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Radio-climatology of India :

I. Radio Refractive Index near the ground surface

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ABSTRACT. Based on the 5-year averages of the values of pressure, temperature and relative humidity near the ground surface, corresponding values of radio-refractive index have been computed for 36 stations in India. These data have then been used to describe and discuss the monthly and seasonal distribution of the radio refractive index near the ground. An exhaustive set of radioclimatic charts have been prepared and the prominent features of the ground radio-refractive index climate have been discussed. An attempt has been made to delineate homoclimes of radio-climate in India.

1. Introduction

1.1. The widespread application of UHF and microwave frequencies to communication, radar and other allied problems has resulted in considerable investigation on the radio propagation in the troposphere. It is now well known that the meteorological conditions in the lower troposphere play a very important role in deciding the radio horizon, signal strength at a given point, seasonal and diurnal variations of signal strength, fading, trapping of radio waves in ducts and anomalous propagation of radar waves. The three meteorological parameters that mainly influence the propagation of UHF and microwaves in the lower troposphere are pressure, temperature and humidity. The radio refractive index of air for these frequencies is, for all practical purposes, a function of the atmospheric pressure, temperature and humidity. Thus these three meteorological parameters, influencing the radio propagation in the microwave region, can be combined into one parameter in the atmospheric radio refractive index. This greatly facilitates the further analysis and study of the effects of meteorological factors on radio wave propagation of the UHF and higher frequencies.

1.2. In this context it becomes necessary to compute the mean values of radio refractive index month by month, season by season, and to prepare all possible types of radio-climatic charts depicting the normal distribution of radio refractive index near the surface as well as for the upper air.

1.3. Though much work has been done in this direction in the United States of America and in New Zealand, no systematic study of the normal distribution of radio refractive index near the surface and in the upper air has been made in India so far. Maheshwari (1965) has done some work on the seasonal variation of the radio refractive index over India but his study is based only on one year's data and is confined only to investigations in the four representative months, *viz.*, February, May, August and November. Two case studies of the distribution of radio refractive index under certain synoptic conditions have also been made (Maheshwari 1962, Venkataraman *et al.* 1963). Such syoptic case studies of the variation of radio refractive index can be really useful only when the normal distribution of the radio refractive index of air near the surface and in the upper air is already known.

2. Projected series of Radio-climatic studies

2.1. Realising that no such data were at present available for the Indian region, the present authors have undertaken a systematic study of the normal distribution of the radio refractive index near the ground and for several isobaric levels in the upper air. They also propose to study the vertical structure of the distribution of radio refractive index over the country.

2·2. The authors intend to bring out a series of papers dealing with the above mentioned topics. The present paper is intended to be the first of the series of the papers dealing with the radio-climatology of India.

3. Radio Refractive Index

3.1. Radio waves travel through vacuum with a speed nearly equal to that of light, *i.e.*, 3×10^{10} cm per second. In any other medium, the speed of radio waves differs from that in vacuum and is equal to $3 \times 10^{10} \times n^{-1}$ cm per second, where n is the radio refractive index of the medium. The radio refractive index, n, of a medium may, therefore, be defined as the ratio of the speed of propagation of radio energy in vacuum to that in the particular medium.

3.2. The value of n for dry air is almost the same for radiowaves as for light waves. However, the n of water vapour (which is always present in some quantity in the lower troposphere) is different for light waves and radio waves. This arises from the fact that water-vapour molecule has a permanent dipole moment which has different responses to the electric forces of different frequencies and at UHF and microwave frequencies water vapour molecules are subjected to electronic polarization. The result is that for these frequencies the dielectric constant, and thus the refractive index, of water vapour is greater than that of dry air.

3.3. In the region of these frequencies, the radio refractive index n for moist air near the surface of the earth has a value of the order of 1·0003. It has also been found that the variation in n is only of the order of a few parts in 10^4. Therefore it has been customary to define a *modified* radio-refractive index, N (also termed as radio-refractivity) as follows —

$$N = (n - 1) \times 10^6$$

Such a modification enables the easy manipulation of N which is of the order of 300 rather than n which is an inconvenient number.

3.4. N is expressed by the well known relation—

$$N = \frac{77.6}{T}\left(P + \frac{4810\ e}{T}\right) = \frac{77.6}{T}\left(P + \frac{4810\ e_s\ RH}{T}\right) \qquad (1)$$

where, N is the modified radio refractive index (or radio refractivity), T is the temperature in degrees Kelvin, e is the partial vapour pressure in mb of the water vapour present in the air, e_s is the saturation vapour pressure in mb, P is the total atmospheric pressure in mb and RH is the relative humidity in per cent.

A detailed treatment of this equation and of the constants appearing therein has been given by Bean (1962).

3.5. For sake of brevity, we have henceforth used for N the expression "radio refractive index" instead of "modified radio refractive index". Also because we are, in the present study, concerned with the distribution of N near the surface of the earth, we have used the expression N_s which denotes the value of the modified radio-refractive index (or radio refractivity) near the surface of the earth.

4. Methods of determination of Radio Refractive Index

4.1. *Direct Method* — In the direct measurement of n for microwave frequencies, resonance of tuned circuits has been made use of. The resonant frequency of a microwave cavity is a function of its dimensions and the index of refraction of its contents. Hence if a cavity is open to the atmosphere, the resonant frequency changes with the n of the air inside the cavity in accordance with the relation —

$$\triangle f / f = -\triangle n / n$$

where f is the resonant frequency of the cavity when filled with air of radio refractive index n. $\triangle f$ is the consequent change in f as a result of the change of n by $\triangle n$. Since n for air is of the order of unity,

$$\triangle f / f = -\triangle n$$

This method of measurement was used in the instruments known as refractometers. Two types of refractometers are available, *viz.*, the Crain type and the Birnbaum type. These have been described by McGavin (1962). The cavities with a critical temperature coefficient are the major components in any of these instuments. Most cavities today are made of invar having a temperature coefficient of approximately one part per million per degree centigrade corresponding to 1 N unit/°C. Such refractometers have been used to measure both the surface and upper air values of n. The refractometers mentioned above were originally designed as ground based equipment but modifications have been made to convert them for airborne use.

4.2. *Indirect Method*—The value of n is measured indirectly by measuring temperature, pressure, and humidity with consequent computation of n and N values. Surface or near the surface measurement of n is done from the surface observations of temperature, pressure and humidity which are standard observations recorded by the meteorological services all over the world. Methods of measuring these parameters are somewhat standard with all the meteorological services.

Usually the temperature is read from mercury or alcohol thermometers, the pressure from mercury barometers, and the humidity is calculated from the observed readings of wet and dry bulb thermometers. Automatic recording instruments like thermographs, microbarograph and hygrograph may also be used. All these instruments are generally located in a special ventilating screen about four feet above ground. That is why, the observed values commonly known as surface observations actually pertain to the values near the earth's surface about four feet above ground.

4.3. *Relative Merits* — Although refractometers may be capable of superior accuracy but the high cost and requirements of competent personnel for running a network of such observing stations seem to outweigh this advantage. In fact, in many cases where long term statistics are required the use of refractometers may not be essential. The data on radio refractive index computed from meteorological parameters has been used most successfully for the determination of average conditions.

4.4. An excellent description of the various techniques for measuring the radio refractive index has been given by McGavin (1962).

5. Brief outline of the Climatology of India

As the climatic variation in different months and seasons results in a corresponding variation in the distribution of radio refractive index, it may be desirable to have an idea of the climatic conditions in India in the different seasons. A brief description of the climatology of the country is available in *Meteorology for Airmen*, Part I (India met. Dep. 1949) and Gazetteer of India (Basu 1965).

6. Scope of the present study

6.1. As mentioned earlier, the present study is the first in a projected series on the radio-climatology of India and deals with the various aspects of the surface distribution of the modified radio refractive index over India. Attempt has been made not only to evaluate the normal monthly values of N_s but also to prepare radio-climatic charts for monthly, seasonal, annual maximum, annual minimum, and annual ranges of N_s .

6.2. Studies have also been made of the east-west and north-south cross-sectional distribution of radio refractive index for four representative months and the monthly maximum and minimum values of N_s over India.

6.3. The monthly variations of N_s at some selected stations have been examined and the Indian radio-climate has been divided into different types of homoclimes of radio refractive index variation.

7. Data

7.1. The present analysis is based on the surface data of the 36 Indian stations as shown in the station locator map (Fig. 1). Mean monthly values of the surface data of pressure P, temperature t (°C) and percentage relative humidity RH for these stations for the 5-year period, 1959–1963, were picked up from the *Climatic Data for the World* and mean values of each of the variables in the equation (1) were computed in the first instance. This was the basic data from which the computations of N_s were made in accordance with the expression in equation (1).

7.2. The choice of the stations was rather arbitrary. The present study was in fact initiated when one of the authors (S.M.K.) was associated with the Radio-meteorology Section of the Central Radio Propagation Laboratory, Boulder, Colorado, U.S.A. The only readily available source of data being the joint W.M.O.—U.S. Weather Bureau publication *Climatic Data for the World*, the choice of the stations was of necessity limited to those listed in this international compilation of climatic data. Nevertheless, the 36 stations are well distributed over the country.

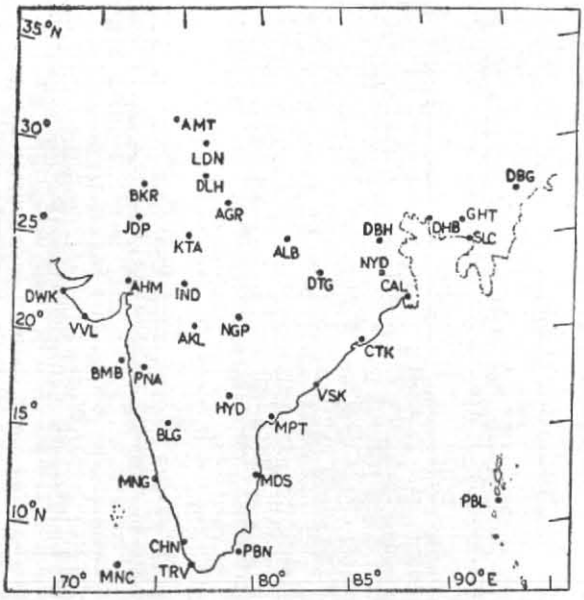

Fig. 1. Station locator map

8. Analysis of the data

8.1. The computed monthly mean values of N_s for all the 36 stations are given in Table 1.

8.2. Seasonal mean values of N_s have been worked out by averaging the values of N_s for the months representing each of the four seasons. These seasonal means of N_s are given in Table 2. Maximum and minimum values, annual range and annual mean values of N_s for each of the 36 stations have also been worked out and are given in Table 2.

8.3. The values of N_s in N units for each of the 36 stations have been plotted on maps for each month and isopleths have been drawn at intervals of 10 N units which may be seen in Figs. 2(a) and 2(b). These charts depict the monthly surface distribution of N_s .

8.4. The seasonal means of N_s for all the 36 stations, computed in the manner described in Section 8·2 above, are given in Table 2. Corresponding maps have also been drawn and these show the seasonal distribution of N_s over India (Fig. 3).

8.5. For each of the 36 stations, the annual maximum and annual minimum values of N_s as well as the values of the annual range of variation of N_s in N units are given in Table 2. These have also been plotted on maps in the Figs. 4 to 6 which show the distribution of annual maximum, minimum and annual range of variation of N_s over India.

8.6. The seasonal variation of N_s at the various stations is graphically shown in Fig. 7 (a).

TABLE 1

Mean monthly N_s at various stations

Station	Lat. (N) °	′	Long. (E) °	′	Mean N_s (N units) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Agra (AGR)	27	10	78	02	313	310	310	305	321	344	376	384	372	340	320	314
Ahmedabad (AHM)	23	02	72	35	305	302	303	314	332	366	380	382	374	336	317	312
Akola (AKL)	20	42	77	02	306	293	294	294	312	344	369	380	362	336	317	313
Allahabad (ALB)	25	27	81	44	320	318	302	295	306	350	384	392	380	352	328	320
Amritsar (AMT)	31	35	74	57	314	316	301	308	302	325	370	377	368	336	326	315
Belgaum (BLG)	15	51	74	31	323	312	326	342	364	367	367	367	370	354	338	325
Bikaner (BKR)	28	00	73	18	304	303	294	288	284	330	360	364	350	306	297	301
Bombay (BMB)	19	04	72	06	352	356	364	370	380	388	389	388	386	382	373	366
Calcutta (CAL)	22	39	88	27	327	330	344	348	372	380	388	390	384	372	342	331
Cochin (CHN)	09	58	76	14	364	373	386	384	386	386	384	384	382	380	376	367
Cuttack (CTK)	20	29	85	52	336	343	360	370	376	380	390	388	390	376	350	340
Daltonganj (DTG)	24	03	84	04	316	312	314	304	308	360	378	380	378	346	313	318
Darbhanga (DBH)	26	10	85	54	326	326	324	332	357	378	384	388	382	366	340	340
Dhubri (DHB)	26	01	89	59	334	334	337	357	376	388	402	396	394	377	355	342
Dibrugarh (DBG)	27	28	94	55	333	334	332	350	364	385	384	386	384	366	344	340
Dwarka (DWK)	22	22	69	05	331	348	370	383	394	400	390	390	390	380	348	335
Gauhati (GHT)	26	05	91	43	336	334	334	348	370	385	395	394	388	376	354	344
Hyderabad (HYD)	17	26	78	27	312	300	302	308	314	342	350	350	350	336	319	319
Indore (IND)	22	43	75	54	294	282	277	276	292	340	372	360	350	316	301	297
Jodhpur (JDP)	26	16	73	03	295	292	298	291	305	350	366	368	362	312	309	300
Kota (KTA)	25	11	75	51	306	301	289	—	294	334	364	374	356	340	324	310
Ludhiana (LDN)	30	56	75	52	316	318	316	310	306	334	370	379	369	334	325	318
Madras (MDS)	13	00	80	11	362	364	366	380	379	370	372	374	380	382	372	360
Mangalore (MNG)	15	22	74	51	354	359	370	376	380	388	388	384	382	382	370	358
Masulipatnam (MPT)	16	11	81	08	358	364	372	384	380	376	376	380	384	369	368	360
Minicoy (MNC)	08	18	73	00	372	374	374	380	386	382	380	380	378	380	379	376
Nagpur (NGP)	21	09	79	07	306	298	294	307	301	350	366	368	364	340	318	315
Naya Dumka (NYD)	24	16	87	15	320	317	322	330	358	384	386	390	384	366	337	325
New Delhi (DLH)	28	35	77	12	314	311	298	300	306	322	370	378	363	332	316	313
Pamban (PBN)	09	16	79	18	376	378	377	390	391	392	392	392	391	390	383	380
Port Blair (PBL)	11	40	92	43	370	370	363	377	386	386	384	384	386	384	382	372
Poona (PNA)	18	32	73	51	307	293	298	306	330	344	352	350	352	332	318	321
Silchar (SLC)	24	49	92	48	330	331	334	353	370	384	384	394	384	374	351	347
Trivandrum (TRV)	08	30	76	59	362	364	370	380	385	380	380	380	381	380	378	369
Veraval (VVL)	22	55	70	22	322	342	358	370	386	398	392	390	386	369	346	330
Visakhapatnam (VSK)	17	42	83	18	344	350	364	380	386	380	382	382	386	377	353	343

— Data not available

TABLE 2

Seasonal mean, Annual maximum, Annual minimum, Annual range and Annual mean values of N_s for the various stations

Station	Mean N_S (N units)							
	Winter (Dec-Feb)	Summer (Mar-May)	Monsoon (Jun-Sep)	Post-monsoon (Oct-Nov)	Annual			
					Max.	Min.	Range	Mean
Agra (AGR)	302	312	369	330	384	305	79	328
Ahmedabad (AHM)	306	316	375	327	382	302	80	335
Akola (AKL)	309	300	385	327	380	293	87	328
Allahabad (ALB)	319	301	377	340	392	295	97	334
Amritsar (AMT)	315	304	360	331	377	301	76	324
Belgaum (BLG)	320	344	368	346	370	312	58	345
Bikaner (BKR)	303	289	351	301	364	284	82	336
Bombay (BMB)	358	371	387	377	389	352	37	373
Calcutta (CAL)	332	355	385	357	390	327	63	357
Cochin (CHN)	368	385	384	378	386	364	22	380
Cuttack (CTK)	341	369	387	363	390	336	54	365
Daltonganj (DTG)	315	309	374	329	380	304	76	332
Darbhanga (DBH)	333	338	383	353	388	324	64	352
Dhubri (DHB)	337	353	395	366	402	334	68	363
Dibrugarh (DBG)	336	349	385	355	386	332	54	356
Dwarka (DWK)	338	382	393	364	400	331	69	369
Gauhati (GHT)	338	351	391	365	395	334	61	361
Hyderabad (HYD)	312	308	348	327	350	300	50	326
Indore (IND)	291	282	355	309	372	276	96	309
Jodhpur (JDP)	296	298	361	311	368	291	77	317
Kota (KTA)	306	—	357	332	374	289	85	—
Ludhiana (LDN)	317	311	360	331	379	306	73	324
Madras (MDS)	362	375	374	377	382	360	22	372
Mangalore (MNG)	357	375	387	376	388	354	34	374
Masulipatnam (MPT)	361	379	379	369	384	358	26	372
Minicoy (MNC)	374	380	380	379	386	372	14	378
Nagpur (NGP)	306	301	362	329	368	294	74	325
Naya Dumka (NYD)	321	337	380	351	390	317	73	347
New Delhi (DLH)	313	301	358	324	378	298	80	324
Pamban (PBN)	378	386	392	387	392	376	16	386
Port Blair (PBL)	371	375	385	383	386	363	23	379
Poona (PNA)	307	311	349	325	352	293	59	323
Silchar (SLC)	336	352	387	363	394	330	64	359
Trivandrum (TRV)	365	378	380	379	385	362	23	372
Veraval (VVL)	331	371	391	357	398	322	76	363
Visakhapatnam (VSK)	346	377	383	365	386	343	43	368

—Data not available

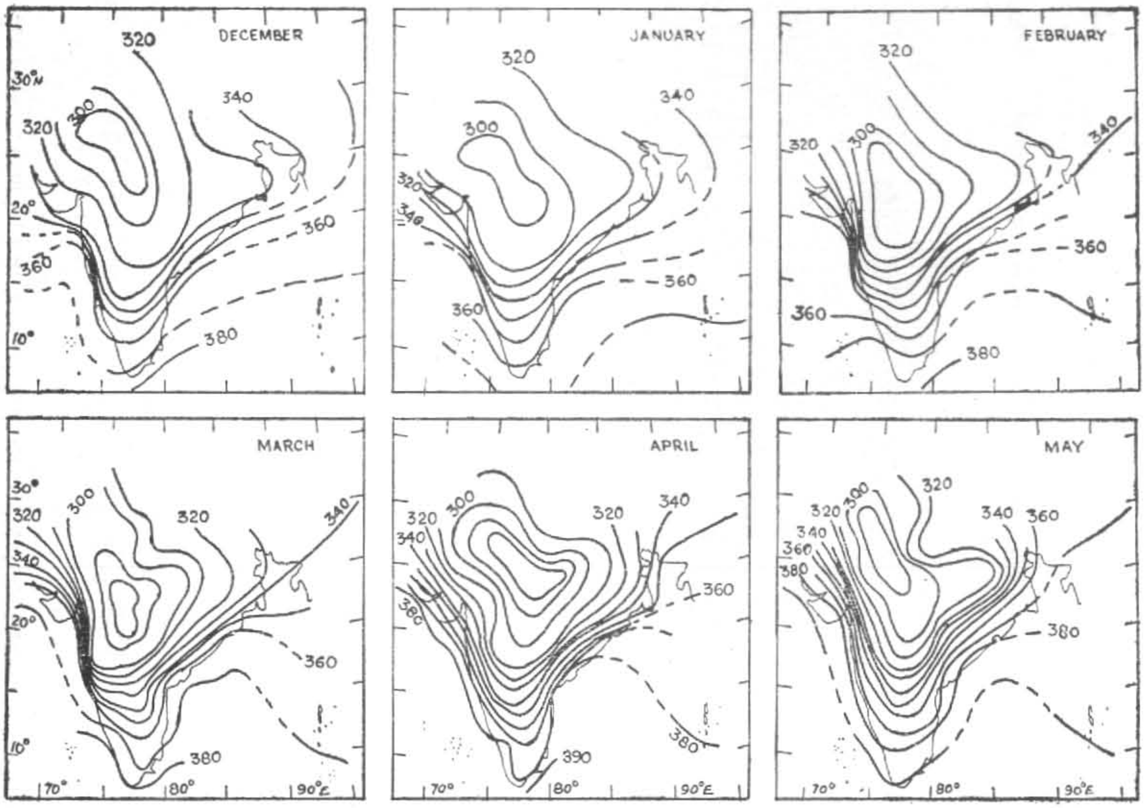

Fig. 2 (a). Surface distribution of radio refractive index (N_s) over India during the different months

TABLE 3

Overall monthly maximum and minimum values of N_s over India

Month	Annual Max. N_s in N units	Station	Annual Min. N_s in N units	Station
January	376	Pamban	294	Indore
February	378	Pamban	282	Indore
March	386	Cochin	277	Indore
April	390	Pamban	276	Indore
May	394	Dwarka	284	Bikaner
June	400	Dwarka	322	New Delhi
July	402	Dhubri	350	Hyderabad
August	396	Dhubri	350	Hyderabad, Poona
September	394	Dhubri	350	HYD, IND, BKR
October	390	Pamban	306	Bikaner
November	383	Pamban	297	Bikaner
December	380	Pamban	297	Indore

8.7. An assessment of climatic variation can be made by plotting the annual mean value of N_s against the annual range at each station. This has been done in Fig. 7 (b).

8.8. For each month, the values of overall maximum and minimum N_s have been picked up from Table 1 and are given in Table 3. These are also graphically presented in Fig. 8.

8.9. The variation of mean monthly N_s for the nine selected stations along an east-west cross-section in the latitudinal belt of 20 to 25°N has been shown in Fig. 9. Similarly, the variation of

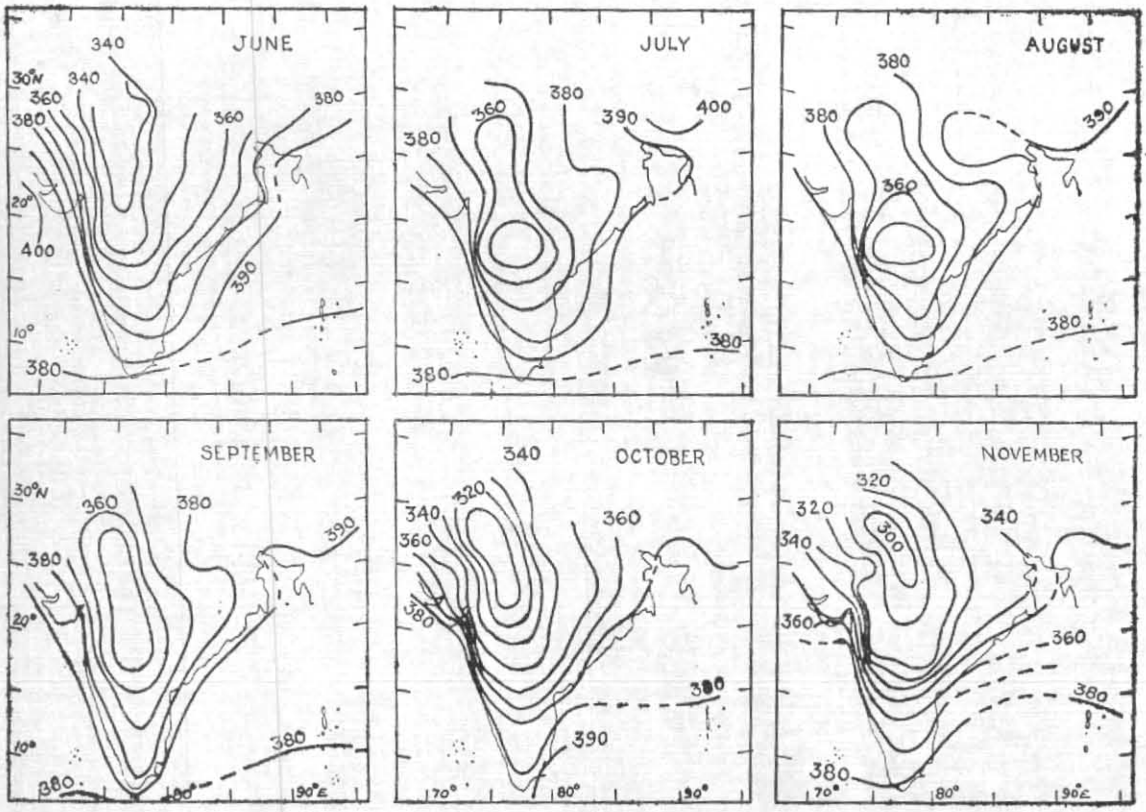

Fig. 2(b). Surface distribution of radio refractive index (N_s) over India during the different months

mean monthly N_s for another 8 selected stations along a north-south cross-section in the longitudinal belt 75 to 80°E is shown in Fig. 10. These cross-sectional variations have been studied for the four representative months in accordance with the recommendations of the CCIR, *viz.*, February, May, August and November.

8.10. Similarly cross-sectional variation of annual range of N_s at each of these stations is shown in Figs. 11 and 12 for the east-west and the north-south cross-sections respectively.

8.11. The monthly variations of mean N_s at sixteen selected stations are graphically presented in Figs. 13 to 16. These sixteen stations have been specially grouped in these diagrams with a view to study the similarities cf the monthly variations of N_s.

9. Discussion

9.1. *Monthly distribution of* N_s

9.1.1. *General Features* — A careful study of the monthly distribution patterns of N_s over India (Figs. 2a and 2b) reveal the following features —

9.1.1.1. The N_s gradient over the coastal areas is steeper than that over the rest of the country. The highest density of isopleths occur along the western coast. This is the pattern during the most of the months.

9.1.1.2. The location as well as the extent of the closed contour of the lowest N_s value during each month shows a tendency to oscillate within the latitudes 18° and 28°N and lie mostly over the arid and semi-arid zones of Rajasthan. The highest values of N_s contours are found to occur along the coasts, extreme south peninsula and over Assam. The highest and lowest values of N_s over the country are of the order of 400 and 280 N units respectively.

9.1.2. *Month by month pattern* (Figs. 2a and 2b) — When the monthly distribution patterns are examined, the following additional facts are revealed—

9.1.2.1. *December* — The area of the lowest values of N_s extends from Bikaner to Indore. The maximum value of N_s over the country in this month is found to be 380 N units and occurs at Pamban. The minimum value of N_s during the month is found to occur at Indore and has a value of 297. The gradient increases from north to south and from east to west. The highest gradient occurs along the west coast. The distribution of N_s is flat over the central, eastern and northeastern parts of the country.

9.1.2.2. *January* — The region of the lowest values of N_s extends from Bikaner to Nagpur. The N_s -gradient is steep in the coastal areas and flat in the entire country outside the peninsula. The maximum value of N_s during the month is 376 N units at Pamban while the minimum value is 294 and occurs at Indore.

9.1.2.3. *February* — The region of the lowest N_s extends further south. The gradient along the west coast near Bombay gets steeper. Gradients outside the peninsula continue to be flat. The maximum value of N_s during the month is 378 at Pamban and the minimum value is 282 at Indore.

9.1.2.4. *March* — The area enclosed by the lowest N_s contour has diminished but its location has not moved further south. The gradients along the east and west coasts are high in comparison to the gradients over the rest of the country and also as compared to the previous months. The gradient continues to be flat outside the peninsula. The maximum value of N_s is 386 N units at Cochin and the minimum value is 277 N units at Indore.

9.1.2.5. *April* — The location of the lowest N_s contour has shifted towards northeast and lies over the central parts of the country. The maximum value of N_s is 390 at Pamban and the minimum value is 276 at Indore. It will be seen that this value of 276 N units is the smallest for the whole year. The characteristic steep gradients on the east and west coasts persist. The N_s gradient outside the peninsula has become steeper as compared to the previous months.

9.1.2.6. *May* — The location of the lowest N_s contour has stretched from the northwest Rajasthan to south Madhya Pradesh. The maximum value of N_s during the month occurs at Dwarka and has a value of 394 while the minimum value is 284 at Bikaner. The N_s gradients are steep not only along the coasts but also over Bengal and Bihar. The gradients are relatively flat over central and northwest India and is in fact less steep than that in April.

9.1.2.7. *June* — It is interesting to note that the contour of the lowest N_s value penetrates further south and the axes of all the contours are north-south oriented. The characteristic gradient along the coasts is less prominent. In fact, the gradient over the entire country (with the exception of the Bombay coast) is almost uniform. The lower values of N_s occur over Rajasthan and central India and the higher values are over the seas, coasts, and the extreme south peninsula; the highest values occurring on the west coast off Dwarka. The maximum value of N_s during the month is 400 and occurs at Dwarka while the minimum value of 322 occurs at New Delhi.

9.1.2.8. *July* — The location of the lowest N_s contour has pushed further south and the closed contour of 350 lies between Poona and Hyderabad. The N_s-gradient is steep on the west coast but flat over the rest of the country. In fact the gradient over the entire country in this month is the least steep of all the months and exhibits a diffuse pattern. While this overall pattern gets more diffuse, the central closed "low" gets "deepened" and is confined to a smaller area. The highest values of N_s occur in the vicinity of the foothills of Assam. The maximum value of N_s during this month is 402 and is observed at Dhubri while the minimum value is 350 occurring over Hyderabad. It may be mentioned that the maximum value of 402 N units is the highest value for any station in India during the entire year.

9.1.2.9. *August* — The location of the lowest N_s contour of 350 has remained practically the same in July. The N_s gradient over the entire country starts getting steeper although it is still considerably diffuse. The central "low" starts expanding in area and thereby getting diffuse. The highest values of N_s occur over the coasts, extreme south peninsula and the Himalayan foothills. The maximum value of N_s during the month is 396 at Dhubri while the minimum value is 350 at Hyderabad and Poona.

9.1.2.10. *September* — The southern limit of the location of the lowest N_s contour of 350 has not moved further south but the entire area enclosed by this contour has extended towards north right upto Bikaner. The N_s gradient is getting steeper over the coasts and the northwest India, while the central low is further expanding in area and thereby getting less steep. The highest values of N_s occur over the coasts, the extreme south peninsula and Assam. The maximum N_s value during the month is 394 at Dhubri while the minimum value of 350 occurs at Hyderabad, Indore and Bikaner.

9.1.2.11. *October* — The southern limit of the lowest N_s contour has moved further north and started deepening again. In this month, the lowest N_s contour covers a smaller area as compared to that covered by the lowest closed contour in September. The N_s gradient over the entire country gets steeper. The highest gradient occurs over the northern parts of the west coast in the vicinity of Bombay while the highest value of N_s occurs over the extreme south portion of the east coast. This is the month when the characteristic steep gradient along the west coast starts

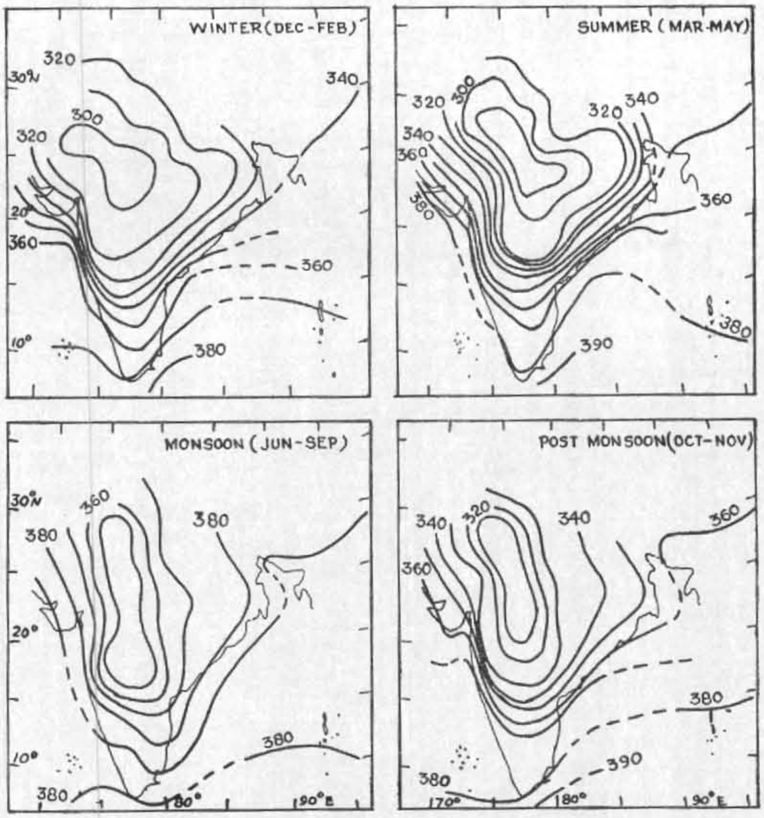

Fig. 3. Seasonal distribution of N_s over India

building up. The maximum value of N_s during the month is 390 occurring at Pamban while the minimum value of 306 occurs at Bikaner.

9.1.2.12. *November* — The area enclosed by the lowest N_s contour has become very small, the value of this closed contour being 300. The N_s gradient over the coasts and the peninsula is steeper than that in October while it starts getting diffuse over the rest of the country. The maximum value of N_s during the month is 383 at Pamban while the minimum value of 297 occurs at Indore.

9.2. *Seasonal distribution of N_s over India*

9.2.1. *General features*

9.2.1.1. It will be seen from Fig. 3 that the seasonal distribution patterns of N_s for the seasons, Winter (December to February) and Summer (March to May) are in many respects similar. Again, the distribution patterns for the seasons, Monsoon (June to September) and Post-monsoon (October and November) are also to some extent similar. The lowest seasonal N_s values occur over the arid and semi-arid zones of Rajasthan and the adjoining parts of the country, while the highest values occur over the extreme south peninsula followed closely by the coastal areas, ocean islands and Assam in that order.

9.2.1.2. The N_s gradients are the highest along the west coast followed by the east coast (Circars coast) and the central parts of the peninsula in that order. The characteristic steep gradient exists between Bombay and Poona. The N_s gradients over the remaining parts of the country (and specially over eastern and northeastern India) are relatively flat.

9.2.2. *Season by Season pattern*

9.2.2.1. *Winter (December to February)* — The study of the seasonal N_s pattern for winter reveals that the lowest values of N_s are over Rajasthan and the central parts of the country extending almost from Bikaner to Indore, the value of the lowest closed contour being 300 N units. There is a steep N_s gradient between Bombay and Poona, the difference of N_s values at Bombay and Poona being 51 N units. Another steep gradient exists in the vicinity of Masulipatnam on the east coast where the difference in the N_s values at Masulipatnam and Hyderabad is 49 N units. The N_s gradient over the rest of the country, except the central and south peninsula, is diffuse. The highest values of N_s during this season are of the order of 380 and occur in the extreme south portion of the east coast.

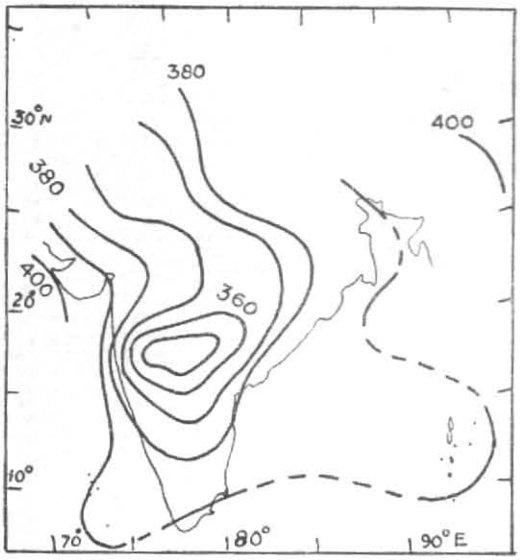

Fig. 4. Annual maximum N_s

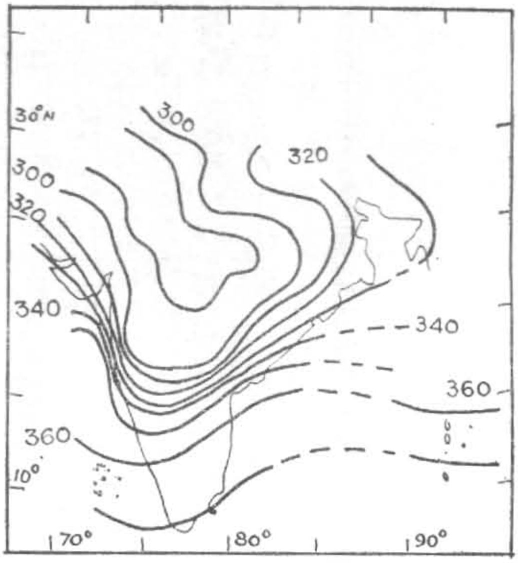

Fig. 5. Annual minimum N_s

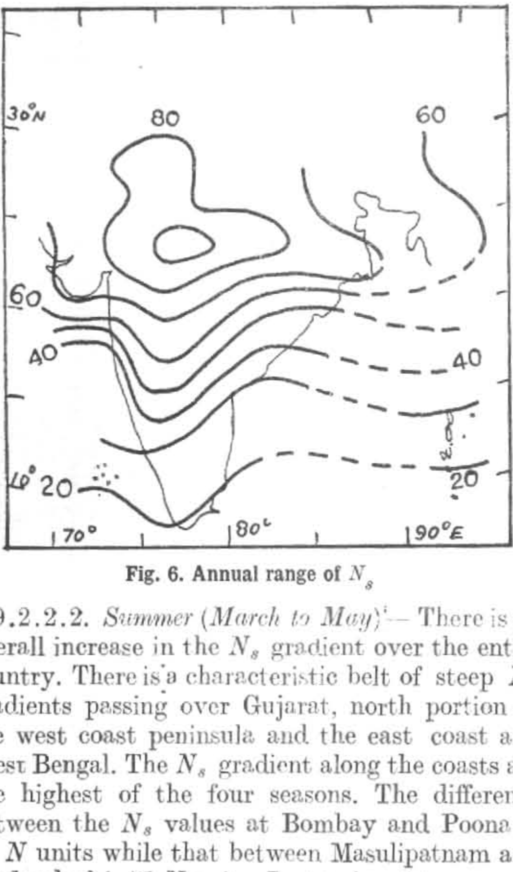

Fig. 6. Annual range of N_s

9.2.2.2. *Summer (March to May)*— There is an overall increase in the N_s gradient over the entire country. There is a characteristic belt of steep N_s gradients passing over Gujarat, north portion of the west coast peninsula and the east coast and West Bengal. The N_s gradient along the coasts are the highest of the four seasons. The difference between the N_s values at Bombay and Poona is 60 N units while that between Masulipatnam and Hyderabad is 71 N units. Just as in winter season, the lowest values of N_s in summer occur over Rajasthan and the central parts of the country, the value of the closed contour being 300 N units. The highest values of N_s are of the order of 390 and occur at Pamban in the extreme south portion of the east coast.

9.2.2.3. *Monsoon (June to September)*— The seasonal pattern of N_s contours changes considerably. N_s values throughout the country are comparatively higher in this season. The region of the lowest N_s contour (350 N units) gets elongated and extends from Bikaner to Hyderabad. The highest values of N_s during this season occur along the coasts, south peninsula and Assam. The N_s gradients over Bihar, West Bengal and Assam are remarkably flat. The strong and characteristic steep gradient along the coasts is very much diffuse. The difference of N_s values between Bombay and Poona is 38 N units during this season while that between Masulipatnam and Hyderabad is only 31 N units.

9.2.2.4. *Post-monsoon (October and November)*— The pattern of N_s distribution during this season is similar to the monsoon pattern. But the gradient along the coasts and over the peninsula starts getting steep. The lowest value of N_s contour is 320 N units and lies between Bikaner and Akola. The highest value of N_s during the season is of the order of 390 and occurs over the extreme south portion of the east coast. The difference between the N_s values at Bombay and Poona in this season is 52 N units while that between Masulipatnam and Hyderabad is 42 N units.

9.3. *Distribution of Annual maximum N_s values*

The contours of the annual maximum N_s for each station are shown in Fig. 4. The highest and the lowest contours are 400 and 350 N units respectively. While the lowest values of annual maximum N_s occur over north peninsula between Poona and Hyderabad, the highest values of annual

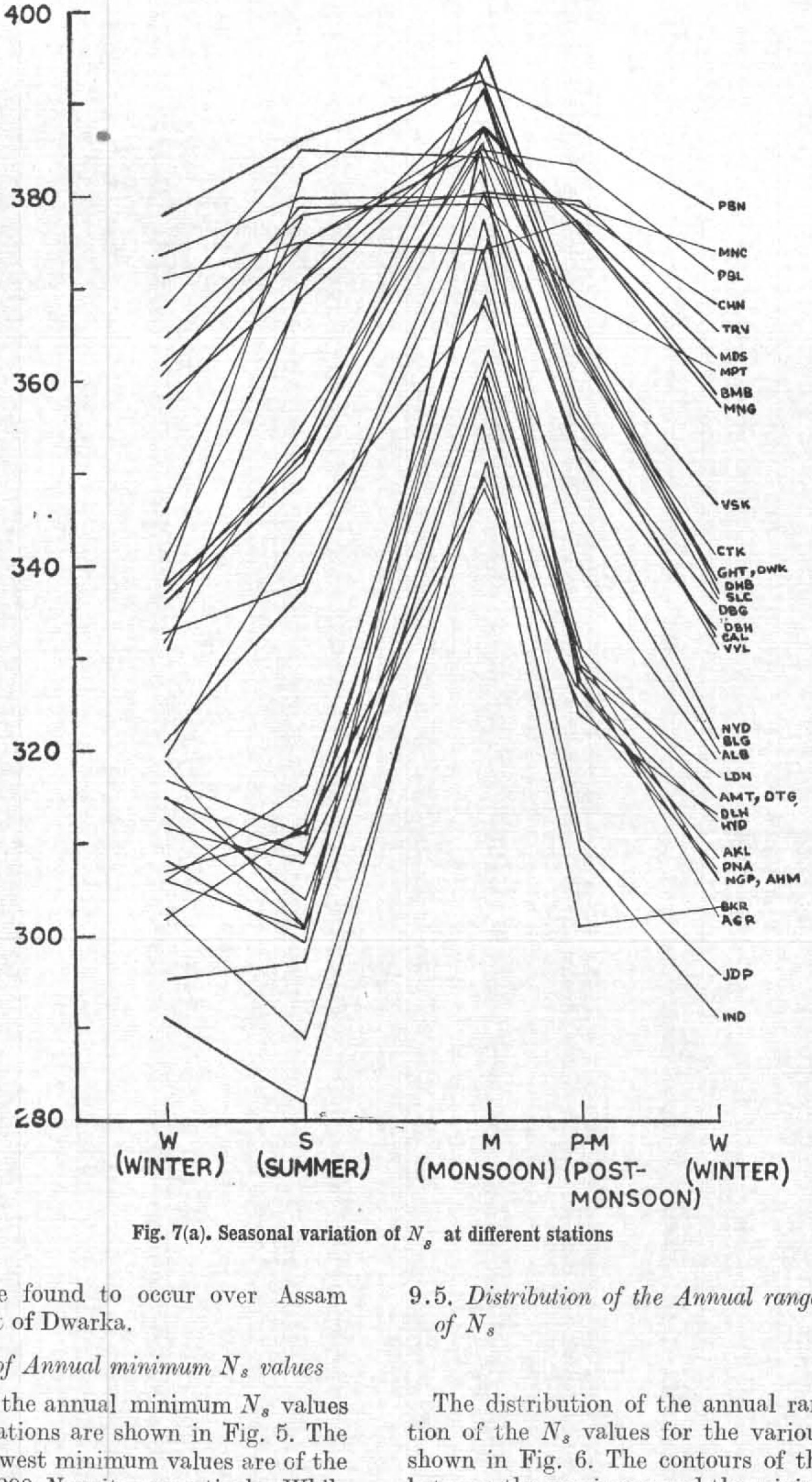

Fig. 7(a). Seasonal variation of N_s at different stations

maximum N_s are found to occur over Assam and the west coast of Dwarka.

9.4. *Distribution of Annual minimum N_s values*

The contours of the annual minimum N_s values for the various stations are shown in Fig. 5. The highest and the lowest minimum values are of the order of 370 and 290 N units respectively. While the lowest values of the annual minimum N_s occur over Rajasthan and the central parts of the country, the highest values of the annual minimum N_s are found to occur over the extreme south peninsula and the ocean islands.

9.5. *Distribution of the Annual range of variation of N_s*

The distribution of the annual range of variation of the N_s values for the various stations is shown in Fig. 6. The contours of the differences between the maximum and the minimum monthly means for each station for the entire year have been drawn in this map. The smallest annual range of N_s variation is of the order of 20 N units and occurs at the extreme south peninsula and the ocean islands. The largest annual ranges of N_s

TABLE 4

Groups of distinct radio-climatic regimes in India

Group	Station	Location	Climatic characteristics	Radioclimatic characteristics	
				Annual mean N_s	Annual range of N_s
I	Pamban Minicoy Port Blair Cochin Trivandrum Madras Masulipatnam Bombay Mangalore Visakhapatnam	Stations below 20°N latitude on coastal areas and ocean islands	Maritime climate, hot and humid	360—390	10—50
II	Cuttack Gauhati Dwarka Dhubri Silchar Dibrugarh Darbhanga Calcutta Veraval Naya Dumka Belgaum	Stations between 15° and 28°N latitude (mainly inland stations) in the southwest monsoon regime	Monsoon climate, humid with large annual rainfall	340—370	50—80
III	Allahabad Ludhiana Amritsar Daltonganj New Delhi Hyderabad Akola Poona Nagpur Ahmedabad Bikaner Agra	Land locked stations in the north and central parts of the country	Distinct rainy and dry seasons with extreme winter and summer at most of the stations	320—340	50—90
IV	Jodhpur Indore	Rajasthan and west Madhya Pradesh	Arid and semi-arid	300—320	70—90

variation are of the order of 90 to 100 N units and occur over a small region around Indore.

9.6. *Seasonal variation of N_s over various stations in India*

Fig. 7 (a) shows the seasonal variation of N_s at the various stations. It is noticed that there is a tendency for many stations to group together and follow similar patterns of N_s variation. Four such groups are easily discernible in Fig. 7(a). These are discussed in the following paragraphs —

9.6.1. *Group I* : (Pamban, Minicoy, Port Blair, Cochin, Trivandrum, Madras, Masulipatnam, Bombay, Mangalore and Visakhapatnam)

In this group of 10 stations, the seasonal mean N_s increases from winter to summer and then to monsoon when it reaches a peak except in case of Cochin, Madras, Masulipatnam and Minicoy when the seasonal mean N_s remains almost the same in monsoon as in summer. After the monsoon season, there is a decline in the seasonal mean N_s which reaches a minimum in the winter season.

9.6.2. *Group II*: (Cuttack, Gauhati, Dwarka, Dhubri, Silchar, Dibrugarh, Darbhanga, Calcutta, Veraval, Naya Dumka and Belgaum)

These 11 stations also follow the same pattern of seasonal variation of N_s as those in Group I. The only difference is that the values of associated N_s in this group are much smaller.

9.6.3. *Group III* : (Allahabad, Ludhiana, Amritsar, Daltonganj, New Delhi, Hyderabad, Akola, Poona, Nagpur, Ahmedabad, Bikaner and Agra)

In this group of 12 stations, the seasonal mean N_s decreases from winter to summer, then rises very sharply reaching the peak in monsoon season. Thereafter the values show a sharp decline upto the post-monsoon season. After that there is a gradual decline upto winter. For this group, the

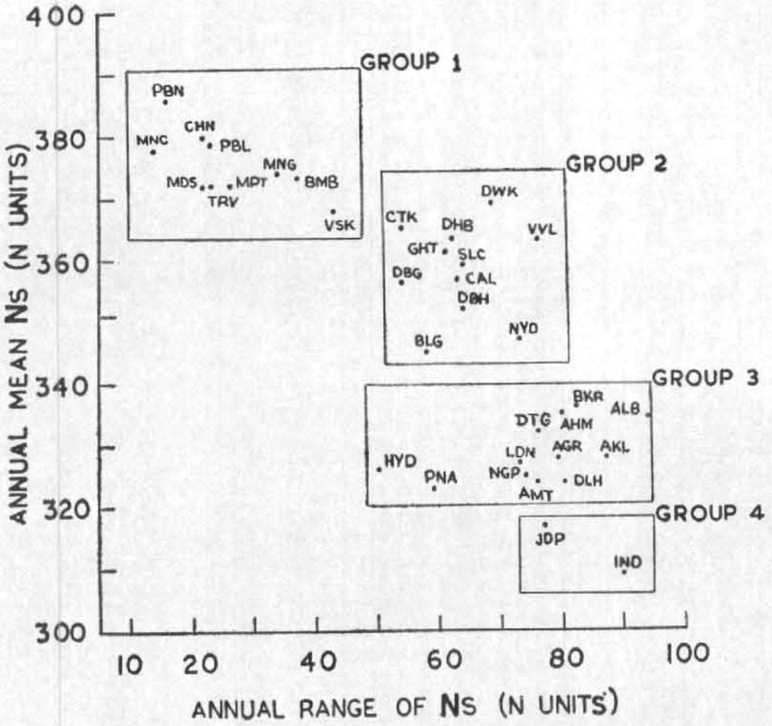

Fig. 7(b). Annual mean N_s *versus* annual range of N_s for the various stations

minimum seasonal N_s values occur in summer. The decrease after post-monsoon to winter is more steep than that from winter to summer. In this group, Bikaner exhibits slight deviation from the rest of the stations in as much as the seasonal mean N_s shows slight increase from post-monsoon to winter in case of this station.

9.6.4. *Group IV* : (Jodhpur and Indore)

The two stations in this group exhibit a rather sharp decline in the mean seasonal N_s values from winter to summer. Thereafter the mean N_s rises very steeply to reach a peak in monsoon, decreasing at first sharply upto post-monsoon and then less steeply to winter. The minimum seasonal N_s values are in summer. This group differs from Group III in as much as the associated values of N_s are smaller in Group IV than those in Group III and also because the decrease in the values of mean N_s from winter to summer in case of Group IV stations is much more sharp than in case of the stations of Group III.

9.7. *Grouping of the various stations according to the distribution of annual mean N_s and the annual range of variation of N_s*

In Fig. 7 (b), the various stations have been grouped according to their annual mean N_s plotted against the annual range of variation of N_s recorded at these stations. It is quite interesting to note that the stations arrange themselves in distinct groups. But what is more intriguing is that the stations arrange themselves in four distinct groups which are the same as those discerned on the basis of seasonal variation of mean N_s (see Section 9.9). This should prove that the grouping of the stations in the four groups, as attempted here in this study, is not entirely arbitrary but is in accordance with a definite scheme of variation of radioclimatic regimes as reflected in the seasonal variation of mean N_s and the distribution of annual mean N_s and the annual range of variation of N_s. Table 4 gives the details of the associated values of annual mean N_s and annual range of N_s for these groups of stations. These groupings delineate the existence of what we might call as homoclimes of radio-climate. But it should be noted that these groupings are based on certain gross radio-climatic features such as seasonal mean N_s, annual mean N_s , or annual range of variation of N_s for each station. It is natural that many of the finer features of radioclimate at any particular station are likely to be lost in these gross averages.

9.8. *Monthly maximum and minimum values of N_s over India*

For each month, the maximum and minimum values among the mean monthly N_s values of the various stations were picked up and plotted in the

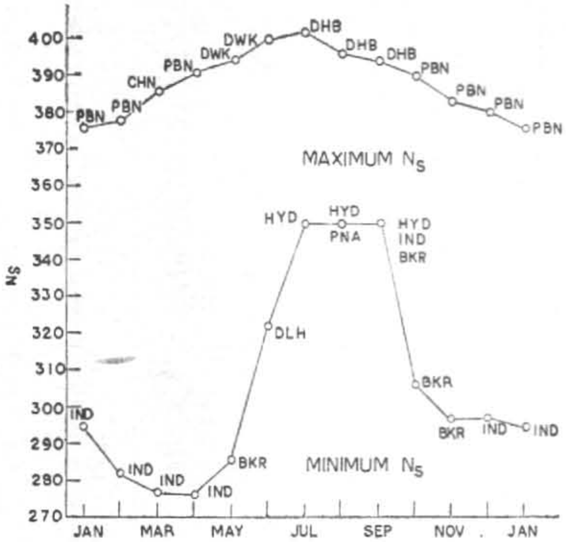

Fig. 8. Monthly maximum and minimum values of N_s over India

manner shown in Fig. 8, which depicts the month by month variation of maximum and minimum N_s values over India. The stations where these values occur have also been given in Fig. 8. A careful examination of this diagram reveals the following facts—

9.8.1. *Variation of monthly maximum N_s over India*

9.8.1.1. The monthly maximum values of N_s range between 376 and 402 N units.

9.8.1.2. The monthly maximum N_s reaches a peak in July and declines steadily on both sides.

9.8.1.3. The highest maximum N_s occurs in July at Dhubri while the lowest maximum N_s occurs in January at Pamban.

9.8.1.4. The place of occurrence of monthly maximum N_s shows interesting consistency. October through February (*i.e.*, during the post-monsoon and winter seasons), the monthly maximum N_s values occur at Pamban in the extreme south portion of the east coast. In March, April and May, the monthly maximum N_s occurs at Cochin, Pamban and Dwarka respectively. This is the summer season. After this during June also (which is the beginning of the southwest monsoon season), the monthly maximum N_s occurs at Dwarka but during the remaining months of the monsoon season, *i.e.*, during July, August and September, the monthly maximum N_s occurs at Dhubri.

9.8.2. *Variation of monthly minimum N_s over India*

9.8.2.1. The monthly minimum values of N_s range between 276 and 350 N units.

9.8.2.2. The monthly minimum values of N_s reach the peak in July and stay there upto September. The values decline rapidly on both sides. While there is one flattened peak during July through September, there are two distinct minima, one in April and the other in November.

9.8.2.3. The highest minimum N_s occurs in July through September at Hyderabad (also at Indore and Bikaner during September) while the lowest minimum N_s occurs in April at Indore.

9.8.2.4. The place of occurrence of monthly minimum N_s shows interesting variation. December through April (*i.e.*, during winter and major part of summer season), the monthly minimum N_s values occur at Indore. During May, the minimum N_s occurs at Bikaner, while in June it takes place at New Delhi. During July through September, *i.e.*, during the active period of southwest monsoon season, the monthly minimum N_s occurs at Hyderabad. During September, Indore and Bikaner also exhibit the same highest value of monthly minimum N_s. During October and November (*i.e.*, during post-monsoon season), the monthly minimum N_s occurs at Bikaner.

9.9. *Variation of N_s along an east-west cross-section*

Variations of N_s at Silchar, Calcutta, Cuttack, Allahabad, Nagpur, Akola, Indore, Ahmedabad and Veraval, *i.e.*, stations along an east-west cross-section in the latitudinal belt of 20°—25° N for the four representative months (February, May, August and November as per CCIR recommendations) have been shown graphically in Fig. 9. In general, the values of N_s from Silchar to Cuttack do not show any appreciable change during the different months. However, towards west beyond Cuttack, there is a tendency for the N_s to have steep fall upto Indore beyond which again the N_s value rises steeply upto Veraval. The variations of N_s during the four months are seen to follow the same trend. The range of variation of N_s is the smallest during August (representative of southwest monsoon season) and the largest during May (representative of the dry summer season).

9.10. *Variation of N_s along a north-south cross-section*

Variations of N_s at Amritsar, New Delhi, Kota, Indore, Akola, Hyderabad, Madras and Trivandrum, *i.e.*, stations along a north-south cross-section in the longitudinal belt of 75°-80°N, for the four representative months of February, May, August and November have been graphically shown in Fig. 10. The value of N_s in general decreases from north (Amritsar) to a minimum in the central parts of the country (Indore) and then increases up to the extreme south of the country. The

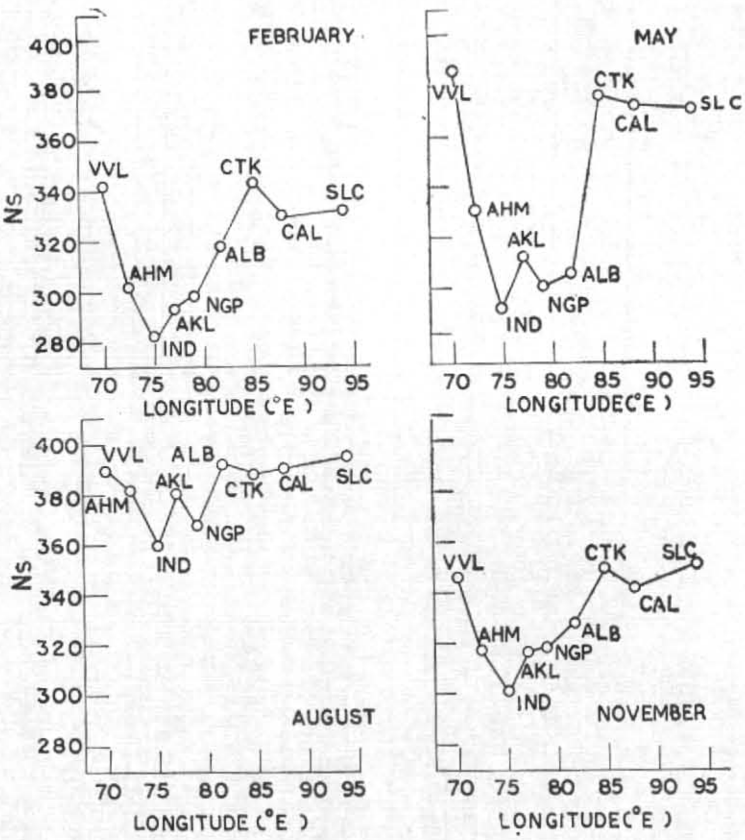

Fig. 9. East-west cross-sectional variation of mean radio refractive index N_s over India (for four representative months)

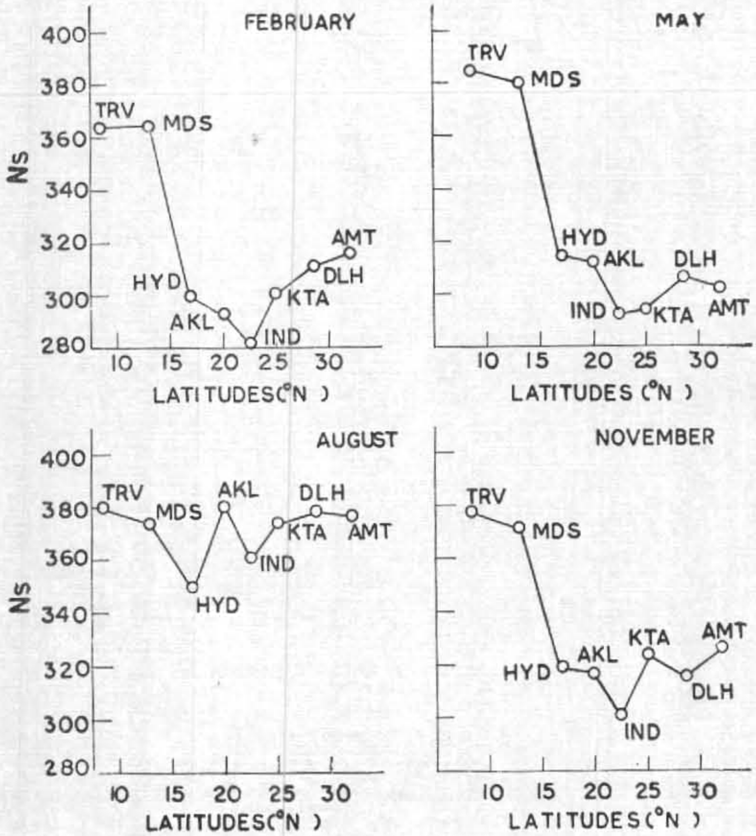

Fig. 10. North-south cross-sectional variation of mean radio refractive index, N_s over India (for four representative months)

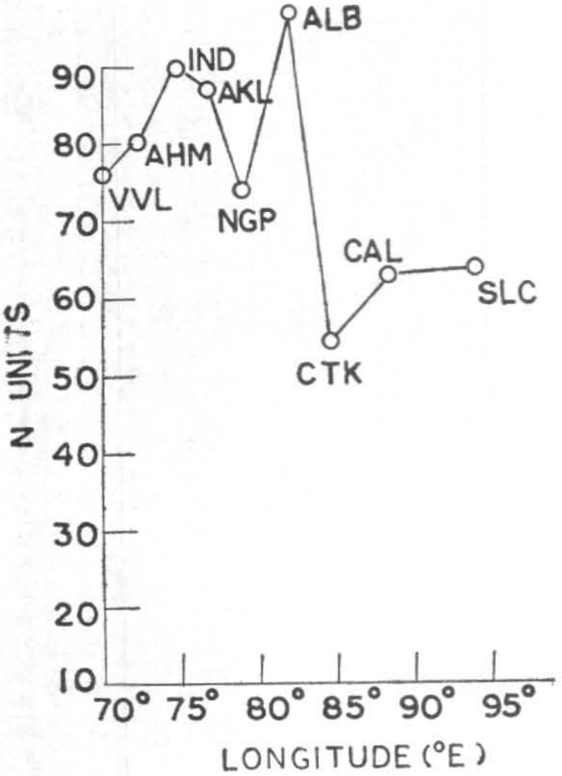

Fig. 11. Annual range of monthly mean N_s along the east-west cross-section

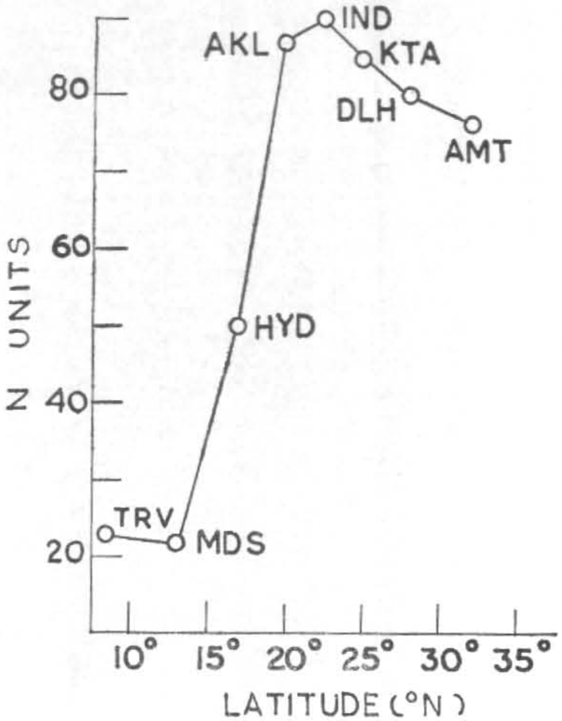

Fig. 12. Annual range of monthly mean N_s along the north-south cross-section

variations of N_s during the four months are seen to follow similar trend. The range of variation of N_s is the smallest during August (representative of the southwest monsoon season) and the largest in May (representative of the dry summer season).

9.11. *Variation of annual range of N_s along the east-west cross-section* (Fig. 11)

The maximum variation of annual range of N_s occurs over Allahabad followed closely by Indore, and the minimum occurs over Cuttack; the values of annual ranges extending between 95 and 55 N units. From Silchar to Calcutta, the annual range is steady and the value is little over 60 N units. It falls between Calcutta and Cuttack and then rises steeply from 54 to 89 N units at Allahabad. Values of annual range again decrease upto Nagpur, increase thereafter upto Indore through Akola and decrease again upto Veraval through Ahmedabad.

9.12. *Variation of annual range of N_s along the north-south cross-section* (Fig. 12)

The annual ranges of N_s reach a maximum value over Indore and a minimum value over Madras, the values being 90 and 22 N units respectively. From Amritsar to Indore, the annual range of N_s increases rather gradually upto a maximum at Indore. Thereafter it first falls slowly up to Akola and then very rapidly upto Madras through Hyderabad. Madras and Trivandrum have the lowest values of annual range of the order of 20 N units. Thus it will be seen that the annual range of variation of N_s has a maximum in central India near Kota, Indore and Akola. The values of annual range of N_s fall both towards the north and the south, the fall being gradual towards the north and rapid towards the south.

9.13. *Monthly variation of N_s at selected stations in India*

The monthly variations of N_s at 16 selected stations have been shown in Figs. 13 to 16. These selected stations are —

Allahabad	Dwarka	Madras	Port Blair
Bikaner	Gauhati	Minicoy	Trivandrum
Bombay	Indore	Nagpur	Veraval
Calcutta	Jodhpur	New Delhi	Visakha-patnam

On a careful examination of the character of monthly variations of N_s at these stations, it is observed that these stations can be classified into the following seven distinct types —

Type 1—New Delhi, Allahabad, Indore and Bikaner (Fig. 13)

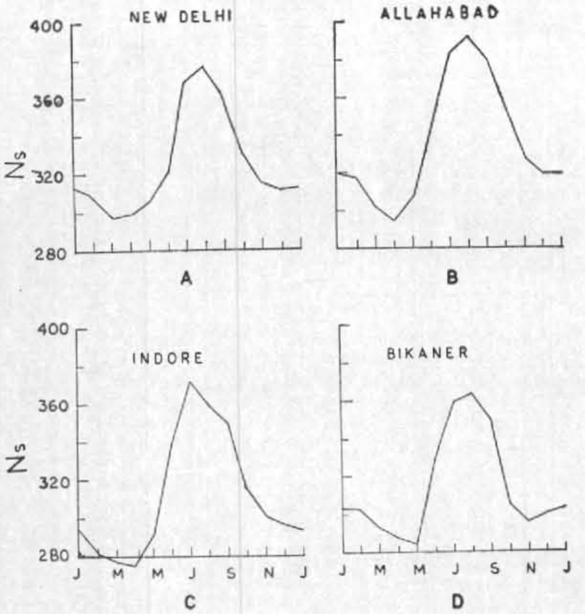

Fig. 13

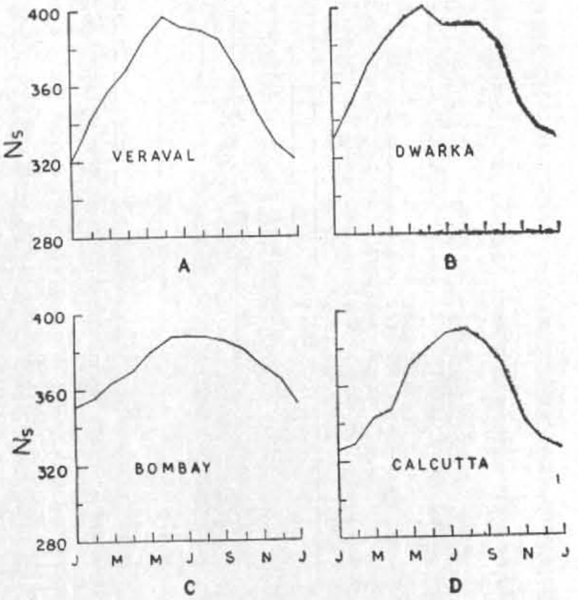

Fig. 14

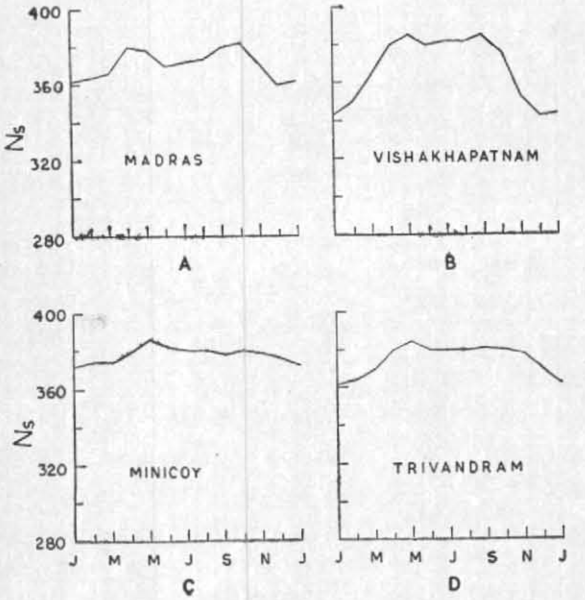

Fig. 15

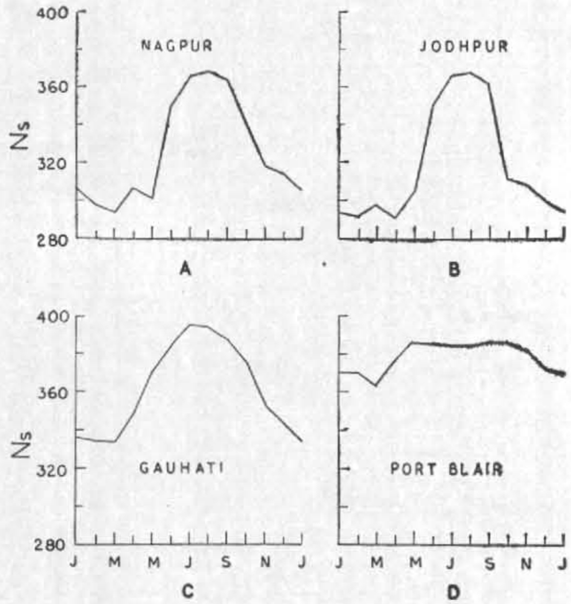

Fig. 16

Figs. 13—16. Monthly variation of N_s at selected stations

Type 2—Veraval, Dwarka, Bombay and Calcutta (Fig. 14)

Type 3—Madras and Visakhapatnam (Figs. 15 A and 15 B)

Type 4—Minicoy and Trivandrum (Figs. 15 C and 15 D)

Type 5—Nagpur and Jodhpur (Figs. 16 A and 16 B)

Type 6—Gauhati (Fig. 16 C)

Type 7—Port Blair (Fig. 16 D)

In an earlier Section (9·7), we had attempted a classification of Indian stations into four groups of homoclimes of radio-climates. That classification was based on gross surface structure of radioclimate over the country. Figs. 13 to 16 depict a finer structure in as much as they exhibit the month by month change in the N_s regime over the selected stations and bring to light many distinct and characteristic features in the monthly variations. It may, therefore, be reasonably concluded that these Indian stations can be further classified into seven types. These typical monthly variations of N_s may be regarded to represent seven types of homoclimes of radio-climates in India each characterised by a distinct and characteristic N_s regime.

10. Conclusions

10.1. The complete radio-climatology of the surface distribution of the modified atmospheric radio refractive index has been worked out on the basis of the computations made from the surface meteorological data of 36 stations in India. A large number of maps and diagrams showing different aspects of the radio-climatology of India have been presented. An attempt has been made to delineate homoclimes of radio-climate in India.

10.2. It is hoped that this study will provide the much desired data to radio-physicists and radio-engineers in radio measurements, propagation studies, frequency planning, and allied investigations.

11. Acknowledgements

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