DISCUSSION OF RESULTS OF SOUNDING BALLOON ASCENTS AT AGRA DURING THE PERIOD JULY 1925 TO MARCH 1928 AND SOME ALLIED QUESTIONS.

BY

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CONTENTS.

Summary.—In this paper, the monthly mean data of temperature, humidity and pressure, and derived quantities like lapse-rate, density and potential temperature obtained from sounding balloon ascents at Agra during the period July 1925—March 1928 are analysed and discussed. Mean monthly pressure differences at different levels between Agra and Europe are considered in their relation to upper wind circulation. The different types of transition from troposphere to stratosphere over Agra are analysed and the seasonal variation of the height and temperature of the tropopause discussed. The complementary nature of the variation of these quantities at Agra and Batavia is pointed out. Diagrams are given showing the probable distribution of temperature and potential temperature in the first 25 km· of the atmosphere over the northern hemisphere in summer and winter.

1. INTRODUCTION.

In Volume XXIV, Part VI of the Memoirs of the Indian Meteorological Department, Dr. Harwood has analysed the data of upper air temperatures and humidities obtained from an earlier series of ascents of sounding balloons at Agra during the period 1915-18. The observations of the period under discussion in this paper (July 1925—March 1928) were obtained under the direction of Mr. G. Chatterjee, M.Sc., Meteorologist in charge of the Upper Air Observatory, Agra. Mr. Chatterjee has devised various improvements in the technique of sounding balloon work at Agra which have resulted in greater accuracy of the records. Owing to the introduction of rubber and vultex balloons, the maximum

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heights attained in the present series of ascents were generally greater than in the older series and much new information has been obtained regarding layers above 10 km. The author had the advantage of working with Mr. Chatterjee at the Upper Air Observatory, Agra, during the period, January 1927 to April 1928.

The total number of records used in the present discussion is 89. The manner in which these flights are distributed in the different years and months is shown in table 1.

TABLE 1.

Year.	Jan.	Feb.	Mar.	Apl.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL.
1925	..	..	..	..	..	..	1	2	3	1	0	0	7
1926	3	0	2	5	2	5	2	3	4	2	4	1	33
1927	2	2	2	3	3	3	1	3	3	9	4	3	38
1928	4	2	5	..	..	..	..	..	..	..	..	..	11
TOTAL . .	9	4	9	8	5	8	4	8	10	12	8	4	89

The distribution of the ascents according to the time of the day is shown in Table 2.

TABLE 2.

	TIME IN HRS. I. S. T.						
	15—16.	16—17.	17—18.	18—19.	19—20.	21—22.	TOTAL.
Number of ascents . .	1	5	33	42	7	1	89

The data of the individual ascents in 1926 and 1927 are given in the respective Annual Summaries of the Indian Meteorological Department, those for 1925 in Appendix C of this paper and those for 1928 will appear in part 14 of Upper Air Data, 1928.

The units used for temperature are degrees absolute on the Centigrade scale, for pressure millibars and for height above sea-level geodynamic kilometres. The unit for lapse-rate is therefore naturally degrees per geodynamic kilometre. For comparison with previous results and results obtained in other parts of the world, tables of temperature, pressure and density are also given for geometric kilometres in Appendix B.

2. TEMPERATURE.

In Table 3 are given the monthly and annual mean temperatures with the number of observations at each level on which the means are based. Up to 3 gkm, the values are given for each half gkm. step and thereafter for each integral gkm. In calculating heights from pressures and temperatures, allowance has been made for humidity.

TABLE 3.—MEAN MONTHLY TEMPERATURES AT DIFFERENT HEIGHTS (GEODYNAMIC).

[*T*=*Temperature in degrees A*, *n*=*number of observations.*]

Height in gkm.	January.		February.		March.		April.		May.		June.	
	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*
20	212·5	*1*	215·5	*1*	198·5	*1*	212·0	*2*	209·5	*1*	..	..
19	208·0	*1*	213·5	*1*	202·5	*2*	206·0	*6*	202·5	*3*	204·5	*1*
18	203·5	*3*	208·0	*3*	202·5	*3*	204·5	*6*	197·5	*3*	201·5	*4*
17	203·0	*3*	205·5	*3*	200·0	*4*	203·0	*6*	199·0	*4*	197·5	*6*
16	203·5	*4*	205·0	*3*	202·5	*5*	202·0	*5*	202·0	*4*	197·5	*6*
15	203·5	*4*	205·5	*3*	205·0	*5*	206·0	*5*	207·0	*4*	204·0	*6*
14	207·0	*5*	210·0	*3*	210·5	*5*	210·5	*6*	212·5	*5*	210·5	*6*
13	212·0	*5*	215·0	*3*	217·0	*5*	214·5	*6*	217·5	*5*	218·0	*6*
12	217·5	*5*	222·5	*3*	223·5	*6*	219·0	*6*	224·0	*5*	226·0	*6*
11	222·5	*6*	228·0	*3*	228·5	*7*	226·0	*7*	231·0	*5*	235·0	*7*
10	227·5	*6*	233·5	*3*	234·5	*7*	232·0	*7*	238·5	*5*	243·0	*8*
9	236·5	*7*	236·5	*3*	240·7	*7*	239·0	*7*	245·0	*5*	251·0	*8*
8	244·0	*7*	243·5	*3*	246·0	*8*	246·0	*7*	252·0	*5*	257·5	*8*
7	250·5	*7*	251·0	*3*	253·0	*9*	253·5	*7*	258·5	*5*	263·0	*8*
6	257·0	*8*	256·5	*4*	260·0	*9*	260·0	*7*	264·5	*5*	268·0	*8*
5	263·5	*8*	263·0	*4*	266·5	*9*	267·0	*8*	271·0	*5*	274·0	*8*
4	270·0	*8*	269·0	*4*	273·5	*9*	273·5	*8*	278·5	*5*	280·0	*8*
3	276·0	*8*	273·0	*4*	280·0	*9*	281·5	*8*	287·0	*5*	287·0	*8*
2·5	278·0	*9*	276·5	*4*	283·5	*9*	285·5	*8*	292·0	*5*	291·5	*8*
2	280·5	*9*	280·5	*4*	287·0	*9*	290·0	*8*	296·5	*5*	296·0	*8*
1·5	283·0	*9*	284·0	*4*	291·0	*9*	294·0	*8*	301·0	*5*	300·0	*8*
1	286·5	*9*	288·0	*4*	295·0	*9*	298·0	*8*	305·5	*5*	305·0	*8*
0·5	289·5	*8*	291·5	*4*	299·0	*9*	302·0	*8*	309·0	*5*	308·0	*8*
Surface (0·17).	290·5	*9*	293·0	*4*	301·5	*9*	302·5	*8*	309·0	*5*	310·5	*8*

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TABLE 3.—MEAN MONTHLY TEMPERATURES AT DIFFERENT HEIGHTS (GEODYNAMIC)—*contd.*

[*T*=*Temperature in degrees A*, *n*=*number of observations*]—contd.

Height in gkm.	July.		August.		September.		October.		November.		December.		Annual mean.	Range.
	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	*n.*	T.	
20	..	..	..	..	..	..	..	..	208·5	*2*	..	..	..	..
19	..	..	..	..	..	..	205·0	*1*	205·5	*3*	207·0	*1*	..	..
18	..	..	201·0	*2*	200·0	*3*	197·0	*5*	204·0	*4*	202·0	*2*	201·2	11·0
17	..	..	194·0	*2*	194·5	*3*	191·5	*5*	203·5	*5*	199·5	*2*	198·9	14·0
16	..	..	194·5	*2*	196·5	*4*	194·5	*5*	201·5	*5*	202·5	*3*	199·8	10·5
15	..	..	203·0	*3*	202·5	*4*	201·5	*6*	204·0	*5*	207·5	*3*	204·4	5·5
14	209·5	*1*	210·5	*4*	209·5	*4*	208·0	*6*	206·0	*5*	210·5	*3*	209·6	6·5
13	219·5	*2*	219·5	*4*	218·5	*5*	216·0	*7*	211·5	*5*	211·0	*4*	215·8	8·5
12	230·0	*2*	229·5	*5*	226·5	*5*	223·5	*9*	219·0	*5*	216·0	*4*	223·0	14·0
11	239·0	*2*	238·0	*5*	236·5	*7*	231·5	*10*	227·0	*6*	221·0	*4*	230·3	18·0
10	247·5	*2*	246·0	*7*	243·5	*7*	239·0	*10*	234·0	*7*	228·0	*4*	237·3	20·0
9	254·0	*3*	253·5	*8*	251·5	*8*	245·5	*11*	241·0	*8*	236·0	*4*	244·1	18·0
8	260·0	*3*	260·5	*8*	259·0	*8*	252·5	*11*	246·5	*8*	244·5	*4*	251·0	17·0
7	266·0	*3*	266·0	*8*	264·5	*8*	259·0	*11*	252·5	*8*	251·5	*4*	257·4	15·5
6	272·0	*4*	271·0	*8*	270·0	*8*	265·5	*11*	259·0	*8*	259·0	*4*	263·6	15·5
5	277·5	*4*	277·0	*8*	273·5	*10*	271·0	*12*	265·5	*8*	266·0	*4*	269·6	14·5
4	282·5	*4*	281·5	*8*	279·0	*10*	277·0	*12*	270·5	*8*	273·5	*4*	275·7	13·5
3	287·0	*4*	286·5	*8*	284·5	*10*	282·0	*12*	276·5	*8*	279·0	*4*	281·2	14·0
2·5	289·0	*4*	289·0	*8*	287·5	*10*	285·0	*12*	279·0	*8*	282·0	*4*	284·9	15·5
2	291·5	*4*	291·5	*8*	291·0	*10*	289·0	*12*	282·0	*8*	284·0	*4*	288·3	16·0
1·5	294·0	*4*	294·5	*8*	294·5	*10*	293·5	*12*	284·5	*8*	285·0	*4*	291·6	18·0
1	296·0	*4*	298·0	*8*	298·0	*10*	297·5	*12*	288·0	*8*	288·5	*4*	295·3	19·0
0·5	299·0	*4*	301·0	*8*	300·5	*10*	301·0	*12*	291·0	*8*	291·5	*4*	298·6	19·5
Surface (0·17).	301·0	*4*	302·5	*8*	300·5	*10*	300·5	*12*	293·0	*8*	293·5	*4*	299·8	20·0

Fig. 1 shows the annual variation of temperature at different heights over Agra.

From the surface to 3 gkm. the highest mean temperatures occur in May and June, from 4 to 13 gkm. in July-August and from 16 to 20 gkm. in February. At 14 and 15 gkm., there is no pronounced maximum or minimum in any month. The highest temperatures up to 3 gkm. thus occur in a part of the year which is recognised as the hot season in north-west India, while from 4 to 13 gkm. they occur during the active monsoon season. During the latter season, although the lower atmosphere is cooled by the frequent rains and attendant humidification, a large amount of heat is liberated in the atmosphere above the level of low clouds by the condensation of water-vapour and the absorption of solar radiation in the moist atmosphere. The lowest mean temperatures up to 2 gkm. occur in January, from 2·5 to 8 gkm. in February, from 9 to 13 gkm. in December and from 15 to 18 gkm. in October. Some of these conclusions may have to be slightly modified when more data have accumulated.

The range of variation of the monthly mean temperatures during the year decreases from a maximum of 20°C at the surface to 13°·5C at 4 gkm. and increases above that level to a second maximum of 20°C at 10 gkm. The range is lowest (4°·5C) at 15 gkm. and increases again above that level, but owing to the smallness of the number of observations the change from level to level is not regular. The minimum range at 4 gkm. and the increase of range from 4 to 10 gkm. are due to the facts that during the hot months of the year, the lapse-rate of temperature is very high from the surface up to 4 gkm. and above this height, there is a more or less sharp decrease in lapse-rate; and that during the months June to August when the temperature at 4 gkm. is highest, the height-temperature curve between 4 and 10 gkm. follows approximately the curve of saturation adiabatic and hence the lapse-rates are generally smaller than in the drier months. The same reason is responsible for the decrease of range above 10 gkm. to 15 gkm. The saturation adiabatic in this region becomes (owing to the low temperature) practically identical with the dry-air adiabatic and hence the lapse-rates in the monsoon are larger than in the other months. Table 3(*a*) shows the differences between the temperatures given in Table 3 above and those interpolated at the corresponding geodynamic levels from Table 9 of Harwood's paper (denoted respectively by (R) and (H)). The differences are given to the nearest 0·5°C.

TABLE 3(*a*).—TEMPERATURE DIFFERENCES (R)—(H).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
11	1·0	2·5	—2·0	—4·0	—0·5	—4·0	0·5	4·0	2·0	—4·0	—1·0	—7·5
10	3·0	2·5	—1·0	—0·5	5·0	—1·5	3·0	4·0	1·5	—1·5	—2·0	—5·5
9	6·5	—0·5	—1·0	1·5	6·5	0·0	3·0	4·5	2·0	0·0	—1·5	—1·5
8	7·0	—1·0	0·0	2·5	5·5	0·0	2·5	5·0	3·0	1·0	—2·0	1·5
7	6·0	1·0	2·5	2·5	4·5	—1·0	2·5	5·0	2·5	1·0	—3·5	2·5
6	5·5	1·0	3·5	2·5	3·0	—1·5	3·0	3·5	2·0	1·0	—3·5	3·5
5	4·0	0·0	3·0	3·0	2·5	0·0	3·5	3·0	—0·5	0·5	—2·0	3·0
4	3·5	0·0	4·0	2·0	3·5	0·5	3·0	2·0	—1·0	0·5	—2·5	3·0
3	2·5	—2·5	5·5	3·0	4·5	1·0	2·0	1·5	0·0	0·0	—4·5	2·5
2	0·0	—2·0	4·5	2·5	7·0	3·0	1·0	1·0	1·5	2·5	—3·5	2·5
1	0·5	—2·0	5·0	2·0	8·0	5·5	—1·0	2·0	2·0	3·0	—1·0	—0·5
Surface (0·17)	0·0	—0·5	12·5	1·0	8·0	5·5	—1·0	4·0	0·5	3·0	1·0	8·0

It will be seen that some of these differences exceed 5°C, but this is not surprising when we take note of (1) the total number of observations used in each series for making up

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the means and (2) the differences in the times of ascent. Harwood's means for January and March were obtained from 2 and 3 observations respectively and for February and December from 4 observations each. There were again only 4 observations in the present series for February, July and December. These numbers refer to the lower levels; with increase of height, there is a further decrease in number particularly in the earlier series owing to the shortness of the flights. It will also be seen from Table 2 of this paper and Table 13 of Harwood's that while practically all the ascents in the present series were in the afternoon, a large proportion of those in the former series were made in the morning. For example, 2 out of 3 successful ascents in March, 3 out of 6 in May and 5 out of 11 in June in the earlier series were made at 5 hrs. in the morning. Owing to the greater homogeneity of the conditions under which the present series of ascents were made, it was thought not desirable to average the data of the two series.

3. LAPSE-RATES.

The mean monthly values of lapse-rates in different layers are given in Table 4.

TABLE 4.—MEAN MONTHLY LAPSE-RATES IN DEGREES CENTIGRADE PER GEODYNAMIC KILOMETRE.

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean.
20	..	..	..	..	..	..	..	..	..	..	..	..	..
19	—4·4	—2·1	2·0	—4·7	—4·9	..	..	..	..	..	—4·5	..	—3·1
18	—2·8	—5·1	—0·7	—1·4	—5·1	—5·2	..	..	..	—9·7	—2·1	—6·7	—4·3
17	—0·4	—2·7	—2·3	—1·3	—0·9	—4·5	..	—6·7	—5·5	5·6	—1·1	—2·7	—3·1
16	1·1	—0·5	2·3	—0·2	3·3	0·1	..	0·6	2·1	3·1	—2·0	3·7	1·1
15	—0·1	0·7	2·4	3·9	4·7	6·4	..	8·2	5·9	6·1	2·3	4·9	4·1
14	3·3	4·4	5·8	4·1	4·3	6·9	..	8·6	6·9	6·8	2·0	3·1	5·1
13	5·1	5·3	6·5	4·3	5·0	7·6	8·6	8·9	8·9	8·3	5·9	2·5	6·3
12	5·2	7·3	6·1	4·3	6·2	7·9	10·5	9·2	8·0	7·9	7·2	5·1	7·1
11	5·2	4·8	5·2	6·6	7·2	8·6	8·9	8·5	8·8	7·7	7·3	4·9	7·0
10	5·3	5·7	5·9	6·2	7·6	7·9	8·3	7·7	6·9	7·3	7·4	7·2	6·9
9	6·9	3·0	6·1	7·2	6·5	8·0	6·3	7·6	7·8	6·8	7·1	7·6	6·7
8	7·3	5·9	5·9	6·9	7·0	6·4	6·3	6·9	7·1	7·1	5·5	8·6	6·7
7	6·5	7·6	6·6	7·1	6·3	5·5	5·7	5·2	5·9	6·4	5·7	7·6	6·3
6	5·2	5·9	6·9	6·5	6·1	5·1	5·8	5·2	5·4	6·6	6·8	7·6	6·1
5	6·4	6·4	6·7	7·2	6·4	5·9	5·6	5·9	4·6	6·0	6·4	6·9	6·2
4	6·4	6·4	6·9	6·2	7·7	5·9	5·1	4·7	5·3	5·5	5·2	7·3	6·1
3	6·0	3·7	6·4	8·0	8·4	7·4	4·3	4·8	5·4	5·0	5·7	5·8	5·9
2·5	4·5	6·3	7·1	7·9	9·4	8·6	4·0	5·1	6·3	5·8	5·7	5·7	6·4
2	5·5	7·4	7·3	8·9	9·2	8·8	4·3	4·8	6·5	8·5	6·1	4·0	6·8
1·5	5·0	5·9	7·6	8·5	9·4	8·4	4·9	6·3	7·1	8·2	4·6	2·5	6·5
1	6·4	7·0	7·3	8·3	8·8	8·8	5·5	6·7	7·1	8·8	6·8	6·1	7·3
0·5	5·7	5·9	8·5	3·8	8·2	7·6	6·0	5·7	5·3	6·7	5·5	6·1	6·3

For discussing lapse-rates, it is convenient to divide the year into seasons. From the point of view of upper air conditions, the year may be divided into—

(1) Winter—November to February.
(2) Early hot season—March and April.
(3) Later hot season or pre-monsoon period—May and June.
(4) Monsoon season—July and August.
and (5) Post-monsoon period—September and October.

The seasonal mean values of temperatures and lapse-rates arranged according to the above division of the year into seasons are given in table 5.

TABLE 5.—SEASONAL MEAN VALUES OF TEMPERATURES AND LAPSE-RATES.

Height in gkm.	Temperatures (°A).					Height in gkm.	Lapse-rates (°C/gkm.)				
	Nov., Dec., Jan., Feb.	Mar., April.	May, June.	July, Aug.	Sept., Oct.		Nov., Dec., Jan., Feb.	Mar., April.	May, June.	July, Aug.	Sept. Oct.
20	212·0	205·5	209·5	..	..	..	..	..	..	..	..
19	208·5	204·5	203·5	..	205·0	19 —20	—3·3	—1·4	—4·9	..	..
18	204·5	203·5	199·5	201·0	198·5	18 —19	—4·6	—1·1	—5·1	..	—9·7
17	203·0	201·5	198·0	194·0	193·0	17 —18	—1·7	—1·8	—2·7	—6·7	—5·5
16	203·0	202·5	200·0	194·5	195·5	16 —17	0·6	1·1	1·7	0·6	2·6
15	205·0	205·5	205·5	203·0	202·0	15 —16	2·0	3·2	5·5	8·2	6·0
14	208·5	210·5	211·5	210·0	209·0	14 —15	3·3	4·9	5·6	8·6	6·9
13	212·5	215·5	217·5	219·5	217·0	13 —14	4·7	5·4	6·3	8·7	8·1
12	219·0	221·5	225·0	230·0	225·0	12 —13	6·2	5·2	7·1	9·9	7·9
11	224·5	227·5	233·0	238·5	234·0	11 —12	5·6	5·9	7·9	8·7	8·3
10	231·0	233·5	241·0	247·0	241·0	10 —11	6·4	6·1	7·7	8·0	7·1
9	237·5	239·5	248·0	254·0	248·5	9 —10	6·2	6·7	7·3	6·9	7·3
8	244·5	246·0	255·0	260·0	256·0	8 — 9	6·6	6·4	6·7	6·6	7·1
7	251·5	253·5	261·0	266·0	262·0	7 — 8	6·9	6·9	5·9	5·5	6·1
6	258·0	260·0	266·0	271·5	268·0	6 — 7	6·4	6·7	5·6	5·5	6·0
5	264·5	267·0	272·5	277·0	272·0	5 — 6	6·5	7·0	6·1	5·7	5·3
4	271·0	273·5	279·0	282·0	278·0	4 — 5	6·3	6·6	6·8	4·9	5·4
3	276·0	281·0	287·0	287·0	283·0	3 — 4	5·3	7·2	7·9	4·5	5·2
2·5	279·0	284·5	291·5	289·0	286·0	2·5— 3	5·6	7·5	9·0	4·5	6·1
2	281·5	288·5	296·0	291·5	290·0	2 — 2·5	5·8	8·1	9·0	4·5	7·5
1·5	284·0	292·5	300·5	294·0	294·0	1·5— 2	4·5	8·1	8·9	5·6	7·7
1	287·5	296·5	305·5	297·0	297·5	1 — 1·5	6·6	7·8	8·8	6·1	7·9
0·5	291·0	300·5	308·5	300·0	301·0	0·5— 1	5·8	6·2	7·9	5·9	6·0
Surface (0·17).	292·5	302·0	310·0	302·0	300·5	..	..	..	..	..	..

D

The variation of the average lapse-rate with height in each season is shown in fig. 2.

(1) During the winter, there is generally a layer of well-marked maximum lapse-rate between 1 and 1·5 gkm. Above 4 gkm., the mean lapse-rate slowly increases with height reaching a feeble maximum between 7 and 8 gkm. and then decreases slowly up to 13 gkm. and rapidly thereafter.

(2) In March and April (and especially in the latter month), the mean lapse-rates are markedly higher up to 4 gkm., than at higher levels, the maximum values on the average of the two months exceeding 8°C/gkm. between 1·5 and 2·5 gkm.[1] There is a feeble minimum of 6·5°C/gkm. between 4 and 5 gkm. The general course of the curve between 4 and 11 gkm. is similar to that of the winter curves, the slight differences being probably attributable to the smallness of the number of observations. The marked decrease in lapse-rate becomes manifest only above 15 gkm.

(3) The curve for the pre-monsoon period is remarkable for its double maximum, one going up to 9°C/gkm. between 1·5 and 3 gkm. and the other to 8°C/gkm. between 11 and 12 gkm. A minimum value of 5·5°C/gkm. occurs between 6 and 7 gkm.

The sudden decrease of lapse-rate marking the top of the troposphere occurs only above 16 gkm. and is sharper than in periods (1) and (2).

(4) The monsoon curve presents some new features. The changes from the hot season are most marked below 5 gkm. The lapse-rates are much smaller below this level than in the hot season, the lowest values being between 2 and 5 gkm. and less than 5°C/gkm. Below 2 gkm., the values are about 6°C/gkm. Above 5 gkm. the values increase (with a probable minimum between 7 and 8 gkm.) to a maximum of 9°C gkm. between 12 and 13 gkm. The sharp decrease of lapse-rate begins at about 16 gkm.

Although the number of observations are few especially in the higher layers, it is not likely that the general conclusions will be appreciably modified by further observations as the differences between the values obtained from the individual flights in this season are small.

(5) The monsoon generally withdraws from the United Provinces by the middle of September. The lapse-rate curve of September-October is intermediate in character between that for May-June and that for the monsoon. The two regions of maximum lapse-rates occur between 1 and 2 gkm. and between 11 and 14 gkm. The minimum occurs between 3 and 5 gkm. The decrease of lapse-rates above 14 gkm. is more gradual than in July-August.

The relative frequencies with which different lapse-rates occur in different layers in all the seasons are shown in Table 6. The steadiness of the values in May-June and July-August is remarkable. Although we are not dealing with the same number of observations in different layers and in different seasons, we may safely conclude that the scatter of lapse-rates in all layers is greatest during the winter.

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[1] The smaller lapse-rate below 1·5 gkm. is probably due to the fact that the soundings were generally made after 17 hrs. and cooling due to radiation had set in at the surface.

Table 6.—Seasonal Frequencies of Lapse-Rates.

(a) November, December, January and February.

Height in gkm.	Number of observations.	Range of lapse-rates.													
		-3·0.	—3·0 to —2·1.	—2·0 to —1·1.	—1·0 to —0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
20 —21	2	1	1	..	..	..	..	..	..	..	..	..	..	..	..
19 —20	4	3	1	..	..	..	..	..	..	..	..	..	..	..	..
18 —19	6	3	1	1	1	..	..	..	..	..	..	..	..	..	..
17 —18	12	5	1	1	1	3	1	..	..	..	..	..	..	..	..
16 —17	13	2	2	2	1	1	1	2	..	1	1	..	..	..	..
15 —16	15	..	..	3	1	1	4	2	..	2	1	..	..	..	..
14 —15	15	..	..	..	1	3	..	5	1	2	1	1	1	..	..
13 —14	16	..	..	..	..	..	2	2	2	3	4	..	1	1	1
12 —13	17	..	..	..	..	..	1	1	..	2	3	4	5	..	1
11 —12	17	..	..	..	..	..	1	..	2	3	4	3	2	2	..
10 —11	19	..	..	..	..	..	..	1	..	3	1	8	4	1	1
9 —10	20	..	..	..	..	..	1	2	..	1	3	3	4	4	2
8 — 9	22	..	..	..	..	1	1	..	..	3	3	1	5	7	1
7 — 8	22	..	..	..	..	..	..	2	..	1	5	4	5	4	1
6 — 7	22	..	1	..	..	..	..	..	1	1	5	5	7	2	..
5 — 6	24	..	..	..	..	..	..	..	1	3	4	9	4	2	1
4 — 5	24	..	..	..	..	1	..	..	..	2	6	8	7	..	..
3 — 4	24	..	..	..	..	..	1	1	2	4	10	3	1	1	1
2·5— 3	24	..	1	..	..	..	..	2	3	3	4	6	4	..	1
2 — 2·5	25	..	..	..	..	..	1	2	2	5	6	2	2	4	1
1·5— 2	25	1	1	..	..	1	1	2	3	3	4	3	3	2	1
1 — 1·5	24	..	..	..	..	..	1	..	3	2	4	3	7	2	2
0·5— 1	22	..	..	..	..	1	..	1	2	1	8	3	4	2	..
(b) March and April.															
22 —23	1	..	1	..	..	..	..	..	..	..	..	..	..	..	..
21 —22	1	..	1	..	..	..	..	..	..	..	..	..	..	..	..
20 —21	1	..	..	1	..	..	..	..	..	..	..	..	..	..	..
19 —20	3	1	1	..	..	..	1	..	..	..	..	..	..	..	..
18 —19	8	..	2	3	..	3	..	..	..	..	..	..	..	..	..
17 —18	9	1	3	2	1	1	1	..	..	..	..	..	..	..	..
16 —17	9	1	..	1	..	3	1	1	1	1	..	..	..	..	..
15 —16	10	..	..	..	1	..	3	..	2	2	1	1	..	..	..
14 —15	9	..	..	..	..	..	1	1	..	3	1	3	..	..	..
13 —14	11	..	..	..	..	..	..	1	3	1	1	3	2	..	..
12 —13	11	..	..	..	..	..	2	..	1	2	2	2	..	2	..
11 —12	12	..	..	..	..	..	2	..	1	1	1	2	2	2	1
10 —11	14	..	..	..	..	..	..	..	1	4	3	2	1	2	1
9 —10	13	..	..	..	..	..	1	..	..	1	1	3	5	1	1
8 — 9	14	..	..	..	..	..	..	..	..	2	5	3	3	1	..
7 — 8	15	..	..	..	..	..	..	..	..	1	2	6	2	3	1
6 — 7	16	..	..	..	..	..	..	..	..	1	2	6	6	1	..
5 — 6	16	..	..	..	..	..	..	..	..	1	3	6	3	2	1
4 — 5	16	..	..	..	..	..	1	..	..	1	3	5	5	1	..
3 — 4	17	..	..	..	..	..	..	..	1	1	3	4	2	2	4
2·5— 3	17	..	..	..	..	..	..	..	1	1	2	1	5	5	2
2 — 2·5	16	..	..	..	..	..	..	..	..	..	2	1	7	4	2
1·5— 2	16	..	..	..	..	..	..	..	..	1	1	1	2	7	4
1 — 1·5	14	..	..	..	..	..	..	..	..	1	1	2	3	7	..
0·5—1	16	..	..	..	..	..	..	..	..	1	1	3	2	4	5

D 2

TABLE 6.—SEASONAL FREQUENCIES OF LAPSE-RATE—*contd.*

(c) *May and June.*

Height in gkm.	Number of obser-vations.	Range of lapse-rates.													
		<−3·0.	−3·0 to −2·1.	−2·0 to −1·1.	−1·0 to −0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
19 —20	2	1	1	..	..	..	..	..	..	..	..	..	..	..	..
18 —19	4	4	..	..	..	..	..	..	..	..	..	..	..	..	..
17 —18	7	3	1	2	..	1	..	..	..	..	..	..	..	..	..
16 —17	10	2	1	..	..	..	1	2	2	1	1	..	..	..	..
15 —16	10	..	..	..	..	..	..	1	1	4	..	1	..	2	1
14 —15	10	..	..	..	1	..	..	..	..	..	3	4	1	1	..
13 —14	11	..	..	1	..	..	..	..	..	..	1	4	4	1	..
12 —13	11	..	..	..	..	..	..	1	..	..	..	3	4	3	..
11 —12	11	..	..	..	..	..	..	..	..	..	..	2	4	4	1
10 —11	12	..	..	..	..	..	..	..	..	..	..	2	6	4	..
9 —10	13	..	..	..	1	..	..	..	..	..	..	1	6	4	1
8 — 9	13	..	..	..	..	..	..	..	..	..	4	5	3	1	..
7 — 8	13	..	..	..	..	..	..	..	..	4	5	2	1	1	..
6 — 7	13	..	..	..	..	..	1	..	1	2	4	3	2	..	..
5 — 6	13	..	..	..	..	..	..	..	..	3	4	3	3	..	..
4 — 5	13	..	..	..	..	..	..	..	..	3	2	3	3	1	1
3 — 4	13	..	..	..	..	..	..	..	..	1	..	2	4	6	..
2·5— 3	13	..	..	..	..	..	..	..	..	..	1	..	1	4	7
2 — 2·5	13	..	..	..	..	..	..	..	..	..	..	..	1	7	5
1.5 —2	13	..	..	..	..	..	..	..	..	..	..	1	..	8	4
1 —1·5	12	..	..	..	..	..	..	..	..	..	..	..	1	7	4
0·5—1	12	..	..	..	..	..	..	..	2	..	1	2	4	1	2

(d) *July and August.*

Height in gkm.	Number of obser-vations.	<−3·0.	−3·0 to −2·1.	−2·0 to −1·1.	−1·0 to −0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
17 —18	2	2	..	..	..	..	..	..	..	..	..	..	..	..	..
16 —17	2	..	..	..	..	2	..	..	..	..	..	..	..	..	..
15 —16	2	..	..	..	..	..	..	..	..	..	..	..	1	1	..
14 —15	3	..	..	..	..	..	..	..	..	..	..	..	1	1	1
13 —14	5	..	..	..	..	..	..	..	..	..	..	..	2	2	1
12 —13	6	..	..	..	..	..	..	..	..	..	..	..	..	1	5
11 —12	7	..	..	..	..	..	..	..	..	..	..	..	2	2	3
10 —11	7	..	..	..	..	..	..	..	..	..	..	1	2	4	..
9 —10	9	..	..	..	..	..	..	..	..	..	..	4	3	2	..
8 — 9	11	..	..	..	..	..	..	..	..	..	1	6	4	..	..
7 — 8	11	..	..	..	..	..	..	..	1	1	8	1	..	..	..
6 — 7	11	..	..	..	..	..	..	..	..	3	8	..	..	..	..
5 — 6	12	..	..	..	..	..	..	..	..	1	9	1	1	..	..
4 — 5	12	..	..	..	..	..	1	1	..	4	5	1	..	..	..
3 — 4	12	..	..	..	..	..	..	..	2	7	2	1	..	..	..
2·5— 3	12	..	..	..	..	..	..	1	1	5	5	..	..	..	..
2 — 2·5	12	..	..	..	..	..	..	1	4	3	2	2	..	..	..
1·5— 2	12	..	..	..	..	..	..	..	1	3	6	..	..	..	2
1 — 1·5	11	..	..	..	..	..	..	..	1	1	3	3	2	..	1
0·5— 1	12	..	..	..	..	..	..	..	1	2	4	2	2	1	..

TABLE 6.—SEASONAL FREQUENCIES OF LAPSE-RATE—*concld.*

(e) September and October.

Height in gkm.	Number of obser-vations.	Range of lapse-rates.													
		<-3·0.	—3·0 to —2·1.	—2.0 to —1·1.	—1·0 to —0·1.	0 to 1·0.	1·1 to 2·0.	2·1 to 3·0.	3·1 to 4·0.	4·1 to 5·0.	5·1 to 6·0.	6·1 to 7·0.	7·1 to 8·0.	8·1 to 9·0.	>9·0.
20 —21	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
19 —20	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
18 —19	1	1	..	..	..	..	..	..	..	..	..	..	..	..	..
17 —18	8	8	..	..	..	..	..	..	..	..	..	..	..	..	..
16 —17	8	..	..	..	1	1	..	3	1	1	1	..	..	..	..
15 —16	9	..	..	..	..	..	..	..	..	3	2	2	1	1	..
14 —15	10	..	..	..	..	..	1	..	..	1	..	4	2	..	2
13 —14	10	..	..	..	..	..	..	..	..	..	..	1	2	6	1
12 —13	12	..	..	..	..	..	..	..	..	..	..	1	4	7	..
11 —12	14	..	..	..	..	..	..	..	..	..	1	1	3	8	1
10 —11	17	..	..	..	..	..	..	..	1	1	3	3	4	4	1
9 —10	17	..	..	..	..	..	..	..	..	2	..	4	8	2	1
8 — 9	19	..	..	..	..	..	..	..	..	..	4	5	7	3	..
7 — 8	19	..	..	..	..	..	..	1	1	..	4	8	5	..	..
6 — 7	19	..	..	..	..	..	..	..	..	4	3	8	4	..	..
5 — 6	19	..	..	..	..	..	1	1	2	5	1	6	3	..	..
4 — 5	22	..	..	..	..	..	1	..	2	6	7	2	3	1	..
3 — 4	22	..	..	..	..	..	1	2	3	2	9	3	1	1	..
2·5— 3	22	..	..	..	..	..	..	2	1	3	3	6	5	2	..
2 — 2·5	22	..	..	..	..	..	..	..	1	..	4	3	5	3	6
1·5— 2	22	..	..	..	..	..	..	..	..	3	1	3	3	7	5
1 — 1·5	22	..	..	..	..	..	..	..	..	1	3	..	3	9	6
0·5— 1	20	..	..	..	..	..	1	..	3	2	4	1	7	1	1

4. PRESSURE.

Table 7 gives the monthly mean values of pressure at different heights over Agra. The values have been corrected for humidity. Curves of annual variation are shown in figure 3.

TABLE 7.—MEAN MONTHLY PRESSURES (mb).

Height in gkm.	Jan.	Feb.	Mar.	Apl.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual mean.	Range.
20	51	51	52	53	53	..	..	..	..	..	52	..	..	..
19	60	61	62	63	64	..	..	..	63	63	61	61	62	..
18	71	72	73	73	75	76	..	76	75	74	72	73	74	5
17	84	86	87	87	89	90	..	91	90	89	85	87	88	7
16	100	101	103	103	106	108	..	108	107	106	101	102	104	8
15	118	120	123	122	125	128	..	129	128	126	120	121	124	11
14	140	142	145	144	149	151	151	152	152	150	143	143	147	12
13	166	167	171	170	175	178	180	180	179	175	169	167	163	14
12	195	196	201	200	205	209	211	211	209	206	199	197	203	16
11	228	229	234	233	239	242	244	244	244	239	232	231	237	16
10	265	265	271	271	277	280	283	282	281	277	270	269	274	18
9	311	310	315	315	322	323	324	325	324	321	313	314	318	15
8	359	357	363	363	369	370	371	372	372	369	361	363	366	15
7	413	412	417	418	423	423	423	424	425	422	414	417	419	13
6	474	471	479	478	483	482	482	483	484	482	475	479	479	13
5	543	540	546	546	550	549	548	549	550	549	543	547	547	10
4	617	614	621	621	625	621	619	621	622	623	618	621	620	11
3	702	700	704	703	707	703	700	702	704	706	702	705	703	7
2·5	747	745	749	748	750	747	745	747	748	750	747	750	748	5
2	794	791	796	795	796	791	789	792	794	798	795	797	794	6
1·5	845	842	845	844	844	839	838	840	842	847	845	847	843	9
1	899	896	898	895	895	890	889	891	894	899	899	901	896	12
0·5	955	953	952	949	948	942	943	944	947	952	954	957	950	15
Surface (0·17)	994	991	989	985	982	977	979	980	984	989	993	995	987	18

B

The results up to 11 gkm. are in general agreement with those found by Harwood. At the surface the minimum pressure occurs in June and between 1 and 3 gkm. in July. The maximum at the surface occurs in December. The epochs of maximum and minimum are practically reversed at a height of 6 gkm., with the former occurring in the period May to October and the latter in winter. Between 2 and 5 gkm., there are two minima in the year, one in the winter and the other in July. Above 6 gkm., the character of the annual variation remains practically the same as at 6 gkm. but the maxima occur definitely in the monsoon months July-September. The range of variation decreases from 18 mb. at the surface to 5 mb. at 2·5 gkm. and then increases to 18 mb. at 10 gkm. Thereafter, it again decreases to 2 mb. at 20 gkm. When the variation at each level is considered as a percentage of the actual mean pressure at that level, it is a maximum between 12 and 17 gkm. with a value of about 8 per cent. and a minimum at 2·5 gkm. with a value of 0·7 per cent.

4a. COMPARISON OF PRESSURES IN THE UPPER AIR OVER AGRA, BATAVIA AND EUROPE.

Tables 8 and 9 give the monthly mean differences of pressure in millibars at different levels between Agra and Batavia and Agra and England respectively. The data for Batavia are those given by van Bemmelen[1] and those for England by W. H. Dines[2]. The heights in these tables are geometric and not geodynamic kilometres.

TABLE 8.—MEAN MONTHLY DIFFERENCES OF PRESSURE BETWEEN AGRA AND BATAVIA. BATAVIA—AGRA (mb.).

Height in km.*	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
20	−1	−1	0	−1	−1	..	..	..	..	0	..	..
19	0	−1	0	−1	−2	−3	..	−2	−1	0	1	−2
18	2	1	1	1	0	−3	..	−3	−1	1	3	0
17	3	2	2	1	0	−3	..	−4	−2	1	5	−1
16	4	4	3	2	1	−4	..	−5	−2	1	6	1
15	7	6	4	5	3	−3	..	−6	−4	1	8	2
14	8	8	5	6	3	−2	−4	−7	−4	1	8	4
13	9	10	6	7	4	−2	−7	−7	−4	2	9	7
12	10	12	7	8	6	−2	−6	−6	−3	2	11	9
11	11	12	7	8	7	−1	−6	−5	−4	2	10	7
10	11	13	7	8	5	0	−5	−4	−3	2	9	7
9	12	14	9	10	5	1	−3	−3	−2	3	12	7
8	12	14	9	10	6	2	−1	−1	−1	4	12	7
7	11	13	9	8	5	3	0	0	−1	3	12	7
6	9	14	6	7	3	3	1	0	−1	3	10	4
5	8	12	5	5	3	3	3	2	1	3	9	3
4	9	12	5	5	3	6	5	4	4	4	9	4
3	6	8	4	5	1	5	8	6	4	3	7	2
2	4	6	2	3	2	7	9	6	5	0	3	1
1	1	4	2	4	5	10	11	9	7	2	1	−1

* Heights in this table are given in geometric kilometres.

[1] *Proc. Kon. Akad. Wetenschappen*, Amsterdam, Vol. 30, p. 1313, (1918).

[2] *Geoph. Mem.* No. 13, London M. O.

TABLE 9.—MEAN MONTHLY DIFFERENCES OF PRESSURE BETWEEN AGRA AND ENGLAND. AGRA—ENGLAND (mb.).

Height in km.*	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
15	8	10	12	9	10	11	..	11	12	11	6	10
14	11	13	16	13	15	14	12	14	14	14	10	13
13	14	15	19	16	17	17	17	17	18	15	11	14
12	16	17	21	18	19	20	20	19	19	18	17	16
11	19	19	25	21	21	21	20	20	21	20	15	20
10	20	21	26	23	24	21	21	19	21	20	17	22
9	21	21	24	20	24	20	18	19	19	19	15	21
8	21	20	23	20	23	18	16	16	18	19	15	21
7	22	21	23	20	21	16	14	14	17	17	14	21
6	20	17	24	19	20	14	12	13	16	17	13	21
5	20	17	22	18	18	13	9	9	13	15	13	21
4	15	13	19	16	16	8	3	4	8	12	11	17
3	14	12	16	11	12	4	—1	0	6	11	9	14
2	10	9	12	8	7	—2	—5	—2	2	9	9	12
1	3	1	3	—1	—2	—10	—12	—9	—4	4	2	5

* Heights in this table are given in geometric kilometres.

Taking first the difference of pressure between Batavia and Agra, the mean gradient is for westerly winds north of the equator between November and May. The gradient increases to a maximum at 8—9 km. and thereafter decreases to a very small value at 20 km. The present observations do not show the existence of any marked resultant gradient in winter for easterly winds below 2 km. between the equator and Agra which Harwood finds and associates with the north-east monsoon. This may be due to the variable position of the high pressure area over the Deccan in winter at a height of 1 and 2 km. separating the regions of easterly and westerly winds. During the active monsoon months July and August there is a large excess of pressure at the surface at Batavia over that at Agra ; this excess rapidly decreases with height and becomes zero at 7 km. which is in agreement with Harwood's results. Above 7 km. the gradient reverses sign and the maximum gradient for easterly winds north of the equator occurs between 11 and 15 km. Conditions are similar in June and September, but the gradient for easterly winds is generally weaker and the reversal of gradient occurs at a greater height in June. In the transition month October, gradients are generally weak at all levels.

E 2

The pressure differences between Agra and England given in table 9 show that the gradient is generally a maximum at some height varying from 7 km. in winter to 11 km. in the monsoon. From Teisserenc de Bort's maps of 4 km. isobars it seems probable that pressures in Asia at the latitude of England are lower than those in England in January and larger in July. The winds between North India and Central Asia near the 4 km. level may therefore be expected to be even stronger in winter and weaker in the monsoon than are indicated by the pressure differences given in the above table.

5. HUMIDITY.

The mean monthly values of relative humidity up to 8 gkm. are given in Table 10. In working up the humidity-traces of the meteorographs it was assumed that the displacement of the humidity-pen was proportional to the relative humidity. There are also reasons to believe that the tension to which the hairs were subjected was in some cases excessive. Owing to these limitations, the humidity-values cannot be considered to have more than qualitative significance.

TABLE 10.—MEAN MONTHLY RELATIVE HUMIDITIES.

Height in gkm.	Jan.		Feb.		Mar.		April.		May.		June.		July.		Aug.		Sept.		Oct.		Nov.		Dec.	
	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*
10	..		..		..		..		..		..		81	*2*	67	*6*	65	*2*	..		..		..	
9	..		..		..		..		15	*4*	..		90	*3*	73	*7*	61	*3*	..		..		..	
8	36	*6*	..		33	*3*	23	*7*	14	*4*	51	*7*	90	*3*	80	*7*	47	*6*	23	*8*	..		..	
7	37	*6*	41	*3*	37	*7*	25	*7*	15	*4*	51	*8*	92	*3*	80	*7*	47	*6*	25	*8*	35	*8*	31	*4*
6	39	*6*	39	*4*	52	*8*	28	*7*	19	*4*	56	*8*	89	*4*	78	*7*	54	*7*	29	*10*	35	*8*	31	*4*
5	40	*6*	44	*5*	52	*8*	27	*8*	21	*4*	58	*8*	88	*4*	67	*7*	65	*9*	33	*10*	38	*8*	31	*4*
4	37	*6*	48	*5*	48	*8*	32	*8*	26	*4*	61	*8*	90	*4*	66	*7*	69	*9*	36	*11*	47	*8*	32	*4*
3	39	*6*	54	*5*	51	*8*	30	*8*	28	*4*	56	*8*	91	*4*	85	*7*	66	*9*	39	*11*	53	*8*	36	*4*
2·5	39	*6*	57	*5*	47	*8*	28	*8*	25	*4*	52	*8*	93	*4*	92	*7*	67	*9*	45	*11*	51	*8*	37	*4*
2	39	*6*	58	*5*	44	*8*	25	*8*	22	*4*	45	*8*	93	*4*	89	*7*	68	*9*	48	*11*	51	*8*	39	*4*
1·5	41	*5*	61	*4*	37	*8*	24	*8*	20	*3*	39	*8*	91	*4*	82	*7*	68	*9*	46	*11*	52	*8*	36	*3*
1	47	*4*	59	*4*	38	*4*	23	*6*	19	*3*	37	*8*	90	*4*	79	*7*	64	*8*	44	*11*	55	*8*	38	*3*
0·5	49	*4*	69	*1*	35	*2*	24	*6*	..		31	*7*	89	*4*	..	..	56	*6*	43	*10*	61	*5*	36	*1*
Surface (0·17)	51	*6*	60	*5*	24	*8*	25	*8*	26	*4*	27	*9*	89	*4*	77	*5*	71	*9*	45	*11*	55	*8*	51	*4*

It is well-known that the hair hygrometer ceases to function below 250° A. The tabulation of humidity values was therefore generally not continued beyond 1 or 2 km. above the level at which they ceased to change with height. The mean values of the ascending and descending curves were taken.

Even the monthly averages of humidity show considerable differences from those given by Harwood. This is not surprising in view of the limitations of hygrometric measurement as mentioned above, the smallness of the number of observations, and the possible range of variation from day to day or even from year to year.

The maximum humidity at all levels occurs in the monsoon month July. There is a secondary maximum in February due to the passage of western disturbances. The corresponding months found by Harwood are August and January. The progressive increase of humidity during the hot season shown by Harwood's data does not appear in the present figures. The driest months from the point of view of relative humidity appear to be the hot season months April and May and not the winter months November, December and January. The contrast between Harwood's and the present figures for November is very strong and is to some extent influenced by the fact that two of the ascents included in the present discussion were made in wet weather. Even if these days are excluded the present humidity values are higher than Harwood's. In the other winter months also, the present values may be somewhat high owing to the fact that many of the ascents in the winter of 1927-28 were made on "disturbed" days.

Variation of humidity with height in different seasons.

During the winter months, there is generally increased humidity at the surface apparently connected with the ground inversion. In disturbed weather, other maxima of humidity at different levels from 1·5 to 6 gkm. are met with. In the hot season months March-May a maximum of humidity is very frequent at some level between 3 and 5 gkm. Its position marks the top of the surface layer of air with the large lapse-rate of temperature. Conditions are somewhat similar in June before the advent of the monsoon, but in this month, humidities above 4 or 5 gkm. are much higher than in May. In July-August, there are generally two heights of maximum humidity one at 1·5 to 2·5 gkm. and the other at about 7 gkm. marking respectively the heights of low and middle clouds. During times of active monsoon the humidity is generally very high throughout, while during times of weak monsoon, there is usually a comparatively dry layer somewhere between 3 and 6 gkm. As is well known, when a dry layer of the atmosphere is superposed on a moist layer and the whole is raised bodily, conditions will become favourable for instability at the surface of transition between the two layers. It is this characteristic combined with the weakness of the upper winds that probably make the monsoon season in the United Provinces specially favourable for thunderstorms. With the retreat of the monsoon in the latter half of September and in October, the humidity values show a maximum near 2 gkm. associated with a well-morked inversion.

The mean monthly values of vapour pressure and mixing ratio are given in tables 11 and 12.

TABLE 11.—MEAN MONTHLY VALUES OF VAPOUR PRESSURE (mb.).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10	..	..	..	..	..	..	0·5	0·3	0·3	..	..	..
9	..	..	..	..	..	..	1·0	0·8	0·6	..	..	..
8	0·1	..	0·2	0·1	0·1	0·9	1·8	1·7	0·9	0·2	..	..
7	0·3	0·3	0·3	0·3	0·3	1·4	3·1	2·6	1·4	0·5	0·3	0·3
6	0·6	0·6	1·0	0·6	0·6	2·2	5·2	4·0	2·6	0·9	0·6	0·6
5	1·0	1·1	1·8	0·9	1·0	3·7	7·0	5·2	4·0	1·7	1·3	1·0
4	1·7	2·0	2·9	2·0	2·4	6·1	10·7	7·0	6·5	2·9	2·4	2·0
3	3·1	3·1	5·2	3·1	4·4	8·7	14·9	13·0	9·3	4·4	4·4	3·4
2·5	3·4	4·7	5·6	3·7	5·6	10·7	16·9	16·9	10·7	6·1	4·7	4·0
2	4·0	6·1	7·5	4·7	6·5	12·2	19·2	18·0	13·9	8·7	5·6	5·2
1·5	5·2	8·1	7·5	6·1	7·5	13·9	23·1	21·8	18·0	11·4	7·0	5·2
1	7·0	10·0	10·0	7·0	9·3	18·0	24·6	24·6	20·4	13·0	9·3	7·0
0·5	8·7	13·9	11·4	9·3	..	18·0	29·5	..	20·4	15·9	12·2	..
Surface (0·17)	10·0	13·9	8·7	10·0	15·9	18·0	33·3	31·4	26·2	16·9	12·2	12·2

TABLE 12.—MEAN MONTLY VALUES OF MIXING RATIO.

(gms. of water-vapour per kgm. of dry air).

Height in gkm.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
10	..	..	..	..	..	..	1·0	0·8	0·6	..	..	..
9	..	..	..	..	..	..	2·0	1·5	1·1	..	..	..
8	0·3	..	0·3	0·2	0·2	1·4	3·1	2·8	1·4	0·4	..	..
7	0·4	0·5	0·5	0·4	0·4	2·0	4·6	3·9	2·0	0·7	0·5	0·4
6	0·8	0·8	1·4	0·7	0·7	2·8	6·7	5·1	3·4	1·2	0·8	0·7
5	1·2	1·3	2·1	1·1	1·2	4·2	8·1	5·9	4·6	1·9	1·5	1·2
4	1·7	2·0	2·8	2·0	2·4	6·3	10·9	7·1	6·7	2·8	2·4	2·0
3	2·8	2·8	4·6	2·8	3·9	7·8	13·5	11·8	8·3	3·9	3·9	3·0
2·5	2·8	4·0	4·7	3·1	4·7	9·0	14·5	14·5	9·0	5·2	4·0	3·3
2	3·1	5·0	5·9	3·7	5·1	9·7	15·5	14·5	11·0	6·8	4·4	4·1
1·5	3·8	6·0	5·6	4·6	5·6	10·5	17·7	16·5	13·6	8·5	5·2	3·8
1	4·9	7·0	7·0	4·9	6·5	12·8	17·7	17·7	14·5	9·1	6·5	4·9
0·5	5·7	9·2	7·5	6·1	..	12·1	19·9	..	13·7	10·5	8·0	..
Surface (0·17)	6·3	8·8	5·5	6·3	10·2	11·7	21·8	20·5	17·0	10·8	7·7	7·7

6. DENSITY.

The monthly mean values of density are given in table **13**. The values have been corrected for humidity.

TABLE 13.—MEAN MONTHLY DENSITIES. (gms. per cubic metre).

Height in gkm.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean.	Range.
20	84	82	91	87	88	..	..	..	..	..	87	..	..	..
19	101	100	105	105	108	109	..	..	..	107	103	103	..	..
18	*121*	*121*	125	124	**132**	131	..	**132**	131	131	123	126	127	11
17	*144*	146	152	149	156	159	..	**163**	161	161	145	151	153	19
16	*171*	172	177	178	183	190	..	**193**	190	191	175	175	181	22
15	*202*	203	209	206	210	219	..	**221**	220	218	205	203	211	19
14	*236*	*236*	240	238	244	250	251	251	**252**	251	242	236	244	16
13	273	*271*	275	276	280	285	**286**	**286**	285	282	278	276	279	15
12	312	*307*	313	318	319	**322**	**319**	320	321	321	317	318	317	15
11	357	*350*	357	359	360	359	365	357	359	359	356	**364**	358	*14*
10	406	*395*	403	407	404	401	398	399	402	403	402	**411**	403	16
9	458	457	457	459	458	458	*443*	446	449	455	452	**463**	455	20
8	513	**517**	514	514	510	500	*496*	497	499	509	510	**517**	508	21
7	574	572	574	575	570	559	*552*	554	559	567	571	**577**	567	25
6	643	640	641	640	636	625	*614*	619	623	632	638	**644**	633	30
5	**717**	714	713	712	706	696	*685*	688	698	704	711	716	705	32
4	**795**	794	789	790	780	770	*758*	765	773	782	**795**	790	782	37
3	884	**891**	874	868	856	849	*843*	848	858	870	882	879	867	48
2·5	934	**937**	917	911	893	*888*	890	893	902	914	930	924	911	49
2	**984**	979	963	953	932	*925*	933	938	943	958	979	975	955	59
1·5	**1,038**	1,030	1,009	997	973	*968*	983	984	988	1,000	1,031	1,033	1,003	70
1	**1,090**	1,079	1,055	1,047	1,017	*1,009*	1,034	1,030	1,035	1,046	1,083	1,085	1,051	81
0·5	**1,145**	1,132	1,104	1,090	1,064	*1,058*	1,085	1,078	1,088	1,094	1,136	1,140	1,101	87
Surface (0·17)	**1,190**	1,173	1,138	1,130	1,100	*1,098*	1,120	1,115	1,130	1,140	1,175	1,175	1,140	**100**

The annual range decreases with increase of height from the surface up to 11 gkm. and increases thereafter, reaching a secondary maximum at 16 gkm. Considered as a percentage of the mean density, the range decreases rapidly from the surface up to 2·5 gkm., then more slowly up to 11 gkm. where it becomes a minimum and increases again to ranges exceeding that at the surface at a height of 16 and 17 gkm. It is interesting to note that over England, the minimum range occurs at a height of 8 km.[1]

[1] S. N. Sen, *Q. J. R. Met. Soc.*, 50, 1924, p. 29.

7. POTENTIAL TEMPERATURE.

The mean monthly dry-air potential temperatures are given in table 14.

TABLE 14.—MEAN MONTHLY POTENTIAL TEMPERATURES.
(0A ; standard pressure being 1000 mb.).

Height in gkm.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual mean.	Range.
20	..	..	..	..	462	..	..	..	..	..	..	..	462	..
19	..	..	452	452	448	452	..	..	..	455	454	466	454	..
18	**436**	433	430	434	*416*	424	..	421	420	*416*	435	429	427	20
17	415	**417**	405	411	400	395	..	*389*	390	385	413	405	402	28
16	**397**	**397**	389	389	386	376	..	*369*	375	371	390	391	385	28
15	377	379	376	378	377	369	..	*364*	367	366	375	**382**	374	18
14	365	369	367	368	369	363	361	362	362	*360*	361	**370**	365	10
13	357	**361**	**361**	358	360	360	**361**	360	359	358	*354*	*354*	359	7
12	349	356	356	349	353	356	**361**	359	356	354	350	*346*	354	15
11	341	350	348	345	350	354	**360**	357	356	351	347	*338*	350	22
10	*334*	343	342	339	346	351	**357**	355	352	347	341	*334*	345	23
9	332	333	336	334	340	348	**351**	**351**	349	341	338	*330*	340	21
8	*328*	329	330	330	337	344	**347**	**347**	345	337	331	*328*	336	19
7	*324*	*324*	326	326	331	337	**341**	**341**	339	332	326	*324*	331	17
6	*319*	*319*	321	322	327	331	**336**	335	333	328	321	321	326	17
5	315	*314*	318	319	322	326	**331**	329	325	323	317	317	321	17
4	*310*	*310*	314	314	319	321	**325**	323	320	318	311	314	317	15
3	306	*303*	309	311	317	**318**	**318**	317	315	312	306	309	312	15
2·5	302	*301*	308	310	317	**317**	315	314	313	310	303	306	310	16
2	*300*	*300*	306	309	**317**	316	312	312	311	309	301	303	308	17
1·5	*297*	298	305	308	**316**	**316**	309	309	309	308	299	300	306	19
1	*295*	297	304	308	**315**	**315**	306	308	308	307	297	297	305	20
0·5	*293*	296	303	306	**314**	**314**	304	306	305	306	295	295	303	21
Surface (0·17)	*291*	292	303	304	311	**313**	303	304	302	302	294	294	301	22

The values for each flight were obtained graphically according to the method described by Sir N. Shaw.[1]

Up to 12 gkm. the minimum mean monthly potential temperatures occur *generally* in January, but at some heights are shifted to December or February. This may be due to the smallness in the number of observations. Up to 3 gkm., the maximum occurs in May-June, and between 4 and 13 gkm. either in July or August.[2] The character of the annual variation undergoes a reversal above 13 gkm., the minimum occurring above that level in August and the maximum in one of the months December, January or February. The smallest annual variation is at 13 gkm.

[1] *Q. J. R. Met. Soc.*, 51, 1925, p. 216.
[2] If we consider the moisture contained in the atmosphere also, the part of the year when the lower layers have maximum heat energy per unit volume i July and August.

The general nature of the curves of annual variation of potential temperature (fig. 4) bears a striking resemblance to the idealised potential temperature curves of cyclones and anti-cyclones represented in Sir N. Shaw's Manual of Meteorology, Vol. II, p. 118, the monsoon season July and August corresponding to anti-cyclones and the winter to cyclones. The height at which the difference between the potential temperatures of cyclones and anti-cyclones becomes a minimum in European latitudes is 9 km., which may be compared with the height (13 gkm.) of minimum seasonal variation of potential temperature over north India.

8. MONTHLY MEAN TEMPERATURE-ENTROPY, PRESSURE-DEW-POINT AND WIND DIAGRAMS.

The monthly mean temperature-entropy and pressure-dew-point graphs are drawn in figures 5(*a*) to (*l*). The north and east components of monthly mean winds over Agra obtained from the daily pilot balloon ascents of the period 1914-25 are also drawn in the same figures. In spite of the fact that the temperature-humidity and wind-diagrams refer to different periods and the former are very limited in number, the combination serves to give one a more complete picture of the structure of the atmosphere over Agra in different seasons. It is hoped to discuss a few selected individual tephigrams in a later paper.

Some general features of the curves may be briefly indicated :—

(1) In the period November to May, the atmosphere above 9 or 10 km. is more or less stable for rising saturated air. The rate of increase of the westerly component of velocity with height also diminishes at about this height. There is a small yet distinct northerly component of velocity up to at least 12 km.[1] With the progress of the hot season from the end of February to May there is a gradually increasing thickness of surface air up to 5 km. which is strongly unstable for rising saturated air and approaches instability even for dry air. It is well-known that the frequency of dust-storms also increases similarly. Conditions in June are similar to those in May in the first 4 km. but the moisture-content is greater above that level and between 4 and 13 km., the tephigram follows approximately the curve of saturation adiabatic. Above 13 km. the atmosphere becomes stable.

(2) In July and August, there is a close approach to labile equilibrium for rising saturated air from 2½ to 14 km. These limits are slightly contracted in September and the stability also is somewhat greater above 5 km. It will be noticed that in these three months, if an adequate supply of moist air could be introduced at or below 2 km., instability extending practically throughout the troposphere would result ; actually, all fresh advances of monsoon into the United Provinces introduce moist air in these layers and are accompanied by thunderstorms.

(3) In October the atmosphere is definitely stable above 7 km. ; below that level it is unstable for rising saturated air but the chances of supply of moisture at lower level become so small that instability is rarely reached.

[1] It is possible that in the higher layers, this is a characteristic peculiar to days on which high pilot balloon flights were possible.

9. THE STRATOSPHERE OVER AGRA AND ITS SEASONAL VARIATIONS.

For classifying the nature of the transition from the troposphere to the stratosphere and defining the height of the tropopause H_c, similar conventions as those in use in the London Meteorological Office were adopted. They are :—

Type I.—When the stratosphere commences with an inversion, H_c is the height of the first point of zero lapse-rate.

Type II.—When the stratosphere begins with an abrupt transition to a lapse-rate below 2° per kilometre without inversion, H_c is the height of the abrupt transition.

Type III.—When the change of lapserate is gradual, the base of the stratosphere is taken at the point where the mean fall of temperature for the kilometre next above is 2° or less, provided it does not exceed 2° per kilometre for any subsequent kilometre.

Type IV.—A fourth composite type with an inversion above a transition of type II or III is often met with between November and April. In the latter case, however, the last proviso is not always strictly satisfied ; immediately below the inversion corresponding to type I, there is often a thin layer with lapse-rate exceeding 2°C/gkm.

When the transition occurs in two stages two values of H_c and T_c are given, one corresponding to each stage. Photographs of two records showing tropopause of type IV are shown in figure 6 (a) and (b).

From the point of view of seasonal variation of the type, height and temperature of the tropopause over Agra, the year may be divided broadly into two parts :—

(1) *Middle of May to end of October.*

During this period, the type of tropopause is either I or II ; if II, the initial sudden change of lapse-rate is followed by an inversion soon after, so that there is always an inversion of temperature in the stratosphere. The mean value of H_c is 16·5 gkm. and of T_c 194°·5 A.

(2) *November to middle of May.*

In this period, types III and IV are more frequent. There is almost always an inversion of temperature above 17 gkm. The mean values of H_c and T_c during this period are 16·2 gkm. and 201°A if we take the values corresponding to the higher value of H_c on occasions when transitions were of type IV and 14·9 gkm. and 203°·5 if we take values corresponding to the lower values of H_c.

The individual values of the heights and temperatures of the tropopause are plotted against the dates of the ascents in figures 7(*a*) and (*b*). When the transition is of type IV, values corresponding to both positions of change of lapse-rate are plotted. The smoothed monthly mean values of H_c and T_c are given in table 15.

Table 15.

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
H_c gkm.	15·2	15·4	16·1	16·3	16·4	16·4	16·4	16·4	16·4	16·2	15·5	15·0
T_c °A	203	203	203	203	201	196	194	193	193	194	200	203

A remarkably sudden fall of the height of the tropopause and a rise in its temperature occur between October and November. This takes place more or less simultaneously with the setting in of winter conditions over North India and more than a month and a half later than the time of withdrawal of the monsoon. The high levels and low temperatures of tropopause over Agra between the months May and October may be due to two causes :—

(1) strong convective action in the higher layers of the troposphere, and
(2) advective movement of air in the higher layers of the troposphere from lower latitudes or from regions where convection is vigorous.

It is very probable that during July and August when the monsoon is vigorous over the United Provinces, and the prevalent wind direction at the cirrus level is from Bengal and Assam where rainfall is particularly heavy, both (1) and (2) are important causes. To a smaller extent, this is also true for June and September. To account for the high position of the tropopause in May and October, we have to fall back on (2) alone. It is known that the air movement over Agra in the months May to October has a small yet distinct southerly component above 6 or 7 km. up to the cirrus level and possibly also up to the tropopause. In Europe, the maximum height of the tropopause occurs in October and Gold[1] connects this with the incoming of air at and near the cirrus level from lower latitudes. In Canada[2] also the maximum value of H_c occurs in the period July-September.

It is of interest to note that the annual variation of H_c and T_c over Batavia is complementary to that over Agra. In figures 8(*a*) and (*b*), diagrams similar to 7(*a*) and (*b*), have been drawn for Batavia. The annual variation of H_c at Batavia is not so conspicuous as at Agra, but that of T_c is quite marked.

The minimum values of T_c occur during December and January over Batavia.

Values of T_c are plotted against the corresponding values of H_c in figure 9. The values for the Batavian ascents from 1910 to 1915[3], for the English ascents in 1924[4], and for Canadian ascents in 1914 and 1915[5] are also plotted for comparison. It is well-known that over European latitudes, a rise of the tropopause is generally accompanied by a fall of its temperature ; this is also true for Agra in winter and early hot season, but over Batavia throughout the year and over Agra in the monsoon the tropopause does not show any tendency to rise above 17·5 gkm. in spite of decreasing temperature. (The single point at 18·6 gkm. observed over Batavia on 2nd October 1912 appears to be exceptional). It is also known that in general, the lower the temperature of the tropopause, the stronger is the inversion in the first few kilometres of the stratosphere[6]. There must therefore be a strong force resisting the further raising of the tropopause.

In this connection, it may be noted that over Agra high temperature in the neighbourhood of 10 gkm. is associated with a large fall of temperature in the next few kilometres above. The effect is mainly seasonal, but not entirely so. The coefficient of cor-

[1] *Geoph. Mem.*, No. 5, London M. O.

[2] *Upper Air Investigation in Canada*, (published by the Canadian Meteorological Service), p. 19, 1915.

[3] W. van Bemmelen, *Kon. Mag. et Met. Observ. te Batavia*, Verhandelingen No. 4.

[4] *The Observatories Year Book, 1924*, M. O. London.

[5] Loc. Cit.

[6] P. R. K. Rao, Distribution of temperature in the lower stratosphere, *Ind. Met. Dept. Scientific Notes*, Vol. I, No. 10.

relation between T_{10}, the temperature at 10 gkm. and $T_{10}—T_{16}$ the fall of temperature between 10 and 16 gkm. is 0·93 with a probable error of 0·02. Apparently the low temperature of T_c over tropical regions is therefore mainly of tropospheric origin.

10. UPPER AIR TEMPERATURES AND ENTROPIES OVER THE NORTHERN HEMISPHERE IN SUMMER AND WINTER.

It is of interest to compare upper air temperatures over Agra with those over other countries. In figure 10, winter temperatures over Agra are compared with summer and winter temperatures over Europe[1] and in figure 11 monsoon temperatures over Agra with summer and winter temperatures over Batavia. In the latter figure, the curves of saturation adiabatic corresponding to surface temperatures 295° and 305°A have also been drawn. The small difference between the summer and winter temperatures over Batavia and the close parallelism of these curves and of the Agra monsoon curve to the curve of saturation adiabatic are noteworthy features. At all levels below 13 gkm, Agra shows during the monsoon higher temperatures than Batavia in summer.

Sir Napier Shaw, in his " Manual of Meteorology ", Vol. II, p. 100, has given a diagram showing the variation with latitude of upper air temperatures over the northern hemisphere in summer and winter. In figure 12,[2] that diagram has been amplified by the inclusion of Agra data and data over other places up to 25 gkm. as far as they are available. Some of the prominent features of the diagram may be briefly summarised :—

(1) The coldest air over the earth which is at a temperature of about 190°A lies at a height of about 17 gkm. over the equator in the form of a flat ring surrounded by rings of warmer air.[3] It is displaced towards higher latitudes in summer.[4]

(2) In the lower layers of the stratosphere, over tropical and sub-tropical regions, temperature definitely increases with height. The Agra and Batavia results indicate a temperature of about 220° A and the American results about 230°A at a height of 24 km.

(3) In the northern summer, the region of highest temperatures in the troposphere is shifted to 20—40°N, the region of sub-tropical anticyclones (*vide* isobars at 8 km. in Sir Napier Shaw's Meteorology, Vol. II, p. 262.) There is, however, the possibility that Agra temperatures are exceptionally high during the monsoon and exaggerate the high temperatures over this region.

(4) The height of the tropopause is more or less constant from the equator to about 30°N during northern summer and has a steep downward slope towards the north between 30° and 50° in summer and between 25° to 45° in winter. The curve of variation of H_c with latitude has the same general characteristics as that deduced by V. Bjerknes[5] from upper winds.

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[1] W. H. Dines, Characteristics of the Free Atmosphere, *Geoph. Mem.* No. 13.

[2] First published in *Nature*, June 1, 1929, p. 923.

[3] The possibility of this was pointed out by V. Bjerknes in his paper " On the Dynamics of the Circular Vortex, etc." *Geofys. Publ.* Vol. II, No. 4, p. 90.

[4] It is interesting to note that over Batavia in July, the easterly component of wind is a maximum (16 m.p.s.) at a height of about 14 gkm. and changes rapidly to a westerly of 5 m.p.s. at 19 km. (Sir N. Shaw, Meteorology, Vol. II, p. 272). If the law of geostrophic balance hold at these latitudes, this would require a temperature gradient with temperature decreasing towards the south between these levels and a corresponding modification of figure 12.

[5] Loc. Cit. Fig. 21, p. 65.

A diagram showing the distribution of potential temperature over the northern hemisphere in summer and winter (modified from that given on page 116 of Sir N. Shaw's Meteorology, Vol. II) is given in figure 13.[1] The potential temperatures plotted are temperatures in degrees absolute which the air at any place would assume if compressed or expanded adiabatically to 1,000 mb. Since the potential temperature θ and entropy φ of dry air are connected by the relation

$$\varphi = C_p \log \theta + \text{constant}.$$

where c_p is the specific heat of dry air at constant pressure, lines of equal potential temperature are also lines of equal entropy. For convenience, isentropics for values of entropy 10×10^6 to 18×10^6 C. G. S. units in steps of 10^6 units have also been drawn, entropies being measured from a zero at 100°A and 1000 mb.[2]

It is possible that the trough of high entropy near 25°N will become less marked when more data from similar latitudes in other parts of the world are available. Over the inter-tropical belt, the values of entropy are markedly high below about 10 gkm. and low between 12 and 20 gkm. with a pronounced concentration of isentropics between 17 and 20 gkm. The analogy of this diagram of zonal distribution of entropy to that of seasonal variation of entropy over Agra is very striking.

It is hoped to discuss in a later paper the relationship between the general circulation of the atmosphere and the distribution of temperature and entropy with special reference to the Indian monsoon region.

In conclusion, I wish to express my indebtedness to Mr. G. Chatterjee for his valuable co-operation and help. My thanks are also due to Mr. K. P. Ramakrishnan for substantial assistance in the tabulation and arrangement of data.

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[1] In addition to the data used in preparing fig. 12, some data obtained from sounding balloon ascents at Poona during the winter of 1928-29 have also been utilised.

[2] Sir N. Shaw. 'Tables for calculating the entropy of air'. Report of the Meeting of the International Commission for the exploration of the Upper Air, Leipzig, 1927, p. 51 *et seq.*