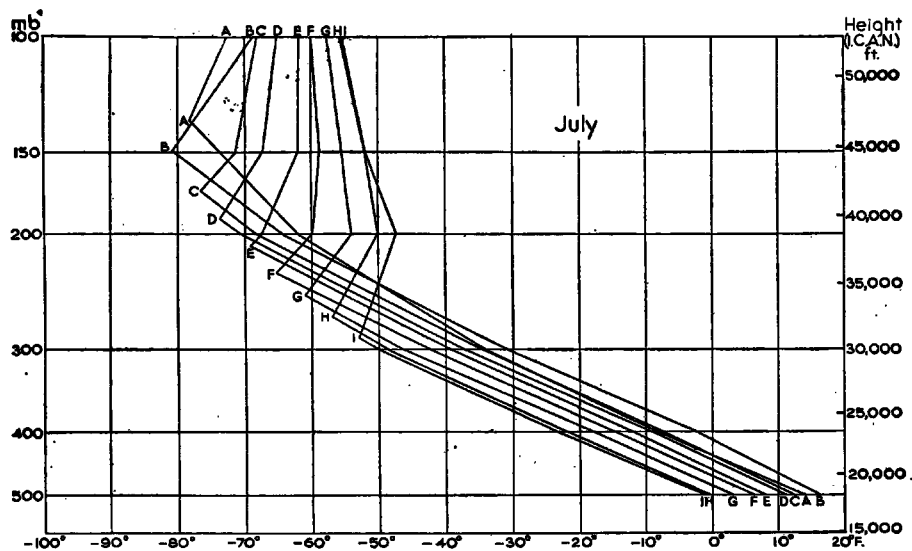


		Tropopause range (mb.)									
		K	J	I	H	G	F	E	D	C	B A
		359-340	339-320	319-300	299-280	279-260	259-240	239-220	219-200	199-180	179-160 159-140
No. of ascents reaching 100 mb.		1	6	12	12	14	20	43	59	49	29 3
No. of ascents reaching 150 mb.		7	8	15	18	25	28	48	69	59	33 3



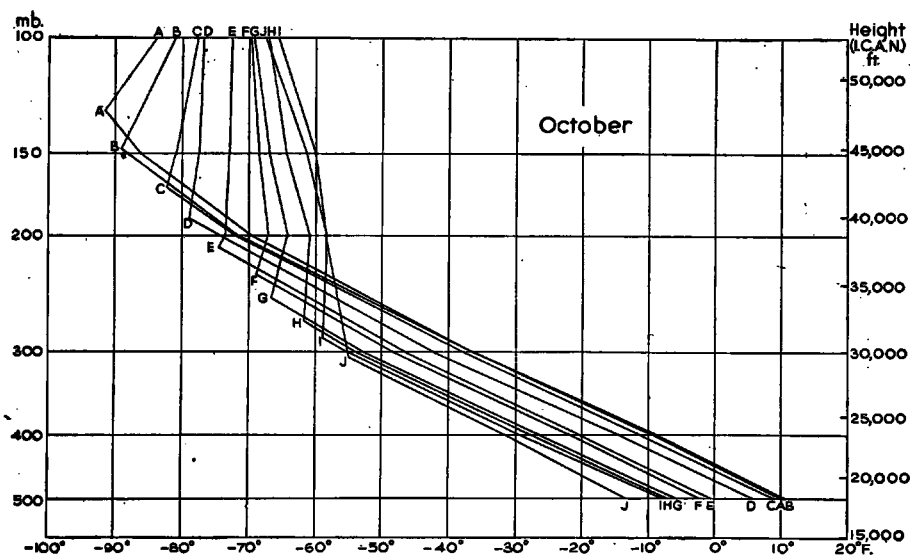
		Tropopause range (mb.)									
		K	J	I	H	G	F	E	D	C	B A
		379-360	359-340	339-320	319-300	299-280	279-260	259-240	239-220	219-200	199-180 179-160
No. of ascents reaching 100 mb.		10	5	16	14	21	21	33	38	54	33 11
No. of ascents reaching 150 mb.		13	6	16	18	22	28	39	45	64	35 12

FIG. 1.—MEAN TEMPERATURE-PRESSURE CURVES, LARKHILL
Observations grouped according to tropopause pressure



Tropopause range (mb.)

	I	H	G	F	E	D	C	B	A
	299- 280	279- 260	259- 240	239- 220	219- 200	199- 180	179- 160	159- 140	139- 120
No. of ascents reaching 100 mb.	12	25	40	70	88	42	16	4	4
No. of ascents reaching 150 mb.	12	29	47	89	95	47	17	4	5



Tropopause range (mb.)

	J	I	H	G	F	E	D	C	B	A
	319- 300	299- 280	279- 260	259- 240	239- 220	219- 200	199- 180	179- 160	159- 140	139- 120
No. of ascents reaching 100 mb.	8	13	25	32	49	59	38	37	25	12
No. of ascents reaching 150 mb.	8	15	28	38	54	68	42	45	27	12

FIG. 1—MEAN TEMPERATURE-PRESSURE CURVES, LARKHILL—continued
Observations grouped according to tropopause pressure

TABLE I—STANDARD DEVIATIONS OF TEMPERATURE ABOUT THE MEAN, LARKHILL

The figures in brackets are the number of observations

			All observations Pressure level (mb.)				
			500	300	200	150	100
January 1942-50	..	..	9.9	6.3	11.7	11.0	9.5
April 1942-51	..	..	8.8	5.8	12.1	8.8	6.8
July 1942-51	..	..	5.9	5.9	9.5	7.9	6.8
October 1942-50	..	..	8.6	7.2	8.8	9.0	7.6

	Observations according to tropopause pressure (20-mb. range)* Pressure level (mb.)					Observations in troposphere Pressure level (mb.)		Observations in stratosphere Pressure level (mb.)	
	500	300	200	150	100	300	200	300	200
1948-50									
January ..	5.1	4.7	5.3	5.4	6.0	5.7(283)	4.4(95)	6.9(39)	11.0(227)
April ..	4.5	4.6	5.1	4.7	5.4	5.3(245)	3.9(47)	6.5(61)	12.9(259)
July ..	4.2	4.2	4.5	4.9	5.1	6.4(345)	4.3(73)	3.2(9)	8.8(281)
October ..	5.6	5.1	4.7	5.0	5.0	8.9(333)	5.1(130)	6.8(17)	8.2(223)

* Mean standard deviations for all ranges containing 10 or more observations.

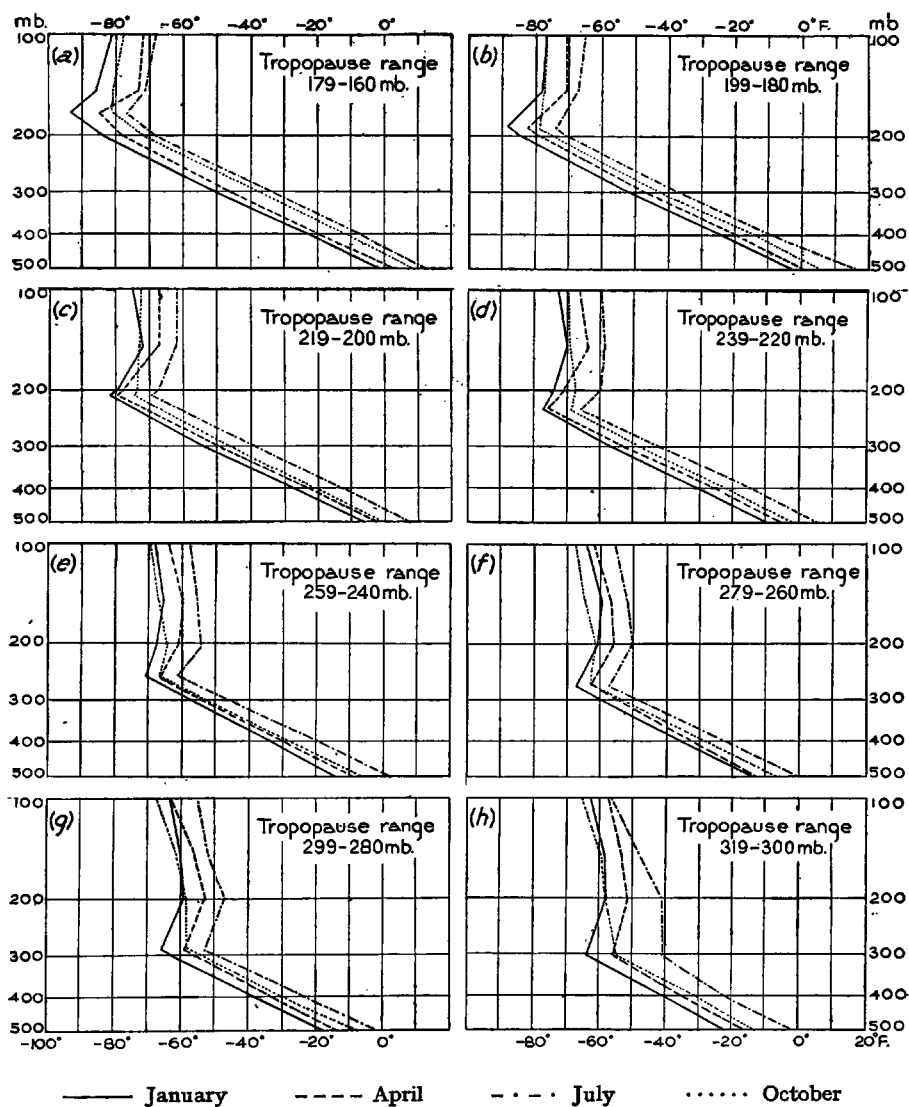
are greater than the corresponding figures for all observations, is presumably because of the much shorter period used in computing the data for the troposphere and stratosphere. It is evident, however, that the standard deviations of temperature at fixed levels in the lower stratosphere are of the same magnitude as the standard deviations at the same levels for all observations, including those occasions when the levels were in the troposphere; this result is, perhaps, surprising.

The grouping of the individual temperature observations about the curves shown in Fig. 1 is not particularly close (see Table I). Though errors in deciding the tropopause level, errors in observation, and the apparent diurnal variation of temperature all help to accentuate this variability, it seems certain that the temperatures are distributed about the means shown in Fig. 1 with standard deviations of the order of 4° or 5°F. In spite of this, however, forecasters and others may find these mean curves useful for comparison with individual ascent curves.

Lapse rates of temperature.—The original purpose of this classification of upper air temperatures was to study the changes in mean lapse rate in the upper troposphere and lower stratosphere between the various seasons. Fig. 2 shows the mean temperature-pressure curves for the four months January, April, July, October for eight ranges of tropopause pressure, and the more important seasonal changes are apparent on these diagrams; the ordinate is again the logarithm of pressure.

Upper troposphere.—There is, perhaps, a slight tendency for greater lapse rates in summer than in winter (e.g. curves (b), (d), (e), (f) and (g) of Fig. 2) but in some of the tropopause-pressure ranges the reverse is noted, especially just under the tropopause. The mean lapse rate† in the layers just below the

† Mean lapse rates were obtained by dividing mean-temperature differences by mean thicknesses of the layers between the appropriate pressure levels. It can be shown that a mean lapse rate so obtained is a close approximation to the mean of all the lapse rates for individual occasions.



		Tropopause range (mb.)							
		319-300	299-280	279-260	259-240	239-220	219-200	199-180	179-160
		<i>number of observations</i>							
January	..	15	18	25	28	48	69	59	33
April	..	18	22	28	39	45	64	36	11
July	..	4	12	29	47	89	95	47	17
October	..	8	15	28	38	55	68	42	45

FIG. 2—MEAN TEMPERATURE-PRESSURE CURVES, LARKHILL: COMPARISON OF SEASONS

Observations grouped according to tropopause pressure

tropopause for all the categories in Fig. 2 are

January	April	July	October
<i>degrees Fahrenheit per thousand feet</i>			
3.4	3.2	3.4	3.5

Presumably the negligible seasonal change in lapse rate is because in the neighbourhood of southern England penetrative convection is not important in modifying the temperature of the upper troposphere, which is largely governed by the horizontal advection of air of varying temperature and by vertical motions associated with the large-scale weather features, depressions and anticyclones.

Lower stratosphere.—The most striking thing about the curves in Fig. 2 is that, in each case, the lapse rate just above the tropopause is greatest in October and, in most cases, least in April or January. The means of the lapse rates just above the tropopause for the eight tropopause-pressure ranges in Fig. 2 are

January	April	July	October
<i>degrees Fahrenheit per thousand feet</i>			
−1.5	−1.7	−1.3	−0.3

Considering only the data in the curves in (c) to (h) of Fig. 2 it is seen that the lapse rates in the layer 200–150 mb., which in each case is not immediately above the tropopause but some distance into the stratosphere, again have a maximum in October, except for curves in (g) of Fig. 2 where the maximum is in July; the minimum is usually in January. The mean lapse rates between 200 and 150 mb. for these six tropopause-pressure ranges are

January	April	July	October
<i>degrees Fahrenheit per thousand feet</i>			
−0.3	−0.3	+0.2	+0.3

The explanation of this maximum lapse rate in the lower stratosphere in October is not clear. It may be argued that temperatures in the upper stratosphere follow the calendar with little lag, being greatest at the summer solstice and least at the winter solstice; temperatures in the upper troposphere, however, might be expected to lag behind the seasons as shown by the calendar, as the greater summer temperatures have to be conveyed to the upper levels by turbulence both small scale (convectonal and this mainly in the tropics) and large scale (depressions, anticyclones). Fig. 2 does not lend much support to this argument, however, even allowing that April is nearer the summer solstice than October. The difference in temperature in the upper troposphere between October and April is small but the difference in temperature in the lower stratosphere between these months is much larger, the October temperatures being similar to those for January.

Without classification according to tropopause pressure, monthly mean temperatures for Larkhill at the 150- and 100-mb. levels (in the stratosphere on the great majority of occasions) show that the April means are slightly greater than the October means but are considerably less than the annual means. This is also true of Lerwick, Tromsø and Aklavik, so that this peculiarity of October stratospheric temperatures appears to be true of much of the higher northern latitudes. For Larkhill the mean temperatures at 150 and 100 mb. for October are less than those for January.

The total amount of ozone in the atmosphere in temperate latitudes of the northern hemisphere is at a maximum in the spring (March–April) and a minimum in October⁸. As ozone absorbs ultra-violet radiation strongly this is a possible explanation of the maximum lapse rate in the lower stratosphere in

October. A good series of temperature observations in the ozone layer (60,000–120,000 ft.) is required to be certain of this explanation. The few observations discussed by Scrase⁹ show greater temperatures at 60,000 ft. and above in the spring than in the autumn but the differences are small; many more observations are required to confirm this feature.

There is also the possibility that the mean lapse rates in the lower stratosphere for October were influenced by the type of weather in the Octobers analysed. In each month the weather was predominantly undisturbed with surface pressure above the average.

Duperier¹⁰ has pointed out that in the mean over southern England there is a slight inversion of temperature in the lower stratosphere on occasions of high surface pressure and a lapse on occasions of low surface pressure. In Fig. 1 it is seen that low tropopauses are associated with comparatively large lapse rates and high tropopauses with inversions in the lower stratosphere. Since surface pressure and tropopause height are related (correlation coefficient $+0.68$ according to Dines²), Duperier's finding is confirmed in the present analysis.

Statistics of tropopause pressure.—A few statistics of tropopause pressure are presented as they emerged in the analysis.

Fig. 3 shows the frequency of occurrence of tropopause within the various 20-mb. pressure ranges. It will be noted that though the mean tropopause pressure varied appreciably from season to season, the mode was more nearly constant. Applying the empirical formula (see e.g. Brooks and Carruthers¹¹)

$$\text{Mode} = \text{Mean} - 3(\text{Mean} - \text{Median}),$$

the following values are obtained for the modes

January	April	July	October
<i>millibars</i>			
195	211	212	206

Monthly mean tropopause pressures are influenced greatly by the predominating type of weather and a seasonal variation is not apparent from the data for Larkhill for the 5 yr. 1946–50¹. For example, the highest and lowest monthly mean tropopause pressures occurred in the following months:—

Monthly mean tropopause pressure		
	Lowest	Highest
1946	February	September
1947	September	February
1948	September	January and April
1949	February	November
1950	March	April

Priestley³ found that in 1944 the lowest mean monthly tropopause height at Larkhill occurred in October and the highest in January. The same lack of consistent seasonal variation in monthly mean tropopause pressure is apparent in the data for Lerwick for the period 1946–50¹²; as at Larkhill the values varied erratically from year to year. It is possible that data for a large number of years may show a tendency for a seasonal variation in tropopause pressure over southern England, though such a seasonal variation will be reversed in individual years.

Priestley³ gave curves showing the mean temperatures at the tropopause above Larkhill appropriate to different tropopause pressures for the winter and summer halves of the year 1944 and for the whole year, and compared these with the mean annual curve for Lerwick. Similar curves are shown in Fig. 4 for each of the months January, April, July and October, the means being computed

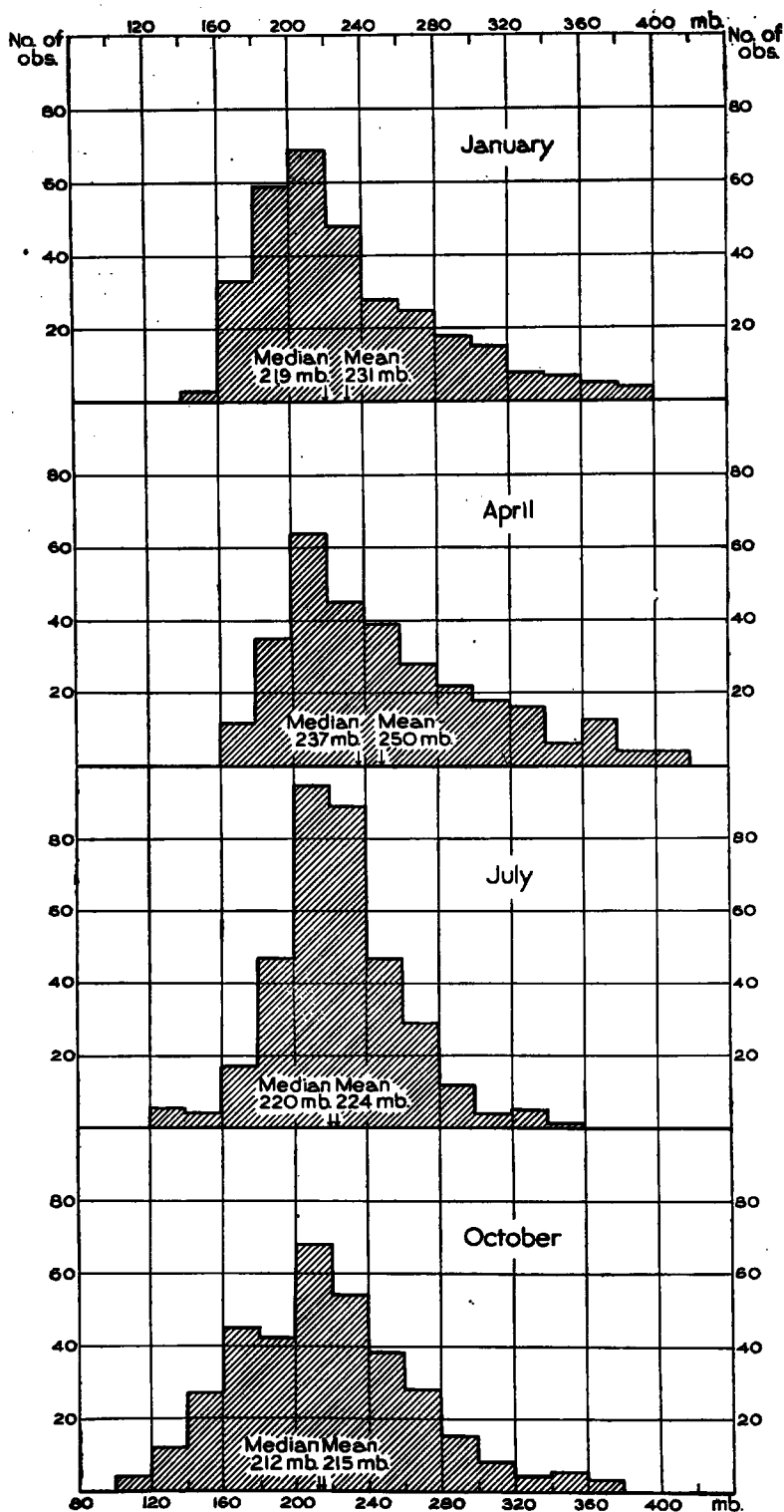


FIG. 3—FREQUENCY OF OCCURRENCE OF TROPOPAUSE PRESSURE WITHIN CERTAIN RANGES

over the 3 yr. 1948-50 ; as in the rest of the analysis, the tropopause pressures were grouped in ranges of 20 mb. and each point in Fig. 4 represents the mean temperature for all tropopauses within that particular pressure range for that month. Priestley used 10-mb. ranges of tropopause pressure. The ordinate in Fig. 4 is height on the standard I.C.A.N. pressure scale, and is adopted as an approximation to true height. Also shown on Fig. 4 is a line whose slope gives the dry adiabatic lapse rate. Sawyer⁴ uses potential temperature at the tropopause as a criterion of continuity. Potential temperature might have been taken as abscissa in Fig. 4 but actual temperature was preferred as demonstrating seasonal changes more easily.

There is an indication on the January and July curves in Fig. 4 that for very low tropopause heights bodily sinking of the air in the layers bordering the tropopause surface may be responsible for much of the variation of tropopause level, as the curves there have slopes similar to the dry adiabatic lapse. The number of observations with very low tropopause height is small, however, and no great reliance can be placed on this argument. For the most part, as Priestley also pointed out for the 1944 data, the tropopause mean temperature-height

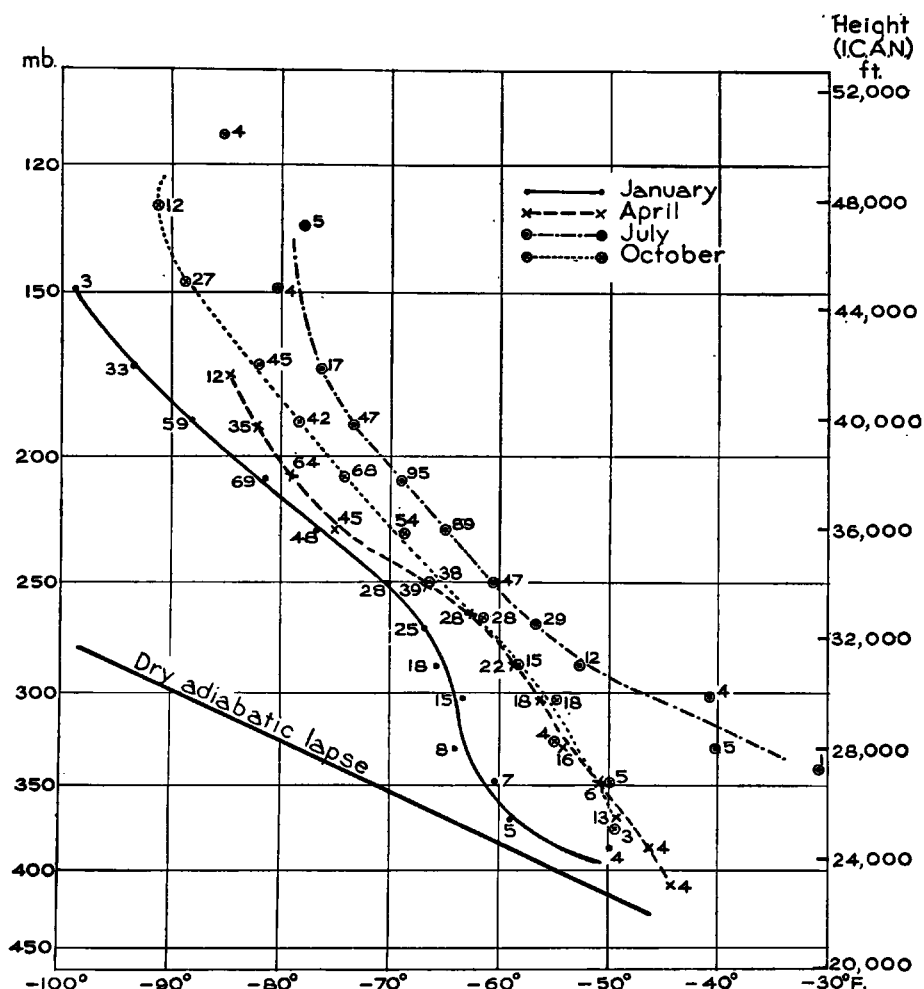


FIG. 4—TROPOPAUSE MEAN TEMPERATURE-HEIGHT RELATION

curves are considerably steeper than the adiabatic lapse rate. Priestley remarked that in his curves the greatest rate of rise of temperature with increasing tropopause pressure was between 270 and 180 mb. This is not shown generally on the curves in Fig. 4, though in January and April the rate of rise does fall off for pressures greater than about 270 mb.

The points in Fig. 4 for July and October tropopauses at heights above 45,000 ft. (pressures less than 150 mb.) appear out of harmony with the general run of the curves through the other points. It may be that they represent conditions at a tropical tropopause, the appropriate curves for which would not be continuous with those shown, which are essentially for a temperate tropopause. There are too few observations to be certain of this.

Tropopause temperatures within the 20-mb. tropopause-pressure ranges adopted for the analysis have considerable scatter; the distribution about the mean is flatter than the "normal". Standard deviations of tropopause temperatures about the mean for the tropopause-pressure ranges 239–200 mb., 219–200 mb., 199–180 mb. were calculated for each of the four months discussed in this analysis; they did not vary greatly from category to category or from month to month. Mean values of these standard deviations were:—

January	April	July	October
<i>degrees Fahrenheit</i>			
5.1	4.9	4.8	4.4

The greatest and least values were 5.5°F. (July, 219–200 mb.) and 3.8°F. (October, 199–180 mb.) respectively. These standard deviations are very similar to those given in Table I for the variation of temperature at a fixed level.

Variation of temperature in the lower stratosphere.—On p. 5 it was shown that temperatures at a level usually in the lower stratosphere have a scatter about their mean value represented by a standard deviation of the order 6–12°F. This standard deviation is reduced to the order 4–6°F. by classifying the temperatures according to tropopause pressure. It is of interest to study some possible causes or associations of the scatter in the temperatures of the lower stratosphere within each tropopause-pressure range. This has been done by evaluating the coefficients of correlation between

- (a) temperature at 150 mb. and height of the 300-mb. level
- (b) temperature at 150 mb. and surface pressure
- (c) temperature at the tropopause and height of the 300-mb. level,

in each restricting the analysis to observations having tropopause pressures within the same 20-mb. range and for the same month. Table II gives the results of this analysis. Only three ranges of tropopause pressures are considered; the numbers of observations in other ranges are smaller.

It will be remembered that Dines² found a high correlation between the pressure at 9 Km. and the height of the tropopause (+0.84) and a significant correlation (–0.47) between the pressure at 9 Km. and the temperature at the tropopause. The height of the 300-mb. level is approximately equivalent to the pressure at 9 Km. Dines found that surface pressure was also related to temperature at the tropopause (correlation coefficient –0.52). These correlations of Dines suggested the pairs of values correlated in Table II.

The figures in Table II (a) may be roughly interpreted as follows: if the temperature at 150 mb., T_{150} , is assumed to depend on the pressure of the tropopause, P_e , and the height of the 300-mb. level, H_{300} , independently, then the correlation coefficients quoted are equivalent to partial correlation coefficients between T_{150} and H_{300} without first classifying with respect to P_e . Similar meanings may be attached to the coefficients in Table II (b) and Table II (c).

TABLE II—CORRELATION COEFFICIENTS, LARKHILL

		Tropopause range (mb.)			Tropopause range (mb.)		
		239-220	219-200	199-180	239-220	219-200	199-180
		(a) Temperature at 150 mb. and height of 300-mb. level			(b) Temperature at 150 mb. and surface pressure		
January	..	-0.38	-0.54	-0.15	-0.28	-0.37	-0.07
April	..	-0.09	-0.16	-0.24	-0.15	-0.06	+0.04
July	..	-0.46	-0.45	-0.50	-0.30	-0.50	-0.26
October	..	-0.43	-0.49	-0.62	-0.35	-0.25	-0.23
		(c) Temperature at tropopause and height of 300-mb. level			Number of observations		
January	..	0.00	-0.28	-0.27	48	69	59
April	..	0.00	+0.09	-0.06	44	64	35
July	..	+0.44	+0.18	+0.11	89	95	47
October	..	+0.26	+0.12	-0.05	50	68	42

Though the numbers of pairs of observations used in computing Table II are from 35 to 95, these pairs cannot all be considered unrelated. For example, on a day in which little change of weather occurs it is to be expected that the four upper air soundings will not differ greatly. Assuming a "persistence length" of about three days¹³ it may be surmized, therefore, that the numbers of independent pairs of observations will be about 30 for each of the entries in Table II, roughly 10 independent observations from each specific month for 3 yr. Thus the levels of significance for a single correlation coefficient in Table II will be approximately¹⁴ :—

0.1%	1%	10%
0.57	0.46	0.31

The coefficients in Table II (a) may be considered under two hypotheses :—

(i) as evidence for or against a general relation, irrespective of season or tropopause pressure, between T_{150} and H_{300} when the data are classified according to tropopause

(ii) as evidence for or against relations between T_{150} and H_{300} which may or may not change with season or with tropopause pressure.

Table II (b) and Table II (c) may be considered similarly.

For Table II (a), hypothesis (i), the fact that the coefficients all have the same sign supports the deduction that there is a general relation between T_{150} and H_{300} . Transforming each coefficient r to its equivalent Z (Fisher's Z transformation¹⁴), taking the mean and re-converting, a value of $r = -0.4$ is found for Table II (a) as a whole, the appropriate number of observations for significance-test purposes being $12(30-3)+3 = 327$. This mean correlation is thus significant at the 0.1 per cent. level. It may also be shown that the distribution of the 12 values of r in Table II (a) is not inconsistent with the hypothesis that there is no real variation between the values for different months or different tropopause pressures. The mean coefficient $r = -0.4$ indicates that about 15 per cent. of the variance of T_{150} is due to its dependence on H_{300} . Table II (b) and Table II (c) do not suggest any general relationship as does Table II (a).

Regarding hypothesis (ii) above, Table II (a) would indicate that the negative correlation between T_{150} and H_{300} is probably significant in July and October but of little importance in January and April. The relationship between surface pressure and T_{150} , Table II (b), if it is real at all, varies in a similar manner with season, but is much less marked. It was shown by Bannan, Frith and Shellard⁶ that the type of circulation, cyclonic, anticyclonic or intermediate,

at the 300-mb. level is of more significance in varying the temperature and humidity of the upper troposphere and lower stratosphere than the type of pressure distribution at the surface, and this rough conclusion is confirmed by the higher coefficients of Table II (a) as compared with Table II (b). The coefficients in Table II (c) are low and may have no significance. The positive correlations of July and October are surprising, being contrary to the trend shown in Table II (a) and Table II (b). They may indicate that tropopause temperatures in summer and autumn are more influenced by tropospheric phenomena than in the other seasons.

The negative correlation between temperatures of the lower stratosphere and the height of the 300-mb. surface shown in some months in Table II (a) has a rough physical explanation as has been pointed out previously⁶. Tropopause height is related to mean tropospheric temperature, or, in other words, to the air-mass type. Subsidence and ascent associated with depressions and anticyclones of temperate latitudes also influence tropopause height (shown for example by the Dines correlation coefficient of $+0.84$ between pressure at 9 Km. and tropopause height). Subsidence and ascent are also roughly related to low and high values respectively of the 300-mb. surface. In a particular tropopause-pressure range one would expect to find temperatures at, say, 150 mb. appropriate to tropical air which had subsided to bring the tropopause within the pressure range considered, and also those appropriate to polar air which had ascended in sympathy with a lifting of the tropopause to bring it within the range considered. Thus the tropical air at the 150-mb. level, with increased temperature following subsidence, would be associated with a low value of the height of the 300-mb. level, and similarly polar air would be cold following ascent and associated with high values of the height of the 300-mb. level. This argument assumes that the subsidence and ascent necessary to bring our tropical and polar air into the same tropopause-pressure category cause a warming and cooling respectively, which are more than enough to offset the normal temperature differences in the lower stratosphere; for the same state of dynamical development, e.g. for the same surface pressure for lack of a better index, the tropical air will have a higher tropopause and lower temperature in the lower stratosphere than the polar air. This assumption is reasonable for, as shown in Fig. 4, the average relation between tropopause pressure and tropopause temperature, in the great majority of cases, is such that adiabatic descent or ascent will make temperatures in the lower stratosphere higher or lower respectively than the average for the appropriate tropopause pressure.

Possible uses of the classification.—It is clear that if statistics of any characteristic are to be separated for troposphere and stratosphere then a classification with respect to tropopause height (or pressure) is necessary; temperature lapse rate is an example. It may be possible to assess the utility of such a classification for other purposes from the discussion in previous sections, though the analysis described is only for a short period.

As stated in the Introduction mean temperatures in the upper atmosphere in the neighbourhood of the tropopause are much influenced by the type of weather predominating in the period considered; for some purposes, of course, the reasons for the large variations from period to period, e.g. from a month of one year to the same month of the next year, are unimportant. If, however, it is desired to sift the observations so as to remove part, at least, of what may be called the dynamic influences, then the classification according to tropopause height (or pressure) undoubtedly does this.

Comparison of seasons.—Fig. 2 allows a comparison of mean temperatures in the various seasons. It may be argued that, since tropopause pressure may have a seasonal variation, the curves in Fig. 2 are not strictly comparable, and that,

perhaps, for example, the curve for the January tropopause-pressure range 219–200 mb. should be compared with the July curve for a different tropopause range. It was seen on p. 11, however, that no definite seasonal trend in tropopause pressure is apparent in the data of the last few years.

Table III gives the mean temperatures for Larkhill at the 150-mb. level for four different months for four tropopause-pressure ranges and also for all observations for the same period 1948–50. The mean temperatures for a period of 9 or 10 yr. are given in the last column. It is seen that, on the whole, the seasonal differences for the tropopause-classified data are closer to those for the long period than those for all observations for the short period 1948–50, especially for those tropopause categories further removed from the 150-mb. level, i.e. for high tropopause pressures. Summing up, it can be said that there is some evidence that seasonal temperature differences in the lower stratosphere are better shown by data classified according to tropopause pressure when data for only a few years are available. There is little doubt, however, that statistics from all observations, regardless of tropopause pressure, should give the best indication of seasonal changes when data for a long period (10 yr. or more) are available for analysis.

TABLE III—MEAN TEMPERATURE AT 150 MB. OVER LARKHILL

		1948-50				All observa- tions	1942-50
		Tropopause range (mb.)					All observa- tions
		259-240	239-220	219-200	199-180		
		<i>degrees Fahrenheit</i>					
January	..	-65.6	-69.9	-72.1	-78.2	-70.3	-69.3
April	..	-59.8	-63.9	-67.2	-70.5	-61.3	-64.0*
July	..	-55.3	-58.8	-62.0	-67.3	-60.2	-59.7*
October	..	-66.9	-68.6	-72.9	-77.4	-72.8	-71.4

* 1942–51.

Year-to-year variations.—As remarked previously (see p. 2) the mean temperature for a particular month at a level usually in the lower stratosphere may vary widely from year to year, and most of the variation may be explained by the character of the weather as reflected in the height (pressure) of the tropopause. To study year-to-year temperature variations in the lower stratosphere, e.g. to try to relate ozone content with air temperature, it is desirable to eliminate as much as possible of the dynamic effect on temperatures, and the classification with respect to tropopause pressure may be used for this purpose.

Table IV is an illustration of how mean temperatures at a fixed level may be compared from year to year; in it are given the mean temperatures at various levels for three different ranges of tropopause pressure for each of the months January, April, July and October for each year 1948, 1949, 1950 and also the mean temperatures computed from all observations regardless of tropopause pressure. The number of observations used to form these means was often quite small and unevenly distributed among the four observing hours of the day; the mean temperatures were accordingly corrected for diurnal variation, i.e. corrected to the mean which would apply if the numbers of day and night observations were the same. To do this estimates of the apparent diurnal variation at different levels were obtained from mean temperatures for Larkhill for several years for the various hours of observation, after the manner of Kay⁸. The maximum correction necessary ranged from 0.4°F. at 400 mb. to 1.2°F. at 100 mb. Also given in Table IV, for comparison purposes, are the monthly mean heights of the 300-mb. level for the appropriate tropopause pressures and also for all observations, and the mean monthly tropopause pressures.

TABLE IV—MEAN TEMPERATURE CORRECTED FOR DIURNAL VARIATION, MEAN HEIGHT OF THE 300-MB. LEVEL AND MEAN TROPOPAUSE PRESSURE, LARKHILL

The figures in brackets are the number of observations on which the mean is based

Tropo- pause range	mb.	Mean temperature										Mean height of 300-mb. level				Mean tropopause pressure									
		400 mb.					300 mb.					150 mb.					100 mb.				feet				
		1948	1949	1950	1948	1949	1950	1948	1949	1950	1948	1949	1950	1948	1949	1950	1948	1949	1950	1948	1949	1950	1948	1949	1950
January ..	199-180	-28.0	-21.9	-25.2	-52.2	-49.6	-53.2	-75.8	-80.4	-77.8	-72.9	-79.3	-76.3	29,890	30,470	30,190	29,890	30,470	30,190	29,890	30,470	30,190	29,890	30,470	30,190
	219-200	-24.0	-24.8	-30.1	-51.0	-52.8	-56.4	-69.4	-75.8	-71.5	-69.6	-77.7	-74.3	29,730	30,400	29,940	29,730	30,400	29,940	29,730	30,400	29,940	29,730	30,400	29,940
	239-220	-28.8	-28.7	-32.3	-54.3	-55.9	-58.4	-67.4	-71.3	-70.3	-69.9	-74.4	-71.6	29,470	30,040	29,780	29,470	30,040	29,780	29,470	30,040	29,780	29,470	30,040	29,780
	ALL	-35.7 (123)	-26.9 (124)	-30.4 (124)	-57.9 (117)	-52.7 (120)	-56.0 (122)	-62.9 (98)	-74.9 (109)	-73.0 (114)	-68.4 (65)	-76.1 (98)	-71.3 (101)	29,060 (117)	30,090 (120)	29,890 (122)	29,060 (117)	30,090 (120)	29,890 (122)	29,060 (117)	30,090 (120)	29,890 (122)	29,060 (117)	30,090 (120)	29,890 (122)
	April ..	199-180	-22.3	-19.7	-22.7	-48.5	-46.5	-49.6	-68.7	-71.7	-68.3	-70.0	-71.4	-67.0	30,430	30,610	30,130	30,430	30,610	30,130	30,430	30,610	30,130	30,430	30,610	30,130
219-200		-22.8	-21.6	-24.5	-50.0	-49.0	-52.0	-65.8	-70.5	-68.1	-65.5	-70.7	-66.1	30,440	30,370	30,000	30,440	30,370	30,000	30,440	30,370	30,000	30,440	30,370	30,000
239-220		-24.3	-23.5	-28.1	-52.1	-51.5	-55.3	-60.2	-69.0	-62.4	-63.7	-70.4	-66.0	30,110	30,160	30,080	30,110	30,160	30,080	30,110	30,160	30,080	30,110	30,160	30,080
ALL		-29.7 (119)	-24.3 (120)	-32.3 (120)	-51.2 (116)	-49.5 (119)	-53.2 (110)	-58.3 (98)	-67.9 (111)	-57.6 (98)	-61.6 (80)	-68.9 (106)	-62.9 (79)	29,730 (116)	30,170 (119)	29,480 (110)	29,730 (116)	30,170 (119)	29,480 (110)	29,730 (116)	30,170 (119)	29,480 (110)	29,730 (116)	30,170 (119)	29,480 (110)
July ..		199-180	-6.8	-9.9	-10.8	-34.9	-37.4	-36.6	-69.5	-67.6	-64.1	-65.3	-66.7	-60.4	31,210	31,240	30,960	31,210	31,240	30,960	31,210	31,240	30,960	31,210	31,240	30,960
	219-200	-13.0	-11.5	-11.4	-39.9	-39.1	-38.3	-62.8	-64.3	-59.0	-61.9	-64.7	-58.3	30,870	31,100	30,890	30,870	31,100	30,890	30,870	31,100	30,890	30,870	31,100	30,890
	239-220	-16.1	-13.3	-14.4	-43.3	-40.0	-42.7	-59.2	-60.4	-57.3	-59.4	-63.3	-57.4	30,720	31,030	30,690	30,720	31,030	30,690	30,720	31,030	30,690	30,720	31,030	30,690
	ALL	-14.9 (124)	-13.3 (124)	-14.7 (124)	-41.5 (123)	-40.7 (122)	-41.6 (122)	-61.6 (119)	-62.2 (120)	-56.8 (116)	-60.8 (94)	-63.8 (116)	-57.3 (93)	30,740 (123)	31,000 (123)	30,690 (122)	30,740 (123)	31,000 (123)	30,690 (122)	30,740 (123)	31,000 (123)	30,690 (122)	30,740 (123)	31,000 (123)	30,690 (122)
	October ..	199-180	-13.3	-14.9	-17.6	-40.4	-44.5	-43.9	-78.9	-75.9	-77.9	-78.2	-77.1	-76.4	30,890	30,650	30,790	30,890	30,650	30,790	30,890	30,650	30,790	30,890	30,650	30,790
219-200		-20.6	-19.1	-21.5	-46.3	-45.7	-47.1	-69.9	-75.4	-71.7	-70.0	-73.7	-72.2	30,340	30,530	30,390	30,340	30,530	30,390	30,340	30,530	30,390	30,340	30,530	30,390
239-220		-20.9	-23.2	-21.6	-47.4	-49.4	-47.9	-68.5	-68.7	-66.4	-69.7	-70.2	-70.7	30,270	30,070	30,060	30,270	30,070	30,060	30,270	30,070	30,060	30,270	30,070	30,060
ALL		-19.0 (124)	-19.6 (124)	-21.1 (124)	-44.6 (124)	-45.7 (119)	-47.1 (122)	-72.5 (120)	-73.7 (114)	-72.1 (120)	-73.2 (99)	-73.8 (106)	-72.5 (105)	30,460 (124)	30,380 (119)	30,390 (122)	30,460 (124)	30,380 (119)	30,390 (122)	30,460 (124)	30,380 (119)	30,390 (122)	30,460 (124)	30,380 (119)	30,390 (122)

It will be noted that in the lower stratosphere and to a less extent also in the upper troposphere, the year-to-year variations are in most cases smaller in the classified mean temperatures than in the means from all observations. Large variations in mean temperatures (all observations) are related to large variations in mean tropopause pressure, as would be expected from the Dines correlations.

As was noted on p. 15 there is a relation in some months between temperatures of the lower stratosphere in a particular tropopause-pressure category and the corresponding height of the 300-mb. pressure level. From Table IV it is seen that this relation is also apparent in the means, though again not in a marked degree. Table V gives correlation coefficients between mean temperatures at 150 mb. and corresponding mean heights of the 300-mb. level. Nine of these are not particularly significant (the coefficients are calculated from 3 pairs of values only); with two random samples, each distributed normally, the chance of getting such correlations would be greater than 1 in 10. For the other 3, the chances would be between 1 in 50 and 1 in 20.

TABLE V—CORRELATION COEFFICIENTS BETWEEN MONTHLY MEAN TEMPERATURES AT 150 MB. AND CORRESPONDING MEAN HEIGHTS OF THE 300-MB. LEVEL, LARKHILL

		Tropopause range (mb.)		
		239-220	219-200	199-180
January	..	-0.98	-0.96	-0.99
April	..	-0.72	-0.74	-0.98
July	..	-0.82	-0.63	-0.74
October	..	+0.61	-0.99	-0.99

It is concluded that if statistics were available for, say, 10 yr. it would be possible to compare monthly mean temperatures from year to year within the same tropopause-pressure ranges, after allowing for the small influence of the height of the 300-mb. level by means of a regression equation computed from the long period of observations. There may be other dynamic heating or cooling effects for which it might be possible to allow in this manner, but it would appear (see p. 15) that the height of the 300-mb. level is the most important. The Dines correlations do not point to any other significant independent parameter.

Temperatures in the upper troposphere might be treated similarly, though within tropopause-pressure categories the relation between the weather type (as reflected, for example, by the height of the 300-mb. level) and the temperature is probably not so great as in the lower stratosphere.

Conclusions.—From this short analysis of the Larkhill upper air observations for four months in each of the years 1948, 1949 and 1950 it is concluded that :—

(1) For a statistical analysis of any upper air characteristic, classification with respect to tropopause height (pressure) is essential to separate tropospheric and stratospheric individualities.

(2) The lapse rate in the lower stratosphere is notably greater in autumn than in other seasons. This may be linked with the annual minimum of ozone in that season; available evidence indicates that autumn temperatures in the ozone layer are perhaps lower than corresponding spring temperatures, but data are insufficient to demonstrate this conclusively.

(3) Lapse rate in the upper troposphere has little, if any, seasonal variation.

(4) To compare monthly mean temperatures in the lower stratosphere from year to year, except for purely climatological purposes, it is necessary

to eliminate some, at least, of the dynamical effects associated with the general character of the weather of particular months. Classification with respect to tropopause height (pressure) goes some way towards this, and with a longer series of observations than treated here it should be possible to allow for the probably small residual effect on these means arising from vertical motions associated with the predominating weather. Mean monthly temperatures so obtained would then be suitable for correlation with such things as ozone amounts, solar or cosmic influences, though a hemisphere-wide distribution of such temperature observations would probably be essential for such analyses.

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