

A study of turbulent characteristics of atmospheric boundary layer over monsoon trough region using Kytoon and Doppler sodar

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Abstract. As a part of the MONTBLEX-90 observational programme, Kytoon and Doppler sodar observations were taken at Kharagpur. These data are analysed to study the turbulent characteristics of the atmospheric boundary layer in terms of stability, temperature structure function (C_T^2) and velocity structure function (C_V^2). C_T^2 follows a $Z^{-4/3}$ law on most of the days, whereas the variation of C_V^2 is not systematic. C_T^2 and C_V^2 values are found to vary between 10^{-5} – $10^{-1} \text{ m}^{4/3} \text{ s}^{-2}$ and 10^{-5} – $10^{-2} \text{ }^\circ\text{C}^2 \text{ m}^{-2/3}$ respectively.

Keywords. Temperature structure parameter (C_T^2); velocity structure parameter (C_V^2); turbulent dissipation (ϵ); mixing ratio.

1. Introduction

During the main phase of the Monsoon Trough Boundary Layer Experiment 1990 (MONTBLEX-90) a Doppler sodar manufactured by M/s Aerovironment, USA, Model 2000, was operated at Kharagpur during May–September 1990. The Doppler sodar measures all the three components (u, v, w) of wind in the height range of 45–1050 m. Along with Doppler sodar, a Kytoon payload was hoisted on 28 occasions. Using Doppler sodar and Kytoon data, structure functions estimated during early morning and evening hours are discussed with respect to the boundary layer pattern observed by Doppler sodar. The features of nocturnal boundary layer observed by Doppler sodar are also discussed.

2. Experimental details

To start with, a brief description and specifications of both the Doppler sodar and Kytoon are given.

2.1 Doppler sodar specifications

Specifications are shown in table 1. The total wind speed and its east-west, north-south and vertical components are printed at a height interval of 30 m beginning at 45 m and reaching up to 1050 m.

2.2 Specifications of Kytoon payload

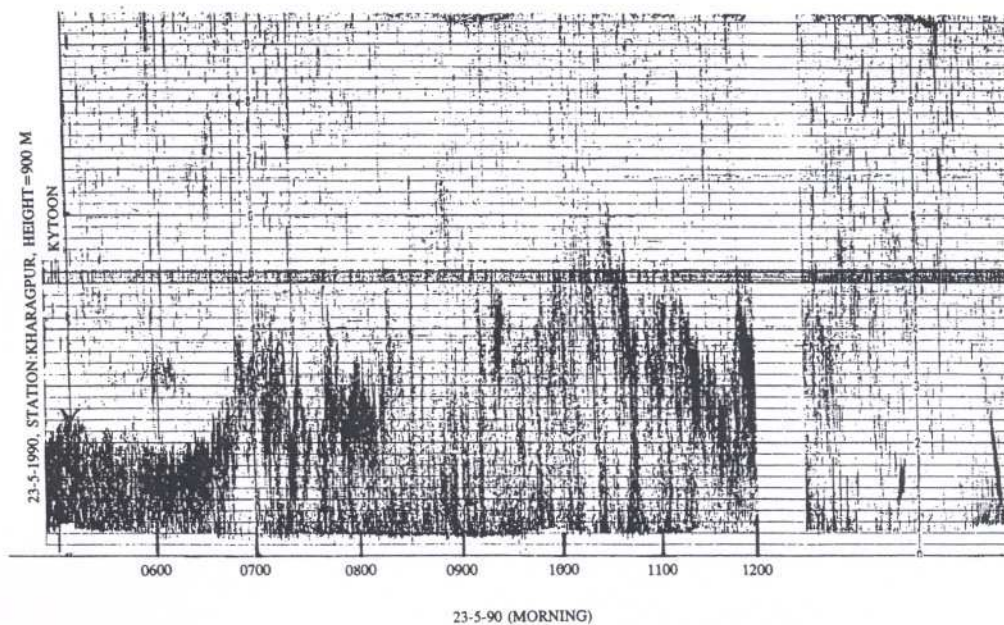
The Kytoon system consists of a 2.3 m^3 aerodynamically shaped balloon which can be raised to a height of 1500 m with the help of a tether. The payload consists of sensors for

Table 1. Specifications of Doppler sodar.

No	Wind component	Measurement range	Accuracy
1.	Horizontal wind speed	0 to ± 25 m/s	0.2 m/s
2.	Vertical wind speed	0 to ± 3.7 m/s	0.1 m/s
3.	Horizontal wind direction	0 to 359 deg.	5 deg for wind speed > 1.5 m/s

Table 2. Specifications of Kytoon payload.

Sensor	Resolution	Response time
Temperature (dry)	0.01°C	3 s
Temperature (wet)	0.01°C	12 s
Humidity	0.1%	
Pressure	0.1 mb	
Wind speed	0.1 m/s	
Wind direction	1°	
Weight of the entire payload	200 g	

**Figure 1.** Sodar echogram on 23-5-90 morning.

wind, wind direction, pressure, dry bulb temperature and wet bulb temperature. The data from these sensors can be transmitted on 401 MHz telemetry to the ground receiver. The receiver has a microprocessor and with an initial input of data from five sensors, about 30 derived parameters are evaluated. Specifications of the payload are shown in table 2.

2.3 Description of the Sodar and Kytoon data

The Doppler sodar, though a versatile instrument that gives entire wind data, with all three components, standard deviations and the backscatter intensity, was not supplied

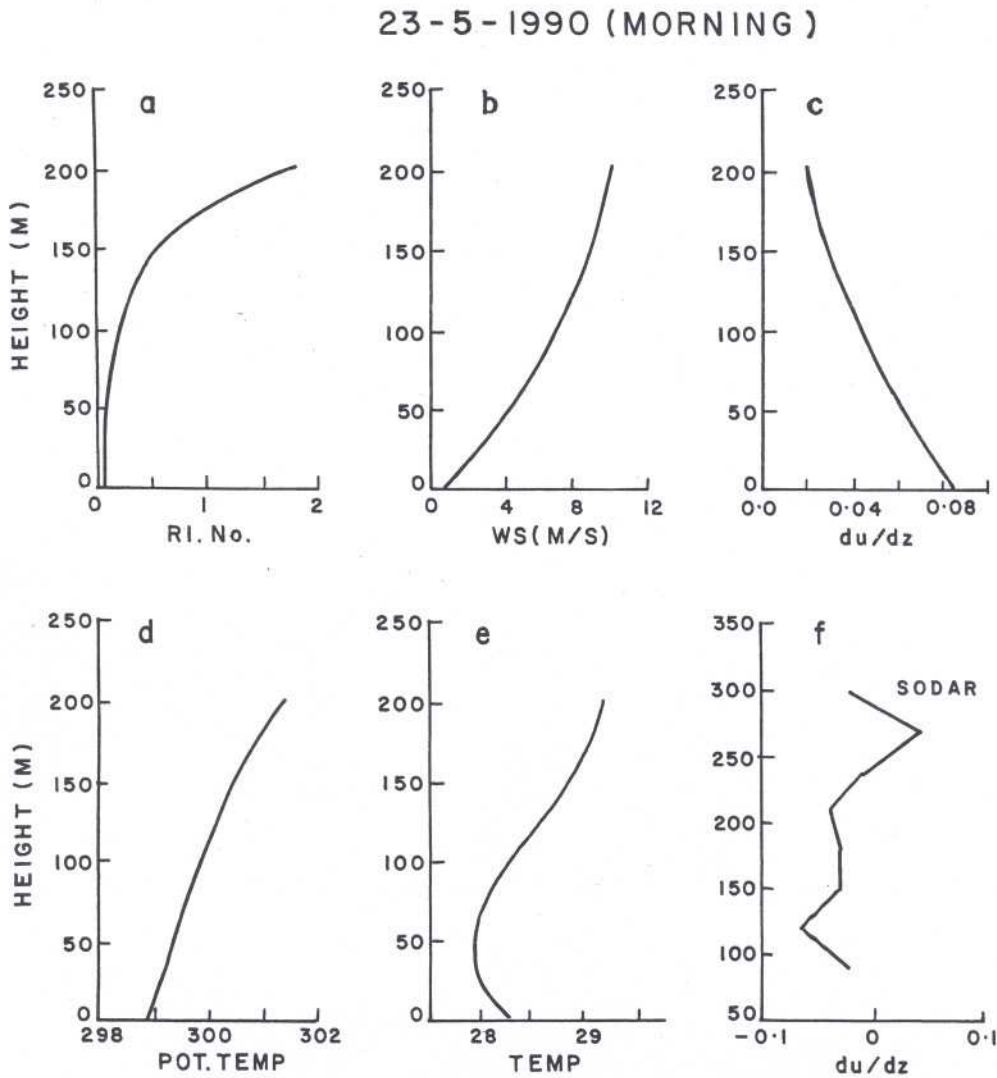


Figure 2(a)-(f). (a) Vertical variation of Richardson no (Ri) on 23-5-90 using Kytoon data; (b) for wind speed; (c) for wind speed gradient (du/dz); (d) for potential temperature; (e) for dry bulb temperature; (f) same as in figure 2(c) using sodar data.

with the necessary software for evaluating the temperature structure functions. The alternative is to use output power and backscattered power values and then evaluate the necessary structure functions, which is a rather difficult task and was not possible at Kharagpur. Hence, an attempt is made to evaluate structure functions using Kyttoon data in this paper. The sodar data are used for obtaining qualitative information on the boundary layer, like type of inversion, height of inversion and thermals.

The Kyttoon data were available in terms of height versus temperature, potential temperature, mixing ratio and pressure. The data were printed every 20 seconds and smoothed using a spline technique.

3. Temperature and velocity structure functions in the boundary layer

The structure constants, C_v^2 , C_T^2 i.e. the r.m.s differences in the values of the instantaneous

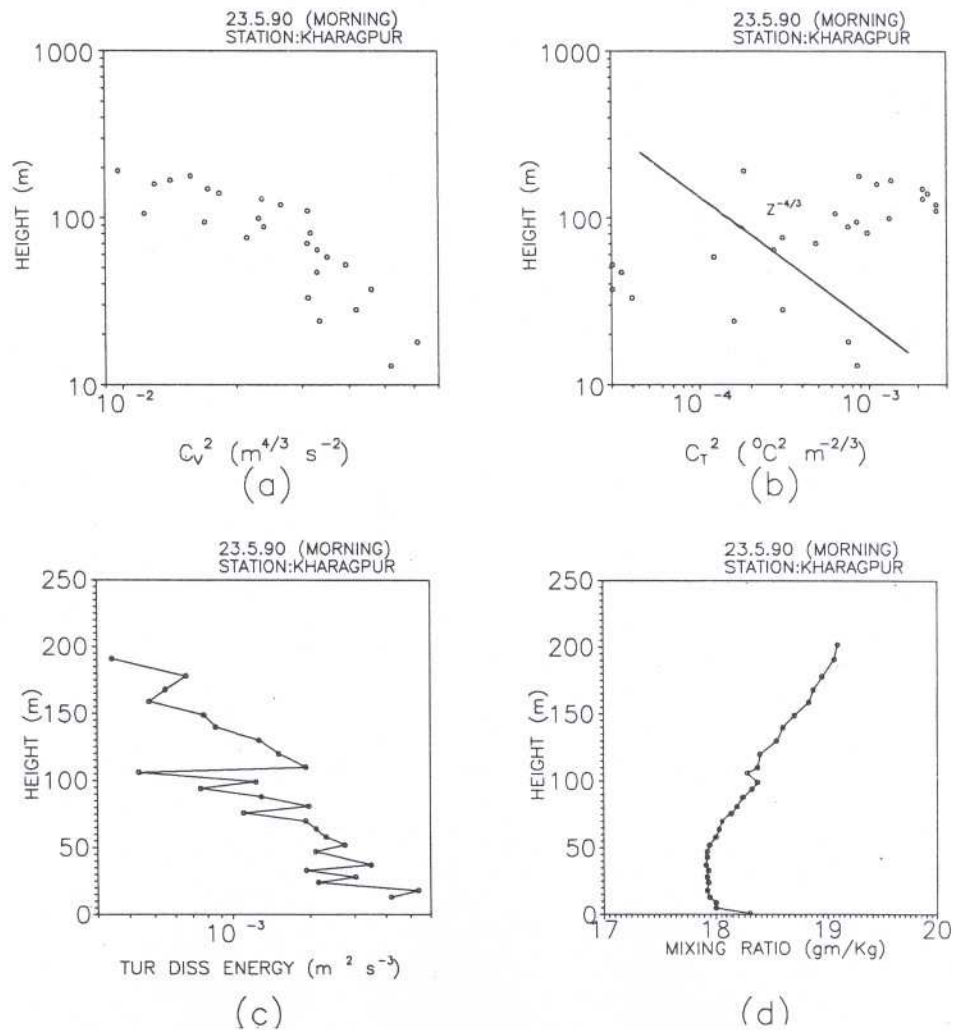


Figure 3(a-d). (Continued)

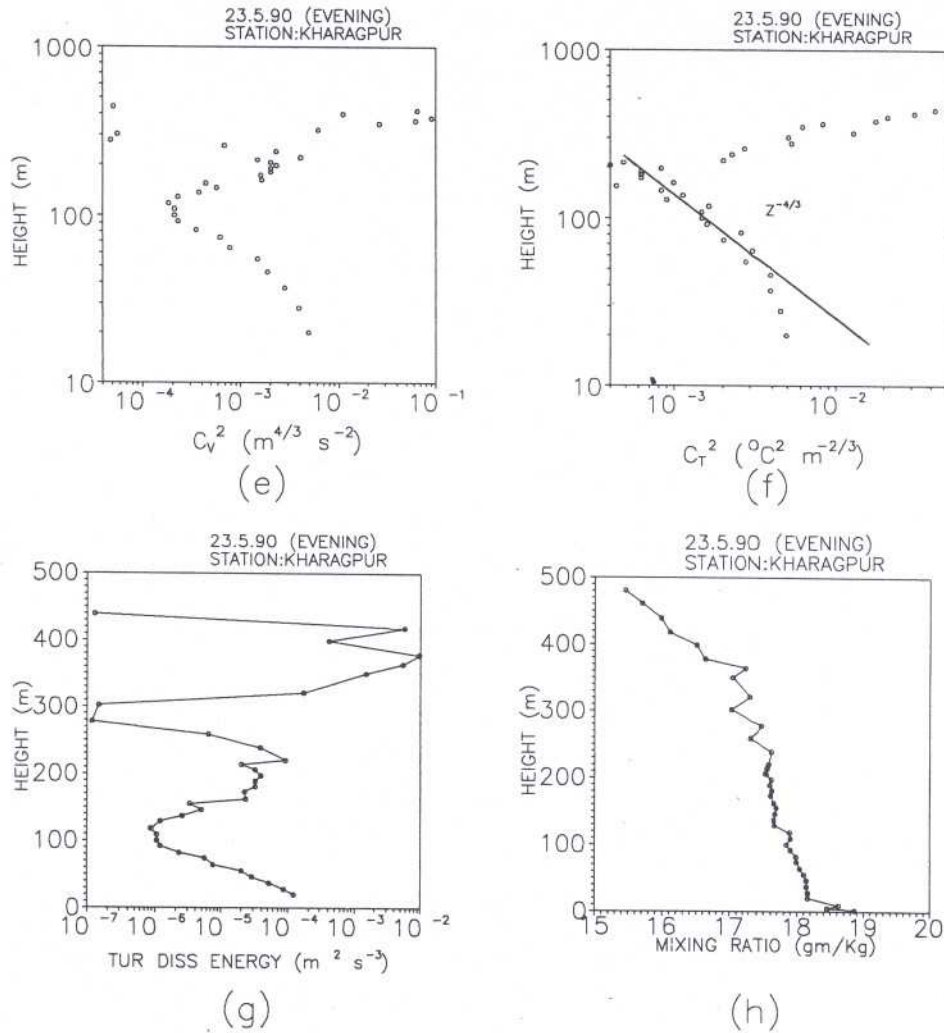


Figure 3(a)–(h). (a) Vertical variation of C_V^2 on 23-5-90 morning using Kyttoon data; (b) same, but for C_T^2 ; (c) same, but for ϵ ; (d) same, but for mixing ratio; (e) same as in figure 3(a) but on 23-5-90 evening; (f) same as in figure 3(b) on 23-5-90 evening; (g) same as in figure 3(c) on 23-5-90 evening; (h) same as in figure 3(d) on 23-5-90 evening.

velocity or temperature at two points in the atmospheric volume separated by unit distance, are given by

$$C_V^2 = \frac{[V(x) - V(x + \Delta x)]^2}{(\Delta x)^{2/3}}, \quad (1)$$

$$C_T^2 = \frac{[T(x) - T(x + \Delta x)]^2}{(\Delta x)^{2/3}}, \quad (2)$$

where Δx is the separation between two sensors lying within the inertial subrange of velocity fluctuations. C_V^2 and C_T^2 define the turbulence intensity in the atmosphere. Higher the values of C_V^2 and C_T^2 , higher is the turbulence. Brown and Clifford (1976) have studied

the variation of C_V^2 and C_T^2 with respect to boundary layer height for day time under unstable conditions. For stable atmospheres C_V^2 becomes small except for large values in layers of large shear associated with winds. Measured values of temperature structure parameter C_T^2 have been found to obey the following relation with the altitude:

$$C_T^2 = aZ^{-4/3}, \quad (3)$$

while the C_V^2 obeys the relation,

$$C_V^2 = b + cZ^{-2/3}, \quad (4)$$

23-5-1990 (EVENING)

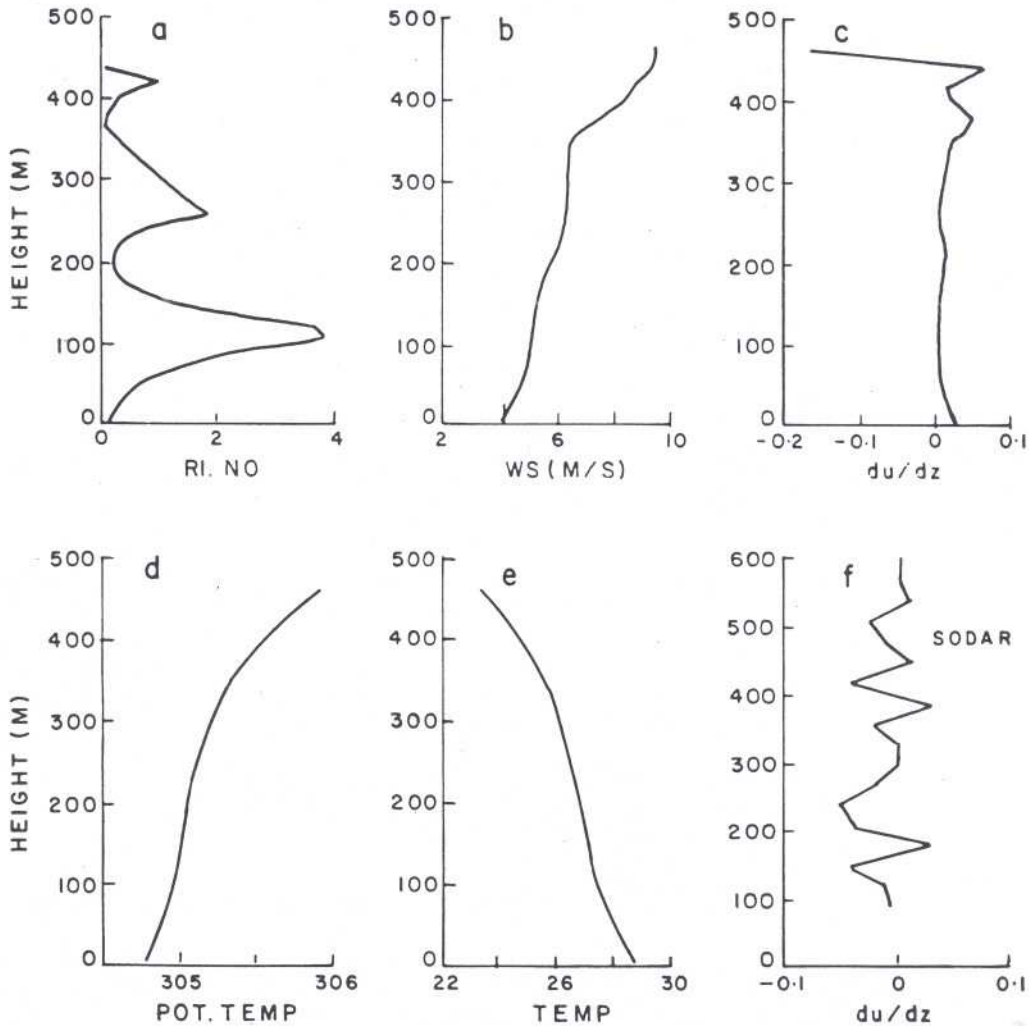


Figure 4(a)-(f). (a) Same as in figure 2(a) on 23-5-90 evening; (b) same as in figure 2(b) on 23-5-90 evening; (c) same as in figure 2(c) on 23-5-90 evening; (d) same as in figure 2(d) on 23-5-90 evening; (e) same as in figure 2(e) on 23-5-90 evening; (f) same as in figure 2(f) on 23-5-90 evening.

where a, b, c are constants and Z is the altitude. Measurements of C_V^2 and C_T^2 using sodar data have been reported by Gaynor (1977). Variations in the temperature structure parameter have been studied by Neff (1975) and Singal *et al* (1982) as a function of the height of the morning rising inversion.

Frisch and Clifford (1974) have shown that C_V^2 is nearly constant with height throughout the mixing layer not exhibiting a falloff with height as does C_T^2 . Frisch and Ochs (1975) have shown from *in situ* measurements that the C_T^2 decreases with height as $-4/3$ power extending atleast up to 80% of the convective mixed layer. C_T^2 lies in the range 10^{-5} – 10^{-2} between 90 and 400 m range with variable integration (6–60 minutes). C_V^2 lies in the range 10^{-5} – 10^{-1} in the similar height range with similar integration period.

Also in the inertial subrange, it is observed that,

$$2\varepsilon^{2/3} = C_V^2, \varepsilon = \left(\frac{1}{2}C_V^2\right)^{3/2}, \quad (5)$$

where ε is the rate of destruction of the turbulent kinetic energy ($\text{m}^2 \text{s}^{-3}$) (Tatarskii 1971). Caughey *et al* (1978) have computed the variations of the dissipation parameter ε from the sodar derived values of the structure parameters. Thomson *et al* (1978) have also reported the time and altitude variation of ε . Gaynor (1977) reported variation of ε with respect to stability conditions. Comparison of C_T^2 obtained with sodar and ε values obtained with balloon at Sgnlok mountain has been reported by Guryanov *et al* (1987), who observe that the sodar estimates are regularly higher, about twice the balloon estimates during

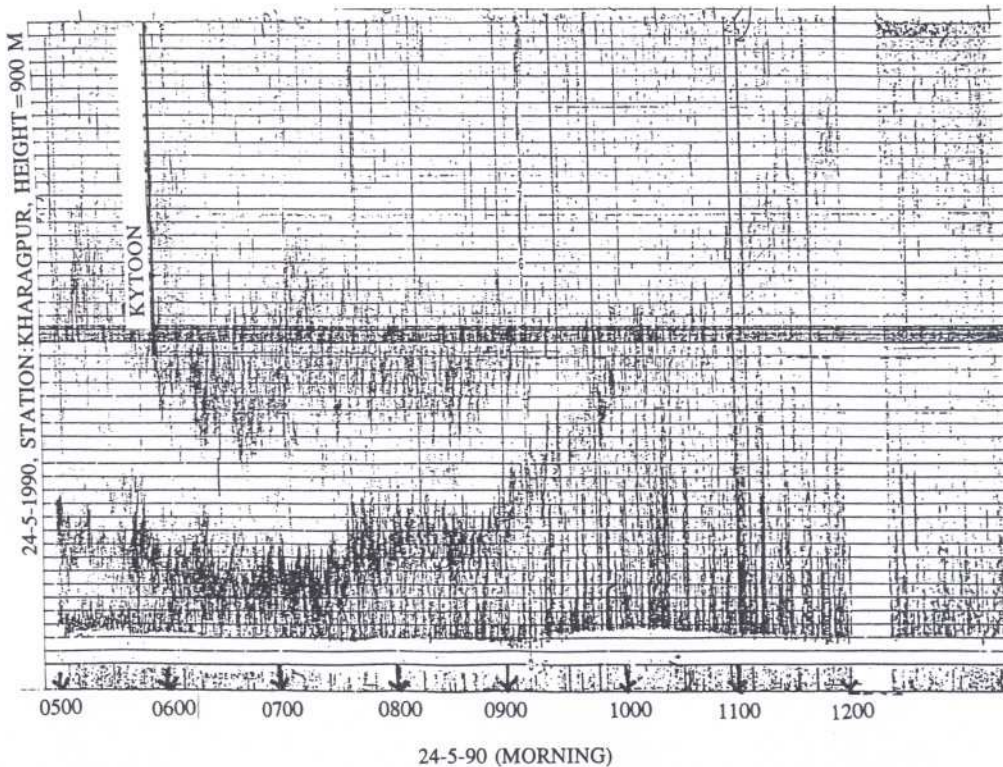


Figure 5. Sodar echogram on 24-5-90 morning.

night time. These discrepancies have not found any suitable explanation. In these experiments the scatter of C_T^2 as observed by sodar and Kytoon was between 10^{-7} and 10^{-2} . In the present paper an attempt is made to study the boundary layer and evaluate the structure parameters C_T^2 , C_V^2 and dissipation of energy ε with respect to synoptic conditions prevailing at Kharagpur.

4. Analysis of data

The smoothed Kytoon data are utilised to evaluate the Richardson number, C_T^2 , C_V^2 and ε . The smoothed data on potential temperature and mixing ratio have also been

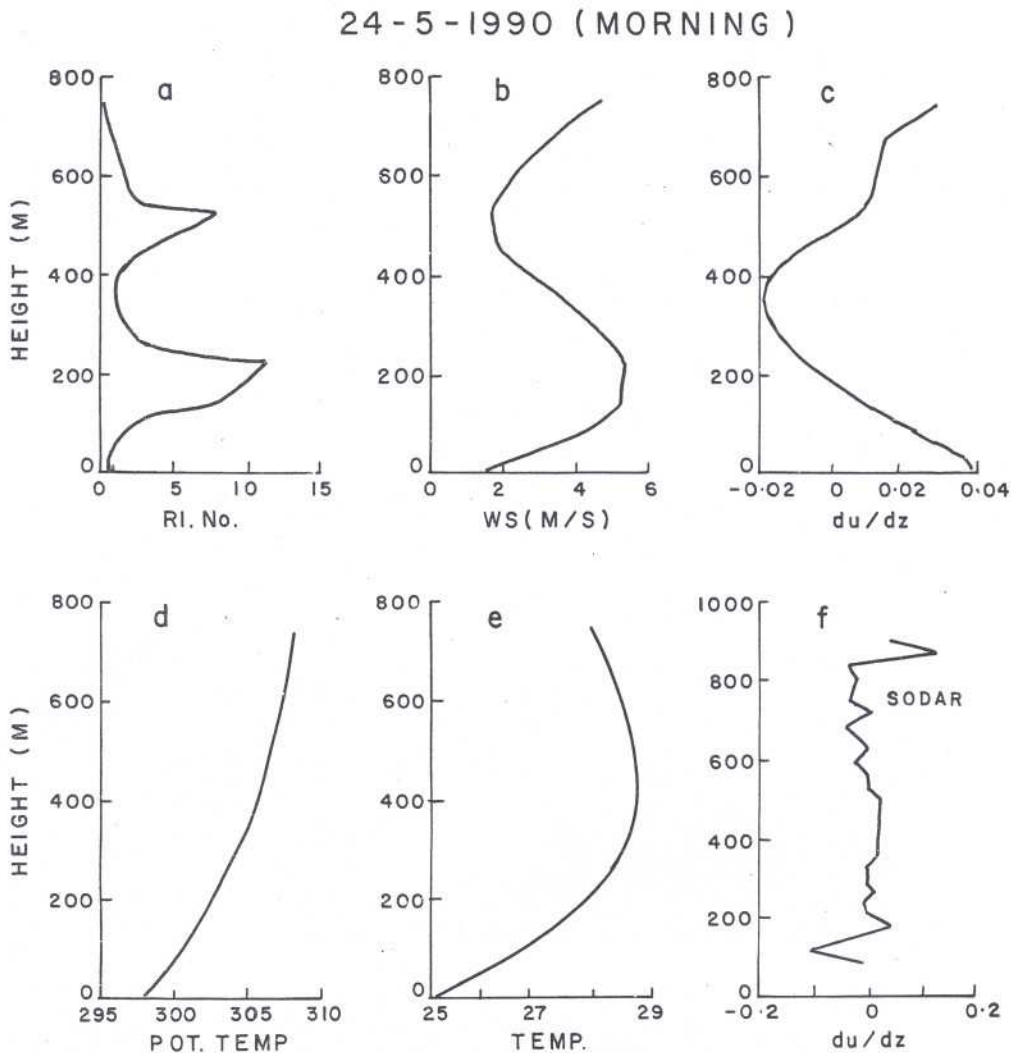


Figure 6(a)-(f). (a) Same as in figure 2(a) on 24-5-90 morning; (b) same as in figure 2(b) on 24-5-90 morning; (c) Same as in figure 2(c) on 24-5-90 morning; (d) same as in figure 2(d) on 24-5-90 morning; (e) same as in figure 2(e) on 24-5-90 morning; (f) same as in figure 2(f) on 24-5-90 morning.

utilised to plot the respective profiles on the day of interest. Only a few specific cases are discussed. As the Kyttoon data are available during synoptic hours, only the simultaneous data available on the Doppler sodar are looked into. Basically, the dynamics of the early morning boundary layer formation at Kharagpur are analysed in terms of stability in the boundary layer.

As mentioned earlier, only 28 flights of Kyttoon were possible and only the data pertaining to three limited flights are used in the analysis.

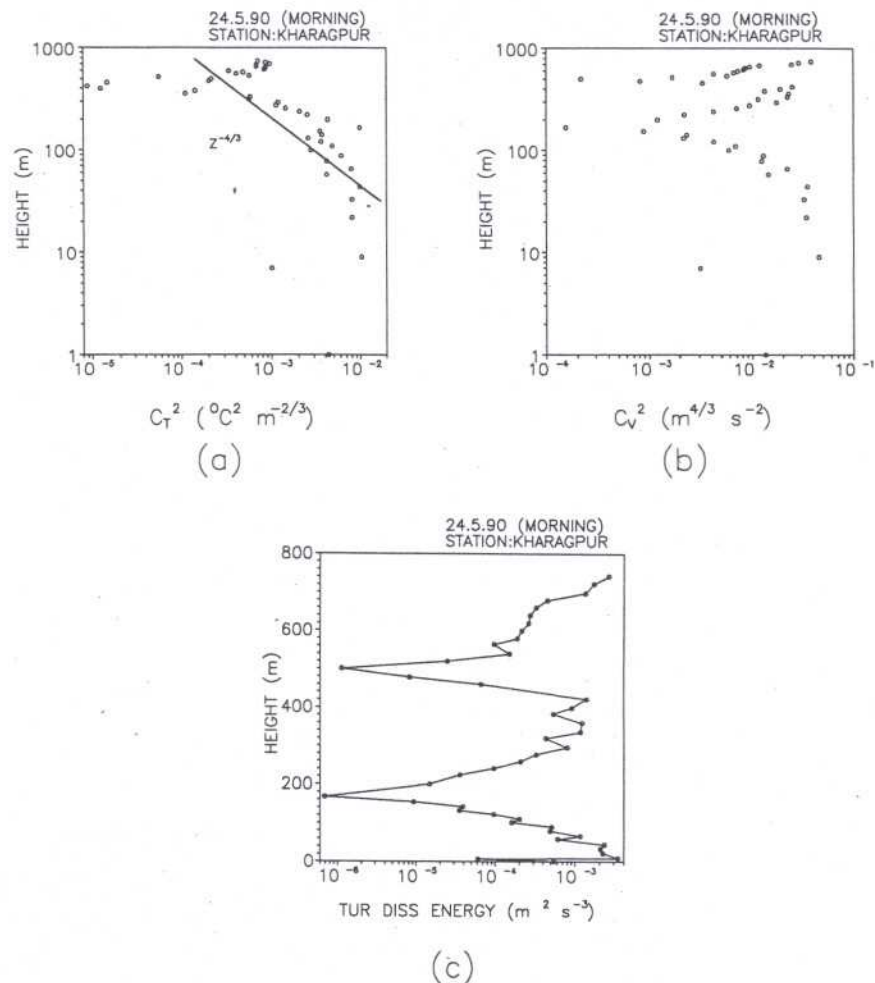


Figure 7(a)–(c). (a) Same as in figure 3(a) on 24-5-90 morning; (b) same as in figure 3(b) on 24-5-90 morning; (c) same as in figure 3(c) on 24-5-90 morning.

4.1 Intercomparison of echogram and the Kyttoon derived parameters

Only three-days data pertaining to Kyttoon flight which are of interest because of some abnormalities observed at the time of hoisting are analysed. The sodar data are utilised qualitatively. The data on following dates are looked into:

No	Date	Period	Time	Max. height reached by Kytoon	Availability of Sodar data
1.	23.5.1990	Morning	0529 hrs, IST	202 m	Available.
2.	23.5.1990	Evening	1652 hrs, IST	480 m	Insufficient.
3.	24.5.1990	Morning	0551 hrs, IST	763 m	Available.
4.	4.6.1990	Morning	0606 hrs, IST	590 m	Available.

Each flight is dealt with separately.

4.1.1 23.5.90 morning flight (synoptic conditions: clear sky): During this flight the sodar echogram (figure 1) showed a ground-based inversion around 220 m. The Kytoon could reach only 202 m. The nocturnal boundary layer height increased upto 400 m around 0700 hrs and after this it decreased until 0800 hrs. Later the routine evolution of the boundary layer took place. With lapse of time the Kytoon observed Richardson number (figure 2a) was around zero indicating neutral stability up to 50 m. Later the Richardson number started increasing and reached a value of 2, showing a stable layer which is again established by the potential temperature profile (figure 2d). Winds increased steadily and reached a speed of 10 m/s at 200 m (figure 2b). Wind gradients (figure 2c) at ground level are of relatively small amplitude but decreased with height attaining a value 0.02 s^{-1} at 200 m. Figure 2f shows the sodar observed wind gradients, which are also small in amplitude but vary between -0.1 and $+0.1$.

C_V^2 and C_T^2 profiles are shown in figures 3a and 3b respectively. C_V^2 follows a $-4/3$ law whereas C_T^2 does not. A minimum in C_T^2 is observed at 30 m and a maximum at 100 m. Figure 3c shows the dissipation of turbulent energy which decreases steadily with height. Figure 3d shows the mixing ratio profile for the same launch. The surface

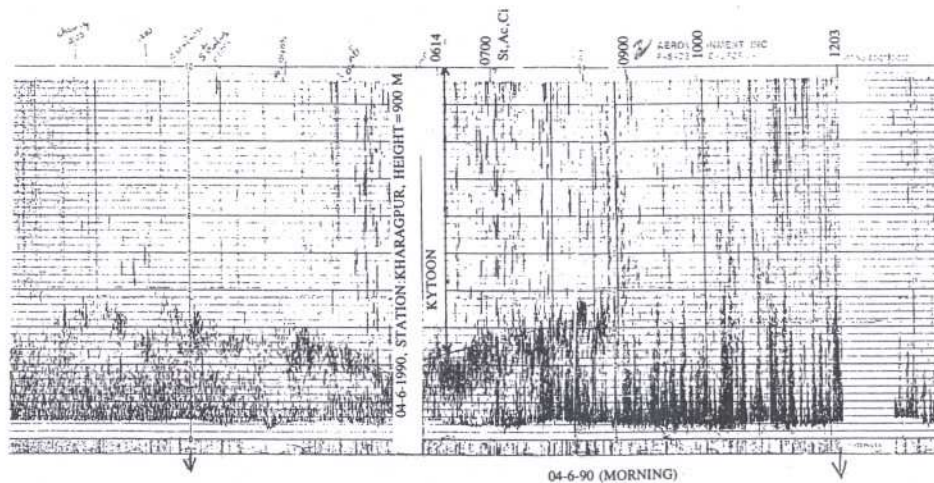


Figure 8. Sodar echogram on 04-6-90 morning.

value is around 18.3 g/kg and gradually increases to 19.0 g/kg at 200 m. This increase can be explained in terms of advection of moisture from the surrounding area.

4.1.2 23.5.90 evening flight (synoptic conditions: cloudy): During this launch the Doppler sodar was not functioning properly. The Kytoon could reach a height of 480 m. The Kytoon observed Richardson number (figure 4a) shows a strong stability ($Ri \approx 4.0$) around 100 m and similar peaks at 200 and 380 m with lesser amplitude. Winds (figure 4b) steadily increase up to 10 m/s at 480 m. Wind gradients (figure 4c) are near zero up to a height of 350 m, but beyond this height they are negative and steep. Potential temperature (figure 4d) shows a steady increase again confirming a stable layer. The sodar observed wind gradients (figure 4e) are varying between $+0.05$ and -0.05 s^{-1} .

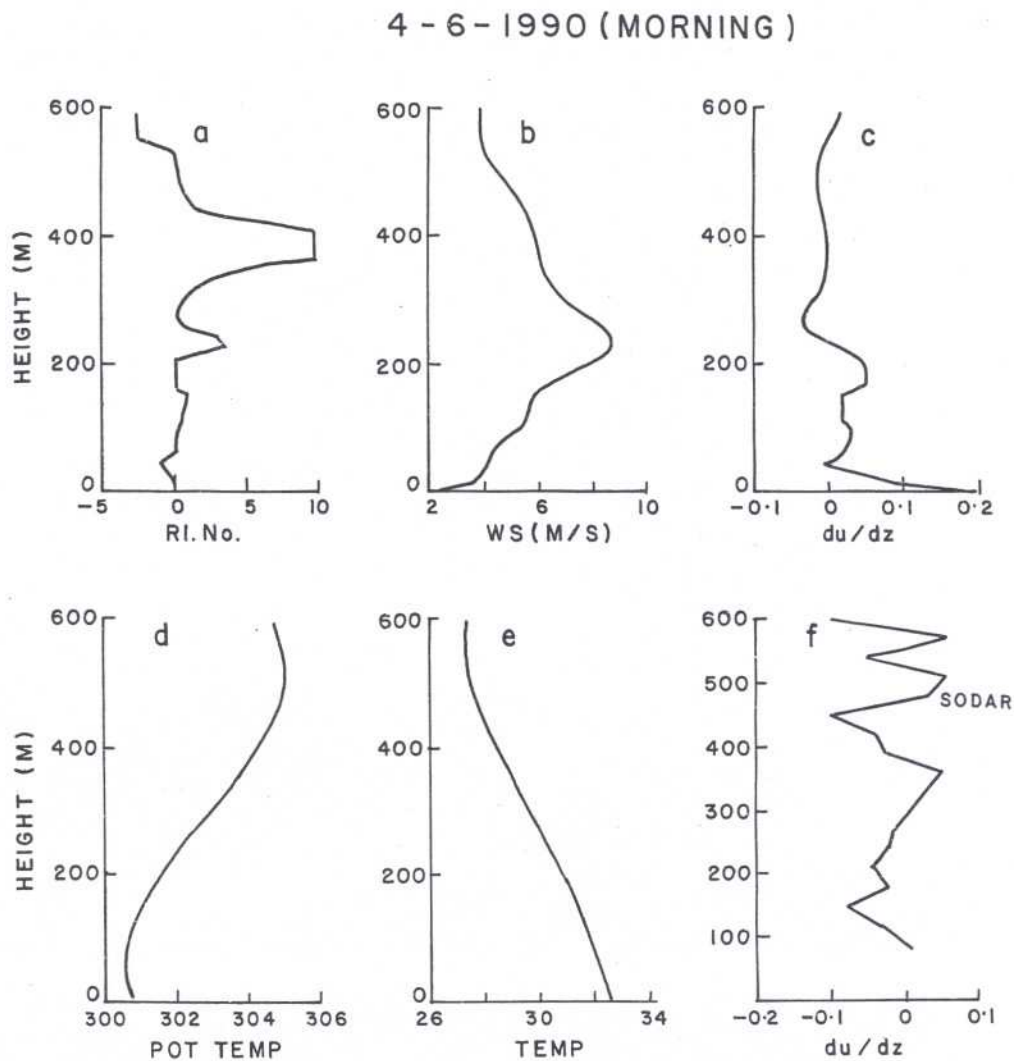


Figure 9(a)-(f). (a) Same as in figure 2(a) on 04-6-90 morning; (b) same as in figure 2(b) on 04-6-90 morning; (c) same as in figure 2(c) on 04-6-90 morning; (d) same as in figure 2(d) on 04-6-90 morning; (e) same as in figure 2(e) on 04-6-90 morning; (f) same as in figure 2(f) on 04-6-90 morning.

Referring to figure 3e and 3f, C_V^2 and C_T^2 profiles follow $-4/3$ law and show a decreasing trend with height up to 200 m. A minimum at 200 m is found for both the profiles. Figure 3g (dissipation of turbulent energy, ϵ) shows a minimum at 300 m and increases beyond that height. The mixing ratio (figure 3h) exhibits the usual steady decrease from 18.5 g/kg at ground to 15.5 g/kg at 480 m.

4.1.3 24.5.90 morning flight (synoptic conditions: clear sky): Figure 5 shows the echogram for 24.5.90 morning flight. The ground-based inversion had a trend typical of the nocturnal boundary layer. Right from 0500 hrs another inversion developed and was floating around 500 m, till it merges with the ground-based one at 1000 hrs. After 1030 hrs the routine evolution of boundary layer takes place. Figure 6a shows the profile of Richardson number clearly indicating two stable regions at 200 and 460 m respectively corresponding to the two inversions observed on the echogram. Wind

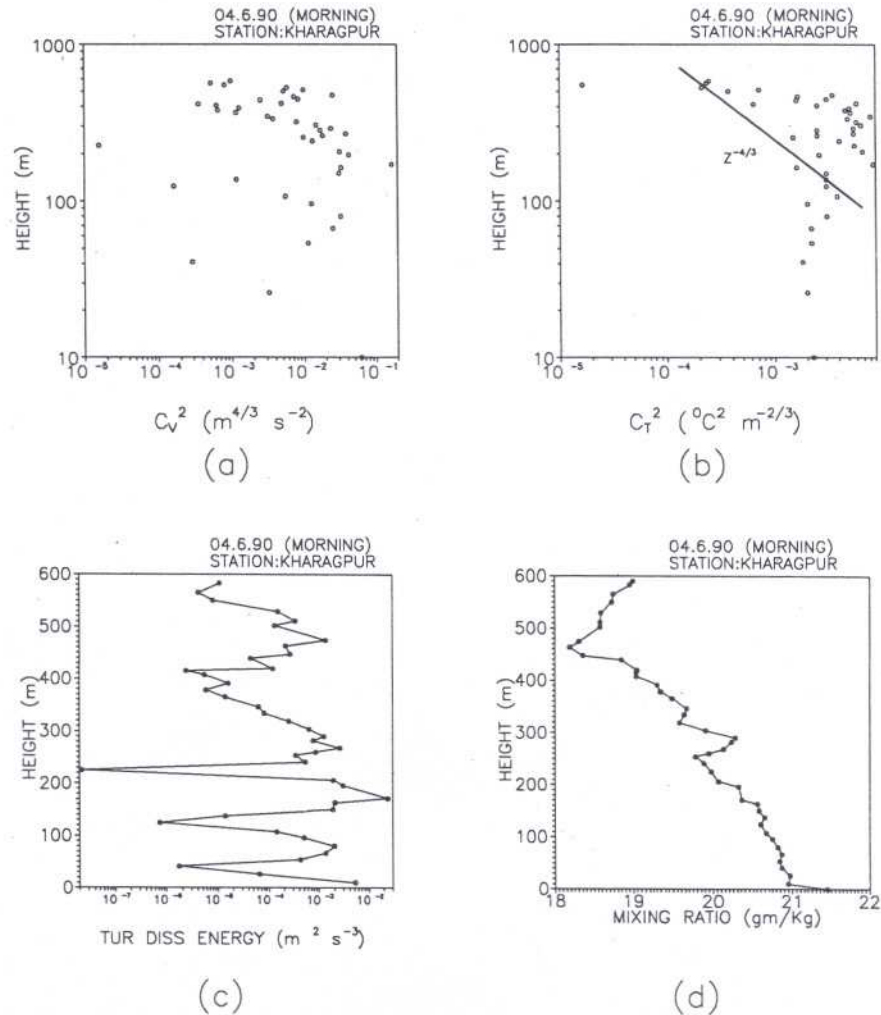


Figure 10(a)-(d). (a) Same as in figure 3(a) on 04-6-90 morning; (b) same as in figure 3(b) on 04-6-90 morning; (c) same as in figure 3(c) on 04-6-90 morning; (d) same as in figure 3(d) on 04-6-90 morning.

speed (figure 6b) and wind gradients (figure 6c) do not show significant variations. But the wind speed is minimum at 460 m, the second inversion level. The dry bulb temperature (figure 6e) profile shows a temperature strata between 200 and 400 m. Thus the region between two inversions has a nearly constant temperature. During this Kytoon flight the wet bulb sensor was not working and hence the mixing ratio parameter is not available.

Variations of C_T^2 and C_V^2 and dissipation of turbulent energy are shown in figures 7a, 7b and 7c respectively. Figure 7b shows clearly two minima at the inversion heights 200 and 460 m. In the case of C_T^2 a falloff with $-4/3$ power law is observed to follow up to 500 m whereas for C_V^2 two minima are observed at 200 and 460 m. These minima in the C_V^2 and Richardson number profiles coincide with the minima observed in the ϵ profile.

4.1.4 04.6.90 morning flight (synoptic conditions: slightly cloudy): Figure 8 shows the sodar echogram on 4.6.90. The Kytoon was hoisted at 0606 hrs. On this day the nocturnal boundary layer height varied between 300 and 500 m. At 0530 hrs its height reduced to 180 m and then it started increasing.

The Kytoon data analysis shows a strong stability $Ri \approx 10$ (figure 9a) around 400 m. This may be because of steep gradients of potential temperature (figure 9d) at 400 m and minimum wind gradients (≈ 0) (figure 9c) around 400 m. In general on this day the wind gradients were low. The sodar derived wind gradients (figure 9f) also showed variations around zero.

Figures 10a, b, c and d show C_V^2 , C_T^2 , ϵ and mixing ratio profiles respectively for 4.6.90. The C_V^2 profile (figure 10a) is highly scattered, and the C_T^2 profile (figure 10b) does not obey the $-4/3$ law. Between 20 and 200 m region C_T^2 is almost constant. Above 200 m a falloff is observed. The dissipation of turbulent energy (figure 10c) shows a steady decrease. The sudden decrease in ϵ observed at 220 m is an isolated point which may be wrong. Figure 10d shows the mixing ratio profile showing a steady decrease from a surface value of 21.5 g/kg.

5. Conclusions

- The nocturnal boundary layer height decreases in the early morning hours and then increases followed by another decrease and again followed by a routine increase.
- On 24.5.90 two inversions are observed and at these inversions, the Richardson number is very high, whereas C_V^2 showed two dips at the inversion heights. Consequently the turbulent energy dissipation also showed two minima at the inversion heights.
- A steady decrease in mixing ratio was observed on all launches of Kytoon except on 23.5.90 morning when a small increase with height was observed up to 200 m. This may be due to the advection of moisture from the surrounding area.
- The C_T^2 profile follows a $-4/3$ law up to 200 m on two days, i.e. 23rd and 24th May 1990. C_V^2 variations are not systematic. Sometimes C_V^2 is found to obey a $-4/3$ law. The $-4/3$ law is not obeyed for both C_T^2 and C_V^2 on 4th June.
- C_V^2 and C_T^2 values lie in the range 10^{-5} – 10^{-1} and 10^{-5} – 10^{-2} respectively.

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