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A study of sodar observed shear echo structures in relation to wind velocity and other turbulence parameters

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सार — पवन वेग, घर्षणी वेग और रिचर्डसन संख्या के मौसम विज्ञान संबंधी प्राचलों में परिवर्तनों से संबंधित रात्रिकालीन स्थायी अवस्थाओं के दौरान भूमि पर विभिन्न प्रकार की सोडार प्रेक्षित संरचनाओं का अध्ययन किया गया है। इन अध्ययनों के लिए मई 1977 से अप्रैल 1982 के आंकड़े प्रयोग में लाए गए। इसमें यह देखा गया है कि पृष्ठीय पवनों का सतही संरचनाओं पर आधारित लम्बी नुकीली सतह में योगदान होता है जब कि घर्षणी वेग और रिचर्डसन संख्या का परिवर्तन, क्रमशः 100 मीटर और उससे अधिक की ऊंचाई के स्थायी स्तरों में भंवरों के निर्माण और विघटन के विषय में सूचना देता है।

ABSTRACT. The various types of sodar structures observed on land during nocturnal stable conditions have been studied in relation to the changes in meteorological parameters of surface wind speed, frictional velocity and Richardson's number. The data for the period May 1977 to April 1982 have been used for these studies. It has been found that surface winds contribute to the tall spiky surface based layer structures while the behaviour of the frictional velocity and Richardson's number give information about the formation and break up of the eddies in the stable layers of height upto 100 m and more respectively.

1. Introduction

Solar heating and nocturnal cooling of ground surface is responsible for developing thermal boundary layer in the lower atmosphere. The height and structural details of this layer keep on varying depending upon the progress and meteorological conditions of the day. Typically on land an unstable convective boundary layer is developed during day time and a stable boundary layer during night time. The nocturnal stable boundary layer on a clear day begins to establish soon after sunset, continues to grow till early morning and dissipates after sunrise when a thermally convective atmosphere starts developing on the ground. Apart from radiative cooling it has been found that other parameters like shear generated turbulence and horizontal advection of cold air are also responsible for the growth of the nocturnal boundary layer. Out of these factors wind effects are more complex in nature and have been drawing attention (Blackadar 1957; Kaimal & Izumi 1965; Clarke 1970; Businger & Arya 1974) from time to time.

We had been looking at the nocturnal thermal boundary layer structures at Delhi for the past many years with the help of monostatic sodar (Singal & Gera 1982). The system has the capability to observe the thermal boundary layer to a height range of 700 m from the ground level. As stated above, since thermal boundary layer can be modified under the influence of winds in the boundary layer, in the following we, therefore, report studies made on the nocturnal sodar shear echo structures with respect to the turbulent parameters of surface wind velocity and other related parameters like frictional velocity and Richardson's number etc.

2. Data

The analysis has been carried out on the basis of the data procured for the period May 1977 to April 1982. Sodar and electrical anemometers were housed close to each other at the National Physical Laboratory (N.P.L), New Delhi. These instruments were respectively recording the thermal structures of the boundary layer and the surface wind speed. Hourly averaged values of the recorded data were used for analytical purposes. The meteorological data for the first significant layer of the atmosphere were obtained from the radiosonde flights made at 00 and 1200 GMT at Aya Nagar observatory of India Meteorological Department (IMD), New Delhi. It may, however, be mentioned that this site is located in rural surroundings about 20 km south of the N.P.L. which is located in an urban area.

3. Analytical results and discussion

Typical shear echo structures of the nocturnal boundary layer observed by sodar (Fig. 1) are surface based layers with flat, short spiky & tall spiky top and stratified layers with or without the oscillations superimposed over them. A study of the relative occurrence probabilities of these structures shows that short spiky

TABLE 1

Percentage occurrences of the different types of stable sodar structures for various range of surface wind speeds

Layer structure type	Percentage occurrence for speed (u) (m/s)					Percentage occurrence for speed (u) (m/s)				
	$u \leq 2.5$	$2.5<u\leq 5$	$5<u\leq 7.5$	$u>7.5$	Total	$u \leq 2.5$	$2.5<u\leq 5$	$5<u\leq 7.5$	$u>7.5$	Total
	Height $\leq$ 150 m					**Height > 150 m**				
Tall spiky top	20.5%	8.0%	1.9%	1.3%	31.7%	26.8%	28.4%	10.1%	3.0%	68.3%
Short spiky top	44.0%	4.3%	0 %	0 %	48.3%	37.8%	10.7%	2.7%	0.5%	51.7%
Flat top	67.5%	8.6%	1.2%	0.8%	78.1%	13.0%	5.7%	3.2%	0 %	21.9%
	Height < 200 m					**Height > 200 m**				
Stratified	48.8%	16.2%	5.3%	0.5%	78.8%	16.9%	8.6%	3.0%	0.7%	29.2%

top surface based layers occur for 40% of the time, tall spiky top surface based layers occur for 28% of the time, flat top surface based layers occur for 14% of the time and stratified layer structures for 18% of the time. Futher it has been seen that the maximum observed height of the flat top layer is 300 m (mean at 175 m), of the short spiky top layer is 350 m (mean at 230 m), of the tall spiky top layer is 550 m (mean at 250 m) and of the stratified layers is 600 m (mean at 300 m). A comparison of the sodar observed height of the shear echo structures with the corresponding height of temperature inversion recorded by the radiosonde system shows that sodar observed height of the nocturnal boundary layer compares only in 30% cases with the radiosonde observed inversion boundary layer height, a behaviour which can be expected also since the two sites of observation have entirely different environments.

The observed fine structure of the nocturnal shear echoes may be due to the variation in wind speed, the consideration being based on the observation that sodar gives a reflex image of the turbulent boundary layer wherein the turbulence is being generated by temperature and wind inhomogeneities (Brown and Hall 1978). Since changes in surface wind velocity can result in turbulence, therefore, one of the most outstanding modification in the nocturnal boundary layer under the effects of surface winds can be the change in the fine structure of the nocturnal shear echoes. For a systematic study of the relationship of the various types of structures with surface wind speed, we have divided the observed nocturnal boundary layer into two zones, the lower zone and the upper zone. As in the case of stability studies (Singal *et al.* 1985), the lower zone has been kept upto 150 m in case of flat top, short spiky top and tall spiky top layers and upto 200 m in case of stratified layers. The upper zone exists above these respective limits only.

The occurrence probabilities of the various types of shear echo structures in the two zones corresponding to various values of suface level wind speeds have been studied and are given in Table 1. The tabulated results have been normalised taking into consideration the total data for any one type of shear echo structures in the whole height range of observation. The following can be easily seen from the tabulated results :

(*i*) Percentage occurrence of tall spiky top surface based layers for heights beyond 150 m is more (68.3%) compared to those observed at heights upto 150 m (31.7%). Further, tall spikes beyond 150 m pertain more often to wind speeds upto 5 m/s while those upto 150 m pertain more often to wind speeds upto 2.5 m/s.

(*ii*) Percentage occurrence in case of short spiky top surface based layer structures is equally divided for the two height ranges, *i.e.*, upto 150 m and beyond 150 m with bulk of them occurring (81.8%) for wind speeds ranging upto 2.5 m/s.

(*iii*) Smooth top surface based layers occur more (78.1%) for the height range upto 150 m compared to height range beyond 150 m (21.9%) with bulk of them (80.5%) occurring for surface wind speeds upto 2.5 m/s.

(*iv*) Percentage occurrence of stratified layer structures is more (70.8%) for height range upto 200 m compared to height range beyond 200 m (29.2%) with stratification being seen more often (64.9%) for surface wind speeds upto 2.5 m/s.

The above results clearly show that stable structures of flat top, short spiky top and stratified layers are generally formed when the surface wind speed is low (*i.e.*, within 2.5 m/s) while stable layer structures of tall spiky top have been formed more often in the presence of moderate surface winds (upto 5 m/s). Based on this finding for further consideration of the processes involved in the formation of the observed structure we can treat flat top, short spiky top and stratified layers as one type of stable layer structures while tall spiky top structures may be another kind of a stable layer involving different phenomena of turbulence.

Frictional wind velocity (Hanna *et al.* 1982) may be a better element to correlate with the observed sodar

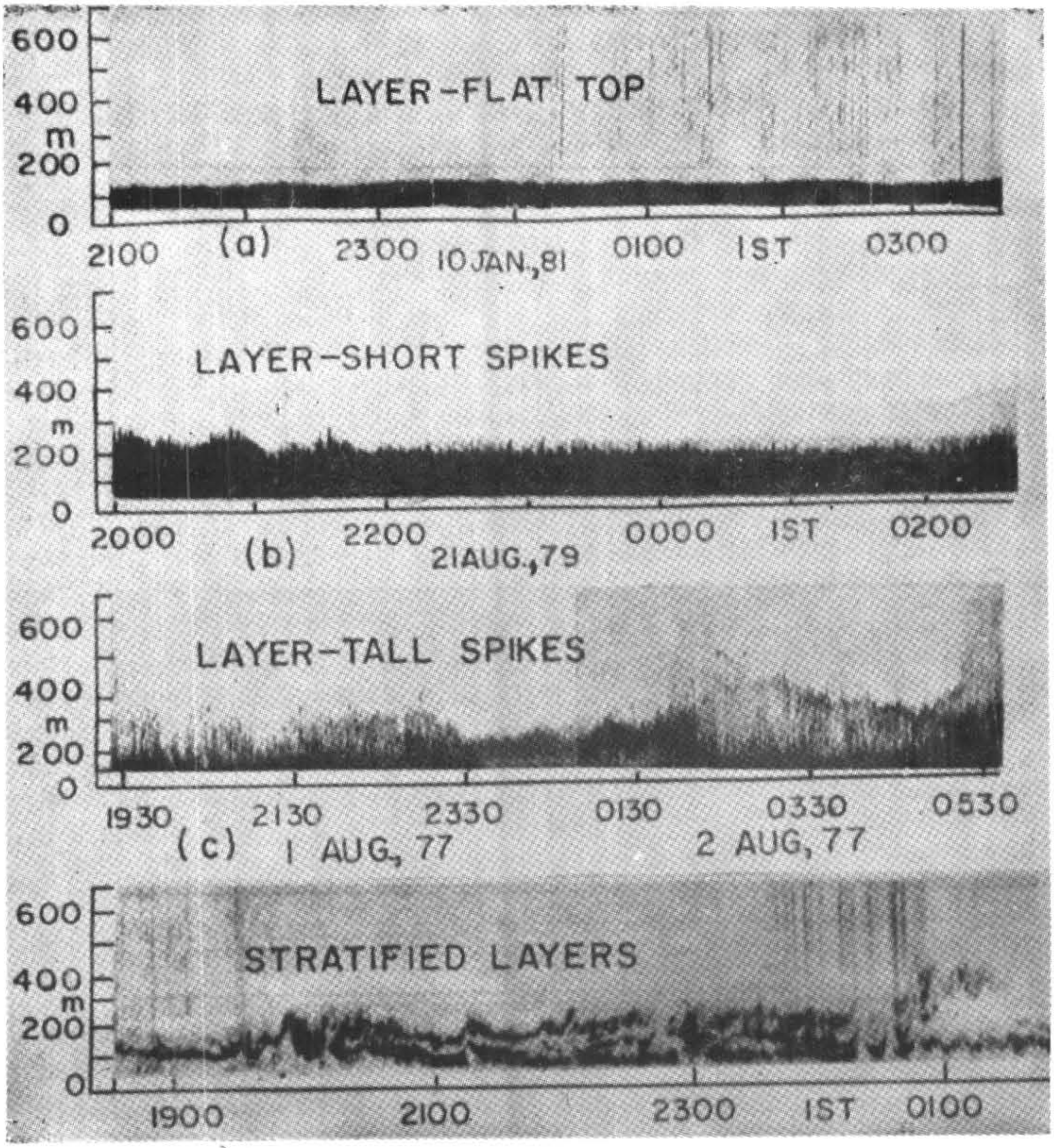

Fig. 1. Various types of nocturnal boundary layer structures seen on sodar echograms :
(a) Flat top surface based layer,
(b) Short spiky top surface based layer,
(c) Tall spiky top surface based layer
(d) Stratified layers

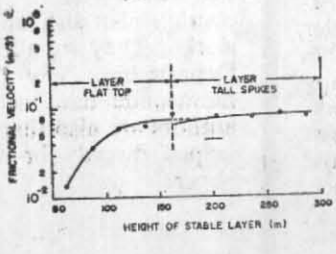

Fig. 2. A plot of the frictional wind velocity as a function of the height of the stable layer

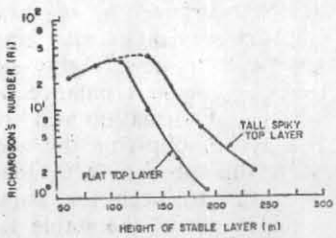

Fig. 3. A plot of the Richardson's number as a function of the height of stable layer for the flat/short spiky top and long spiky top

structures as compared to surface wind speed alone since it takes into account the effect of ground elements also. Frictional wind velocity U^* is defined as

$$U^* = \frac{k\bar{U}}{\ln (Z/Z_0)}$$

where, $\bar{U}$ is the average wind speed at height Z, Z_0 is the roughness length (Sutton 1951), a parameter characteristic of the surface and takes into account the height of the tallest nearby buildings and k is dimensionless Von Karman's constant which has a value approximately equal to 0.4. Roughness length Z_0 is generally taken equal to one tenth the height of the roughness elements such as buildings, trees etc.

Taking the height of roughness elements approximately equal to 30 m for NPL site and using other data from the radiosonde soundings at Aya Nagar, Delhi, the frictional wind velocity U^* has been computed for different heights of the stable layer structures. From the plot of the computed average values of the parameter (Fig.2) it is seen that firstly with the increase in the height of the stable layer, the magnitude of the frictional wind velocity increases while at a layer height around 150 m it becomes maximum which it maintains with further increase in the height of the stable layer.

The information about the frictional wind velocity can be very important to throw light on the nature of the turbulence phenomena occurring in the stable boundary layer. However, to probe further, a look into the variation in another turbulence parameter, the Richardson's number R_i can be useful. This parameter (Sutton 1951) considers the effect of both wind and temperature field on the layer structure. It is defined as

$$R_i = \frac{g}{T} \frac{d\theta/dz}{(du/dz)^2}$$

where g is the acceleration due to gravity, T is the ambient temperature, $d\theta/dz$ is the gradient of potential temperature and du/dz is the gradient of wind speed.

The values of the Richardson's number have been computed as a function of the height of the stable boundary layer using radiosonde data from Aya Nagar, Delhi Observatory. Different values of the Richardson's number have been obtained as a function of height for the two distinct types of stable layers, flat/short spiky top and long spiky top. It can be seen from the plot of the average value of the parameter (Fig. 3) that the flat top stable layer has a point of inflexion around 110 m while the long spiky top stable layer shows only a decreasing trend in the Richardson's number for increasing height of the structure. It may be noted that spiky top layer structure has the lowest structural height of 140 m.

The above study of the behaviour of frictional velocity and Richardson's number as a function of the height of the stable layer clearly shows that a transition in the characteristics of the stable boundary layer occurs when the layer height is within 100-150 m. To this information, the basic concepts of turbulence due to Kolmogoroff (Sutton 1951) can be applied according to which larger eddies are formed when energy is being fed into the system but too large eddies cannot remain stable for a long time and start breaking into smaller eddies such that there is a transfer of energy from larger eddies to smaller eddies and the energy remains conserved till a size is reached when there is no further breakdown of eddies and energy is dissipated due to the viscosity of the medium. Additionally, the stability concept of Richardson's number can also be applied according to which an increasing trend in the magnitude of Richardson's number indicates higher stability and *vice versa*.

Applying these concepts and keeping in mind the transition in characteristic turbulence parameters in the stable layer height of 100-150 m, it can be said that the process of eddy formation in the stable layer is occurring upto a height of 100 m, the energy needed for the purpose being realized from the increased cooling of the ground under low wind conditions after the sunset. The stability is on the increase under these conditions since the values of the Richardson's number and the frictional wind velocity are continuously increasing in this height range. In the transition range the breaking of larger eddies into smaller eddies starts since it is difficult to keep highly stable conditions for a long time, of course a balance being maintained into the processes of formation and breaking of eddies. The wind may be supplying the necessary imbalancing energy in this process with inertial and gravitational forces trying to keep the balance. With further increase in the height of the stable layer, the process of breaking of the eddies is more active bringing in increased turbulence which is seen by the decreasing trend in the values of Richardson's number in both flat/short spiky top layer and tall spiky top layer. This observation is further supported by the decreasing trend only in the computed values of the Richardson's number for the tall spiky top stable layer structures.

4. Conclusion

It has been seen that surface wind speed hardly gives any significant information about the formation of flat/short spiky top and long spiky top structures seen on sodar echograms. However, the turbulence parameters of frictional wind velocity involving ground effects and Richardson's number are able to throw light on the stability conditions in terms of the eddy processes going on in the stable boundary layer. Layer structures upto about 125 m represent conditions of formation of thermal eddies while higher layer heights represent conditions for breaking of thermal eddies. Further, it can be inferred that tall spiky top layer structures or stable layer structures of height more than 125 m are more turbulent, *i.e.,* their stability is lower as compared to stable layer structures of height within 125 m.

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References

Blackadar, A.K., 1957, "Boundary layer wind maxima and their significance for the growth of nocturnal inversions", *Bull. Am. met. Soc.*, **38**, 283-290.

Brown, E.H. and Hall, F.F. Jr., 1978, "Advances in atmospheric acoustics", *Rev. Geophys. Space Phys.*, **16**, 47-110.

Businger, J.A. and Arya, S.P.S., 1974, "Heights of the mixed layer in the stably stratified planetary boundary layer", *Advances in Geophysics*, **18A**, 73-92.

Clarke, R.H., 1970, "Observational studies in the atmospheric boundary layer", *Quart. J. met. Soc.*, **96**, 91-114.

Hanna, S.R., Briggs, G.A. & Haskar, R.P. Jr., 1982, "*Handbook of Atmospheric diffusion*", Technical Information Centre, U.S. Department of Energy, USA, 1982, pp. 3-6.

Kaimal, J.C. and Izumi, Y., 1965, "Vertical velocity fluctuations in a nocturnal low level jet", *J. appl. Met.*, **4**, 576-584.

Singal, S.P. and Gera, B.S., 1982, "Acoustic remote sensing of the boundary layer", *Proc. Ind. Acad. Sci.* (Engg. Sc.), **5**, Pt. 2, 131-157.

Singal, S.P., Aggarwal, S.K., Pahwa, D.R. and Gera, B.S., 1985, "Stability studies with the help of acoustic sounding", *Atmospheric Environment*, **19**, 221-228.

Sutton, O.G., 1951, "Atmospheric turbulence & diffusion", published in "*Compendium of Meteorology*" edited by T. F. Malone, American Meteorological Society, Boston, Mass. U.S.A., pp. 492-509.