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Radio Refractive Index structure of upper troposphere over India

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ABSTRACT. The mean monthly values of radio refractive index for 12 radiosonde stations in India based on the data during the years 1956-60 have been calculated (at 300, 200, 150 and 100-mb levels) and their monthly variation is studied. The distribution of refractive index at 300, 200 and 100-mb levels has been discussed and compared with that of the lower troposphere during January and August. The variation of the annual range of the index with latitude and altitude is also described.

It is seen that there is a marked difference in the refractive index structure between the lower and upper tropospheres over India. The annual range decreases markedly in the upper troposphere as compared to that in the lower. The range of the index is maximum over the stations in north India at 300 mb and shows similarity with that in the lower troposphere in this respect.

1. Introduction

Variations of the radio refractive index in the atmosphere have a direct bearing on the accuracy of tracking satellites and other high altitude objects. With this end in view, the refractive index variations associated with the passage of tropical cyclones (Venkataraman *et al.* 1963) and monsoon depressions (Srivastava, *see* ref.) were studied earlier. Although the refractivity, N, in the lower troposphere may cause considerable bending of radio waves to the extent of 70 per cent (Bean, Horn and Riggs 1960, Bean and Dutton 1964), the refractive index structure of the upper troposphere is nevertheless important from the propagation point of view for high altitude objects. Also, the mean monthly values of N may be used to estimate the departures from normals caused by high-level subsidence inversions and troughs in westerlies and easterlies.

In the present paper the mean monthly values of radio refractive index at 300, 200, 150 and 100-mb levels have been calculated for 12 stations in India based on the radiosonde data during the years 1956 to 1960 and their monthly variation studied. The distribution of refractive index at 300, 200 and 100-mb levels has been discussed and compared with that of the lower troposphere during January and August. The variation of the annual range of the index at different levels from surface to 100 mb is also shown.

2. Method of Calculation

The modified radio refractive index N given by Smith and Weintraub (1953) is —

$$N = \frac{77{\cdot}6}{T}\left(P + \frac{4810e}{T}\right) \qquad (1)$$

where P is the total atmospheric pressure in mb, e is the water vapour pressure in mb and T is temperature in ° A. This equation is equally valid for microwaves in the upper troposphere and stratosphere upto 30 km or so.

However, the contribution of water vapour term in Eq. (1) was found to be negligible at 9 km and above by the graphical extrapolation method which was used by Ananthakrishnan *et al.* (1965) for calculating the precipitable water vapour in the atmosphere over India.

Hence Eq. (1) at 9 km and above reduced to

$$N = 77{\cdot}6\ P/T \qquad (2)$$

The mean monthly values of temperatures at 300, 200, 150 and 100-mb levels based on the afternoon data reported by radiosondes for the years 1956-1960 were used in Eq. (2) to study the monthly variation of N. Since the diurnal variation of T and hence of N is negligible in the upper troposphere, the values of N reported in the paper may be utilized for climatological purposes at any time during a month. It may also be mentioned that the values of N at 100-mb level may be utilized after extrapolation to study the refractive index structure in the stratosphere upto 30 km over India assuming it to be isothermal (Schulkin 1952).

Distribution of N over India was studied for all the twelve months at 300, 200, 150 and 100-mb levels, but only the diagrams for January and August which are of interest are reproduced in Figs. 1 and 2. These two months are typical of northeast and southwest monsoons respectively.

3. Results and Discussions

3·1. *Distribution of N at 300, 200 and 100-mb levels* — It may be seen from Fig. 1 (a) that the highest values of N at 300 mb occur over northwest India during January and the lowest values

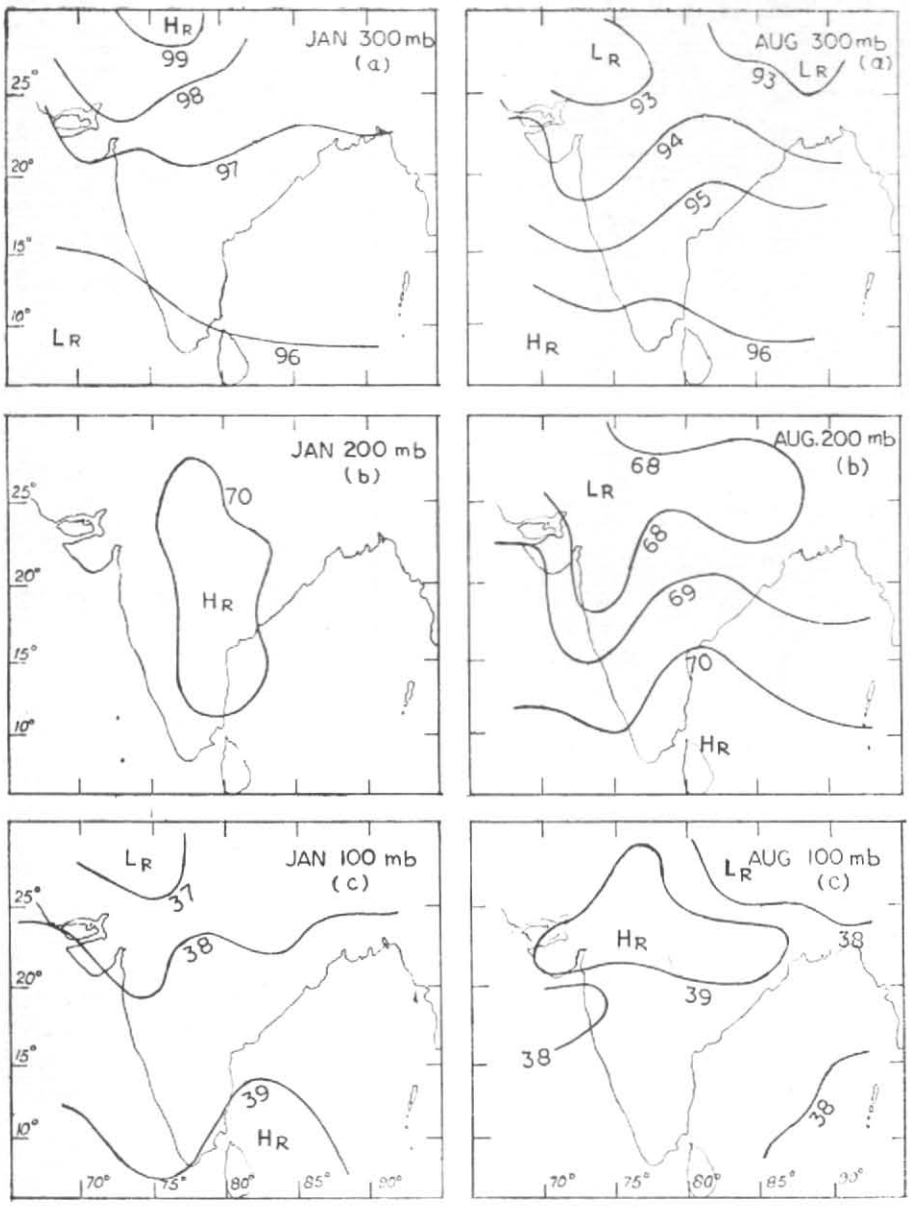

Fig. 1 Fig. 2

N structure in *N* units

TABLE 1

Annual Range of Refractivity (in N unit) over India at different levels

Station	Levels (mb)							
	Surface	850	700	500	300	200	150	100
Allahabad	91	65	43	—	5·1	3·7	1·0	1·4
Bombay	34	45	30	10	3·1	2·1	1·8	1·2
Calcutta	60	56	34	—	3·9	3·1	1·6	1·4
Gauhati	58	42	30	—	4·7	2·4	1·6	1·8
Jodhpur	72	60	40	—	5·9	2·7	1·0	1·6
Madras	15	40	30	16	1·5	0·6	0·8	0·6
Nagpur	70	43	32	—	3·1	2·3	1·3	1·0
New Delhi	82	60	40	—	5·9	2·8	1·3	2·0
Port Blair	20	23	21	18	1·9	2·3	1·8	2·4
Trivandrum	17	15	19	—	1·1	1·0	0·8	0·8
Veraval	68	37	15	—	3·5	2·0	1·6	1·0
Visakhapatnam	22	36	30	—	1·5	2·3	1·3	1·0

are found over extreme south Peninsula. With the increase in height, *i.e.*, at 200 mb, N values concentrate over the central parts of the country (Fig. 1 b). The highest values however shift further southwards over the Peninsula at 100 mb and the lowest values of N occur over northwest India (Fig. 1 c). It may be noticed that N-structure at 300 and 200-mb levels is markedly different than that in the lower levels.

During August, lowest values of N at 300-mb occur over north India and highest over extreme south Peninsula (Fig. 2 a). N structure remains practically the same till 200 mb except that the lowest values shift slightly southwards (Fig. 2 b.) At 100-mb level on the other hand, N structure changes markedly, since highest values of N occur over the central parts of the country (Fig. 2 c). However, low values of N continue to persist over northeast India.

It may, therefore, be summarised that as expected, N-structure in the lower troposphere is governed by the variations in the water vapour content of the different air masses, while N-structure in the upper troposphere over India is related to the thermal structure. For this reason, there is marked difference in N-structure between lower and upper tropospheres.

3.2. *Annual range of N over India* — The values of the annual range of radio refractive index $\triangle N$ (difference between the highest and the lowest values of N in a year) are given in Table 1 for 12 radiosonde stations in India. Data from the lower and middle tropospheres has also been included in Table 1 in order to understand the variation of the annual range with height from the surface upwards. However, some of the results at 500-mb level wave left out due to the paucity of observations and also due to unreliable values of the dew point temperatures.

3.2.1. *Latitudinal variation* — The latitudinal variation of the annual range of the index is determined by the different air masses which affect Indian region (Roy 1946). The geographical location of the stations also influences the range to a certain extent.

3.2.1.1. *300 mb* — The range of the index shows a well marked similarity with that in the lower troposphere. New Delhi, Jodhpur and Allahabad show the highest annual range of the order of 5 to 6 N-units. It decreases southwards on the west coast of Peninsula becoming lowest at Trivandrum (1 N-unit).

3.2.1.2. *200 mb* — Excluding Port Blair, there is very slight latitudinal variation of the index over the country at this level; the highest range is of the order of 3 N-units at Allahabad and Calcutta and the lowest range of 0·6 N-units at Madras.

3.2.1.3. *150 and 100 mb* — There is hardly any noticeable latitudinal variation at these levels over the country.

It may, therefore, be concluded that in general, the annual range of the index is highest and almost constant over north India at surface, 850, 700 and 300-mb levels and decreases southwards over the Peninsula.

TABLE 2

Mean monthly values of Radio Refractive Index of the upper troposphere based on the data during years 1956-1960

Level (mb)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					ALLAHABAD (Lat. 25°27′N, Long. 81°44′E, Elevation 98 m)							
300	97·7	97·0	98·2	97·0	94·6	93·9	93·1	93·5	93·9	95·4	96·5	97·8
200	69·6	69·3	69·3	69·3	68·4	68·1	67·5	67·8	68·8	68·9	69·9	70·2
150	54·1	54·4	54·1	54·4	54·1	53·9	53·9	53·9	54·4	54·6	54·9	54·9
100	37·2	37·6	37·4	38·0	38·4	38·2	38·2	38·0	38·4	38·6	38·0	37·8
					BOMBAY (Lat. 19°07′N, Long. 72°51′E, Elevation 15 m)							
300	96·2	96·2	96·2	95·8	94·3	93·1	93·5	93·1	94·3	94·6	95·4	96·2
200	69·3	69·6	69·3	68·6	68·4	67·5	67·5	67·7	68·1	68·6	69·3	69·6
150	54·6	54·6	54·4	54·1	54·1	54·1	53·1	53·6	54·9	54·6	54·6	54·6
100	38·0	38·2	38·2	37·8	38·2	38·0	37·4	37·8	38·0	38·6	38·2	38·2
					CALCUTTA (Lat. 22°39′N, Long. 88°27′E, Elevation 6 m)							
300	97·0	96·5	97·4	96·2	94·6	93·9	93·5	93·9	94·3	95·4	96·2	96·5
200	69·6	69·6	69·6	69·3	68·6	68·1	67·8	68·4	68·4	69·3	69·9	70·9
150	54·6	54·9	55·2	54·6	54·6	54·4	54·1	54·6	54·9	55·4	55·7	55·4
100	38·4	38·8	38·2	38·4	38·8	38·0	38·2	39·0	39·0	39·4	39·2	38·8
					GAUHATI (Lat. 26°05′ N, Long. 91°43′ E, Elevation 54 m)							
300	97·4	96·5	97·8	96·5	94·6	93·5	93·1	93·5	94·3	95·4	96·5	97·4
200	69·6	68·9	69·3	68·9	68·4	67·5	67·8	68·1	68·4	69·3	69·6	69·9
150	53·9	53·9	53·9	54·1	53·9	53·6	53·9	54·1	53·9	55·2	55·2	55·2
100	37·4	37·4	37·6	37·0	37·6	38·4	38·0	37·8	38·4	38·8	38·4	38·2
					JODHPUR (Lat. 26°18′N, Long. 73°01′ E, Elevation 224 m)							
300	98·4	97·8	98·6	98·2	95·8	93·9	92·7	92·7	93·9	95·4	97·4	98·2
200	69·6	69·6	69·6	70·2	68·9	68·1	67·5	67·8	68·4	69·3	70·2	70·2
150	54·1	54·4	53·9	54·6	54·6	53·9	54·5	54·1	54·6	54·9	54·6	54·4
100	37·0	37·8	37·4	37·6	38·0	38·0	37·8	38·4	38·6	38·2	37·8	37·2
					MADRAS (Lat. 13°00′N, Long. 80°11′E, Elevation 16 m)							
300	96·2	96·2	96·2	95·4	95·0	95·4	95·8	95·8	95·8	96·2	95·8	96·5
200	70·2	70·2	69·9	69·6	69·6	69·6	69·6	70·2	69·9	70·2	70·2	70·6
150	55·4	55·7	55·4	55·4	55·4	55·7	55·4	56·0	56·0	56·2	56·0	56·0
100	39·0	39·0	38·6	38·6	38·6	38·4	38·4	38·8	38·6	39·0	39·0	39·0
					NAGPUR (Lat. 21°06′N, Long. 79°03′E, Elevation 310 m)							
300	97·0	97·0	97·8	97·0	95·8	94·3	94·3	94·3	94 6	96·2	96 5	97·4
200	70·2	70·2	70·2	70·2	69·6	68·9	68·6	68·9	69·3	70·2	70·9	70·6
150	55·2	55·4	55·2	55·2	55·2	54·9	54·9	55·4	55·4	55·7	56·2	55·7
100	38·6	38·8	38·2	38·8	38·6	38·3	39·0	39·0	38·2	39·0	39·2	38·2
					NEW DELHI (Lat. 28°35′, Long. 77°12′E, Elevation 216 m)							
300	99·0	99·0	99·0	97·8	95·8	93·9	93·1	93·5	94·3	96·2	97·8	98·6
200	69·9	96·9	70·2	69·6	68·6	67·8	67·8	68·1	68·6	69·6	70·2	70·6
150	53·9	54·1	53·9	53·9	53·9	53·9	54·4	54·6	55·2	55·2	54·9	54·6
100	37·0	37·4	37·2	37·2	37·6	38·6	38·8	39·0	38·6	38·6	37·8	37·6

TABLE 2 (*contd*)

Level	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					PORT BLAIR (Lat. 11°40′N, Long. 92°43′ E, Elevation 79 m)							
300	96·2	95·8	96·2	95·4	95·0	94·6	95·4	95·4	95·4	95·8	96·2	96·5
200	69·9	69·9	70·2	69·3	69·3	68·6	69·3	69·9	69·9	70·2	70·6	70·9
150	55·4	55·4	55·7	54·9	54·4	54·9	55·4	55·4	55·7	56·2	56·2	56·2
100	38·0	39·2	38·4	37·6	38·4	38·0	38·8	37·2	38·4	39·0	40·0	39·6
					TRIVANDRUM (Lat. 08°28′N, Long. 76°57′E, Elevation 8 m)							
300	95·8	96·2	95·8	95·4	95·4	95·8	96·5	96·2	96·2	96·2	96·2	96·2
200	69·6	70·6	70·2	69·6	69·6	69·9	70·6	70·2	69·6	70·2	70·6	70·6
150	55·4	56·0	55·7	55·4	55·4	55·7	56·2	56·0	56·0	56·2	56·2	56·0
100	38·8	38·8	38·8	38·6	38·8	39·0	38·4	38·4	38·6	38·8	39·2	39·0
					VERAVAL (Lat. 20°53′N, Long. 70°22′E, Elevation 8 m)							
300	97·0	97·0	97·0	96·6	95·4	95·0	94·3	94·6	95·0	95·8	97·4	97·8
200	69·9	70·2	69·6	69·6	68·9	68·9	68·9	69·3	69·3	69·9	70·9	70·6
150	55·2	55·4	55·2	54·6	54·9	55·2	55·2	55·7	55·4	55·7	56·2	56·2
100	38·6	39·0	38·6	38·2	38·6	39·0	38·4	39·0	38·4	39·2	38·8	38·4
					VISAKHAPATNAM (Lat. 17°43′N, Long. 83°14′E, Elevation 3 m)							
300	96·2	96·5	96·2	95·8	95·0	95·4	95·4	95·0	95·4	96·2	96·5	96·5
200	69·9	70·2	69·6	69·6	68·6	68·8	69·3	69·3	69·9	70·2	70·6	70·9
150	55·4	55·7	54·9	55·2	55·4	55·4	55·7	55·2	56·0	55·7	56·2	56·2
100	38·8	39·2	38·6	38·6	39·2	39·2	38·8	38·6	38·8	39·2	39·4	39·6

3.2.2. *Variation with altitude* — The annual range of N decreases from the surface to 850 mb at Allahabad, Calcutta, Jodhpur, Nagpur, New Delhi and Veraval. The coastal stations over the Peninsula, *i.e.*, Bombay, Madras and Visakhapatnam indicate a rise in the annual range at 850-mb as compared to the surface and 700 mb. The annual range at Trivandrum and Port Blair remains constant with height upto 500 mb. Above this height the annual range of N falls markedly at all the stations since the effect of the annual variation in temperatures of the upper troposphere over N is much less than that of the moisture content in the lower troposphere.

3.3. *Monthly variation of N*—The mean monthly values of N in the upper troposphere based on the normals of the afternoon data during the year 1956-1960 are given in Table 2.

The monthly variation of N at 300, 200 and 150-mb levels is described below. The results at 100-mb level were not included as the changes in the mean monthly values were very small.

3.3.1. *Allahabad* — The lowest values of N occur in July at 300 and 200-mb levels. It is also lowest at 150 mb during June to August. The highest value of N occurs in March at 300 mb and in December at 200 mb. N is highest in November and December at 150 mb.

3.3.2. *Bombay* — The lowest values of N occurring during June and August at 300 mb become maximum during December to March. At 200 mb the lowest values occur in June and July and the highest values in December and March. The highest and the lowest values of N occur in September and July respectively.

3.3.3. *Calcutta* — July is the month of lowest N at all levels; the highest values corresponding to 300, 200 and 100-mb levels occur in March, December and November respectively.

3.3.4. *Gauhati* — The lowest value of N at 300 mb is found in July but in June it is at 200 and 150-mb levels. The maximum values occur

in March and December at 300 and 200-mb respectively. N is highest during October to December at 150 mb.

3.3.5. *Jodhpur* — N is lowest during July/August at 300 mb and only in July at 200 mb while it occurs in March and June at 150 mb. N is highest in January at 300 mb and in October at 150 mb. The values are highest at 200 mb in April, November and December.

3.3.6. *Madras* — N is lowest in May and highest in December at 300 mb. The monthly changes in N are quite small at 200 and 150 mb.

3.3.7. *Nagpur* — The lowest values of N occur during June to August at 300 mb, in July at 200 mb and in June/July at 150 mb. It is highest in March at 300 mb and in November at 200 and 150-mb levels.

3.3.8. *New Delhi* — N is lowest in July at 300 mb and it is so in June and July at 200 mb; at 150 mb the lowest values occur during March to June. The highest value of N is found during January to March at 300 mb, in December at 200 mb and in September and October at 150 mb.

3.3.9. *Port Blair* — The lowest value of N occurs in June at 300 and 200-mb levels while it is so in May at 150 mb. N is highest in December at 300 and 200 mb and during October to December at 150 mb.

3.3.10. *Trivandrum* — N is lowest in April and May and highest in July at 300 mb. The monthly variation, alike Madras, is very small at 200 and 150-mb levels.

3.3.11. *Veraval* — N is lowest in July at 300 mb, during May to July at 200 mb and in April at 150 mb. December and November are the months of highest N during the year at 300 mb and 200-mb levels respectively, whereas highest values occur in November and December at 150 mb.

3.3.12. *Visakhapatnam* — The lowest values of N at 300 mb occur during May, June and August but at 200 and 150-mb levels they occur in May and March respectively. The highest values of N are found in November, December and February at 300 mb, only in December at 200 mb and in November and December at 150 mb.

3.4. *Monthly variation of N lapse between 300 and 200 mb* — The monthly values of N lapse between 300 and 200 mb were calculated from the Table 2. It was found that the maximum lapse occurs in March-April at all the stations except Port Blair and Trivandrum. The minimum lapse generally occurs during July to September at all the stations except Madras, Port Blair and Trivandrum.

4. Conclusions

4.1. There is a well marked difference in N structures between lower and upper tropospheres over India.

4.2. The annual range of the modified radio refractive index decreases markedly in the upper troposphere as compared to that in the lower troposphere. The range of the index is maximum over the stations in north India at 300 mb and shows similarity with that in the lower troposphere.

4.3. The lapse of N is maximum in March to April and minimum in July to September at all the stations over the country except Port Blair and Trivandrum.

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