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Normal Density Distribution in the Atmosphere

D. A. MOOLEY

Meteorological Office, New Delhi

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1. Introduction

Starting from the surface distribution of pressure and temperature S. N. Sen [1] calculated the density distribution on the surface of the earth and by proceeding further, calculated the upper air densities for the summer by using the mean temperature lapse rates in the various layers of the atmosphere. His calculation extended upto 12 km and he found out that the density of air in the neighbourhood of 8 km is nearly constant throughout the year all over the globe.

Napier Shaw [2] has stated that at the level of the 8th kilometre, the density is normally constant all the year round and apparently uniform all over the world with a notable exception at Agra, June to November. His remarks were based on the data of a limited number of stations which extended mainly upto 10 km.

An investigation into the density distribution has been undertaken with a view to examine these remarks.

The sources of the upper air data have been given at the end. For northern Hemisphere, summer data have been taken as mean of July and August data and those for winter as mean of December, January and February. The only southern Hemisphere station is Batavia and for it summer has been taken to be mean of December, January and February and winter as mean of July and August.

2. Method of calculation

The densities have been calculated by using the formula $\rho = p/RTv$ in the usual notation. Virtual temperature corrections smaller than 0.2°C are neglected. The value of the gas constant used is $R = 0.28704 \times 10^7$ ergs/degree which has been adopted by I.M.O. Density data for Indian and Pakistan stations for summer and winter are given under Tables 1 and 2. The data for American, British and a few other foreign stations for summer and winter are given under Tables 3 and 4. Normal monthly densities at Indian and Pakistan stations for 7, 8, 9 and 10 gkm are given in Table 5.

Curves giving the distribution of pressure and density with height over different latitudes are shown in the two diagrams—one for the northern summer and the other for the northern winter (Fig. 1). The tropopause shown are the generally accepted winter and summer tropopause positions. It can be easily seen from the diagrams that the density in the neighbourhood of the 8th km varies little over the globe during the winter and in summer it varies little north of latitude 40° N. Within the tropics the variation of density near the 8th km with latitude and from season to season appears to be appreciable. V. Bjerknes [3] has also drawn similar diagrams—one for the month of February and the other for August representative of winter and summer conditions respectively. Instead of *isopycnics* he has drawn *isosteres*. His diagram is based on the data of four stations only *viz*. Batavia, Agra, Pavia and Pawlowsk. The curves are in general agreement.

The existence of this isopycnic level over the whole globe and all the year round was first discovered by Wagner [4].

Assuming that surface pressure and lapse rate of temperature in the atmosphere are uniform, Gold [5] has shown that the height of the isopycnic level should be about 8 km.

Upto a height of 8-10 gkm, the densities at all latitudes, level for level, are greater in winter than in summer. Above this level there is a reversal *i.e.*, the densities in summer are greater than those in winter.

The seasonal variation in temperature extends upto 8-10 gkm and seems to be the controlling factor. Above 8-10 gkm,

seasonal variation in temperature is little and above tropopause it changes sign and, therefore, pressure variation is the predominant factor which determines density distribution. Pressures above this level are higher, level for level, in summer than in winter.

At any level, lowest densities are observed in the neighbourhood of latitude 30° N below 10 gkm in summer and the highest densities in the neighbourhood of equator above 10 gkm.

Summer. Upto 10 gkm, the density decreases appreciably with latitude from the equator to the latitude 30° N and, thereafter, it increases fairly rapidly upto latitude 50° N. There is slight latitudinal variation beyond 50° N. Above 10 gkm, the density generally decreases from the equator towards the pole, the rate of decrease being rapid beyond 40° N.

Winter. Upto 8 gkm, the density gradually increases from equator towards the pole. In the layer 8—10 gkm there is little latitudinal density variation. Above 10 gkm, the density decreases appreciably with latitude from equator towards the pole.

Tables 3 and 4 show that density values for the 8th gkm for summer and winter vary little from place to place in temperate latitudes. Whereas, as seen from Tables 1 and 2 the variation of density at the same level, from summer to winter is appreciable in India and Pakistan.

To investigate further into the constancy of the density in the neighbourhood of 8 gkm, the densities for Indian and Pakistan stations were calculated for the different months of the year for the heights 7,8,9 and 10 gkm from the normal monthly upper air data for the stations. These are given under Tables 5 (*a*), (*b*), (*c*) and (*d*). The Table also gives the average annual densities and the variations at the stations and average monthly densities over India together with density variations over India in the different months. It can be easily seen that lowest densities at 7, 8, 9 and 10 gkm are observed over India and Pakistan during July, density generally decreasing from January to July and increasing from July to December. Density is uniform at 10 gkm over northern India in July. In the end, I would thank Shri P.R. Krishna Rao for suggesting me the work, Shri P.R. Pisharoty for his valuable guidance and Shri K.N. Rao for making most of the data available to me.

SOURCES OF DATA

1.	Indian and Pakistan Stations	Data collected by India Meteorological Department
2.	England ..	Observatories year book of London Meteorological Office (upto 1937)
3.	U.S.A. Stations	The data of these stations are based on radio-sonde ascents during 1939-41. They have been taken from the Monthly Weather Review
4.	Batavia ..	W. V. Bemmlen, Konig, Magn. en Met. Obs. Batavia, Verhandhugen No. 4 (1946).

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2. Napier Shaw, *Manual of Meteorology*, **2**, Art. 21, p. 415.
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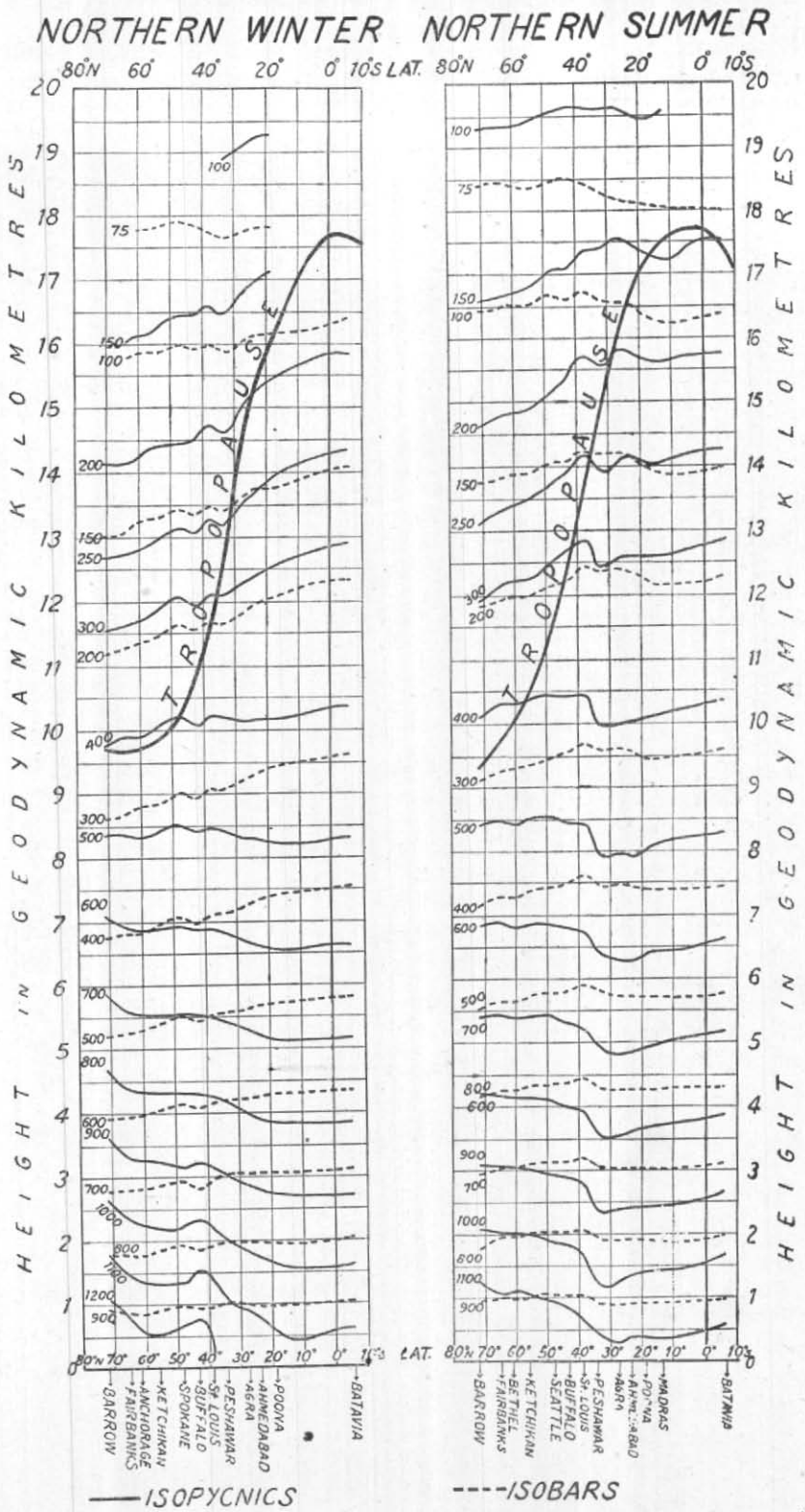

Fig. 1 Normal density distribution in the atmosphere

TABLE 1

Normal Density values at Indian and Pakistan stations in SUMMER (gm/m^3)

gkm									
26.0									
25.0				38					40
24.0				44	46				48
23.0				54	53		53		56
22.0	63			64	63	64	64		66
21.0	74		75	75	75	75	76		77
20.0	88		89	90	91	93	93		92
19.0	107		109	109	109	111	112		112
18.0	129		132	132	134	134	137		134
17.0	156	158	163	161	162	162	165		160
16.0	187	189	194	190	193	193	195	193	188
15.0	221	220	225	220	222	226	223	223	216
14.0	252	251	255	251	254	255	254	252	248
13.0	286	285	285	284	286	287	286	286	281
12.0	324	321	319	318	320	321	321	320	315
11.0	363	361	357	357	358	357	358	358	355
10.0	406	404	398	398	401	400	400	401	398
9.0	455	451	444	443	447	446	446	447	445
8.0	508	503	495	494	497	497	498	498	498
7.0	565	561	552	551	553	552	555	556	560
6.0	629	627	615	614	618	617	618	622	626
5.0	700	696	686	684	691	689	688	690	693
4.0	778	776	762	758	766	762	763	764	764
3.0	859	859	846	843	847	843	845	838	842
2.5	906	906	892	888	892	885	890	876	887
2.0	950	949	938	936	940	930	935	917	929
1.5	995	995	989	986	989	976	981	957	973
1.0	1039	1043	1038	1036	1039	1020	1029	1010	1017
0.5	1086	—	1091	1090	1086	—	1076	—	1067
Surface	1136	1081	1129	1138	1128	1100	1113	1099	1116

Station	Madras	Poona	Sambal-pur	Calcutta	Ahmed-abad	Jodhpur	Agra	Jacob-abad	Pesha-war
Latitude	13°	18°32′	21°28′	22°39′	23°	26°18′	27°	28°17′	34°

TABLE 2

Normal density values at Indian and Pakistan stations in WINTER (gm/m^3)

gkm								
30.0			17					
29.0			19					
28.0			23					23
27.0		27	27					27
26.0		31	31					31
25.0		36	36					36
24.0		43	43	43		43		42
23.0	51	51	52	50		51		50
22.0	61	60	61	60		60		59
21.0	72	72	73	71		71		70
20.0	87	85	87	86	86	86		82
19.0	105	104	105	105	103	102		98
18.0	128	126	126	127	123	123		116
17.0	154	153	150	150	146	146	142	137
16.0	182	181	178	178	171	173	168	161
15.0	214	212	209	209	200	203	195	189
14.0	248	245	243	241	235	236	229	221
13.0	283	281	279	277	273	273	269	257
12.0	321	321	320	318	316	314	315	305
11.0	363	363	361	361	361	359	363	358
10.0	408	409	406	409	407	406	412	411
9.0	457	458	457	460	460	459	463	467
8.0	512	512	513	517	515	516	519	525
7.0	571	573	573	576	575	578	583	588
6.0	638	638	638	640	644	645	648	657
5.0	709	709	710	713	716	718	722	731
4.0	787	788	789	789	797	797	805	816
3.0	875	877	876	881	882	886	892	901
2.5	922	919	921	927	930	934	943	951
2.0	965	969	973	975	983	983	992	999
1.5	1010	1023	1024	1023	1027	1034	1042	1048
1.0	1053	1072	1077	1071	1095	1087	1091	1104
0.5	—	1115	1126	1125	—	1140	1137	1151
Surface	1093	1165	1185	1166	1157	1176	1185	1189
Station Latitude	Poona 18°32′	Sambalpur 21°28′	Calcutta 22°39′	Ahmedabad 23°	Jodhpur 26°18′	Agra 27°	Jacobabad 28°17′	Peshawar 34°

TABLE

Nomal Density Distribution at

Height in gkm	Barrow	Fairbanks (Alaska)	Nome (Alaska)	Anchorage (Alaska)	Bethel (Alaska)	Juneau (Alaska)	Ketchikan (Alaska)	Spokane (Wash.)	Seattle (Wash.)	Bismarck (N. Dak.)	Ellendale	St. Paul (Minn.)	Boise (Idaho)	Buffalo (N. Y.)	Medford (Oreg.)	Omaha (Nebr.)	Denver (Col.)
	71° 23′N	64° 51′N	64° 30′N	61° 13′N	60° 45′N	58° 18′N	55° 21′N	47° 40′N	47° 32′N	46° 47′N	45° 49′N	44° 58′N	43° 34′N	42° 56′N	42° 23′N	41° 18′N	39° 46′N
20.0	89	90	90		90				93	93		94	94		93	94	
19.0	105	105	106		105		106	97	109	111	117	110	110		110	112	111
18.0	120	122	123	122	123	124	123	129	129	130	138	128	127	130	130	133	132
17.0	140	142	143	144	143	144	144	150	152	154	160	151	153	152	154	157	157
16.0	163	165	168	167	166	167	169	178	178	181	185	181	179	181	178	187	187
15.0	188	193	193	193	194	193	197	207	207	214	214	211	211	212	209	220	220
14.0	219	223	225	226	227	227	230	241	241	249	246	249	245	247	242	255	257
13.0	253	261	264	263	265	265	268	282	279	288	283	287	286	286	285	295	294
12.0	294	307	311	309	310	312	316	329	326	331	328	329	331	329	330	334	328
11.0	346	363	361	370	362	367	367	375	373	376	378	372	377	372	375	378	378
10.0	404	416	413	415	414	418	420	421	421	422	421	420	424	419	422	422	425
9.0	465	471	468	469	469	471	471	473	474	473	471	468	473	469	473	469	472
8.0	524	529	526	528	525	528	529	528	528	527	526	524	530	524	527	525	527
7.0	588	592	587	589	585	590	591	589	590	587	586	583	589	585	587	583	585
6.0	657	658	655	657	654	642	658	653	654	650	648	647	653	650	651	647	648
5.0	732	732	729	733	729	731	731	726	727	719	722	719	724	721	720	718	720
4.0	814	815	809	814	809	813	810	802	806	795	800	798	798	800	798	794	792
3.0	905	905	898	907	901	902	901	883	891	877	885	882	876	889	881	876	866
2.5	955	953	948	953	949	952	947	925	936	920	929	925	917	933	925	919	907
2.0	1009	1002	999	1004	999	1006	999	970	984	963	976	971	959	983	971	963	953
1.5	1065	1052	1053	1054	1055	1057	1051	1013	1035	1010	1024	1018	1003	1031	1021	1010	—
1.0	1128	1103	1111	1106	1112	1108	1105	1059	1088	1059	1079	1069	1056	1081	1069	1058	—
0.5	1196	1153	1171	1158	1169	1161	1158	—	1144	—	1132	1124	—	1134	1122	1116	—
Surface	1277	1190	1232	1214	1226	1217	1214	1119	1200	1132	1137	1163	1081	1179	1139	1146	996

3.

some foreign stations in SUMMER (gm/m^3)

Height in gkm	Batavia	San Juan (P.R.)	Pearl Harbour	Miami (Fla.)	Brownsville	San Antonio	Elapso	Sandiego	Dallas	Phoneix	Atlanta (Ga.)	Albuquerque (N. Mex.)	Oklahoma City	Nashville (Tenn)	Oakland (Calif)	St. Louis
	6° S	18° 28′N	21° 22′N	25° 55′N	25° 55′N	29° 27′N	31° 50′N	32° 44′N	32° 51′N	33° 26′N	33° 39′N	35° 03′N	35° 34′N	36° 07′N	37° 44′N	38° 45′N
20.0																
19.0																
18.0																
17.0																
16.0																
15.0																
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6.0																
5.0																
4.0																
3.0																
2.5																
2.0																
1.5																
1.0																
0.5																
Surface																

TABLE

Normal Density values at

Height in gkm	Barrow 71° 23'N	Fairbanks (Alaska) 64° 51'N	Nome (Alaska) 64° 30'N	Anchorage (Alaska) 61° 13'N	Juneau (Alaska) 58° 18'N	Ketchikan (Alaska) 55° 21'N	England (mostly sealand) 53°N	Spokane (Wash.) 47° 40'N	Bismarck (N. Dak.) 46° 47'N	Ellendale 45° 49'N	St. Paul (Minn.) 44° 58'N	Boise (Idaho) 43° 34'N	Buffalo (N.Y.) 42° 56'N	Medford (Oreg.) 42° 23'N	Omaha (Nebr.) 41° 18'N	Denver (Col.) 39° 46'N	St. Louis 38° 45'N
20.0							79			95				87			
19.0							94	102		109				101			
18.0			111	114		115	109	119	121	125	120			119	112	122	118
17.0			129	132		134	129	139	137	144	137	140	121	143	141	143	141
16.0		151	150	153		154	152	161	161	165	161	165	161	166	165	167	164
15.0	176	175	177	178	181	181	177	189	187	189	188	191	185	195	191	196	192
14.0	204	204	205	207	210	213	208	219	217	218	219	224	216	225	223	227	224
13.0	238	239	238	242	245	247	244	257	253	253	255	262	252	264	260	266	261
12.0	278	281	279	282	289	289	289	304	298	291	299	309	296	311	303	311	306
11.0	325	330	327	333	337	343	340	357	353	339	353	362	348	355	356	364	359
10.0	382	395	385	392	396	401	395	413	409	395	407	415	403	416	411	419	412
9.0	451	461	452	455	469	462	452	469	468	457	467	473	463	471	469	474	469
8.0	527	523	519	521	524	525	513	532	529	523	526	532	525	531	529	530	528
7.0	608	591	590	589	590	592	580	596	593	592	591	597	590	593	593	595	592
6.0	689	665	665	662	665	665	651	665	664	665	662	667	662	663	663	664	663
5.0	773	745	746	742	741	743	729	742	741	743	740	743	739	736	739	739	738
4.0	866	832	836	829	827	827	817	825	825	831	826	827	827	820	823	821	822
3.0	967	927	934	924	917	921	911	913	921	928	924	919	925	909	918	911	916
2.5	1011	978	988	974	971	971	962	970	973	981	977	969	982	959	970	960	969
2.0	1073	1034	1046	1028	1028	1024	1016	1023	1030	1038	1034	1021	1040	1010	1024	1016	1024
1.5	1139	1095	1199	1081	1087	1081	1075	1080	1097	1102	1098	1078	1105	1064	1089	—	1086
1.0	1214	1166	1180	1141	1148	1142	1136	1144	1174	1177	1175	1139	1170	1122	1158	—	1158
0.5	1312	1248	1259	1213	1211	1203	1198	—	—	1265	1257	—	1239	1192	1239	—	1227
Surface	1405	1329	1341	1299	1271	1335	1258	1205	1263	1275	1297	1162	1279	1205	1275	1077	1277

4

some foreign stations in WINTER (gm/m^3)

		101			88	100		89			92		92		20.0
104	105	116			106	116		106	108	108	109	109	112		19.0
123	122	134	121	124	126	137		127	126	129	132	132	138	138	18.0
145	144	155	146	146	148	156	151	149	149	152	157	158	167	164	17.0
169	170	179	179	172	174	180	176	173	176	177	184	187	197	192	16.0
199	199	207	200	201	202	209	205	202	204	207	215	217	228	225	15.0
231	231	238	233	233	235	243	238	235	239	241	249	251	260	258	14.0
269	270	275	271	272	273	283	277	275	275	280	284	289	296	295	13.0
318	315	319	316	317	319	324	319	319	320	321	326	330	333	334	12.0
367	364	368	368	365	369	367	365	367	370	370	371	375	375	374	11.0
418	415	421	420	416	421	414	418	417	420	419	420	422	420	418	10.0
473	469	476	473	472	475	465	472	473	474	472	472	471	469	466	9.0
530	527	533	532	527	532	520	529	527	531	530	528	526	523	518	8.0
592	589	595	593	589	590	583	592	589	592	591	588	586	582	575	7.0
660	658	662	660	657	661	653	657	655	659	657	655	653	644	641	6.0
735	733	736	736	731	733	730	730	727	733	729	727	724	714	711	5.0
816	816	819	816	813	813	808	809	810	813	807	802	800	790	789	4.0
905	909	910	909	906	902	895	897	902	902	895	888	889	875	875	3.0
954	962	961	957	955	949	943	946	953	946	946	936	937	923	921	2.5
1006	1017	1014	1009	1013	999	972	998	1005	997	997	987	987	971	968	2.0
1060	1076	1073	—	1073	1048	1052	1050	1064	1051	1056	1041	1042	1021	1016	1.5
1108	1141	1138	—	1137	1101	1115	1104	1126	—	1116	1101	1097	1072	1065	1.0
1178	1208	1206	—	1209	1161	1186	1162	1188	—	1179	1160	1154	1123	1115	0.5
1249	1255	1243	1059	1242	1197	1268	1226	1268	1099	1238	1222	1223	1176	1180	Surface

Oakland (Calif.	Nashville (Tenn.)	Broken Arrow	Albuquerque	Atlanta (Ga.)	Phoneix	Dallas	Sandiego	Charleston	Elapso	San Antonio	Brownsville	Miami (Fla.)	Swan Island	Batavia	Height in gkm
37° 44′N	36° 07′N	36°N	35° 03′N	33° 39′N	33° 26′N	32° 51′N	32° 44′N	32° 34′N	31° 50′N	29° 27′N	25° 55′N	25° 55′N	17° 22′N	6°S	

TABLE 5

Normal Density (gm/m^3) at different stations in India and Pakistan

(*a*) Height : 7 gkm

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year	Percentage variation Range × 100/Mean
Madras						563	563	565	565	565	569			
Poona	573	571	572	573	569	564	560	562	563	568	568	569	568	2
Sambalpur	574	575	570	567	567	557	552	551	560	564	565	570	564	4
Calcutta	573	575	569	571	562	550	549	552	560	565	567	573	564	5
Ahmedabad	575	576	573	573	565	556	554	553	559	565	570	571	566	4
Jodhpur	573	578	576	574	—	562	549	554	559	569	575	580	567	5
Agra	578	578	577	575	571	558	554	555	559	568	575	576	569	4
Jacobabad	583	582	573	576	576	556	555	556	565	574	—	—	570	5
Peshawar	591	585	579	581	568	567	561	559	567	577	580	588	575	6
Average density over India	577	577	573	574	568	559	555	556	562	568	571	575	568	
Percentage variation of density over India	3	2	2	2	2	3	3	3	1	2	3	3		7

(*b*) Height : 8 gkm

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year	Percentage variation Range × 100/Mean
Madras						495	494	506	507	507	512			
Poona	513	511	514	515	510	506	502	504	506	509	510	512	509	3
Sambalpur	512	513	509	507	506	499	494	495	501	511	503	511	505	4
Calcutta	513	515	510	512	503	493	492	495	502	506	508	512	505	5
Ahmedabad	517	516	505	513	508	497	496	497	502	507	510	514	507	4
Jodhpur	512	517	513	517	—	502	493	501	501	510	516	518	508	5
Agra	515	515	517	514	512	500	497	499	501	508	514	517	509	4
Jacobabad	520	518	515	518	514	499	498	499	506	514	—	—	508	4
Peshawar	527	523	520	518	511	508	498	497	509	518	520	525	514	6
Average density over India	516	515	513	513	509	500	496	499	504	510	512	516	508	
Percentage variation of density over India	3	2	3	2	2	3	2	2	2	2	3	3		7

TABLE 5 (Contd)

Normal density (gm/m^3) at different stations in India and Pakistan

(*c*) Height : 9 gkm

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	year	Percentage variation Range × 100/Mean
Madras						455	455	455	455	454	458			
Poona	457	455	459	459	456	452	450	453	453	455	457	458	455	2
Sambalpur	457	456	451	453	452	448	444	444	451	451	455	460	452	4
Calcutta	456	459	455	456	450	443	443	444	450	453	453	456	451	4
Ahmedabad	459	461	447	460	455	448	447	446	452	453	457	460	454	3
Jodhpur	454	462	458	460	—	447	444	449	448	457	457	464	455	4
Agra	459	460	461	462	459	448	446	447	450	455	457	460	455	4
Jacobabad	463	462	456	463	—	447	445	446	454	459	—	—	455	4
Peshawar	468	466	464	463	456	455	446	445	450	459	464	468	459	5
Average density over India	459	459	456	459	455	449	447	448	451	455	457	460	455	
Percentage variation of density over India	3	2	3	2	2	3	3	2	2	2	2	3		5

(*d*) Height : 10 gkm

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	year	Percentage variation Range × 100/Mean
Madras						406	406	406	408	406	411			
Poona	409	407	409	409	409	407	403	404	405	406	408	409	407	1
Sambalpur	407	410	402	406	404	401	398	398	404	406	405	410	404	3
Calcutta	405	408	405	408	404	397	399	397	403	405	404	405	403	3
Ahmedabad	406	413	397	407	405	401	401	400	404	406	407	409	405	4
Jodhpur	404	411	408	411	—	398	397	403	400	408	406	407	405	3
Agra	407	405	407	411	408	403	398	402	403	407	407	408	405	3
Jacobabad	411	412	403	408	—	400	399	403	407	413	—	—	406	3
Peshawar	409	411	411	413	407	402	398	398	400	407	411	412	407	4
Average density over India	407	410	405	409	406	402	400	401	404	407	407	409	405	
Percentage variation of density over India	2	2	3	2	1	2	1	2	2	2	2	2		4