ndian J. Met. Hydrol. Geophys. (1976), 27, 1, 49-54

551.501.81 : 551.513.11(540)

Super-refraction over west coast off Bombay

S. KUMAR, DAYAKISHAN and G. KRISHNAMURTHY

Regional Meteorological Centre, Bombay

(Received 13 January 1975)

ABSTRACT. The echoes observed in absence of any clouds over west coast off Bombay, during March-April 1974 are due to the super-refraction of the radar waves in the lower layers of atmosphere over the sea. These were found to occur whenever the sum of the ratios of the actual lapse rates of specific humidity and potential temperature to their critical values (for the occurrence of super-refraction) was unity or more. It is suggested that sea breeze circulation is mainly responsible for the formation of these echoes over west coast off Bombay during hot weather period.

The movement of the echoes, their intensity, distance from the station and their multiplicity have been correlated with the development, type and strength of the sea breeze circulation.

1. Introduction

The radar echoes observed in the absence of any conventional reflecting targets, have been studied by a number of workers. Various suggestions have been given for their possible sources. Rai (1961) has studied these echoes observed near Bombay. He has referred to them as angels and has related them to the existence of sharp refractive index gradients in the horizontally stratified layers over west coast off Bombay. But in his observations he was not able to show the existence of large gradients of temperature and humidity required for the occurrence of such echoes. Datar and Sikdar (1964) have suggested that the regions of subsidence of dry air to the lower moist levels, caused by the sea breeze circulation, might be the source of these echoes. In the present study a quantitative analysis of the gradients of specific humidity and potential temperature occurring in these layers has been made. The values of these gradients have been correlated with the occurrence of super-refraction echoes.

2. Data

The radar set used for the present study is the storm warning X Band B.E.L. radar*. Study of radar echoes observed during hot weather period of March-April 1974 was made. In this study 12 GMT radiosonde data only was used since the echoes were observed generally in the afternoon/evening. Sea surface temperatures were obtained from *Sagar Samrat* (Oil and Natural Gas Commission Research ship) which was in coastal waters at a distance of 100 km from Bombay. Since humidity values were not available either from *Sagar Samrat* or any other source at sea, these values were taken from Colaba observatory, which gives fair representation of the moisture content over sea surface.

3. Description of echoes observed

Fig. 1 shows the observations recorded on 21 March 1974. At 1145 IST some dot echoes, returns from Konkan coast and reflections from Gujarat coast were observed (Fig. 1 a). At 1245 hr the echoes from Konkan coast disappeared but dot echoes and reflections from Gujarat coast were still seen (Fig. 1 b). By 1435 IST a well marked wavy line concave towards the station appeared as seen in Fig. 1(c). This well-marked line type of echo continued for about an hour after which it started weakening.

Fig. 2 shows the photographic sequence obtained on 27 March 1974. The line echoes appeared at 1530 IST only and were well marked (Fig. 2 a). Without changing character, the line echoes moved towards the station and were at 80 km northwest of Bombay at 1630 IST (Fig. 2 b). At 1700 IST the line echoes were 70 km away from station (Fig. 2 c) and were seen weakening later on.

On 28 March the line echoes first appeared at 1130 IST (Fig. 3 a). The echoes were north-south oriented and were seen at a distance of 100 km. By 1415 IST the first line echoes moved further towards the station and a second line was seen forming at a distance of 120 km (Fig. 3 b). By 1615 hr multiple line echoes became clear (Fig. 3 c), the

---

*Characteristics : Wave length—X Band; Minimum range—400 km; Display—PPI and RHI ; Peak power—200 KW ; and Beam width—Conical 1°

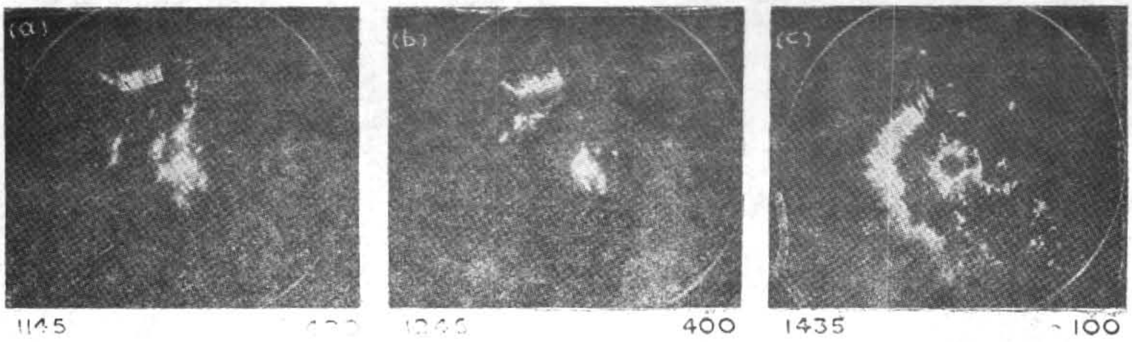

Fig. 1. 21 March 1974

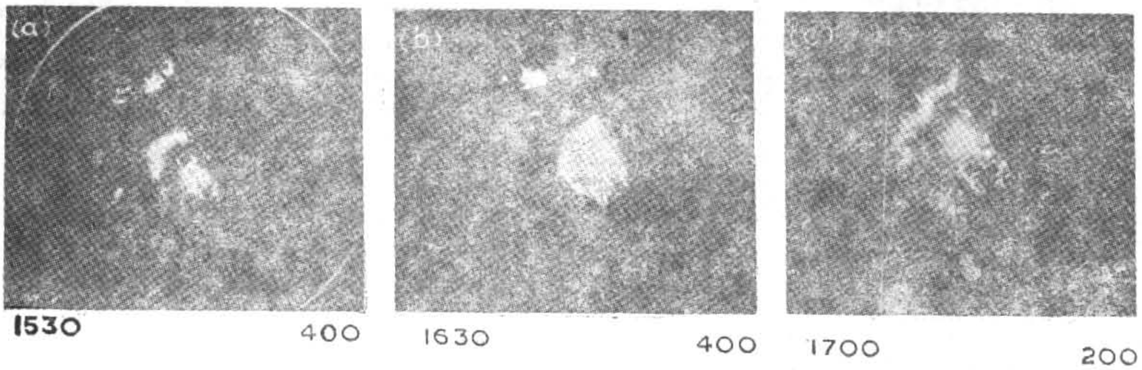

Fig. 2. 27 March 1974

PPI radarscope photographs at Bombay airport. Figures given below the photographs (from left to right) are time in IST and range in km respectively

first line being at 50 km followed by second at 110 km and third at 180 km from the station. These echoes continued to move towards the station and weakened (Figs. 3 b and 3 c).

Fig. 4 shows the echoes observed on 9 April 1974. The echoes were first sighted at 1230 IST, continued upto 1730 IST and thereafter started weakening. At 1620 hours there were three line echoes at 25, 50 and 80 km. The last one, of course, was very faint, possibly due to attenuation of the beam.

Observations on 10 April also showed two lines. These were seen at 1555 hr and moved slowly towards the station. By 1700 IST the first line was at 10 km and the other one at 20 km (Fig. 5). The echoes, being very near to the station, got mixed with the permanent echoes and therefore, it is difficult to indentify them clearly in the photograph.

4. Discussion

It is interesting to note that while on some occasions only single line echoes were observed but on other days there were two or three line echoes. In the following paragraphs an attempt has been made to correlate the existence of these echoes with the sea breeze circulation.

The sea breeze circulation causes subsidence of warm dry air over the moist sea surface layer. This results in steep inversion over the coastal waters. Since eddy diffusion in the inversion layer is low, a steep gradient of humidity is also set up in the same shallow layer. Thus sea breeze circulation leads to the formation of ducts, generally extending from the ground, in which steep refractive index gradients occur. Such steep gradients cause radar wave to bend sufficiently to strike the sea surface and causing super-refraction echoes to appear on the radar.

The formula giving the radio refractive index (n) as a function of atmospheric pressure (P), potential temperature (T) and partial water vapour pressure (e) is

$$(n-1) \times 10^6 = \frac{70}{T}\left(P - \frac{e}{7} + \frac{4800}{T}\, e\right)$$

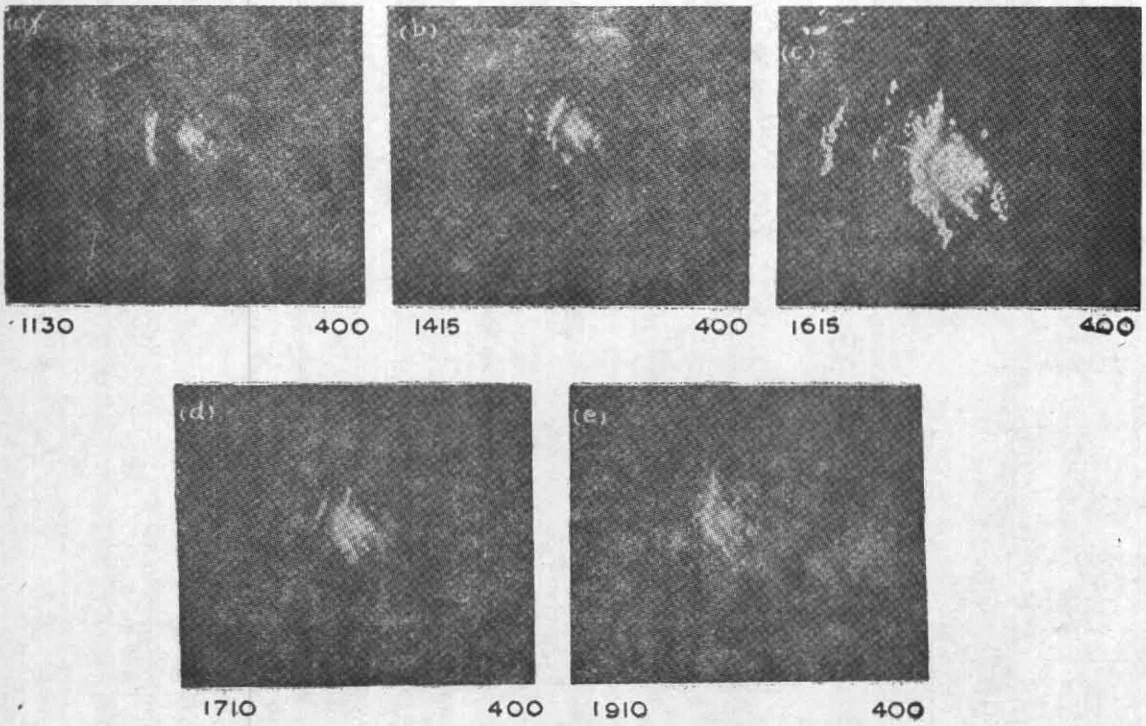

Fig. 3. 28 March 1974

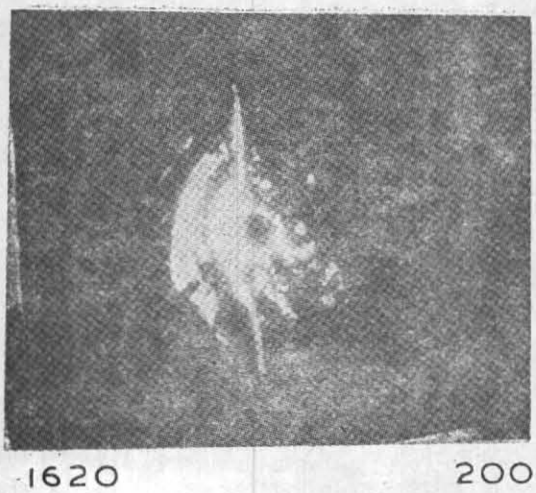

Fig. 4. 9 April 1974

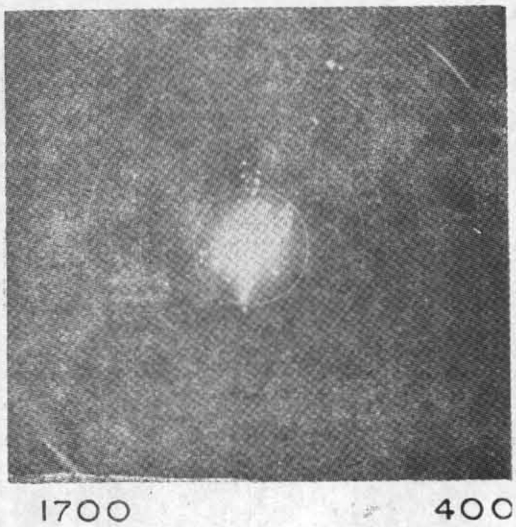

Fig. 5. 10 April 1974

PPI radarscope photographs taken at Bombay airport. Figures given below the photographs indicate (from left to right) time in IST and range in km respectively

Booker (1951) has calculated the critical lapse-rates of specific humidity α' and potential temperature β' which produce a lapse rate of radio refractive index sufficient to cause a downward curvature of the radar waves equal to the curvature of the earth. He has dealt the problem in two parts.

Booker considered (1) a situation in which the potential temperature was uniform with height and found the critical lapse rate α' of specific humidity to make the downward curvature of radio ray equal to the curvature of earth and (2) a situation in which specific humidity was uniform

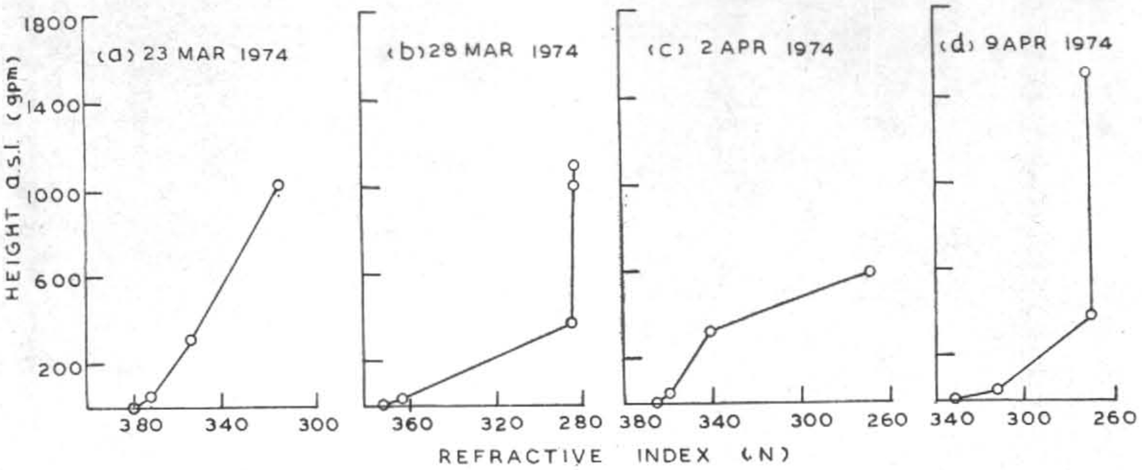

Fig. 6. Variation of refractive index with height

TABLE 1

Lapse rate of mixing ratio and potential temperature in the lower layers of the atmosphere over sea

Date (1974)	Type of echoes	Thickness of layer from surface (gpm)	Sea temp. (°C)	Temp. at top of layer (°C)	Lapse rate of pot. temp. (β)	Mixing ratio (gm/kg)		Lapse rate of mixing ratio (α)	Value of $\frac{\alpha}{\alpha'}+\frac{\beta}{\beta'}$
						Surface	Top		
20 Mar	Line	560	28	29·0	—0·32	17·0	4·2	0·69	1·5
21 Mar	Do.	400	28	20·0	—0·42	18·0	11·0	0·52	1·1
22 Mar	Dots	400	29	20·8	+0·32	18·7	13·4	0·44	0·8
23 Mar	No echoes	300	29	27·0	—0·01	18·8	15·9	0·30	0·6
25 Mar	Dot	400	30	28·0	0·00	16·6	15·0	0·12	0·2
26 Mar	Line	480	30	27·0	—0·13	16·6	3·5	0·78	1·6
27 Mar	Do.	480	30	25·0	—0·03	18·0	9·5	0·70	1·4
28 Mar	Do.	390	30	30·4	—0·31	17·7	6·3	0·88	1·9
29 Mar	Do.	350	31	33·4	—0·60	13·7	6·3	0·63	1·4
1 Apr	Dot	270	31	27·0	0·0	19·4	15·5	0·43	0·9
2 Apr	No echoes	300	31	25·6	+0·05	16·8	14·1	0·27	0·5
4 Apr	Line	600	29	32·0	—0·50	14·1	3·6	0·48	1·0
5 Apr	Do.	460	29	31·4	—0·50	19·6	3·6	1·99	2·3
6 Apr	Do.	250	29	32·0	—0·72	20·2	5·3	1·4	3·0
7 Apr	Do.	220	28	30·0	—0·33	15·7	6·9	1·2	2·5
9 Apr	Do.	200	30	33·2	—0·53	11·8	6·0	0·87	1·9
10 Apr	Do.	180	30	34·8	—0·83	20·0	15·0	0·80	1·8
13 Apr	Do.	390	30	27·4	—0·3	19·3	11·6	0·57	1·2

with height and found the critical value of lapse rate of potential temperature β' to make the downward curvature of radio waves equal to the curvature of the earth. These critical values as given by Booker (1951) are as follow :

$$\alpha' = 0\cdot 5 \text{ gm/kg/100 ft}$$

$$\beta' = -5^\circ\text{F/100 ft}$$

Let α and β be the lapse rates of specific humidity and potential temperature. Following the treatment of Booker, further we find that in the case of simultaneous variations in potential temperature and the specific humidity, the condition for the curvatures of the radar beam and the earth to be equal, resulting in trapping of the radar beam, will be

$$\frac{\alpha}{\alpha'} + \frac{\beta}{\beta'} = 1 \qquad (1)$$

For the curvature of the radar beam to be greater than that of the earth, resulting in the return of the radar beam to the earth well before the normal radar horizon, the condition will be

$$\frac{\alpha}{\alpha'} + \frac{\beta}{\beta'} > 1 \qquad (2)$$

Combining Eqs. (1) and (2), we find that super-refraction should occur when

$$\frac{\alpha}{\alpha'} + \frac{\beta}{\beta'} \geqslant 1 \qquad (3)$$

The values of α and β have been calculated (Table 1) for the lower layers of atmosphere over sea surface. It can be seen from the table that whenever Eq. (3) was satisfied, the super-refraction echoes were observed and on other days the echoes were not seen. The values of refractive index have also been calculated for some important cases and curves drawn to show variation of refractive index with height. On 23 March and 2 April, when no echoes were formed, the variation was much less steep (Figs. 6 a and 6 c), while on 28 March and 9 April, the variation in refractive index was very steep and there was an abrupt change (Figs. 6 b and 6 d) indicating the height of the duct. Thus steep gradients of temperature and humidity occurring within these ducts result in the formation of super-refraction echoes.

Near formation—On some occasions the echoes were observed at a distance of less than 30 km. On these days the prevailing winds were northeasterlies, *i.e.*, off-shore. These winds delayed the onset of sea breeze and allowed the surface temperature to rise very high. This resulted in the development of strong sea breeze circulation as suggested by Estoque (1961). The stronger circulation causes formation of ducts of smaller thickness in which lapse rates of temperature and humidity exceed the required criteria for the occurrence of super-refraction echoes.

Distant formation—On many occasions echoes were initially formed at a distance of 100-150 km. On these days the prevailing low level winds were northwesterlies, *i.e.*, on-shore. Since the sea breeze circulation with on shore winds is weaker and causes ducts of greater thickness to be formed this results in the occurrence of super-refraction echoes at greater distances from the station.

Movement of the echoes — The echoes generally start appearing in the forenoon and continue to exist till late afternoon. During this period, the echoes are observed to move towards the station. This can be associated with the development and movement of the sea breeze circulation. As the sea breeze circulation develops and moves inland the thickness of the duct satisfying the required criteria of lapse rates become smaller and therefore, echoes are observed near the station. Therefore, the echoes appear to move towards the station till late afternoon.

Datar and Sikdar (1964) have observed the westerly movement of the echoes in the late evening and the night (2145 to 2306 IST). The sea breeze at this time generally starts weakening or rather dissipating. With the result the inversion established over sea surface during daytime starts lifting up and weakening. This results in upwards diffusion of moisture. Therefore, the thickness of the required duct increases in the late evening or night. Hence super-refraction echoes appear to move away from the station. This gives westerly movement to the echoes in late evening or night. Rai (1961) has also confirmed the movement of the echoes towards the station in the afternoon and away from the station in the late evening in his sequence of photographs.

Multiple echoes — On some days multiple echoes were observed (28 March, 9 and 10 April). The echoes were generally identical in shape and nearly equidistant from each other. As can be seen from Table 1, on these days the gradients of humidity and temperature were very high in the lower layers of atmosphere over sea. Thus, ducts of small thickness were formed and these ducts probably extended to greater distances towards the sea. Hence multiple echoes were obtained generally starting from short distances from the station.

TABLE 2

Relationship of the distance of super refraction echoes with surface pressure, temperature and time of onset of sea breeze

Date (1974)	Time of onset of sea breeze (IST)	Max. surfrace temp. (°C)	Time (GMT)	Pressure at 12 GMT (mb)	Distance of nearest echoes (km)
20 Mar	0530	30·6	10	1007·4	50
21 Mar	0530	30·6	08	1006·4	50
22 Mar	0600	32·2	06	1005·1	No line
23 Mar	0330	30·6	08	1007·0	No echo
25 Mar	0600	33·0	08	1005·0	No line
26 Mar	0530	32·0	06	1006·5	100
27 Mar	0400	31·2	07	1006·5	70
28 Mar	0500	32·2	11	1005·5	50
29 Mar	0300	34·4	07	1006·3	80
1 Apr	0530	32·0	08	1004·2	No line
2 Apr	0330	31·5	07	1004·5	No echoes
4 Apr	0430	36·0	07	1004·5	N/R
5 Apr	0530	34·2	05	1004·5	50
6 Apr	0530	33·2	11	1004·8	50
7 Apr	0500	34·0	06	1004·7	N/R
9 Apr	0630	38·2	06	1004·3	25
10 Apr	0600	38·2	08	1003·0	10
13 Apr	0530	33·2	08	1005·0	Line

Echo distance versus surface temperature and pressure—Table 2 suggests that late setting in of sea breeze causes well marked echo activity. It also suggests that markedly high surface temperatures cause the echoes to be observed near the station. Both observations are in agreement with the earlier discussion. Thus it appears that a combination of late setting in of sea breeze, high surface temperature and low surface pressure, results in the occurrence of well marked super-refraction echoes towards the station.

5. Conclusions

(*i*) It is suggested that sea breeze circulation helps in causing steep gradient of temperature and humidity, over sea surface layers required for the occurrence of super-refraction.

(*ii*) With off-shore type of sea breeze, the echoes are observed generally near the station.

(*iii*) With on-shore type of sea breeze, the echoes are observed generally away from the station.

(*iv*) The development and movement of the echoes towards (late afternoon) and away (late evening or night) from the station is caused by the development and weakening of the sea breeze circulation.

Acknowledgements

The authors are thankful to Dr. A.K. Mukherjee, Director, Regional Meteorological Centre, Bombay and Shri C. E. J. Daniel, Meteorologist in-charge, Bombay Airport, for their guidance during the course of the study.

REFERENCES

Booker, H. G.	1951	Compendium of Meteorology, Amer. Met. Soc., pp. 1290-1295.
Datar, S. V. and Sikdar, D. N.	1964	*Indian J. Met. Geophys.*, **15**, 3, pp. 459-462.
Defant, Fzierich	1951	Compendium of Meteorology, Amer. Met. Soc., pp. 655-659.
Estoque, M. A.	1961	*Quat. J. R. Met. Soc.*, **87**, pp. 136-146.
Rai, D. B.	1961	*Indian J. Met. Geophys.*, **12**, 2, pp. 307-316.
	1961	*Ibid.*, **12**, 3, pp. 439-446.