551·58 : 621·396·9(54)

Radio-Climatology of India : IV. Vertical structure of Radio Refractive Index distribution in the lower troposphere

S. M. KULSHRESTHA and K. CHATTERJEE

Meteorological Office, New Delhi

(*Received 15 July 1966*)

ABSTRACT. Based on the 5-year averages of the values of pressure, temperature and relative humidity at the ground surface, 850-mb level (about 5000 ft a.s.l.) and 700-mb level (about 10,000 ft a.s.l.), the corresponding values of modified radio-refractive index (or radio-refractivity) have been computed for these three levels for each month at various stations in India. These data have been utilised to describe and discuss the vertical structure of radio-refractivity distribution in the lower troposphere upto an approximate height of 10,000 ft a.s.l. Various radio-climatic charts have been prepared and the prominent features of the lower tropospheric radio-climate over the country have been discussed.

1. Introduction

1.1. In a continuing series of studies on the radio-climatology of India, the authors(Kulshrestha and Chatterjee 1966a, 1966b, 1967) have discussed the distribution of radio-refractivity, N, near the ground surface, at 850 mb (approximately 5000 ft a.s.l.) and at 700-mb level (approximately 10,000 ft a.s.l.) over India. The present paper is the fourth in the series and deals with the vertical structure of radio-refractivity distribution in the lower troposphere over the country. Herein, the composite patterns of monthly distribution of radio-refractivity in the lower troposphere have been presented for all the twelve months and the significant features of the prevalent distribution patterns have been discussed. Similarly, composite diagrams for seasonal distribution of N, annual maximum and minimum N, annual range of variation of N have been presented. Vertical variations of N along an east-west and a north-south cross-section have been discussed.

1·2. Besides presenting the above mentioned composite diagrams and discussing them, the vertical N-profiles for all the twelve months have been drawn for various stations in the country for all the twelve months. The vertical gradients between ground surface and 5000 ft a.s.l. and between 5000 and 10,000 ft a.s.l. have been worked out for each month at the various stations.

2. Data

2·1. The present study utilizes the data of N_s , N_{850} and N_{700} values worked out on the basis of 5-year averages of the mean monthly values of P, T and RH. While the ground surface values N_s were computed for 36 stations (Kulshrestha and Chatterjee 1966a), those for the 850 and 700-mb levels (N_{850} and N_{700}) were calculated for the 13 and 12 available stations respectively (Kulshrestha and Chatterjee 1966b, 1967).

2·2. For the monthly mean values of N_s , N_{850} and N_{700} for various stations and for their seasonal means, annual maximum and minimum values, and annual range of variation at each station, reference may be made to the authors' earlier papers in the present series (Kulshrestha and Chatterjee, *op. cit.*).

2·3. Figs. 1 (a) and 1 (b) depict the composite patterns of the isopleths of N_s , N_{850} and N_{700} drawn for all the twelve months. Similarly, Fig. 2 illustrates the composite patterns for the isopleths of seasonal mean values of N_s , N_{850} and N_{700} for the four seasons, *viz.*, winter, summer, monsoon and post-monsoon. Figs. 3, 4 and 5 show the superimposed isopleths of the annual maximum, annual minimum and annual range of variation of N_s , N_{850} and N_{700} values.

2·4. The vertical structure of lower tropospheric radio-refractivity distribution along two chosen cross-country cross-sections were also investigated. For this purpose, the following two cross-sections were selected—

(*i*) *North-south cross-section* — Srinagar/Amritsar, New Delhi, Nagpur, Madras and Trivandrum. This cross-section lies very nearly in the longitudinal belt 75° — 80°E.

(*ii*) *East-west cross-section* — Silchar, Gauhati, Calcutta, Cuttack, Allahabad, Nagpur, Akola, Indore, Ahmedabad and Veraval. This cross-section lies very nearly in the latitudinal belt 20° — 26°N.

It may be noted that the two cross-sections intersect at Nagpur. Figs. 6 and 7 exhibit the variations of N in the lower tropospheric along these two cross-sections in the four representative months.

2·5. Diagrams depicting the monthly variations of the vertical structure of radio-refractivity over

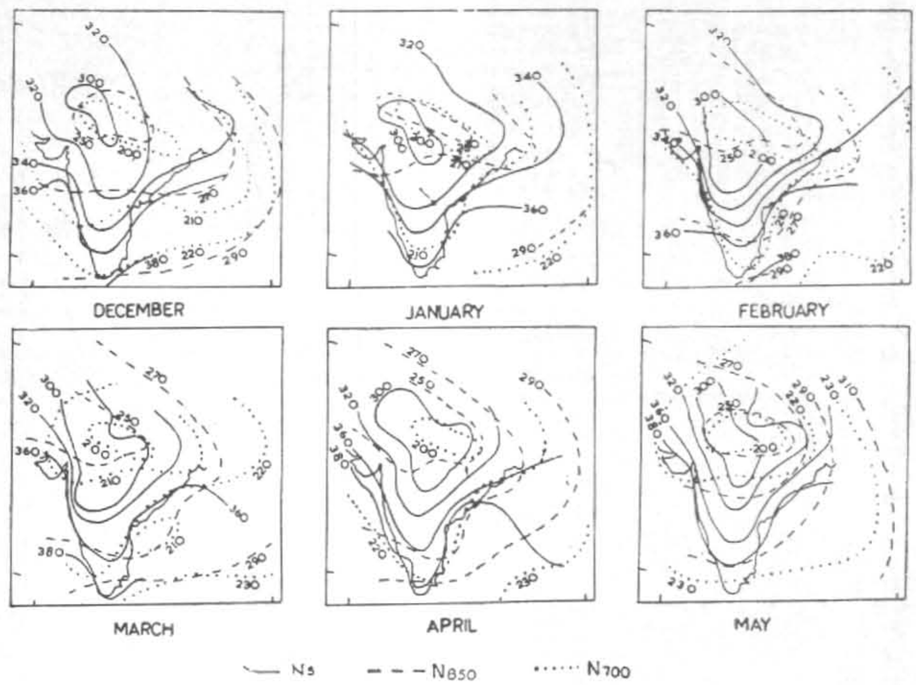

Fig. 1(a)

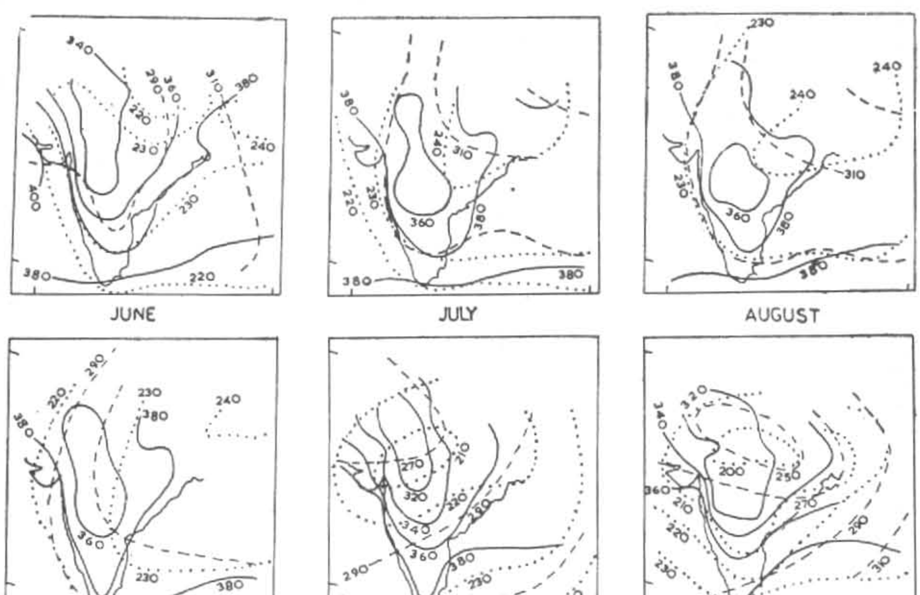

Fig. 1(b)

Fig. 1. Composite patterns of monthly distribution of radio-refractivity in the lower troposphere over India

12 different stations were prepared and these were grouped according to the similarity of pattern of vertical structure and its variation over each station. These diagrams are presented in Figs. 8 to 10.

2.6. Maps have been drawn showing N-profiles for the 12 stations for each month. These appear in Figs. 11a, 11b, 12a and 12b; the maps pertaining to months in one season appearing in one figure. Thus Fig. 11a pertains to winter season, while Figs. 11b, 12a and 12b correspond to summer, monsoon and post-monsoon seasons respectively. Care has been taken to draw each profile, on the map of India, in a position adjacent to the geographical location of the station to which the profile pertains. On these profile diagrams, the abscissa denotes N values in N units while the ordinate represents heights above sea level in thousands of feet. The numbers along the profiles represent gross vertical gradients $\triangle N/\triangle h$ (in N units per 1000 ft) between ground surface and 5000 ft a.s.l. and between 5000 and 10,000 ft a.s.l. The negative sign before these gradient values has been retained to emphasize the fact that radio-refractivity decreases with height. Values of $\triangle N/\triangle h$ for the various stations are listed in Table 1.

2.7. To facilitate comparison of the vertical profiles at various stations in the four representative months, composite diagrams for vertical profiles were drawn for each of the four representative months. These are shown in Fig. 13.

3. Discussion

3.1. *Composite patterns of the monthly distribution of radio-refractivity at ground, 850-mb and 700-mb levels* (Figs. 1a and 1b).

3.1.1. *General features*

3.1.1.1. Figs. 1(a) and 1(b) show the composite patterns of radio-refractivity distribution over India obtained by superimposing the isopleths of N_s , N_{850} and N_{700}. The configuration and locations of these isopleths give an idea of the N distribution over the country upto a height of about 10,000 ft a.s.l.

3.1.1.2. The region comprising of Rajasthan, west Uttar Pradesh, and northwest Madhya Pradesh is characterised by the occurrence of persistently low values of N at all levels upto 10,000 ft a.s.l. in the troposphere. On the other hand, western coast, extreme south Peninsula, east coast and Assam valley are characterised by higher values of N at these levels.

3.1.1.3. The horizontal gradient of radio-refractivity becomes more diffuse with increase in height.

3.1.1.4. The axes of the isopleths generally show an anti-clockwise shift with height except in case of the monsoon months when there is a clockwise shift, with height, in the orientation of the axes of the isopleths.

3.1.2. *Month by month pattern* (Figs. 1a and 1b).

3.1.2.1. *December*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 380, 294 and 221 N units cccurring over Pamban, Port Blair and Port Blair respectively. The minimum values of N_s, N_{850} and N_{700} over the country during this month are 297, 249 and 202 N units occurring over Indore, Allahabad and Allahabad /Jodhpur respectively. It is worthy of note that the maximum values of N_{850} and N_{700} occur over the same place, *viz.*, Port Blair. The same is true for the minimum values of N_{850} and N_{700} which occur over Allahabad.

3.1.2.2. *January*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 376, 295 and 220 N units occurring over Pamban, Port Blair and Port Blair respectively. The minimum values of N_s, N_{850} and N_{700} over the country during the month are 294, 250 and 205 occurring over Indore, Jodhpur and Allahabad respectively. In this month also, the maximum values of N_{850} and N_{700} occur over the same place, *viz.*, Port Blair.

3.1.2.3. *February*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 378, 288 and 216 N units occurring over Pamban, Trivandrum and Port Blair/Gauhati respectively. Similarly the minimum values of N_s, N_{850} and N_{700} are 282, 244 and 201 N units over Indore, Jodhpur and Allahabad respectively. December through February, the maximum values of N_s and N_{700} occur over Pamban and Port Blair respectively.

3.1.2.4. *March*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 386, 296 and 225 N units occurring over Cochin, Trinvandrum and Trivandrum respectively. Similarly the minimum values of N_s, N_{850} and N_{700} are 277, 248 and 203 N units occurring over Indore, Jodhpur and Allahabad respectively. It is worthy of note that the maxima of N_{850} and N_{700} during this month occur over the same place, *viz.*, Trivandrum. It is also seen that the minima of N_s, N_{850} and N_{700} during January through March occur over the same places, *viz.*, Indore, Jodhpur and Allahabad respectively.

TABLE 1

Values of vertical gradient of radio-refractivity ($-\triangle N/\triangle h$) over various stations in different months

	$-\triangle N/\triangle h$ in N units per 1000 ft																							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
Allahabad (ALB) (25°27′N, 81°44′E)	13	13	16	11	12	10	12	9	13	9	16	12	16	14	17	15	16	15	19	13	17	11	17	10
Bombay (BMB) (19°04′N, 72°06′E)	19	13	21	11	22	10	24	9	22	11	18	14	18	15	17	16	17	15	19	14	19	13	21	13
Calcutta (CAL) (22°39′N, 88°27′E)	14	12	14	12	17	12	17	11	17	14	16	15	18	17	17	15	15	17	13	17	15	12	16	12
Gauhati (GHT) (26°05′N, 91°43′E)	13	12	13	13	12	12	14	15	14	16	15	14	17	15	16	15	17	14	17	13	17	15	16	14
Jodhpur (JDP) (26°16′N, 73°03′E)	10	9	13	10	12	9	12	6	14	7	16	11	15	16	15	14	17	14	14	11	16	10	12	10
Madras (MDS) (13°00′N, 80°11′E)	19	13	23	11	24	10	24	11	19	14	16	13	15	16	15	14	17	14	20	17	18	17	18	14
Nagpur (NGP) (21°09′N, 79°07′E)	8	14	11	10	12	8	14	7	13	8	17	10	14	13	17	15	18	15	15	14	14	12	13	12
New Delhi (DLH) (28°35′N, 77°12′E)	15	8	16	10	11	11	12	9	12	9	11	11	15	16	15	16	14	15	15	13	15	9	15	10
Port Blair (PBL) (11°40′N, 92°43′E)	16	16	18	14	17	14	19	15	19	15	18	15	17	14	16	15	17	14	16	12	15	17	16	14
Trivandrum (TRV) (08°30′N, 76°59′E)	17	16	16	16	17	15	17	15	20	13	17	16	20	15	19	15	20	15	18	14	20	14	17	14
Veraval (VVL) (22°55′N, 70°22′E)	11	11	18	9	20	9	22	11	25	10	23	14	20	15	18	16	19	15	19	14	16	12	15	11
Visakhapatnam (VSK) (17°42′N, 83°18′E)	15	14	18	12	20	9	22	10	22	11	18	13	17	15	15	14	17	13	17	14	17	12	17	12

I — Values between ground surface and 5000 ft a.s.l. II — Values between 5000 and 10,000 ft a.s.l.

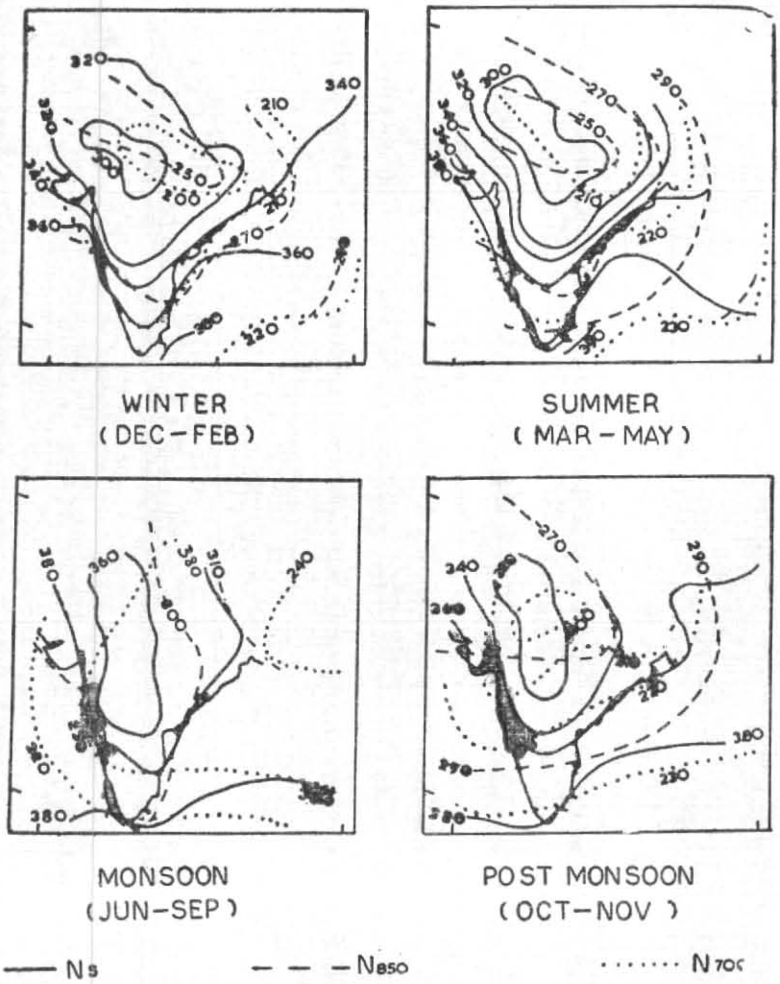

Fig. 2. Composite patterns of seasonal distribution of radio-refractivity in the lower troposphere over India

3.1.2.5. *April*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 390, 298 and 228 N units occurring over Pamban, Trivandrum/Port Blair, and Port Blair respectively. Similarly the minimum values of N_s, N_{850} and N_{700} are 276, 242 and 202 N units occurring over Indore, Allahabad and Allahabad respectively. It will be noted that the maxima of N_{850} during February through April occur over Trivandrum while the minima for N_s during December through April occur over Indore.

3.1.2.6. *May*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 394, 308 and 232 N units occurring over Dwarka, Gauhati and Gauhati respectively. Similarly the minimum values of N_s, N_{850} and N_{700} are 284, 249 and 207 N units occurring over Bikaner, Allahabad and Allahabad respectively. It is worthy of note that the minimum N_{700} values from December through May occur over Allahabad.

3.1.2.7. *June*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 400, 311 and 242 N units occurring over Dwarka, Gauhati and Gauhati respectively, *i.e.*, over the same places as in May. Similarly the minimum value of N_s, N_{850} and N_{700} are 322, 276 and 221 N units occurring over New Delhi, New Delhi and New Delhi/Trivandrum respectively. It is of interest to note that the troposphere over New Delhi during June exhibits minima for radio-refractivity at all levels, *viz.*, ground surface, 850-mb level (about 5000 ft a.s.l.) and 700-mb level (about 10,000 ft a.s.l.).

3.1.2.8. *July*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 402, 318 and 243 N units occurring over Dhubri, Gauhati and Allahabad respectively. Similarly the minimum values of N_s , N_{850} and N_{700} are 350, 292 and 223 N units occurring over Hyderabad, Veraval and Trivandrum respectively.

3.1.2.9. *August*

The maximum values of N_s , N_{850} and N_{700} over the country during this month are 396, 318 and 246 N units occurring over Dhubri, Gauhati and Gauhati respectively. Similarly the minimum values of N_s , N_{850} and N_{700} are 350, 293 and 224 N units over Hyderabad/Poona, Trivandrum and Trivandrum respectively. It will be noted that the minima for N_{700} from June through August occurs over Trivandrum and the maxima for N_{850} from May through August occur over Gauhati.

3.1.2.10. *September*

The maximum values of N_s, N_{850} and N_{700} over the country during this month are 394, 308 and 240 N units occurring over Dhubri, Calcutta and Gauhati respectively. Similarly the minimum values of N_s , N_{850} and N_{700} are 350, 283 and 222 N units and occur over Hyderabad/Indore/Bikaner, Srinagar and Jodhpur respectively. It will be noted that the maxima of N_{700} occur over Gauhati from May through September. The maxima of N_s from July through September occur over Dhubri.

3.1.2.11. *October*

The maximum values of N_s , N_{850} and N_{700} over the country during this month are 390, 300 and 235 N units occurring over Pamban, Port Blair and Port Blair respectively. Similarly the minimum values of N_s , N_{850} and N_{700} are 306, 263 and 210 N units and occur over Bikaner, Jodhpur and Allahabad respectively.

3.1.2.12. *November*

The maximum values of N_s , N_{850} and N_{700} over the country during this month are 383, 313 and 231 occurring over Pamban, Port Blair and Trivandrum respectively. Similarly the minimum values of N_s , N_{850} and N_{700} are 297, 249 and 199 N units and occur over Indore, Allahabad and Allahabad respectively. It will be noted that the minima of N_s , N_{850} and N_{700} during November and December occur over the same places, *viz*, Indore, Allahabad and Allahabad respectively. The maxima for N_s occur at Pamban from October through February and again in April.

3.2. *Composite patterns of the seasonal distribution of radio-refractivity at ground surface, 850-mb and 700-mb levels* (Fig. 2).

3.2.1. The lowest seasonal values of radio-refractivity in the lower troposphere over India are found to occur over Rajasthan and the adjoining region while the highest seasonal values occur over coastal areas, the seas and Assam valley.

3.2.2. The largest seasonal values of radio-refractivity occur in monsoon season while the lowest seasonal values occur in winter and summer seasons. It is seen that the largest seasonal values of N_s , N_{850} and N_{700} for all the four seasons are 393, 313 and 243 N units occurring over Dwarka, Gauhati and Gauhati respectively in the monsoon season whereas the lowest values are 282, 246 and 203 N units occurring respectively over Indore in summer, Allahabad in summer and Allahabad in winter.

3.2.3. The distribution pattern has a steep horizontal gradient in the lowest levels of the troposphere but this horizontal gradient becomes more and more diffuse in the upper layers.

3.3. *Composite pattern of the distribution of annual maximum radio-refractivity over the country* (Fig. 3)

The annual maximum value of radio-refractivity near the ground surface varies between 360 and 400 N units; those for the 850-mb and 700-mb levels vary between 300-320 and 250-230 N units respectively. The highest values of annual maximum N_s occur over west coast and Assam. In the upper levels at 850 and 700 mb, the highest annual maximum values occur over Assam. The lowest annual maximum N_s occurs over north peninsula between Poona and Hyderabad; while those at 850 and 700-mb levels occur over the western boundaries of the country and over extreme south peninsula.

3.4. *Composite pattern of the distribution of annual minimum radio-refractivity over the country* (Fig. 4)

The annual minimum value of N_s varies between 290 and 370 N units; those for the 850 and 700-mb levels vary between 240-280 and 200-220 N units respectively. The highest values of annual minimum N_s are found to occur over the extreme south peninsula and the Bay Islands; those for the 850 and 700-mb levels occur over extreme south peninsula, Assam valley and Bay Islands. The lowest values of annual minimum radio-refractivity near the ground surface are found to occur over Rajasthan and the central parts of the country. In the upper levels at 850 and 700 mb, the lowest annual minimum values of radio-refractivity are found to occur over Uttar Pradesh, Rajasthan and adjoining areas.

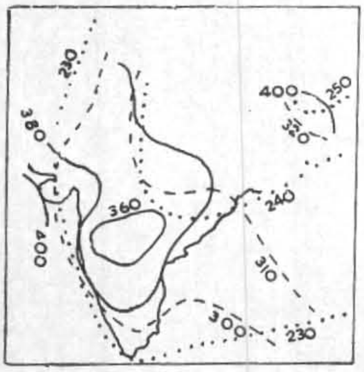

Fig. 3. Annual maximum

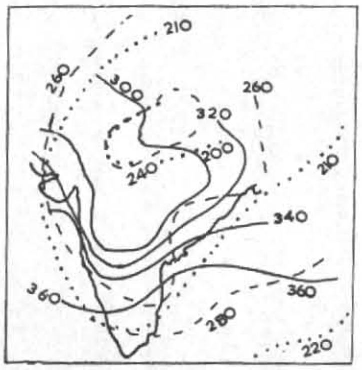

Fig. 4. Annual minimum

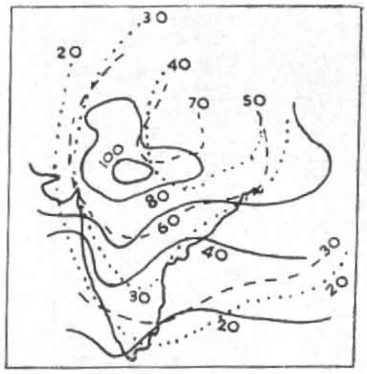

Fig. 5. Annual range

Figs. 3–5. Compoisite pattern of annual distribution of radio-refractivity in the lower troposphere over India

3.5. *Composite pattern of the distribution of annual range of variation of radio-refractivity over the country* (Fig. 5)

The isopleths of the spot values of $(N_{s\,max} - N_{s\,min})$ for the entire year have been drawn. Similarly the isopleths of spot values of $(N_{850\ max} - N_{850\ min})$ and $(N_{700\ max} - N_{700\ min})$ for the entire year have been drawn. All these isopleths have been superimposed to obtain a composite pattern of the distribution of the annual range of variation of radio-refractivity from ground surface to 700-mb level which corresponds approximately to 10,000 ft a.s.l. Near the ground surface, the largest ranges of variation of radio-refractivity are of the order of 100 N units and occur over the region between Allahabad and Indore. At the 850-mb level (5000 ft a.s.l.), the largest annual range variations are of the order of 70 N units and occur over the central and sub-Himalayan Uttar Pradesh. In the still higher levels at 700 mb (10,000 ft a.s.l.), the largest annual range variations are of the order of 40 N units only and occur over Uttar Pradesh and Bihar. It is very interesting to note that while the largest ranges of annual variation of radio-refractivity decrease from about 100 N units near ground surface to about 40 N units at 10,000 ft a.s.l., the smallest ranges of variation are found to have the same order of magnitude (20 N units) at all levels in the lower troposphere and occur over south peninsula and the Bay Islands.

3.6. *Composite patterns of the latitudinal variations of the lower-tropospheric radio-refractivity along a north-south cross-section of the country during the four representative months* (Fig. 6)

The selected north-south cross-section was-- Srinagar, Amritsar, New Delhi, Nagpur, Madras and Trivandrum. It lay very nearly in the longitudinal belt 75°—80° E.

3.6.1. *February*

Ground surface radio-refractivity N_s shows the largest variations along the cross-section but the range of variation decreases successively in the upper levels. As we move southward along the cross-section, radio-refractivity decreases upto New Delhi at all levels and continues to decrease upto Nagpur near the ground surface. But in the upper levels, radio-refractivity shows a rise from New Delhi to Nagpur. In fact the rise continues, at 850-mb level, upto Madras whereas at the 700-mb level there is a slight fall in the value of radio-refractivity from Nagpur to Madras. N_s , however, exhibits a steep rise from Nagpur to Madras. From Madras, upto Trivandrum, while the N_s remains practically the same N_{850} and N_{700} exhibit a rise which is quite steep at the 850-mb level.

3.6.2. *May*

Ground surface radio-refractivity N_s shows the largest variations along the cross-section whereas the range of variation reduces successively in the upper levels. While N_s shows a slight rise from extreme north of the country upto New Delhi, the N_{850} registers an appreciable fall from Srinagar to New Delhi. Values of radio-refractivity during May change little from New Delhi to Nagpur although there is a slight fall from New Delhi to Nagpur near the ground surface and a slight increase at higher levels. From Nagpur to Madras, there is a distinct increase in radio-refractivity values, the increase being more spectacular at ground surface and reducing successively in the higher levels. The increase continues from Madras to Trivandrum although the magnitude of change between these two stations is about the same at all levels. It is worthy of note that during this month, while N_s and N_{850}

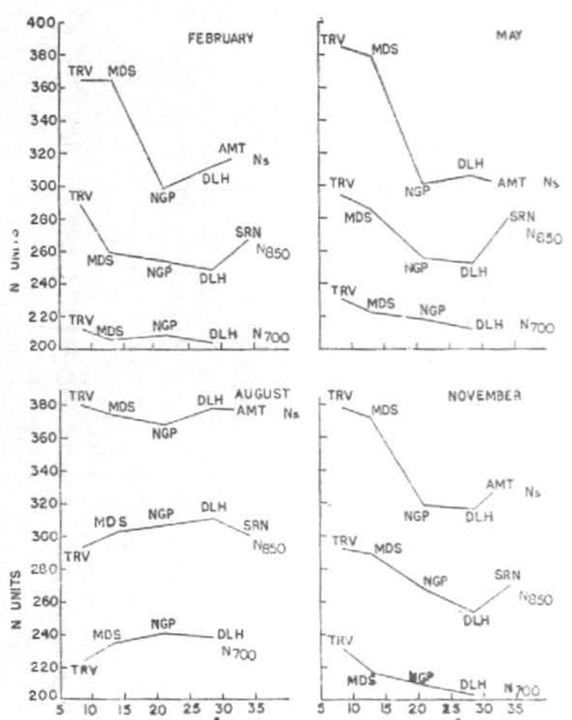

Fig. 6. Composite pattern of the variations of radio-refractivity in the lower troposphere along the north-south cross-section during four representative months

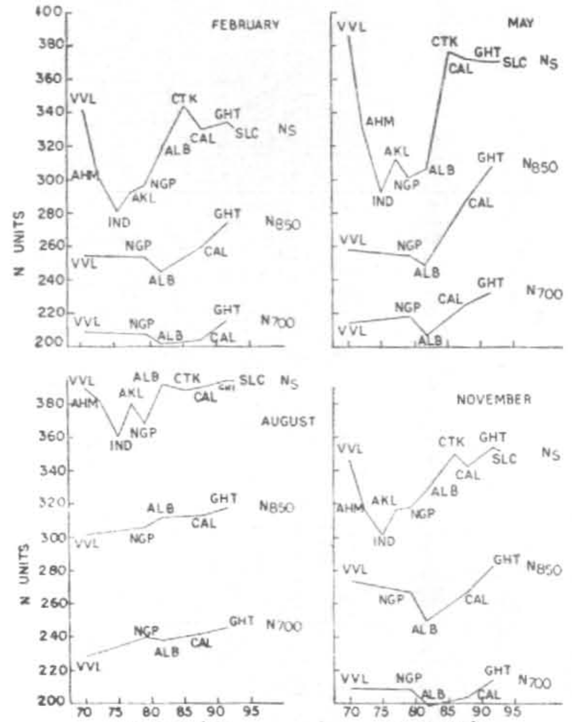

Fig. 7. Composite pattern of the variations of radio-refractivity in the lower troposphere along the east-west cross-section during four representative months

show a decrease in the central parts of the cross-section, N_{700} increases gradually from north to south.

3.6.3. *August*

The cross-sectional variations of radio-refractivity are very small at all levels in this month which may be taken to represent the monsoon season. Radio-refractivity increases slightly upto New Delhi at all levels, the increase continuing upto Nagpur at the 700-mb level. At ground surface and at 850-mb level, the radio-refractivity decreases from New Delhi to Nagpur. From Nagpur down south to Trivandrum through Madras, N_s increases gradually whereas N_{850} and N_{700} decrease gradually.

3.6.4. *November*

In this month, the radio-refractivity regime reverts to the condition where the N_s shows the largest variations along the cross-section whereas the range of variation reduces successively in the upper levels. The trend of the cross-sectional variation is, however, similar at all levels. With a minimum value at New Delhi, the radio-refractivity values increase on both sides along the cross-section. The increase is quite steep from Nagpur to Madras at all levels. Between Madras and Trivandrum, N_{700} continues to increase steeply while the N_s and N_{850} increase less spectacularly between these two stations.

3.7. *Composite patterns of the longitudinal variations of the lower-tropospheric radio-refractivity along an east-west cross-section of the country during the four representative months* (Fig. 7)

The selected east-west cross-section was: Silchar, Gauhati, Calcutta, Cuttack, Allahabad, Nagpur, Akola, Indore, Ahmedabad and Veraval. It lay very nearly in the latitudinal belt 20°—26°N. It will be seen from Fig. 7 that the cross-sectional variation patterns of N_s , N_{850} and N_{700} show the following similarities. The minimum value of N_s occurs at Indore in all the four months. The N_s values at Cuttack and Veraval in all the four months are the highest values. The patterns of variation of N_{850} and N_{700} show the same trend in all the four months with Gauhati exhibiting the highest values and the lowest values occurring over Allahabad. The only exception is the case of N_{850} in August when Allahabad does not exhibit the lowest value of all the stations along the cross-section. It is interesting to note that such similarities of cross-sectional variation pattern are not exhibited in the case of the north-south cross-section discussed in Sec. 3·6.

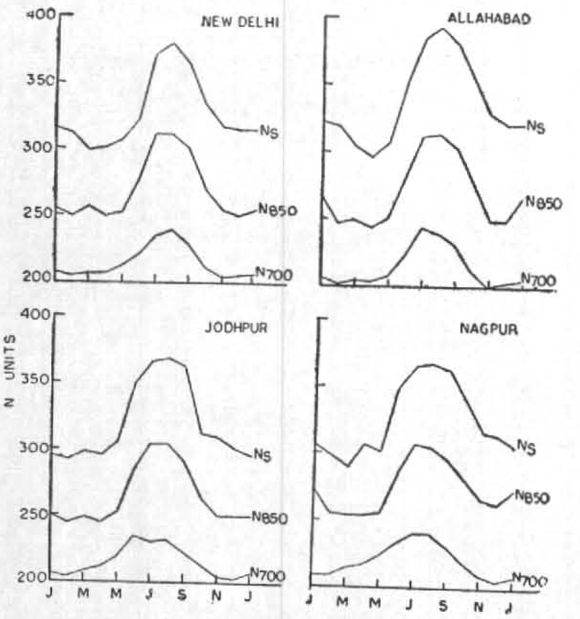

Fig. 8

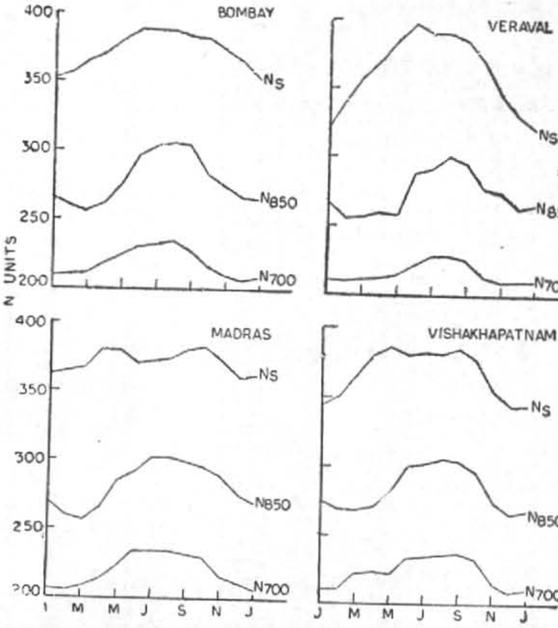

Fig. 9

Figs. 8-9. Monthly variations of the vertical structure of radio-refractivity over different stations in ndia

3.7.1. *February*

N_{850} and N_{700} values decrease from Gauhati to Allahabad through Calcutta, whereas the N_s values at first increase upto Gauhati, then decrease upto Calcutta, rise again upto Cuttack, and then fall gradually upto Indore through Allahabad, Nagpur and Akola. The N_{850} and N_{700} values on the other hand rise from Allahabad to Nagpur and then increase very little upto Veraval. The N_s values show a steep rise from Indore to Veraval through Ahmedabad.

3.7.2. *May*

N_{850} and N_{700} values decrease from Gauhati to Allahabad through Calcutta, whereas the N_s values rise slowly from Silchar upto Cuttack through Calcutta, then fall very steeply to Allahabad continuing a further but less steep decrease upto Nagpur and then, after a sharp rise upto Akola, fall again at Indore which indicates the minimum N_s values for the cross-section. On the other hand, the N_{850} and N_{700} values rise rather steeply from Allahabad to Nagpur. Thereafter N_{850} values continue to rise less markedly upto Veraval whereas the N_{700} values fall slightly from Nagpur to Veraval. The N_s values, however, show a very marked rise between Indore and Veraval through Ahmedabad.

3.7.3. *August*

The N_{850} and N_{700} values decrease very slowly from Gauhati to Allahabad through Calcutta, the N_{850} maintaining this decrease throughout the cross-section upto Veraval through Nagpur. N_{700}, however, shows a slight rise from Allahabad to Nagpur but decreases again to Veraval. On the other hand, the N_s decreases slowly from Silchar to Cuttack through Gauhati and Calcutta, shows slight rise upto Allahabad, executes a saw-tooth variation pattern between Allahabad and Ahmedabad. It however, continues to rise between Indore and Veraval through Ahmedabad.

3.7.4. *November*

N_{850} and N_{700} decrease from Gauhati to Allahabad through Calcutta and then show a rather steep rise to Nagpur. Thereafter while N_{850} shows a slight rise upto Veraval, the N_{700} remains practically the same upto Veraval. On the other hand, the N_s values at first show an increase from Silchar to Gauhati then decrease upto Calcutta, rise again upto Cuttack, then fall appreciably upto Nagpur through Allahabad. Thereafter between Nagpur and Akola, decrease in N_s value is very little but the decrease is appreciable between Akola and Indore. From Indore to Veraval through Ahmedabad, the N_s values rise appreciably again.

3.8. *Monthly variations of the vertical structure of radio-refractivity over different stations*

Figs. 8 to 10 show the month by month variations in N_s , N_{850} and N_{700} over the 12 selected stations in India. These diagrams depict the month by month variation of the radio-refractivity structure in the vertical in the lower troposphere over these stations. In other words, these diagrams describe

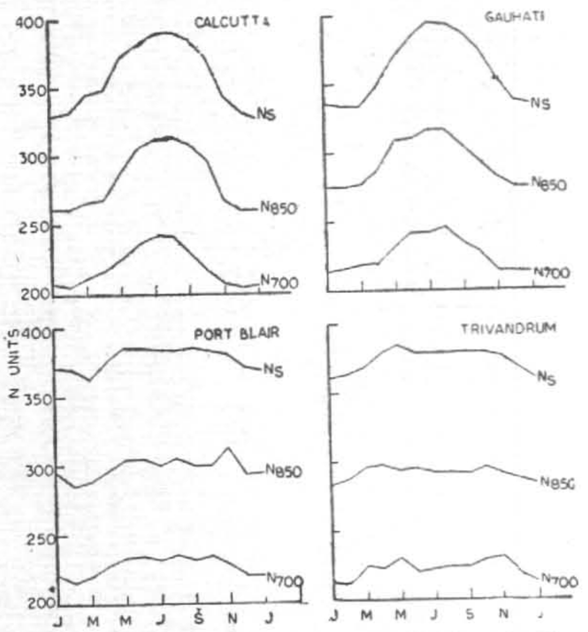

Fig. 10. Monthly variation of the vertical structure of radio-refractivity over different stations in India

the lower-tropospheric radio-climate over these stations. On the basis of the similarities of this lower tropospheric radio-climate pattern, these stations can be classified into the following five distinct types —

Type I	New Delhi, Allahabad, Jodhpur, Nagpur	Inland (land-locked) stations	Fig. 8
Type II	Bombay, Veraval	West coast stations	Fig. 9
Type III	Madras, Visakhapatnam	East coast stations	
Type IV	Calcutta, Gauhati	Assam valley and adjoining region	Fig. 10
Type V	Port Blair, Trivandrum	Extreme south peninsula and Bay Islands	

These types can be regarded to depict five homoclimes of lower tropospheric radio-climate over the country.

3.9. *Vertical profiles of radio-refractivity in the lower troposphere over the 12 selected stations for each month*

3.9.1. Figs. 11(a), 11(b), 12(a) and 12(b) depict the vertical profiles of radio-refractivity over the 12 stations, the maps pertaining to one season appearing in one figure. As already pointed out in Section 2·6, the abscissa denotes N values in N units while the ordinate represents heights above sea level in thousands of feet. The vertical gradient $\triangle N/\triangle h$ has been calculated in two increments, *viz.*, between ground surface and 5000 ft a.s.l. and between 5000 and 10,000 ft a.s.l. The values of these gross vertical gradients have been indicated along the profiles on these diagrams. The negative sign before these gradient values has been retained to emphasize that radio-refractivity decreases with height.

3.9.2. Generally speaking, the N-gradient in the vertical is more steep (*i.e.*, $-\triangle N/\triangle h$ is higher) in the lowest 5000 ft of the troposphere than between 5000 and 10,000 ft a.s.l.

3.9.3. There are, however, exceptions when the N-gradient in the lowest 5000 ft is less steep than in the next 5000 ft layer. These exceptions are —

Jan	Nagpur	Aug	New Delhi
Apr	Gauhati	Sep	New Delhi, Calcutta
May	Gauhati	Oct	Calcutta
Jul	Jodhpur, Madras, New Delhi	Nov	Port Blair

3.9.4. There are a few cases where the N-gradient remains the same throughout the 10,000-ft layer above ground. These are —

Jan	Allahabad, Veraval, Port Blair
Feb	Trivandrum, Gauhati
Mar	New Delhi, Gauhati
Jun	New Delhi

3.9.5. Between ground surface and 5000 ft a.s.l., the largest values of $-\triangle N/\triangle h$ are found to occur over the coastal areas whereas the largest values of the gradient between 5000 and 10,000 ft a.s.l. occur over the extreme south peninsula, the Bay Islands and the eastern part of the country.

3.9.6. Between ground surface and 5000 ft a.s.l., the steepest N-gradient occurs over Veraval during May and has a value —25 N units per 1000 ft. The least value of N-gradient in this layer is —8N units per 1000 ft and occurs over Nagpur in January.

3.9.7. In the layer between 5000 and 10,000 ft a.s.l., the steepest N-gradient has the value of —17 N units per 1000 ft and occurs over —

Calcutta	July, September and October
Madras	October and November
Port Blair	November

The least value of N-gradient in this layer is —6N units per 1000 ft occurring over Jodhpur in April.

3.9.8. The difference in the gradient values in the two layers are the largest in the winter and summer months and the least during the monsoon months.

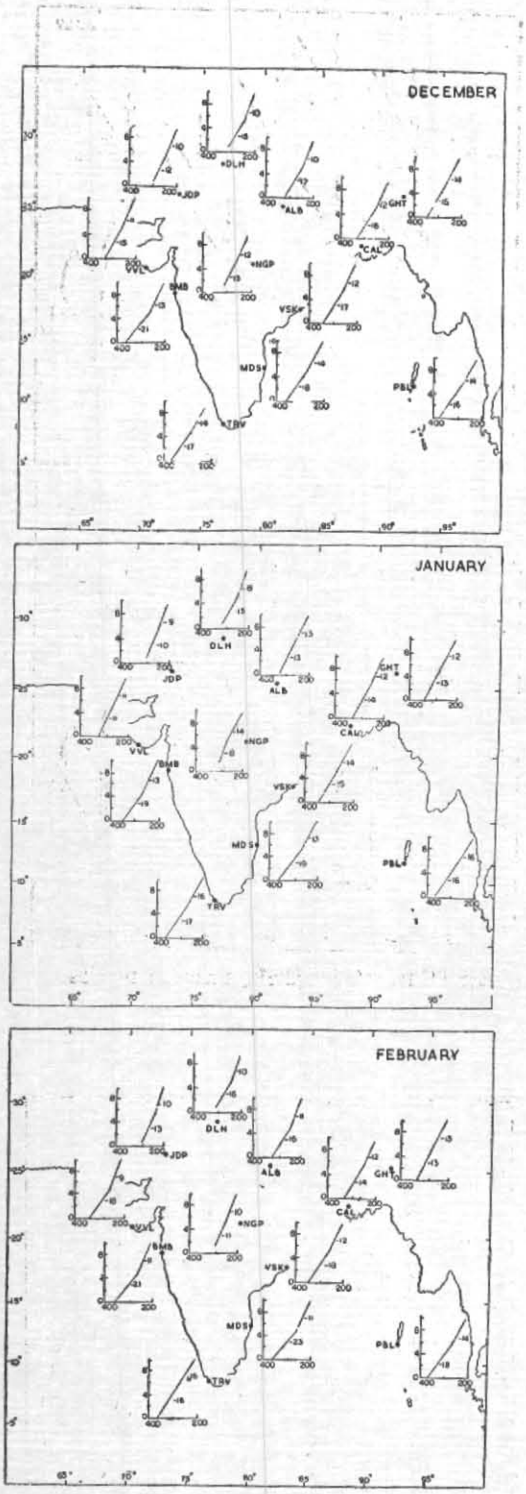

Fig. 11 (a). Winter months

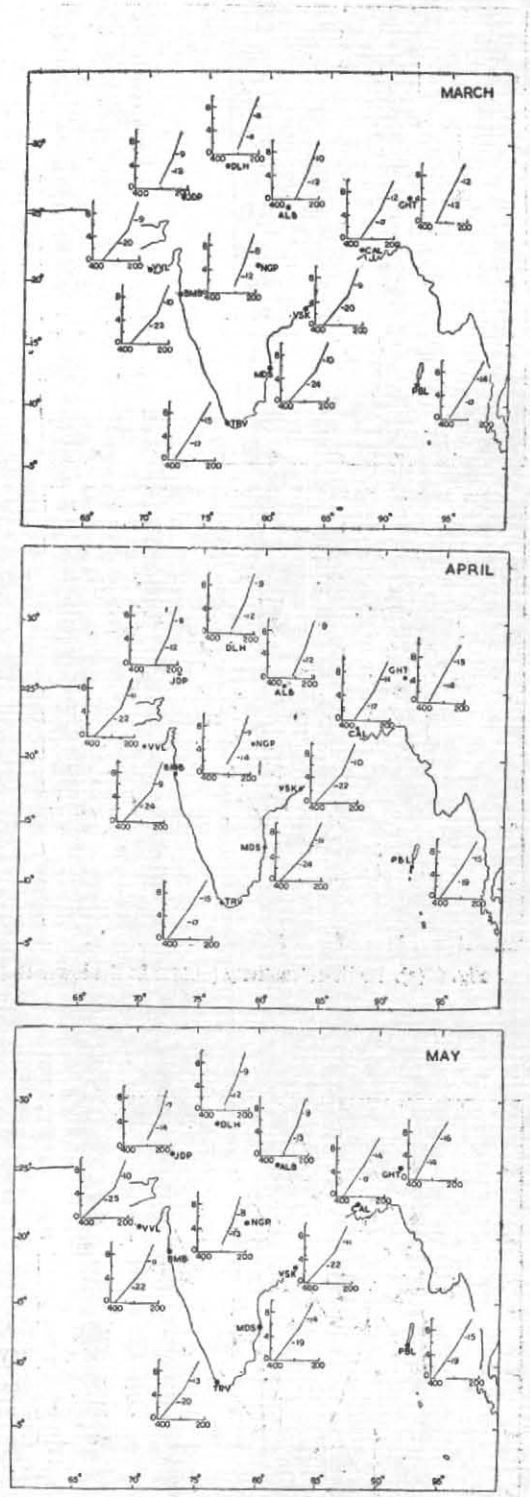

Fig. 11(b). Summer months

Fig. 11. Radio-refractivity profiles in the lower troposphere over different stations

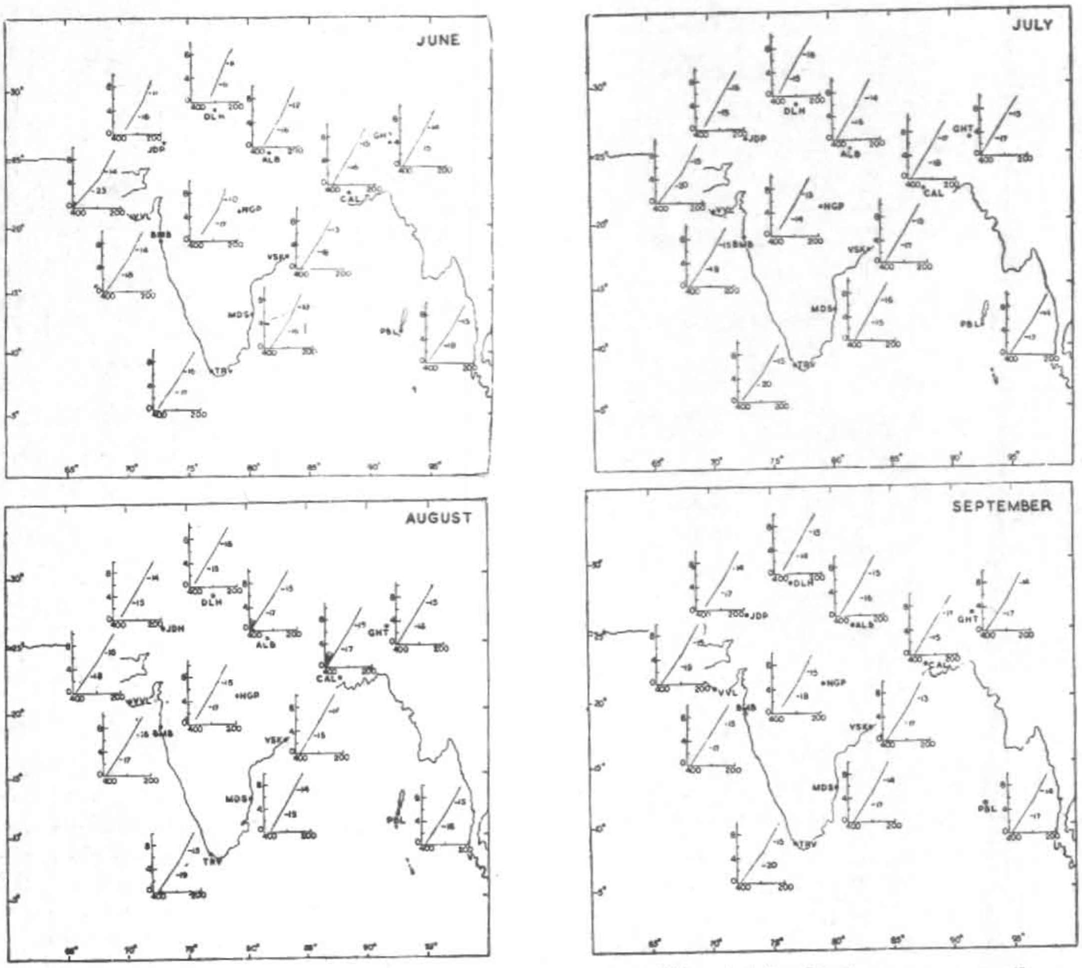

Fig. 12(a). Radio-refractivity profiles in the lower troposphere over different stations during monsoon months

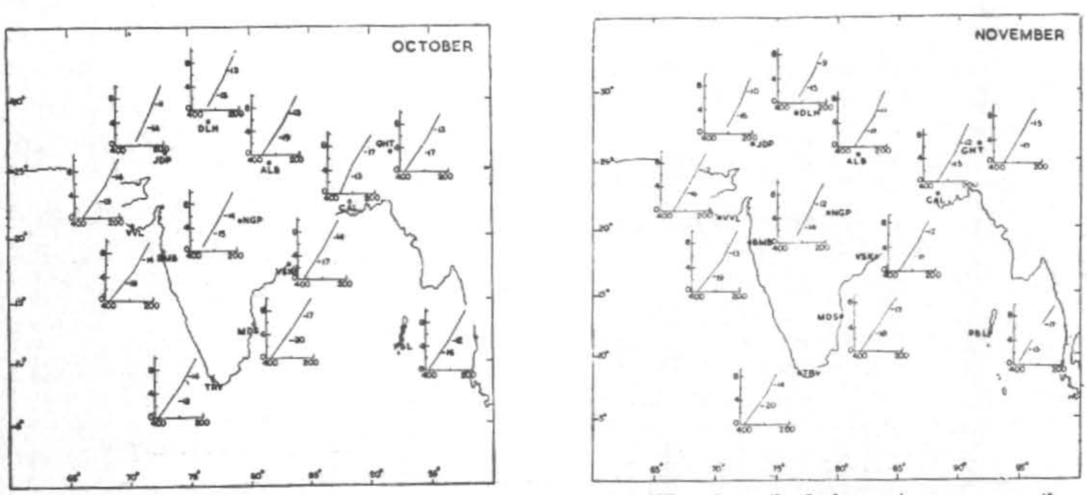

Fig. 12(b). Radio-refractivity profiles in the lower troposphere over different months during post-monsoon months

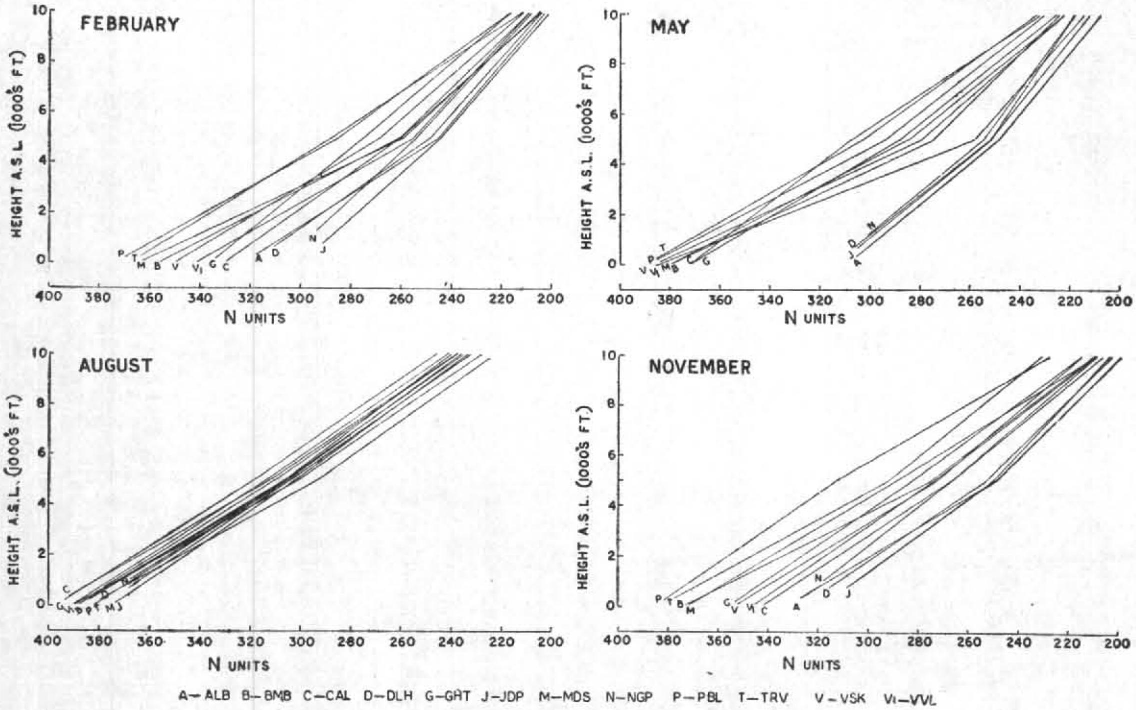

Fig. 13. Vertical profiles of radio-refractivity over India

3.10. *N-profile composites for the 12 stations during the four representative months* (Fig. 13)

3.10.1. In order to bring out the seasonal and regional variation of the N-gradient in the vertical, the N-profiles for the 12 stations have been grouped together in composite diagrams for the four representative months recommended by CCIR, *viz.*, February, May, August and November. These four composite N-profile diagrams are shown in Fig. 13 and are discussed below.

3.10.2. *February*

During this month, the N_s values vary between 292 N units at Jodhpur to 370 N units at Port Blair, that is, a variation of 78 N units at the ground surface. This range of variation decreases with the height and at 10,000 ft a.s.l., all the profiles are seen to be restricted to a narrow range of about 15 N units between 201 and 216 N units.

3.10.3. *May*

In this month, the N-profiles tend to arrange themselves in two groups. Allahabad, Jodhpur, New Delhi and Nagpur form one distinct group where the N_s variation is between 300 and 320 N units. The remaining stations (*viz.*, Calcutta, Gauhati, Bombay, Madras, Veraval, Visakhapatnam, Port Blair and Trivandrum) form the other group where N_s ranges between 370 and 390 N units. In the higher layers, the N-profiles of these two groups tend to come nearer each other and at 10,000 ft a.s.l., both the groups are confined to the range 210 to 240 N units. It may be noted that the N-profile for Veraval (which belongs to the second group of stations exhibiting higher N_s values) shows a greater decrease of N with height and meets the N-profiles of the first group at 5000 ft a.s.l. Thereafter this N-profile of Veraval also follows the trend of the N-profiles of the first group of stations which were characterised by smaller values of N_s.

3.10.4. *August*

In this month, the N-profiles for all the 12 stations are grouped together in one band and have nearly equal values of the N-gradient in the vertical. At ground surface, the N_s values range between 368 and 394 N units (a variation of 26 N units) while the range of variation of N at 10,000 ft a.s.l. is from 224 to 246 N units (a range of 22 N units).

3.10.5. *November*

In this month, while the range of N_s for the 12 stations varies between 309 and 382 N units (a range of 73 N units), the variation at 10,000 ft a.s.l. is from 204 to 231 N units (a range of 27 N units only). It is, however, interesting that the profiles have a tendency to arrange themselves in three distinct groups as follows.

Group 1 : Allahabad, New Delhi, Jodhpur

Group 2 : Calcutta, Veraval, Bombay, Gauhati, Visakhapatam, Madras

Group 3 : Port Blair, Trivandrum

This tendency for grouping is much more evident at 10,000 ft a.s.l. On comparison with the profiles in May (Section 3.10.3), it will be seen that these groups are the same as in May except that the second group of May has been further divided into two groups in November. It is also to be noted that such groups are exhibited only in May and November which may be taken to represent the pre-monsoon and the post-monsoon seasons. There is no evidence of such groupings in the winter and monsoon representative months.

3.10.6. It is also worthy of note that these groupings follow the same trend as was delineated in Sec. 3.8, the only difference being that the Group 2 of November combines the stations of Types II, III and IV mentioned in Sec. 3.8.

4. Conclusions

Radio-climatology of the vertical structure of radio-refractivity distribution over the country has been worked out. A large number of maps and diagrams showing different aspects of the vertical distribution of radio-refractivity in the lower troposphere over India have been presented.

It is earnestly hoped that this study will provide the much desired data to radio-physicists and communication-engineers and will prove a useful aid in radio/radar measurements, ground-to-air and air-to-ground communication, propagation studies, frequency planning and allied investigations.

5. Acknowledgements

The authors express their grateful thanks to Dr. L. S. Mathur, Deputy Director General of Observatories (Instruments) for providing facilities for the work and for his interest in the progress of this programme of radio-meteorological investigations which has resulted in the authors' present series of four papers on the Radio-Climatology of India.

REFERENCES

Kulshrestha, S. M. and Chatterjee, K. 1966a *Indian J. Met. Geophys.*, **17**, 3, pp. 367-384.

1966b *Ibid.*, **17**, 4, pp. 545-558.

1967 *Ibid.*, **18**, 2, pp. 185-196.