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Some high Sounding Balloon Ascents and Upper Air Temperatures upto 35 km over India

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ABSTRACT. Data from 34 sounding balloon ascents over India reaching 30 km and above have been collected and the seasonal mean temperatures derived from them are briefly discussed. Temperatures at 30 and 35 km shown by these data, of the order of 220° to 230 °A, have been compared and found to agree reasonably well with temperatures at same heights over similar latitudes in other parts of the world. It is shown that Koteswaram's estimates of temperatures over Central India at these heights are very high and that up to 36 km the sounding balloon data do not show any large increase of temperature with height above 25 km. Using means of sounding balloon data over 9 stations in India up to 1940, a diagram showing the distribution of upper air temperatures over India up to 35 km in summer and winter has been drawn and presented. The chief features of the variation of the height and temperature of tropopause and of the lapse rate, the annual range and the horizontal gradient of temperature have been stated and briefly discussed.

The outstanding points which emerge from the study are—(*i*) The summer tropopause over India is higher and cooler than the winter tropopause. The transition from the tropical type to the polar type stratosphere occurs at 30°N in winter and at latitudes north of India in summer ; (*ii*) Maximum lapse rates in the troposphere up to 30°N occur at 12-14 km in summer and 9-11 km in winter. The region of high lapse rates shows a variation similar to the height of tropopause ; (*iii*) In the lower stratosphere, counter-lapse rates increase with height above the tropopause up to 19-21 km after which they decrease. The counter-lapse rates are generally higher in summer than in winter. Above 25 km, the counter-lapse rates are of the order of 0·5 to 1°C per kilometre ; (*iv*) Summer temperatures are higher than winter temperatures up to 14 km above which the reverse happens up to 20 km. Above 20 km again the summer temperatures are higher than winter temperatures. The annual range of temperature is maximum at 8 to 10 km and decreases rapidly thereafter with height. The range is large over North India and very small over South India and (*v*) In the troposphere, the horizontal gradient of temperature is positive in summer except between 4 and 11 km north of latitude 27°N where it is negative. In winter, it is negative below 11 to 12 km and positive above. The temperature gradient is rather small south of latitude 15°N. In the lower stratosphere between 16 and 20 km, it is positive and steep in the lower latitudes south of 13°N and decreases with latitude north of it.

1. Introduction

Sounding balloon ascents with Dines meteorographs were made by the India Meteorological Department from various stations in India up to 1940 inclusive. Of these ascents, 34, mostly during the years 1939 and 1940, reached heights of over 30 km and 8 of them reached heights exceeding 34 km. The highest ascent which went up to 36·54 km was at Ahmedabad on 24 July 1939, the pressure and temperature at that height being 4 mb and 224°A respectively. Means of Indian sounding balloon data so far published or discussed give temperatures only up to 25 or 26 km and it has been generally assumed that very little information is available for higher levels from sounding balloon ascents. It is the purpose of this paper to collect together the data obtained from the 34 high sounding balloon ascents reaching 30 km and above, in order to obtain an idea of the temperatures and pressures at those heights and utilise them along with the more numerous data for the lower levels from a large number of stations to get a picture of the normal temperature distribution in summer and winter up to 35 km over India.

2. Data

Complete data for all the ascents in question are included in the *Upper Air Data, Volume XIII—Part B* for the relevant years published by the India Meteorological Department. Table 1 gives the pressures and temperatures for the 34 ascents for heights from 10 km upwards. Table 2 gives the height and type of tropopause and the highest point reached with the corresponding pressures and temperatures for each ascent. Most of the ascents were made in the evening after 1700 IST with a view to avoid

TABLE 1

Pressure and Temperature of the atmosphere from 10 km upwards

Date	AGRA (27°08'N 78°01'E)				CALCUTTA (23°32'N 88°20'E)					
	16 Sep 1937	19 Nov 1938	29 Apr 1939	17 Oct 1940	20 Jul 1939	10 Oct 1939	25 Nov 193)	24 Jun 1940	25 Jun 1940	25 Jun 1940
Time of ascent (IST)	0809	1735	1917	1656	1535	1705	1651	1626	0457	2035
36 km	..	4·0 *228·5*	..	..	..	..	..	..	..	..
35	..	4·7 *228·0*	..	..	..	..	..	..	..	..
34	..	5·4 *227·5*	..	..	..	..	..	6·0 *230·0*	..	5·6 *224·5*
33	..	6·3 *227·0*	..	..	..	..	..	7·0 *229·0*	..	6·5 *224·0*
32	..	7·4 *226·0*	..	8·1 *222·0*	..	7·6 *220·0*	..	8·2 *228·0*	..	7·6 *224·0*
31	11·5 *250·5*	8·6 *225·0*	..	9·5 *222·0*	..	8·9 *219·0*	10·5 *244·5*	9·5 *227·0*	..	8·9 *224·0*
30	13·0 *250·5*	10·0 *224·5*	11·0 *228·5*	11·0 *222·0*	11·5 *227·0*	10·5 *218·5*	12·0 *243·0*	11·0 *226·0*	11·0 *239·0*	10·5 *223·0*
29	15·0 *250·0*	11·5 *223·5*	12·5 *227·0*	13·0 *222·0*	13·0 *227·0*	12·5 *218·0*	14·0 *242·0*	13·0 *225·0*	13·0 *234·5*	12·5 *221·5*
28	17·0 *250·0*	13·5 *222·5*	15·0 *226·0*	15·0 *222·0*	15·0 *227·0*	14·5 *218·0*	16·0 *240·5*	15·0 *224·0*	15 0 *231·0*	14·5 *219·0*
27	19·5 *250·0*	16·0 *222·0*	17·5 *225·5*	18·0 *222·0*	17·5 *227·0*	17·0 *217·5*	18·5 *239·5*	17·5 *222·5*	17·5 *227·0*	17·0 *218·5*
26	22·5 *249·0*	19·0 *220·0*	20·0 *224·5*	20·5 *221·5*	20·5 *227·0*	20·0 *217·0*	21·0 *238·0*	20·5 *222·0*	20·0 *224·5*	20·0 *217·5*
25	26·0 *241·5*	22·0 *217·0*	23·5 *223·0*	24·5 *220·0*	24·0 *226·0*	23·5 *216·5*	24·5 *235·5*	24·5 *221·5*	23·5 *221·0*	23·0 *216·0*
24	30·5 *233·5*	26·0 *215·0*	27·5 *221·0*	28·5 *219·0*	28·0 *225·0*	27·5 *215·5*	28·5 *233·5*	28·5 *220·5*	28·0 *218·5*	27·0 *213·5*
23	35·0 *229·0*	30·5 *213·5*	32·5 *219·0*	33·5 *217·0*	33·0 *222·0*	32·5 *213·5*	33·0 *230·0*	33·5 *218·5*	32·5 *216·0*	32·0 *211·0*
22	41·0 *221·0*	36·0 *210·5*	38·0 *215·5*	39·0 *215·0*	38·5 *216·5*	38·0 *211·5*	38·5 *224·5*	39·0 *217·0*	38·5 *211·0*	37·5 *210·5*
21	48·0 *217·0*	42·5 *206·0*	44·5 *211·0*	46·0 *212·5*	45·0 *212·0*	45·0 *207·0*	45·5 *222·0*	46·0 *214·0*	45·5 *205·0*	44·5 *210·0*
20	57·0 *212·0*	50·5 *201·0*	53·0 *204·5*	54·5 *208·5*	53·0 *210·0*	53·5 *204·5*	53·0 *217·0*	54·0 *208·0*	53·5 *200·5*	53·0 *198·0*
19	67·0 *209·5*	60·0 *201·5*	62·5 *200·5*	64·0 *205·0*	63·5 *200·5*	63·5 *199·0*	62·5 *211·0*	64·5 *199·0*	64·0 *196·0*	63·5 *190·0*
18	79·0 *206·0*	71·0 *198·0*	74·5 *202·5*	76·0 *201·5*	75·5 *189·0*	75·5 *195·5*	74·0 *203·0*	76·5 *193·0*	76·5 *193·5*	76·0 *183·5*
17	93·5 *205·5*	85·0 *197·0*	88·5 *201·5*	90·5 *201·5*	91·0 *186·0*	90·5 *193·0*	88·0 *194·5*	91·5 *193·0*	91·5 *193·5*	91·5 *188·0*
16	111 *207·0*	102 *201·0*	105 *204·5*	108 *205·5*	109 *193·0*	108 *196·0*	106 *190·5*	110 *198·5*	109 *198·5*	110 *195·0*
15	131 *211·0*	121 *204·0*	124 *207 0*	127 *209·0*	130 *203·0*	129 *203·0*	126 *195·0*	130 *206·0*	130 *205·5*	131 *204·0*
14	155 *217·0*	143 *208·5*	147 *213·0*	150 *212·0*	154 *213·0*	153 *210·0*	149 *206·0*	154 *214·0*	153 *213·0*	154 *213·5*
13	181 *225·0*	169 *212·5*	173 *216·0*	177 *218·5*	181 *223·0*	180 *219·0*	177 *210·5*	180 *224·5*	180 *222·0*	182 *223·0*
12	210 *231·0*	199 *215·0*	202 *221·0*	206 *226·5*	211 *231·5*	210 *226·0*	207 *220·0*	210 *233·0*	210 *230·5*	212 *231·5*
11	244 *237·5*	233 *223·5*	236 *227·5*	240 *235·0*	244 *240·0*	244 *235·0*	242 *230·0*	244 *240·5*	244 *238·5*	245 *240·0*
10	282 *244·0*	271 *232·0*	275 *236·0*	278 *242·0*	282 *248·5*	283 *244·0*	281 *238·5*	281 *248·5*	281 *247·0*	283 *249·0*

TABLE 1—(*contd*)

Pressure and temperature of the atmosphere from 10 km upwards

CALCUTTA—*contd* (23°32′N 88°20′E)					AHMEDABAD (23°02′N 72°35′E)						
30 Jun 1940	1 Jul 1940	13 Nov 1940	15 Nov 1940	30 Nov 1940	24 Jul 1939	3 Aug 1939	2 Nov 1939	13 Jun 1940	1 Dec 1940	9 Dec 1940	Date
1323	2342	1409	1436	1516	1856	1905	1800	1905	1758	1800	Time of ascent (IST)
..	..	..	..	..	4·4	..	..	..	..	..	36 km
					223·5						
5·0	..	..	..	..	5·1	..	..	..	..	..	35
234·0					*223·5*						
5·9	..	..	..	6·1	6·0	..	..	..	5·1	..	34
232·0				*227·5*	*223·5*				*216·0*		
6·8	..	..	..	7·1	7·0	..	..	..	5·9	..	33
230·5				*227·5*	*224·5*				*216·0*		
7·9	..	..	..	8·3	8·1	..	7·5	..	7·0	..	32
229·0				*227·5*	*225·0*		*218·0*		*216·0*		
9·2	..	..	..	9·7	9·5	..	*9·0*	10·5	8·2	9·0	31
227·0				*227·5*	*224·5*		*218·5*	*231·5*	*215·5*	*223·5*	
11·0	10·5	10·5	11·5	11·5	11·0	10·5	10·5	12·0	9·7	10·5	30
224·5	*217·5*	*224·5*	*225·5*	*227·0*	*223·5*	*215·5*	*218·5*	*231·5*	*213·5*	*222·0*	
12·5	12·0	12·5	13·5	13·0	13·0	12·0	12·0	14·0	11·5	12·5	29
223·5	*217·5*	*224·0*	*225·0*	*226·0*	*223·0*	*215·5*	*219·0*	*231·0*	*212·5*	*221·0*	
14·5	14·5	14·5	15·5	15·5	15·0	14·0	14·0	16·0	13·5	14·5	28
221·5	*217·0*	*223·5*	*224·5*	*225·5*	*222·5*	*215·5*	*219·0*	*230·0*	*211·0*	*220·5*	
17·5	17·0	17·0	18·0	18·0	17·5	16·5	16·5	19·0	16·0	17·0	27
220·0	*217·0*	*223·0*	*224·0*	*225·0*	*221·5*	*215·5*	*219·0*	*229·0*	*209·5*	*219·5*	
20·0	19·5	20·0	21·0	21·0	20·5	19·5	19·5	22·0	19·0	19·5	26
218·5	*217·0*	*222·5*	*223·5*	*224·0*	*220·0*	*215·5*	*219·0*	*228·5*	*208·0*	*218·5*	
23·5	23·0	23·5	24·5	24·5	24·0	23·0	23·0	25·5	22·5	23·0	25
217·5	*216·5*	*219·5*	*223·0*	*223·0*	*217·5*	*213·0*	*216·0*	*227·0*	*206·0*	*218·0*	
28·0	27·0	27·5	29·0	28·5	28·5	27·0	27·0	30·0	26·5	27·0	24
216·5	*216·0*	*217·0*	*222·0*	*221·5*	*215·5*	*211·5*	*214·0*	*225·5*	*203·5*	*217·0*	
33·0	32·0	32·0	34·0	33·5	33·5	32·0	32·0	34·5	31·5	32·0	23
214·5	*214·5*	*214·0*	*220·0*	*220·0*	*216·0*	*209·5*	*212·5*	*223·5*	*202·0*	*216·0*	
38·5	37·5	38·0	39·5	39·5	39·5	38·0	37·5	40·5	37·5	37·5	22
210·5	*212·0*	*210·5*	*217·0*	*217·5*	*215·0*	*208·0*	*211·0*	*221·0*	*200·0*	*215·5*	
45·5	44·5	44·5	47·0	46·0	46·5	45·0	44·0	47·5	44·5	44·0	21
206·0	*208·0*	*207·0*	*210·0*	*215·0*	*209·5*	*204·5*	*208·0*	*218·0*	*197·0*	*210·0*	
54·0	52·5	53·0	55·0	54·5	55·0	53·0	52·5	56·0	53·0	52·0	20
201·5	*203·0*	*201·0*	*205·0*	*211·0*	*205·5*	*202·5*	*204·5*	*215·0*	*195·0*	*204·0*	
64·5	62·5	63·0	65·5	64·0	65·0	63·5	62·0	66·0	63·5	62·0	19
196·0	*197·0*	*197·0*	*203·0*	*207·0*	*201·5*	*199·0*	*199·5*	*211·5*	*194·5*	*201·0*	
77·0	75·0	75·5	77·5	76·0	77·5	75·5	74·0	78·0	76·0	73·5	18
191·0	*191·0*	*194·0*	*203·0*	*203·0*	*197·5*	*193·0*	*194·5*	*207·0*	*198·0*	*199·0*	
92·0	89·5	90·0	92·0	90·5	92·5	90·5	88·5	92·0	90·0	87·5	17
193·0	*192·0*	*194·0*	*204·5*	*203·0*	*191·5*	*191·0*	*192·0*	*201·0*	*200·5*	*201·0*	
110	107	108	110	107	111	108	106	110	107	104	16
200·5	*196·5*	*197·0*	*206·0*	*204·0*	*196·0*	*195·0*	*195·0*	*197·0*	*204·0*	*203·0*	
130	128	128	130	127	132	129	127	131	127	124	15
208·5	*203·0*	*205·0*	*209·0*	*207·5*	*205·0*	*202·5*	*197·5*	*201·0*	*209·0*	*207·0*	
153	151	152	152	150	156	153	151	155	150	146	14
217·0	*210·5*	*212·0*	*214·0*	*212·0*	*214·5*	*210·5*	*202·5*	*210·0*	*214·0*	*210·0*	
180	178	178	178	176	183	180	178	182	175	173	13
225·5	*218·5*	*219·5*	*221·5*	*218·0*	*224·0*	*219·5*	*212·5*	*220·0*	*219·0*	*215·0*	
209	208	208	207	206	213	211	209	213	205	202	12
232·5	*226·5*	*227·5*	*230·0*	*224·5*	*232·5*	*229·0*	*223·5*	*228·5*	*225·5*	*221·0*	
243	242	242	242	240	247	245	243	246	239	236	11
241·0	*235·0*	*236·0*	*238·0*	*232·5*	*240·5*	*237·0*	*232·0*	*237·5*	*232·5*	*228·0*	
279	280	280	279	278	284	282	282	285	276	274	10
249·0	*244·0*	*242·5*	*244·5*	*240·5*	*248·5*	*244·0*	*240·0*	*246·5*	*238·0*	*235·5*	

TABLE 1—(*contd*)

Pressure and Tamperature of the atmosphere from 10 km upwards

Date	SAMBALPUR (21°28′N 83°58′E)						POONA (18°32′N 73°51′E)		MADRAS (13°04′N 80°15′E)			BANGA-LORE (12°58′N 77°36′E)	
	27 Mar 1939	20 Nov 1939	23 Nov 1939	11 Jan 1940	23 Feb 1940	24 May 1940	11 Dec 1940	14 Dec 1940	20 Oct 1940	9 Nov 1940	9 Dec 1940	25 Feb 1938	4 Dec 1939
Time of ascent (IST)	1610	1750	1750	1759	1840	1845	1540	1500	1720	1738	1700	1746	1802
36 km	..	..	..	..	..	..	..	..	..	..	..	..	..
35	..	..	..	..	..	..	..	..	..	..	..	..	..
34	..	..	..	..	..	..	..	..	..	..	..	..	5·5
													229·0
33	..	..	6·7	..	..	..	..	..	..	..	..	6·5	6·5
			229·0									*227·0*	*229·0*
32	..	..	7·8	..	..	..	8·0	7·5	..	..	..	7·5	7·5
			229·0				*225·0*	*219·0*				*227·0*	*229·0*
31	..	..	9·1	..	..	..	9·0	9·0	8·5	9·0	..	9·0	9·0
			228·5				*225·0*	*217·5*	*219·0*	*216·5*		*226·0*	*228·5*
30	11·0	11·0	10·5	10·5	10·5	11·0	10·5	10·5	10·0	10·5	10·0	10·5	10·5
	222·5	*224·0*	*228·0*	*227·0*	*221·5*	*226·0*	*224·0*	*216·5*	*218·0*	*215·5*	*220·0*	*225·5*	*227·5*
29	13·0	12·5	12·5	12·5	12·5	12·5	12·5	12·5	12·0	12·5	12·0	12·5	12·0
	222·5	*224·0*	*226·5*	*226·0*	*221·5*	*225·0*	*222·5*	*216·0*	*218·0*	*214·5*	*219·0*	*225·5*	*227·0*
28	15·0	14·5	14·5	14·5	14·5	14·5	14·5	14·5	14·0	14·5	14·0	14·5	14·0
	223·0	*224·0*	*226·0*	*225·0*	*221·0*	*224·5*	*221·5*	*216·0*	*218·0*	*214·0*	*218·0*	*225·5*	*227·0*
27	18·0	17·0	17·0	17·0	17·0	17·0	17·0	17·0	16·5	17·0	16·5	17·0	16·5
	223·5	*224·0*	*224·5*	*223·5*	*221·0*	*223·5*	*220·5*	*216·0*	*217·0*	*213·5*	*217·5*	*225·0*	*225·0*
26	21·0	20·0	20·0	19·5	20·0	20·0	20·0	20·0	19·5	20·0	19·5	20·0	19·0
	224·0	*224·0*	*224·0*	*223·0*	*221·0*	*222·5*	*219·0*	*215·5*	*216·0*	*213·0*	*216·5*	*221·0*	*223·0*
25	24·5	23·5	23·0	23·0	23·0	23·5	23·5	23·0	23·0	24·0	23·0	23·5	22·0
	224·5	*223·0*	*222·5*	*221·0*	*220·0*	*220·0*	*217·0*	*214·5*	*215·0*	*211·0*	*214·5*	*218·0*	*222·0*
24	28·5	27·5	27·0	27·0	27·0	27·5	27·5	27·0	27·0	28·0	27·0	27·5	26·0
	224·5	*221·5*	*220·5*	*219·0*	*219·5*	*217·5*	*215·0*	*213·5*	*214·0*	*210·0*	*211·0*	*215·5*	*221·0*
23	33·0	32·5	31·5	31·5	32·0	32·5	32·5	32·5	31·5	33·0	31·5	32·0	31·0
	224·5	*220·0*	*218·0*	*216·5*	*218·5*	*215·0*	*213·5*	*212·0*	*212·0*	*208·0*	*209·5*	*215·0*	*220·5*
22	39·0	38·0	37·5	37·0	37·5	38·0	38·5	38·0	37·0	39·0	37·5	38·0	36·0
	223·0	*217·5*	*215·5*	*214·0*	*217·0*	*213·0*	*212·0*	*209·0*	*206·5*	*205·5*	*206·0*	*213·0*	*217·0*
21	45·5	44·5	43·5	44·0	44·0	45·0	45·0	45·0	44·0	46·5	44·0	44·5	43·0
	221·0	*216·0*	*212·5*	*210·5*	*215·0*	*204·0*	*211·0*	*205·0*	*204·0*	*202·5*	*202·0*	*208·5*	*212·0*
20	53·5	52·5	51·5	52·0	51·5	53·0	53·0	53·0	52·0	55·0	53·0	53·0	50·0
	216·0	*209·5*	*207·5*	*206·5*	*211·5*	*204·0*	*209·0*	*203·0*	*201·5*	*199·5*	*198·0*	*198·5*	*207·0*
19	62·5	62·0	61·5	61·5	61·0	63·0	63·0	63·0	62·0	65·5	63·0	63·0	60·0
	211·0	*200·0*	*201·0*	*204·5*	*207·5*	*199·0*	*201·5*	*202·5*	*198·0*	*197·5*	*191·0*	*195·5*	*203·0*
18	74·0	74·0	73·0	73·0	72·0	75·0	75·0	75·0	74·0	78·0	75·0	74·5	71·0
	208·5	*193·5*	*197·0*	*202·0*	*204·0*	*194·5*	*194·5*	*202·0*	*195·5*	*197·5*	*187·0*	*195·5*	*197·0*
17	87·0	88·0	87·0	87·0	85·5	90·0	89·0	89·0	89·0	93·0	89·0	89·0	85·0
	205·0	*195·0*	*194·5*	*197·5*	*202·0*	*191·5*	*197·5*	*202·5*	*192·0*	*201·0*	*190·0*	*197·5*	*195·0*
16	103	105	104	104	101	108	107	106	106	111	108	106	102
	203·0	*198·5*	*195·5*	*197·0*	*202·5*	*192·5*	*200·5*	*205·0*	*196·0*	*205·0*	*194·0*	*201·5*	*192·5*
15	123	125	124	124	120	129	127	125	127	131	128	126	122
	207·5	*201·0*	*199·0*	*202·0*	*207·0*	*201·0*	*202·5*	*208·0*	*199·0*	*210·5*	*198·0*	*208·0*	*196·0*
14	145	148	147	147	143	153	150	148	150	154	154	148	145
	211·0	*206·0*	*204·5*	*207·5*	*212·0*	*211·0*	*207·0*	*211·5*	*205·0*	*216·0*	*207·5*	*213·0*	*201·5*
13	171	175	174	172	168	179	176	174	177	181	179	175	172
	216·0	*215·5*	*211·5*	*215·0*	*214·5*	*221·5*	*215·5*	*216·0*	*214·0*	*223·0*	*217·0*	*219·0*	*209·5*
12	201	205	204	202	197	209	207	204	208	211	210	204	202
	222·0	*223·0*	*220·5*	*222·5*	*217·0*	*228·0*	*224·0*	*221·0*	*222·0*	*230·0*	*227·0*	*224·0*	*216·0*
11	234	240	238	235	231	243	240	238	242	245	244	238	236
	225·0	*231·0*	*230·0*	*231·0*	*220·5*	*236·0*	*233·0*	*228·0*	*230·0*	*237·5*	*235·0*	*229·0*	*225·5*
10	273	278	277	274	270	281	280	277	281	283	282	276	275
	230·5	*240·0*	*236·5*	*238·5*	*227·5*	*245·5*	*241·0*	*236·0*	*237·5*	*244·5*	*243·0*	*234·0*	*233·5*

TABLE 2

Date / Time of ascent (IST)	AGRA (27°08′N 78°01′E)				CALCUTTA (23°32′N 88°20′E)					
Date	16 Sep 1937	19 Nov 1938	29 Apr 1939	17 Oct 1940	20 Jul 1939	10 Oct 1939	25Nov 1939	24 Jun 1940	25 Jun 1940	25 Jun 1940
Time of ascent (IST)	0809	1735	1917	1656	1535	1705	1651	1626	0457	2035
	III	I	IV	II	I	I	I	I	I	I
Hc (km)	16·38	17·42	16·64 18·96	16·43	17·05	16·76	16·06	17·47	17·40	17·94
Pc (mb)	104	79·0	94·0 63·0	100	90·0	93·0	104	84·0	85·0	77·0
Tc (°A)	206·0	196·0	201·0 200·0	202·5	185·5	192·5	190·5	192·5	193·0	183·5
H (km)	31·00	36·00	30·58	32·06	30·70	32·56	31·24	34·04	30·70	34·76
P (mb)	11·5	4·0	10·0	8·0	10·0	7·0	10·0	6·0	10·0	5·0
T (°A)	250·5	228·5	230·0	222·0	227·5	220·5	245·0	230·0	241·0	225·0

Date / Time of ascent (IST)	CALCUTTA—*contd* (23°32′N 88°20′E)					AHMEDABAD (23°02′N 72°35′E)					
Date	30 Jun 1940	1 Jul 1940	13 Nov 1940	15 Nov 1940	30 Nov 1940	24 Jul 1939	3 Aug 1939	2 Nov 1939	13 Jun 1940	1 Dec 1940	9 Dec 1940
Time of ascent (IST)	1323	2342	1409	1436	1516	1856	1905	1800	1905	1758	1800
	I	I	II	II	I	I	I	III	I	I	I
Hc (km)	17·76	17·91	16·42	15·57	17·71	16·58	17·03	16·50	15·61	19·15	17·91
Pc (mb)	80·0	76·0	100	118	80·0	100	90·0	97·0	118	62·0	75·0
Tc (°A)	190·5	191·0	194·0	206·5	203·0	192·0	190·5	193·5	197·0	194·0	199·0
H (km)	35·06	30·89	30·41	30·82	34·13	36·54	30·15	32·44	31·17	34·10	31·73
P (mb)	5·0	9·0	10·0	10·0	6·0	4·0	10·0	7·0	10·0	5·0	8·0
T (°A)	234·0	217·0	225·0	226·0	227·0	224·0	215·5	218·0	232·0	216·0	224·5

Date / Time of ascent (IST)	SAMBALPUR (21°28′N 83°58′E)						POONA (18°32′N 73°51′E)		MADRAS (13°04′N 80°15′E)			BANGALORE (12°58′N 77°36′E)	
Date	27 Mar 1939	20 Nov 1939	23 Nov 1939	11 Jan 1940	23 Feb 1940	24 May 1940	11 Dec 1940	14 Dec 1940	20 Oct 1940	9 Nov 1940	9 Dec 1940	25 Feb 1938	4 Dec 1939
Time of ascent (IST)	1610	1750	1750	1759	1840	1845	1540	1500	1720	1738	1700	1746	1802
	I	IV	I	I	I	I	I	I	I	I	I	IV	I
Hc (km)	16·21	14·57 17·76	16·50	16·62	16·57	16·71	18·41	17·41	17·42	18·30	18·00	17·25 19·09	16·09
Pc (mb)	100	135 77·0	95·0	93·0	92·0	95·0	76·0	83·0	82·0	74·0	75·0	85·0 62·0	100
Tc (°A)	202·0	202·0 193·5	194·5	196·0	201·5	191·0	194·5	201·5	191·5	197·0	187·0	196·5 195·5	192·5
H (km)	30·08	30·50	33·76	30·38	30·33	30·47	32·76	32·44	31·54	31·72	30·00	33·67	34·76
P (mb)	11·0	10·0	6·0	10·0	10·0	10·0	7·0	7·0	8·0	8·0	10·0	6·0	5·0
T (°A)	222·5	224·0	229·0	227·5	221·5	226·5	226·0	220·0	219·5	217·0	220·0	227·0	228·0

NOTE—Hc, Pc, Tc=Height (km), pressure (mb) and temperature (°A) respectively at the tropopause
H, P, T=Highest point reached and pressure (mb) and temperature (°A) at that level
I, II, III, IV—Indicate the type of tropopause. When the tropopause is of type IV the height (km), pressure (mb) and temperature (°A) corresponding to both the transitions have been given

errors due to direct insolation. A few ascents were made earlier in the afternoon or in the morning. In such cases, a specially designed cage was used to prevent insolation affecting the meteorograph. It is seen that the ascents are distributed over seven stations in different latitudes between 13° and 27°N and over all the months of the year. Fig. 1 shows the height-temperature curves for the ascents at each of the stations separately.

It is seen that the ascent at Agra on 16 September 1937 shows very high temperatures at all heights. This ascent was made in the morning at 0809 IST and although a special cage was used for protecting the meteorograph from insolation, it appears probable that the instrument was affected by direct solar insolation thus causing the high temperatures. A depression centred near Agra the day previous to the ascent was breaking up against the Himalayan foot hills to the north. It is not clear if the abnormally high temperatures were in some way connected with the special weather situation. Omitting the above ascent and grouping the other ascents into two seasons, summer (April to September) and winter (October to March), the seasonal mean temperatures for six stations are given in Table 3. As Madras and Bangalore are in the same latitude and the upper air temperatures over these stations do not differ appreciably, their data have been combined to give a single mean. For Poona and Madras-Bangalore, means can be worked out only for winter as there were no high ascents in summer. The means in Table 3 are also plotted in Fig. 2 as seasonal height-temperature curves. The number of ascents is too few to determine monthly means.

3. Discussion of results

It is seen from Table 3 and Fig. 1 that the increase of temperature with height above the tropopause is well marked up to 20 or 21 km with a counter-lapse of 4 to 6° C km^{-1} in summer and 2 to 4°C km^{-1} in winter. The counter-lapse of temperature decreases with height and is of the order of 3°C km^{-1} in summer and 2° C km^{-1} in winter between 21 and 26 km. It is of the order of 1°C km^{-1} above 26 km with no appreciable seasonal variation. There is a latitudinal variation in the lapse rate of temperature both in the lower stratosphere and in the troposphere as discussed in Section 4.

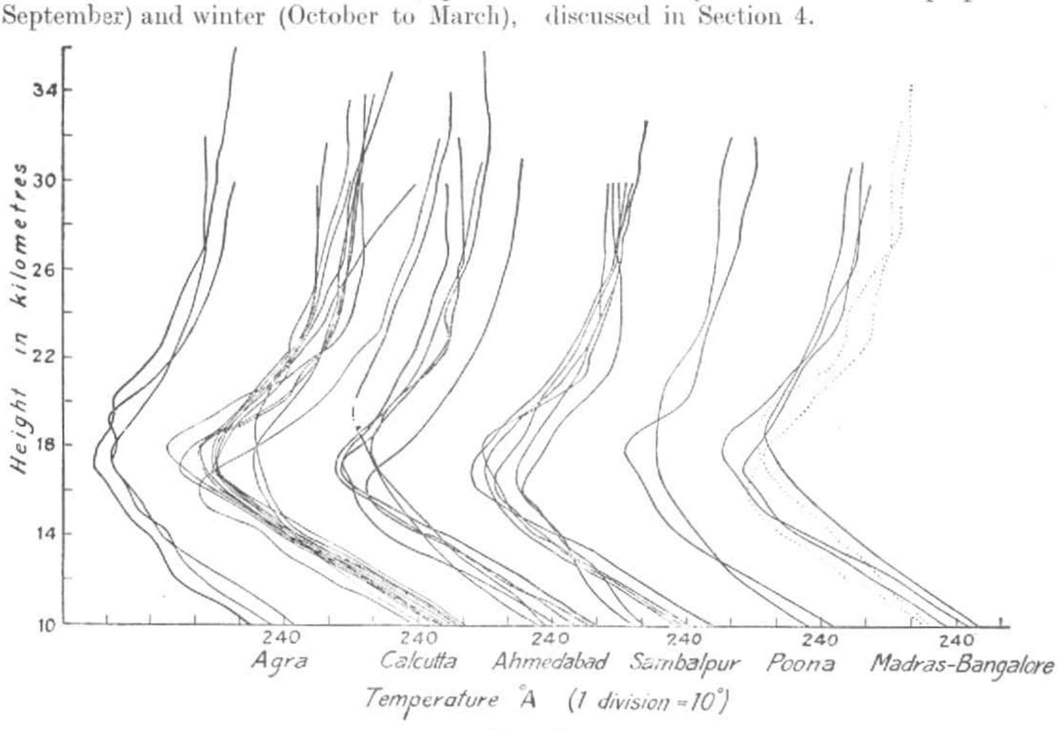

Fig. 1

TABLE 3

Seasonal mean temperatures at different heights in °A

Height (km)	AGRA		CALCUTTA		AHMEDABAD		SAMBALPUR		POONA		MADRAS—BANGALORE	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
36	..	228·5	..	..	223·5	..	..	..	..	..	..	..
35	..	228·0	234·0	..	223·5	..	..	..	..	..	..	..
34	..	227·5	228·8	227·5	223·5	216·0	..	..	..	..	..	229·0
33	..	227·0	227·8	227·5	224·5	216·0	..	229·0	..	..	..	228·0
32	..	224·0	227·0	223·7	225·0	217·0	..	229·0	..	222·0	..	228·0
31	..	223·5	226·0	227·5	228·0	219·0	..	228·5	..	221·2	..	222·5
30	228·5	223·3	225·2	224·3	223·5	218·1	226·0	224·3	..	220·2	..	221·3
29	227·0	222·7	224·2	223·7	223·2	217·9	225·0	223·8	..	219·3	..	220·8
28	226·0	222·3	222·9	223·3	222·7	217·3	224·5	223·5	..	218·7	..	220·5
27	226·5	222·0	222·0	222·7	222·0	216·7	223·5	223·1	..	218·3	..	219·6
26	224·5	220·7	221·3	222·0	221·3	216·0	222·5	223·0	..	217·2	..	217·9
25	223·0	218·5	220·1	220·9	219·2	214·0	220·0	222·1	..	215·8	..	216·1
24	221·0	217·0	218·9	219·5	217·5	212·0	217·5	221·0	..	214·2	..	214·3
23	219·0	215·2	216·7	217·3	216·3	210·7	215·0	219·6	..	212·7	..	213·0
22	215·5	212·8	213·3	214·5	214·7	209·3	213·0	217·6	..	210·5	..	209·6
21	211·0	209·9	209·3	210·3	210·7	205·7	209·0	215·2	..	208·0	..	205·8
20	204·5	204·7	206·5	204·3	207·7	202·0	204·0	210·6	..	206·0	..	200·9
19	200·5	203·2	197·0	201·7	204·0	198·6	199·0	205·9	..	202·0	..	197·0
18	202·5	199·7	190·3	198·1	199·2	196·5	194·5	202·5	..	198·2	..	194·5
17	201·5	199·3	190·5	196·0	194·5	196·3	191·5	199·8	..	200·0	..	195·1
16	204·5	203·3	196·4	197·7	196·0	199·3	192·5	199·9	..	202·8	..	197·8
15	207·0	206·5	204·5	203·5	202·8	202·7	201·0	204·1	..	205·3	..	202·3
14	213·0	210·2	213·1	210·5	211·7	207·3	211·0	208·9	..	209·3	..	208·6
13	216·0	215·5	222·2	218·2	221·2	214·7	221·5	214·7	..	215·7	..	216·5
12	221·0	220·7	230·5	225·8	230·0	223·4	228·0	220·8	..	222·7	..	223·8
11	227·5	229·2	238·7	234·5	238·3	231·1	236·0	226·7	..	230·5	..	231·4
10	236·0	237·6	247·3	242·7	246·3	238·3	245·5	233·7	..	238·5	..	238·5

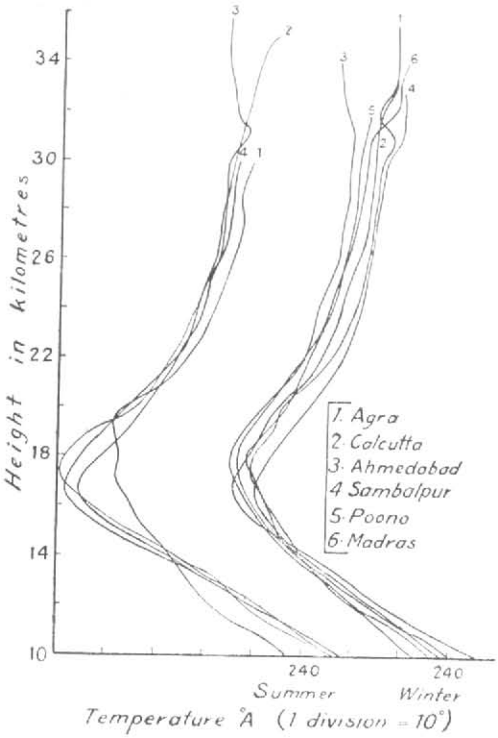

Fig. 2

Table 3 also shows that while temperatures are higher in summer than in winter upto 14 km the position gets reversed at higher levels up to 20 km with winter temperatures becoming higher than summer temperatures. Above 20 km again, the summer temperatures appear to be higher than winter temperatures. This feature is examined further in Section 4. At heights above 30 km the summer temperatures appear to be higher by 2 to 5°C as compared to winter temperatures at stations in the northern latitudes of India. There does not appear to be any appreciable latitudinal variation of temperature at these high levels.

It will be interesting to compare the temperatures at heights of 30 and 35 km shown in Table 3 with those observed in other countries. Scrase[1] has tabulated temperatures at 100,000 ft (30 km) in winter and summer at 7 stations in different latitudes. Similar information for Indian stations at 30 and 35 km from the available sounding balloon data is given in Table 4.

TABLE 4

	Station	Latitude	Temperature at 30 km		Temperature at 35 km	
			Summer °A	Winter °A	Summer °A	Winter °A
1	Agra	27°N	229	223	—	228
2	Calcutta	24°N	225	224	234	—
3	Ahmedabad	23°N	223	218	223	—
4	Sambalpur	21°N	226	224	—	—
5	Poona	19°N	—	220	—	—
6	Madras & Bangalore	13°N	—	221	—	—

It is interesting to note that the summer and winter temperatures at 30 km over Agra (27°N), *viz.*, 229° and 223°A are about the same as those over New Mexico (32°N), *viz.*, 233° and 224°A and summer temperature of 232°A at 30 km over Bermuda (32°N) also agrees with the summer temperature over Agra.

Goldie[2] has constructed a diagram showing distribution of temperature in the upper air up to 45 km on the basis of available means of sounding balloon and radiosonde data, temperature data from sound propagation experiments in England during the War and from certain physical considerations. Temperatures at 30 and 35 km in summer and winter at latitudes 10°, 20° and 30°N picked out from Goldie's diagram are given in Table 5 below.

TABLE 5

Latitude	Temperature at 30 km		Temperature at 35 km	
	Summer °A	Winter °A	Summer °A	Winter °A
10°N	223	216	229	219
20°N	221	214	228	216
30°N	218	210	226	213

Comparing these temperatures with those in Table 4 it is seen that Goldie's diagram shows 5° to 10°C lower temperatures than those from Indian sounding balloon data.

In Fig. 3, the temperatures and pressures at heights of 30 km and above from individual ascents are plotted. A mean curve for the year as a whole has been drawn which may be taken to represent the conditions over Central India. It is seen from this curve that the mean temperature and pressure at 30 km are 224°A and 10·8 mb and at 35 km 228°A and 4·9 mb. It is interesting to compare these figures with the values of temperatures and pressures over Central India deduced by Koteswaram[3]. His values for 30 km are 267°A and 11·4 mb and for 35 km 292°A and 3·7 mb. It is seen that while the pressure values more or less agree, the temperature values are widely different, Koteswaram's temperatures being higher by about 43°C at 30 km and by about 65°C at 35 km. It is believed that temperatures and pressures from sounding balloon records being direct measurements are more reliable and should be taken to represent the true conditions. It may be noted that even in the Agra ascent on 16 September 1937 referred to in Section 2, which showed abnormally high temperatures at all levels, the temperature recorded at 30 km was only 250·5°A which is about 17°C less than the temperature deduced by Koteswaram. It should be remarked here that the temperatures from the sounding balloon ascents represent conditions in the late evening or early night. There is, however, no reason to think that the mean diurnal variation of temperature in the lower stratosphere at heights of 30 and 35 km is appreciable. It is seen that information available from high sounding balloon ascents over India does not show up to a height of 35 or 36 km any large increase of temperature with height.

4. Upper Air Temperature distribution over India in Summer and Winter

Sounding balloon data are available for a number of stations in India between latitudes 34°and 13°N, although the period and volume of data are not the same for all stations. It would be useful at this stage to have a picture of the latitudinal variation of upper air temperatures over India upto the highest possible height. Accordingly, a diagram showing upper air temperatures over India up to 35 km in summer and winter has been drawn (Fig. 4) utilising the means of sounding balloon data for 9 stations (*viz.*, Peshawar, Jacobabad, Agra, Jodhpur, Ahmedabad, Calcutta, Sambalpur, Poona-Hyderabad and Madras-Bangalore) worked out at the Upper Air Section of the Poona Meteorological Office and the data from the 34 high sounding balloon ascents. The mean of June and July has been taken to represent summer (monsoon) conditions and mean of December and January to represent winter conditions. Isopleths of temperature have been drawn at intervals of 10°A in the tropopause and at 5°A intervals in the stratosphere. The isopleth for 273°A and the mean height of tropopause are also shown.

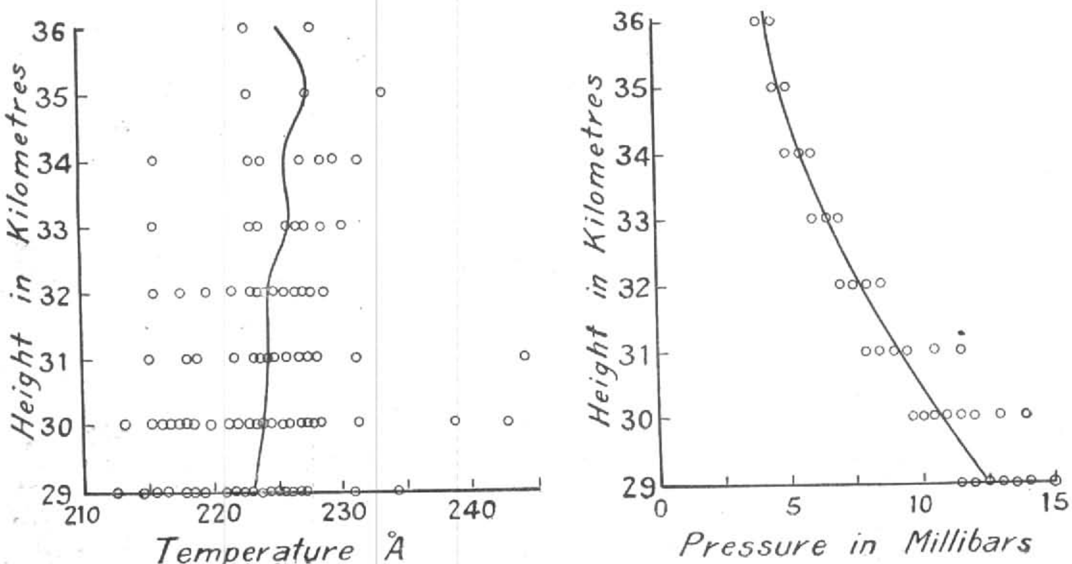

Fig. 3

Sounding balloon data reaching the tropopause are not available for latitudes south of Madras-Bangalore (13° N) except for one ascent at Trichinopoly (10° 49′ N, 78° 42′ E) on 14 December 1940. In this ascent the tropopause was reached at 15·61 km where pressure and temperature were 112 mb and 197°A respectively. The ascent reached 22·98 km at which height pressure and temperature were 33 mb and 227°A respectively. Radiosonde ascents made from Trivandrum (8° 29′ N, 76° 57′ E) since 1947 have reached the tropopause only on a few occasions and the data are insufficient for obtaining any monthly or seasonal means. In view of the paucity of data from Indian stations in the latitudes south of 13°N, Batavia (6° S) mean temperature data which have been compared with Poona-Hyderabad data by Ramanathan[4] have been utilised in drawing the isopleths of temperature over the low latitudes taking it to represent approximately the conditions over India at 6°N.

Although the general latitudinal variation of upper air temperatures is known from Ramanathan's[5] and Goldie's[2] diagrams, the diagram in Fig. 4, which is based on data from a number of Indian stations at different latitudes, shows some interesting features which are indicated and briefly discussed below.

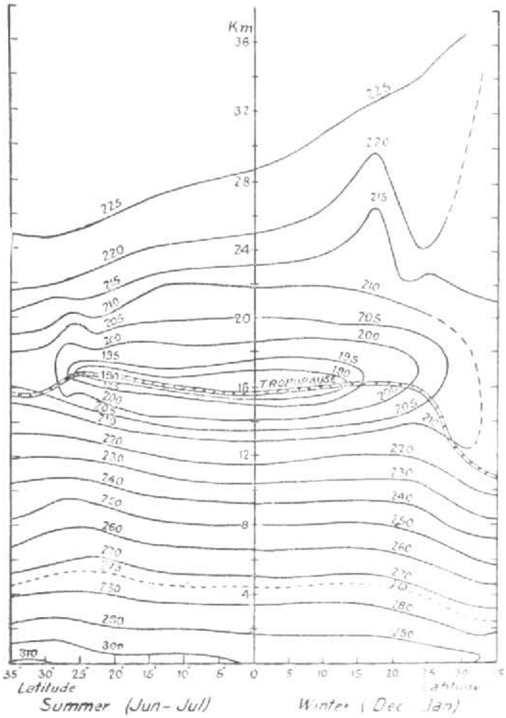

Fig. 4. Upper air temperatures over India

(*i*) The lowest temperatures in the atmosphere over India occur at a height of 16·5 to 17 km at the tropopause over latitudes south of 27°N in summer and at the tropopause at a slightly lower level (16 to 16·5 km) over latitudes south of 15°N in winter. It is interesting to note in this connection that the lowest temperature ever recorded in the sounding balloon ascents was 181°A (—133·6°F) at 16·1 km at Agra (27°N) on 4 October 1928. The lowest temperature recorded over South India was 182·5°A at 17·0 km at Bangalore on 12 March 1940.

(*ii*) In summer, the height of tropopause which is about 15 km at latitude 34°N increases with decrease of latitude and is about 16·8 km over Agra. As we go further south in latitude there is a slight decrease in the height of tropopause. Between Agra (27°N) and Madras (13°N) there is a decrease of only about 0·5 km in the mean height of the summer tropopause. In winter, the tropopause height over Peshawar (34°N) is 12 km and this increases rapidly with decrease of latitude to 15·7 km over Agra and there is no appreciable latitudinal variation in the height as we go southwards. On the mean, the summer tropopause is higher than the winter tropopause over the Indian latitudes and this is obviously connected with the larger convection in the troposphere in summer than in winter. This appears to be true in general both in the northern and southern latitudes[6].

The occurrence in winter of a low tropopause (12 km) over Peshawar and a much higher tropopause at Agra, only 7° south of it in latitude, shows that the transition from the tropical to the temperate latitude (or polar) stratosphere in winter occurs over India somewhere between 27° and 34°N (probably at about 30° N). In summer, this transition occurs, as we know from Ramanathan's diagram, at 40-45°N. In winter, Peshawar is mostly in polar continental air while Agra is mostly in tropical air with its characteristic high tropopause. However, it is known that on a number of occasions in winter, Agra is invaded by polar air masses with low tropopause (11 to 12 km) at the rear of western disturbances moving across northern India.

(*iii*) Fig. 5 shows the distribution of the lapse rate of temperature with latitude and height in summer and winter. Isolines of lapse rate have been drawn at intervals of 2°C km^{-1}. It is seen that high lapse rates occur between 1 and 2 km over latitudes 10° to 20°N. In winter, inversions or low lapse rates occur frequently in the first one kilometre. Above 2 km the lapse rate decreases with height up to 5 to 6 km in summer and up to 3 to 4 km in winter. These heights are 7 to 8 km in summer and 1 to 2 km in winter in the northern latitudes above Agra. Lapse rate increases with height thereafter and in the region south of latitude 27°N reaches a maximum of 9 to 9·5° C km^{-1} between 12 and 14 km in summer. In winter it reaches a maximum of 7·5 to 8·5°C km^{-1} between 11 and 13 km south of latitude 20°N and between 9 and 11 km at higher latitudes. North of latitude 27°N, the maximum lapse rate of 7°C km^{-1} occurs at 11 to 13 km in summer and of 8°C km^{-1} at 6 to 7 km in winter. It is seen that the height of the region of maximum lapse rates in the troposphere shows a latitudinal variation similar to the height of tropopause. As has been pointed out by Ananthakrishnan[7], the region of high lapse rates forms the " Emission layer " and the tropopause occurs at a higher level if the " Emission layer " is at a higher level. In summer, generally higher lapse rates occur between 18° and 27° N than over the lower latitudes. In winter, generally higher lapse rates occur over the lower latitudes south of 18°N than over the higher latitudes.

Above the region of maximum lapse rates, the lapse rate decreases rapidly with height to zero at a height of 16 to 17 km, which is the region in which the tropopause occurs, except at Peshawar (34°N) where the tropopause occurs at 15 to 16 km in summer and at 11 to 12 km in winter. The zero lapse rate over Peshawar occurs at about 17 km in summer and at about 11 km in winter.

Above the tropopause, lapse rates are generally negative, *i.e.*, temperature increases with height, except in winter over Peshawar where the lapse rate is negative between 11 and 13 km, positive and of small magnitude above it up to 17 km and then nearly zero

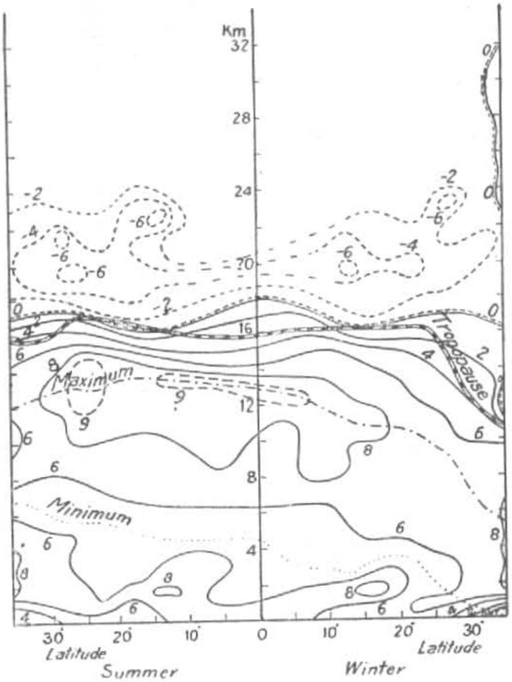

Fig. 5. Lapse rate of temperature °C/km

at higher levels. This is more or less the characteristic lapse rate distribution in the polar stratosphere of temperate latitudes in summer so that Peshawar can be said to have the polar summer stratosphere in winter and tropical stratosphere in summer.

Immediately above the tropopause the negative lapse rate (or counter-lapse) which, on the mean, is small in the first one kilometre increases with height and reaches a maximum between 19 and 21 km, the value being about -6°C km^{-1} in summer and —4°C km^{-1} in winter. Above 21 km, the rate of counter-lapse decreases with height and becomes less than -2° C km^{-1} above 23 km. The rate of counter-lapse of temperature in the lower stratosphere between 16 and 23 km shows a slight latitudinal variation. In summer the counter-lapse rates are higher over north India (18°-27°N) than over south India while in winter they are higher over south India than over north India. At heights above 25 km up to 35 km, the counter-lapse rates are of the order -1° to -0·5°C km^{-1} with a tendency for higher lapse rate in summer than in winter.

(*iv*) Temperature is higher over north India than over south India in summer up to 16 km while in winter temperature is higher over south India than over north India up to 11 km with a reversal at higher levels. In the lower stratosphere, temperature is generally higher over north India than over south India.

In the troposphere, the horizontal gradient of temperature in summer is positive (*i.e.*, temperature increases with latitude) except between 4 and 11 km north of latitude 27°N where it is negative. This negative gradient is because in summer (monsoon) there is a ridge of higher temperatures between 18° and 27°N in the troposphere up to 14 km due to the warming of air by the latent heat released from the condensation of water vapour in the monsoon. In winter, the horizontal gradient of temperature is negative below 11 to 12 km and positive above. The horizontal temperature gradient is rather small in the lower latitudes south of 15°N. Steep positive horizontal temperature gradients of 1·3 to 1·4° C per degree latitude occur between 8 and 11 km over latitudes 18° to 22°N in summer. Steep negative horizontal temperature gradients occur in winter between 22° and 34°N between 6 and 11 km, the steepest values being 1·4 to 1·5°C per degree latitude between 8 and 10 km over 27° to 34°N.

At and near the tropopause, between 16 and 20 km, the horizontal gradient of temperature is positive and steep, the values being 1 to 1·5°C per degree latitude in the lower latitudes below 13°N, decreasing with latitude up to 25°N and increasing again to 1 to 1·3°C per degree latitude between 25° and 35°N. The steepest horizontal temperature gradients in the lower stratosphere occur at 17 to 18 km over the region south of latitude 13°N. It is at these heights which correspond to the tropopause that the easterly winds reach their maximum strength and decrease in speed with height at higher levels. It is interesting to note that going from the upper troposphere to the lower stratosphere, there is no change at the tropopause in the sign of the horizontal temperature gradient but only a change in its magnitude. At heights above 20 km the horizontal temperature gradients are negative below latitude 15°N and positive at the northern latitudes.

(*v*) Temperatures are higher in summer and lower in winter in the troposphere up to about 14 km. At higher levels, in a region of about 6 km, about 3 km on either side of the tropopause, the position gets reversed with winter temperatures being higher than summer temperatures. In Fig. 6 the difference between summer and winter temperatures for the different latitudes are plotted against height. The mean of Calcutta, Sambalpur and Ahmedabad has been taken to represent conditions at latitude 22°N.

The diagram shows the following characteristics—

(*a*) In the troposphere below 14 km the annual range of temperature, *i.e.*, the difference of temperature between summer and winter, is fairly large at latitudes north of 27°N and decreases rapidly with latitude being markedly less in lower latitudes. It is very small at the latitude of Madras-Bangalore (13°N). At 10 km, where the annual range is maximum, the range at Poona (18°N) is less than one fourth the range at Peshawar (34°N) while the range at Madras is about one tenth the range at Peshawar. It should be remarked here that the maximum temperature in the year does not occur in June-July at all heights or at all the latitudes nor does minimum temperature occur everywhere in December-January. Therefore, the range of temperature shown in Fig. 6 is not exactly but only approximately the annual range, specially below 3 or 4 km where the maximum temperature in the year occurs in April-May and the annual range would be greater than that shown.

(*b*) The annual range of temperature decreases slightly from the surface upto 4 or 5 km and thereafter increases rapidly with height up to 10 km where it is maximum. Above 10 km, it decreases very rapidly with height reaching nearly zero at a height between 14 and 15 km where there is very little or no seasonal variation of temperature. At higher levels, the annual range of temperature becomes negative, *i.e.*, the winter temperatures are higher than summer

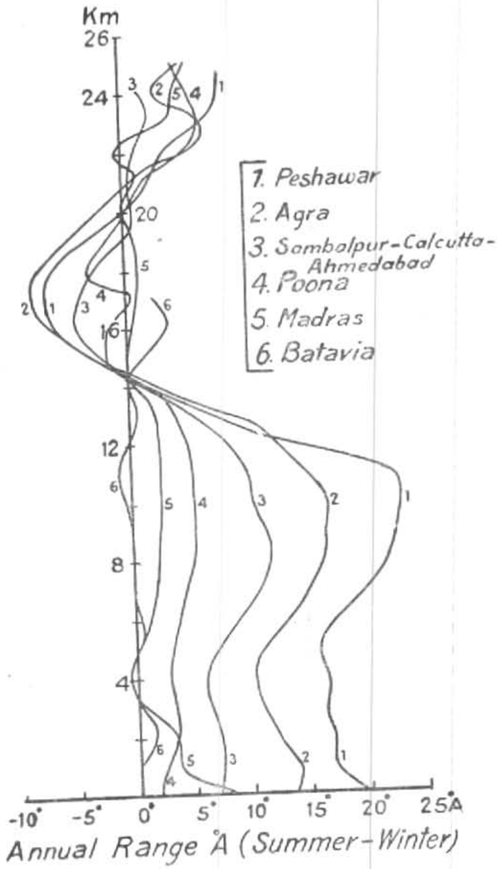

Fig. 6

temperatures and increases in magnitude, reaching a maximum at about 17 km, in the region in which the tropopause occurs. It decreases at higher levels reaching nearly zero at about 21 km where again temperatures are more or less uniform. Above 21 km again, the summer temperatures are higher than winter temperatures and the range shows a tendency to increase with height up to 25 km above which there appears to be no appreciable variation. This type of variation in the annual range of temperature in respect of Agra was pointed out by Ananthakrishnan[7] and it is now seen that it is true generally for all the Indian latitudes and that it is very much more prominent in north India, north of 22°N than in south India. It is interesting to note that the important facts of this variation of the annual range of temperature are closely related to the variation of lapse rate of temperature in the troposphere and lower stratosphere. As we have already noted earlier, the lapse rate of temperature shows similar variation being maximum at 9 to 10 km and a minimum at 15 km. The negative lapse rates above the tropopause reach a maximum value at a height of 2 to 3 km above it and decrease to a minimum at about 21 km. Summer temperatures are lower than winter temperatures between 15 and 21 km because of the larger lapse rates of temperature in the upper troposphere in summer than in winter resulting in a higher tropopause with lower temperature in summer than in winter. Above the tropopause, the counter-lapse rate of temperature is higher in summer than in winter and the lower temperature of the summer tropopause is made up in a height of 5 to 6 km so that at 21 km the temperature is nearly the same in summer and winter.

It is proposed to discuss in a later paper the distribution of pressure and potential temperature in the upper air over India as also the distribution and relation of horizontal pressure and temperature gradients in upper air with the general circulation of the atmosphere over India.

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