Characteristics of turbulence in the atmospheric surface layer over a complex terrain

B S Murthy & T Dharmaraj
Indian Institute of Tropical Meteorology, Pune 411 008

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Measurements of fluctuating wind components and temperature have been made in the atmospheric surface layer over a complex terrain in the campus of the Indian Institute of Tropical Meteorology, Pune, using sonic anemometer at 5.2 m above the surface. Characteristics of turbulence, i.e. spectra of wind velocity components and turbulence statistics of wind are presented. The peak of normalized w-spectrum over a complex terrain for near-neutral condition was found to be \( -0.6 \) as compared to \(-0.4\) over homogeneous terrain. The non-dimensional frequency maximum for \( w \)-component spectrum was observed to be \( 0.9 \) as compared to \(-0.5\) over homogeneous terrain. Empirical formulae for standard deviation of velocity components have been tested against observations over hilly terrain. Vertical flux of turbulence kinetic energy as a function of stability is also discussed.

1 Introduction

Turbulence in the atmospheric surface layer (ASL) plays an important role in the transportation of heat and moisture near the surface to higher up in the atmospheric boundary layer. According to the Monin-Obukhov hypothesis, various statistics of atmospheric parameters such as gradients, variances and covariances, when normalized by appropriate powers of the scaling velocity \( u_\ast \) and the scaling temperature \( T_\ast \), become universal functions of the ratio of height of measurement (\( z \)) to Monin-Obukhov length (\( L \)) or stability parameter \( z/L \). The empirical formulae for the non-dimensional statistics of ASL have been determined from Kansas data\(^1\). These formulae have been tested in later field experiments over homogeneous terrain and found to be valid. Very few experiments were conducted over complex terrain to study Monin-Obukhov similarity theory. Divergence of turbulence kinetic energy is important in the energy budget of the atmospheric boundary layer\(^2\). Several researchers have made direct measurements of the flux. McBean\(^4\) discussed the stability dependence of normalized kinetic energy flux using their observational results. Experiments that were made over relatively smooth surfaces show that the turbulent kinetic energy flux is evidently upward in unstable conditions and tend to be downward in stable conditions\(^3,5,6\).

Spectra of turbulence provide useful information on the scales of motion that contribute to the production and dissipation of energy. 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 the functions of the reduced frequency or wave number \( (\pi=nL/u_\ast) \) and the stability parameter, \( z/L \). Analysis based on experimental data from the 1968 Kansas experiment shows 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\(^7\).

Very few experiments involving micro-meteorological towers were conducted over complex terrain to study the characteristics of turbulence when terrain features change along the air flow. Panofsky et al\(^8\) have conducted some experiments over various terrains like, on tops of hills, over land downstream of a water surface and over rolling terrain to study the spectra of velocity components over complex terrain. They have used a number of towers located at upwind and downwind of the line of change of roughness. When air moves over terrain with changed characteristics, then (i) for wavelengths very short relative to the fetch over the new terrain, the spectral densities are in equilibrium with the new terrain, (ii) for wavelengths long compared to the fetch, spectral densities remain unchanged if the ground is horizontal, and decrease when the flow is uphill for the longitudinal velocity component only and (iii) since vertical velocity spectra contain relatively less low-wave-number energy than that of horizontal velocity spectra, energetic vertical velocity fluctuations tend to be in equilibrium with local terrain.

The aim of this paper is to probe the characteristics of turbulence over a hilly terrain (IITM campus) in
terms of spectral features and turbulence statistics of wind velocity components under unstable and stable conditions.

2 Experiment
A field experiment was conducted during 12-15 May 1992 in the premises of IITM, Pune, to study the characteristics of turbulence in the surface layer. The experimental site (bare soil) in the campus (18°32'N, 73°51'E) is surrounded by hills of approximately 100 m on all sides except north. The distance from the tower to the foot of hills is nearly 200 m. The terrain with hills around is believed to induce complex wind fields with marked horizontal and vertical variability in wind speed, direction and turbulence. The Pune city is located in the western ghats of India at ~550 m AMSL. A sonic anemometer (Applied Technology Inc., USA) with a path length of 15 cm was mounted on a tower of height 5.2 m. The data were collected at 10 Hz sampling frequency for 15 min duration in each hour during daytime. Of course, this duration is short for convective conditions to include low frequency contribution to the turbulence kinetic energy. But, we could archive only 15 min data with the existing facility at that time. With this data one can study spectral features in the inertial subrange and turbulence statistics. We have not made an attempt to determine dominant eddy size as it may result in underestimation, as sufficient low frequency is not reached.

3 Results and discussion

3.1 Wind spectra
Since sonic anemometer data were collected during daytime, most of the data runs fall under unstable category with negative z/L values. Some data runs were discarded because of spikes in the time series. Only one day (14 May 1992) data were collected up to 2200 hrs IST. The prevailing wind during daytime was SSE (Fig. 1). Winds were moderate with a speed of ~3 m s\(^{-1}\). Since prevailing winds are south-easterly, turbulence measurements by sonic anemometer, located on the lee side of the hill, are possibly influenced by terrain-induced circulation. To study the characteristics of wind spectra under different stability conditions, some data runs have been selected which fall under unstable and stable conditions with z/L ranging from −0.917 to 0.263. The prevailing surface weather conditions during the data runs (analyzed here) are presented in Table 1. In the unstable
Table 1 — Prevailing surface weather conditions on 12, 14 and 15 May 1992 for the data runs analyzed

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Period</th>
<th>$z/L$</th>
<th>Mean wind speed m/s</th>
<th>Prevailing wind direction deg</th>
<th>$u_*$ m/s</th>
<th>$\bar{w}^2$ m$^2$/s$^2$K</th>
<th>Mean air temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1000</td>
<td>15.92</td>
<td>-0.917</td>
<td>1.90</td>
<td>293</td>
<td>0.22</td>
<td>0.191</td>
<td>34.31</td>
</tr>
<tr>
<td>12</td>
<td>1000</td>
<td>15.96</td>
<td>-0.591</td>
<td>1.40</td>
<td>168</td>
<td>0.20</td>
<td>0.091</td>
<td>31.38</td>
</tr>
<tr>
<td>15</td>
<td>0600</td>
<td>16.67</td>
<td>-0.003</td>
<td>2.66</td>
<td>162</td>
<td>0.35</td>
<td>0.003</td>
<td>27.89</td>
</tr>
</tbody>
</table>

Unstable data runs

Stable data runs

| 14   | 2100   | 15.61  | 0.128 | 1.11                | 143                           | 0.15      | -0.008                  | 31.42                    |
| 14   | 2200   | 15.15  | 0.263 | 0.68                | 177                           | 0.09      | -0.004                  | 31.29                    |

Similarity would be obtained for the stable data runs if $z/L$ decreases from -0.003 to -0.003, and $z/L$ from -0.591 to -0.917. Similarly, two data runs with moderately stable ($z/L = 0.128$) and very stable ($z/L = 0.263$) stability conditions are selected for analysis. Spectra of wind components were calculated using fast Fourier transform. Following Kaimal et al.\(^7\), $S(f)$ was normalized with $u_*$ and $\varphi_{\varepsilon}$ and plotted against reduced frequency $f_z/u$ to study wind spectra over a hilly terrain. Here, $u$ is the mean wind speed, $u_*$ the friction velocity, $z$ the height of measurement of wind and $\varphi_{\varepsilon}$ the non-dimensional dissipation function. Figure 2 shows normalized unstable spectra of velocity components $u$, $v$ and $w$ that represent longitudinal, meridional and vertical velocities, respectively. The lines in $w$-spectra are polynomial fits to the observed values. The magnitude of ordinate in $w$-spectra was observed to increase with increasing instability ($-z/L$). The non-dimensional frequency maximum ($n$, corresponding to the peak in spectral density) shifted to lower value as instability increased from -0.003 to -0.917. This is in agreement with Monin-Obukhov similarity theory that vertical velocity spectrum scales with stability parameter ($z/L$) for unstable conditions over homogeneous terrain. The inertial subrange spectra of wind should collapse to a single straight line with a slope of $-2/3$ over a homogeneous terrain.\(^7\) In the present case, spectra of wind over non-homogeneous terrain did not fall on a single straight line for different stability. This feature suggests that the empirical relation for $\varphi_{\varepsilon}$ may need some modification in the case of non-homogeneous terrain.

The horizontal spectra of wind showed $-2/3$ slope in the inertial subrange but no shift was observed in the non-dimensional frequency maximum as instability increases, indicating that spectra of $u$ and $v$ components do not follow Monin-Obukhov similarity...
Over homogeneous terrain, usually the spectral energy in the prevailing wind direction (u-component) should be higher than that in the cross-wind direction (v-component). In the present case, the magnitude of spectral energy for v-component was observed to be higher than that for u-component (Fig. 2). This may be due to circulation on the lee side of the hill where measurements were taken.

The magnitude of peak of normalized w-spectrum over a complex terrain for near-neutral condition was found to be ~0.6 as compared to ~0.4 over homogeneous terrain. The non-dimensional frequency maximum \( n = \frac{\bar{u}}{u_*} \) for w-spectrum was observed to be 0.9 as compared to ~0.5 over homogeneous terrain.

The non-dimensional frequency maximum of w-component for stable conditions was observed to shift to higher value as stability \(-z/L\) increased from 0.128 to 0.263 (Fig. 3). The ordinate of w-component spectra for stable conditions reduced, as expected, when stability increased.

### 3.2 Turbulence statistics

The variation of \( \sigma_u/u_* \) with \(-z/L\) has received considerable attention over the years because of the relative ease with which shear stress could be obtained from vertical velocity measurements, if \( \sigma_u/u_* \) was 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 \(-z/L\). Standard deviations of velocity components normalized by friction velocity are plotted against \(-z/L\) (Fig. 4). In near-neutral conditions \( \sigma_u/u_* \) is ~1.25. It increased with instability for \(-z/L > 0.1\). At \(-z/L = 2.0\), \( \sigma_u/u_* \) has reached 2.3. In moderately to strong convective conditions, it follows free-convection prediction, i.e. \( \sigma_u/u_* = 1.8 (-z/L)^{1/3} \).

An empirical formula, \( \sigma_u/u_* = 1.25 (1 - 3z/L)^{1/3} \), following Panofsky, has been drawn to compare with the best fit curve (Fig. 4). The empirical formula determined for a flat terrain underestimated \( \sigma_u/u_* \) over the hilly terrain, as the best fit curve, \( \sigma_u/u_* = 1.25 (1 - 8z/L)^{1/3} \) (dashed line in Fig. 4) lies above the formula curve (solid line in Fig. 4). Over hilly terrain, turbulence in the vertical direction is relatively high as compared to that over flat terrain. This can be attributed to the upslope winds along the heated slopes of hills around during daytime and consequent subsidence from above. The normalized standard deviations of u and v components (Fig. 4) showed considerable scatter and variability with \(-z/L\). According to Panofsky, standard deviations of horizontal velocity components scale with the height of the mixed layer \( h \) rather than the height of measurement \( z \) for unstable conditions. They follow the formula, \( \sigma_u/u_* - \sigma_v/u_* = (12 - 0.5 h/L)^{1/3} \) for flat terrain. Since \( h \), the height of mixed layer, is not known, this formula could not be checked. In near-neutral stability, we observed

\[ n = \frac{\bar{u}}{u_*} \]
\( \sigma_u / u_* - \sigma_v / u_* = 1.8 \) over the hilly terrain. Kaimal et al.\(^7\) and Busch and Larsen\(^2\) reported \( \sigma_u / u_* \) to be \( \sim 1.8 \) and \( \sigma_v / u_* \) to be \( \sim 1.6 \) in neutral stratification.

The dependence of the vertical flux of turbulent kinetic energy (TKE), \( \omega_3 \), normalized by the cube of friction velocity on stability \( (-z/L) \) is shown in Fig. 5. The vertical flux of TKE is given by \( \omega_3 = 1/2 \ \sqrt{u^2 + v^2 + w^2} \), 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 the TKE per unit mass. The parameter \( \omega_3 \) remained more or less constant for near-neutral conditions with no definite sign in the range of \( 0.01 < -z/L < 1.0 \). For \(-z/L > 1.0\), \( \omega_3 \) is positive and increased with increasing instability (Fig. 5). Wyngaard and Cote\(^5\), reported an upward TKE flux over a stubby field and Maitani and Mitsuta\(^10\) also reported an upward flux over bare soil under unstable conditions. In the present case, we have found that \( \omega_3 \) is, sometimes, downward though the atmosphere is very unstable with \(-z/L=0.7\). This can be attributed to terrain effects like upslope winds along the heated hill slopes and subsidence from above in very unstable conditions. It might have resulted from circulation in the lee side of the hill where measurements were taken. Of course, this could also be derived from the inadequate short averaging time.

Fig. 4 — Normalized velocity components as a function of stability. (Solid line represents Panofsky formula and dotted line the present case)
Fig. 5 — Vertical flux TKE as a function of stability (15 min) as merely a random result. This has to be confirmed in a further study by increasing the sampling duration to one hour.

4 Summary and conclusions

Wind spectra and turbulence statistics over a complex terrain were studied as a function of stability parameter \( z/L \) for unstable and stable conditions. The spectra of velocity components over a complex terrain showed \(-2/3\) slope in the inertial subrange following Kolmogorov's isotropic turbulence in the small-scale range. The inertial subrange spectra of wind over non-homogeneous terrain did not collapse into a single straight line for different stability conditions, suggesting that the empirical relation for \( k/e^{2/3} \) may need some modification for non-homogeneous terrain. The non-dimensional frequency maximum of vertical velocity spectrum was observed to shift systematically as stability changes. The observed differences in wind spectra between non-homogeneous and homogeneous terrain are only in the magnitude of normalized spectral energy peak and non-dimensional frequency maximum of vertical velocity spectrum under neutral stability condition. These results are tentative as they are inferred from a few data runs. Much scatter was found in the turbulent statistics of horizontal wind components. The standard deviation of vertical velocity followed the empirical formula for flat uniform terrain and its magnitude increased with increasing instability. The vertical flux of TKE increased with increasing instability and was sometimes negative during convective conditions, possibly due to terrain-induced circulation on the lee side of the hill where measurements were taken.

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References