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Atmospheric surface layer spectra over a tropical desert station during Indian summer monsoon

M. N. PATIL and S. S. PARASNIS

Indian Institute of Tropical Meteorology, Pune -411008, India

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सार – इस शोध–पत्र में 1990 में मानसून द्रोणी परिसीमा स्तर के दौरान तीव्र प्रतिक्रिया संवेदी–ध्वनि पवन वेगमापी (8.33 हर्टज़) से एकत्र किए गए पवन घटकों (यू.,वी.और.डब्ल्यू.) और तापमान (टी.) के प्रेक्षणों का उपयोग करते हुए प्रक्षोभों की विशेषताओं का अध्ययन किया गया है। इस विश्लेषण से यह पता चलता है कि पवन और तापमान के स्पेक्ट्रा मोनिन–ओबुकोव स्केलिंग के अनुरूप है। उच्च आवृति वाले भाग में स्पेक्ट्रल वक्र –2/3 का उतार दिखाती है जो जड़त्वीय उपश्रेणी की विघमानता को बताती है। भँवर के आकारों में दैनिक परिवर्तन की भी यहाँ चर्चा की गई है।

ABSTRACT. Characteristics of turbulence have been studied using the observations of wind components (*u*, *v* and *w*) and temperature (*T*) collected by fast response sensor the sonic anemometer (8.33 Hz) during the Monsoon Trough Boundary Layer Experiment in 1990. The analysis showed that the spectra of wind and temperature obeyed the Monin-Obukhov scaling. The spectral curve showed a slope of –2/3 in high frequency portion which indicated the existence of inertial subrange. The diurnal variation in the eddy sizes were brought out.

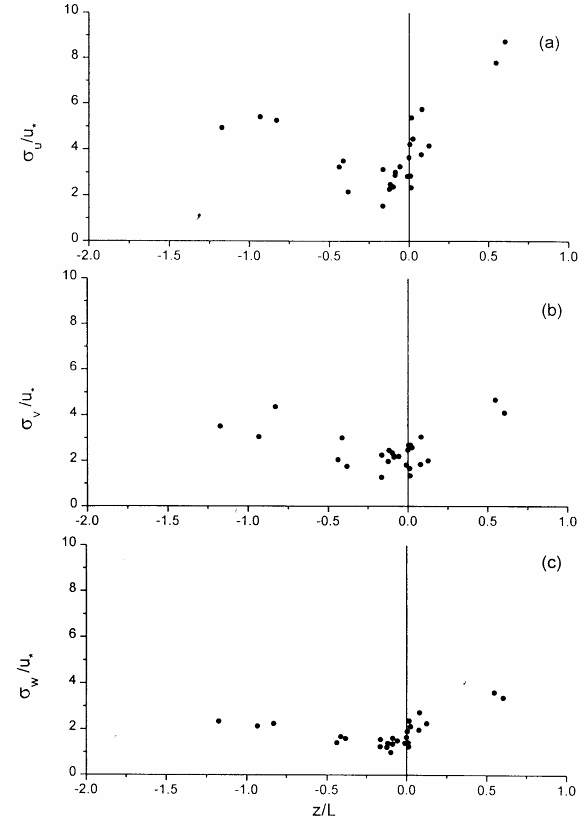
Key words − Turbulence, Desert, Spectra, Surface layer, Monsoon trough, MONTBLEX.

1. Introduction

Turbulence plays an important role in the transport of heat, momentum and moisture from the surface layer to the atmospheric boundary layer above. In the boundary layer, diffusion of atmospheric properties occurs by eddy diffusion. The idea about the sizes of eddies can be more realistically formulated in terms of the differences in velocity existing instantaneously between one point and another in the fluid. Spectra of turbulence provide useful information on the scales of motion that contribute to the production and dissipation of energy and are important for understanding the dynamical characteristics of the atmosphere. It is known that spectra of wind and temperature obey the –5/3 power law in inertial subrange (Kolmogorov, 1941). There are three major spectral regions relevant to boundary layer flow *viz*. the energy containing range, the inertial sub-range and the region of dissipation. The energy containing range, has the bulk of turbulent energy produced by wind shear and buoyancy. In the inertial subrange, the energy is neither produced nor dissipated but transferred to smaller scales. In the dissipation range, the kinetic energy is converted to internal energy. The power spectra, in general, are dependent on height, surface roughness, mean velocity and thermal stability. Extension of the Monin-Obukhov scaling to the spectra of velocity and temperature leads to the assumption that the properly scaled logarithmic spectra $fS(f)$ should be function of the reduced frequency or wave number ($n = f\,z/u$) and the stability parameter z/L only. Analysis based on experimental data from the 1968 Kansas experiment (Kaimal *et al*., 1972) showed that the Monin-Obukhov similarity hypotheses are indeed applicable to spectra of velocities and temperature over a wide wave number region, if the terrain is sufficiently homogeneous. In India, very few studies have been reported on the sizes of turbulent eddies (Vernekar *et al*., 1993). The purpose of the investigation reported in this paper is to examine the spectra of wind and temperature in the surface layer and study the eddy sizes during different stability conditions. For this study, the observations obtained from an experiment specially designed for monsoon trough boundary layer studies in India (*i.e*. MONTBLEX) are utilized.

2. Experiment and observations

Monsoon Trough extends from north-west India to the Gangetic West Bengal. At the western end of the monsoon trough, dry convection conditions prevail while at the eastern end deep moist condition exists. To study the dynamics of monsoon trough in the atmospheric boundary layer, Monsoon Trough Boundary Layer



Figs. 1(a-c). Variation of (a) σ_u/u_* (b) σ_v/u_* and (c) σ_w/u_* with z/L

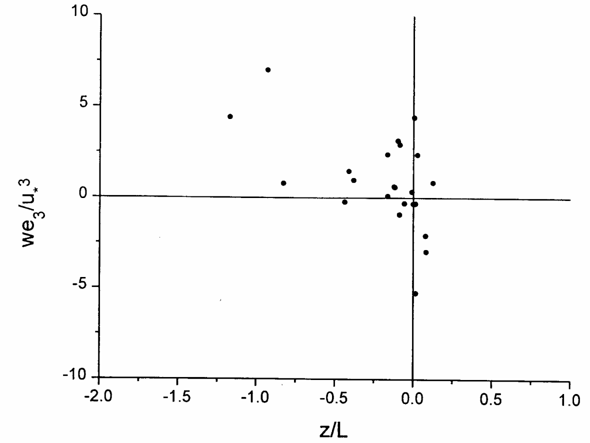


Fig. 2. Variation of we_3/u_*^3 with z/L

Experiment (MONTBLEX) (Goel and Srivastava, 1990), was conducted in the summer monsoon of 1990.

As a part of MONTBLEX, the data set was recorded at the campus of Central Arid Zone Research Institute, Jodhpur (26.2° N, 73.1° E) over a flat and homogeneous terrain. Jodhpur represented conditions of dry convection. The surface roughness parameter (Z_0) over Jodhpur estimated in previous work (Kusuma, 1996) is 1.23 cm which is in good agreement with the type of terrain (fairly level grass terrain). The main tower was 30 m high and there were six levels of measurements at 1, 2, 4, 8, 15 and 30 m. High accuracy sonic anemometer was deployed at 4 m. The measurements were sampled at 8.33 Hz. The data was collected for about 15 minutes duration during each hr for a selected period. The observations were classified into unstable and stable cases using the stability parameter (*z*/L), *z* being the height of the measurement and L the Monin-Obukhov length. Details of the tower location and other characteristics of the instruments can be found in Rudra Kumar *et al.* (1995).

TABLE 1

σ_u/u_*, σ_v/u_* and σ_w/u_* under different stabilities

z/L range	σ_u/u_*	σ_v/u_*	σ_w/u_*
–0.09 to –5,7	3.59	2.77	1.68
–0.08 to 0.08	3.85	2.23	1.83
0.09 to 0.70	6.89	3.59	3.09

3. Analysis of spectra of wind and temperature

By resolving a series of measurements into frequency or wave number components, it is possible to see how eddies of different time and space scales contribute to the overall turbulence. The fast response data of wind components and temperature from sonic anemometer have been subjected to spectrum analysis using Fast Fourier Technique (FFT) following the methodology adapted by Kaimal *et al.* (1972) and Kaimal (1988).

The following relations were used to estimate the ϕ_ϵ and ϕ_h (Hogstorm, 1988). The quantity, ϕ_ϵ and ϕ_h are the relevant shape functions (nondimensional forms) for the dissipation of turbulent kinetic energy and thermal stratification respectively for the surface layer.

$$\phi_\varepsilon^{2/3} = 1 + 0.5|z/\mathrm{L}|^{2/3}, \quad \text{for } z/\mathrm{L} \le 0 \tag{1a}$$

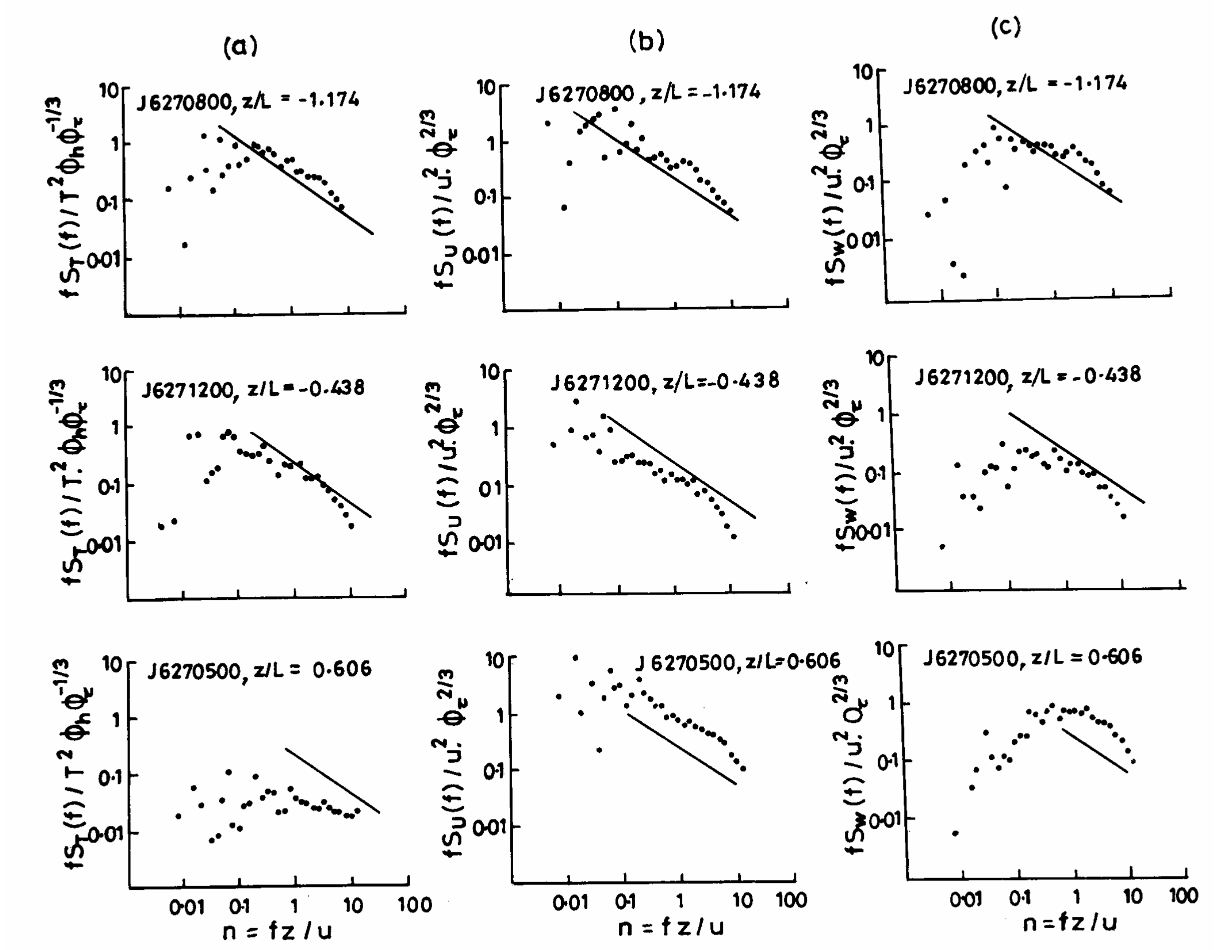
$$\phi_\varepsilon^{2/3} = 1 + 5|z/\mathrm{L}|^{2/3}, \quad \text{for } z/\mathrm{L} \ge 0 \tag{1b}$$

$$\phi_h = 1 + 16|z/\mathrm{L}|^{-1/2}, \quad \text{for } z/\mathrm{L} \le 0 \tag{2a}$$

$$\phi_h = (1 + 5\,z/\mathrm{L}), \quad \text{for } z/\mathrm{L} \ge 0 \tag{2b}$$

$$\phi_m = (1 - 16\,z/\mathrm{L})^{-1/4}, \quad \text{for } z/\mathrm{L} \le 0 \tag{3a}$$

$$\phi_m = (1 + 5\,z/\mathrm{L}), \quad \text{for } z/\mathrm{L} \ge 0 \tag{3b}$$



Figs. 3(a-c). Normalized (a) *T* , (b) *u* and (c) *w* surface layer spectra over Jodhpur

where L is the Monin-Obukhov length, *z* is the height where the observations were made. *z*/L is given by

$$\frac{z}{\mathrm{L}} = \frac{-(g/T)\left(\overline{w'\theta'}\right)_s}{u_*^3 / \mathrm{kz}} \tag{4}$$

where g is the acceleration due to gravity (9.8 ms^{-2}), *T* is the temperature, $\left(\overline{w'\theta'}\right)_s$ is the sensible heat flux, u_* is the frictional velocity and k is the von karman constant (0.4). The eddy size (λ) for *u*, *v*, *w* and *T* component have been obtained using following relation :

$$\lambda = \frac{\mathrm{z}}{n_{\mathrm{Peak}}} \tag{5}$$

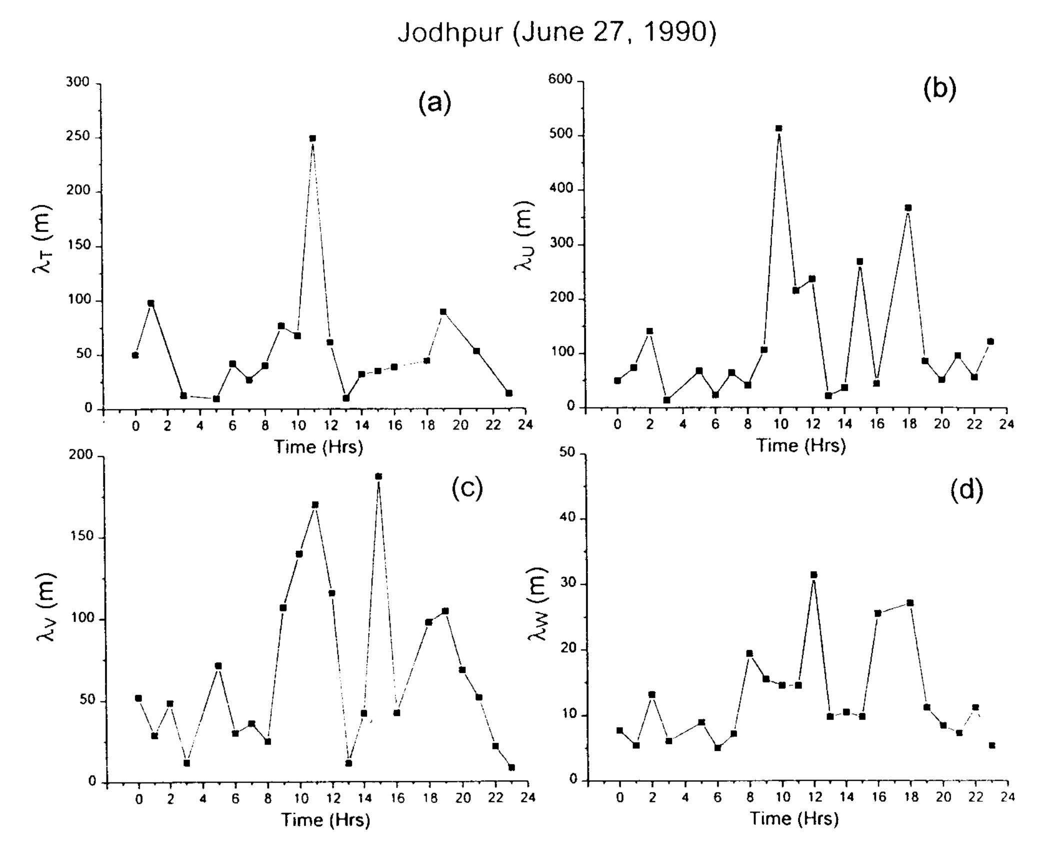
where *z* is the observational height and n_{peak} is the peak frequency ($f\ z\ /\ \bar{u}$) in the spectra of *u*, *v*, *w* and *T* components.

Spectra of wind component and temperature were obtained using FFT. The data were processed by applying cosine window tapering, mean trend removal and co-ordination rotation before being subjected to FFT. Two segments each of 4096 points were taken for FFT analysis and the spectra were averaged. In the computation, *u*, *v*, *w* components of wind and *T* were used to obtain spectral densities for *u* [$S_u(f)$], *v* [$S_v(f)$], *w* [$S_w(f)$] and *T* [$S_T(f)$]; where *f* is the frequency. *S*(*f*) is the spectral density at frequency *f* for the respective components (*u*, *v*, *w* and *T*).

4. Characteristics of turbulence

4.1. *Turbulence statistics*

Standard deviations of velocity components normalized by friction velocity plotted against *z*/L are shown in Figs. 1(a-c). The variation of σ_w/u_* with *z*/L has received considerable attention over the years because



Figs. 4(a-d). Diurnal variation of eddy sizes (a) *T*, (b) *u*, (c) *v* and (d) *w* over Jodhpur

of the relative ease with which shear stress can be obtained from vertical velocity measurements if σ_w / u_* is a well established function of stability. According to Monin-Obukhov similarity theory, the standard deviations of velocity components, when normalized by their appropriate scaling parameters, should be universal functions of *z*/L. In near neutral conditions, as there was wide scatter in the values of σ_u / u_*, σ_v / u_* and σ_w / u_* the turbulence production was due to the both dynamical as well as thermal instability. The mean values of σ_u / u_*, σ_v / u_* and σ_w / u_* under different stability conditions are given in Table 1.

These values are nearly in agreement with the values given by Panofsky and Dutton (1984) which are an average of many observations both over land and sea. In unstable conditions σ_u / u_*, σ_v / u_* and σ_w / u_* are functions of *z*/L and increased with increase in instability.

In Fig. 2, the dependence of the vertical flux of turbulent kinetic energy (TKE), we_3, normalized by cube of friction velocity, on stability (*z*/L) is shown. The vertical flux of TKE is given by $we_3 = 1/2\ w\ (u^2+v^2+w^2)$ where *u*, *v* and *w* are longitudinal, transverse and vertical components of fluctuating wind velocities respectively and $e_3 = (u^2+v^2+w^2)/2$ is TKE per unit mass. In unstable conditions, we_3 is positive and increased with increasing instability. Wyngaard and Cote (1971) reported an upward TKE flux over a stubby field and Maitani and Mitsuta (1967) also reported an upward flux over bare soil under unstable conditions.

4.2. *Spectra of wind and temperature*

The power spectra of wind velocity components (*u* and *w*) and temperature (*T*) are plotted as a function of dimensionless frequency, $n = f\, z / \overline{u}$ in Fig. 3. The spectral densities are normalized by the respective variances. According to Kolmogorov theory, the majority of mechanical and thermal production of turbulence occurs at low frequencies in the region of spectral peaks. The energy contained in low frequency eddies (bigger eddies) is transferred to higher frequency eddies (small eddies) until it is finally dissipated. There is an inertial subrange in the high frequency part where energy is transferred successively without any dissipative losses. The relationship between spectral density S(f) and natural frequency (f) follows –5/3 law. *i.e.* $S(f)\ \alpha\ f^{5/3}$ or $fS(f)\ \alpha\ n^{-2/3}$.

Fig. 3 show the scaled logarithmic spectra of wind components $\left[fS_u(f)/u_*^2\,\phi_\varepsilon^{2/3}, fS_w(f)/u_*^2\,\phi_\varepsilon^{2/3}\right]$ and temperature $\left[fS_T(f)/T_*^2\,\phi_h\phi_\varepsilon^{-1/3}\right]$ plotted against the normalized frequency ($n = fz/\bar{u}$) for different stability conditions over Jodhpur. The observations were stratified into unstable and stable cases using the stability parameter (z/L). It is seen that, the spectra of wind and temperature followed –2/3 power lawin-high frequency portion. The magnitude of the peak in the spectra (*u*, *v*, *w* and *T*) for unstable conditions is more than that of stable conditions. This peak is shifted towards higher frequencies for stable conditions. All spectra exhibit a tendency to approach the "–2/3 power law" at frequencies greater than 0.1 depending on the stability conditions. Temperature and velocity spectra at higher frequencies showing similar behaviour have been reported elsewhere (Kaimal, 1988). Under stable conditions, in some cases, the spectra of temperature and wind show the slope greater than –2/3. This may be due to the existence of buoyant subrange in stable conditions. Existence of this range demands higher slope than –2/3 as quoted by Lumley (1964).

4.3. *Sizes of eddies*

It is interesting to study the temporal evolution of eddy sizes for whole day (24 hr). The general characteristics of the eddy sizes of wind component and temperature over Jodhpur (dry convection zone) are presented in Fig. 4, where the time is IST. They show nearly cyclic behaviour with small values at night and dawn. The eddy sizes increased from sunrise and reached maximum at mid-day (11-15 hr). It showed decrease at sunset and during night. Eddy sizes were comparatively higher during daytime. This could be due to strong solar heating which enhances the transfer of heat and momentum generating well developed convective instabilities. Thus, the strong transfers of heat and momentum are associated with larger eddies. On the other hand, at night, without the solar input, there is a sharp decline of convective situations, and this reduces considerably the transfer of heat and momentum. The variation of normalized peak frequency of vertical component of wind with respect to stability is given in Fig. 5. It showed lower peak frequency (high eddy sizes) in unstable cases where as higher peak frequency (smaller eddy sizes) in stable conditions. The eddies for *u* and *v* components of wind and temperature showed decrease in size with increase in stability on an average. By and large, the eddy sizes were within a range of 14-286 m for *u* component, 5-31 m for *w* component and of 9-248 m for *T*.

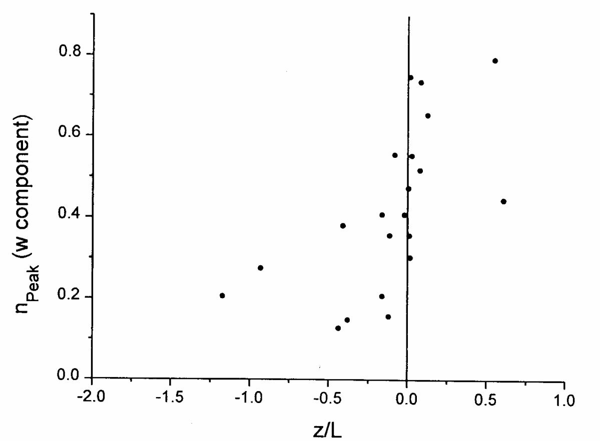


Fig. 5. Variation of normalized peak frequency of vertical wind component with z/L

5. Summary of the results

The analysis of wind and temperature observations using sonic anemometer over dry convection zone of the monsoon trough showed the following characteristics of turbulence in the atmospheric surface layer.

(*i*) The spectra of wind and temperature obeyed the Monin-Obukhov scaling. The spectral curve showed a slope of -2/3 in high frequency portion which indicated existence of inertial subrange.

(*ii*) The eddy sizes of wind and temperature showed diurnal variation. Eddies attained higher sizes in the noon hrs and their size decreases with the decrease in intensity of solar radiation.

(*iii*) The vertical flux of turbulent kinetic energy increased with increasing instability and was some times negative to near zero during convective conditions indicating the influence of monsoon on the flow.

(*iv*) The mixing due to the temperature inhomogeneity is most important during the daytime afternoon to fast and deeply mixing of the boundary layer. During night-time the thermal as well as dynamical importance are almost similar. These mixing are greatly dependent on the stability of the atmospheric flow. The atmosphere is well mixed for the z/L < -0.10. In stable conditions, the mixing will be suppressed. During night-time, the increase in wind shear is enhancing both the heat and momentum to increase the rate of mixing in the boundary layer.

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