STUDY OF VARIATION IN UPPER AIR DENSITY OVER INDIA

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The paper presents the seasonal variations and distribution of atmospheric density in the upper air over Indian region. The study reveals the density gradient has a down slope from North to South during winter and South to North, upto 200 mb level in summer. At 850 mb level the isopycnic lines form a shallow trough over East coast and at 700 mb level over Bombay-Poona region while over the rest of the country the isopycnics show no special features. At 500 mb level there is a well marked trough of density over North Western India. Above 200 mb level an altogether different picture throughout the year is noticed.

One of the meteorological parameters which has received scant attention in the field of Indian meteorological literature is the study of upper air density and variations in it in different seasons. It is well known that density is directly proportional to pressure. The latter has been thoroughly investigated and plays a key role in the field of Meteorology. The authors' attention was drawn to the study of density variation in the upper air of India in the course of studying the variation in thunderstorm frequencies over North India. The mean monthly data given in Normals of Climat-Temp. based on radiosonde data for the years 1951–65 were used in this study[1]. The data relate to the mandatory levels, like surface, 850 mb, 700 mb, 500 mb, 300 mb, 150 mb and 100 mb and those for 14 stations in Indian sub-continent have been used in this study.

THEORETICAL CONSIDERATIONS

It is well-known that the density equation $\rho = P/RT$ is valid for completely dry air. But in the atmosphere water vapour will always be present. Therefore, the total pressure of a parcel of unsaturated air may be regarded as the sum of the partial pressure which would be exerted by the dry air and the water vapour independently.

Since the value of gas constant for water vapour is 8/5 times that of dry air, the density of water vapour is given by the formula $\rho_v = 5e/8RT$ wherein e=vapour pressure in mb. Density of dry air is given by the equation, $\rho_d = p - e/RT$. Thus the density of a parcel of unsaturated air or a parcel of mixture of dry air and water vapour can be written as :

$$\rho_m = \frac{5e}{8RT} + \frac{p-e}{RT}$$

$$= \frac{1}{RT}\left(p - \frac{3e}{8}\right)$$

$$= \frac{348.4}{T}\left(p - \frac{3e}{8}\right)$$

where ρ_m = density of unsaturated air in gm/m³, R = gas constant, T = temp in K° and p = pressure in mb.

Starting with this generalised form of equation, air densities from surface upto 100 mb level were computed for 14 stations for twelve months. For such computations, the monthly means of pressure, dew point and temperature data given at each standard pressure level were used. The results of the computer programme showing variations in mean monthly upper air densities for all these stations are given, separately for each level, in Tables 1 to 8. Locator map of the stations, data of which has been used in the analysis is given in Map 6.

TABLE 1

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Surface Level)

Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	1154.5	1149.8	1148.2	1146.1	1145.2	1153.2	1153.7	1154.1	1153.3	1154.8	1155.9	1155.2
Bombay	1182.0	1177.1	1165.3	1153.1	1144.1	1142.8	1147.7	1153.1	1153.3	1156.7	1167.4	1177.7
Veraval	1190.1	1183.9	1171.5	1164.0	1146.9	1138.9	1141.0	1149.2	1153.8	1158.4	1170.1	1182.5
East Coast												
Madras	1183.5	1168.7	1160.5	1147.3	1139.8	1138.2	1142.5	1145.7	1147.1	1153.9	1165.8	1174.6
Vishakha-patnam	1174.6	1166.3	1155.6	1144.5	1133.9	1132.0	1138.9	1138.9	1141.5	1150.7	1164.9	1174.9
Calcutta	1206.7	1189.7	1166.0	1147.7	1139.5	1131.3	1141.2	1141.2	1147.0	1160.0	1186.4	1204.9
Inland Stations												
New Delhi	1201.5	1181.1	1157.5	1131.5	1109.1	1095.5	1103.6	1110.7	1128.3	1146.8	1183.1	1198.5
Poona	1114.6	1102.6	1090.7	1082.8	1080.7	1088.2	1095.1	1098.6	1097.9	1098.0	1114.2	1120.7
Amritsar	1201.3	1193.8	1207.7	1136.9	1114.1	1094.8	1100.5	1106.2	1118.5	1140.8	1178.2	1196.1
Ahmedabad	1189.2	1180.5	1154.9	1136.7	1123.0	1121.9	1130.8	1135.8	1139.4	1150.9	1169.5	1183.6
Jodhpur	1183.0	1166.4	1136.9	1114.5	1098.9	1093.4	1102.7	1108.5	1116.1	1134.9	1161.8	1178.3
Gauhati	1210.0	1196.8	1176.1	1156.8	1147.0	1137.5	1135.0	1136.9	1143.7	1159.5	1186.4	1204.5
Nagpur	1143.4	1139.6	1125.9	1104.9	1088.7	1090.2	1108.9	1111.2	1114.2	1127.7	1145.9	1157.3
Allahabad	1207.3	1188.5	1156.1	1128.0	1113.5	1111.8	1121.0	1126.7	1132.3	1151.5	1187.5	1204.9

TABLE 2

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 850 mb)

Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	1012.9	1011.5	1008.2	1002.9	1006.0	1009.2	1012.9	1012.8	1012.1	1011.7	1012.1	1013.1
Bombay	1015.8	1010.8	1002.6	995.9	995.5	1003.9	1006.8	1009.2	1009.1	1005.2	1006.6	1013.9
Veraval	1026.9	1017.3	1005.5	997.4	992.2	1000.1	1005.2	1009.9	1008.7	1005.0	1012.3	1019.3
Minicoy	1016.7	1014.2	1006.7	1006.7	1007.2	1010.1	1011.4	1012.5	1012.8	1012.4	1013.6	1015.2
East Coast												
Madras	1020.5	1013.9	1006.0	998.9	993.3	999.1	1001.8	1005.8	1003.2	1007.5	1014.9	1020.8
Vishakhapat-nam	1022.2	1014.2	1002.7	994.8	989.8	989.8	1000.8	1001.5	1002.2	1007.8	1016.7	1021.5
Calcutta	1035.2	1026.5	1010.4	996.9	992.3	995.1	1000.1	1000.8	1002.7	1010.2	1025.5	1041.3
Portblair	1015.9	1012.7	1009.0	1006.1	1004.6	1005.6	1007.3	1007.8	1009.4	1008.8	1010.1	1015.5
Inland Stations												
New Delhi	1043.6	1033.6	1015.7	997.9	983.4	979.1	988.0	995.2	998.4	1008.3	1025.0	1036.8
Poona	1010.8	1002.9	996.5	992.1	993.4	1002.2	1005.7	1008.6	1006.4	1002.0	1006.9	1010.2
Amritsar	1047.1	1045.1	1020.4	1002.7	987.4	976.4	985.4	990.9	995.8	1007.0	1028.9	1040.6
Ahmedabad	1028.8	1020.6	1009.2	997.5	990.7	997.8	1004.2	1007.3	1007.4	1008.4	1017.2	1024.1
Jodhpur	1038.9	1030.9	1011.4	996.2	983.1	983.7	989.6	994.3	998.0	1002.5	1019.1	1034.1
Gauhati	1042.0	1035.3	1020.0	1008.5	1003.2	999.7	998.0	999.1	1001.1	1010.7	1026.0	1036.9
Nagpur	1022.1	1011.6	999.1	986.7	979.1	988.1	999.7	1001.9	1001.6	1006.4	1017.8	1024.7
Allahabad	1037.1	1028.5	1018.2	995.3	981.9	983.0	994.7	996.5	1000.0	1008.8	1024.8	1033.6

TABLE 3

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 700 mb)

Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	859.7	859.5	858.6	854.7	855.4	861.1	860.0	857.4	858.5	859.6	860.3	859.7
Bombay	866.2	865.4	861.4	854.9	851.1	852.6	853.7	853.5	856.8	860.1	860.7	863.5
Veraval	866.7	865.7	862.7	852.7	851.2	848.8	850.5	850.9	856.8	861.2	861.9	864.7
East Coast												
Madras	860.8	860.8	859.5	855.4	852.1	855.4	857.8	858.0	858.6	860.8	859.9	860.1
Vishakhapatnam	864.8	865.3	861.4	855.9	850.1	851.2	852.9	853.8	854.8	857.9	860.3	862.5
Calcutta	876.5	875.1	869.7	860.9	853.0	849.1	849.5	849.4	852.6	859.5	865.7	869.9
Inland Stations												
New Delhi	891.3	884.8	875.1	863.3	852.0	845.2	846.3	848.6	862.1	865.8	874.9	882.0
Poona	867.1	864.8	867.8	852.9	848.6	850.3	851.8	852.1	854.9	860.3	860.1	861.3
Amritsar	893.0	894.1	877.4	863.3	853.1	841.5	843.1	845.9	852.5	865.4	869.0	884.4
Ahmedabad	874.0	872.6	868.3	859.7	854.3	851.4	849.1	849.9	857.6	863.0	867.1	870.6
Jodhpur	885.0	881.6	874.0	863.5	851.5	846.1	845.4	846.9	854.8	866.0	871.5	877.3
Gauhati	888.4	887.3	877.1	865.3	858.1	851.0	848.9	850.0	853.1	862.4	876.4	883.2
Nagpur	872.0	870.3	864.1	855.0	848.6	850.3	852.5	852.2	855.3	861.7	864.4	867.2
Allahabad	881.5	878.1	871.5	860.6	851.4	847.2	847.4	848.3	853.2	862.7	867.2	874.9

TABLE 4

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 500 mb)

Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	650.7	651.0	649.3	648.1	648.5	649.8	652.2	651.2	650.5	650.7	651.0	650.7
Bombay	655.6	652.7	656.6	654.4	649.3	644.2	643.5	641.1	644.7	647.3	650.5	653.9
Veraval	659.9	656.6	658.1	655.1	649.5	645.2	644.2	644.5	645.4	648.5	653.7	657.9
East Coast												
Madras	652.9	650.0	650.7	650.5	649.0	649.0	649.8	649.3	649.8	649.5	650.5	650.5
Vishakhapatnam	653.7	653.4	653.7	652.9	650.5	646.3	644.3	644.3	645.6	649.8	650.0	652.9
Calcutta	667.9	662.6	661.6	657.4	650.2	642.2	639.7	640.1	643.4	650.0	653.9	657.4
Inland Stations												
New Delhi	677.6	675.5	671.0	664.4	657.1	653.9	638.9	639.6	648.3	657.9	666.7	671.3
Amritsar	681.8	681.3	675.2	664.1	657.9	647.8	638.8	642.1	648.5	660.6	670.8	673.1
Jodhpur	671.0	668.7	668.7	663.1	655.6	646.4	639.4	641.3	644.9	651.7	660.3	668.7
Allahabad	669.2	668.2	666.7	660.9	654.4	644.1	638.8	639.0	642.8	650.5	658.1	663.4
Nagpur	659.3	657.9	659.6	657.6	653.7	652.4	642.1	641.8	645.9	649.8	654.4	657.1
Ahmedabad	662.1	665.4	662.9	659.3	652.9	646.6	641.3	641.6	643.9	650.4	657.9	660.3
Gauhati	665.9	667.2	665.1	656.4	648.3	641.1	639.3	640.5	644.1	651.9	658.1	662.4
Poona	655.1	655.1	656.1	653.7	649.5	644.2	643.3	643.3	645.2	647.8	649.5	652.9

TABLE 5

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 300 mb)

Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	431.5	431.9	431.5	429.6	428.2	429.8	432.4	432.1	431.9	431.5	431.4	432.3
Bombay	433.3	432.6	435.0	433.5	426.4	422.3	421.3	421.8	423.8	427.5	431.0	433.9
Veraval	436.6	435.5	436.8	433.9	428.2	424.7	423.0	424.9	425.9	429.4	437.1	437.0
East Coast												
Madras	432.8	431.7	431.4	430.0	428.2	428.4	430.1	430.0	430.7	430.1	430.7	432.3
Vishakhapatnam	433.0	431.9	433.0	431.5	427.5	426.1	426.4	425.1	424.2	428.5	432.3	433.1
Calcutta	436.2	436.6	436.8	433.5	426.3	421.5	420.4	421.6	424.0	427.3	432.6	434.8
Inland Stations												
Amritsar	454.0	449.2	450.9	444.0	435.9	424.0	416.4	419.8	426.3	438.4	448.0	449.5
New Delhi	447.1	447.1	447.2	441.8	432.1	423.3	418.4	419.9	424.5	432.4	436.4	445.0
Jodhpur	442.9	442.7	444.4	440.5	431.5	422.6	418.9	420.6	423.7	430.5	437.9	442.5
Allahabad	440.3	440.5	442.9	437.7	429.2	422.6	419.4	420.3	423.3	428.9	435.3	439.7
Nagpur	436.8	435.9	438.2	435.3	429.2	424.7	423.2	424.2	425.9	431.4	435.0	436.6
Ahmedabad	440.3	440.5	440.6	441.9	429.6	425.1	422.5	423.7	425.7	433.3	447.1	448.0
Gauhati	437.9	437.9	439.9	434.8	424.9	420.6	418.7	420.3	423.5	428.7	434.8	439.3
Poona	432.1	434.4	433.5	431.0	425.7	421.3	420.8	420.6	423.0	426.8	430.7	434.2

TABLE 6

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 200 mb)

Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	315.3	315.9	315.1	313.9	313.2	313.9	316.7	316.7	315.7	312.6	315.6	316.7
Bombay	313.0	313.0	313.5	312.7	309.1	307.8	306.6	306.7	308.6	311.3	313.3	314.9
Veraval	314.3	315.6	313.5	313.0	309.3	307.5	307.5	312.2	310.4	312.5	316.0	316.0
East Coast												
Madras	315.9	315.4	314.9	314.2	313.2	315.1	314.4	314.3	315.1	316.6	315.4	315.4
Vishakhapatnam	314.7	316.0	313.7	313.6	311.5	311.1	311.5	311.3	312.7	314.3	316.3	316.0
Calcutta	313.0	313.7	311.6	311.5	308.9	306.1	305.7	305.7	307.6	310.7	313.6	312.6
Inland Stations												
Amritsar	318.0	314.4	319.3	317.7	310.8	305.3	302.7	305.2	307.6	313.6	319.1	320.7
New Delhi	315.3	315.6	315.4	313.7	308.3	306.0	304.7	305.5	307.2	311.8	315.0	316.7
Jodhpur	314.4	315.1	312.7	313.0	308.7	306.3	301.5	304.8	307.8	311.5	314.2	317.2
Allahabad	319.1	314.0	313.5	312.1	309.0	305.5	304.7	304.9	307.6	310.7	313.6	315.3
Nagpur	315.9	315.9	315.7	314.6	312.2	309.8	310.0	310.5	311.1	315.4	317.2	316.9
Ahmedabad	320.4	316.6	315.7	314.7	310.2	308.7	307.5	309.0	311.2	315.1	317.7	317.6
Gauhati	312.6	310.7	311.6	310.8	306.1	303.6	303.6	305.7	306.8	310.9	312.5	312.6
Poona	313.5	313.5	312.2	311.2	308.1	305.2	304.4	304.0	306.1	310.4	312.6	312.9

TABLE 7

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 150 mb) Unit :gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	252.3	252.7	251.4	251.6	250.8	251.1	252.3	253.1	252.7	253.3	252.6	252.1
Bombay	247.3	248.5	247.3	247.2	246.9	246.5	244.9	244.3	245.9	248.6	248.0	249.0
Veraval	247.8	249.7	246.3	245.6	246.2	245.2	249.0	250.3	249.0	249.0	251.4	248.1
East Coast												
Madras	251.7	251.3	251.0	250.5	250.4	251.1	251.6	251.3	251.7	251.7	251.3	252.0
Vishakhapatnam	250.3	251.1	248.1	249.5	248.3	249.0	249.6	249.6	250.1	250.1	251.2	251.3
Calcutta	245.9	246.7	245.7	247.1	245.6	245.9	244.5	244.8	246.5	249.0	249.2	248.0
Inland Stations												
Amritsar	243.0	242.6	243.5	242.5	239.7	240.9	241.3	242.5	244.1	245.5	245.9	244.9
New Delhi	243.1	243.6	242.3	242.2	242.4	243.0	243.2	244.8	245.3	246.4	246.1	243.6
Jodhpur	244.5	244.8	243.4	243.6	243.0	243.4	240.2	243.0	244.2	246.2	246.9	246.4
Allahabad	244.1	244.8	242.1	243.2	244.0	242.7	242.3	242.8	244.7	246.1	247.3	247.1
Nagpur	249.2	250.1	247.0	248.1	248.5	247.1	247.0	248.5	249.3	251.5	251.4	250.2
Ahmedabad	250.5	249.1	247.6	246.9	246.4	246.6	244.7	247.6	249.1	251.3	251.0	249.8
Gauhati	244.8	243.5	243.0	245.2	242.6	242.4	237.3	243.4	243.6	247.3	246.7	245.0
Poona	248.9	249.2	247.3	246.7	245.7	243.4	242.3	242.2	245.2	248.6	248.5	247.3

TABLE 8

MEAN MONTHLY ATMOSPHERIC DENSITY VALUES

(Isobaric Level : 100 mb) Unit : gm/cu metre

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
West Coast												
Trivandrum	177.1	176.9	176.5	176.5	177.5	174.9	174.5	174.2	174.1	175.5	176.9	174.9
Bombay	173.8	174.4	173.5	174.5	175.0	175.5	174.3	172.4	174.5	175.0	174.3	174.4
Veraval	172.7	175.9	172.2	170.5	172.3	172.7	174.0	175.0	174.8	175.1	173.4	171.9
East Coast												
Madras	176.5	176.7	175.8	176.3	176.3	174.8	174.6	174.4	175.5	175.5	175.0	175.0
Vishakhapatnam	175.9	176.0	174.6	175.6	175.8	175.9	175.2	174.8	175.1	176.1	175.9	176.8
Calcutta	173.8	172.9	171.4	173.9	174.4	175.0	174.5	173.6	175.3	175.9	175.0	173.6
Inland Stations												
Amritsar	166.1	165.4	167.6	165.9	166.5	169.0	169.9	171.0	171.3	169.0	167.2	166.6
New Delhi	168.1	168.5	167.4	168.1	170.3	172.8	174.0	174.1	173.9	173.3	170.2	169.0
Jodhpur	167.7	169.1	168.2	168.9	170.5	171.7	171.7	172.4	175.0	172.4	170.7	169.7
Allahabad	169.5	170.7	169.7	170.3	172.1	173.0	173.1	172.5	173.1	173.1	171.9	170.6
Nagpur	174.4	174.7	174.0	173.6	174.8	174.5	174.8	175.3	175.3	176.6	175.4	174.1
Ahmedabad	174.0	173.6	172.7	171.1	174.3	174.8	173.9	175.3	175.9	176.2	174.5	173.3
Gauhati	169.1	167.7	168.9	170.9	172.3	174.1	171.9	172.4	173.1	173.4	170.4	170.5
Poona	—	—	—	175.7	—	—	176.8	173.6	174.1	174.6	174.6	—

ANALYSIS OF THE DATA

Density Distribution in Winter Months

Consequent upon the movement of the sun towards the Tropic of Capricorn after 22 Sept. the summer monsoon of the Indian sub-continent withdraws and the seasonal monsoon over North India disappears. Hence, the normal pattern of north-east trades in the lower troposphere and upper westerlies aloft in the middle troposphere sets in. This fact is well reflected in the density pattern that develops over India from October onwards. The dry winds with lower temperature settle over the country, as the density is inversely proportional to temperature the upper air densities show a continuous increase at all levels up to 200 mb. The highest density values are registered in Dec./Jan. at Amritsar from surface upto 200 mb level and level to level, the lowest values of density are at Trivandrum, thus establishing the fact that there is a continuous slope in density from North to South at the same constant pressure surface across the Indian sub-continent.

TABLE 9

MINIMUM AND MAXIMUM AIR DENSITY VALUES AT STANDARD ISOBARIC LEVELS (COASTAL STATIONS)

Unit : gm/cu metre

Standard isobaric levels	Jan.	Feb.	Mar.	Apr.	May	Jun.
Surface	1155—1207 *52	1150—1190 40	1148—1171 23	1144—1164 20	1134—1147 13	1131—1153 22
850 mb	1013—1035 22	1011—1027 16	1003—1010 7	995—1003 8	992—1006 14	990—1009 19
700 mb	860—877 17	859—875 16	859—870 11	853—861 8	850—855 5	849—861 12
500 mb	651—668 17	650—663 13	649—662 13	648—657 9	649—651 2	642—650 8
300 mb	431—437 6	432—437 5	431—437 6	430—433 3	426—428 2	421—430 9
200 mb	313—316 3	313—316 3	312—315 3	311—314 3	309—313 4	306—315 9
150 mb	246—252 6	247—253 6	246—251 5	246—252 6	246—251 5	245—251 6
100 mb	173—177 4	173—177 4	171—177 6	171—177 6	172—177 5	173—176 3

Standard isobaric levels	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Surface	1139—1154 15	1139—1154 15	1141—1154 13	1151—1160 9	1156—1186 30	1155—1205 50
850 mb	1000—1013 13	1000—1013 13	1002—1012 10	1005—1012 7	1007—1025 18	1013—1041 28
700 mb	849—860 11	849—858 9	853—859 6	858—861 3	860—866 6	860—870 10
500 mb	640—652 12	640—651 11	643—651 8	647—651 4	650—654 4	651—658 7
300 mb	420—432 12	422—432 10	424—432 8	427—431 4	431—437 6	432—437 5
200 mb	306—317 11	306—317 11	308—316 8	311—317 6	313—316 3	313—317 4
150 mb	245—252 7	244—253 9	246—253 7	249—253 4	248—253 5	248—252 4
100 mb	174—175 1	172—175 3	174—175 1	175—176 1	174—177 3	172—177 5

*Mean monthly range variation in atmospheric density (gm/ m³) values.

TABLE 10

MINIMUM AND MAXIMUM AIR DENSITY VALUES AT STANDARD ISOBARIC LEVELS

Unit : gm/cu metre

Standard isobaric levels	Jan.	Feb.	Mar.	Apr.	May	Jun.
Surface	1115—1207 *92	1103—1197 94	1091—1208 107	1083—1157 74	1081—1147 66	1088—1137 49
850 mb	1011—1047 36	1003—1045 42	997—1020 23	992—1009 17	979—1003 24	976—1002 26
700 mb	867—893 26	865—894 29	864—877 13	853—865 12	849—858 9	841—851 10
500 mb	655—682 27	655—681 26	656—675 19	653—664 11	648—658 10	641—654 13
300 mb	432—453 21	434—449 15	433—451 18	431—444 13	425—436 11	421—425 4
200 mb	312—320 8	311—317 6	312—319 7	311—318 7	306—311 5	304—310 6
150 mb	243—251 8	243—250 7	242—248 6	242—248 6	240—249 9	241—247 6
100 mb	166—174 8	165—175 10	167—174 7	166—176 10	167—175 8	169—175 6

Standard isobaric levels	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Surface	1095—1135 40	1099—1137 38	1098—1144 46	1098—1159 61	1114—1187 73	1121—1205 84
850 mb	985—1006 21	991—1009 18	996—1007 11	1002—1011 9	1007—1029 22	1010—1041 31
700 mb	843—853 10	846—852 6	853—862 9	860—866 6	860—876 16	861—884 23
500 mb	639—643 4	639—642 3	643—649 6	648—661 13	649—671 22	653—673 20
300 mb	416—423 7	420—424 4	423—426 3	427—438 11	431—448 17	434—449 15
200 mb	301—310 9	304—311 7	306—311 5	310—312 2	313—319 6	313—321 8
150 mb	237—247 10	242—249 7	244—249 5	245—251 6	246—251 5	244—250 6
100 mb	170—177 7	171—175 4	171—176 5	169—177 8	167—175 8	167—174 7

*Mean monthly rangevariation in atmospheric density (gm/m^3) values

Tables 9 & 10 give the range in variation of upper air density values for coastal and inland stations respectively. These tables reveal the fact that the range starts widening from November to January at all levels for coastal stations. But similar widening is noticed foı inland stations from October itself at all levels. Another interesting feature is that at the coastal stations the largest variations in this range are recorded from surface up to 300 mb level in January; but for inland stations, the same are recorded from surface upto 700 mb level in February and from 500 to 200 mb levels in January. For the coastal stations, there is no appreciable widening in the range of density variation above 300 mb level for the months, October to March. This total absence of the impact of winter over the density distribution is noticed for inland stations from 150 mb level and upwards. As there is little variation in temperature in East-West direction over India during winter months, an attempt was made to compute a rate of change in density per one degree change in temperature along a North-South axis, which stretches from Trivandrum to Amritsar. The results are given in Table 11.

TABLE 11

DENSITY GRADIENT OVER INDIA FROM OCTOBER TO MARCH Unit : gm/m³/OC)

mb. level	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
850	4.0	5.0	4.3	4.1	4.2	5.0
700	4.1	4.3	3.2	3.0	3.4	3.2
500	3.5	2.5	2.5	2.5	2.5	1.8
300	1.9	1.9	1.9	1.9	1.9	1.9
200	1.4	1.3	1.5	1.6	2.0	1.5
150	1.2	1.1	1.1	1.1	1.2	1.2
100	0.9	0.9	1.1	1.1	1.0	0.9

The Table 11 shows that the density gradient reaches its maximum in November at 850 and 750 mb T levels, but it does so at 500 mb level in October. It is curious to note that from November to February, there is no variation in density gradient at 500, 300, 150 and 100 mb levels. But the gradient shows a decreasing tendency at 850 and 700 mb levels and rising tendency at 200 mb level during the same months. It is possible to infer from this fact the cold north-westerly draughts continue to penetrate southwards at 850 and 700 mb levels during winter and that they seem to have no effect at levels higher than these. In the month of March, the density gradient is high and equal to that in November at 850 mb level, shows little change from its February value at 700 mb and shows a sudden fall from February value at 500 and 200 mb levels; but remains constant at 300 mb level.

Tables 1 & 2 show that along the west and east coasts, there is a tendency of increase in density from south to north from October to March at all levels. At 200 mb level, the same trend is noticed only from October to December; but from January to March, this trend is reversed as Madras and Trivandrum record the highest values in mean monthly density and then there is a progressive decrease from south to north. For inland stations, the highest values of mean monthly densities are registered at Amritsar/New Delhi during the winter season and these values decrease southwards, thus creating a down slope from north to south and facilitating divergence in upper winds at all levels. At 200 mb level, maximum density values are recorded in January and February either at Ahmedabad or Allahabad, thus suggesting that the south-north axis of density gradient tilts westwards or eastwards. In March and April no such tilt is noticed in the position of this axis.

Density Distribution in Summer Monsoon Months

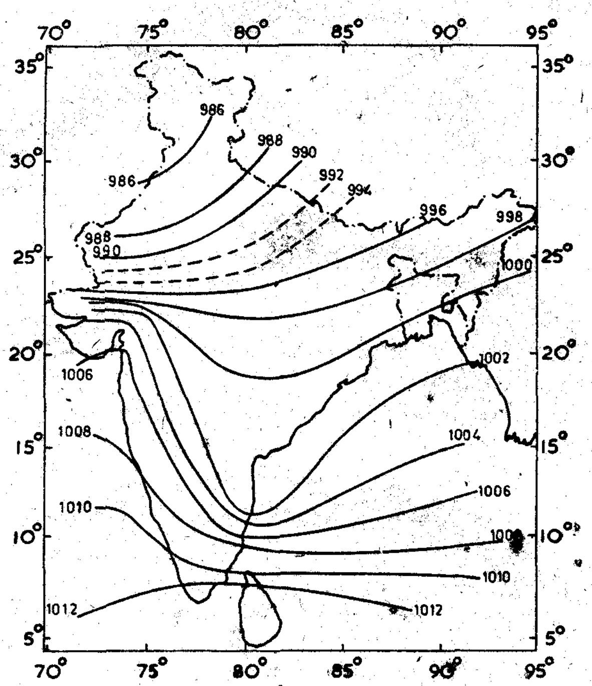
Consequent upon the crossing of equator by the Sun on 22 March and its northward movement, the Indian sub-continent starts warming up and the initial impact of the unstable conditions produced by this seasonal change is reflected in the sudden decrease in the mean monthly density values for April for all stations and at all levels. The north-south axis representing the density gradient assumes different positions at different levels, stretching from Veraval to Nagpur at surface, from Gauhati to Nagpur at 850 mb from Gauhati to Veraval at 700 mb, from Amritsar to Trivandrum at 500 and 300 mb level, and from Amritsar to Calcutta at 200 mb level. The density gradient between Trivandrum and Amritsar for this month is zero at 850 mb level. This shows that there is a weakening in the influence of dry and cold westerlies at Amritsar which in turn may indicate that the process of disintegration of sub-tropical westerly jet may be beginning at this level and then spreading upwards as the summer advances. The density gradient between these two stations however, shows an increase over March values at 700 and 500 mb levels.

In May, the effect of Indian summer is clearly shown by the continued fall in mean monthly density values for all stations and at all levels upto 200 mb. Trivandrum is the only exception at 850 and 700 mb level to this general pattern since the density values rise at 850 mb and show little change at 700 mb level. If analysis of variation in density is confined to coastal stations, different pattern seem to emerge at different levels. At the surface levels, Trivandrum stands out as the only station in which the monthly mean density values show a steep rise in June and then these values remain unchanged upto September. For other coastal stations, whether situated on east or west coast, there is a fall in mean monthly density value in June from that in May and then there is a continuous rise from July to Sept. At 850 mb level, there is a continuous increase in these values from May to September. At 700 mb level, except Veraval on the west coast and Calcutta on the east, the rest of the stations follow the pattern noticed at 850 mb level. In both Veraval and Calcutta the monthly mean density values for June is lower than that in May and then this value starts increasing from June to September whereas it shows little change in July and August from the June value. At 500 mb level, at Trivandrum values show a continuous increase from May to July and then a slight fall in August and September and in Madras, there is no change in values from May to September. In Bombay, there is a steady fall in these values in June, July and August and an increase in September whereas in Veraval and Vizag, there is a slight fall in July and no change in August from its July value and slight rise in September. In Calcutta, there is a fall in density values in July, and slight change in August and a rise in September. The same pattern of fall in values in June, little or no change in July and August and an increase in September is noticed at 300 and 200 mb levels except in Trivandrum and Madras, where there is a steady rise in these values from May to September.

For inland stations, the impact of the summer monsoon season produces different patterns. At the surface level, except Nagpur, all other stations show a fall in density in the month of June and then a continuous rise from July to September. At 850 mb level, only New Delhi, Amritsar and Gauhati show a fall in the values. Jodhpur shows little change and Nagpur, Allahabad and Ahmedabad show an actual increase in June value, which confirms the fact that the monsoon has not reached either the extreme north-east or north-west parts of India till the end of June. At 700 mb level, the pattern of a fall in June from its May value and a continuous and steady rise from July to September is followed by all these stations except Nagpur which shows a continuous rise from May to September. At 500 mb level, the picture changes abruptly showing that at all stations, there is a continuous fall from May to July, July values for all stations at this level are the lowest in this season and the remarkable fact is that from Gauhati in the east to Amritsar in the north-west and from Ahmedabad near west coast to Nagpur in the inland part of the country, there is little variation in mean monthly density values for this month. Only Amritsar and Jodhpur show an increase in August values at this level. The rest of the stations show little change in July and August values and all show rise in September. At 300 mb level, Amritsar records the lowest value and at 200 mb level in July, Gauhati and Jodhpur record the lowest value in density. There is little change in August values at these levels and a rise in September.

CLIMATOLOGICAL SIGNIFICANCE OF VARIATION IN UPPER AIR DENSITY

From a study of temperature at different levels, during the southwest monsoon season, it has been established that they are high over north-western and northern India and level to level, they steadily decrease southwards right upto Trivandrum. In consequence of this temperature gradient an upward slope of isopycnic surfaces towards south is created at all levels upto 200 mb level throughout the latitudinal extent of India. It is seen from Map 1, that at 850 mb level, there is considerable packing of isopycnic lines over Saurashtra and west Rajasthan area. There is a steep fall in density of 20 gm per cubic metre from Veraval to Amritsar, thus bringing out the fact that the dry, hot and sandy surface in Rajasthan affects the density distribution at this height which in turn indicates rapid changes in temperature distribution over the surface. Over the rest of north India, the isopycnic lines present no striking feature. Over peninsular India, the



Map 1—Isopycnic lines (in gm/m³) at 850 mb isobaric level.

packing of lines along the west coast and western parts of the Deccan plateau, again shows steep variation in density at this level. This obviously suggests the possibility of rapid changes in temperature and mixing ratio (which is the amount of water vapour per kg of dry air). The Table 12 giving temperature and mixing ratios for July and August will be useful in this connection.

TABLE 12

TEMPERATURE-MIXING RATIOS FOR SOUTHERN HALF OF INDIA AT 850 mb LEVEL

Station	July		Aug.	
	Temp. (°C)	Mixing ratio (gm/kg)	Temp. (°C)	Mixing ratio (gm/kg)
Minicoy	17.8	12.2	17.5	11.8
Trivandrum	17.3	12.0	17.4	13.9
Bangalore	18.9	14.1	18.9	13.6
Bombay	18.7	13.9	18.1	13.5
Nagpur	20.7	14.9	20.1	15.0

The Table 12 shows clearly that there is a density gradient across peninsular India as amount of water vapour increases from west to east. The isopycnic lines form a shallow trough near the east coast over Madras-Vizag region. To understand this phenomenon again examination of the temperature and mixing ratios along and off the east coast will be necessary.

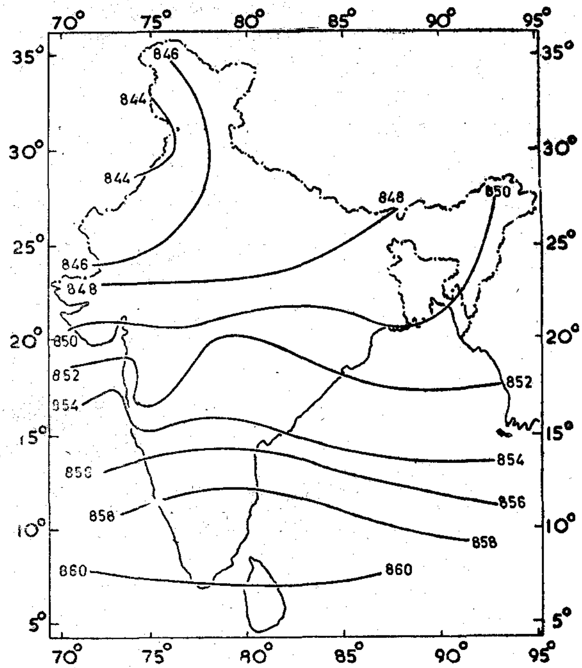
TABLE 13

TEMPERATURE-MIXING RATIOS FOR EASTERN-COAST OF INDIA AT 850 mb LEVEL

Station	July		Aug.	
	Temp. (°C)	Mixing ratio (gm/kg)	Temp. (°C)	Mixing ratio (gm/kg)
Madras	20.4	13.0	19.2	13.0
Vizag	20.5	14.4	20.3	14.4
Calcutta	20.5	15.2	20.3	15.2
Port Blair	18.8	13.2	18.6	13.3

The Table 13 establishes convincingly that there is a progressive increase in the amount of water vapour at this level from Madras to Calcutta. It is a curious fact that Port Blair at this level is cooler than the eastern coast and the amount of water vapour over there is much less than that on the eastern coast. It is moreover, remarkable to note that from Nagpur to the eastern coastal region delimited by such far-flung stations like Madras and Calcutta, the atmospheric temperature and density at 850 mb level show little variation.

At 700 mb level, (Map 2) no such density trough appears over the eastern coast; but instead, a shallow trough over Central Maharashtra is noticed. The Table 14 for temperature and mixing ratio at this level for Bombay, Poona and Nagpur helps in understanding the reason for this shallow trough.



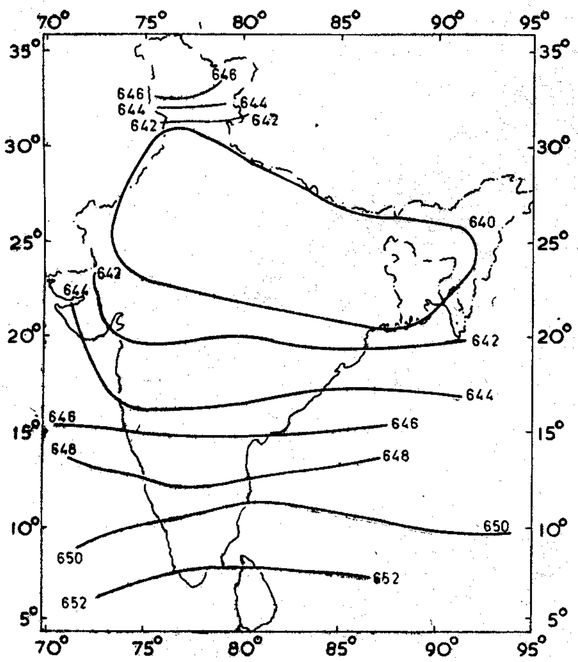
Map 2—Isopycnic lines (in gm/m³) at 700 mb isobaric level.

TABLE 14

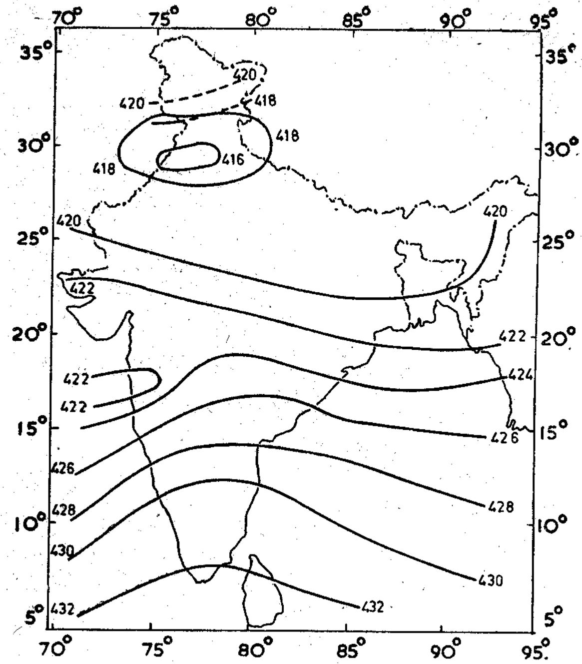
TEMPERATURE-MIXING RATIOS FOR CENTRAL MAHARASHTRA AT 700 mb LEVEL

Station	Temperature (°C)	Mixing ratio (gm/kg)
Bombay	11.2	8.3
Poona	11.8	9.0
Nagpur	11.5	0.7

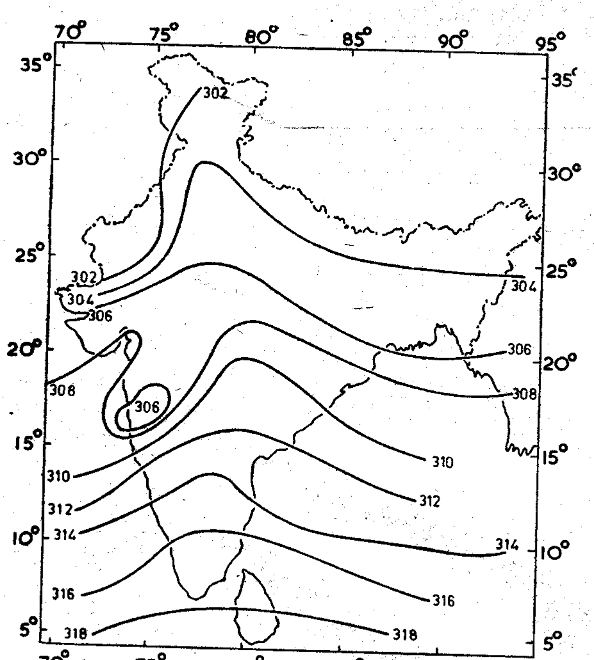
The progressive increase in the amount of water vapour from Bombay, Poona to Nagpur explains the reason for the shallow trough at this level. At 500 mb level (Map 3) the whole of North India is encompassed by a single isopycnic line. The air density from Amritsar towards Jammu and Kashmir shows a steady increase and also from Nagpur southwards the air density shows again a steady increase. Again at 300 mb level, (Map 4) the picture of the density distribution over India shows considerable change. It shows a well marked low over North-West India and there is, in close proximity, density slightly increases over Jammu and Kashmir. South of this low too, the density distributions show a continuous rise in density. Progressive rise in density from Amritsar northward and southward brings out the existence of a density trough over northwest India around this level. Over peninsular India, there is a shallow density low over Bombay-Poona region and then there is a steady increase in density southward. At 200 mb level (Map 5) no density trough appears over northwestern India and density values show a steady increase from north to south over the whole of India except for a shallow around Poona. It is a curious fact that from the middle level of mid-troposphere i.e. from 500 mb level, the density pattern changes both upwards into upper troposphere and downward into the middle and lower troposphere. But the density distribution at 500 mb level presents a flat and featureless picture over North India with no stricking aspect about it. Dr. Pisharoti[2] states that during the monsoon over India, the temperatures are high over the southern edge of the Himalayan massif and level for level, steadily decrease southward at least upto Ceylon. This horizontal temperature gradient towards the south produces a thermal wind leading to a steady decrease of the peninsular westerlies with height; by



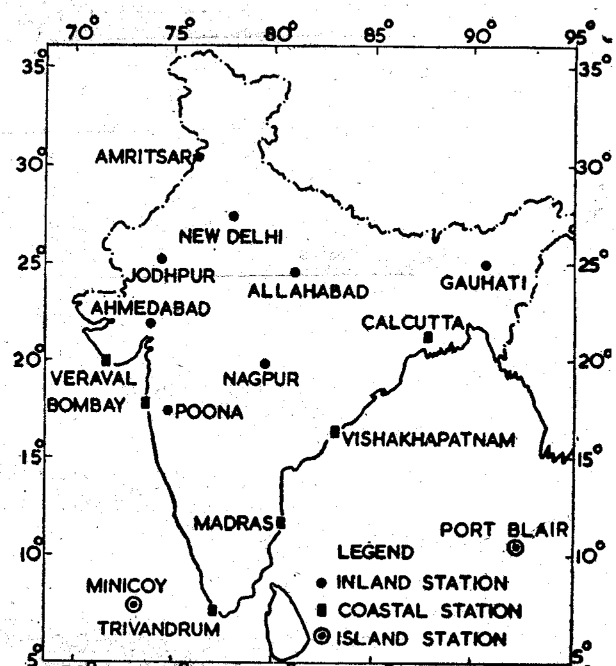
Map 3—Isopycnic lines (in gm/m³) at 500 mb isobaric level.



Map 4—Isopycnic lines (in gm/m³) at 300 mb isobaric level.



Map 5—Isopycnic lines (in gm/m³) at 200 mb isobaric level.



Map 6—Location map

600 mb level, they have all become easterlies. In our opinion the thermal wind just counter balances the flow of the westerlies over North India and might be substantially decreasing the force of the westerlies over peninsular India around 500 mb level. This appears to be the most plausible way in which the unusual density patterns at 500 mb level can be explained satisfactorily. Obviously the easterlies might be prevailing above 500 mb level.

Ramage[3] states that anabatic winds on the southern slopes of the Himalayas, according to Floh are part of the large scale summer circulation. Though strongest in the afternoon, they prevail throughout the day. They coincide with the northern rainfall maximum and presumably form part of a local vertical circulation in which air returns southwestward in the middle troposphere and tends to sink over the northern plains. That subsidence warming diminishes surface pressures, inhibits rain and by increasing the middle tropospheric lapse rate favours a showers regime. The monsoon trough roughly coincides with a relative rainfall minimum and a relative maximum in thunderstorm frequency. A mechanism operating 24 hr a day would explain why the monsoon trough displays very little diurnal variation. Table 15 fails to show effect of this subsidence warming and consequent increased lapse rates in middle troposphere either at Gauhati in north eastern India or Jodhpur in western India or Amritsar in northwestern India. The lapse rates between 700 to 500 mb levels is 14 to 15°C and that between 500 to 300 mb levels is 22 to 23°C at all northern stations. The density variation at 700 mb or 300 mb level does not show any special feature that could be justifiably attributed to '24 hr prevailing anabatic winds of the Himalayan south slopes'. It is needless to point out that neither the temperature distribution as indicated by the middle tropospheric lapse rates nor the density variation at these levels seem to support the special role assigned to the anabatic flow by Ramage[3]. On the contrary the density distribution shows little variation over the whole of north India at 500 mb level or at a height of 5 to 6 km. It is possible to argue that the mean monthly density values may not take note of the diurnal variation in it. The authors of the present paper have investigated the probable correlation between the density values at different levels and the daily rainfall for the months June to September 1973. The daily density values for this year which incidentally, was a normal monsoon year, fail to show any remarkable variation at any middle tropospheric level which could be favourably interpreted to support Ramage's hypothesis relating to the role of anabatic winds of the Himalayan southern slope. The

TABLE 15

MEAN MONTHLY AIR TEMPERATURE DIFFERENCES BETWEEN STANDARD ISOBARIC LEVELS

Unit : °C

Station	Surface to 850 mb					850 to 700 mb					700 to 500 mb				
	May	Jun.	Jul.	Aug.	Sept.	May	Jun.	Jul.	Aug.	Sept.	May	Jun.	Jul.	Aug.	Sept.
Amritsar	4.3	4.8	5.9	6.4	5.8	13.7	13.0	10.2	9.4	10.3	20.5	20.0	15.0	15.6	16.4
New Delhi	5.0	11.0	6.5	7.3	4.8	14.6	13.3	10.6	9.0	12.7	20.3	20.9	14.4	14.1	13.5
Jodhpur	8.0	8.6	8.1	7.8	8.0	14.5	11.8	9.7	8.8	10.5	19.8	17.7	15.4	15.6	14.1
Allahabad	7.2	7.8	7.6	7.2	7.6	14.8	12.7	9.0	8.7	9.3	19.4	16.5	14.1	14.0	14.1
Gauhati	6.8	7.3	7.6	7.6	7.3	10.0	8.8	8.5	8.6	9.0	14.3	13.9	13.8	13.9	14.4
Nagpur	6.7	7.8	6.2	6.5	6.2	14.7	12.2	9.2	8.5	9.6	19.8	18.3	14.1	14.1	14.0
Veraval	4.0	8.2	9.1	9.2	8.5	11.6	7.9	6.8	5.6	8.0	17.5	16.2	15.0	15.1	13.6
Calcutta	6.2	8.4	7.7	7.9	8.0	11.7	9.4	8.1	7.9	8.4	16.9	15.2	13.9	14.1	14.4
Ahmedabad	8.7	10.0	8.7	8.9	8.9	13.6	10.4	8.0	7.3	9.7	18.9	16.0	14.8	14.8	13.1

Station	500 to 300 mb					300 to 200 mb				
	May	Jun.	Jul.	Aug.	Sept.	May	Jun.	Jul.	Aug.	Sept.
Amritsar	25.0	22.4	21.7	22.3	23.4	15.6	18.3	20.8	20.7	18.7
New Delhi	23.2	19.5	22.1	22.8	22.0	15.0	19.2	21.1	20.8	19.4
Jodhpur	23.5	22.2	22.1	22.4	23.4	16.5	18.8	18.4	19.9	20.3
Allahabad	22.7	22.7	22.7	23.0	23.4	18.0	19.2	20.5	20.2	20.4
Gauhati	22.7	22.5	22.1	22.5	23.1	18.4	19.0	20.1	20.8	19.7
Nagpur	23.0	20.9	23.4	24.1	24.3	20.3	21.2	22.2	22.0	21.4
Veraval	24.1	23.9	23.3	24.3	24.5	18.8	19.5	20.5	22.8	20.9
Calcutta	22.7	22.5	22.9	23.4	23.6	19.3	20.4	20.7	20.0	20.0
Ahmedabad	23.5	23.5	23.5	24.0	24.6	18.7	20.2	20.8	21.2	21.6

idea here is not to deny altogether the existence of such a flow; but only to point out that no decisive role can be attributed on the basis of the available information, to this wind. Now, in so far as the role of large lapse rates—that too at middle tropospheric levels—in facilitating the occurence of thunderstorms is concerned, it would be pertinent to point out that the thermodynamic instability is an inherent feature of the upper atmosphere of northern India during southwest monsoon. Large lapse rates are not, to say the least, the only criteria available for measuring this instability and may not provide the best means for explaining 'a relative maximum in thunderstorm frequency'. These large lapse rates can be noticed even at stations like Veraval and Ahmedabad which are situated far away from the Gangetic Plains.

The study of upper air density variation above 200 mb level brings out the salient fact that all through the year, the density values decrease from south to north, as the temperature also shows the same pattern. The prevalence of lower temperature over southern latitudinal India is quite consistent with the solar radiation analysis.

TABLE 16

DENSITY GRADIENTS ALONG AMRITSAR-TRIVANDRUM AXIS

Unit : gm/cu metre/°C

Pressure levels (mb)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
850	4.1	4.2	5.0	0.0	2.8	3.1	3.7	3.7	3.4	4.0	5.0	4.3
700	3.0	3.4	3.2	3.5	1.5	3.0	3.2	3.0	3.0	4.1	4.3	3.2
500	2.5	2.5	1.8	2.5	2.4	2.4	2.3	3.0	3.2	3.5	2.5	2.5
300	1.9	1.9	1.9	1.8	1.9	1.9	1.7	1.7	1.9	1.9	1.9	1.9
200	1.6	2.0	1.5	1.5	1.2	1.5	1.4	1.4	1.4	1.4	1.3	1.5
150	1.1	1.2	1.2	1.2	1.1	1.3	1.1	1.1	1.2	1.2	1.1	1.1
100	1.1	1.0	0.9	0.9	0.8	0.9	1.0	0.9	1.0	0.9	0.9	1.1

CONCLUSION

The study of upper air density and temperature shows that during winter months, i.e. from October to March, the density gradient has a down slope from north to south. But in summer, particularly from June to September the density gradient shows a down slope from south to north upto 200 mb. The upper air density distribution in July presents a complex pattern at different levels. At 850 mb level the isopycnic lines form a shallow trough over the east coast and there is a packing of these lines across the Deccan Plateau and also over western parts of Rajasthan. At 700 mb level, there is again a shallow trough over Bombay-Poona region but over the rest of the country the isopycnic lines show no special features. At 500 mb level, there is no striking aspect about these lines except for the fact that only one line encompasses the whole of north India. At 500 mb level, there is a well marked trough of density over north-western India; but at 200 mb level there is no such trough. The study of upper air density variation above 200 mb level presents an altogether different picture throughout the year.

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