OVER-LAND REFRACTION OF HIGH-FREQUENCY RADIO WAVES IN INDIA

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ABSTRACT From a study of the vertical distribution of the mean modified refractive index of the lowest kilometre of the atmosphere over three land stations computed from routine aeroplane flight and radio-sonde reports, conclusions are drawn regarding radio propagation conditions over these stations at some selected hours of the day and in different months of the year. While combined effects of temperature inversion and humidity lapse with height explain on super-refraction at these stations most occasions, some cases of super-refraction are observed with lapse rates in both temperature and humidity. Meteorological origin of the mean M.R.I profiles is discussed.

ATMOSPHERIC SUPER-REFRACTION AND FORMATION OF RADIO-DUCTS

The refractive index, μ of the atmosphere for radio waves is given to a sufficient degree of accuracy, by the relation :

$$\mu = 1 + \frac{80}{T}\left(P + \frac{4800\,e}{T}\right) \times 10^{-6} \qquad \dots (1)$$

where P = the atmospheric pressure in millibars,

e = the partial pressure of water vapour in milibars,

and T = the temperature in degrees absolute.

If $d\mu/dh$ is the refractive index gradient at height h above the earth's surface, the curvature of a radio-ray for small angles of elevation ($\lesssim 15^\circ$), at that height is

$$\frac{1}{\rho} = -\frac{1}{\mu}\frac{d\mu}{dh} \qquad \dots (2)$$

where ρ is the radius of curvature of the ray. Following radio practice, we treat the earth's surface as flat and measure ray curvature with reference to a flat earth. It becomes necessary to modify the refractive index in that case and the modified refractive index (M.R.I.) is given by the following relation,

$$\mu' = \left\{(\mu - 1) + \frac{h}{R}\right\} \times 10^{6} \qquad \dots (3)$$

where R is the radius of the earth. It can be shown from the theory of radio-ray propagation (Appleton, 1946) that if ϕ_h is the inclination of a ray to the horizontal at a height h, where the modified refractive index is μ_h' then,

$$\frac{1}{2}(\phi_h^2 - \phi_0^2) = \mu_h' - \mu_0' = \Delta\mu' \tag{4}$$

where ϕ_0, μ_0' are the corresponding values at the transmitter height h_0. Equation (4) gives the bending of the rays in terms of the modified refractive index variation over an interval of height $(h - h_0)$. If $\Delta\mu' > 0$, $\phi_h > \phi_0$, and the ray is bent upward with reference to a flat earth. If $\Delta\mu' = 0$, $\phi_h = \phi_0$, and the ray moves parallel to the earth's surface. But if $\Delta\mu' < 0$, $\phi_h < \phi_0$, and the ray is bent downward to strike the earth. In the last case radio-energy is mostly confined in a narrow layer close to the earth's surface and is able to reach distances far beyond the geometrical horizon giving rise to what is known as unorthodox radio vision (Booker, 1948; Saha, 1949). The height at which upgoing radiation is reflected back downwards marks the top of a radio-duct.

The negative gradient of μ' with height thus produces super-refraction or radio-ducts. The types of super-refracting layers commonly met with in the atmosphere are shown by the $\mu' - h$ curves in figure 1.

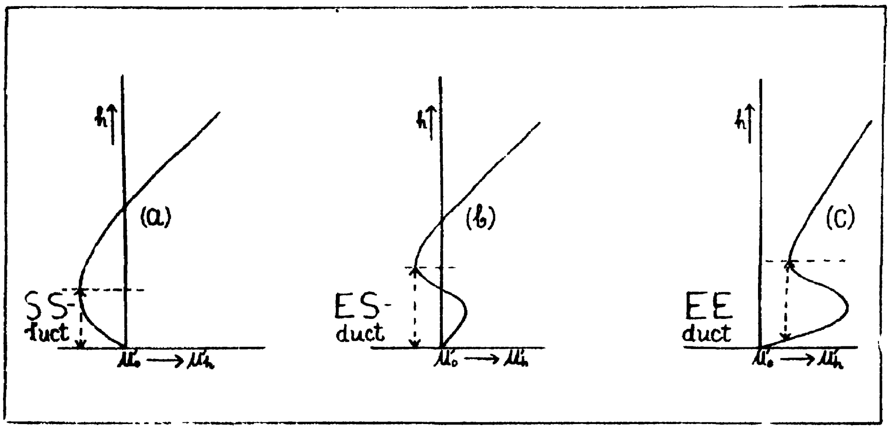

FIG. 1

Types of super-refracting layers or radio-ducts.

In the first and second curves μ' reaches a negative value relative to the origin. In (*a*) the duct reaches the earth's surface and is called the SS-duct (Surface-layer and Surface-duct). In (*b*) the refracting layer is elevated but the radio-duct still extends from the minimum of modified refractive index (M.R.I.) to the ground level and is called the ES-duct (Elevated-layer and Surface-duct). In (*c*) the local minimum of the M.R.I. exceeds the value at the earth's surface giving what is known as the EE-duct (Elevated-layer and Elevated-duct). In the last case, the radio-duct only extends from the local minimum of the μ' down to the level where this value is regained.

Considerations of the meteorological variables involved in equations (1) and (3) make it clear that while the distribution of the atmospheric pressure with height causes a slight uniform decrease of refractive index with height, temperature and humidity distributions are the main factors which determine the vertical distribution of the M.R.I. and thus control radio propagation in the lower atmosphere. In a well-mixed atmosphere in which the lapse rate of temperature is dry, abiabatic and the specific humidity falls off slowly with height, $\Delta\mu' > 0$ and the radio refraction is said to be normal or standard. Radio range in such an atmosphere hardly exceeds the optical range of the transmitter. But when the atmosphere is stratified, strong temperature inversion may form and there may also develop a marked negative gradient of humidity with height. In such an atmosphere $\Delta\mu' < 0$, and the result is the formation of a highly super-refracting layer. Sometimes the effect of temperature distribution may act in a direction opposite to that of humidity gradient but it is the resultant effect exercised through the relation (1) that becomes the determining factor

RADIO REFRACTION OVER LAND

The important role played by atmospheric refraction in short wave propagation was widely demonstrated during World War II by radar operations in different parts of the world. Abnormally long ranges of communication at low levels were reported in many parts but the most impressive reports came from the tropics where the effects of high temperature and high humidity produced marked super-refraction. But the bulk of these reports related to over-water transmission. The difficulty of low-elevation wave propagation over land may have substantially restricted use of the radar in many parts of the continents.

Smith-Rose and Stickland (1946) have experimentally demonstrated that over-land radio-wave propagation between any two points on the earth's surface is affected by meteorological conditions of the medium in much the same way as over-water transmission. Variations in the refractive index gradient of the medium caused by meteorological phenomena like fog, cold front and high wind produce corresponding variations in the receiving signal strength at a distant point. Their work calls for more detailed information on the fine structure of the propagation medium. The lapse rate of the refractive index with height requires to be determined with greater accuracy than heretofore. Only then can field intensities and reception strengths be determined with any exactitude.

In the present study refractive index (modified) values have been computed for three land stations in India and their vertical profiles examined for super-refraction of radar waves. Diurnal and seasonal variations are studied and inferences drawn regarding propagation conditions at these stations at different times of the year.

AVAILABLE METEOROLOGICAL DATA

Theoretical works (Eckersley, 1938; Booker, 1946) have shown that efficient trapping of a radio-wave is possible only when the width of a radio-duct is greater than a critical minimum value. The critical width, however, decreases as the frequency of the wave is increased. For high frequency radio waves, as used in radar, the critical duct-width is contained within the lowest 1,000 ft. of the atmosphere. Hence meteorological data of the lowest kilometre of the atmosphere can provide suitable basis for studying radio refraction in the atmosphere.

Low-level meteorological soundings up to a height of 1 km or so have not formed part of routine upper-air work in India. A series of clown balloon ascents were arranged by Chatterjee and Sur (1929) at Jhikergachha (Lat. 23° 06′ N., Long. 49° 08′ E.) in connection with a study of the Nor'-wester problem. Ramdas (1943) has recorded a series of micro-meteorological observations at Poona but these relate to the lowest 35 ft. only. Observations from high towers or low-level aeroplane flights suitable for use in radio-meteorological work are practically non-existent in this country. Perhaps, the only record of a low-level aeroplane flight specially made for radio-meteorological work is to be found in a paper by Hatcher and Sawyer (1947) on the structure of sea-breeze at Madras and the associated radio-duct.

Routine radio-sonde observations are hardly ideal for the type of work here undertaken because of the excessively high rate of ascent of recording instruments which allows only a few observations to be taken in the lowest kilometre. In the case of aeroplane flights these draw-backs may be removed if the terrain is plain but the high speed of the aircraft necessitates large corrections to the readings of the recording instruments. In spite of these sources of error, the author found it practicable to work with the routine corrected data published by the Indian Meteorological Department in daily weather reports. Volumes of these data accumulated in wartime. They are now available in suitable form for studying the refractive condition of the atmosphere. Aeroplane and balloon flight observations of temperature and humidity at Calcutta, Nagpur, and Madras during the period 1944-46 are used in the present paper. Observations of Calcutta were available at 0100, 0700 and 1300 hours G M T, for all the months and at 1700 G M.T. for the months of March, April, July, and October. Of these the observations at 0100 GMT were obtained by aeroplane flights while those at 1300 and 1700 GMT were radio-sonde observations. Observations of Nagpur and Madras were aeroplane flight observations and were available at 0100 ond 0600 GMT only. Mean temperature and vapour pressure at standard and chosen pressure levels were obtained graphically for each month and these mean values were used for computing the value of the M.R.I., employing relations (1) and (3). Computed values of the M R.I. were then plotted against height in charts A1, A2, B, and C. The statistics of the data used for each curve in these charts is givan in Table I and the scatter of the observations about their mean at Calcutta is given in terms of the standard deviation for four representative months in Table II.

DIURNAL AND SEASONAL VARIATION OF REFRACTION

The vertical profiles of the modified refractive index presented in charts A1, A2, B and C show diurnal and seasonal variation which may be discussed as follows :

Charts A1 and A2.—Calcutta. The mean structure of the lower atmosphere over Calcutta during the night and early morning hours of the winter months of December to February is a strong temperature inversion and a normal negative gradient of humidity. Mean M.R.I. profiles for this period do not reveal the presence of any radio-duct but the vertical gradient of the modified refractive index definitely indicates marked tendency towards super-refraction. M.R.I. curves for midday hours show normal refraction. Atmospheric conditions in March become highly favourable for super-refraction. Strong temperature inversion and marked lapse of humidity with height combine to form radio-ducts during evening which continue throughout night and last as late as morning hours as evidenced by the ascent curves for the month in charts A1 and A2. These radio-ducts are of the SS-type. In April and May temperature inversion still forms but during these months the inversion layer is most often elevated above the ground. In figure 2 an early morning ascent in April at Jhikergachha, taken from the clown balloon ascent data of Chatterjee and Sur (1926), shows the presence of an elevated temperature

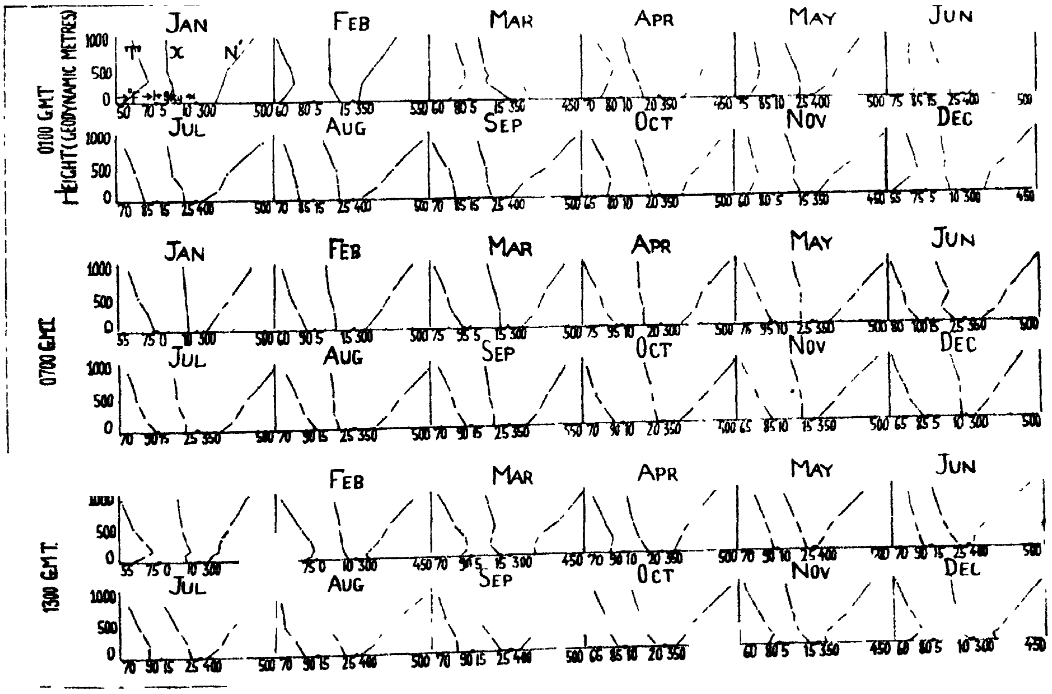

Chart A 1.

Vertical distributions of mean temperature T(°F), humidity mixing ratio x(g/Kg), and *modified refractive index μ' at* Calcutta in different months. Times of ascent : 0100, 0700, and 1300 GMT.

inversion and an ES-duct. Figure 3 and figure 4 show the confines of the inversion layer and the steepness of inversion over Calcutta at some hours of the day and in different months of the year. The height of the top of the inversion layer in April is probably that of the elevated inversion

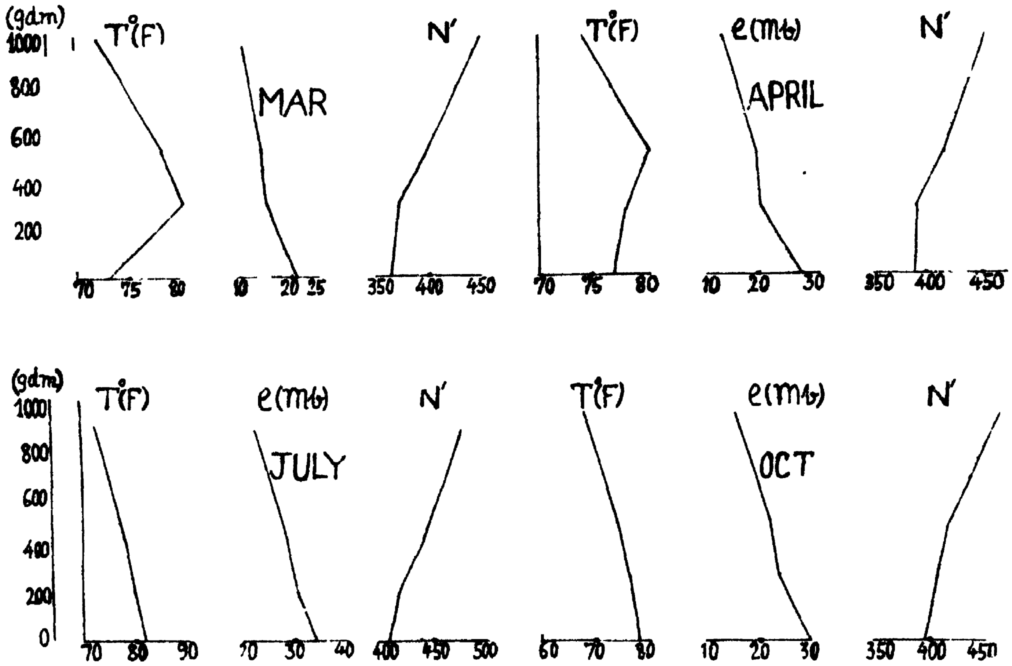

Chart A 2.

Vertical distributions of mean temperature T(°F), vapour pressure e(mb), and *modified refractive index* μ' at Calcutta in four months. Mean time of ascent : 1700 GMT (Mean of times of ascent between 1500 and 1800 Z)

TABLE I

Statistics of data, Number of observations used for mean M.R.I. curves.

Station.	Time of ascent	Month. J	F.	M	A	M	J	J	A	S	O	N	D
Calcutta	0100Z	22	45	45	42	21	20	40	34	12	27	12	22
	0700	19	20	17	19	18	18	38	17	12	28	02	15
	1300	50	20	09	19	22	22	20	13	10	18	10	20
	1700	—	—	07	08	–	—	12	—	—	07	—	—
Nagpur	0100	35	51	48	71	29	28	44	44	26	43	25	53
	0600	35	52	46	42	28	25	29	25	27	33	28	51
Madras	0100	24	25	24	22	27	25	29	24	23	48	27	27
	0600	25	20	22	19	07	19	28	08	—	20	18	26

layer. Temperature inversion disappears during the SW monsoon and the lapse rate of moisture is also very small then. The M.R.I. profiles show that microwave propagation must be quite orthodox from June to September. In October the inversion re-forms It strengthens in November when the atmosphere becomes highly refracting again. It is interesting to compare the above remarks with an actual record of radar performance over the delta area of Bengal in 1943 which is reproduced in Table III below from a paper by Durst (1946). The high scatter of the observations about their mean in winter and early summer months as given by those of the representative months in Table II is probably due to the frequent changes in air masses over the area caused by the passage of western depressions during these

TABLE II

Scatter of temperature observations. Standard deviation values at Calcutta (°F).
(D. B.—Dry bulb ; W. B.—Wet bulb)

Time of ascent.	Jan			April.			July			Oct		
	Ht(gdm)	D.B.	W.B.	Ht.	D B.	W.B	Ht.	D.B.	W.B.	Ht	D.B.	W.B.
0100Z	0	4.2	3.9	0	4.1	4.1	0	1.0	1.0	0	3.7	3.6
	315	4.9	3.7	274	3.0	4.4	193	1.4	1.1	276	2.0	2.8
	530	4.4	4.2	495	4.1	4.6	414	1.7	1.8	495	2.5	3.6
	980	4.2	5.1	958	4.6	3.9	876	1.7	1.5	955	2.8	4.1
0700	0	4.9	3.2	0	4.3	3.8	0	4.1	1.4	0	4.1	3.8
	323	4.6	3.6	266	4.1	3.2	187	2.7	1.3	278	3.1	3.3
	539	4.4	4.1	490	4.6	3.4	409	2.5	1.7	498	2.8	3.4
	991	4.9	4.9	955	3.5	3.8	876	1.7	1.5	960	3.1	3.7

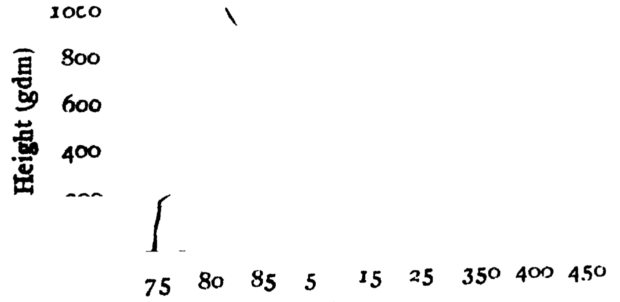

FIG. 2

Elevated radio-duct at Jhikergachha, Bengal. Time of ascent, 0100 GMT. 9th April, 1929.

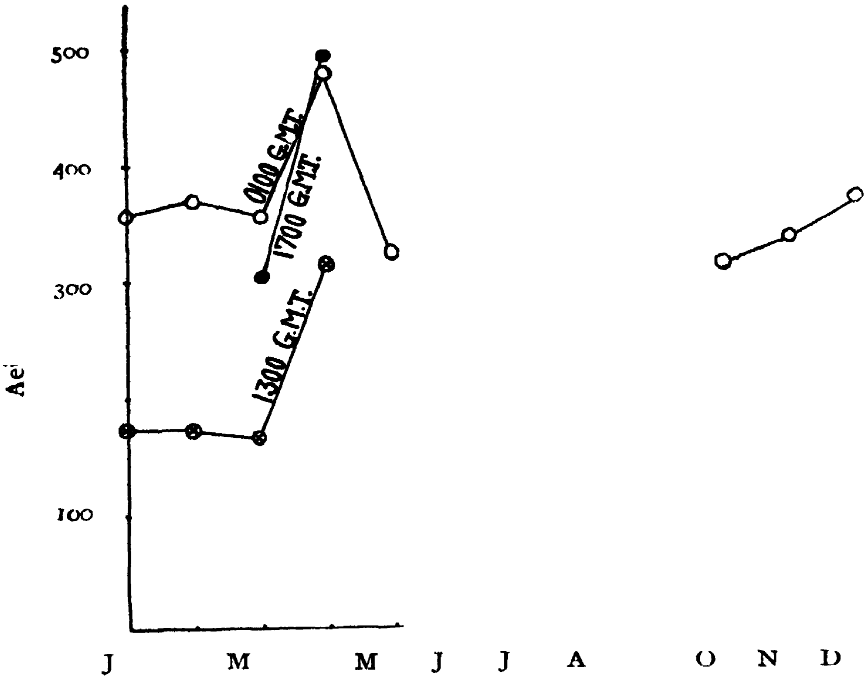

FIG. 3

Mean height of top of inversion layer at Calcutta in different months Symbols for times of ascent are: "crossed circle" 1300, "dot" 1700, and O 0100 GMT. (1700Z is mean of ascents between 1500 and 1800Z)

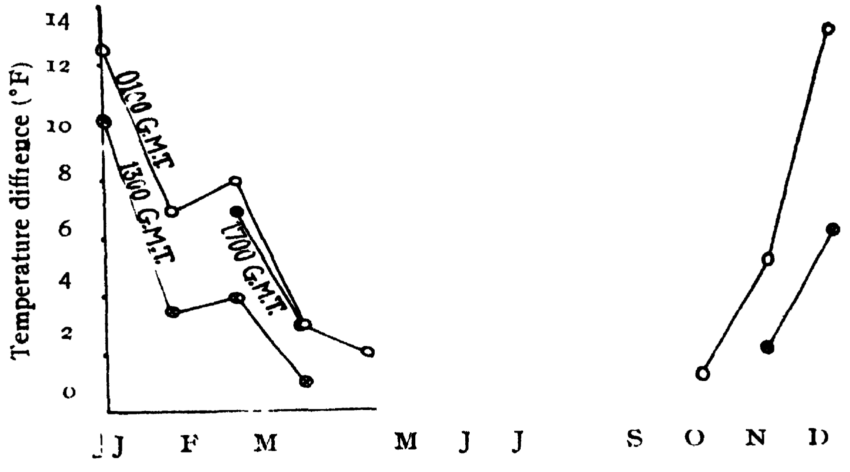

FIG. 4

Mean temperature difference between the ground and the top of the inversion layer at Calcutta in different months. Mean times of ascent in symbols are "crossed circle" 1300, "dot" 1700, and O 0100Z. (1700Z is mean of ascents between 1500 and 1800Z)

periods. Little air mass change obtains during the SW monsoon season, hence the low scatter during this period. Air mass conditions fluctuate again during the post-monsoon season when tropical cyclones from the Bay of Bengal affect the region and these fluctuations probably explain the somewhat high scatter during this period.

TABLE III

Number of nights per month on which inland super-refraction was experienced by radars in Bengal in 1943 (after Durst)

Wave length	J	F	M		M	J	A	S	O	N	D
1½ m	30	27	24	20	25		11	08	25	28	31
7 m	08	05	08	13	12		10	05	06	02	00

Chart B—Nagpur, 0100 *G M T. Curves, December—March*: In spite of strong temperature inversion small negative gradient of humidity does not permit the formation of any super-refracting layers during this period. But the trend of the M.R.I. profiles definitely indicates that during these months the lower atmosphere over Nagpur would produce radio-refraction in excess of the standard rate.

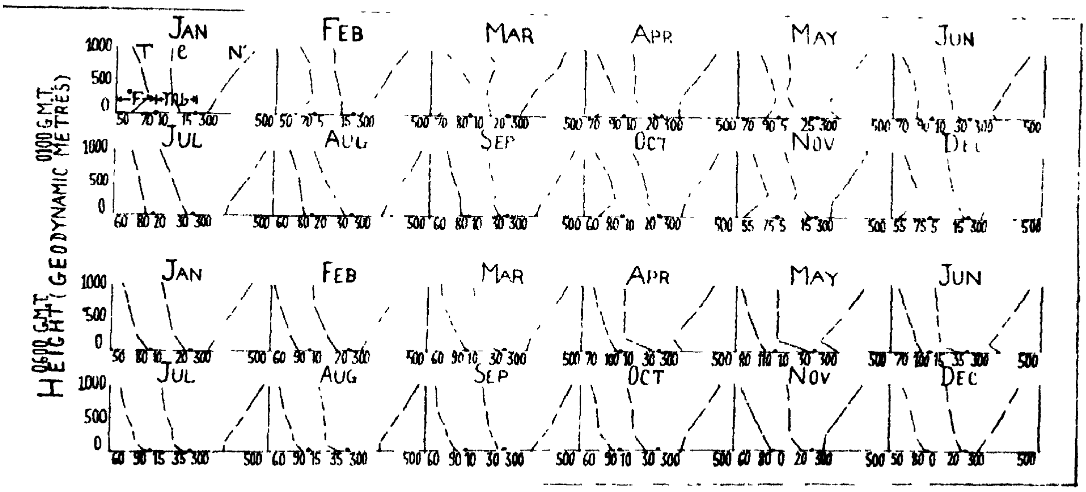

Chart B.

Vertical distributions of mean temperature T(°F), vapour pressure e(mb), and *modified refractive index* μ' at Nagpur in different months. Times of ascent : 0190 and 0600 G. M. T.

April to mid-June and October to November.—Strong temperature inversion or isothermal condition up to a height of 1000 feet to 1500 feet and marked vapour pressure lapse rate in the first 1000 feet of the atmosphere are favourable for pronounced super-refraction during these transition months. SS-duct forms and its width decreases from about 1000 feet in April to about 300 feet in June. The duct appears to be strongest in May.

Mid-June to September.—During the SW monsoon the atmosphere becomes well-mixed and homogeneous in the vertical and both temperature and humidity fall slowly with height. The resultant effect is a normal or standard lapse rate of the modified refractive index with height.

0600 *G.M.T. Curves.*—The midday temperature curves show lapse rate at all the levels. Inspite of temperature lapse which by itself inhibits super-refraction of any kind, marked lapse rate of humidity in some months makes the atmosphere super-refracting even at midday. An examination of the M.R.I. profiles for midday enables us to draw the following conclusion:

December to March. Atmospheric refraction is normal.

April to mid-June.—The atmosphere is highly super-refracting. SS-duct radio-duct would appear to form, the width of which decreases from about 700 ft. in April to about 300 feet in June.

Mid-June to November.—M.R.I. curves for the months of July and August indicate the presence of a highly refracting layer of the SS- type within the first 400 feet of the ground. During the remaining months, the refraction is standard.

Chart C—Madras, 0100 GMT curves. October to January.—During these months which cover most of the period of the NE monsoon over Madras the mean temperature distribution in the lower atmosphere is either isothermal or exhibits a slight temperature inversion. But inspite of temperature condition being favourable, slow lapse rate of humidity makes refraction almost normal.

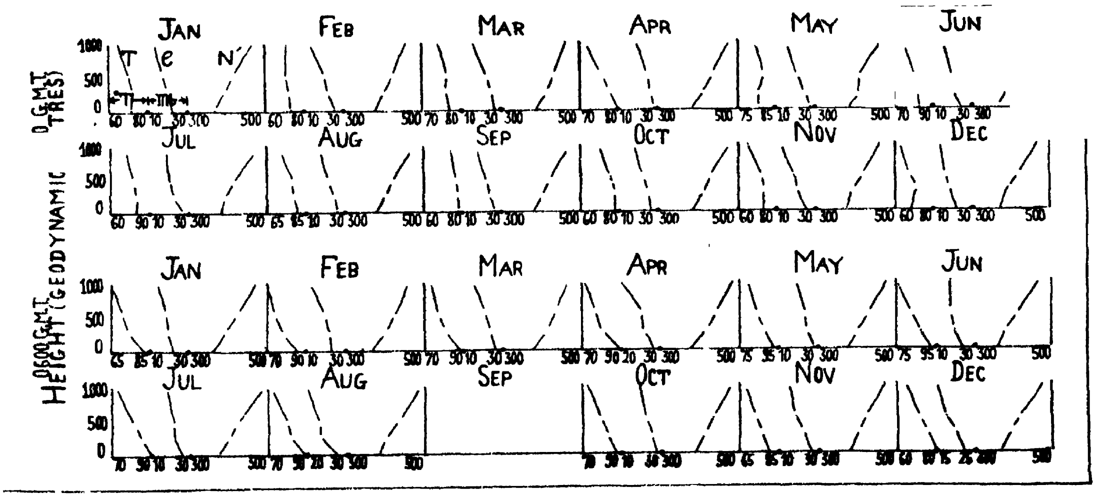

Chart C.

Vertical distributions of mean temperature T(°F), vapour pressure e(mb), and *modified refractive index* μ' at Madras in different months. Times of ascent : 0100 and 0600 G. M. T.

February to May.—In these summer months, except May, both temperature and humidity fall with height. But the rate of decrease of humidity being slow, the M.R.I. curves exhibit more or less normal or standard refractive condition. In May, the temperature curve shows an isothermal layer to a height of about 750 feet and an inversion layer aloft up to a height of about 1500 feet. Above 1500 feet level, there is normal temperature lapse rate. The temperature and humidity conditions as revealed by the mean curves would give rise to an elevated duct of the ES-type, as shown in the appropriate M.R.I. curve.

June to July.—During these months, there is lapse of both temperature and humidity with height. The humidity lapse rate, however, is fairly high and the result is a slightly more refracting atmosphere than the normal.

August to September.—Temperature and humidity decrease slowly with height. M.R.I. profiles would seem to indicate normal refractive condition in these months.

06—G.M.T. curves. Owing to temperature lapse and slow decrease of humidity with height, refraction is normal at midday in all months except September for which no data were available.

Hatcher and Sawyer's investigation on the sea-breeze structure at Madras has shown that when strong sea-breeze prevailed during afternoon hours in summer months, radio-ducts appeared to form over the coastal strip as well as over the adjoining sea areas. ES-ducts probably form in such conditions owing to the relative orientation of the cool sea breeze underneath the warm continental air flowing out towards the sea.

METEOROLOGICAL ORIGIN OF THE MEAN M.R.I. PROFILES

The vertical distribution of the mean modified refractive index as shown in charts A, B and C may be explained qualitatively in terms of the mean atmospheric conditions that occur in India in different months. For this purpose, representative air-flow charts for three dominant seasons in India are presented in figures 5-7. It is well-known that temperature inversion and

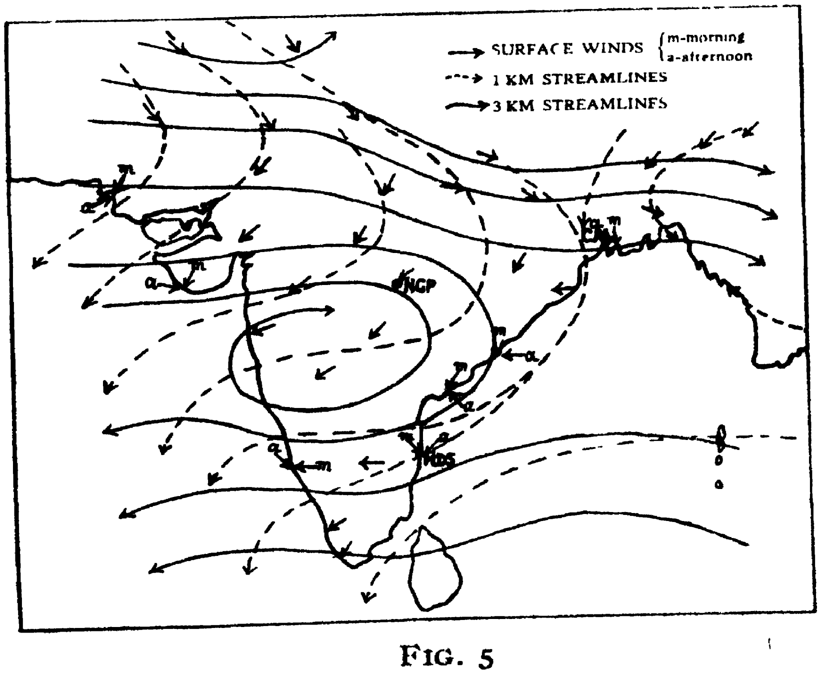

FIG. 5
Winter air-flow chart, December

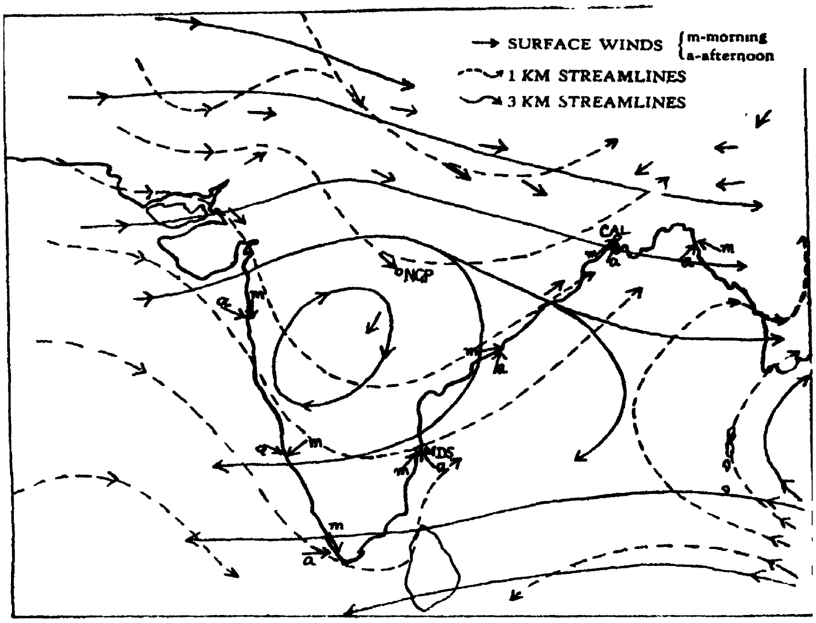

FIG. 6
Summer air-flow chart, April

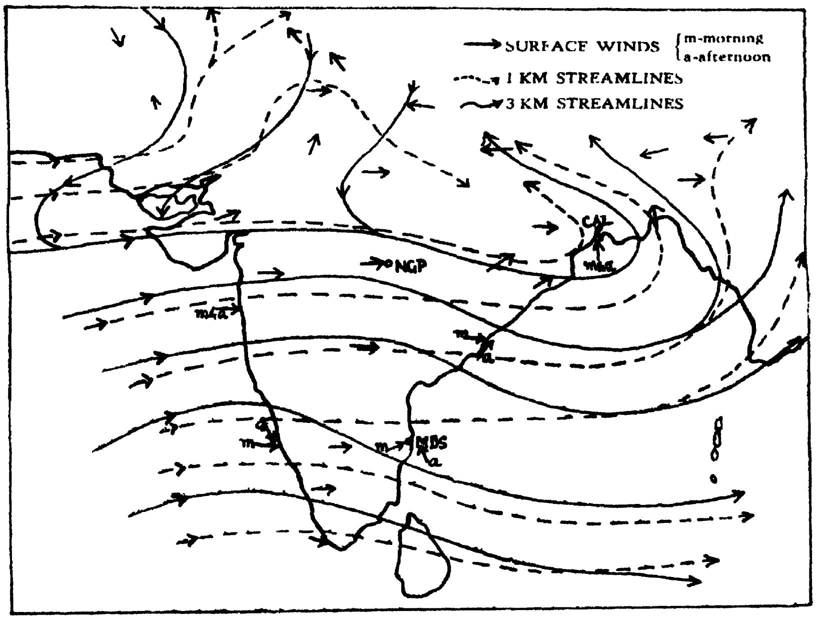

FIG. 7
Monsoon air-flow chart, August

negative gradient of humidity with height originate in certain meteorological conditions. Some of these are: (1) rapid cooling of the ground layers by radiation at night, (2) subsidence of air from high levels, and (3) horizontal advection of dry and warm air over cool and moist air. The first two are satisfied when anticyclonic conditions prevail over the area under investigation, whereas, the third is met with mostly in coastal areas where the sea-breeze phenomenon is common and also over some areas where the local pressure distribution brings in a thin layer of cool and moist air underneath warm continental air. An examination of figures 5-7 in the light of the foregoing observations enables the following conclusions to be drawn in regard to the mean temperature and humidity profiles. During the period October to February, which covers most of the winter season, the air circulation over India is anticyclonic from the ground to a high level. The result is large-scale subsidence of air and marked vertical stability of the lower atmosphere. Extreme dryness of the air keeps the skies cloudless and rapid nocturnal radiation builds up a steep temperature inversion which lasts till the following morning when the inversion is destroyed by insolation and replaced by a temperature lapse rate. Temperature distribution, therefore, is extremely favourable for the development of a strong radio-duct during evening and night hours but the effect of a slow lapse rate of humidity somewhat counteracts this process. Over Madras, the temperature inversion is only slight and slow lapse rate of humidity with height seldom permits the formation of a super-refracting layer in winter months. Figure 6, which depicts the mean airflow for the summer months of March to May, shows the same high level subsidence though in the very lowest levels the subsidence is being replaced by the opposite effect of convection indicated by the somewhat cyclonic bend of the streamlines. Over the land, the air still being dry, nocturnal cooling develops temperature inversion. But the inversion is less marked now than in winter months. There is also a slow decrease of humidity with height. But locally during this period there is influx of moisture in the lowest levels over deltas and coastal areas either in the form of a sea-breeze or as a steady moist current maintained by the local pressure distribution. When such incursion of moisture takes place close to the ground, an elevated temperature inversion results and the humidity falls off rapidly in going from the lower moist layer to the upper dry layer. An elevated radio-duct of the ES or EE-type forms. Examples of the formation of such elevated radio-ducts have already been cited in the case of Madras and south Bengal in the preceding pages.

During the period of the south-west monsoon from June to September the atmosphere is thoroughly mixed by marked convection indicated by the cyclonic curvature of the streamlines up to a high level and the result is a lapse rate in both temperature and humidity and a normal radio-refraction. But the propagation inferences drawn in the case of midday M. R. I. curves for Nagpur and early morning curves for Madras for this period show variations from the general rule. Inspite of the normal temperature lapse rate, marked negative gradient of humidity with height makes all the difference. The rapid increase in wet-bulb temperature in unison with the rise in air temperature about midday hours close to the ground establishes a steep lapse rate of humidity with height and this more than offsets the inhibitive effect of a temperature lapse rate and favours the formation of a super-refracting layer. The dependability of the observed values of the wet-bulb temperature has not been questioned in the present paper and is subject to further investigation.

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