551.551.4:621.396.96

An explanation of anomalous radar propagation following thunderstorm activity

S. RAGHAVAN

Meteorological Office, New Delhi

(*Received 2 March 1964*)

ABSTRACT. Several cases of anomalous propagation of a 3-cm radar beam observed at Madras in the rear of thunderstorms, cannot be satisfactorily explained by the process suggested by previous workers on this subject. The anomalous echoes appear to be from ground targets, obtained after partial reflection of the radar beam at a thin boundary layer between the downdraught air of the thunderstorm and the environmental air. Sufficient refractive index change, required to produce the reflection can occur only in cases when the downdraught air is more moist than the environment, and this agrees with the observations. The mechanism suggested does not depend on the presence of rainfall at the ground.

1. Introduction

1.1. In a previous paper (Raghavan 1962), the author had referred to a number of cases of 'anomalous propagation' or 'super refraction' of a 3-cm radar beam in the rear of thunderstorms occurring around Madras in the southwest monsoon season. It was also mentioned that this phenomenon did not occur in the post monsoon months.

1.2. A few cases of anomalous propagation following a thunderstorm have been reported by other workers (Coons 1947, De 1959 and Mathur and Kulshrestha 1961). The explanation given by Coons is that an abnormal moisture lapse is set up near the ground behind the storm owing to the evaporation of rainfall near the surface. The effect of this in setting up a duct is enhanced by the effect of the cooling of the earth's surface by the thunderstorm. The maintenance of this stable condition was favoured in the case considered by Coons by the presence of low clouds and a light wind. Mathur and Kulshrestha have given a similar explanation and they stress the importance of light winds. De has said that the downdraught from the thunderstorm is moist and cool and hence it sets up the temperature and humidity distribution favourable for super-refraction. This favourable layer extended, in his case, to a height of 2300 feet. The relatively large number of cases of this phenomenon observed in Madras, have enabled the author to analyse the propagation of 3-cm waves in the rear of a thunderstorm in greater detail. This analysis indicates that the above explanations are inadequate to cover the phenomena observed at Madras. A mechanism consisting of reflection from a thin boundary layer is proposed in this paper.

2. Observations

2.1. The thunderstorms studied in Madras belong mainly to the two well marked seasons.

2.1.1. The southwest monsoon season comprising the months June to September when thunderstorms or lines of thunderstorms pass roughly from northwest to southeast or west to east. Thunderstorms in this season occur generally in the afternoons or evenings. The storms are often associated with severe squalls. In a large number of cases abnormal propagation was observed in the wake of these storms.

2.1.2. The post monsoon. or northeast monsoon season (October and November) when thunderstorms are fewer in number. These form over the sea in the early morning hours and move roughly westwards and can be tracked several miles inland. Squalls

TABLE 1

Thunderstorms in June

Date	Details of thunderstorm	Surface temp. (°C)		Vapour pressure at surface (mb)		Surface winds after thunder-storm	Duration of anomalous propaga-tion (hrs)	Direction and maximum range of anomalous echoes
		before	after	before	after			
31-5-60/ 1-6-60	Thunderstorm activity till 2305 hrs. Rainfall over station : Nil	30·8	28·9	30·2	33·4	SW about 8 km/hr	0005–0530	W and NW 60 n.m.
12-6-60	Number of cells moved from west over station between 2045 and 2130 hrs. Rainfall : 0·3 mm	31·0	29·4	27·9	33·5	E 18 km/hr	2210–0200	N and NW 40 n.m.
19-6-60	Line of thunderstorms moved from west over station. Rainfall at station : 2 mm	30·5	27·7	30·1	33·4	SE 20 km/hr up to 2400 hrs. Weaker later	2000–0045 of next day	W 50 n.m.
22-6-60	A line of thunderstorm tracked from 40 n.m. west of station. Moved over station at 2030 hrs. Rainfall continued upto 2150 hrs, amount 10 mm	29·2	23·7	30·8	29·3 (Decrease in vapour pressure)	W 10 km/hr	No anomalous propagation	
23-6-60	Lines of thunderstorms tracked from about 40 n.m. NW of station. Moved past station by 1916 hrs. Rainfall over station : Nil	29·2	27·1	24·3	27·9	S/SW 10 km/hr	1950–2350	W and NW 40 n.m. NNE 20 n.m.
29-6-60	Thunderstorm activity till 2135 hrs. Rainfall : 0·5 mm	30·8	28·8	23·5	27·7	SW 18 km/hr	2135-2300	W 20 n. m. S and NNE 18 n. m.

are quite weak though rainfall is appreciable. Not even a single case of abnormal propagation was noticed in this season.

2.2. Particulars of a few June thunderstorms representing the southwest monsoon season are listed in Table 1 along with details of anomalous propagation, if any, observed. Table 2 gives similar particulars for a few October thunderstorms. An example of anomalous echoes in June is shown in Fig. 1. Fig. 2 gives the normal ground clutter for comparison. The echoes observed were carefully compared with super-refraction echoes obtained in fair weather periods (Raghavan and Soundararajan 1962).

2.3. Significant features of the echoes and the inferences which may be drawn from them are given below.

2.3.1. The echoes seen in the rear of thunderstorms correspond closely in position, appearance and intensity to super-refraction echoes in fair weather and most of these can be identified with ground targets. Hence these are echoes from ground objects obtained probably after refraction or reflection in the atmosphere.

2.3.2. The echoes usually extend to distances of about 40 nautical miles or more in the west and northwest and about 20 nautical

TABLE 2

Thunderstorms in October

Date	History of thunderstorm	Surface temperature (°C)		Vapour pressure at surface (mb)		Remarks
		before	after	before	after	
10-10-59	Thunderstorm moving W to E, came over station at 0440 hrs. Rainfall 3·5 mm. Squall NW, 61 km/hr	26·5	22·5	27·0	24·5	None of the cases was followed by anomalous propagation
19-10-59	Thunderstorm moving E to W touched station 0150. Rainfall 12 mm	22·0	20·8	23·3	22·3	
23-10-59	Line of thunderstorms moving from SE to NW, came over station at 0950 hrs. Rainfall 10·2 mm	27·5	24·0	29·4	26·8	
25-10-59	Line of thunderstorms moving SE to NW, came over station at 2250 hrs. Rainfall 2·7 mm	25·5	24·5	29·3	27·0	
26-10-59	Line of thunderstorms moving E to W, came over station at 1615 hrs. Rainfall 1 mm	34·0	25·0	32·4	27·9	

miles in the rest of the land area. They do not show any perceptible movement. Changes with time consist only of increase or decrease of intensity or number of echoes. Hence the reflecting layer, if any, must be a rather extensive one and not subject to any movement.

2.3.3. The radar was operated at angles of elevation of 0° or 1°. Since the beam width of the radar was 4° in the vertical plane, an appreciable amount of power would have been radiated at higher angles also.

2.3.4. The echoes were observed even in some cases when there was little or no rainfall reaching the ground. On the contrary the October storms gave considerable amount of rainfall but no anomalous echoes. The explanation given by the workers cited above, fails to explain this fact.

2.3.5. The duration of the echoes ranged from a few minutes to a few hours after the thunderstorm. There was no particular relation with surface windspeed. There were cases of persistent anomalous propagation even in moderate to strong winds. Hence whatever postulate is made to explain the echoes, it should provide sufficient refractive index gradient inspite of the mixing caused by the wind.

3. The Mechanism

3.1. The only mechanism which can explain all the above facts appears to be that the thunderstorm produces a downdraught which is cooler than the environmental air but *not* necessarily more moist. As shown in Tables 1 and 2, the surface vapour pressure at Madras just after the thunderstorm (which may be taken to be characteristic of the downdraught air) was *higher* than the vapour pressure before the thunderstorm (characteristic of the environmental air) in most of the cases met with in June. In October the vapour pressure after the thunderstorm was *lower* than the vapour pressure before the storm. The initiation of the downdraught is probably produced by the process outlined by Mull and Rao (1950), and has no direct relation with the rainfall or other conditions at the surface.

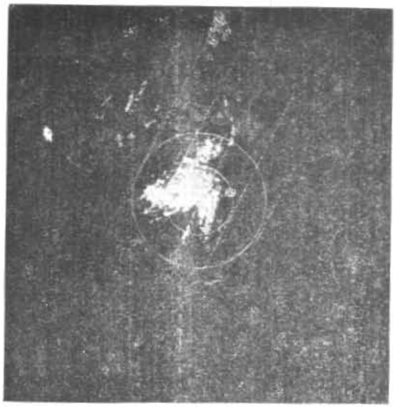

Fig. 1. An example of anomalous echoes following thunderstorm

Date : 12 June 1960, Time: 2310 IST

Range : 50 n. miles, Elevation: 1°

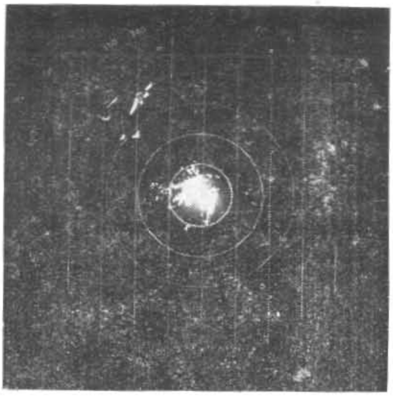

Fig. 2. Normal ground clutter at Madras

Range : 50 nautical miles

Elevation : 1°

3.2. We may further assume that this downdraught air which is in all cases denser than the environmental air, spreads as a shallow and extensive layer near the ground in the area swept by the storm with the relatively warmer and lighter environmental air above it. The boundary between these two masses of air will be a thin layer having favourable vapour pressure discontinuity if the downdraught is more moist than the environment. Propagation from the radar to a ground object at a range of 40 nautical miles or more, involving total or partial reflection from this boundary is, therefore, conceivable. However, in those cases when the downdraught is drier than the environment the effect of the vapour pressure gradient in the boundary layer is opposed to that of the temperature gradient and anomalous propagation is impossible.

3.3. The above explanation does not depend on the presence of rainfall at the ground and its evaporation to give rise to a favourable humidity gradient. However, it is necessary to show quantitatively that the necessary refractive index gradients exist at the required heights to produce sufficient reflection at the angles involved.

4. Quantitative evaluation

4·1. With a radar operated at 0° elevation, a reflecting layer should be available at a range of 20 nautical miles (37 km) in order to get an echo by the above mechanism at a range of 40 nautical miles. If such a layer is assumed to be horizontal as seen by an observer at M (Fig. 3) on the earth's surface, the radar beam travelling horizontally along RL will be incident on the layer at L. Since the path RL is entirely in the downdraught air, the path followed is an unrefracted one, provided L is close enough to ground to justify neglect of the effect on refractive index of pressure variations. If the range RL is 37 km, the height LM is readily shown to be h=108 metres. The glancing angle of incidence RLL_2 will be approximately 0·4°. If the layer of separation of the downdraught and environment is higher the beam will be incident on the layer at a still higher angle. Further it may be expected that a boundary layer between two masses of air with different wind speeds should be inclined at a small angle to the horizontal. Hence the glancing angle of incidence will be 0·5° or more.

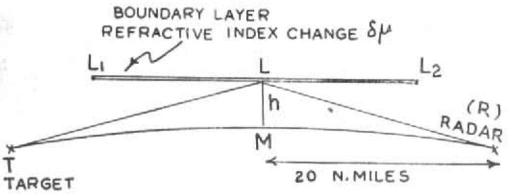

Fig. 3. Reflection from a boundary layer
(see para 4.1 of text)

4.2. Jones (1958) has considered reflection at a thin boundary layer at a small glancing angle of incidence. As shown by him if the refractive index change in the layer is $\delta\mu$, the critical angle $\phi_0 = (2\ \delta\mu)^{\frac{1}{2}}$. For $\delta\mu = 1\times 10^{-5}$, $\phi_0 = 0{\cdot}26°$. Even for $\delta\mu = 5\times 10^{-5}$ which is a large gradient rarely obtainable $\phi_0 = 0{\cdot}57°$. Hence the glancing angle of incidence in the cases considered above will be greater than the critical angle. This rules out total reflection at the boundary. Partial reflection discussed by Jones can, however, apply in this case.

4.3. If the surface temperature is T, vapour pressure is e and if the temperature and vapour pressure changes in the boundary layer are δT and δe, we have (Kerr 1951)

$$\delta\mu = \left[-\frac{A}{T^2}\left(p + \frac{2\,Be}{T}\right)\delta T + \right.$$
$$\left. + \frac{AB}{T^2}\,\delta e\ \right]10^{-6}$$

provided we neglect the contribution to $\delta\mu$ caused by pressure changes. Using the values of A and B given by Kerr and taking typical values for $T = 303°$ K, e = 30 mb,

$$\delta\mu = [-1{\cdot}68\ \delta T + 4{\cdot}13\ \delta e].\ 10^{-6}.$$

For the date 23 June 1960 in Table 1, this gives $\delta\mu = 18\times 10^{-6}$*.

4.4. Thus $\delta\mu$ values of the order of 15×10^{-6} are typical. To allow for some mixing and consequent destruction of the gradient a value of 10×10^{-6} would be a more realistic assumption.

4.5. De (1959) explains anomalous propagation after a thunderstorm in terms of the modified refractive index profile (M-profile) in a layer of a height of 2300 feet. However, in the above cases with a $\delta\mu = 10\times 10^{-6}$, if the change is spread over a layer of the order of 600 metres the M variation, taking into account the height term, is not at all an inversion. Hence the mechanism considered by De (1959) is not suitable in the present case and there is a need to postulate a *thin*† layer close to the ground over which the refractive index gradient is concentrated.

4.6. Jones shows that the power Pr received from the ground target by the radar receiver after propagation involving partial reflection at a layer at height h, which has a refractive index change $\delta\mu$, is

$$Pr = \frac{A}{64\ \pi h^2}\cdot\ \ \frac{(\delta\mu)^4}{\phi_0{}^5}\cdot\ P$$

where P is the transmitted power, A is the area of the antenna aperture. This is subject to the condition that the entire beam is intercepted by the layer. Substituting the constants of the radar set as $P = 20\times 10^3$ watts, $A = 1$ metre^2 and taking $\phi_0 = 0{\cdot}5°$, $\delta\mu = 10\times 10^{-6}$, $h = 100$ metres, we obtain $Pr = 2\times 10^{-12}$ watts approximately. This is about 13 db higher than the minimum detectable power of the radar. If the entire beam is not intercepted there would be a further decrease in received power, but still it would remain higher than the minimum detectable. Hence sufficiently strong reflection to give the observed echoes is possible.

---

*For the cases when the downdraught is drier, both δT and δe are negative and hence the refractive index of the environmental air is higher than that of the downdraught. However the value of $\delta\mu$ is too small to produce sufficient reflection

†The possibility that such a thin layer could exist in the atmosphere is supported by the observations of angel echoes by Jones and other workers, which cannot be explained by other means

4.7. A computation similar to the above for the case discussed by Mathur and Kulshrestha (1961) shows that $\delta\mu$ in that case was as high as 45×10^{-6} and it is not surprising that they could get echoes up to 60 miles.

5. Conclusion

It is thus seen that the frequent occurrence of anomalous propagation in one season and its absence in the other is explained by the different moisture content of the thunderstorm downdraught. The mechanism postulated namely partial reflection at a thin boundary layer explains the observed echoes without depending on the presence of rainfall.

6. Acknowledgement

The author wishes to record his gratitude to Dr. L. S. Mathur, Deputy Director General of Observatories, for his keen interest in this study and to Shri Y. P. Rao, Director, Regional Meteorological Centre, Madras for his constant encouragement which made the work possible.

REFERENCES

Coons, R. D. 1947 *Bull. Amer. met. Soc.*, **28**, pp. 324-329.

De, A. C. 1959 *Indian J. Met. Geophys.*, **10**, 4, pp. 420-424.

Jones, R. F. 1958 *Quart. J. R. met. Soc.*, **84**, pp. 437-442.

Kerr, D. E. 1951 *Propagation of Short Radio Waves*, Rad. Lab. Series, 13, McGraw Hill, New York, p. 13.

Mathur, L. S. and Kulshrestha, S. M. 1961 *Indian J. Met. Geophys.*, **12**, 1, pp. 71-77.

Mull, S. and Rao, Y. P. 1950 *Ibid.*, **1**, pp. 291-297.

Raghavan, S. 1962 *Ibid.*, **13**, Spl. No. (March), pp. 119-126.

Raghavan, S. and Soundararajan, K. 1962 *Ibid.*, **13**, 4, pp. 501-509.