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Sodar structures of inversion characteristics over Calcutta

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Abstract : In this paper remote sensing capability of a sound radar (SODAR) installed at Indian Statistical Institute, Calcutta has been presented for studying the various micrometeorological characteristics over Calcutta. During night-time different stable structures show great atmospheric variabilities and their identification, time of occurrences and duration will provide most valuable informations towards the research activities in the field of Communication, Atmospheric pollution and Atmospheric dynamics.

Keywords : Sodar, stable structure, thermal plumes, fumigation and radiosonde.

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1. Introduction

Much progress has been made in research and study of the convective boundary layer occurring during day time. The turbulent structure of atmospheric layer (ABL) may be described in terms of mixed layer scaling (Kaimal *et al* 1976). In contrast, studies in the field of nocturnal stable boundary layer are considerably less. Many investigators have explored the problem of stable boundary layer from observational and theoretical view points. Related studies (Brost and Wyngaard 1978, Caughey *et al* 1979) show that the stable boundary layer in the atmosphere is continuously evolving. This means that its structure can not be described only by steady state equations involving the local parameters (i.e. surface heat and momentum flux) but also in terms of a prognostic equation which describes the time evolution of the boundary layer.

Each of the occurrences of stable ABL is dominated by different physical processes. A few examples of such processes are topographical slope effects (Brost and Wyngaard 1978), intermittent turbulence (Kondo *et al* 1978), and internal gravity waves (Finnigan and Einaudi 1981). Temperature inversions have a two

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fold importance in that, (i) they are spatially widespread and persist relatively over a long period of time, and (ii) they exercise a stabilising influence on air motion so that turbulence is suppressed and strong humidity gradients may develop. Layers, over which an intense super-refraction can occur to the point of ducting condition, may be formed and with the help of these gradients may trap microwaves. Thickness of this layer has shown great variability. For such temperature inversions responsible for these layers, it has been found that two processes, namely, radiation and subsidence would be necessary.

Acoustic sounding technique (SODAR), based on interaction of acoustic waves with the wind and the temperature turbulence of the lower atmosphere, has been extensively used to probe the microstructure of the planetary boundary layer (PBL). Obviously this remote sensing technique, provided by the sodar, offers continuity in both space and time. Detailed informations regarding the early development of sodars and experimental work investigating the micro-structure of the PBL in the decade of 1961-1977 can be found in the review paper (Brown and Hall 1978).

At the Indian Statistical Institute (ISI)—Calcutta, a sound radar (SODAR) system has been installed for continuous monitoring of the atmospheric boundary layer upto 1 km height range. This project was funded by the Dept. of Science and Technology, Govt. of India in 1985. Calcutta is located slightly away from the sea-coast and has a frequent thunderstorm/nor'wester activities almost round the year. Moreover, because of its higher humidity content, the climatology of this eastern coastal region is comparatively different from the climatology of other coastal stations within India. Depending on micro-/mesoscale meteorological condition of the lower atmosphere around the observational site, different types of atmospheric structures are recorded on the sodar echographs. The information contained in the structure are sometimes easy to read but many a time appear to be difficult to interpret. The recorded echo structures during the period of 1986-87 can be grouped into two broad classes, thermal and shear echoes. Detailed characteristics of the shear echoes observed in that period are analysed and discussed in the subsequent sections.

2. SODAR signature of boundary layer behaviour over Calcutta

During daytime, the solar radiation heats up the earth's surface and this in turn heats the air mass of the lower atmosphere resulting in convective mixing. The mixed layer may be of a few kilometer deep. Within this depth, in absence of condensation, the vertical temperature gradient is almost close to dry adiabatic. While the heating is in progress, just above the ground a shallow layer which is markedly superadiabatic, is formed. The mixed layer is mostly surmounted by

(i) a sharp inversion, or a well-defined stable layer which may have been formed solely by the convective mixing of layers below, and (ii) sharpening of a pre-existing inversion which has limited the vertical extent of the convection columns. Typical examples of atmospheric structures as detected by radiosonde flight are shown in Figure 1. These soundings are experimented in the early

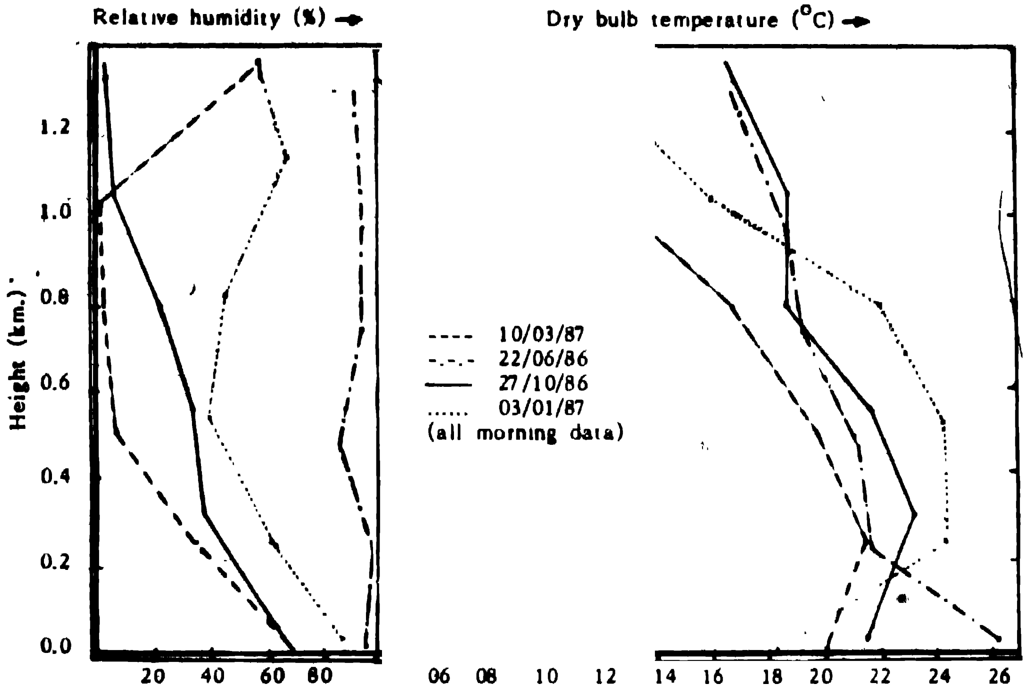

Figure 1. Radiosonde observation of lower atmosphere at Dum Dum.

morning hours at the India Meteorological Dept. (IMD), Dum Dum which is about 2 kms from the sodar site and indicates clearly the presence of nocturnal inversion over this region.

Round-the-clock operated monostatic sodar at ISI also indicates the various micrometeorological and meso-meteorological conditions (Figure 2) surrounding the sodar site. The morning echogram shows a surface-based layer of statically stable air. Turbulence is generated in the layer due to solar heating of the ground. Slow build-up of the convection develops a mixed boundary layer which erodes the morning stable inversion at 0900 IST onward and the depth of mixed boundary layer increases gradually (Figure 2a). Thermal plumes, like the rising of stalagmites from ground, are formed around 1145 IST on 22/5/86 under rising inversion as shown in Figure 2(b). This transition period from stable to unstable atmospheric conditions is recognised as the most active fumigation period.

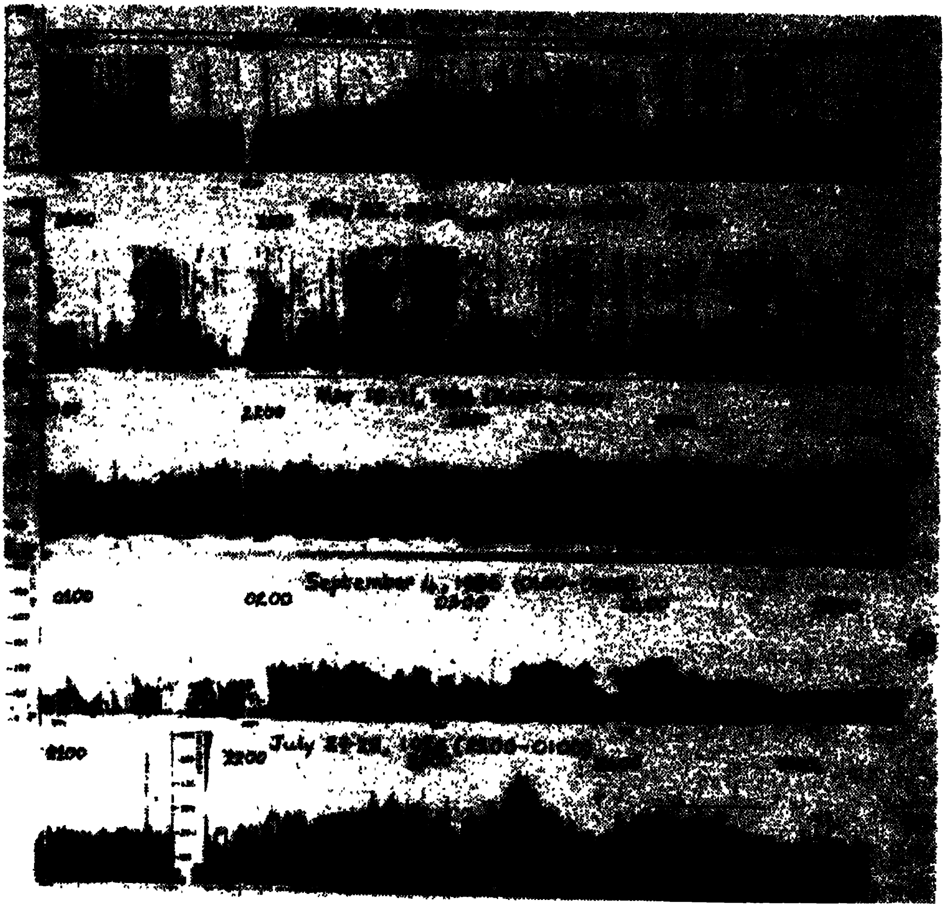

Figure 2. Various boundary layer condition over the sodar-site.
(a) Breaking of inversion and subsequently starting of thermal plumes (0700-1130, 9/2/86).
(b) Plume characteristics (1000-1400, 22/5/86).
(c) Stable inversion characteristics (2100-0100, 10-11 May, 1986).
(d) Mixed characteristics (0100-0500, 4/9/86).
(e) Stable characteristics with wavy layers (2100-0100, 27-28 July, 1986).

The trapped effluents in stable conditions are spread out and may create fumigation. Rise in surface temperature bears a simple relation with rising inversion (Kaimal *et al* 1976) as,

$$\frac{\delta T}{\delta t}=K\frac{\delta h}{\delta t}+0.8$$

where $\frac{\delta T}{\delta t}$ is the temperature rise and $\frac{\delta h}{\delta t}$ is the inversion rise with respect to time and K is a constant depending upon the topological factors, wind conditions etc.

The maximum temperature of this city is observed within 1300-1400 IST in the summer season. Plume height and plume occurrence rate also happened to be maximum during that period. On 22/5/86, the sky was not so clear and the maximum temperature was recorded around 1200 IST. This is also reflected in sodar echogram of plume structure as shown in Figure 2(b). With the gradual reduction of solar heating in the afternoon hours, the vertical height of the plume also gradually decreases.

The plumes disappear completely within dusk and short-ranged strong echoes having abrupt but almost uniform upper limits begin to appear at 2100-2300 IST on 10/5/86 (Figure 2(c)) and this has been mostly observed within the height range of 200-300 meters above the ground. Height of the stable layer varies from month to month in this coastal region. Such inversions are formed largely by the turbulent transfer of heat down towards the ground which is being cooled radiatively. At night, due to radiative transfer of heat, the earth surface cools and during such time of transition, shear echoes are observed. Height of the shear echo structures gives a measure of the depth of stable boundary layer. The shear echo may also occur in an unstable situation, say next to the ground when the temperature profile is unstable but the wind (and hence wind shear) is so strong that the mixing is dominated by the turbulence rather than by organised convection. A mixed structure as observed during 0100-0400 IST on 4/9/86 is shown in Figure 2(d).

The night time atmospheric structures have a high degree of variabilities showing presence of ground based layer of variable thickness, the appearence of highly variable multiple layers, the wavemotions within and above the inversion and turbulence structures. All these contribute towards the maximum atmospheric variability at night. The formation of waves enables one in studying the dynamics of boundary layer. The mechanism of wave generation includes both static and dynamic instabilities (Singal *et al* 1985). The wavy layers as shown in Figure 2(e), characterise calm or very light wind condition (2100-2200 IST on 27/7/86), while waves with herringbone type represent strong wind shear (2200-0100 IST on 28/7/86).

Characteristics of the convective and stable boundary layers have been described mathematically by several authors (Clark 1970, Deardoff 1972, Businger and Arya 1974) but most of the equations describing the boundary layer heights are based on local parameters such as surface-heat and momentum-flux only. However, recent study (Brost and Wyngaard 1978) has showed that the stable atmospheric boundary layer is continuously evolving and can not be described by steady-state equations. Obviously height of the boundary layer should be expressed in terms of a prognostic equation which describes the time evolution of the boundary layer. Though the height of an unstable PBL can be determined by the height of an inversion base for which prognostic equations have been successfully derived (Stull 1976), the boundary layer height at stable condition is not so well defined from the mean potential temperature and humidity profile.

3. Statistics of ground based and elevated inversion

The ground based inversion is generally a night time phenomenon. It has been observed that, in general, the ground based inversion height increases after sunset and matures slowly till mid-night, remains more or less steady for a few hours and then starts rising after 2/3 hours of sunrise when the ground becomes hot. The height of the ground-based inversion depends upon several meteorological conditions prevailing over that site. It is minimum in the winter season at Calcutta while it attains high value in the premonsoon. The monthly variation of ground-based inversion height in this region during one year period (April 1986-March 1987) is shown in Figure 3 along with their maximum and minimum

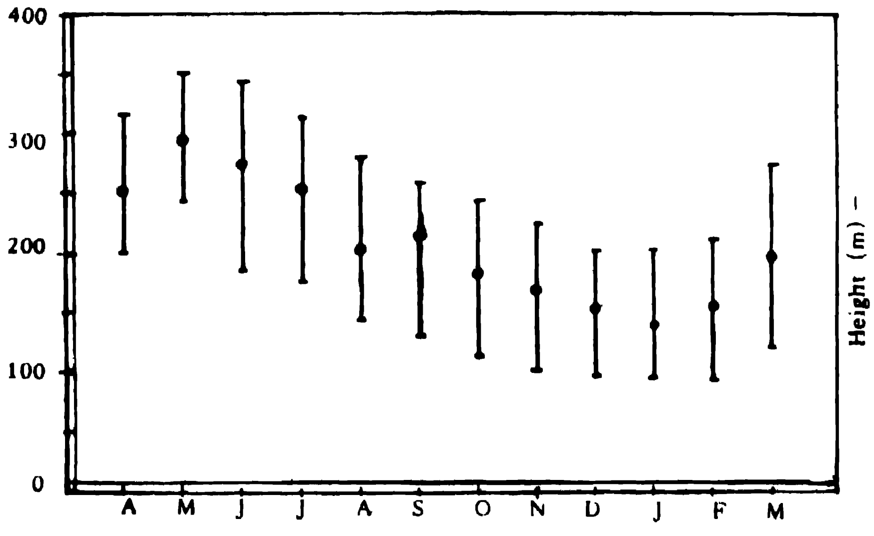

Figure 3. Monthly variation of ground-based inversion (1986-87).

value. The occurrence of elevated/multilayers at this region is also a night time phenomenon, of course, sometimes elevated/ground-based inversions are noticed during daytime due to the passage of sea-breeze and fronts, but their percentages are very low.

Sodar data of about 300 days of the one year period (1986-87) were analysed to study the occurrences of various atmospheric structures over this region. Percentage occurrence of the various structures is shown in Figure 4. The stable structures occur normally at night time and is about 66% while the unstable structures, which occur mostly after sunrise to sunset, is about 28%. The mixed structures of plumes capped by an inversion, representing the morning transition, is about 4% only. The height attained by the inversion layer, before it completely dissappears, is about 350 to 450 meters. On a few occassions no structures have been observed during the night-time.

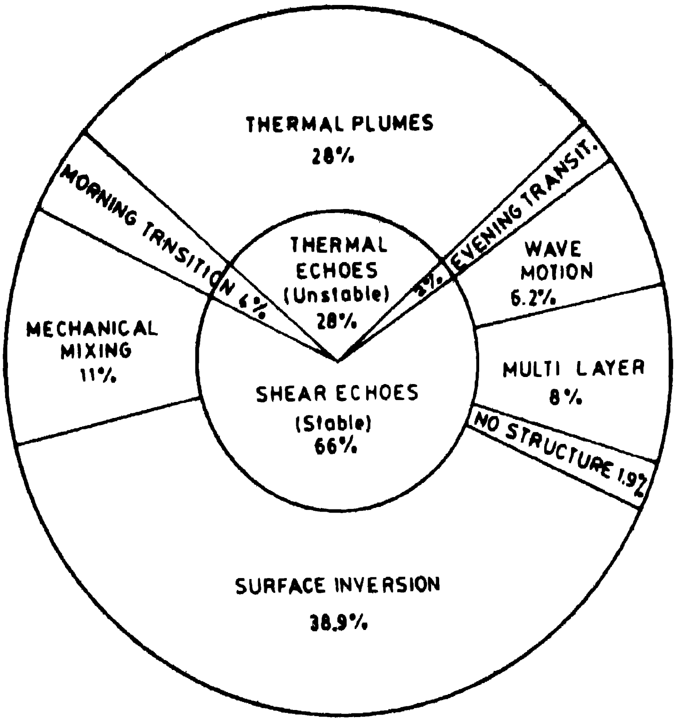

Figure 4. Occurrence percentage of various structures recorded on ISI sodar (April '86-March '87).

Regarding the detailed structures of the ground-based inversions, it has been shown (Singal *et al* 1985) that the height of shear echo structures provides a measure of depth of the stable boundary layer, while the stratification denotes turbulent interface between two layers of stable structures (Brost *et al* 1978). The time-variant structures give information of the thermally induced changes taking place in the ABL. Different characteristics of the ground based structures usually prevailed over Calcutta during the one year period can be summerised as follows :

(i) During light or no-wind conditions, strong short-ranged echoes having abrupt but almost uniform upper limit appears (Figure 5a) at 0000-0200 IST on 22/10/86. Thickness of these echo layers may slightly increase with time if same weather conditions persist. This type of ground based structures are mostly prevailed in the winter and post-monsoon months over Calcutta and their thickness vary from 100-200 m. Maximum depth of surface-based inversion occurs in the pre-monsoon season and it attains a height of 300-350 m during this period.

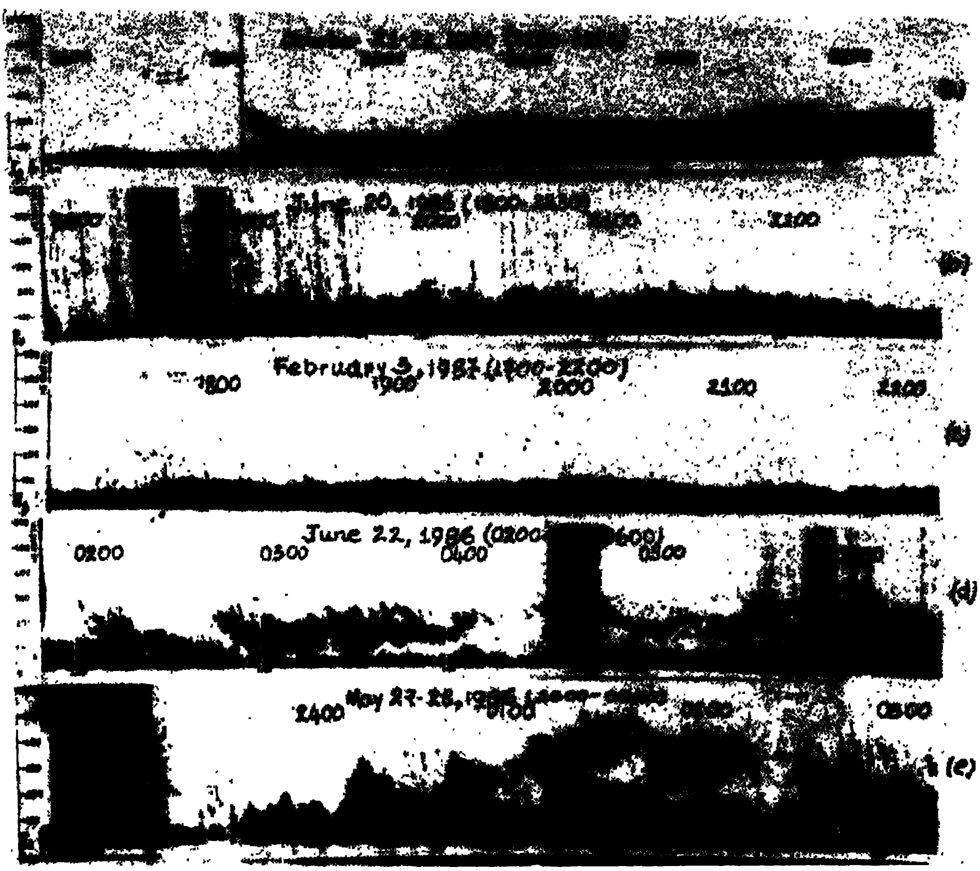

Figure 5. Various characteristics of inversion structure.
(a) Passage of cold fronts (2100-0230, 21-22 October, 1986).
(b) Stable structure with random spikes developed after rain (1800-2230, 20/6/86).
(c) Stable inversion with dot struture (1700-2200, 3/2/87).
(d) Multilayer structure (0200-0600 22/6/86).
(e) Stable structure showing wave like peaturbation (2300-0300, 27-28 May, 1986).

(ii) As the wind velocity increases, mixing within the stable layer occurs and flat top of the surface-based layers shows random spike structure. Though these are mostly short, as shown on 20/6/86 during 1900-2100 IST (Figure 5b), may be discrete and tall also. The appearence of spike indicates the gustiness of wind (Caughey *et al* 1979). Tall spikes over the surface based inversion are usually observed in the pre-monsoon and post-monsoon seasons over Calcutta. Surface winds are also found to be high. Sometimes nor'westers/thunderstorms are observed in the evening hours during the season. Short-lived small scale irregularity/dot structures are also noticed occassionally during night time (1745-2100 IST on 3/2/87) as shown in Figure 5(c). Although their frequency is low, they are supposed to form due to excess of water-vapour present in the lower atmosphere soon after the precipitation.

(iii) Another frequent phenomena is the occurrence of stratified layer structures (0245-0545 IST on 22/6/86), as shown in Figure 5(d), which are mostly observed within 100-400 m height range and is found to occur in all seasons. In this coastal region, their occurrence frequency is comparatively high with pretty

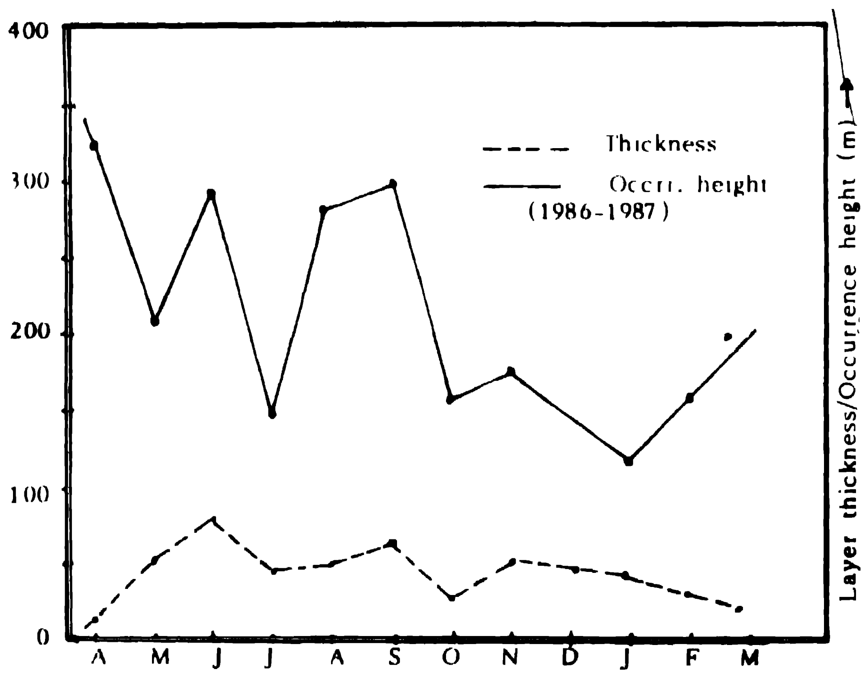

Figure 6. Monthly variation of elevated structure (Calcutta).

high humidity content of the lower atmosphere. Most probably the formation of these structures are related to the water-vapour content of the lower atmosphere. In fact, they are found to occur sometimes after thunderstorm and rain in this region. Scruitinising one year sodar data of this region, we have observed that about 40% of evening thunderstorms initiated the formation of elevated structures. These structures may be due to subsidence effect and are associated with some oscillatory characteristics exhibiting features of typical wave motion under clear weather conditions (0000-0115 IST on 28/5/86) as in Figure 5(e) and some vortices or slightly rounded sawtooth uuder turbulent weather conditions.

The monthly variation of these elevated structures in this region is shown in Figure 6. Their occurrence frequency is maximum in the winter months and is minimum in the monsoon months over Calcutta. The thickness of the elevated layer is highly variable and may vary from 15 to 80 meters. Similarly their height of occurrences show large variations, ranging from 125 m to about 325 m. Sometimes these layers are associated with multiple layers separated from one another by 50 m height. Also they are sometimes merged with ground-based inversions after persisting for 1-2 hours or disappear completely.

Most of these elevated structures are formed after sunset and persist for 4-5 hours till the sun rises. Figure 7 shows the relative time of occurrences of these

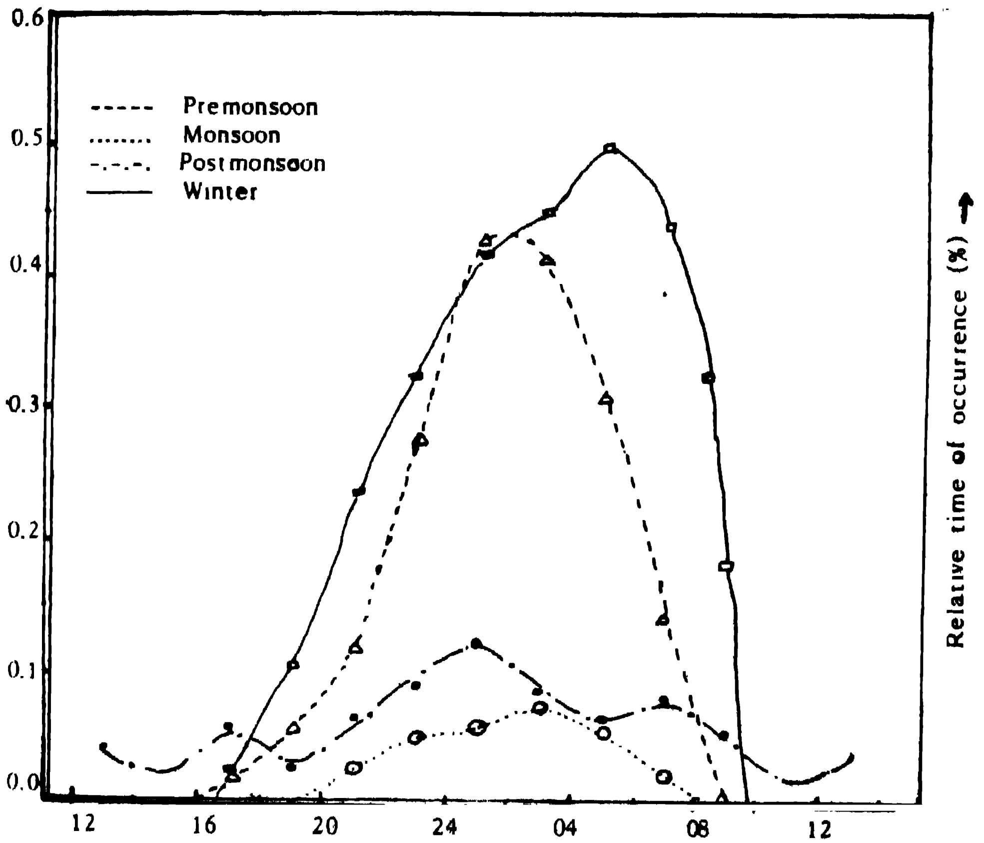

Figure 7. Seasonal time of occurrences of elevated structure (Calcutta).

layers in different seasons. From this curve it appears that most of them occurred around 0000 hours and completely dissipated around 0830 hours. Average duration of their occurrences is about 3 hours though very short-lived layers are also observed for 15 to 40 minutes duration. These layers, which are merely the more extreme examples of anisotropic irregularities, may be prevalent in the troposphere. An inspection of sodar and refractometer data reveals that the horizontal dimensions of a few km of these layers represent a realistic assumption. The results obtained from refractometer and radar soundings (Lane 1963) has made evidence of preliminary supporting of this concept.

Thus, sodar can effectively be used for continuous monitoring of the lower atmosphere that consists of different degrees of refractive index turbulence and stratification. Since large gradients of refractivity are often coupled to temperature inversion (Nilsson 1977), information obtainable from sodar can be used to predict the behaviour of tropospheric communication (Das *et al* 1989). Infact, the importance of changes of radio refractive index over the first few hundred meters above the ground is essential for estimation of the bending of the radiowaves towards the earth. The refractive index structure parameter in a given volume of atmospheric air, especially in a thin transition zone, often has a large value compared to an adjacent equal volume of air. This causes anomalous propagation conditions through multiple interference, focussing and defocussing of the transmitted energy. Higher refractivity gradients correspond mostly to the presence of perturbations and multilayer structures. Various types of structure recorded on sodar echograms can be used as an effective indicator of the LOS microwave propagation characteristics (Gera and Sarkar 1980). Quantitative measurements of the temperature structure parameter from the sodar data would further add to these information in near future.

4. Conclusion

Quantitative evaluation of acoustic echoes and their comparison with the lower atmospheric measurements is a subject of current research interest. Sodar information are micro-meterological in nature and are in real time and space. They add the information to the data-base already collected through thermograph, anemometer, tethered balloon, kytoon and instrumented tower etc. Information from these and other related instruments also help many a time to understand sodar structures. It is evident from the present discussion that both stable and unstable temperature gradients can very nicely be identified by an acoustic-radar. Boundary layer information on the Pasquill stability categories (Singal *et al* 1985) predicts the pollutant concentration volume available for diffusion. Changes from land to sea breeze or vice-versa and the advection of cold air masses at any time can lead to fumigation in and around an industrial area responsible for effluent emission.

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References

Brost R A and Wyngaard J C 1978 *J. Atmos. Sci.* **35** 1427

Brown E H and Hall F F 1978 *J. Geophys. Space Phys.* **16** 47

Businger J A and Arya S P S 1974 *Advances in Geophysics* **18A** (New York : Academic) p 73

Caughey S J, Wyngaard J C and Kaimal J C 1979 *J. Atmos. Sci.* **36** 1041

Clark R H 1970 *Quart. J. Royal Meteorol. Soc.* **96** 91

Das J, De A K, Dutta Majumder D, Sen A K and Basumallick S K 1989 *Indian J. Phys.* **63B** 149

Deardoff J W 1972 *Mon. Weather Review* **100** 95

Finnigan J J and Einaudi F 1981 *Quart. J. Roy. Meteorol Soc.* **107** 807

Gera B S and Sarkar S K 1980 *Indian J. Radio and Space Physics* **9** 86

Kaimal J C, Wyngaard J C, Caughey S J and Reading C J 1976 *J. Atmos. Sci.* **33** 2152

Kondo, Kanechika J O and Yasuda N 1978 *J. Atmos. Sci.* **35** 1012

Lane J A and Meadows R W 1963 *Nature* **197** 35

Nilsson J 1977 *URSI Commission F Colloque onvert La Baule (France), Proceedings Comptes Rendus 28 April-6 May 1977*

Singal S P, Aggarwal S K, Pahwa D R and Gera B S 1985 *Atmos. Environ.* **19** 221

Stull R B 1976 *J. Atmos. Sci.* **33** 1260