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HUMIDITY OF THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE OVER SOUTHERN ENGLAND

BY

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HUMIDITY OF THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE OVER SOUTHERN ENGLAND

SUMMARY

Observations of air temperature and frost-point temperature* made on 130 high-altitude flights, usually to heights of 38,500 ft. (international standard atmosphere) or above, are presented. The observations are analysed with respect to their height above or below the tropopause thus emphasizing any differences between troposphere and stratosphere. Correlation coefficients between frost points and other parameters at various levels are evaluated. Frost points at fixed levels are analysed to show the variation between different synoptic (circulation) types, between different seasons and between different air masses. Changes in frost point in passing through frontal surfaces are discussed and attention is drawn to some observations made in the neighbourhood of jet streams. The observations in the lower stratosphere are restricted to occasions of near or below average tropopause height because of the height limitation of the aircraft.

§ 1—INTRODUCTION

Temperature and humidity in the upper atmosphere were observed on 130 high-altitude flights made over England between 1943 and 1950. From August 1943 to August 1946 the ascents were made by aircraft of the High Altitude Flight based at Boscombe Down and from September 1946 to the end of June 1950 by aircraft of the Meteorological Research Flight based at the Royal Aircraft Establishment, South Farnborough; a height of at least 38,500 ft. was usually attained.

Before these observations were made there was no reliable information about the amount of water vapour in the upper troposphere and lower stratosphere; it was generally supposed that the air was nearly saturated in the upper troposphere, but widely divergent views were held as to the humidity in the stratosphere. The observations described and discussed here have gone some way towards dispelling this ignorance. Much remains to be discovered, but the broad character of the water-vapour distribution in the atmosphere up to 40,000 ft. over southern England is now known.

The object of this Memoir is to present the results of these first high-altitude humidity observations (a few of the early observations have already been discussed[1, 2]†) and to consider them in terms of their mean values and their relation to various other parameters. It has not yet been possible to detect any very definite relation between the synoptic weather situation and the pattern of water-vapour distribution in the vertical except in a few broad respects, though this may be because the number of observations is small.

§ 2—DATA AVAILABLE

The aircraft ascents dealt with include those made from Boscombe Down in 1943–46 and more recent ones from South Farnborough, the majority of which were made during 1949

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* The frost-point temperature is the temperature of an ice surface whose vapour pressure is equal to the pressure of the water vapour actually present in the air.

† The index numbers refer to the bibliography on p. 36.

and 1950. Measurements were made of temperature and frost point, usually at 1,000-ft. intervals, from low level to the aircraft ceiling. Temperatures were measured using Meteorological Office flat-plate resistance thermometers with balanced-bridge indicators. Frost-point measurements were made on the early (Fortress) ascents using the Meteorological Office Mark I aircraft frost-point hygrometer, but on the later (Mosquito) ascents the Meteorological Office pressurized Mark IIa aircraft frost-point hygrometer was generally used. The principles of the above instruments are described in the "Meteorological air observer's handbook"[3]. The frost-point hygrometer is also described by Dobson, Brewer and Cwilong[1].

The ceiling of the Mosquito aircraft employed for these flights varies between 38,000 and 41,000 ft., whilst that of the Fortress used for the ascents of 1943–45 varied from 33,000 to 37,000 ft.; more than three-quarters of the ascents reached or exceeded the 200-mb. level (38,500 ft., international standard atmosphere scale).

Until June 1948 ascents were usually made only when there was a good prospect of penetrating well into the stratosphere, and ascents were generally made over the Midlands or southern England in the area of lowest forecast tropopause. After that date ascents were made regardless of the forecast tropopause height, mainly over South Farnborough, but more recently over a radio-sonde station, either Larkhill or Downham Market, near the time of a routine sounding in order to facilitate the fitting of the observations into the general synoptic picture. Thus there is some bias in the observations towards low tropopause. The mean height of the tropopause over southern England (from radio-sonde ascents) is about 36,000 ft., whilst that given by the aircraft ascents is about 35,000 ft.

It is estimated that the temperature measurements, taking speed correction errors into account, are accurate to within $\pm$ 0·5°F. Lag was rendered unimportant by taking readings in level flight only. The accuracy of the frost-point measurements varies according to the frost point, being greatest at the higher frost points. At values below − 100°F. readings are probably accurate to within $\pm$ 3°F., the error decreasing to less than $\pm$ 2°F. between − 100° and − 80°F. and to less than $\pm$ 1°F. between − 40° and 0°F.

§ 3—TREATMENT OF DATA

In the sections which follow the variation of frost point and of frost-point lapse-rate across the tropopause are examined, and the relationships which may exist between the height of the tropopause and the humidity of the air at various levels studied. Unfortunately the usual definitions of the tropopause (as given, for example, in the introduction to the *Daily Aerological Record*) are not precise. For the purposes of this Memoir the following definitions were adopted:—

Type I. There is an abrupt change of lapse rate to inversion, and for no subsequent 3,280-ft. (1-Km.) layer does the lapse rate exceed 1·1°F./1,000 ft. (2°C./Km.). The tropopause height, H_c, is the height of the abrupt change.

Type II. There is an abrupt change to a lapse rate of less than 1·1°F./1,000 ft., or to an isothermal condition, and for no subsequent 3,280-ft. layer does the lapse rate exceed 1·1°F./1,000 ft.—H_c is the height of the abrupt change.

Type III. Where there is no abrupt change of lapse rate, H_c is taken as the height of the level at which the lapse rate first becomes less than 1·1°F./1,000 ft., provided that it does not exceed this value for any subsequent 3,280-ft. layer.

In addition the following rules were adopted :—

(i) An abrupt change is defined as one in which the mean lapse rates measured over 1,000-ft. layers on either side of the change differ by at least 2°F./1,000 ft.

(ii) Where there is a double or multiple tropopause the lowest of the levels satisfying the above definitions is taken as the main tropopause.

Using these admittedly rather inelegant definitions Table I has been constructed. This table shows, for every ascent, the air temperature and the frost-point temperature at fixed pressure levels. The ascents are grouped according to tropopause height, each group covering a range of 2,000 ft. on the international standard atmosphere (I.C.A.N.) scale (see "Meteorological air observer's handbook"[3]), and the corresponding pressures are shown.

Normally observations were made every 1,000 ft. so that the height of the tropopause can be determined, approximately, to the nearest 500 ft. In Table I, however, the pressure at the tropopause is that of the observation deemed nearest to the tropopause and is given to the nearest millibar. Whenever the tropopause height coincided with one of the limits of a height group the group was determined by reference to neighbouring radio-sonde observations.

The observations in each group are arranged according to season. Since the available evidence indicates that mean tropopause pressure over southern England is a maximum in mid February and a minimum in mid August (Dines[4]) the seasons are defined as follows :—

Winter	January, February, March
Spring	April, May, June
Summer	July, August, September
Autumn	October, November, December.

As stated above, observations were usually made every 1,000 ft. ; the temperatures and frost points for the fixed levels, 500, 450, 400, 350, 325, 300, 275, 250, 225, 200, 187 mb., were linearly interpolated, where necessary, from these observations and form the main body of Table I. Observations could not always be made at all levels. In a few cases the observed frost-point temperatures were higher than the air temperatures ; in the majority of these, however, cirrus cloud was present at the same level and small ice particles may have lodged in the air intake of the hygrometer leading to erroneous readings. In these cases, therefore, saturation with respect to ice is assumed and the frost-point and air temperatures are given the same value. On two occasions however (September 7, 1943 at 325 mb. and July 18, 1949 at 275 mb.) supersaturation was observed in the absence of cirrus cloud and these observations are given in the table without alteration. Air temperature and frost-point temperature at the tropopause are also given in Table I.

The ascents are classified according to the air mass ; this classification is of course somewhat arbitrary. The usual abbreviations (P = polar, A = arctic, T = tropical, Pc = polar continental, Pm = polar maritime) are used. When the ascent penetrated a frontal surface the upper air-mass type is noted first—thus Pm/P—and an asterisk in the table denotes the lowest observation in the upper of the two air masses, when this observation is above the 500-mb. level.

The observations are classified roughly according to the type of circulation ; anticyclonic, cyclonic and intermediate circulation types are denoted by *a*, *c* and *i* respectively. It sometimes happened that though the circulation was, say, anticyclonic near the earth's surface, it was cyclonic at the 300-mb. level. When the lower and upper circulations differed this is noted, the first entry in the column referring to the upper circulation. As in the case of air-mass classification the circulation type is sometimes difficult to decide, and is then more a matter of opinion than of definite fact.

The tropopause is an important boundary in the atmosphere. It is in fact the boundary between what appear to be two different régimes—the troposphere characterized by the effects of convection and the stratosphere which lies beyond the limit of thermal convection from the surface of the earth ; the possibility that it is also a notable boundary in the humidity distribution

TABLE I—AIR TEMPERATURE AND FROST-POINT TEMPERATURE

Where there is a double tropopause the pressure and type for the upper discontinuity is given in brackets.
When the ascent penetrated a frontal surface separating two different air masses the upper air mass is noted first and an asterisk in
Circulation types: *a* = anticyclonic, *c* = cyclonic, *i* = intermediate. When the circulation type at 300 mb. differs from that
Observations within 600 miles of the axis of a jet stream are marked †.

Winter = January-March Spring = April-June

Tropopause Pressure	Tropopause Type	Date	Time	Place	500 mb. Temp-erature	500 mb. Frost point	450 mb. Temp-erature	450 mb. Frost point	400 mb. Temp-erature	400 mb. Frost point	350 mb. Temp-erature	350 mb. Frost point
mb.			G.M.T.		degrees Fahrenheit							
				TROPOPAUSE RANGE 410–376 mb.								
		Winter										
410 (376)	I (I)	8.2.50	1200	South England	− 31	..	− 44	− 51	− 51	− 81	− 51	− 92
		Spring										
393	II	2.5.50	1500	Larkhill	− 17	− 41	− 28	− 49	− 42	− 50	− 46	− 82
400	II	5.5.44	1100	South England	− 21	− 30	− 33	− 42	− 47	− 55	− 47	− 89
				TROPOPAUSE RANGE 376–344 mb.								
		Winter										
376	I	19.1.48	1500	Southampton	− 36	..	− 47	..	− 61	..	− 64	..
		Spring										
360	I	4.4.48	1500	South England	− 25	..	..	..	..	..	− 45	− 94
		Autumn										
344 (310)	II (I)	8.12.47	1200	Farnborough	− 24	..	..	..	− 47	− 65	− 53	− 85
				TROPOPAUSE RANGE 344–315 mb.								
		Winter										
344 (274)	II (II)	17.2.48	1600	Southampton	− 19	..	..	..	..	..	..	..
		Autumn										
329	I	19.10.48	1030	Farnborough	− 20	..	− 31	− 40	− 42	− 47	− 53*	− 59*
				TROPOPAUSE RANGE 315–287 mb.								
		Winter										
315 (270)	II (I)	22.1.48	1200	Cambridge	− 17	..	..	..	..	..	..	..
300	I	7.2.45†	1400	South England	− 10	− 64	− 22	− 65	− 32	− 69	− 46	− 72
		Spring										
301	I	25.4.50	1500	Larkhill	− 23	− 42	− 26	− 50	− 33	− 56	− 43	− 70
		Summer										
300	I	8.6.45†	—	South England	− 11	− 26	− 21	− 39	− 33	− 53	− 43	− 59
301	II	5.7.49	0930	Farnborough	− 3	− 37	− 14	− 46	− 26	− 47	− 38	− 61
301	I	22.8.43	1600	South England	− 2	..	− 12	− 30	− 23	− 43	− 35	− 55
		Autumn										
300	I	23.10.45†	1300	South England	− 13	− 22	− 21	− 46	− 29	− 71	− 39	− 73
300	I	22.12.43	1500	South England	− 14	− 44	− 22	− 48	− 32	− 53	− 45	− 50
				TROPOPAUSE RANGE 287–262 mb.								
		Winter										
281	I	8.1.48	1430	Southampton	− 31	..	..	..	− 40	− 75	− 47	− 70
274	I	20.1.48	1130	Southampton	− 31	..	− 41	− 58	− 51	− 69	− 60	− 67
277 (250)	II (I)	6.2.48†	1430	Farnborough	− 16	..	..	..	− 39	− 57	− 51	− 78
274 (238)	I (I)	7.2.50	1200	Farnborough	− 13	− 31	− 24	− 30	− 36	− 53	− 47	− 73
274	I	11.2.49	1200	Farnborough	− 16	..	− 26	− 32	− 38	− 38	− 50	− 55
287	II	20.2.48	1130	Farnborough	− 27	..	..	..	..	..	..	..
287 (220)	II (I)	27.2.48	1100	Southampton	− 12	..	..	..	..	..	..	..
		Spring										
274	I	25.4.45	—	South England	− 7	− 20	− 18	− 30	− 31	− 43	− 45	− 49
275	II	3.5.44†	1600	Humber Area	− 10	− 60	− 19	− 63	− 29	− 65	− 41*	− 55*
287 (250)	II (I)	5.5.49	1000	Farnborough	− 3	..	− 14	− 29	− 26	− 40	− 40	− 54
274 (238)	I (I)	17.5.50	1500	Downham Market	− 8	− 52	− 19	− 50	− 31	− 47	− 43	− 65
262	I	18.5.49	1100	Farnborough	− 8	− 40	− 18	− 51	− 26	− 47	− 39	− 50
274	II	18.5.50	1500	Downham Market	− 12	− 30	− 19	− 43	− 31	− 58	− 44	− 67
262	I	18.5.50	1500	Larkhill	− 9	− 34	− 17	− 54	− 29	− 58	− 42	− 63
287	I	23.5.50	1500	Larkhill	− 9	− 9	− 19	− 19	− 31	− 32	− 45	− 49
275	I	30.5.45	1300	South England	− 11	− 13	− 21	− 26	− 32	− 39	− 47	− 52
287 (240)	II (I)	29.6.48	1500	Farnborough	− 4	− 28	− 18	− 27	− 26	− 36	− 36*	− 46*
		Summer										
262	I	18.7.49	1000	Farnborough	− 3	− 14	− 12	− 30	− 24	− 40	− 39	− 45
280	I	19.7.45	1500	South England	+ 3	− 55	− 7	− 49	− 19	− 44	− 33	− 54

AT FIXED PRESSURE LEVELS ON 130 ASCENTS

the table denotes the lowest observation in the upper of the two air masses when this observation is above the 500-mb. level. near the surface it is noted before the surface type.

Summer = July–September Autumn = October–December

325 mb. Temperature	325 mb. Frost point	300 mb. Temperature	300 mb. Frost point	275 mb. Temperature	275 mb. Frost point	250 mb. Temperature	250 mb. Frost point	225 mb. Temperature	225 mb. Frost point	200 mb. Temperature	200 mb. Frost point	187 mb. Temperature	187 mb. Frost point	At tropopause Temperature	At tropopause Frost point	Air mass	Circulation type
degrees Fahrenheit																	
TROPOPAUSE RANGE 410–376 mb.																	
– 47	– 91	– 47	– 98	– 45	–105	– 40	–110	– 44	–110	..	..	..	..	– 52	– 74	P	*i*
– 46	– 89	– 47	– 97	– 46	– 99	– 48	–103	– 49	–109	– 54	–111	..	..	– 44	– 48	P	*c/i*
– 51	– 91	– 51	– 96	..	..	..	..	..	..	..	..	..	..	– 47	– 55	P	*c*
TROPOPAUSE RANGE 376–344 mb.																	
– 61	..	– 61	– 89	– 59	– 94	– 57	– 93	– 56	– 89	– 54	– 74	..	..	– 66	..	..	..
– 45	– 99	– 44	–104	– 47	–109	– 48	–110	..	..	..	..	..	..	– 46	– 94	P	*c*
– 55	– 90	– 55	– 95	– 53	– 96	– 53	–100	..	..	..	..	..	..	– 55	– 84	Pm	*c*
TROPOPAUSE RANGE 344–315 mb.																	
– 57	– 79	– 59	– 87	– 61	– 92	– 60	– 97	– 58	–108	..	..	..	..	– 56	– 60	P/A	*c/a*
– 58	– 63	– 54	– 84	– 50	–100	– 50	–104	– 50	–110	– 49	–114	..	..	– 58	– 62	Pm/P	*i*
TROPOPAUSE RANGE 315–287 mb.																	
– 54	– 85	– 56	– 91	– 58	– 94	– 52	– 99	– 51	–102	..	..	..	..	– 57	– 88	Pm	*i/c*
– 52	– 75	– 59	– 80	– 55	– 91	– 55	–101	– 57	–106	..	..	..	..	– 59	– 80	Pm/P	*i*
– 46	– 67	– 51	– 81	– 50	– 87	– 48	–106	– 49	–108	..	..	..	..	– 51	– 81	P	*i*
– 48	– 69	– 53	– 81	– 50	– 92	– 47	–101	– 50	–110	..	..	..	..	– 53	– 81	P	*i*
– 40	– 67	– 44	– 81	– 45	– 84	– 46	– 86	– 48	– 97	– 49	–101	..	..	– 44	– 81	T/P	*c/i*
– 42	– 64	– 49	– 72	– 47	– 84	– 45	– 82	..	..	..	..	..	..	– 49	– 72	P	*c*
– 48	– 78	– 57	– 85	– 57	– 86	– 51	– 95	– 55	–102	– 51	–109	..	..	– 57	– 87	P	*i/c*
– 50	– 62	– 60	– 71	– 55	– 92	– 51	–105	– 46	–115	..	..	..	..	– 60	– 71	P	*i*; *c/i*
TROPOPAUSE RANGE 287–262 mb.																	
– 52	– 71	– 57	– 88	– 63	– 99	– 57	–103	..	..	..	..	..	..	– 62	– 93	Pm/P	*i/c*
– 64	– 67	– 62	– 65	– 68	– 60	– 60	– 62	– 58	..	– 57	– 62	..	..	– 68	– 60	..	..
– 53	– 84	– 56	– 92	– 61	– 98	– 61	–103	– 57	–109	..	..	..	..	– 61	– 99	Pm/P	*c/i*
– 53	– 79	– 59	– 82	– 65	– 88	– 67	– 94	– 66	– 97	– 62	– 98	..	..	– 65	– 88	P/Pm	*i*
– 55	– 71	– 62	– 86	– 67	– 88	– 67	– 94	– 65	– 95	– 55	–100	– 58	– 97	– 67	– 88	P	*i/a*
..	..	– 45	–102	– 49	–104	– 43	–101	– 47	– 99	..	..	..	..	..	..	A	*i*
..	..	– 62	– 63	– 69	– 72	– 66	– 89	– 71	–102	– 65	–115	– 62	–110	– 68	– 68	A	*c/i*
– 53	– 54	– 61	– 64	– 70	– 72	– 68	– 86	– 62	–103	– 57	–103	..	..	– 70	– 72	Pm	*i/c*
– 47	– 61	– 53	– 69	– 61	– 71	– 62	– 95	..	..	..	..	..	..	– 61	– 71	Pm/P	*i*
– 46	– 60	– 52	– 67	– 56	– 74	– 57	– 82	– 53	– 92	– 51	– 99	..	..	– 55	– 69	Pm/P	*c/i*
– 51	– 69	– 58	– 73	– 65	– 80	– 67	– 86	– 64	–100	– 58	–111	– 55	–114	– 65	– 80	Pm	*i*
– 47	– 57	– 55	– 62	– 64	– 69	– 65	– 82	– 57	– 94	– 54	–108	..	..	– 66	– 74	P	*c*
– 50	– 72	– 57	– 76	– 63	– 81	– 64	– 89	– 57	–104	– 54	–111	..	..	– 63	– 81	Pm	*i*
– 50	– 67	– 57	– 73	– 62	– 80	– 63	– 90	– 61	–100	– 56	–108	..	..	– 65	– 84	Pm	*i*
– 54	– 59	– 59	– 68	– 60	– 90	– 59	– 94	– 56	–113	– 48	–105	..	..	– 61	– 79	Pm	*i*
– 55	– 61	– 61	– 65	– 70	– 71	– 62	–100	– 56	–105	– 53	–119	..	..	– 70	– 71	Pm	*i*
– 42	– 50	– 47	– 58	– 55	– 74	– 54	– 73	– 46	– 98	– 43	–110	..	..	– 52	– 67	Pm/P	*c/i*
– 47	– 52	– 54	– 55	– 63	– 62	– 58	– 79	– 50	–100	– 48	–106	..	..	– 68	– 71	P	*c/i*
– 42	– 60	– 51	– 63	– 56	– 73	– 49	– 87	– 47	– 96	– 49	–103	..	..	– 57	– 69	Pm	*c*

TABLE I—

Tropopause Pressure	Tropopause Type	Date	Time	Place	500 mb. Temp-erature	500 mb. Frost point	450 mb. Temp-erature	450 mb. Frost point	400 mb. Temp-erature	400 mb. Frost point	350 mb. Temp-erature	350 mb. Frost point
mb.			G.M.T.		*degrees Fahrenheit*							
				TROPOPAUSE RANGE 262–238 mb.								
		Winter										
250	I	26.1.50	1500	Farnborough	− 15	− 33	− 26	− 30	− 36	− 42	− 48	− 58
260	II	9.2.45†	1100	East Anglia	− 13	− 69	− 23	− 60	− 33	− 51	− 46	− 64
250	I	17.2.49	1500	Farnborough	− 5	..	..	..	..	..	..	..
262 (215)	II (I)	26.2.48	1500	Southampton	− 16	− 72	− 23	− 81	− 31	− 78	− 45	− 86
		Spring										
250	II	22.4.45	—	South England	+ 2	− 45	− 9	− 44	− 21	− 42	− 36	− 56
250	II	25.4.49	1030	Farnborough	− 23	..	− 15	− 80	− 28	− 70	− 39	− 68
250	I	26.4.49†	1030	Farnborough-Isle of Wight	− 7	− 45	− 21	− 50	− 30*	− 65*	− 39	− 60
250	I	17.5.50	1500	Larkhill	− 7	− 36	− 17	− 54	− 30	− 57	− 42	− 62
262	I	23.5.50	1500	Downham Market ..	− 5	− 17	− 16	− 21	− 27	− 35	− 40	− 51
238	I	24.5.48†	1500	Farnborough-London ..	− 14	..	− 23	− 47	− 35	− 62	− 42*	− 61*
		Summer										
262	I	7.7.49	1130	Farnborough	+ 3	− 18	− 8	− 27	− 19	− 35	− 35	− 41
250	I	8.7.49	1100	Farnborough	+ 3	− 17	− 7	− 27	− 20	− 39	− 35	− 56
250	I	14.7.49	1000	Farnborough	+ 2	− 14	− 8	− 9	− 19	− 20	− 31	− 46
262 (238)	II (I)	15.7.49	1030	Farnborough	+ 4	− 12	− 7	− 16	− 20	− 34	− 32	− 46
262	II	8.8.49	1000	Farnborough	+ 6	− 46	− 3	− 55	− 17*	− 48*	− 29	− 57
262	II	26.8.49	1400	Farnborough	+ 5	− 7	− 4	− 22	− 16	− 32	− 30	− 43
250	II	7.9.43	1500	South England	+ 2	− 40	− 8	− 50	− 20	− 57	− 32	− 39
		Autumn										
240	I	24.12.43	1100	South England	− 12	− 26	− 22	− 37	− 33	− 48	− 47	− 66
				TROPOPAUSE RANGE 238–216 mb.								
		Winter										
238	II	21.1.49†	1200	Farnborough	− 2	− 39	− 12	− 45	− 24*	− 32*	− 38	− 47
238	I	21.2.50†	1500	Farnborough	− 16	− 69	− 25	− 73	− 36	− 80	− 47	− 75
227	II	1.3.49†	1130	Farnborough	− 15	..	− 21	− 42	− 32	− 52	− 44	− 67
238 (197)	I (I)	18.3.49†	1100	Farnborough	− 6	− 53	− 17	− 51	− 29	− 52	− 41	− 73
		Spring										
238	II	20.4.50	1500	Larkhill	− 4	− 47	− 13	− 48	− 26*	− 40*	− 39	− 56
227	I	2.5.49	1430	Farnborough	+ 3	− 28	− 10	− 29	− 22	− 50	− 37	− 65
227	II	3.5.49	1100	Farnborough	+ 2	− 36	− 8	− 49	− 21	− 57	− 35	− 58
238 (216)	II (I)	3.5.50†	1500	Larkhill	− 6	− 49	− 15	− 55	− 25	− 49	− 39	− 56
238	I	13.5.50	0900	Larkhill	+ 1	− 31	− 12	− 37	− 25	− 47	− 38	− 57
216	I	15.5.50	1500	Larkhill	− 1	− 46	− 16	− 46	− 24*	− 46*	− 38	− 53
238	I	16.5.50	1500	Larkhill	− 3	− 44	− 15	− 53	− 25	− 57	− 38	− 62
238	I	16.5.50	1500	Downham Market ..	− 6	..	..	..	− 26	− 51	− 39	− 65
225	I	25.5.45	1400	South England	− 5	− 9	− 14	− 58	− 24	− 42	− 37	− 43
228	I	27.5.48	1100	Southampton-London ..	− 5	..	..	..	− 28	− 39	− 38	− 55
216	I	13.6.50	1430	Larkhill	0	− 31	− 13	− 40	− 25	− 46	− 36	− 60
227	I	14.6.49	1400	Farnborough	+ 5	− 22	− 5	− 27	− 17	− 35	− 30	− 51
227	I	15.6.49	1030	Farnborough	+ 4	− 22	− 7	− 35	− 19	− 50	− 33	− 63
		Summer										
238	II	6.7.49	1000	Farnborough	+ 4	− 22	− 7	− 34	− 19	− 43	− 30	− 43
227	I	10.8.49	1000	Farnborough	+ 1	− 31	− 8	− 27	− 20	− 40	− 34	− 56
225	I	17.8.45	1500	South England	+ 3	− 14	− 5	− 29	− 17	− 39	− 27	− 47
227	I	30.8.49	1000	Farnborough	+ 7	− 24	− 2	− 34	− 13	− 29	− 24	− 44
216	I	13.9.49	1100	Farnborough	+ 7	− 14	− 1	− 22	− 13	− 45	− 25	− 43
238	I	16.9.49	1000	Farnborough	− 1	− 17	− 10	− 24	− 22	− 44	− 32	− 58
238	I	20.9.49	1100	Farnborough	0	− 14	− 10	− 25	− 22	− 37	− 33	− 46
227	I	22.9.49	1100	Farnborough	+ 6	− 2	− 3	− 10	− 16	− 17	− 29	− 44
227	I	26.9.49	1100	Farnborough	+ 7	− 12	− 3	− 27	− 12	− 27	− 28	− 38
		Autumn										
227	I	27.10.49†	1100	Farnborough	− 4	− 40	− 12	− 48	− 23	− 57	− 36	− 67
				TROPOPAUSE RANGE 216–197 mb.								
		Winter										
206	I	28.1.49	1230	Farnborough	− 4	− 13	− 15	− 21	− 25	− 35	− 38	− 44
206	I	21.2.49	1500	Farnborough	− 3	− 64	− 10	− 58	− 19	− 43	− 34	− 41
206	II	22.2.49†	1530	Farnborough	− 2	− 6	− 12	− 16	− 24	− 30	− 37	− 45
206	I	2.3.49	1100	Farnborough	− 14	− 33	− 22	− 38	− 32	− 48	− 44	− 72
206	I	17.3.49	1500	Farnborough	− 7	− 32	− 18	− 39	− 30	− 49	− 43	− 55
216	I	31.3.50	1500	Downham Market ..	− 6	− 40	− 15	− 40	− 24	− 48	− 39	− 62

continued

325 mb. Temp-erature	325 mb. Frost point	300 mb. Temp-erature	300 mb. Frost point	275 mb. Temp-erature	275 mb. Frost point	250 mb. Temp-erature	250 mb. Frost point	225 mb. Temp-erature	225 mb. Frost point	200 mb. Temp-erature	200 mb. Frost point	187 mb. Temp-erature	187 mb. Frost point	At tropopause Temp-erature	At tropopause Frost point	Air mass	Circulation type
degrees Fahrenheit																	
TROPOPAUSE RANGE 262–238 mb.																	
−54	−66	−62	−73	−70	−74	−76	−85	−71	−90	−65	−88	−65	−88	−76	−85	Pm	*i*
−53	−73	−58*	−82*	−63	−77	−65	−82	..	..	..	..	..	..	−66	−80	Pm/P	*i*
..	..	..	..	−63	−79	−70	−84	−68	−85	−65	−91	−63	−92	−70	−84	T	*a*
−49	−90	−52	−87	−58	−92	−59	−97	−61	−109	−59	−111	−61	−119	−61	−92	A	*c/i*
−42	−61	−49	−67	−59	−73	−69	−73	−72	−88	−71	−102	−71	−106	−69	−73	P	*i*
−44	−78	−45	−84	−42	−94	−50	−95	−50	−103	−49	−103	..	..	−50	−95	Pm/P	*c/i*
−44	−68	−52	−70	−56	−87	−61	−99	−57	−105	−59	−108	..	..	−61	−99	Pm/P	*i/a*
−49	−58	−56	−66	−63	−73	−69	−79	−68	−91	−59	−108	..	..	−69	−79	Pm	*i*
−47	−61	−54	−75	−62	−73	−65	−82	−58	−97	−56	−99	..	..	−66	−78	Pm	*i*
−47	−56	−53	−61	−61	−67	−66	−74	−64	−86	−55	−107	−56	−113	−69	−76	Pm/P	*i*
−43	−48	−52	−54	−58	−70	−59	−91	−56	−96	−52	−112	..	..	−61	−80	P	*c/i*
−42	−59	−49	−63	−55	−67	−61	−74	−57	−82	−54	−94	..	..	−61	−74	P	*i*
−39	−49	−47	−54	−53	−61	−59	−73	−54	−91	−51	−101	..	..	−59	−73	Pm	*i/c*
−40	−53	−47	−66	−55	−70	−58	−77	−51	−91	−48	−106	..	..	−58	−72	Pm	*c*
−37	−60	−44	−65	−50	−69	−53	−77	−52	−95	−52	−102	..	..	−53	−74	T/Pm	*i*
−38	−58	−45	−61	−52	−68	−55	−79	−53	−86	−51	−105	..	..	−55	−75	Pc	*c*
−38	−34	−46	−47	−54	−54	−63	−67	−62	−84	..	..	..	..	−63	−67	Pm	*i*
−56	−67	−62	−72	−69	−78	−73	−84	−73	−96	..	..	..	..	−74	−87	Pm/P	*i/a*
TROPOPAUSE RANGE 238–216 mb.																	
−45	−55	−54	−63	−63	−74	−73	−82	−75	−93	..	..	..	..	−75	−82	Pm/P	*i*
−53	−73	−58*	−72*	−63	−76	−68	−81	−68	−84	−66	−81	..	..	−70	−84	T/P	*i/a*
−50	−75	−57	−84	−66	−89	−75	−98	−85	−102	−87	−107	−86	−105	−85	−102	Pm/P	*i*
−49	−66	−57	−69	−65	−80	−73	−85	−75	−95	−77	−98	−68	−109	−76	−90	Pm/P	*i*
−46	−60	−54	−65	−62	−67	−72	−72	−76	−78	−73	−94	−69	−99	−75	−77	T/Pc	*a*
−45	−69	−50	−66	−57	−79	−65	−78	−73	−81	−72	−99	−71	−108	−73	−81	Pc	*a*
−42	−66	−50	−68	−57	−74	−67	−76	−72	−83	−73	−93	−71	−97	−72	−83	Pc	*a*
−46	−60	−53	−66	−61	−74	−68	−83	−71	−89	−66	−103	..	..	−71	−85	Pm/P	*i/a*
−46	−63	−54	−69	−64	−73	−73	−81	−74	−94	−75	−99	−74	−105	−75	−85	Pc	*a/i*
−46	−56	−53	−63	−60	−72	−69	−81	−73	−89	−70	−101	−70	−102	−77	−95	Pm/P	*i*
−46	−69	−53	−64	−62	−77	−68	−81	−70	−89	−67	−104	−66	−107	−71	−86	Pm	*i*
−46	−66	−54	−71	−62	−78	−70	−81	−72	−87	−67	−102	−62	−110	−73	−83	Pm	*i*
−45	−60	−51	−67	−57	−68	−60	−79	−65	−87	−61	−101	−61	−115	−65	−87	Pm	*i*
−46	−63	−52	−66	−57	−66	−65	−72	−66	−80	−59	−87	−54	−79	−68	−78	Pm	*c*
−39	−65	−43	−66	−48	−80	−50	−91	−57	−92	−56	−104	..	..	−59	−94	Pm	*c*
−38	−59	−46	−62	−54	−67	−61	−77	−69	−79	−69	−92	−72	−97	−69	−79	Pm/P	*i*
−40	−69	−48	−69	−56	−71	−63	−77	−69	−84	−66	−102	−65	−109	−69	−84	Pm	*i*
−36	−43	−44	−52	−52	−62	−60	−70	−62	−81	−58	−105	..	..	−63	−76	P	*i*
−43	−60	−51	−67	−60	−68	−68	−75	−74	−78	−60	−90	..	..	−74	−78	Pm/P	*i/a*
−35	−59	−44	−71	−53	−70	−60	−69	−69	−78	−59	−104	..	..	−69	−78	Pm	*i/c*
−33	−54	−41	−52	−51	−56	−60	−62	−64	−85	−55	−96	..	..	−64	−85	Pm	*a*
−32	−44	−39	−54	−49	−60	−57	−72	−66	−81	−69	−91	..	..	−70	−84	Pm	*i*
−39	−67	−43	−68	−51	−73	−54	−71	−52	−87	−56	−93	..	..	−56	−73	Pm	*i/c*
−40	−53	−47	−55	−56	−65	−66	−68	−62	−90	−58	−96	−57	−94	−67	−71	Pm	*i*
−36	−49	−44	−56	−55	−55	−65	−65	−67	−80	−59	−105	..	..	−67	−80	Pm	*i*
−35	−42	−43	−45	−52	−56	−63	−64	−71	−71	−70	−86	−70	−95	−71	−71	Pm	*a*
−43	−70	−51	−74	−59	−79	−67	−83	−75	−85	−69	−96	..	..	−75	−85	Pm/P	*i/a*
TROPOPAUSE RANGE 216–197 mb.																	
−45	−53	−53	−65	−59	−80	−64	−92	−70	−98	−70	−103	−69	−107	−72	−102	Pm	*i*
−41	−47	−46	−54	−53	−60	−62	−66	−68	−76	−73	−90	−69	−100	−74	−84	T/Pm	*i*
−44	−52	−52	−63	−50	−78	−68	−81	−78	−86	−85	−92	−86	−96	−85	−94	T/Pm	*i*
−50	−66	−58	−78	−65	−87	−74	−93	−84	−88	−91	−107	−87	−109	−92	−105	P	*i/a*
−50	−70	−56	−76	−65	−75	−71	−83	−78	−88	−82	−95	−78	−97	−83	−93	Pm	*i*
−47	−64	−54	−73	−63	−73	−72	−80	−80	−84	−82	−89	−80	−86	−84	−86	Pm	*a/i*

TABLE I—

Tropopause Pressure	Tropopause Type	Date	Time	Place	500 mb Temperature	500 mb Frost point	450 mb. Temperature	450 mb. Frost point	400 mb. Temperature	400 mb. Frost point	350 mb. Temperature	350 mb. Frost point
mb.			G.M.T.		degrees Fahrenheit							
TROPOPAUSE RANGE 216–197 mb.												
		Spring										
216	II	2.5.49	1100	Farnborough	+ 2	..	− 10	− 29	− 22	− 51	− 37	− 65
200	I	11.5.50	1500	Larkhill	− 1	− 29	− 10	− 41	− 22	− 56	− 37	− 64
206 (180)	III (I)	11.5.50	1500	Downham Market ..	− 1	− 39	− 12	− 42	− 24	− 53	− 37	− 58
206	I	12.5.50	0900	Larkhill	− 1	− 35	− 12	− 47	− 23	− 54	− 36	− 67
216	I	14.5.50	0900	Larkhill	+ 1	− 47	− 9	− 51	− 22	− 60	− 37	− 61
216	I	1.6.50	1500	Larkhill	− 1	− 1	− 9	− 19	− 19	− 39	− 32	− 45
216	I	16.6.49	1030	Farnborough	+ 2	− 36	− 7	− 44	− 18	− 57	− 32	− 53
216	III	22.6.49	1030	Farnborough	+ 10	− 21	− 2	− 30	− 14	− 39	− 29	− 52
		Summer										
206	II	5.8.49	1000	Farnborough	+ 7	− 12	− 5	− 17	− 18	− 25	− 28	− 55
212	I	31.8.49	1000	Farnborough	+ 7	− 13	0	− 31	− 12	− 44	− 24	− 52
197	I	5.9.49	1030	Farnborough	+ 12	− 4	+ 1	− 10	− 9	− 16	− 22	− 31
206	I	12.9.49	1030	Farnborough	+ 7	− 20	− 4	− 18	− 15	− 21	− 27	− 32
TROPOPAUSE RANGE 197–179 mb.												
		Winter										
179	I	20.1.49†	1430	Farnborough	− 5	..	− 16	− 53	− 26	− 61	− 43	− 72
197	I	27.1.49	1530	Farnborough	+ 4	− 39	− 8	− 44	− 17	− 49	− 29	− 50
197	I	15.2.49	1330	Farnborough	+ 1	− 19	− 8	− 25	− 18	− 31	− 33	− 43
187	I	16.2.49	1200	Farnborough	+ 2	− 19	− 8	− 29	− 18	− 52	− 31	− 62
197	I	28.2.49	1230	Farnborough	− 13	− 17	− 22	− 27	− 35	− 42	− 48	− 56
179	I	24.3.49	1600	Farnborough	− 2	..	..	..	..	..	− 37	− 68
180	II	24.3.49	1600	Farnborough	− 4	− 41	− 13	− 50	− 25	− 59	− 38	− 65
		Spring										
197	I	22.4.49	1100	Farnborough	0	− 15	− 10	− 24	− 22	− 32	− 35	− 52
197 (170)	III (I)	30.5.50†	1500	Larkhill	+ 5	− 12	− 4	− 22	− 16	− 34	− 30	− 48
180	I	8.6.50	0900	Larkhill	+ 6	− 26	− 5	− 32	− 17	− 51	− 30	− 58
185	I	12.6.50	1500	Larkhill	+ 4	− 23	− 5	− 18	− 16	− 17	− 28	− 41
197	II	13.6.49	1130	Farnborough	+ 6	− 29	− 4	− 42	− 16	− 56	− 30	− 66
197	II	21.6.49	1500	Farnborough	+ 11	− 23	+ 1	− 33	− 12	− 41	− 26	− 52
187	I	27.6.49	1030	Farnborough	+ 10	− 24	+ 2	− 23	− 11	− 18	− 24*	− 25*
		Summer										
187	II	20.7.49	1000	Farnborough	+ 7	+ 4	− 1	− 3	− 10	− 17	− 25	− 27
197	II	22.7.49	1000	Farnborough	+ 10	− 11	0	− 13	− 10	− 40	− 24	− 44
185	II	25.7.49	0900	Farnborough	+ 16	− 12	− 6	− 12	− 5	− 22	− 20	− 30
180	I	17.8.49†	1000	Farnborough	+ 11	0	+ 2	− 7	− 9	− 14	− 19	− 23
187	II	28.9.49	1300	Farnborough	+ 6	− 32	− 5	− 44	− 15	− 53	− 25	− 62
TROPOPAUSE RANGE 179–162 mb.												
		Winter										
170	I	25.1.49	1500	Farnborough	− 12	− 60	− 20	− 80	− 26	− 92	− 37	− 99
		Spring										
178	I	27.4.49	1030	Farnborough	+ 4	− 54	− 6	− 58	− 17	− 68	− 30	− 83
170	II	20.6.49	1400	Farnborough	+ 8	− 7	− 1	− 18	− 12	− 65	− 25	− 60
177	I	28.6.50†	1500	Larkhill	+ 13	− 32	+ 4	− 46	− 9	− 49	− 21	− 64
		Summer										
170	II	15.8.49	1030	Farnborough	+ 14	− 30	+ 6	− 41	− 6	− 27	− 21	− 32
165	II	19.8.49	1100	Farnborough	+ 12	− 25	+ 5	− 40	− 5	− 56	− 19	− 52
TROPOPAUSE RANGE 162–147 mb.												
		Winter										
150	II	15.2.50†	1500	Farnborough	0	− 10	− 13	− 18	− 23	− 30	− 36	− 45
		Spring										
150	I	30.6.49	1000	Farnborough	+ 13	+ 8	+ 5	− 15	− 4	− 34	− 15	− 42
156	I	26.6.50	1500	Larkhill	+ 13	− 9	+ 3	− 20	− 8	− 39	− 19	− 38
		Summer										
160	I	26.7.49†	0930	Farnborough	+ 9	− 32	− 1	− 41	− 13	− 46	− 27	− 51
160	I	12.8.49	1000	Farnborough	+ 12	− 8	+ 2	− 14	− 9	− 18	− 24	− 34
		Autumn										
150	II	7.10.49	1400	Farnborough	+ 8	− 20	− 2	− 20	− 14	− 19	− 27	− 56
TROPOPAUSE ABOVE 147 mb.												
		Summer										
120	I	4.8.49	1500	Farnborough	+ 9	+ 1	+ 1	− 11	− 12	− 19	− 23	− 40

continued

325 mb.		300 mb.		275 mb.		250 mb.		225 mb.		200 mb.		187 mb.		At tropopause		Air mass	Circulation type
Temperature	Frost point	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point		
degrees Fahrenheit																	
TROPOPAUSE RANGE 216–197 mb.																	
−45	−69	−52	−72	−57	−79	−61	−88	..	..	..	..	..	..	..	..	Pm	*a*
−44	−66	−52	−69	−59	−78	−67	−80	−73	−89	−80	−91	−76	−102	−80	−91	P	*a/i*
−46	−58	−55	−62	−60	−72	−68	−77	−76	−83	−81	−94	−82	−97	−80	−88	P	*a/i*
−45	−74	−52	−77	−58	−81	−65	−79	−71	−87	−76	−99	..	..	−76	−95	Pc	*a/i*
−44	−63	−52	−68	−60	−72	−68	−77	−76	−83	−77	−97	..	..	−79	−84	P	*a/i*
−39	−43	−47	−56	−56	−66	−65	−69	−72	−85	−70	−91	..	..	−75	−88	T	*a*
−40	−57	−46	−63	−55	−63	−65	−66	−70	−81	−70	−96	−66	−100	−71	−90	Pm	*i/a*
−36	−57	−44	−57	−51	−61	−60	−67	−67	−73	−71	−92	−71	−96	−69	−79	Pm	*a*
−32	−67	−39	−65	−44	−71	−52	−73	−54	−76	−60	−84	..	..	−60	−82	T/Pm	*i*
−32	−56	−39	−60	−47	−67	−56	−71	−65	−76	−64	−90	−61	−98	−67	−80	Pm	*i*
−29	−40	−37	−48	−46	−57	−54	−68	−58	−74	−70	−78	−69	−90	−71	−79	Pm	*i*
−35	−43	−43	−49	−53	−64	−60	−75	−66	−82	−68	−92	−67	−93	−70	−88	Pm	*i*
TROPOPAUSE RANGE 197–179 mb.																	
−49	−77	−56	−79	−62	−84	−71	−87	−72	−95	−73	−101	−78	−102	..	..	Pm/P	*i*
−36	−51	−43	−58	−53	−64	−61	−72	−70	−83	−80	−90	−80	−95	−81	−92	Pm	*a/i*
−40	−45	−48	−56	−58	−62	−68	−73	−77	−83	−87	−87	−87	−98	−88	−88	T	*a*
−40	−56	−48	−54	−57	−57	−66	−70	−74	−88	−83	−95	−89	−97	−89	−97	T	*a*
−55	−60	−63	−74	−71	−80	−77	−88	−86	−97	−94	−103	−95	−106	−95	−105	Pm/P	*i*
−43	−67	−50	−70	−58	−78	−67	−86	−74	−94	−82	−101	−85	−98	−89	−102	Pc	*a*
−44	−66	−50	−76	−58	−81	−65	−86	−73	−96	−80	−99	−83	−100	..	..	Pc	*a*
−40	−56	−48	−60	−56	−65	−64	−73	−71*	−82*	−80	−86	−82	−93	−81	−87	Pm/P	*a*
−37	−60	−45	−67	−55	−74	−64	−77	−71	−83	−78	−86	−78	−89	−78	−87	T	*a*
−34	−72	−42	−75	−48	−78	−55	−81	−64	−83	−72	−85	..	..	..	..	Pm	*i*
−36	−41	−42	−52	−51	−57	−60	−62	−69	−77	−74	−89	−77	−92	..	..	T	*a/i*
−38	−71	−45	−75	−52	−80	−58	−73	−66	−77	−74	−88	−75	−93	−74	−89	Pm	*i*
−34	−56	−42	−62	−51	−67	−59	−72	−68	−76	−78	−81	−79	−83	−79	−83	Pm	*a*
−31	−34	−39	−43	−47	−51	−56	−63	−64	−71	−71	−79	−74	−85	−74	−85	T/P	*a*
−32	−36	−37	−44	−47	−50	−55	−61	−64	−70	−72	−79	−76	−79	−76	−79	T/Pm	*i/a*
−32	−46	−41	−41	−49	−50	−55	−61	−64	−66	−72	−73	−72	−90	−72	−73	Pm	*i/a*
−27	−39	−36	−44	−43	−55	−53	−59	−62	−65	−72	−81	..	..	..	..	T/Pm	*a*
−28	−31	−37	−42	−46	−54	−56	−60	−65	−66	−74	−78	−76	−86	..	..	Pm/P	*i/a*
−34	−58	−37	−63	−48	−73	−56	−76	−65	−82	−71	−88	−75	−91	−75	−92	Pm	*a*
TROPOPAUSE RANGE 179–162 mb.																	
−43	−97	−48	−96	−53	−95	−62	−97	−64	−102	−72	−103	−74	−107	..	..	Pm	*i*
−37	−85	−45	−94	−53	−97	−61	−96	−70	−79	−79	−84	−84	−92	..	..	Pm	*i/a*
−34	−55	−42	−61	−51	−64	−59	−72	−66	−80	−73	−88	−77	−87	..	..	Pm	*a*
−28	−59	−36	−70	−44	−73	−53	−76	−63	−80	−69	−82	..	..	..	..	T	*a*
−29	−45	−36	−47	−45	−50	−55	−61	−64	−67	−75	−78	−78	−90	..	..	T	*a*
−27	−57	−35	−59	−43	−64	−53	−71	−63	−74	−73	−81	−76	−81	..	..	Pm	*a*
TROPOPAUSE RANGE 162–147 mb.																	
−42	−50	−50	−58	−59	−68	−69	−73	−77	−86	−88	−94	−93	−101	..	..	T	*i*
−24	−46	−32	−51	−41	−56	−49	−64	−60	−69	−68	−81	..	..	..	..	T	*a*
−28	−41	−35	−45	−45	−53	−53	−67	−62	−78	−71	−87	..	..	..	..	T	*a/i*
−27	−55	−32*	−38*	−39	−46	−48	−49	−54	−74	−62	−85	−66	−92	..	..	T/Pm	*i/a*
−32	−42	−39	−41	−47	−47	−56	−56	−64	−66	−71	−82	−73	−88	..	..	Pm/P	*a*
−32	−45	−40	−55	−50	−69	−60	−68	−63	−86	−64	−91	−67	−95	..	..	Pm	*a/i*
TROPOPAUSE ABOVE 147 mb.																	
−32	−45	−39	−48	−47	−59	−51	−78	−56	−82	−60	−91	−63	−95	..	..	T	*a*

must be considered. For this reason an analysis of the observations is first made using the tropopause as datum level, and this is presented in § 4 which ends with a table of correlation coefficients some of which relate to frost points at fixed pressure levels. The latter naturally lead to a consideration of the variation of frost point at fixed levels, and this is dealt with in § 5, variation according to circulation type, air mass and season being examined in turn.

In § 6 the effect of frontal surfaces on frost-point distribution is investigated, whilst § 7 deals in greater detail with the lapse rate of frost point in the stratosphere. Lastly, those observations made in the neighbourhood of jet streams are mentioned in § 8.

§ 4—VARIATION OF WATER-VAPOUR CONTENT WITH HEIGHT; DATUM LEVEL THE TROPOPAUSE

General discussion.—On examining individual ascents, perhaps the first thing which strikes one is that there is frequently a sharp fall of frost point on entering the stratosphere. This was remarked upon by Dobson, Brewer and Cwilong[1] in their discussion of some of the early Boscombe Down ascents. This rapid fall of frost point does not always occur, however, and there are many ascents in which the lapse rate of frost point is not materially different above and below the tropopause (see § 7). Typical examples of the two types are given in Figs. 1 and 2 respectively.

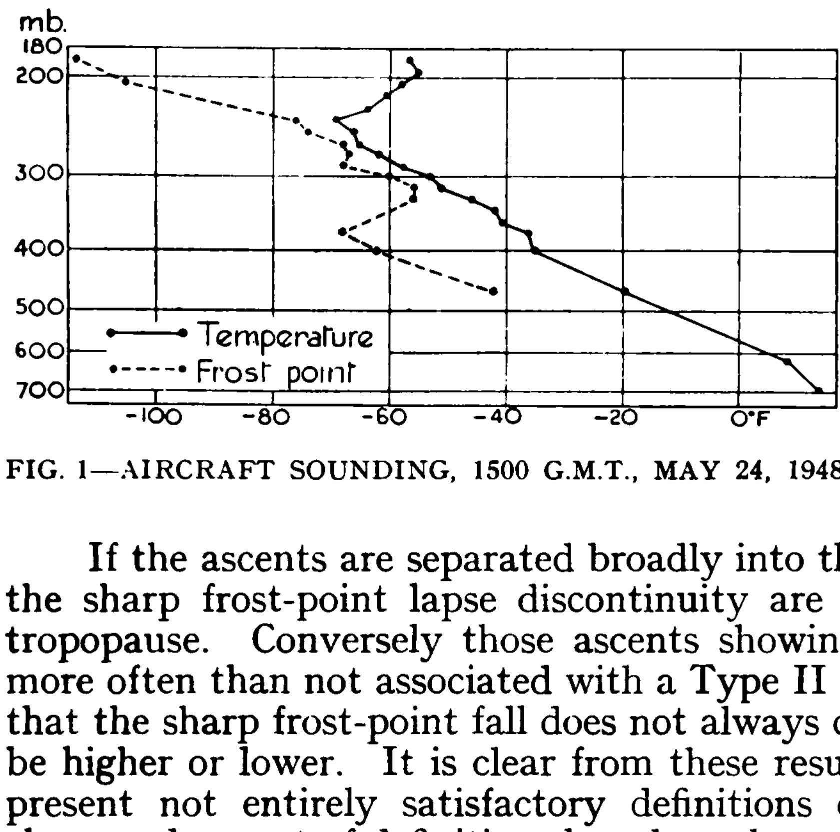


FIG. 1—AIRCRAFT SOUNDING, 1500 G.M.T., MAY 24, 1948

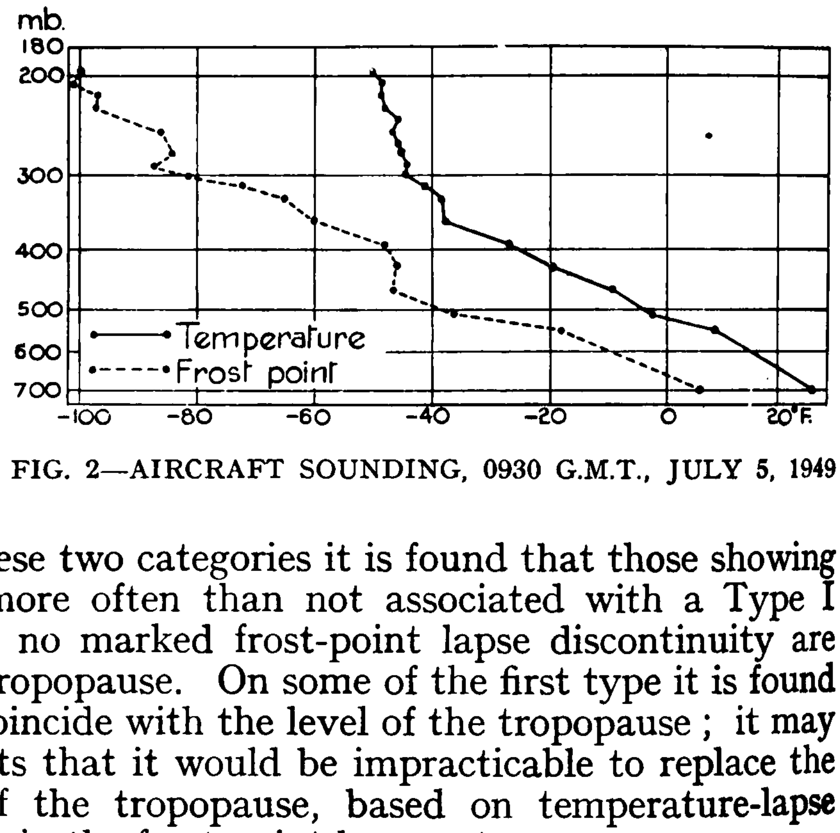


FIG. 2—AIRCRAFT SOUNDING, 0930 G.M.T., JULY 5, 1949

If the ascents are separated broadly into these two categories it is found that those showing the sharp frost-point lapse discontinuity are more often than not associated with a Type I tropopause. Conversely those ascents showing no marked frost-point lapse discontinuity are more often than not associated with a Type II tropopause. On some of the first type it is found that the sharp frost-point fall does not always coincide with the level of the tropopause; it may be higher or lower. It is clear from these results that it would be impracticable to replace the present not entirely satisfactory definitions of the tropopause, based on temperature-lapse changes, by a set of definitions based on changes in the frost-point lapse rate.

Almost invariably the frost point in the stratosphere decreases with increasing height, so that the relative humidity of the air in the stratosphere is almost always very low; the frost points are generally within the range − 80° to − 120°F. (211° to 189°A.). There were two exceptional ascents, however, which indicated conditions of by no means low relative humidity in the stratosphere. They occurred on successive days, January 19 and 20, 1948, and details are included in Table I. The first indicated a relative humidity of 26 per cent. and the second a relative humidity of 75 per cent. (with respect to ice) at the 200-mb. level, which in each case was well inside the stratosphere. As the results of these ascents are completely at variance with all others obtained, and because humidity measurements made using the Mark IIa pressurized hygrometer are always subject to a little doubt owing to the possibility of moister cabin air leaking into the instrument, they have not been included in the analysis. The possibility remains that very occasionally the air in the lower stratosphere may be nearly saturated.

Relative humidity.—In order to investigate the variation of relative humidity through the tropopause the relative humidity (ice) has been computed (by interpolation, if necessary, on the ascent curves) for each ascent, at 25-mb. intervals, from 50 mb. below the tropopause to the top of the ascent. A frequency table summarizing the results is given in Table II.

TABLE II—FREQUENCY OF RELATIVE HUMIDITY (WITH RESPECT TO ICE)

	Relative humidity																Mean relative humidity	Total no. of cases
	0–0·9	1–2·9	3–4·9	5–9·9	10–14	15–19	20–24	25–29	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100		
mb.	*Number of occasions*																%	
P_c − 100	1	7	2	..	..	..	..	..	..	..	..	..	..	..	..	..	2·2	10
P_c − 75	2	17	5	4	..	..	..	..	..	..	..	..	..	..	..	..	2·7	28
P_c − 50	0	25	11	14	3	3	..	..	..	..	..	..	..	..	..	..	5·0	56
P_c − 25	0	6	10	26	16	16	10	5	2	0	0	1	..	..	..	..	12·9	92
Tropopause	0	2	1	8	4	2	12	7	22	19	8	4	9	2	3	3	41·5	106
P_c + 25	0	1	0	3	5	4	7	5	25	15	13	9	5	4	3	2	44·3	101
P_c + 50	0	0	0	4	1	6	9	8	24	18	10	7	8	2	2	1	42·6	100

The outstanding features of this table are (i) the rapid decrease in relative humidity as the stratosphere is entered, and (ii) the fact that the relative humidity continues to decrease, though less rapidly, the further into the stratosphere one goes. Mean values are given for each level. Ten of the ascents penetrated 100 mb. into the stratosphere, the mean relative humidity at that level being only 2·2 per cent., and the range 0·8 to 3·9 per cent. For convenience a table showing relative humidity as a function of temperature and frost point is included as Table III.

TABLE III—RELATIVE HUMIDITY (WITH RESPECT TO ICE), AS A FUNCTION OF TEMPERATURE AND FROST POINT

Compiled from values of saturated vapour pressure over ice given by J. A. Goff and S. Gratch[5]

Frost point	Temperature (°F.)																
	0	−5	−10	−15	−20	−25	−30	−35	−40	−45	−50	−55	−60	−65	−70	−75	−80
°F.	*per cent.*																
− 20	33	44	57	75	100	..	..	..	..	..	..	..	..	..	..	..	..
− 25	25	33	43	56	75	100	..	..	..	..	..	..	..	..	..	..	..
− 30	19	25	32	42	56	75	100	..	..	..	..	..	..	..	..	..	..
− 35	14	18	24	31	41	55	74	100	..	..	..	..	..	..	..	..	..
− 40	10	13	17	23	30	40	54	73	100	..	..	..	..	..	..	..	..
− 45	7	10	13	16	22	29	39	53	73	100	..	..	..	..	..	..	..
− 50	5	7	9	12	16	21	28	39	53	73	100	..	..	..	..	..	..
− 55	4	5	7	9	11	15	20	28	38	52	71	100	..	..	..	..	..
− 60	3	4	5	6	8	11	14	20	27	37	51	71	100	..	..	..	..
− 65	2	2	3	4	6	8	10	14	19	26	36	50	70	100	..	..	..
− 70	1	2	2	3	4	5	7	10	13	18	25	35	49	70	100	..	..
− 75	..	1	2	2	3	4	5	7	9	13	17	24	34	49	70	100	..
− 80	..	..	1	1	2	3	3	5	6	9	12	17	24	34	48	69	100
− 85	..	..	..	..	1	2	2	3	4	6	8	11	16	23	33	47	68
− 90	..	..	..	..	..	1	2	2	3	4	5	8	11	15	22	31	45
− 95	..	..	..	..	..	..	1	1	2	3	4	5	7	10	14	20	29
−100	..	..	..	..	..	..	..	..	1	2	2	3	5	7	9	14	20
−105	..	..	..	..	..	..	..	..	..	1	2	2	3	4	6	9	13
−110	..	..	..	..	..	..	..	..	..	..	..	1	2	3	4	6	8
−115	..	..	..	..	..	..	..	..	..	..	..	..	1	2	3	4	5
−120	..	..	..	..	..	..	..	..	..	..	..	..	..	1	2	2	3

Mean ascent curves.—Values of temperature and frost point were taken from each ascent at 25-mb. intervals from 150 mb. below the tropopause to the top of the ascent, and from these Table IV was compiled. It presents mean values of temperature and frost point for these levels and for three fixed levels for the four seasons.

Fig. 3 shows mean ascent curves, the tropopause being taken as datum level, for the year and for the summer and winter half-years, computed from all ascents (106) which penetrated the tropopause. As the number of ascents is so limited mean curves for each half-year rather than each quarter (as given in Table IV) are plotted. Fig. 4 gives similar mean curves for ascents in which the tropopause was Type I or Type II, omitting those ascents with observations in the troposphere only or in the stratosphere only, whose inclusion might give misleading results.

Fig. 3 indicates that there is little seasonal variation in the moisture content of the lower stratosphere. Frost points not far above the tropopause tend to be higher in summer than in winter, as they do in the troposphere, but further into the stratosphere the reverse appears to be true (see § 5, p. 31). No great significance should be attached to the crossing over of the summer and winter frost-point curves, however, owing to the very limited number of ascents exceeding the P_c–50-mb. level, where P_c is the pressure of the tropopause in millibars. The number of observations of which each point on the year's curves is the mean is indicated by the appropriate figure against the year frost-point curve. Owing to the relatively high seasonal variation in stratosphere temperature the corresponding relative humidities (entered against the temperature curves in Fig. 3) have at all levels in the stratosphere higher values in winter than in summer. In the upper troposphere on the other hand, where the seasonal frost-point variation is greater, values of relative humidity are lower in winter than in summer.

The mean curve for the whole year in Fig. 3 gives an average frost-point fall of 7·3°F. in the 25-mb. layer below the tropopause, and a fall of 11·4°F. in the 25-mb. layer above the tropopause, i.e. there is on the average a marked steepening of the lapse rate as the stratosphere is entered. Turning now to Fig. 4, the corresponding figures are seen to be 7·7° and 13·2°F. for Type I tropopause and 6·6° and 10·7°F. for Type II tropopause. Thus a steep stratospheric frost-point lapse rate tends to be associated with Type I tropopause, i.e. with temperature inversion.

Care must be taken in drawing conclusions from the slopes of the upper parts of the curves in Figs. 3 and 4. The number of observations used to determine the points on these curves

TABLE IV—MEAN VALUES OF

Number of ascents given in brackets

Winter = January–March

	P_c+ 150 mb.	P_c+ 125 mb.	P_c+ 100 mb.	P_c+ 75 mb.	P_c+ 50 mb.	P_c+ 25 mb.	Tropopause
	°F.	°F.	°F.	°F.	°F.	°F.	°F.
WINTER							
Temperature	−34·3 (22)	−41·2 (22)	−47·9 (22)	−54·8 (22)	−61·0 (23)	−67·9 (24)	−72·3 (28)
Frost point	−53·4	−59·4	−65·6	−72·0	−77·3	−84·3	−89·1
SPRING							
Temperature	−27·0 (45)	−33·1 (45)	−39·9 (45)	−46·9 (45)	−54·1 (45)	−61·0 (45)	−67·0 (46)
Frost point	−48·6	−52·4	−57·3	−62·1	−67·8	−74·5	−81·5
SUMMER							
Temperature	−20·4 (26)	−26·8 (26)	−33·8 (26)	−40·7 (26)	−49·1 (26)	−56·7 (26)	−63·2 (26)
Frost point	−40·4	−44·5	−49·6	−55·2	−61·9	−67·4	−76·8
AUTUMN							
Temperature	−26·4 (5)	−32·0 (6)	−37·8 (6)	−43·8 (6)	−49·8 (6)	−55·8 (6)	−63·2 (6)
Frost point	−50·8	−54·8	−60·6	−62·3	−66·0	−72·8	−79·0

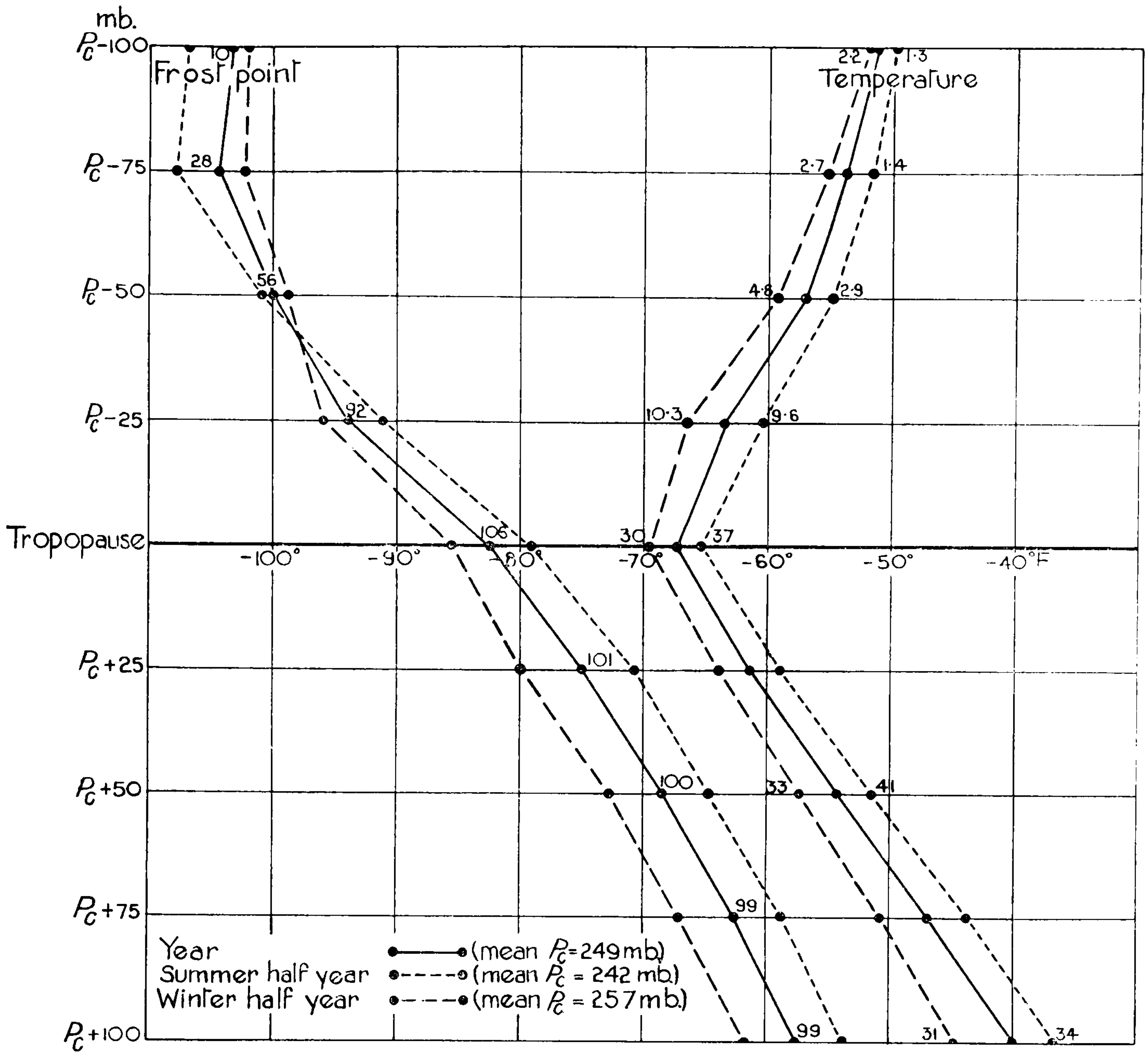


FIG. 3—MEAN ASCENT CURVES; SUMMER, WINTER AND YEAR

The figures against the summer and winter temperature curves indicate the corresponding relative humidities with respect to ice. Those against the year frost-point curve are the number of observations available. Summer half year = May 16th to November 15th; winter half year = November 16th to May 15th.

TEMPERATURE AND FROST POINT

Spring = April–June Summer = July–September Autumn = October–December

P_c— 25 mb.	P_c— 50 mb.	P_c— 75 mb.	P_c— 100 mb.	300 mb.	250 mb.	200 mb.	Mean tropopause height
°F.	°F.	°F.	°F.	°F.	°F.	°F.	mb.
−68·5 −97·7 (26)	−62·2 −98·2 (14)	−58·4 −101·9 (8)	−54·2 −101·7 (4)	−55·1 −76·3 (27)	−64·8 −89·1 (28)	−75·2 −97·4 (19)	251
−63·8 −93·2 (39)	−57·4 −101·4 (26)	−52·8 −105·7 (13)	−48·3 −102·0 (3)	−50·9 −69·1 (46)	−62·2 −82·3 (45)	−64·8 −99·4 (41)	249
−57·4 −90·4 (21)	−51·7 −99·1 (12)	−49·0 −104·0 (3)	−49·0 −101·0 (1)	−44·6 −58·7 (26)	−57·4 −73·5 (26)	−58·4 −95·8 (24)	239
−60·7 −90·6 (6)	−52·0 −98·0 (4)	−50·7 −105·0 (4)	−50·0 −109·5 (2)	−56·5 −80·2 (6)	−57·5 −95·2 (6)	−56·3 −106·3 (3)	290

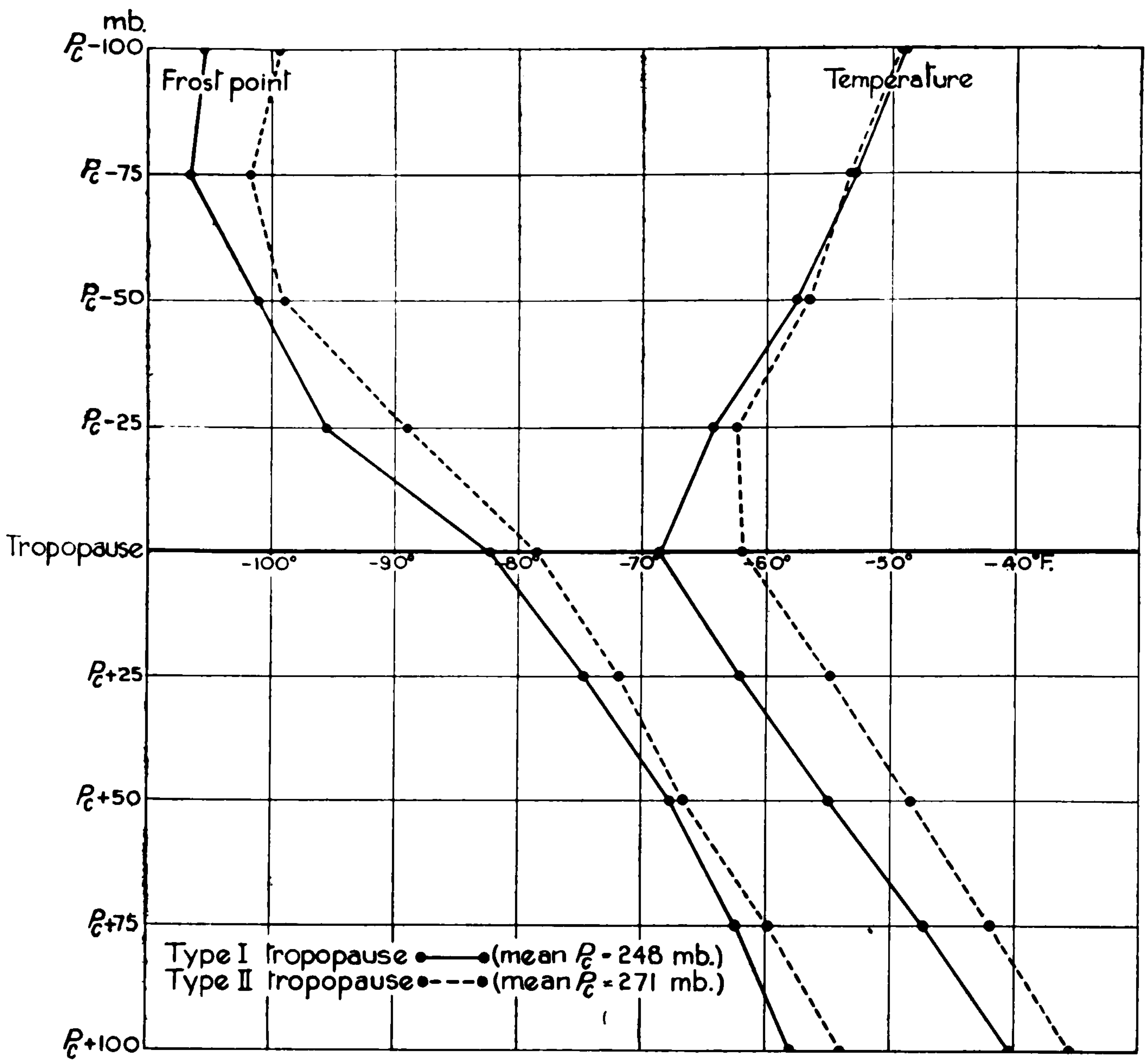


FIG. 4—MEAN ASCENT CURVES; TYPE I TROPOPAUSE AND TYPE II TROPOPAUSE

The number of observations at the various levels is as follows :—

	P_c-100	P_c-75	P_c-50	P_c-25	Tropo-pause	P_c+25	P_c+50	P_c+75	P_c+100
Type I tropopause ..	3	15	34	61	61	61	60	59	59
Type II tropopause ..	3	9	17	24	24	24	24	24	24

decreases rapidly with height. Further, since the aircraft ceiling is limited, the few observations available for the upper points on the curves were necessarily made on occasions of low tropopause. To overcome this difficulty Figs. 5 and 6 are given showing mean ascent curves similar to those in Figs. 3 and 4 respectively but computed from those ascents (49 in number) which had full frost point and temperature data from tropopause pressure $P_c + 100$ mb. to $P_c - 50$ mb.

Fig. 5 indicates again that the average summer stratosphere is, in its lower layers, slightly moister in terms of frost point than the winter one, but that higher up there is little seasonal variation (see § 5, p. 30). Fig. 6 indicates, perhaps more clearly than Fig. 4, the tendency for a steep frost-point lapse rate just above the tropopause to be associated with temperature inversion. Where there is no temperature inversion (Type II tropopause) the discontinuity in frost-point lapse rate at the tropopause is definitely less marked. It may well be that this steepening of frost-point lapse rate is not specially a characteristic of the tropopause, but that it occurs only when there is a temperature inversion, for it is well known that the same effect occurs at subsidence inversions in the troposphere.

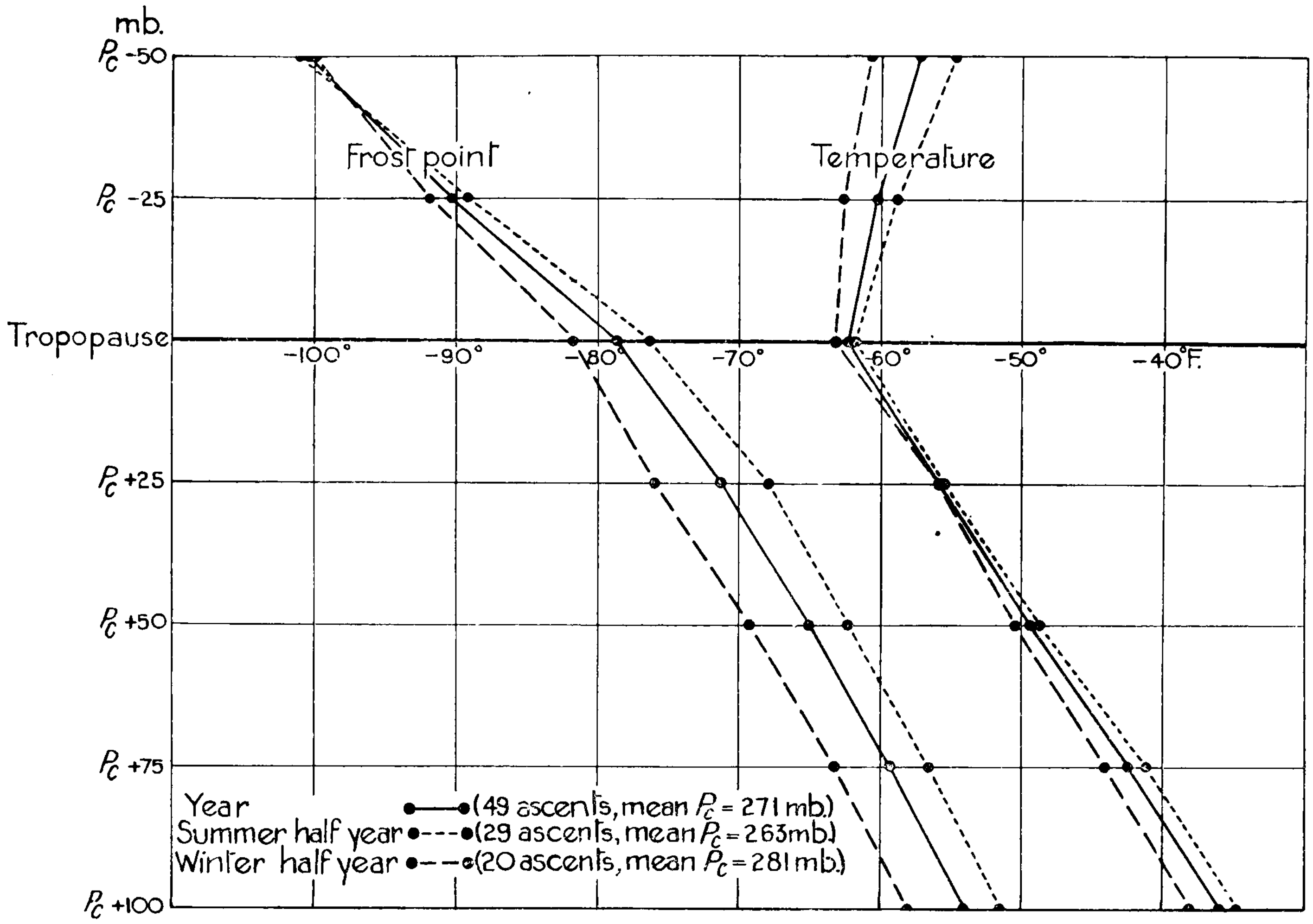


FIG. 5—MEAN ASCENT CURVES; SELECTED ASCENTS; SUMMER, WINTER AND YEAR

Summer half year = May 16th to November 15th; winter half year = November 16th to May 15th.

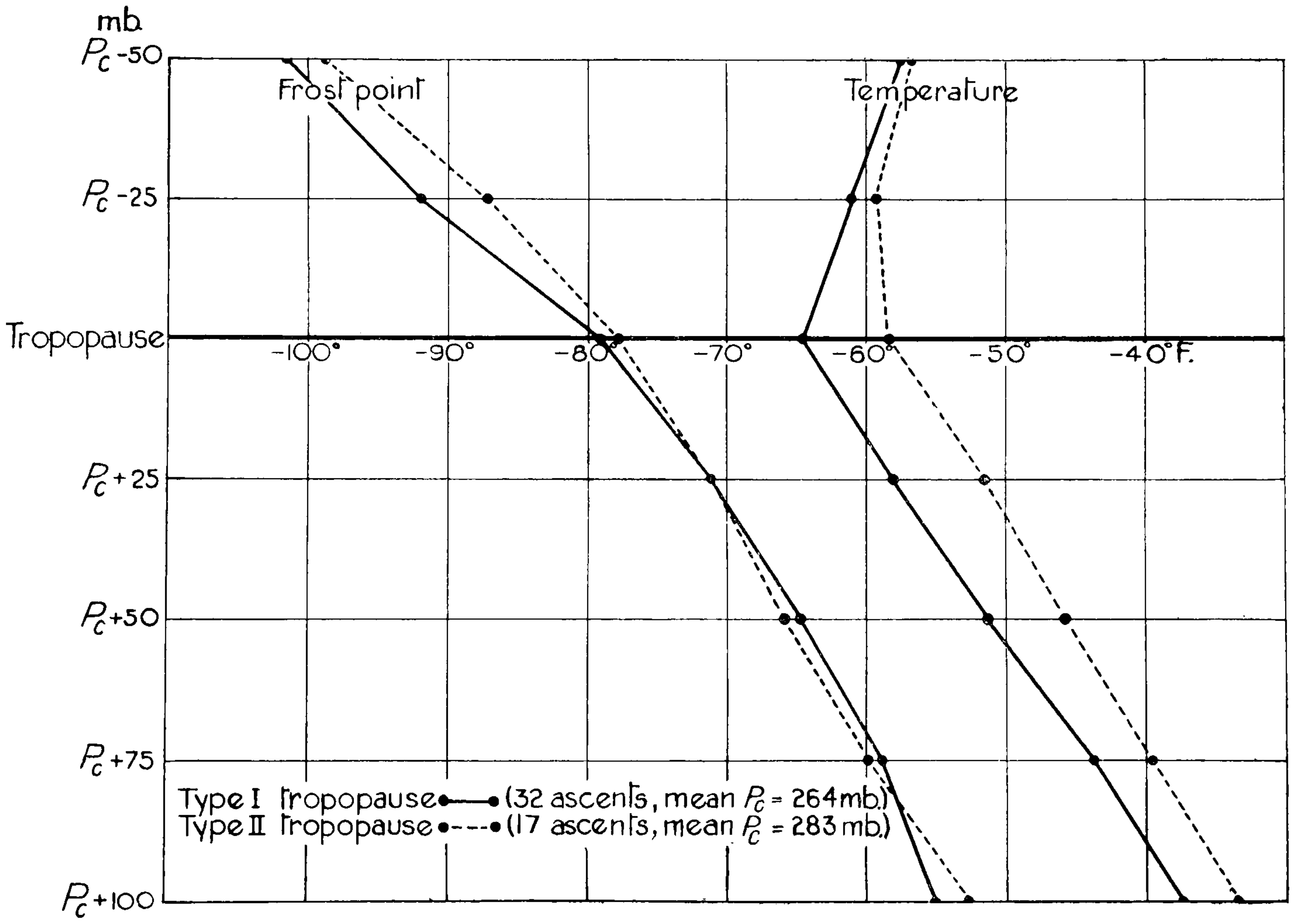


FIG. 6—MEAN ASCENT CURVES; SELECTED ASCENTS; TYPE I TROPOPAUSE AND TYPE II TROPOPAUSE

The mean tropopause pressure for the ascents in Fig. 5 is 271 mb. In Fig. 7 mean ascent curves are shown for those ascents having the tropopause (i) above 271 mb. and (ii) below 271 mb. The higher mean tropopause is of course colder than the lower one; it also has a lower frost point. The same applies to corresponding levels in the two stratospheres, and it will be noticed that in terms of relative humidity there is little between the two. At any fixed pressure level however the air is much drier in terms of frost point if the tropopause is low, and this rule appears to be valid whether the level chosen is in the lower stratosphere or the upper troposphere. There is a slight tendency for both temperature and frost-point discontinuities to be sharper at the higher tropopause than the lower one.

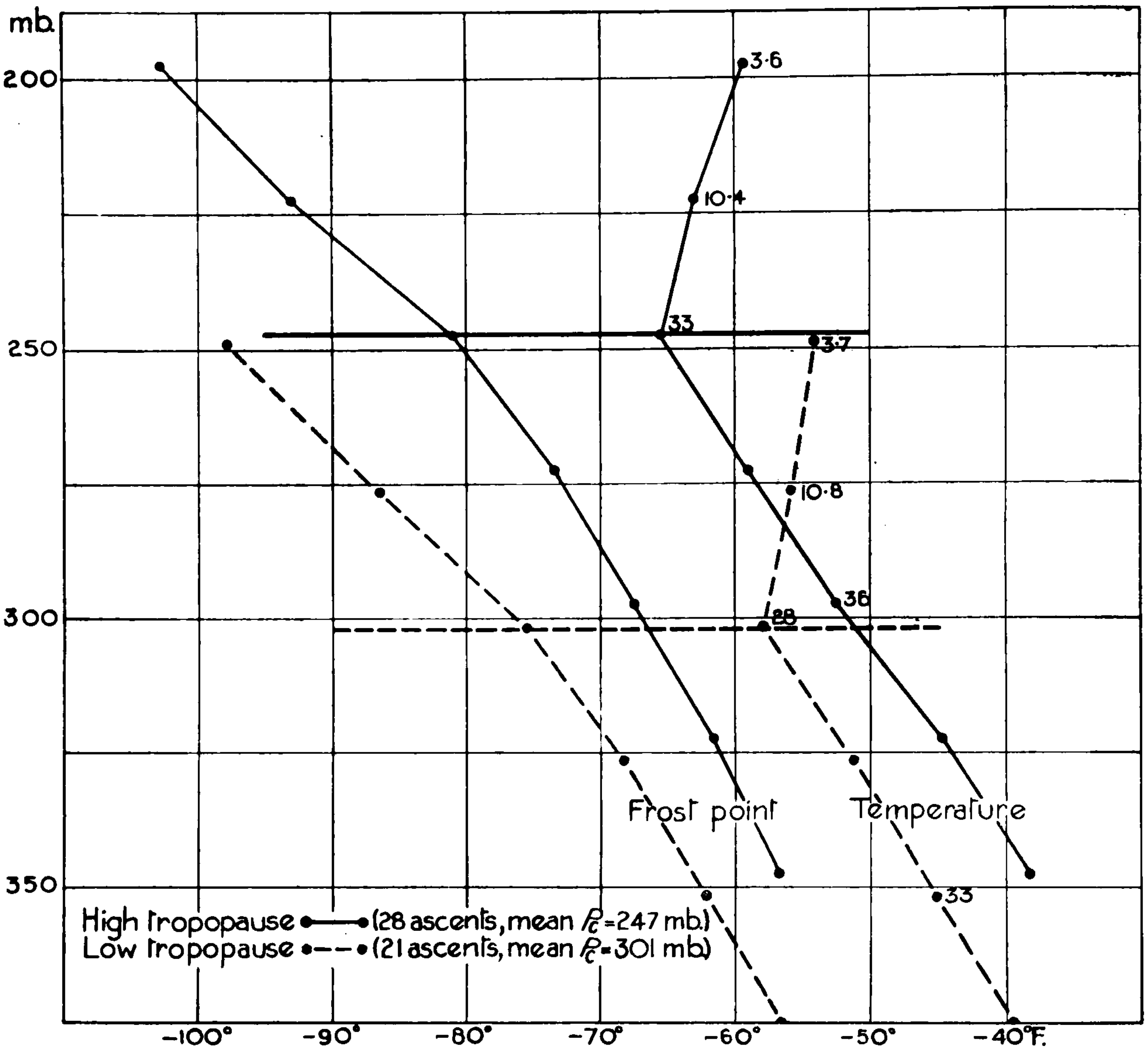


FIG. 7—MEAN ASCENT CURVES; SELECTED ASCENTS; HIGH TROPOPAUSE AND LOW TROPOPAUSE

The figures against the temperature curves indicate the corresponding relative humidity

Returning now to Fig. 5, on the curve for the full year the average frost-point lapse rate in the 25-mb. layer below the tropopause is 7·4°F. In the stratosphere the frost point falls 11·7°F. in the first and 10·3°F. in the second 25-mb. layer. The rate of fall of frost point in the stratosphere thus decreases with height, and it may be that the frost point eventually becomes constant. Fig. 8 shows mean ascent curves for those ascents, 23 in number, which penetrated 75 mb. into the stratosphere, and also for those, only 5 in number, which penetrated 100 mb. into the stratosphere and at the same time afforded full data down to P_c + 100 mb. These curves serve to indicate not only that, at any rate above low tropopauses, the frost point in the stratosphere continues to decrease with height but that the rate of decrease gets less, and that if the frost point does eventually become constant it probably does so at a value approaching − 120°F. Ascents to altitudes considerably above 40,000 ft. are required to settle this point. The lowest temperature yet recorded anywhere in the atmosphere below 100,000 ft. is − 129°F. at a height of 61,000 ft. over Nairobi (recorded by radio-sonde).

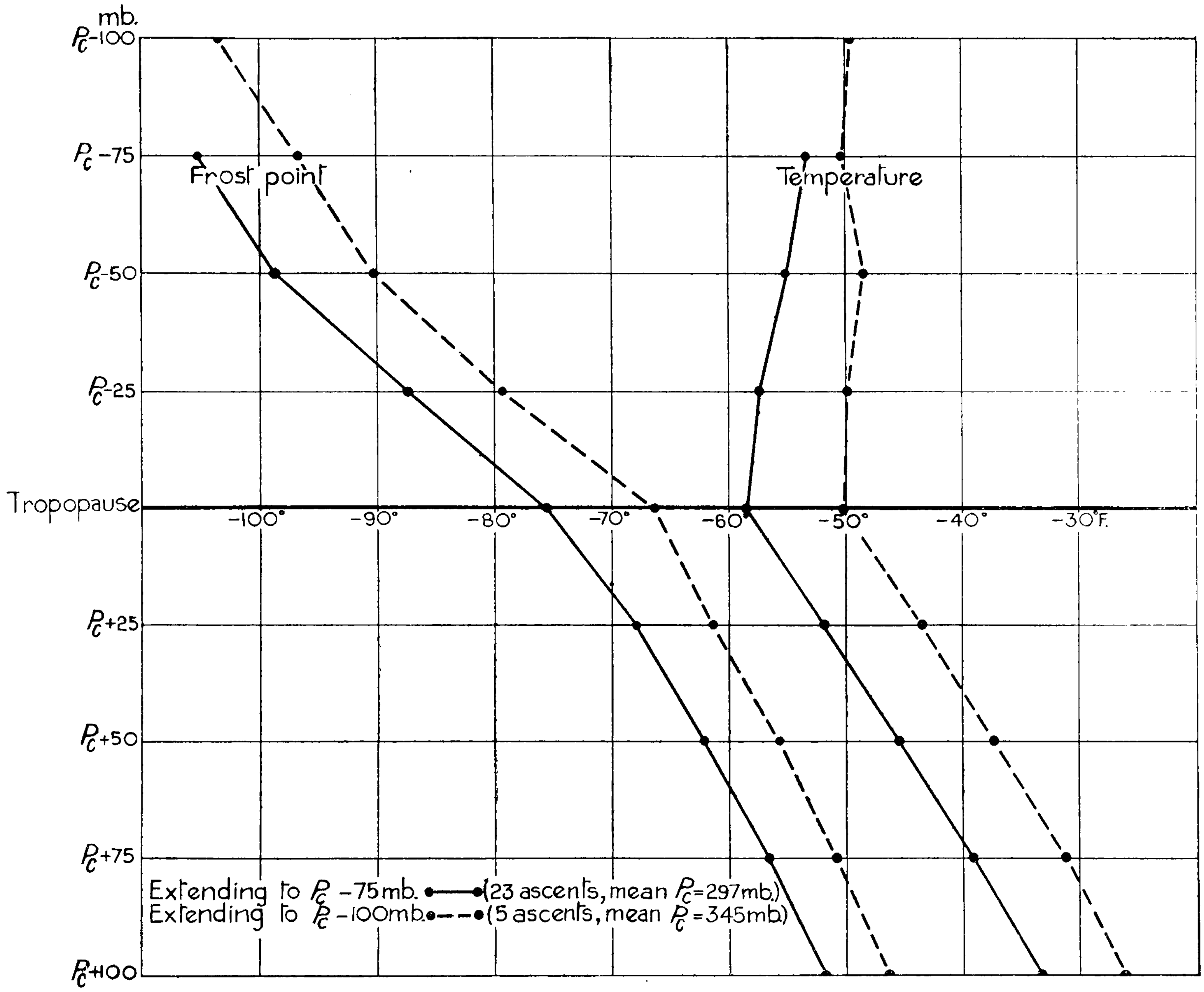


FIG. 8—MEAN ASCENT CURVES; SELECTED ASCENTS EXTENDING TO P_c−75 MB. AND TO P_c−100 MB.

Some correlation coefficients.—The results already discussed suggest that there is a correlation between lapse rate of temperature and lapse rate of frost point in the lower stratosphere. Values of temperature fall and of frost-point fall in the 25 mb. above the tropopause were therefore correlated. The resulting correlation coefficients, together with those for a number of other quantities, are set out in Table V, where the symbols have the following meanings :—

T_x = Temperature fall in the 25 mb. above the tropopause
F_x = Frost point fall in the 25 mb. above the tropopause
P_c, T_c, F_c = Pressure, temperature and frost point, respectively, at the tropopause
F_{c-50} = Frost point 50 mb. above the tropopause
$F_{200}, F_{250}, F_{300}$ = Frost point at 200, 250 and 300 mb. respectively
T_{500} = Temperature at 500 mb.

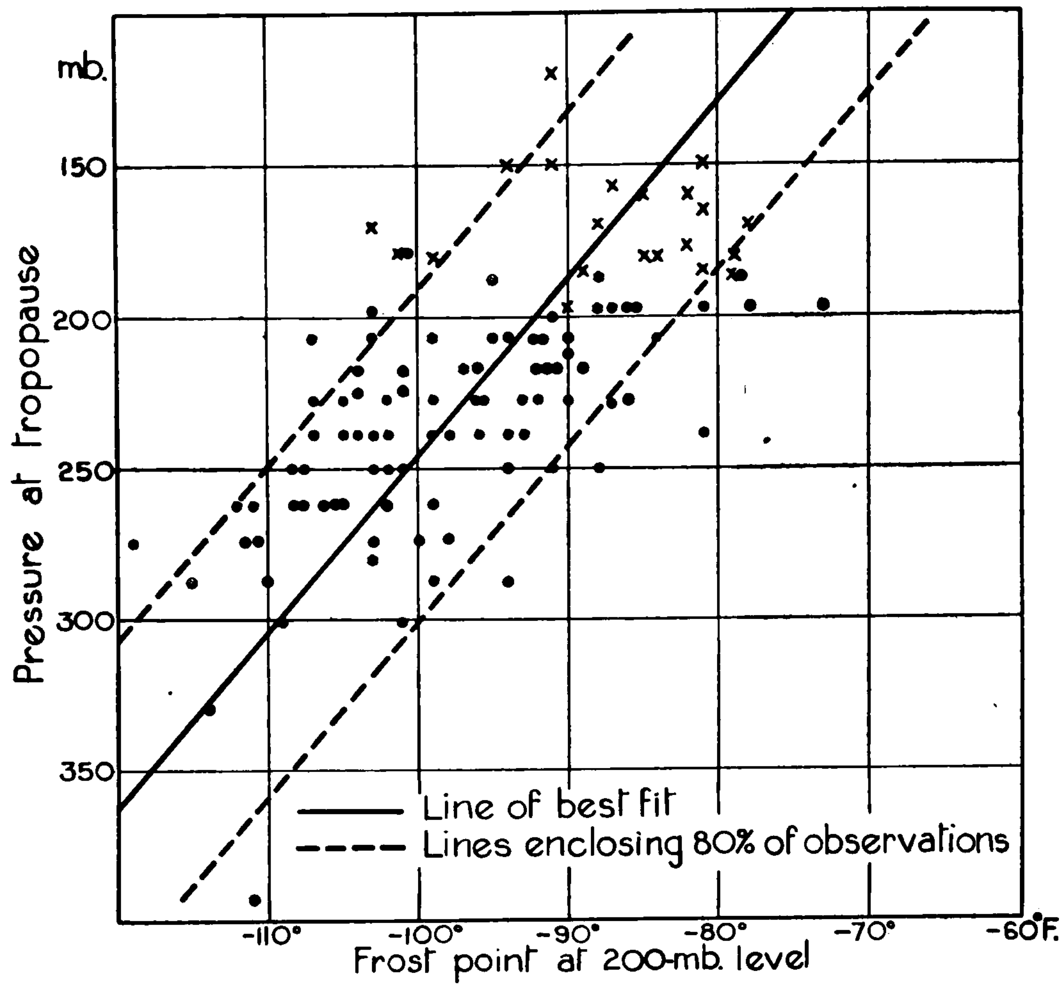


FIG. 9—RELATION BETWEEN TROPOPAUSE PRESSURE AND FROST POINT AT THE 200-MB. LEVEL

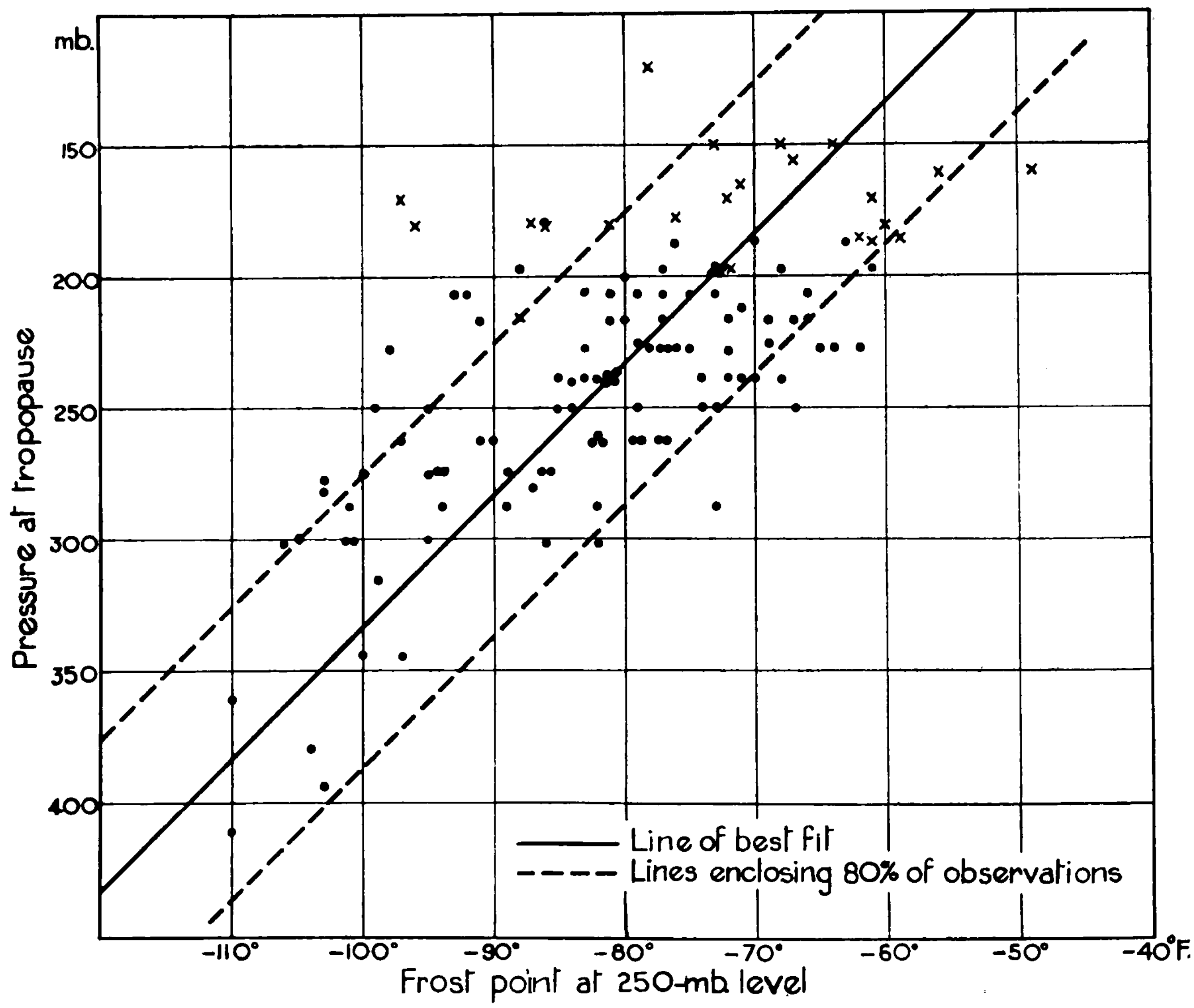


FIG. 10—RELATION BETWEEN TROPOPAUSE PRESSURE AND FROST POINT AT THE 250-MB. LEVEL

In Figs. 9, 10 and 11 crosses indicate observations made when the tropopause was not reached, values of P_t being estimated from radio-sonde data.

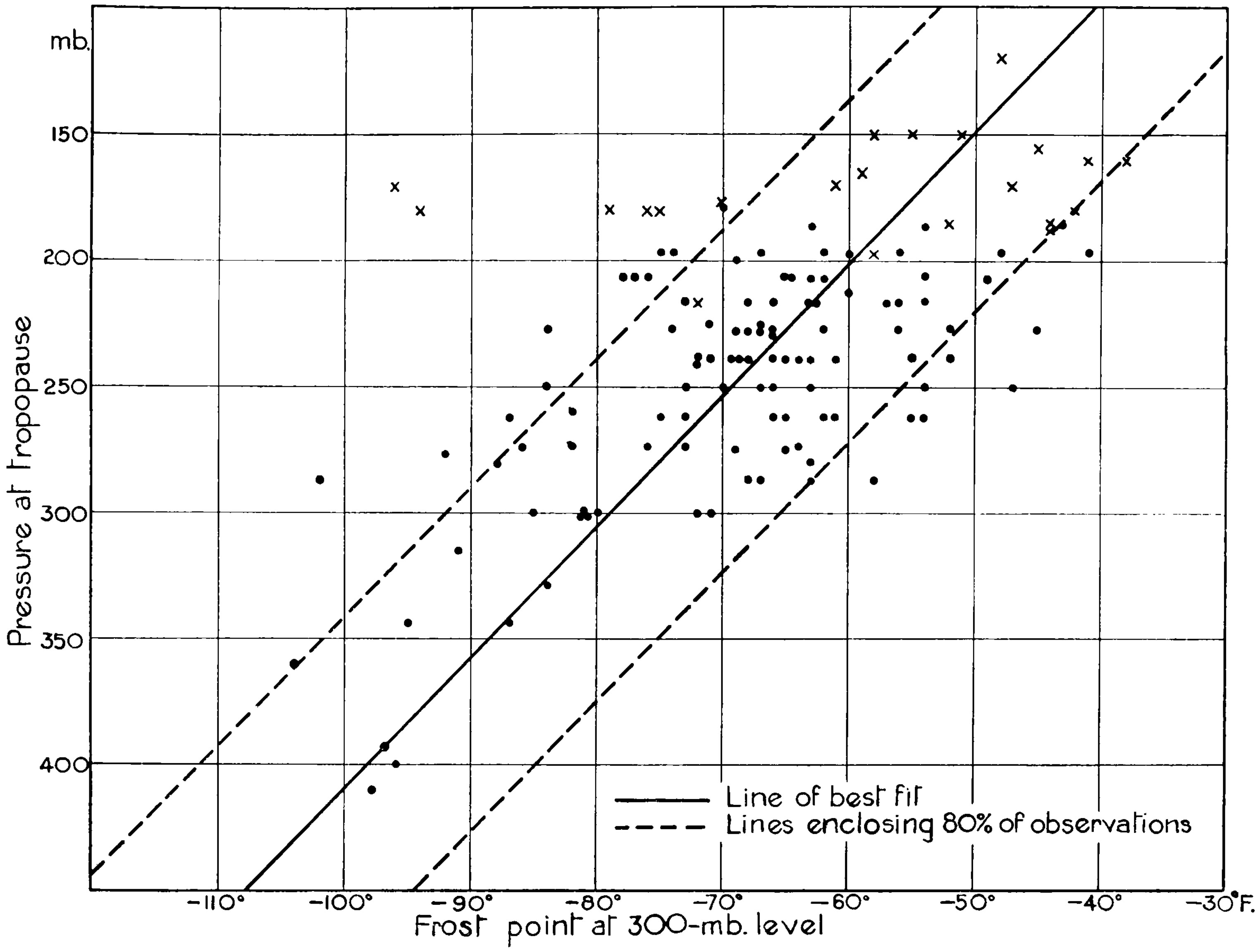


FIG. 11—RELATION BETWEEN TROPOPAUSE PRESSURE AND FROST POINT AT THE 300-MB. LEVEL

TABLE V—SOME CORRELATION COEFFICIENTS

	Correlation coefficient	No. of pairs of values
$T_x : F_x$	−0·38	92
$T_x : F_x$†	−0·49	62
$T_c : P_c$	+0·77	106
$T_{500} : P_c$	−0·68	106
$T_{500} : F_{200}$	+0·65	108
$T_{500} : F_{250}$	+0·83	127
$T_{500} : F_{300}$	+0·80	127

† Type I only.

	Correlation coefficient	No. of pairs of values
$F_c : P_c$	+0·51	106
$F_{c\text{-}50} : P_c$	+0·47	56
$F_{200} : P_c$	−0·66	87
$F_{250} : P_c$	−0·70	105
$F_{300} : P_c$	−0·66	105

The correlations between T_x and F_x, although small, are significant, the probabilities of such values arising by random sampling from an uncorrelated population being in both cases less than one in a hundred.

The high correlation between T_c and P_c represents a well known fact : the higher the tropopause the colder it is. Those between P_c and F_c and between P_c and the frost point 50 mb. above the tropopause (a level chosen as representative of the stratospheric air) are less significant though still indicating a marked relation.

The three correlations between P_c and frost point at the fixed pressure levels 200, 250 and 300 mb. are very significant. These relationships are illustrated in Figs. 9, 10, and 11, which are dot diagrams showing P_c against frost point at the three levels. In each case the full lines are lines of best fit computed by the method of least squares, whilst the dashed lines enclose 80 per cent. of the observations. They indicate that if P_c is known, F_{200}, F_{250} and F_{300} can be predicted to within $9\frac{1}{2}$°, $11\frac{1}{2}$° and $13\frac{1}{2}$°F. respectively, on 80 per cent. of occasions. Alternatively given

F_{200}, F_{250}, or F_{300}, P_c can be predicted to within 55, 56 or 68 mb. respectively on 80 per cent. of occasions. When many more ascents become available it is probable that these figures will be improved, as it may then be possible to construct separate diagrams for each season, air mass and synoptic type. All the dots in Fig. 10, for example, which lie outside the dashed lines to the right of the figure are observations made from June to September inclusive.

These correlations between F_{200}, F_{250} and F_{300} and P_c are similar in magnitude to those found by Dines[4] (0·7 approx.) and Priestley[6] (0·65) between T_{500} and height of tropopause H_c, and it seems possible, therefore, that the frost point at a fixed level may be closely associated with the mean temperature of the troposphere. Priestley has shown that T_{500} can be taken as representative of the whole column of air in the troposphere, and that it is in fact preferable to T_m (the mean temperature from 1000 to 300 mb.) for this purpose. Correlation coefficients have therefore been computed for T_{500} with F_{300}, F_{250} and F_{200} and are included in Table V. The last two are remarkably high, and the highest, that between T_{500} and F_{250}, is illustrated in Fig. 12 as a dot diagram. Here again the line of best fit and lines enclosing 80 per cent. of the observations have been drawn. It follows that given T_{500}, F_{250} can be predicted to within $9\frac{1}{2}$°F. on 80 per cent. of occasions. It may be significant that the correlation between frost point and T_{500} is least at 200 mb., a level which is predominantly stratospheric. Application of a test used by Fisher[7] suggests that the difference in significance indicated by these correlation coefficients is a real difference. This would suggest that the frost point in the stratosphere is less subject to control by tropospheric processes, or is less of an air-mass characteristic, than the frost point at lower (predominantly tropospheric) levels.

Finally, a coefficient of $-$ 0·68 between P and T_{500} has been computed, and this agrees well with Priestley's value of + 0·65 between H_c and T_{500}.

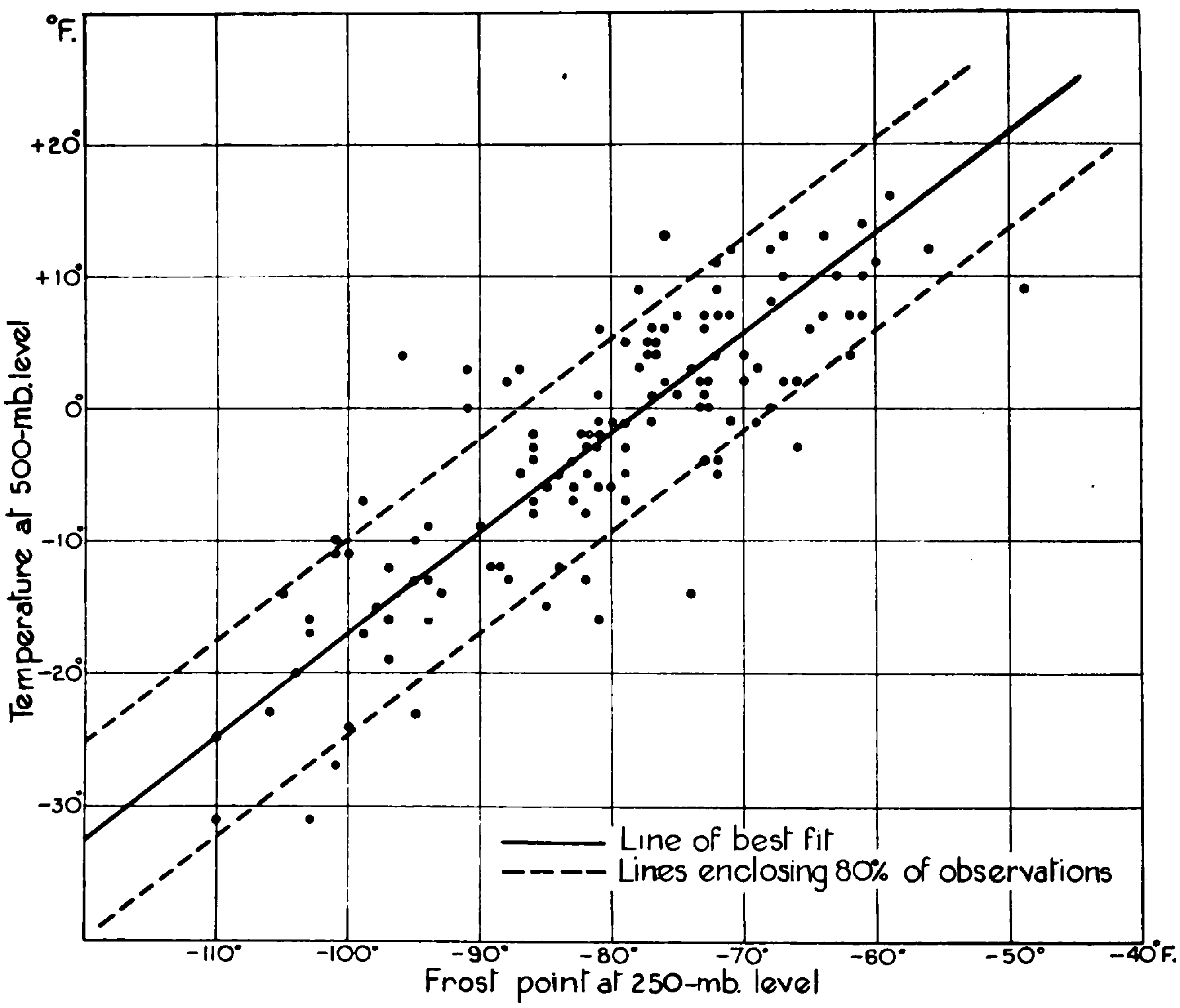


FIG. 12—RELATION BETWEEN TEMPERATURE AT THE 500-MB. LEVEL AND FROST POINT AT THE 250-MB. LEVEL

§ 5—FROST-POINT TEMPERATURE AT FIXED LEVELS

In § 4, p. 21 it is shown that the height of the tropopause and the frost point at fixed levels in the upper troposphere or lower stratosphere are partially related. If observations within each tropopause-height range in Table I are compared the effect of tropopause height on frost point at fixed levels will be largely eliminated.

A noteworthy feature of the distribution of water vapour in the upper troposphere and, to a less extent, in the lower stratosphere, is its large and irregular variation ; at a particular level the water-vapour content varies within wide limits from day to day, and these variations often seem little related to the variations at other levels, so that the character of the distribution of water vapour in the vertical is also changeable. This is not altogether surprising. All water vapour in the troposphere and lower stratosphere presumably has its origin at the earth's surface. The distributing mechanism is first convection and turbulence, and secondly the large-scale circulations in the atmosphere—anticyclones, depressions, trade winds and so on—and their associated vertical air movements. The processes of condensation and precipitation are always tending to return the water to the earth.

Considerable bodily sinking and rising of air occur in the upper troposphere and lower stratosphere, and often follow each other at short intervals. For example, air in the upper troposphere in moving over the top of a typical depression of temperate latitudes sinks on the east side of the ridge, rising again after passing through the upper trough, and all this may occur within 12 to 24 hr. Such subsidence and ascent must have a marked effect on the distribution of water vapour in the vertical.

The degree of convective or mechanical turbulence in the atmosphere also varies enormously, since the thermal stability of the air and the wind shear vary within wide limits. The rate of diffusion of water vapour therefore has corresponding wide variations.

Because of the large fluctuations of humidity it is necessary to consider mean values when comparing frost points in different weather types, air masses or seasons. In the analysis in the following paragraphs this is done, though often the number of observations to be meaned is very small. Because of these small numbers of observations in the various categories it must be emphasized that the results obtained can only be approximate.

Variation of frost point with circulation type.—Table VI, prepared from Table I, gives mean values of temperature and frost point for the three upper circulation types, namely anticyclonic, intermediate and cyclonic, for different seasons and for various ranges of tropopause height. The means are given for those cases where it is possible to make comparisons between the different circulation types. The numbers of observations are small in all the categories, and this must be remembered when making deductions from the mean figures. The ranges of temperature and frost point in the various categories are also given, in brackets, in Table VI. The variations of frost point are considerably greater than those of temperature in the upper troposphere in nearly all cases and are often as much as 30° to 40°F. ; in the lower stratosphere, however, the frost-point variations are at most 18°F. and are comparable with, occasionally less than, variations in temperature.

General character of distribution of humidity with height.—It is seen from Table VI that there is the following broad distinction between cyclonic and anticyclonic circulations with the intermediate cases between them. For similar tropopause heights cyclonic circulations are warmer and have lower frost points than anticyclonic in the neighbourhood of the tropopause (sometimes considerably below the tropopause as well) and in the lower stratosphere.

For the summer observations comparing cyclonic and intermediate circulations the former are warmer and with higher frost point than the latter at the 400-mb. level ; from 325 to 275 mb. the former are colder and with lower frost points, but near the tropopause and at higher levels

TABLE VI—MEAN TEMPERATURE AND FROST POINT FOR

Winter = January–March Spring = April–June

Figures in brackets give the

Tropopause range	Season	Upper circulation type	Air mass type	No. of observations	450 mb. Temp-erature	450 mb. Frost point	400 mb. Temp-erature	400 mb. Frost point
mb.					*degrees Fahrenheit*			
287–262	Winter	*i*	P, Pm	3 (but 2 only at 450 and 225 mb.)	− 25 (2)	− 31 (2)	− 38 (4)	− 55 (37)
		c	Pm	1	..	..	− 39	− 57
	Spring	*i*	Pm	7 (but 6 only at 225 and 200 mb.)	− 19 (4)	− 41 (44)	− 31 (3)	− 49 (33)
		c	P, Pm	3	− 17 (4)	− 36 (24)	− 26 (0)	− 41 (11)
262–238	Spring	*i*	P, Pm	5	− 17 (12)	− 43 (33)	− 29 (5)	− 52 (30)
		c	Pm	1	− 15	− 80	− 28	− 70
	Summer	*i*	P, Pm, T	4 (but 3 only at 200 mb.)	− 7 (5)	− 35 (46)	− 19 (3)	− 41 (37)
		c	P, Pc, Pm	3	− 6 (4)	− 22 (11)	− 18 (3)	− 34 (3)
238–216	Spring	*a*	Pc, T	4	− 11 (5)	− 41 (20)	− 23 (5)	− 49 (17)
		i	Pm	7 (but 6 only at 450 and 187 mb.)	− 12 (11)	− 46 (31)	− 23 (9)	− 47 (22)
		c	Pm	2	.. ..	.. ..	− 27 (3)	− 43 (7)
	Summer	*a*	Pm	2	− 3 (1)	− 31 (7)	− 13 (1)	− 28 (2)
		i	P, Pm	7	− 6 (9)	− 24 (24)	− 18 (9)	− 38 (28)
216–197	Winter	*a*	Pm	1	− 15	− 40	− 24	− 48
		i	P, Pm, T	5	− 15 (12)	− 34 (42)	− 26 (13)	− 41 (19)
	Spring	*a*	P, Pc, Pm, T	7 (but 6 at 225 and 200 mb. and 3 at 187 mb.)	− 9 (10)	− 43 (32)	− 21 (10)	− 50 (21)
		i		1	− 7	− 44	− 18	− 57
197–179	Winter	*a*	Pc, Pm, T	5 (but 4 only at 450 and 400 mb.)	− 10 (5)	− 37 (25)	− 19 (8)	− 48 (28)
		i	Pm	2	− 19 (6)	− 40 (26)	− 31 (9)	− 51 (19)
	Spring	*a*	Pm, T	5	− 3 (9)	− 24 (15)	− 15 (11)	− 28 (24)
		i	Pm	2	− 5 (1)	− 37 (10)	− 17 (1)	− 53 (5)
	Summer	*a*	Pm, T	2	+ 1 (11)	− 28 (32)	− 10 (10)	− 37 (31)
		i	Pm, T	3	0 (3)	− 8 (10)	− 10 (1)	− 24 (26)

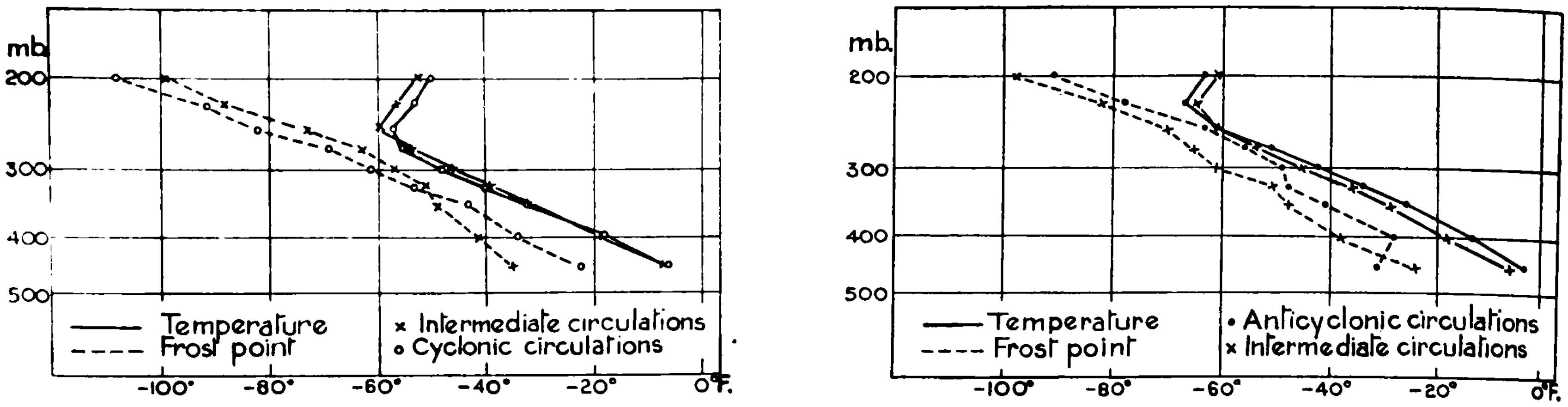
VARIOUS SEASONS AND UPPER CIRCULATION TYPES

Summer = July–September Autumn = October–December

total range of the observations

350 mb.		325 mb.		300 mb.		275 mb.		250 mb.		225 mb.		200 mb.		187 mb.	
Temp-erature	Frost point	Temp-erature	Frost point	Temp-erature	Frost point	Temp-erature	Frost point	Temp-erature	Frost point	Temp-erature	Frost point	Temp-erature	Frost point	Temp-erature	Frost point
							degrees Fahrenheit								
− 48 (3)	− 66 (18)	− 53 (3)	− 74 (8)	− 59 (5)	− 85 (6)	− 65 (4)	− 92 (11)	− 64 (10)	− 97 (9)	− 65 (1)	− 96 (2)	.. ..	.. ..	.. ..	.. ..
− 51	− 78	− 53	− 84	− 56	− 92	− 61	− 98	− 61	−103	− 57	−109	..	..	..	..
− 44 (6)	− 57 (18)	− 51 (8)	− 63 (18)	− 58 (8)	− 70 (12)	− 64 (10)	− 78 (19)	− 64 (10)	− 91 (14)	− 59 (8)	−104 (13)	− 54 (9)	−109 (16)	.. ..	.. ..
− 38 (4)	− 50 (8)	− 45 (5)	− 56 (10)	− 51 (8)	− 62 (9)	− 58 (9)	− 72 (5)	− 59 (11)	− 79 (9)	− 52 (11)	− 95 (8)	− 50 (9)	−102 (11)	.. ..	.. ..
− 40 (6)	− 58 (11)	− 46 (7)	− 61 (12)	− 53 (7)	− 68 (14)	− 60 (7)	− 75 (20)	− 66 (8)	− 81 (26)	− 64 (15)	−93 (19)	− 60 (16)	−105 (9)	.. ..	.. ..
− 39	− 68	− 44	− 78	− 45	− 84	− 42	− 94	− 50	− 95	− 50	−103	− 49	−103	..	..
− 32 (6)	− 49 (18)	− 39 (5)	− 51 (24)	− 46 (6)	− 57 (17)	− 53 (5)	− 63 (13)	− 59 (10)	− 73 (10)	− 56 (10)	− 88 (13)	− 52 (2)	− 99 (8)	.. ..	.. ..
− 32 (5)	− 43 (5)	− 40 (5)	− 53 (10)	− 48 (7)	− 61 (12)	− 55 (6)	− 69 (2)	− 57 (4)	− 82 (14)	− 53 (5)	− 91 (10)	− 50 (4)	−108 (7)	.. ..	.. ..
− 37 (4)	− 59 (9)	− 45 (4)	− 65 (9)	− 52 (4)	− 67 (4)	− 60 (7)	− 73 (12)	− 69 (8)	− 77 (9)	− 74 (4)	− 84 (16)	− 73 (3)	− 96 (6)	− 71 (5)	−102 (11)
− 36 (9)	− 56 (22)	− 44 (7)	− 63 (13)	− 51 (8)	− 66 (9)	− 59 (8)	− 71 (11)	− 66 (10)	− 80 (6)	− 70 (8)	− 86 (10)	− 67 (9)	−101 (11)	− 66 (11)	−107 (18)
− 37 (2)	− 57 (5)	− 43 (7)	− 64 (2)	− 47 (9)	− 66 (0)	− 53 (9)	− 73 (14)	− 57 (15)	− 81 (19)	− 61 (9)	− 86 (12)	− 57 (3)	− 95 (17)	.. ..	.. ..
− 26 (4)	− 41 (6)	− 34 (2)	− 48 (12)	− 42 (2)	− 49 (7)	− 51 (1)	− 56 (0)	− 61 (3)	− 63 (2)	− 67 (7)	− 78 (14)	− 63 (15)	− 91 (10)	.. ..	.. ..
− 29 (9)	− 48 (13)	− 36 (11)	− 51 (24)	− 45 (12)	− 61 (18)	− 54 (11)	− 65 (15)	− 61 (14)	− 70 (11)	− 65 (22)	− 82 (12)	− 61 (13)	− 98 (15)	.. ..	.. ..
− 39	− 62	− 47	− 64	− 54	− 73	− 63	− 73	− 72	− 80	− 80	− 84	− 82	− 89	− 80	− 86
− 39 (10)	− 51 (31)	− 46 (9)	− 60 (23)	− 53 (12)	− 67 (24)	− 60 (12)	− 74 (27)	− 68 (12)	− 83 (27)	− 76 (16)	− 89 (22)	− 80 (21)	− 98 (17)	− 78 (18)	−102 (13)
− 35 (8)	− 59 (22)	− 43 (10)	− 61 (31)	− 51 (8)	− 66 (21)	− 57 (9)	− 73 (20)	− 65 (7)	− 77 (21)	− 73 (9)	− 83 (16)	− 76 (11)	− 94 (8)	− 76 (11)	− 98 (6)
− 32	− 53	− 40	− 57	− 46	− 63	− 55	− 63	− 65	− 66	− 70	− 81	− 70	− 96	− 66	−100
− 34 (9)	− 58 (25)	− 41 (8)	− 57 (22)	− 48 (7)	− 63 (22)	− 57 (5)	− 70 (24)	− 66 (7)	− 78 (16)	− 74 (7)	− 89 (13)	− 82 (7)	− 94 (14)	− 85 (7)	− 98 (5)
− 45 (5)	− 64 (16)	− 52 (6)	− 69 (17)	− 59 (7)	− 77 (5)	− 67 (9)	− 82 (4)	− 74 (6)	− 87 (1)	− 79 (14)	− 96 (2)	− 83 (1)	−102 (2)	− 87 (17)	−104 (4)
− 29 (11)	− 44 (27)	− 36 (9)	− 49 (26)	− 43 (9)	− 57 (24)	− 52 (9)	− 63 (23)	− 61 (9)	− 69 (15)	− 68 (7)	− 78 (14)	− 76 (9)	− 84 (10)	− 78 (8)	− 88 (10)
− 30 (0)	− 62 (8)	− 36 (4)	− 71 (1)	− 43 (3)	− 75 (0)	− 50 (4)	− 79 (2)	− 57 (3)	− 77 (8)	− 65 (2)	− 80 (6)	− 73 (2)	− 87 (3)	.. ..	.. ..
− 23 (5)	− 46 (32)	− 31 (7)	− 49 (19)	− 37 (1)	− 53 (19)	− 45 (5)	− 64 (18)	− 55 (3)	− 67 (17)	− 61 (3)	− 73 (17)	− 71 (1)	− 85 (7)	.. ..	.. ..
− 23 (6)	− 31 (21)	− 31 (4)	− 38 (15)	− 38 (4)	− 42 (3)	− 47 (3)	− 51 (4)	− 55 (1)	− 61 (1)	− 64 (1)	− 67 (4)	− 73 (2)	− 76 (6)	− 75 (4)	− 85 (11)

the former are warmer and with lower frost points than the latter (see Fig. 13). In the tropopause-height range 238–216 mb. the summer intermediate and anticyclonic circulations follow this pattern (Fig. 13) as do the winter and spring observations in the tropopause-height range 216–197 mb.



Tropopause range 262–238 mb.

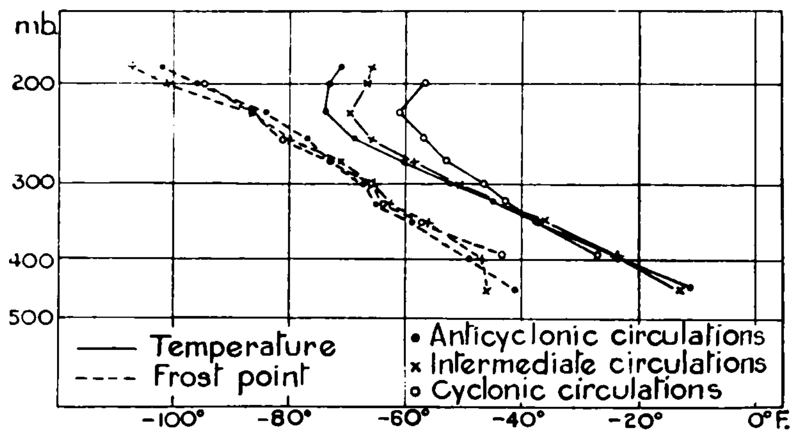
Intermediate circulations	4 obs.
Cyclonic circulations	3 obs.

Tropopause range 238–216 mb.

Anticyclonic circulations	2 obs.
Intermediate circulations	7 obs.

FIG. 13—MEAN SUMMER TEMPERATURE AND FROST POINT

Sometimes, however, the observations do not agree with the general pattern. For example, the cyclonic circulations for the tropopause-height range 287–262 mb. in the spring season are warmer and moister than the intermediate circulations above the 450-mb. level. The spring observations in the tropopause-height range 238–216 mb. confirm the pattern only partially (Fig. 14). One of the cyclonic circulations, May 27, 1948, was exceptionally moist above the tropopause, the observed frost point at 187 mb. (— 79°F.) being reached only once again (July 20, 1948) at this level during the whole series of observations, when it was at the tropopause; for this reason this case is probably not representative. The other cyclonic circulation, on June 13, 1950, followed the pattern, being very dry in the stratosphere.



Tropopause range 238–216 mb.

Anticyclonic circulations	4 obs.
Intermediate circulations	7 obs.
Cyclonic circulations	2 obs.

FIG. 14—MEAN SPRING TEMPERATURE AND FROST POINT

The evidence for and against the general pattern of temperature and frost-point distribution is summarized in Table VII. Observations in the tropopause-height range 197–179 mb., since they give no information in the stratosphere, cannot definitely confirm or deny the general pattern

TABLE VII—SYNOPSIS OF EVIDENCE FOR AND AGAINST PROPOSED TEMPERATURE AND FROST-POINT PATTERN IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE

Numbers of cases in the various circulation types are shown in brackets

Winter = January–March Spring = April–June Summer = July–September Autumn = October–December

Season	Tropopause height range				
	287–262 mb.	262–238 mb.	238–216 mb.	216–197 mb.	197–179 mb.
Winter	Agrees (3*i*, 1*c*)	Agrees mainly (1*a*, 2*i*, 1*c*)	. .	Agrees (5*i*, 1*a*)	Agrees for frost point, not for temperature (5*a*, 2*i*)
Spring	Disagrees (7*i*, 3*c*)	Agrees (5*i*, 1*c*)	Agrees mainly ; not for frost point at 200 mb. circulation *c* (4*a*, 7*i*, 2*c*)	Agrees (7*a*, 1*i*)	Agrees (5*a*, 2*i*)
Summer	. .	Agrees (4*i*, 3*c*)	Agrees (2*a*, 7*i*)	. .	Disagrees (2*a*, 3*i*)

but are included for the partial evidence they provide. In this table there are seven series which agree with the pattern, three which agree partly and two which disagree. Restricting the cases to those of Type I tropopause, i.e. when the tropopause was more clearly defined, there is approximately the same degree of agreement with the pattern.

This temperature and frost-point pattern is consistent with the following scheme of vertical motion in the upper atmosphere : general ascent in anticyclonic cases above a level in the upper troposphere sometimes near, sometimes some distance below, the tropopause, and general subsidence in cyclonic cases above a similar level. This is in agreement with the ideas of Goldie[8].

Marked discontinuity in lapse rate of frost point.—On many occasions there is a marked steepening of the lapse rate of frost point at a level not far from the tropopause. Table VIII gives some details of the relation of this level with the tropopause. It is seen that the more cyclonic the situation the more likely that the discontinuity in the frost-point lapse rate, if it occurs, will be at the tropopause. Only two cyclonic cases in nine occurred with the discontinuity

TABLE VIII—MARKED INCREASE IN LAPSE RATE OF FROST POINT WITH HEIGHT IN NEIGHBOURHOOD OF THE TROPOPAUSE

Circulation type	Total no. of observa-tions	No. of cases with frost-point discontinuity		Mean tropopause height for cases with frost-point discon-tinuity	Range of tropopause heights	Mean of difference in heights of tropopause and frost-point discon-tinuity	Range of differences in heights of tropopause and frost-point discon-tinuity	No. of cases with discontinuity and tropopause at same level	
		Type I tropopause	Type II and multiple tropopause					Type I tropopause	Type II and multiple tropopause
				mb.	mb.	ft.	ft.		
a	46	12	4	208	160–250	+ 2,130	12,000	3	1
i	64	13	11	266	212–393	− 190	6,400	6	4
c	18	7	2	264	216–375	+ 110	5,000	6	1

not at the tropopause. Conversely, the more anticyclonic the situation the more likely that the discontinuity is some distance below the tropopause. The type of tropopause did not appear to affect the result.

It was thought that these discontinuities in lapse rate of frost point might occur more often at lower heights, thus explaining their more frequent association with tropopause level in cyclonic than in anticyclonic circulations (since these have relatively low and high tropopauses respectively). Table IX shows, however, that the frequencies of occurrence of the height of the discontinuity and the height of the tropopause, within various ranges, are remarkably similar, in spite of the large individual variations of the height of the tropopause and frost-point discontinuity. The much closer association of the height of a marked steepening of lapse rate of frost point (when it occurs) with the height of the tropopause in cyclonic than in anticyclonic circulations must therefore be real.

TABLE IX—FREQUENCIES OF OCCURRENCE OF TROPOPAUSE AND OF MARKED STEEPENING OF LAPSE RATE OF FROST POINT WITHIN VARIOUS HEIGHT (PRESSURE) RANGES

The same observations are used for both sets of figures

	Ranges of height (pressure)					Mean height
	376–315 mb.	315–262 mb.	262–216 mb.	216–179 mb.	Above 179 mb.	mb.
Tropopause	2	13	23	9	2	247
Frost-point discontinuity ..	3	13	23	10	..	252

When the discontinuity in the frost-point lapse rate occurs below the tropopause then any corresponding change in the temperature lapse rate is small. It is difficult to visualize the air movements which bring about this state of affairs. It may be that there is a clue here to some, perhaps fundamental, atmospheric process.

Air-mass differences.—In the lower troposphere the dew point varies widely between air-mass types. In the upper troposphere and lower stratosphere it is difficult to make comparisons of water-vapour content (as shown by frost point) since water-vapour content varies with tropopause height. Indeed, analysing the observations with respect to tropopause height as is done in Table I shows that air-mass type appears to have little effect on the frost point, at any rate in the vicinity of the tropopause ; at much lower levels, say about 400 mb., the frost points vary widely, presumably because of subsidence or ascent. For example the summer frost points for tropopause range 262–238 mb., at the levels 275, 250 and 225 mb., do not show any systematic trend from lower to higher values as one progresses from polar through polar continental, polar maritime to tropical air. This rather surprising result is due to the method of analysis, as shown below.

The tropopause height is related to two factors, the air-mass type (or temperature) and the circulation type. The former is well illustrated by the high correlation (0·79) which Dines[4] found between the height of the tropopause and the mean temperature up to a height of 30,000 ft. (9 Km.), confirmed by Priestley[6] ; the latter is shown by the high correlation between tropopause height and surface pressure (0·68) or pressure at 30,000 ft. (9 Km.) (0·84) also found by Dines. In the same way the frost point at, say, the 300-mb. level is related to the air-mass type (or temperature) and also to the circulation type. The former relation is obvious ; tropical air would be expected to have high and polar air low water-vapour content. The latter relation was demonstrated on p. 23. Presumably the two factors, air-mass type (temperature) and circulation type, both aid in the relation between tropopause height and frost point at a fixed level (§ 4, p. 21).

TABLE X—MEAN TEMPERATURE AND FROST POINT IN VARIOUS AIR MASSES

Winter = January–March Spring = April–June Summer = July–September

Season	Circulation type	Air mass	400 mb. Temperature	400 mb. Frost point	400 mb. No. of obs.	300 mb. Temperature	300 mb. Frost point	300 mb. No. of obs.	200 mb. (troposphere) Temperature	200 mb. (troposphere) Frost point	200 mb. (troposphere) No. of obs.	200 mb. (stratosphere) Temperature	200 mb. (stratosphere) Frost point	200 mb. (stratosphere) No. of obs.
			°F.	°F.		°F.	°F.		°F.	°F.		°F.	°F.	
Winter	*i*	P	−40	−56	3	−60	−82	2	..	..	..	−70	−99	2
		Pm	−30	−54	13	−57	−77	14	−80	−102	3	−75	−97	7
		T	−22	−34	3	−52	−62	4	−88	−94	1	−75	−88	3
Spring	*c*	P	−34	−49	2	−55	−62	1	..	..	..	−54	−109	2
		Pm	−27	−50	3	−49	−69	4	..	..	..	−51	−100	4
	i	P	−29	−50	3	−51	−76	3	..	..	..	−71	−102	1
		Pm	−26	−50	19	−53	−69	22	−75	−86	3	−61	−104	18
	a	P	−23	−56	3	−53	−66	3	..	..	..	−79	−94	3
		Pc	−23	−52	4	−52	−71	4	..	..	..	−72	−97	4
		Pm	−15	−49	4	−45	−63	4	−77	−85	3	−71	−94	1
		T	−9	−36	6	−41	−55	7	−71	−85	4	−71	−88	3
Summer	*c*	P	−22	−39	3	−52	−60	3	..	..	..	−50	−109	2
		Pc	−16	−32	1	−45	−61	1	..	..	..	−51	−105	1
		Pm	−19	−39	2	−49	−65	2	..	..	..	−49	−105	2
	i	P	−19	−41	2	−47	−57	2	..	..	..	−56	−99	2
		Pm	−16	−33	12	−43	−55	13	−72	−76	3	−62	−95	8
		T	−15	−30	3	−38	−53	4	−67	−82	2	−56	−93	2
	a	Pm	−11	−37	5	−39	−52	5	−72	−84	3	−62	−91	2
		T	−5	−25	2	−36	−45	2	−73	−79	2	..	..	..

It is clear that comparing frost points of different air masses having similar tropopause heights will mean comparing frost points in different circulation types ; with the same tropopause height tropical air will have a more cyclonic circulation than polar air.

A better comparison of frost points in different air masses may be made by classifying occasions according to circulation type. Table X shows mean temperatures and frost points at the 400-, 300- and 200-mb. levels for various air masses and seasons, when there were sufficient observations for comparison purposes ; the observations at 200 mb. are divided according to whether they were in the troposphere or stratosphere. These means are based on small numbers of observations and the classification into air mass and circulation types is rather arbitrary, so that the figures given cannot be claimed to be representative. Frost-point temperatures at a particular level varied greatly. An increase of frost point going from polar through polar maritime to tropical air masses can be noted in many instances, especially at the 300-mb. level, but there are exceptions ; the frost-point differences between air masses are approximately the same as the temperature differences.

It is seen from Table X that, except in cyclonic circulations, the differences in both air temperature and frost point between air-mass types is less in the stratosphere (200 mb.) than in the upper troposphere. Table XI, constructed from Table X, gives the mean difference in temperature and frost point for all seasons and specified circulation types, between various air masses. The differences in frost point between polar maritime and polar air masses in cyclonic circulations at 400 and 300 mb. are negative ; that at 200 mb. (stratosphere) is positive and

TABLE XI—MEAN DIFFERENCES OF TEMPERATURE AND FROST POINT BETWEEN VARIOUS AIR MASSES (ALL SEASONS) FROM TABLE X

Air masses	Pressure level					
	400 mb.		300 mb.		200 mb. (stratosphere)	
	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point
	degrees Fahrenheit					
Pm — P (excluding *c* circulations)	6	4·3	3·3	4·3	2·3	1
Pm — P (*c* circulations)	5	− 0·5	4·5	− 6	2	6·5
T — P (all circulations)	16	21	10	15	1	9
T — Pm (all circulations) ..	5	12	4·7	8·3	2	5·7

much larger than for the other two circulation types. No explanation can be put forward for these peculiarities associated with cyclonic circulations ; the great majority of the observations, which are in the other two circulation types, do however show a smaller variation of temperature and frost point in the stratosphere than in the upper troposphere, between different air masses.

The fact that for different air masses with the same tropopause height there is little difference in frost point in the upper troposphere and lower stratosphere is consistent with the hypothesis put forward on p. 27, namely that anticyclonic circulations are associated with ascent, and cyclonic with subsidence, in upper levels. For example, suppose height H is below average tropopause height for tropical air but above average for polar air ; then those cases, tropical and polar, with tropopause at height H will be cyclonic and anticyclonic respectively, in the mean. That is, on the hypothesis given on p. 27, the tropical air will have subsided and will thus have lower frost point, while the polar air will have ascended thus having higher frost point than is usual for these air masses at the level H. Thus the effects of air-mass type and circulation type on frost point will tend to cancel each other.

Seasonal variation in frost point.—The same difficulties arise in comparing frost points in different seasons ; since there is a seasonal variation in tropopause height it is not strictly appropriate to compare cases with the same tropopause height in different seasons.

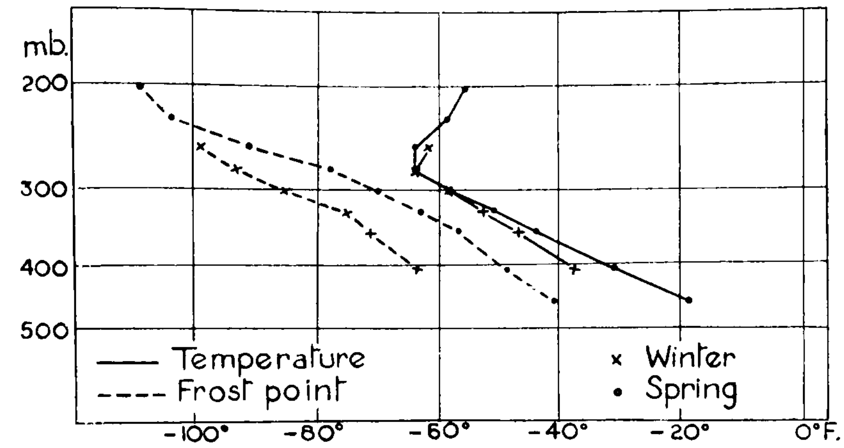
Dewar and Sawyer[9] give seasonal mean heights of the tropopause over southern England based on three years' (1943–45) daily observations by radio-sonde and various irregular observations by sounding balloons over many years ; they are as follows :—

Winter (December–February)	35,000 ft.
Spring (March–May)	34,500 ft.
Summer (June–August)	37,500 ft.
Autumn (September–November)	37,000 ft.

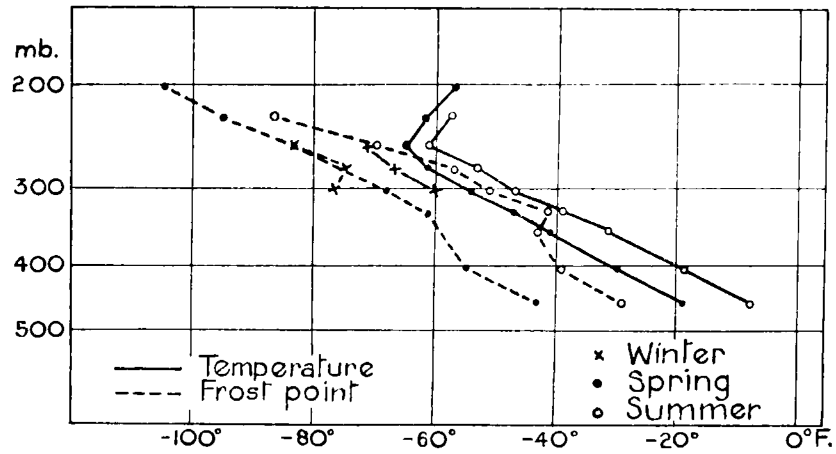
These figures are interpolated from the charts of mean tropopause height, and are only accurate to about 500 ft. The weather characteristics of a particular season probably have a great influence on the mean tropopause height ; e.g. Priestley[6] gives mean tropopause heights for Larkhill for 1944 as follows :—

Winter (December–February)	37,000 ft.
Spring (March–May)	36,300 ft.
Summer (June–August)	37,000 ft.
Autumn (September–November)	34,800 ft.

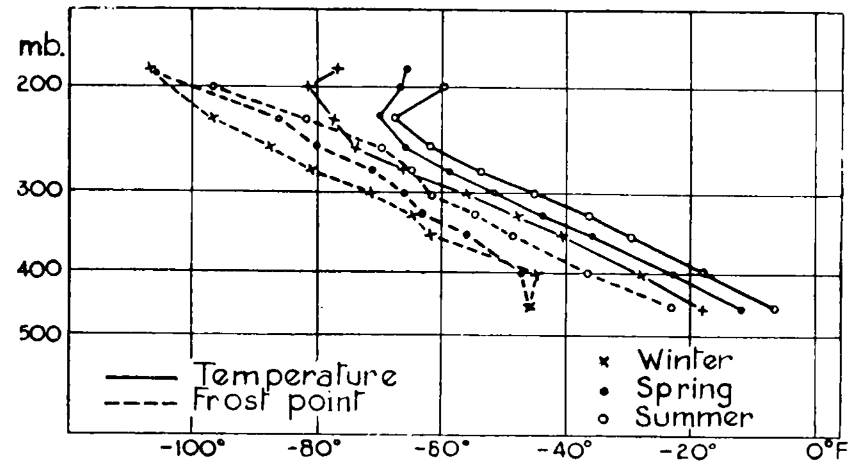
However, it would seem that the seasonal range of tropopause height is small, about 3,000 ft. In Table I the tropopause-height ranges are each 2,000 ft., so that in a comparison of observations in different seasons but having the same tropopause height, the error due to seasonal variation in tropopause height should not be large.



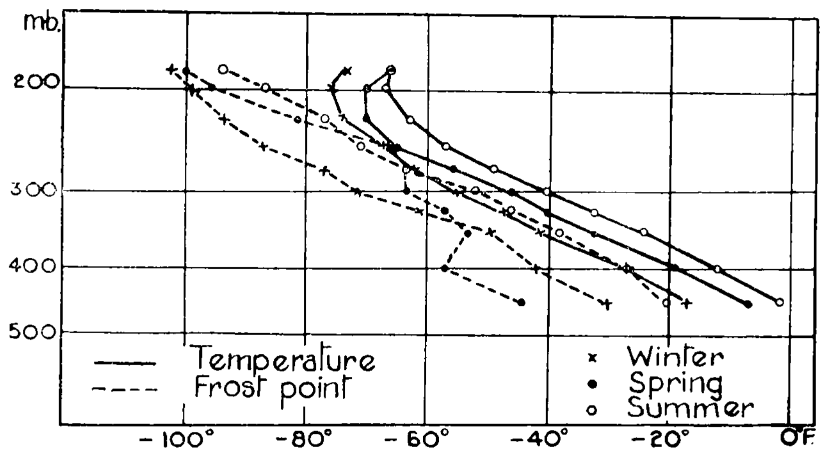
Tropopause range 287–262 mb.
Winter ... 2 obs. Spring ... 7 obs.



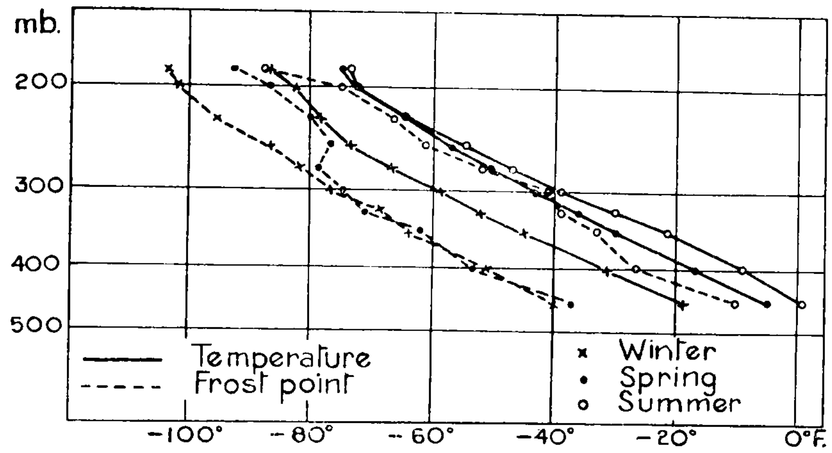
Tropopause range 262–238 mb.
Winter ... 2 obs. Spring ... 4 obs. Summer ... 2 obs.



Tropopause range 238–216 mb.
Winter ... 3 obs. Spring ... 7 obs. Summer ... 6 obs.



Tropopause range 216–197 mb.
Winter ... 2 obs. Spring ... 1 ob. Summer ... 3 obs.



Tropopause range 197–179 mb.
Winter ... 2 obs. Spring ... 2 obs. Summer ... 2 obs.

FIG. 15—MEAN SEASONAL TEMPERATURE AND FROST POINT ; POLAR MARITIME AIR MASS AND INTERMEDIATE UPPER CIRCULATION

Winter = January–March. Spring = April–June. Summer = July–September. Autumn = October–December.

Fig. 15 shows seasonal comparisons (winter, spring, summer) of temperature and frost point for five ranges of tropopause height for polar maritime air and intermediate type circulation. Fig. 16 gives a seasonal comparison for tropical air, anticyclonic circulation. Data were insufficient to make comparisons for other air masses.

It is obvious from these diagrams that the seasonal frost-point changes are smaller in the lower stratosphere than in the upper troposphere (compare results in § 4, p. 14). Table XII which gives the mean changes of temperature and frost point between seasons at heights 2,000 ft. above and below the tropopause, also emphasizes this point. This result is not surprising since transfer processes, turbulence and convection, are presumably more active in the troposphere than in the stratosphere and all moisture changes originate in the lower troposphere.

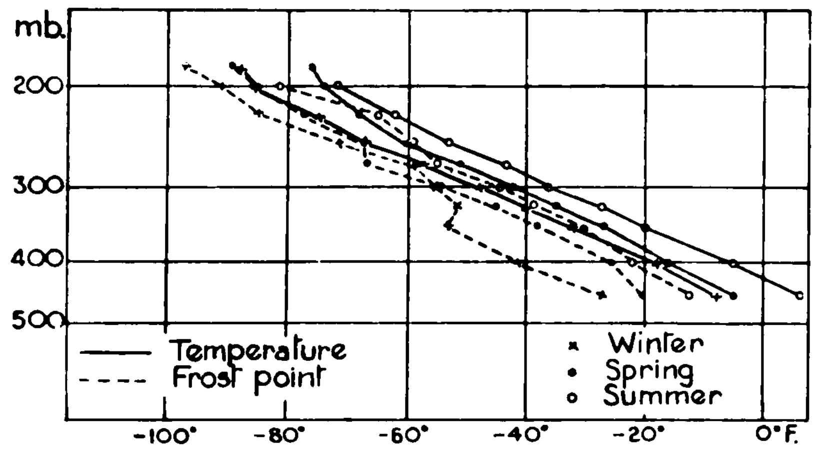
TABLE XII—MEAN SEASONAL CHANGES OF TEMPERATURE AND FROST POINT

Winter = January–March ; Spring = April–June ; Summer = July–September

	2,000 ft. above tropopause		2,000 ft. below tropopause		All levels above 350 mb.	
	Temperature	Frost point	Temperature	Frost point	Temperature	Frost point
			degrees Fahrenheit			
Winter–Spring	8	4	4	12	7	6
Spring–Summer	4	6	6	12	6	11

The figures in the last column (All levels above 350 mb.) were computed from the data shown in Fig. 15, those in the previous columns from the data shown in the first four diagrams of Fig. 15 only, i.e. for the tropopause ranges up to and including 216-197 mb.

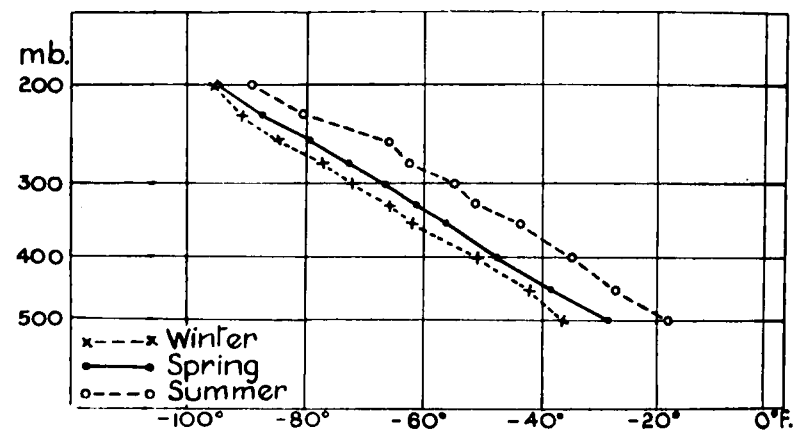
As will be seen in § 7, there is little or no discontinuity in the mean lapse rate of frost point for a particular tropopause height ; in other words the tropopause has little or no effect on the general character of the average distribution of frost point with height. Mean frost-point height curves for the various seasons, computed regardless of tropopause height, should give a rough indication of the seasonal changes in frost point in spite of the differing numbers of circulation and air-mass types in the data from which they were prepared. Such curves for the winter, spring and summer seasons are shown in Fig. 17. It is seen that the seasonal change in frost point decreases more or less steadily from 300 to 200 mb.



Tropopause range 197–179 mb.

Winter ... 2 obs. Spring ... 3 obs. Summer ... 1 ob.

FIG. 16—MEAN SEASONAL TEMPERATURE AND FROST POINT ; TROPICAL AIR MASS AND ANTICYCLONIC UPPER CIRCULATION



	Circulation type			Total no. of obs.
	Anticyclonic	Intermediate	Cyclonic	
Winter ...	5	14	2	21
Spring ...	19	22	6	47
Summer ...	8	19	6	33

FIG. 17—MEAN DISTRIBUTION OF FROST POINT WITH PRESSURE, REGARDLESS OF TROPOPAUSE HEIGHT, FOR WINTER, SPRING AND SUMMER

§ 6—EFFECT OF FRONTAL SURFACES ON FROST-POINT DISTRIBUTION

Seventeen Meteorological Research Flight ascents penetrated a frontal surface at or above the 450-mb. level. Table XIII gives details of these 17 occasions. The height of the frontal surface was determined by considering available neighbouring radio-sonde ascents as well as the aircraft sounding ; usually this height was in little doubt, within 25 mb. The last column of the table gives the decrease in the depression of the frost point below the air temperature in a 50-mb. interval covering the frontal zone or the zone of change in the lapse rate of the frost point, whichever is the smaller, in passing upwards through the frontal surface. On three

TABLE XIII—FROST-POINT CHARACTERISTICS OF FRONTAL SURFACES IN THE UPPER TROPOSPHERE

Date	Type of front	Height of frontal surface	Tropopause height	Decrease in frost-point depression through the front (through 50 mb. or the main change)
		mb.	mb.	°F.
3.5.44	warm	350	275	21*
9.2.45	warm	300	260	11*
6.2.48	warm	450	277	. .
24.5.48	cold	350	238	21
29.6.48	warm	375	285	0
19.10.48	warm	350	330	0
21.1.49	warm	425	238	31
1.3.49	cold	450	227	. .
18.3.49	cold	450	238	15
22.4.49	warm	225	188	3*
25.4.49	cold	450	250	. .
26.4.49	warm	400	250	20*
27.6.49	warm	375	188	17
26.7.49	warm	320	160	27*
8.8.49	cold	425	238	20
21.2.50	warm	300	238	7
20.4.50	warm	400	238	14

* This decrease, the main change, occurred in less than 50 mb.

occasions frost-point observations were not available below the frontal surface. The change in the frost-point depression has been taken as a suitable indicator of change in humidity in passing through the frontal surface. Normally both frost point and temperature fall off with height in the troposphere, but the lapse rate of temperature is much more steady, even when passing through frontal surfaces. Since water vapour is conveyed from one level to another by falling hydrometeors it is not surprising that the distribution of water-vapour content, as shown by frost point, is irregular compared with that of temperature. Thus the change in the frost-point depression is usually a good measure of the change of lapse rate of frost point. It is seen from Table XIII that there are often large changes of frost-point depression through a frontal surface; the mean of the depression figures given is 14·8°F.

It was noted that in six of the cases (1st, 2nd, 4th, 12th, 14th and 15th) the frost point appeared to be abnormally low, just below the frontal surface, compared with the general trend of frost-point distribution with height in the lower air mass. A typical example is shown in Fig. 18. In each of these cases the ascent was made in the vicinity of a jet stream. It may be

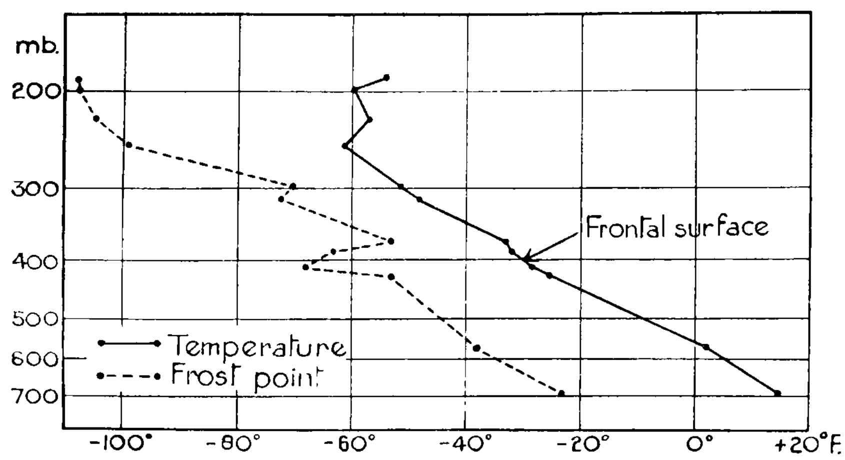


FIG. 18—AIRCRAFT SOUNDING 1030 G.M.T., APRIL 26, 1949

that this dryness below the frontal surface is caused by a vertical circulation associated with the front, though this is difficult to visualize.

§ 7—LAPSE RATE OF FROST POINT IN THE STRATOSPHERE

As previously mentioned in § 4, p. 12, there is often, but not invariably, a sharp increase in the lapse rate of frost point on entering the stratosphere. The mean differences in the frost-point lapse rate in the two layers, tropopause to 25 mb. above and tropopause to 25 mb. below, are given in Table XIV for those ascents which penetrated 25 mb. or more into the stratosphere.

TABLE XIV—MEAN DIFFERENCES IN LAPSE RATE OF FROST POINT IN THE LAYERS TROPOPAUSE TO 25 MB. ABOVE AND TROPOPAUSE TO 25 MB. BELOW

	Circulation type			All types
	Cyclonic	Intermediate	Anticyclonic	
Mean difference (°F./1,000 ft.)	3·9	1·3	1·1	1·8
No. of observations	16	51	19	86

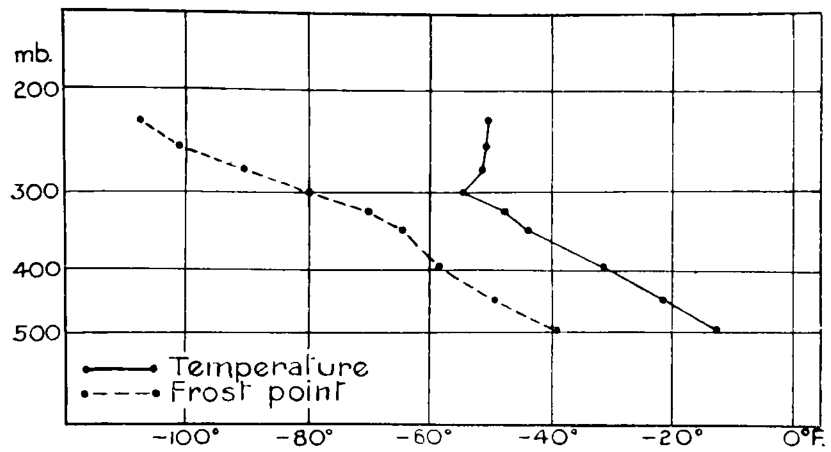
No relation between tropopause height and this discontinuity in the lapse rate of frost point could be discovered within the same circulation type.

It is immediately obvious from Table XIV that the circulation type has a large effect on the steepening of the lapse rate of the front point above the tropopause. The early observations used by Dobson, Brewer and Cwilong[1] were in cyclonic or intermediate circulations, so that the very rapid fall in frost point on entering the stratosphere to which they drew attention results from the predominating cyclonic tendency.

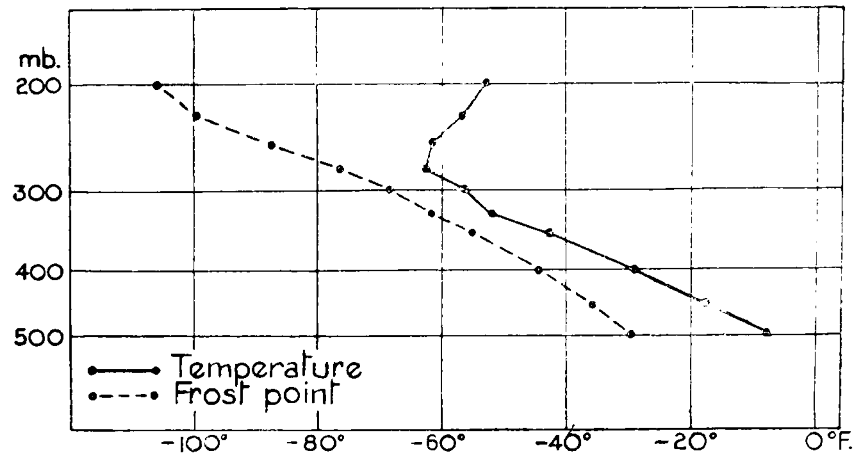
It was shown in § 4, p. 14 that the lapse rate of frost point above the tropopause is partially related to the sharpness of the tropopause, i.e. the rate of increase of temperature with height in the lower stratosphere. This is consistent with subsidence in the lower stratosphere being the cause of the increased lapse rate of frost point in cyclonic conditions.

This steepening of the lapse rate of frost point with height just above the tropopause occurs in a shallow layer, however. It was pointed out by Frith[10] that, contrary to the findings of the first few observations of frost-point temperatures in the lower stratosphere[1] the lapse rate of frost point, on the average, is much the same in the lower stratosphere as in the upper troposphere. This has been mainly confirmed by later observations. The mean temperature and frost-point distributions with pressure, regardless of season, are given in Fig. 19, for the five ranges of tropopause height, 315–287 mb., 287–262 mb., 262–238 mb., 238–216 mb., and 216–197 mb. Complete observations for other tropopause-height ranges were too few to warrant consideration. Pressure is on a logarithmic scale in Fig. 19 so that the ordinate is approximately proportional to height. It will be noted that any steepening of the lapse rate of frost point with height just above the tropopause is temporary.

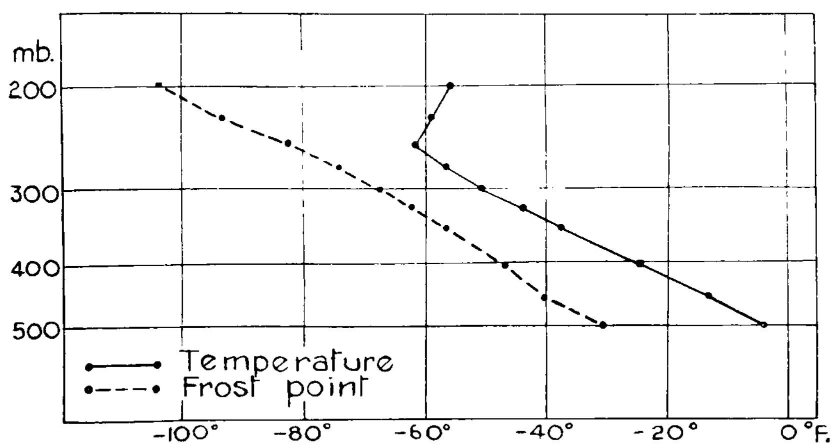
The very rapid fall in frost point with height on entering the stratosphere above depressions can be explained by the mechanism discussed by Goldie[8]. According to this (see for example his Figs. 1 and 2) the formation (or travel) of a depression involves removal of a quantity of air from the depression to the anticyclone in the levels between about the 400-mb. level and the tropopause, together with subsidence in the stratosphere above the depression. This removal in effect creates a discontinuity in the vertical direction by bringing together layers which were separated by possibly 4,000 to 6,000 ft. It must thus result in a steeper step down in frost point in the region of the tropopause over depressions than is found in the originally undisturbed atmosphere, assuming that in the undisturbed atmosphere there was a steady fall of frost point with height.



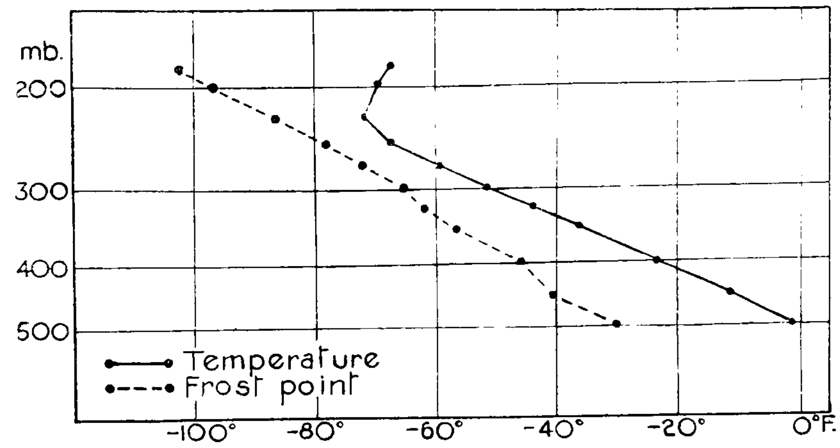
Tropopause range 315–287 mb. (6 obs.)



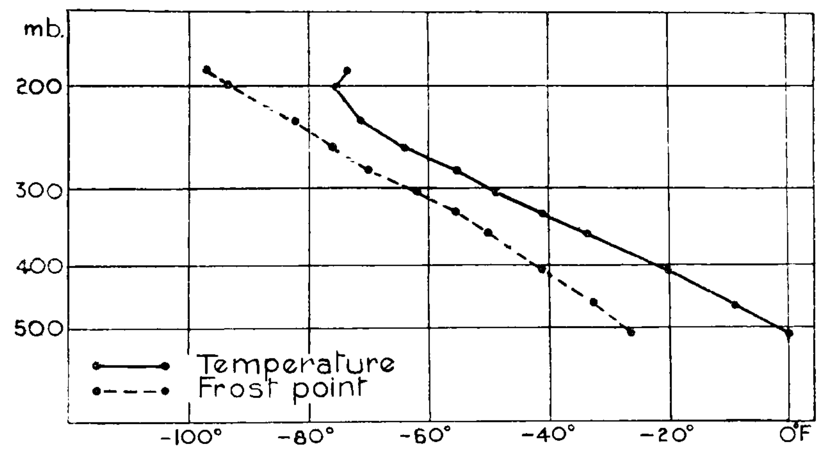
Tropopause range 287–262 mb. (13 obs.)



Tropopause range 262–238 mb. (14 obs.)



Tropopause range 238–216 mb. (15 obs.)



Tropopause range 216–197 mb. (13 obs.)

FIG. 19—MEAN TEMPERATURE AND FROST-POINT DISTRIBUTION WITH PRESSURE ; ALL OBSERVATIONS

§ 8—OBSERVATIONS IN THE NEIGHBOURHOOD OF JET STREAMS

There were 21 ascents in the neighbourhood of narrow zones of high winds in the upper troposphere which are usually called jet streams. The occasions are marked in Table I. The definition of a jet stream is necessarily rather arbitrary ; about 100 kt. or more for the maximum wind speed is taken as the criterion.

No particular patterns or peculiarities in the humidity structure are noticeable in the neighbourhood of a jet stream except in the abnormal dryness beneath frontal surfaces as mentioned in § 6, p. 33. In particular, the frost-point observations lend no support to the theories of Palmén and Nagler[11] or Namias and Clapp[12] which postulate vertical circulations about the direction of the jet ; observations apparently similarly placed with respect to a jet stream sometimes differed largely in character, e.g. on January 21, 1949 and March 18, 1949.

However, the observations are so few in number and the distribution of water vapour so variable in general, as has been remarked previously, that the failure of these frost-point observations to confirm either of these theories is not conclusive.

§ 9—CONCLUSIONS

From these first 130 flights the broad character of the distribution of frost point over southern England is now known up to a height of 39,000 to 40,000 ft. This means that the general nature of the water-vapour distribution is known over southern England in the upper troposphere, and is also known for the lowest layers of the stratosphere when the tropopause is near or below normal height; for tropopauses above the normal height, i.e. above about 36,000 ft., humidity information in the stratosphere is restricted to a few observations in a layer generally not more than 3,000 ft. thick. All deductions regarding the humidity distribution in the lower stratosphere, its variation between seasons, etc., which have been made in previous sections, suffer from this restriction and apply only to occasions with tropopause not above average height.

Thus knowledge of the distribution of water vapour in the lower stratosphere is severely limited. As pointed out by Dobson, Brewer and Cwilong[1], prior to these observations it was thought that the humidity-mixing ratio in the lower stratosphere would be found to be approximately constant with height. The humidity-mixing ratio has, however, been found to fall with height in the shallow layers of the lower stratosphere which it has been possible to investigate, and the mean lapse rate of frost point is similar above and below the tropopause (see § 7). It may be found, when observations can be extended to greater heights, that the frost point does not continue to fall with height; there is some evidence to this effect in § 4, p.18 where it is seen that the mean lapse rate of frost point in the lower stratosphere, on occasions of low tropopause, shows a decrease several thousand feet above the tropopause. Barrett, Herndon and Carter[13] have on one occasion observed air temperatures and dew-point temperatures up to a height of 30 Km. above Minnesota and found that the dew point had a minimum of −107° F. about 1,000 ft. above the tropopause which was at 43,500 ft. approximately. Extension of humidity observations to heights above those reached in the present series are necessary to complete our knowledge of the distribution of water vapour in the lower stratosphere over southern England.

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