Pergamon

Atmospheric Environment Vol. 29, No. 16, pp. 2089–2098, 1995

1352-2310/95 $9.50 + 0.00

1352-2310(94)00328-9

SURFACE LAYER TURBULENCE PROCESSES IN LOW WIND SPEEDS OVER LAND

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(*First received* 22 *January* 1993 *and in final form* 2 *September* 1994)

Abstract—The atmospheric diffusion in the tropics is generally associated with low wind speeds, typically of magnitudes less than 3 m s^{-1}. Low wind speeds would cause significant free convection in the daytime and strong stable conditions in the nighttime. Hence, the atmospheric surface layer turbulence associated with low wind speeds could be different from that of moderate to high wind speeds. The purpose of this paper is to present and discuss the variation of surface layer turbulence parameters and their dependence on atmospheric stability. The turbulence data collected from micrometeorological tower at Indian Institute of Technology (IIT) campus, New Delhi, India, using a sonic anemometer at a height of 4 m as part of the SF_6 tracer diffusion experiments have been analyzed to achieve these objectives. The turbulence statistics computed include averages, variances and covariances of the fluctuating wind components and temperature. In all, 38 hourly test runs were analyzed to compute various parameters such as surface turbulent fluxes of heat and momentum and the variances of velocity fluctuations. Results reveal that the turbulence parameters vary differently with atmospheric stability and wind speed for the wind speeds more than 1 m s^{-1} as against wind speeds less than 1 m s^{-1}. A spectral analysis was carried out on the turbulence data. Results indicate that larger eddies dominate during nighttime as compared to the daytime convective conditions.

Key word index: Surface layer, turbulence, low wind speeds.

1. INTRODUCTION

Studies related to the turbulence characteristics in the surface layer have been limited, predominantly, to the sites located in the mid-latitudes (Smedman, 1991; Wang, 1992). Besides, the commonly used dispersion parameters in air quality models are based on field tracer experiments conducted mostly in mid-latitudes. There is a distinct need to acquire adequate understanding of the turbulence characteristics in the tropics since the intense convective mixing is a dominant feature of the tropical environment. Calm conditions do occur quite frequently in the tropics. The present understanding of the turbulence structure in the surface layer is relatively satisfactory only for moderate to high wind speeds.

Atmospheric turbulence has mainly two components: mechanical (due to frictional wind shear) and thermal (due to temperature gradients). During the daytime, heating of the earth's surface results in the formation of a strong convective boundary layer. The mechanical component of turbulence which is essentially due to wind shear decreases with the decrease in wind speed leading to considerable free convection. However, in the nighttime, a strong stable layer is formed above the Earth's surface due to radiative cooling of the ground leading to thermally stable conditions. Wind speeds near the surface tend to be even lower during nighttime stable conditions. In order to model the turbulent diffusion processes properly in these conditions, a better understanding of the turbulence structure in the surface layer is very important. More specifically, the knowledge of turbulence statistics σ_v and σ_w (standard deviation of crosswind and vertical components of wind vector) is very important for the estimation of atmospheric dispersion of pollutants. The main objective of the present study is to determine the variation of turbulence in the surface layer during daytime convective conditions and nighttime stable conditions in low wind speeds.

The data used in the analysis were collected as part of the SF_6 tracer diffusion experiments conducted in the IIT campus, Delhi, to study the atmospheric dispersion of airborne materials in the tropical regions.

2. EXPERIMENTAL

New Delhi (28.43°N, 77.18°E) is a metropolis located in the northern part of India and is in the tropics. The turbulence data were collected at the campus of IIT, Delhi. The observation site is a relatively flat and open area, except for a few trees in the vicinity. An average roughness length for this site was estimated to be 78 cm in a recent study (Raman *et al.*, 1990).

Observations of the wind and temperature fluctuations were obtained using a fast response three-dimensional sonic anemometer (SWS-211/2EK) mounted at the 4 m level of the 30 m micrometeorological tower located inside the campus. The anemometer was also equipped with a fine wire thermocouple with a time constant of about 0.05 s. The sonic anemometer had a distance constant of about 20 cm. The sampling frequency for wind and temperature fluctuations was set to 1 Hz. Diffusion experiments were conducted at a location 300 m from the micrometeorological tower over a flat and plain field. The data was collected for a total of 38 hourly test runs and the timings of most of these were so planned as to coincide with the diffusion tests. These test runs include stable, unstable and near-neutral atmospheric conditions.

3. DATA ANALYSIS

The turbulence analysis was carried out with u, v, w and T data from the experiments conducted in the months of October and November 1991 and January and February 1992, which are essentially winter months. Horizontal mean wind speed in most of the experiments (test runs) was less than 3 m s^{-1}.

Before carrying out the statistical analysis, time traces were drawn for u, v, w and T values from the sonic anemometer for each test run to look for any distortion (unusual trend) such as the kinks or spikes in the data due to a faulty sensor or presence of drift in calibration. Spurious data points were replaced by the average value of the neighboring points. However, such cases were very limited with just one or two spurious observations out of 3600.

Results from the initial analysis of the complete data set suggested a division of the data, according to the mean wind speed into two groups: (1) $U < 1$ m s^{-1}

Table 1a. Surface layer parameters for $U < 1$ m s^{-1}.

Test	Date (dd-mm-yy)	Time (h)	U (m s^{-1})	z/L	u_* (m s^{-1})	H_0 (W m^{-2})
Daytime convective conditions						
1	13-11-91	1000–1100	0.82	− 3.29	0.265	78.62
2	13-11-91	1600–1700	0.33	− 1.91	0.121	4.83
3	24-01-92	0930–1030	0.61	− 8.95	0.173	39.73
4	24-01-92	1030–1130	0.20	− 47.41	0.116	73.39
Nighttime stable conditions						
5	11-10-91	1800–1900	0.24	198.07	0.021	− 2.94
6	11-10-91	1900–2000	0.24	1150.22	0.011	− 2.14
7	11-10-91	2000–2100	0.24	33.38	0.032	− 1.27
8	11-10-91	2100–2200	0.29	60.48	0.037	− 3.69
9	12-10-91	0000–0100	0.25	9.94	0.018	− 0.06
10	12-10-91	0100–0200	0.24	24.97	0.023	− 0.34
11	12-10-91	0600–0700	0.18	25.05	0.036	− 1.13
12	14-10-91	0500–0600	0.23	34.13	0.014	− 0.09
13	13-11-91	2300–0000	0.16	100.84	0.069	− 22.67
14	14-11-91	0000–0030	0.30	68.15	0.058	− 10.06
15	14-11-91	0500–0600	0.14	216.56	0.043	− 9.34
16	14-11-91	0600–0700	0.13	73.74	0.050	− 4.59
17	24-01-92	1730–1830	0.30	40.16	0.074	− 14.19
18	24-01-92	1830–1930	0.27	661.80	0.015	− 1.55
19	24-01-92	2230–2330	0.26	1664.64	0.008	− 0.38
20	24-01-92	2330–0027	0.24	95.77	0.050	− 6.00
21	25-01-92	0430–0530	0.46	22.29	0.114	− 15.35
22	25-01-92	0530–0630	0.37	51.92	0.059	− 7.68

Table 1b. Arithmetic mean and median for the quantities in Table 1a

	Daytime		Nighttime	
	Mean	Median	Mean	Median
U	0.49	0.47	0.252	0.242
z/L	− 15.39	− 6.12	251.78	64.31
u_*	0.169	0.147	0.041	0.036
H_0	49.14	56.56	− 5.75	− 3.32

and (2) $U \geqslant 1\ \mathrm{m\,s^{-1}}$. Data were further divided according to the atmospheric stability into daytime and nighttime cases which included unstable, stable and near-neutral conditions.

For characterizing the surface layer structure, turbulent fluxes of heat and momentum were estimated using eddy correlation method. Friction velocity, u_*, has been evaluated from the expression

$$u_* = (\tau_*/\rho)^{1/2} = [(\overline{u'w'}^2) + (\overline{v'w'})^2]^{1/4} \quad (3.1)$$

where ρ is the density of air and τ_* is the surface shear stress and $\overline{u'w'}$ and $\overline{v'w'}$ are the turbulent fluxes of momentum in the direction of u and v components of wind velocity, respectively. For the data $U < 1\ \mathrm{m\,s^{-1}}$, the mean value of u_* during the day was $0.169\ \mathrm{m\,s^{-1}}$, whereas during the night the average value was $0.041\ \mathrm{m\,s^{-1}}$, about a factor of 4 less than the daytime value. On the other hand, for $U \geqslant 1\ \mathrm{m\,s^{-1}}$, the mean value of the u_* during the daytime was $0.533\ \mathrm{m\,s^{-1}}$ and during the night was $0.299\ \mathrm{m\,s^{-1}}$.

Surface turbulent sensible heat flux, H_0, was obtained from

$$H_0 = \rho C_p \overline{w'T'} \quad (3.2)$$

where C_p is specific heat at constant pressure. The average value of H_0 during the day was $49.14\ \mathrm{W\,m^{-2}}$ for $U < 1\ \mathrm{m\,s^{-1}}$ and for $U \geqslant 1\ \mathrm{m\,s^{-1}}$ the average value was $73.45\ \mathrm{W\,m^{-2}}$.

Another important surface parameter, Monin–Obukhov (M–O) length scale, was obtained for each of the test runs using

$$L = -\frac{\rho C_p T_0 u_*^3}{k g H_0} \quad (3.3)$$

where g is the acceleration due to gravity, k is Von Karman constant and T_0 is the mean surface temperature. The dimensionless parameter z/L (z = height above the ground) for each test run is listed in Tables 1a and 2a. Ignoring the outliers, the mean values for the daytime and nighttime runs are -15.39 and 251.78, respectively, for $U < 1\ \mathrm{m\,s^{-1}}$, whereas for $U \geqslant 1\ \mathrm{m\,s^{-1}}$, the average values for the daytime and nighttime runs are -0.43 and 1.61, respectively. As indicated by z/L values from Table 2a, near-neutral conditions persisted during the day from 1200 to 1800 h on 14 February 1992 and from 0700 to 0800 h on 15 February 1992. The remaining daytime test runs ($U < 1\ \mathrm{m\,s^{-1}}$) fall more on the unstable side.

Table 2a. Surface layer parameters for $U \geqslant 1\ \mathrm{m\,s^{-1}}$

Test	Date (dd-mm-yy)	Time (h)	U ($\mathrm{m\,s^{-1}}$)	z/L	u_* ($\mathrm{m\,s^{-1}}$)	H_0 ($\mathrm{W\,m^{-2}}$)
Daytime convective conditions						
23	14-02-92	1200–1300	3.48	−0.63	0.615	138.42
24	14-02-92	1300–1400	3.27	−0.69	0.569	147.08
25	14-02-92	1400–1500	3.18	−0.49	0.623	127.54
26	14-02-92	1500–1600	2.96	−0.22	0.590	47.79
27	14-02-92	1600–1700	2.77	−0.09	0.518	13.87
28	14-02-92	1700–1800	2.12	−0.32	0.447	29.31
29	15-02-92	0700–0800	1.56	−0.54	0.339	10.14
Nighttime stable conditions						
30	14-02-92	1800–1900	1.27	1.83	0.317	−56.42
31	14-02-92	1900–2000	1.12	1.95	0.262	−31.71
32	14-02-92	2000–2100	1.18	2.67	0.244	−34.01
33	15-02-92	0000–0100	2.03	1.02	0.386	−44.83
34	15-02-92	0100–0200	1.07	1.26	0.286	−20.25
35	15-02-92	0300–0400	1.18	1.98	0.275	−24.16
36	15-02-92	0400–0500	1.28	1.91	0.277	−21.86
37	15-02-92	0500–0600	1.35	1.39	0.322	−23.52
38	15-02-92	0600–0700	1.23	0.46	0.322	−27.58

Table 2b. Arithmetic mean and median for the quantities in Table 2a

	Daytime		Nighttime	
	Mean	Median	Mean	Median
U	2.76	2.96	1.30	1.23
z/L	−0.43	−0.49	1.62	1.83
u_*	0.533	0.590	0.299	0.286
H_0	73.45	47.78	−31.59	−27.58

Since, this data set has several outliers for the range $U < 1\ \mathrm{m\,s^{-1}}$, arithmetic mean is not a suitable measure of central tendency. In such a situation, median would be more desirable measure of central tendency especially for the variables H_0 and z/L. Thus, the values of median together with those of mean are indicated in Tables 1b and 2b for both wind speed regimes. There is a significant difference in the mean and median values of z/L and H_0 for the range $U < 1\ \mathrm{m\,s^{-1}}$, whereas for the other range (i.e. $U \geq 1\ \mathrm{m\,s^{-1}}$) the difference is much less.

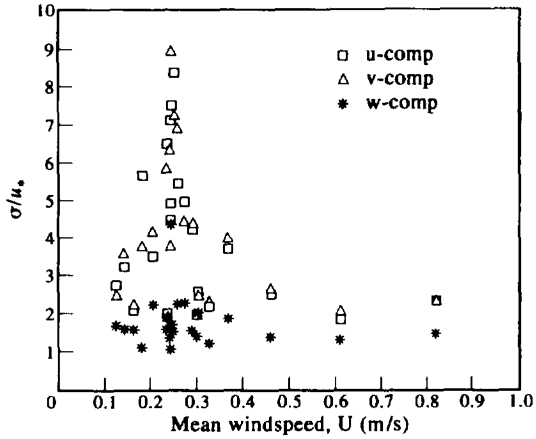

Fig. 1. Scatter diagram showing the variation of standard deviation of wind components normalized by the friction velocity with horizontal mean wind speed for $U < 1\ \mathrm{m\,s^{-1}}$.

4. DISCUSSION OF RESULTS

Dates and durations of the experiments and the corresponding mean wind speeds and stability parameters are listed in Table 1a for $U < 1\ \mathrm{m\,s^{-1}}$ and in Table 2a for $U \geq 1\ \mathrm{m\,s^{-1}}$. Daytime and nighttime experiments are also indicated. The data analyzed are from a total of 38 experiments in which 11 correspond to daytime conditions.

4.1. *Normalized standard deviations*

The analysis included the variation of turbulence (standard deviation of wind velocity components) normalized by the friction velocity (σ_i/u_* ($i = u, v, w$)) with U and z/L. Figures 1 and 2 give the scatter plots for the variation of (σ_i/u_* ($i = u, v, w$)) with mean wind speed for $U < 1\ \mathrm{m\,s^{-1}}$ and $U \geq 1\ \mathrm{m\,s^{-1}}$, respectively. There is far less scatter for $U \geq 1\ \mathrm{m\,s^{-1}}$ and appreciable scatter for $U < 0.3\ \mathrm{m\,s^{-1}}$. The sonic anemometer observations may be subject to errors for wind speeds less than $0.25\ \mathrm{m\,s^{-1}}$. The values of σ_i/u_* ($i = u, v, w$) for each of the test runs are given in Tables 3a and 4a for $U < 1\ \mathrm{m\,s^{-1}}$ and $U \geq 1\ \mathrm{m\,s^{-1}}$, respectively.

According to the Monin–Obukhov similarity theory, the vertical wind variance, σ_w^2, is related to the stability parameter, z/L, as (Panofsky and Dutton, 1984)

$$\frac{\sigma_w}{u_*} = \phi_w(z/L) = \begin{cases} 1.25(1 - 3z/L)^{1/3}, & z/L < 0 \\ 1.25, & z/L \geq 0 \end{cases} \quad (4.1)$$

where $\phi_w(z/L)$ is a dimensionless similarity function. Figures 3 and 4 show the variation of σ_u/u_*, σ_v/u_* and σ_w/u_* with z/L through scatter diagrams for $U < 1\ \mathrm{m\,s^{-1}}$ and $U \geq 1\ \mathrm{m\,s^{-1}}$, respectively. Figure 3 shows that for $U < 1\ \mathrm{m\,s^{-1}}$, σ_w/u_* is fairly constant for stable and near-neutral cases, although the values are slightly higher than the corresponding values for $U \geq 1\ \mathrm{m\,s^{-1}}$. The increase in σ_w/u_* with decrease in U is mainly due to significant decrease in the magnitude of u_* values for $U < 1\ \mathrm{m\,s^{-1}}$ (Fig. 3) as compared to $U \geq 1\ \mathrm{m\,s^{-1}}$ (Fig. 4). Thus, it is clear that equation (4.1) is not valid for the range $U < 1\ \mathrm{m\,s^{-1}}$ for stable conditions. The disagreement may be due to the horizontal inhomogeneity in the surface layer over this site or due to the fact that Monin–Obukhov similarity theory may be suspect in describing turbulence characteristics in very low wind conditions. There is a good agreement with equation (4.1) for $U \geq 1\ \mathrm{m\,s^{-1}}$ on the stable side ($z/L > 0$). For unstable cases in both wind speed categories, equation (4.1) appears to overpredict σ_w/u_* values. However, there are not sufficient data to establish the relationship.

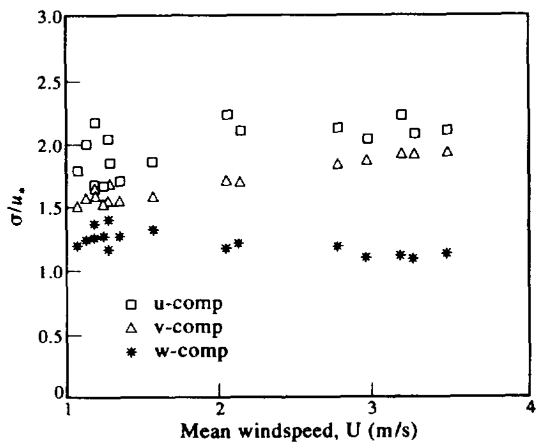

Fig. 2. Same as Fig. 1 but for $U \geq 1\ \mathrm{m\,s^{-1}}$.

Quantitative values shown in Table 4b indicate the mean of σ_w/u_* to be 1.27 in the nighttime (stable conditions) for $U \geq 1\ \mathrm{m\,s^{-1}}$ in agreement with the values reported in the literature for moderate and strong winds (Lumley and Panofsky, 1964; Panofsky and Dutton, 1984). For daytime conditions, the mean value of σ_w/u_* is 1.18. The seven daytime observations for $U \geq 1\ \mathrm{m\,s^{-1}}$ correspond to slightly convective conditions as indicated by the values of z/L (Table 2a).

On the other hand, the ratios (σ_u/u_*, σ_v/u_* and σ_w/u_*) for $U < 1\ \mathrm{m\,s^{-1}}$ are large, particularly during nighttime (Table 3b). The difference in the daytime and the nighttime mean values is less for the vertical component. Values of all the three components during

Table 3a. Components of turbulence intensity and the standard deviation of wind normalized by friction velocity for experiments with $U < 1\ \mathrm{m\,s^{-1}}$.

Test	Date (dd-mm-yy)	Time (h)	i_x	i_y	i_z	σ_u/u_*	σ_v/u_*	σ_w/u_*
Daytime convective conditions								
1	13-11-91	1000–1100	0.761	0.755	0.471	2.35	2.33	1.45
2	13-11-91	1600–1700	0.813	0.868	0.460	2.18	2.32	1.23
3	24-01-92	0930–1030	0.524	0.590	0.368	1.84	2.07	1.29
4	24-01-92	1030–1130	2.006	2.376	1.270	3.51	4.16	2.22
Nighttime stable conditions								
5	11-10-91	1800–1900	0.416	0.321	0.144	4.90	3.78	1.70
6	11-10-91	1900–2000	0.325	0.386	0.189	7.50	8.91	4.37
7	11-10-91	2000–2100	0.584	0.491	0.135	4.48	3.77	1.04
8	11-10-91	2100–2200	0.544	0.564	0.200	4.23	4.39	1.55
9	12-10-91	0000–0100	0.599	0.520	0.110	8.36	7.25	1.53
10	12-10-91	0100–0200	0.692	0.614	0.133	7.12	6.31	1.37
11	12-10-91	0600–0700	1.114	0.744	0.218	5.64	3.77	1.11
12	14-10-91	0500–0600	0.391	0.351	0.116	6.47	5.81	1.91
13	13-11-91	2300–0000	0.881	0.949	0.658	2.08	2.24	1.55
14	14-11-91	0000–0030	0.500	0.472	0.383	2.59	2.44	1.99
15	14-11-91	0500–0600	0.977	1.078	0.481	3.23	3.56	1.59
16	14-11-91	0600–0700	1.101	0.994	0.665	2.77	2.50	1.67
17	24-01-92	1730–1830	0.488	0.495	0.348	1.98	2.00	1.41
18	24-01-92	1830–1930	0.275	0.246	0.126	4.94	4.42	2.27
19	24-01-92	2230–2330	0.172	0.217	0.071	5.44	6.88	2.24
20	24-01-92	2330–0027	0.424	0.401	0.345	1.99	1.88	1.62
21	25-01-92	0430–0530	0.630	0.662	0.344	2.53	2.66	1.38
22	25-01-92	0530–0630	0.593	0.638	0.301	3.71	4.00	1.88

Table 3b. Arithmetic mean with standard deviation and median for the quantities in Table 3a

	Daytime		Nighttime	
	Mean	Median	Mean	Median
i_x	1.026 ± 0.58	0.787	0.595 ± 0.26	0.564
i_y	1.147 ± 0.72	0.811	0.564 ± 0.24	0.507
i_z	0.642 ± 0.36	0.465	0.276 ± 0.18	0.209
σ_u/u_*	2.47 ± 0.63	2.26	4.44 ± 1.95	4.35
σ_v/u_*	2.72 ± 0.84	2.33	4.25 ± 1.96	3.77
σ_w/u_*	1.55 ± 0.40	1.37	1.79 ± 0.71	1.60

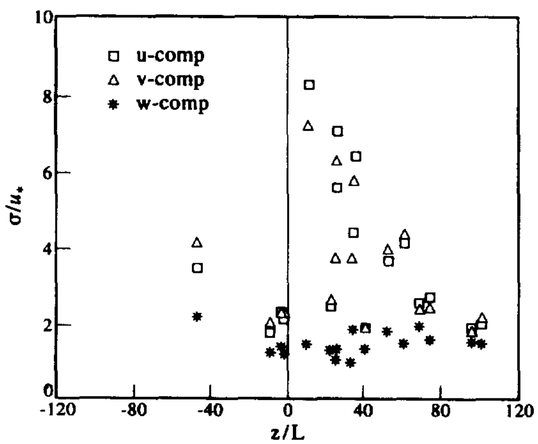

Fig. 3. Scatter diagram showing the variation of standard deviation of wind components normalized by the friction velocity with stability parameter (z/L) for $U < 1\ m\ \mathrm{s}^{-1}$.

the daytime are still reasonably close to those for $U \geqslant 1\ \mathrm{m\,s^{-1}}$.

If we consider these daytime experiments ($U \geqslant 1\ \mathrm{m\,s^{-1}}$) of winter months to be falling roughly in near-neutral stability conditions, a comparison with other studies can be made. Table 5 gives a comparison of the mean values of σ_u/u_*, σ_v/u_* and σ_w/u_* with those from Panofsky and Dutton (1984), Lanzhou (Wang, 1992) and Uppsala (Hogstrom *et al.*, 1982) data. Our results are based, on an average, of seven observations, whereas the results of Panofsky and Dutton (1984) and Lanzhou (Wang, 1992) are based on an average of about 10 and 45 observations, respectively. While Panofsky and Dutton results are based on observations conducted over a flat terrain, including a few urban situations, Lanzhou results are based on experiments conducted on a river valley floor, with rugged side walls several hundred meters

Table 4a. Components of turbulence intensity and the standard deviation of wind normalized by friction velocity for experiments with $U \geqslant 1\ \mathrm{m\,s^{-1}}$.

Test	Date (dd-mm-yy)	Time (h)	i_x	i_y	i_z	σ_u/u_*	σ_v/u_*	σ_w/u_*
Daytime convective conditions								
23	14-02-92	1200–1300	0.373	0.341	0.203	2.11	1.93	1.15
24	14-02-92	1300–1400	0.381	0.351	0.201	2.08	1.92	1.10
25	14-02-92	1400–1500	0.437	0.377	0.221	2.23	1.92	1.13
26	14-02-92	1500–1600	0.407	0.373	0.221	2.05	1.88	1.11
27	14-02-92	1600–1700	0.400	0.344	0.225	2.13	1.84	1.20
28	14-02-92	1700–1800	0.445	0.359	0.258	2.11	1.70	1.22
29	15-02-92	0700–0800	0.405	0.346	0.289	1.86	1.59	1.33
Nighttime stable conditions								
30	14-02-92	1800–1900	0.512	0.388	0.294	2.05	1.55	1.18
31	14-02-92	1900–2000	0.466	0.367	0.293	2.00	1.57	1.26
32	14-02-92	2000–2100	0.449	0.329	0.262	2.17	1.59	1.27
33	15-02-92	0000–0100	0.424	0.325	0.225	2.23	1.71	1.19
34	15-02-92	0100–0200	0.479	0.404	0.321	1.79	1.51	1.20
35	15-02-92	0300–0400	0.392	0.386	0.322	1.67	1.65	1.38
36	15-02-92	0400–0500	0.400	0.366	0.304	1.85	1.69	1.40
37	15-02-92	0500–0600	0.410	0.372	0.305	1.71	1.55	1.27
38	15-02-92	0600–0700	0.436	0.398	0.333	1.67	1.53	1.27

Table 4b. Arithmetic mean with standard deviation and median for the quantities in Table 4a

	Daytime		Nighttime	
	Mean	Median	Mean	Median
i_x	0.407 ± 0.02	0.405	0.440 ± 0.04	0.436
i_y	0.356 ± 0.01	0.351	0.370 ± 0.03	0.372
i_z	0.231 ± 0.03	0.221	0.295 ± 0.03	0.304
σ_u/u_*	2.08 ± 0.10	2.11	1.90 ± 0.20	1.85
σ_v/u_*	1.83 ± 0.12	1.88	1.59 ± 0.07	1.57
σ_w/u_*	1.18 ± 0.07	1.15	1.27 ± 0.07	1.27

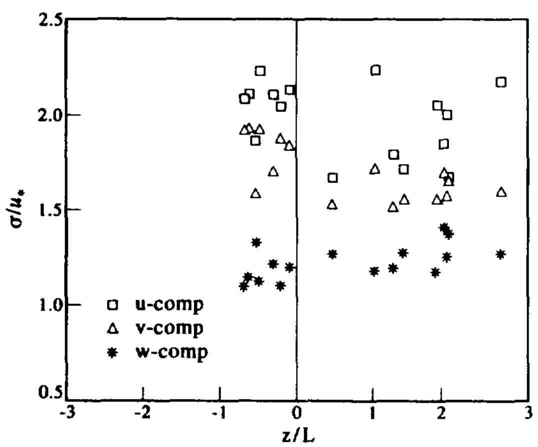

Fig. 4. Same as Fig. 3 but for $U \geqslant 1\ \mathrm{m\,s^{-1}}$.

high. It is believed that the ratios are small for this study (Table 5) because of increased u_* for convective conditions for the same wind speed range as compared to near-neutral conditions for other studies.

4.2. *Intensities of turbulence*

The three components of turbulence intensity represent turbulent mixing in the atmospheric boundary layer and are useful in the estimation of the dispersion parameters of airborne material. These are generally designated as $i_x(=\sigma_u/U)$, $i_y(=\sigma_v/U)$ and $i_z(=\sigma_w/U)$. Their variation with z/L is shown in Figs 5 and 6 and the numerical values for near-neutral conditions are given in Table 6. The results from the other three urban sites are included for comparison. The trends in the three components are similar to the other studies except that of Wang where the large mean value of the lateral component is attributed to the horizontal eddies. The mean and median values of these quantities along with the normalized sigmas are listed in Tables 3b and 4b for each category separately. Standard deviations of the values are included as an indicator of the scatter. Large standard deviation for $U < 1\ \mathrm{m\,s^{-1}}$ indicates large scatter relative to the values for the other range. Moreover, the mean and median values are quite close to each other for $U \geqslant 1\ \mathrm{m\,s^{-1}}$ while there is a clear difference for $U < 1\ \mathrm{m\,s^{-1}}$.

Three components of turbulence intensity for $U < 1\ \mathrm{m\,s^{-1}}$ and $U \geqslant 1\ \mathrm{m\,s^{-1}}$ are given in Tables 3a and 4a, respectively. For the range $U \geqslant 1\ \mathrm{m\,s^{-1}}$, there is not much difference in the mean values of i_x, i_y and i_z for the daytime and nighttime conditions, whereas for $U < 1\ \mathrm{m\,s^{-1}}$, the mean values during the daytime are roughly two times those during nighttime. For the latter case, the turbulence intensities are quite large in comparison to the former case ($U \geqslant 1\ \mathrm{m\,s^{-1}}$) because of the decrease in mean wind speed.

For $U \geqslant 1\ \mathrm{m\,s^{-1}}$ regime, the average values of turbulence intensities for daytime as well as nighttime are less than 0.5. This indicates that the eddies have negligible change as they advect past a sensor following the suggestion of Willis and Deardorff (1976). Thus, for this wind speed range, the Taylor's hypothesis of frozen turbulence is found to be valid.

When the wind speed goes below $1\ \mathrm{m\,s^{-1}}$, the turbulence intensities tend to become large, especially during the daytime because of the increase in turbulence. Tables 3b and 4b show that while the mean of daytime values of the turbulence intensities are higher than the corresponding values for $U \geqslant 1\ \mathrm{m\,s^{-1}}$, the nighttime average values are not different.

Figures 7 and 8 show the scatter plots of turbulence intensity components i_x, i_y and i_z vs U for $U < 1\ \mathrm{m\,s^{-1}}$ and $U \geqslant 1\ \mathrm{m\,s^{-1}}$, respectively. It is seen from Fig. 8 that i_z increases with the decrease in wind speed for $U \geqslant 1\ \mathrm{m\,s^{-1}}$ range. The vertical turbulence intensity is approximately 20% near $U = 3\ \mathrm{m\,s^{-1}}$ and 30% near $U = 1\ \mathrm{m\,s^{-1}}$. While the lateral component does not vary much, there is marginal increase in the longitudinal turbulence intensity, i_x, with the decrease in U. On the other hand, in $U < 1\ \mathrm{m\,s^{-1}}$ range (Fig. 7) all three turbulence intensities are nearly constant for U greater than $0.3\ \mathrm{m\,s^{-1}}$; however there is a large scatter below a wind speed of $0.3\ \mathrm{m\,s^{-1}}$. It is important to point out that the instrument problems become prominent at very low wind speeds.

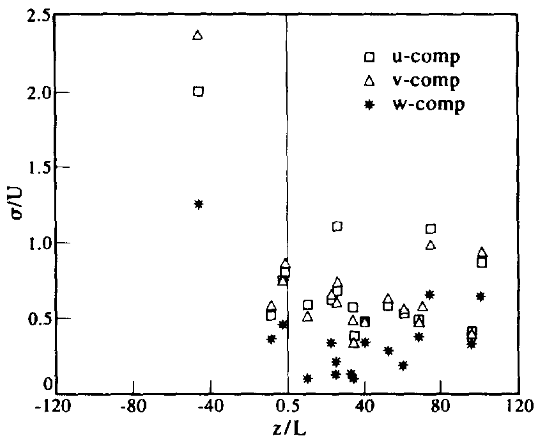

Fig. 5. Scatter diagram showing the variation of turbulence intensity components with stability parameter (z/L) for $U < 1\ \mathrm{m\,s^{-1}}$.

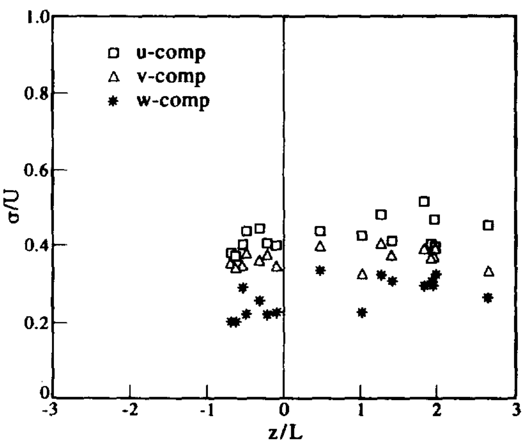

Fig. 6. Same as Fig. 5 but for $U \geqslant 1\ \mathrm{m\,s^{-1}}$.

Table 5. Standard deviation of wind components normalized by friction velocity for near-neutral conditions. Panofsky and Dutton (1984), Lanzhou (Wang, 1992) and Uppsala (Hogstrom *et al.*, 1989) data are included for comparison

Ratios	New Delhi $U \geqslant 1\ \mathrm{m\,s^{-1}}$	Panofsky and Dutton	Lanzhou	Uppsala
σ_u/u_*	2.08 ± 0.10	2.39 ± 0.03	2.36 ± 0.04	2.48 ± 0.04
σ_v/u_*	1.83 ± 0.12	1.92 ± 0.05	2.40 ± 0.08	2.20 ± 0.11
σ_w/u_*	1.18 ± 0.07	1.25 ± 0.03	1.31 ± 0.02	1.46 ± 0.04

Table 6. Turbulence intensity components averaged over near-neutral conditions and based on urban observations in New Delhi, Lanzhou, Uppsala and Beijing (Wang, 1992)

Ratios	New Delhi	Lanzhou	Uppsala	Beijing
σ_u/U	0.41 ± 0.02	0.52 ± 0.01	0.51	0.52
σ_v/U	0.36 ± 0.01	0.53 ± 0.02	0.45	0.42
σ_w/U	0.23 ± 0.03	0.29 ± 0.01	0.31	0.37

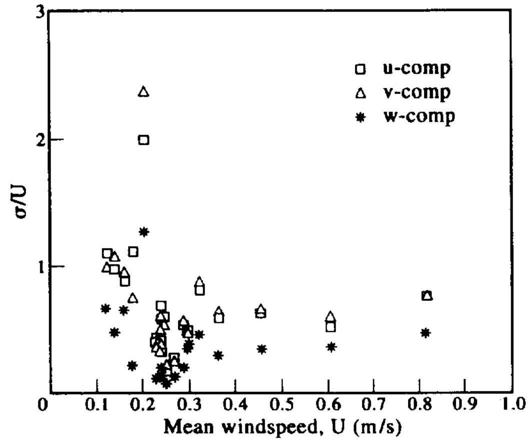

Fig. 7. Scatter diagram showing the variation of turbulence intensity components with horizontal mean wind speed for $U < 1\ \mathrm{m\,s^{-1}}$.

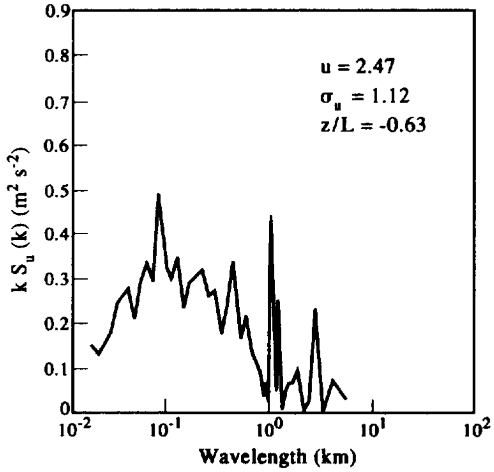

Fig. 9. Spectra of longitudinal turbulence at 1200–1300 LST on 14 February 1992 at a height of 4 m.

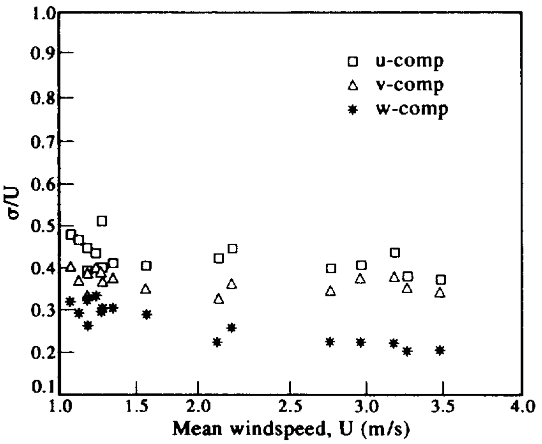

Fig. 8. Same as Fig. 7 but for $U \geqslant 1\ \mathrm{m\,s^{-1}}$.

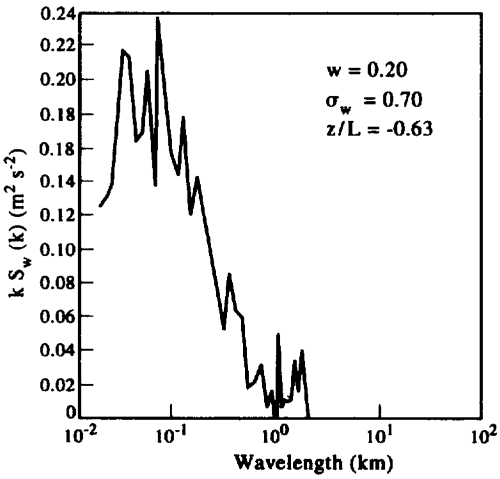

Fig. 10. Spectra of vertical turbulence of 1200–1300 LST on 14 February 1992 at a height of 4 m.

The observations (test runs) in this study pertains to a non-uniform range of z/L values in unstable conditions. Therefore, the behavior of turbulence statistics in unstable conditions cannot be adequately addressed with these observations.

4.3. *Spectra*

The spectra of fluctuating components of wind and temperature were calculated using fast Fourier transform (FFT) technique, after preprocessing the data. Spectra for longitudinal and vertical turbulence on 14 February 1992 at 1200–1300 h (LST) for typical daytime conditions are shown in Figs 9 and 10, respectively. The surface turbulent heat flux was 138 $\mathrm{W\,m^{-2}}$. Both the spectral plots indicate two peaks in amplitude. For longitudinal turbulence the principal and secondary peaks are at wavelengths 0.07 and 1 km and have amplitudes of 0.49 and 0.43 $\mathrm{m^2\,s^{-2}}$, respectively. For vertical turbulence, the principal and secondary peaks are at wavelengths 0.06 and 1 km and have amplitudes of 0.24 and 0.05 $\mathrm{m^2\,s^{-2}}$, respectively. The variance for longitudinal turbulence was 1.25 $\mathrm{m^2\,s^{-2}}$ and for the vertical turbulence was 0.49 $\mathrm{m^2\,s^{-2}}$. However, for lateral turbulence (Table 7) the peaks are at 0.2 and 1 km with amplitudes of 0.65 and 0.5 $\mathrm{m^2\,s^{-2}}$, respectively. The smaller wavelength is probably attributable to surface forcings and the larger wavelength due to roll vortices (relatively larger scale), roughly of the order of the boundary layer height.

In low wind conditions, the contribution to turbulent kinetic energy is mainly due to convection (buoyancy) and wind shear is small. A summary of the spectral amplitudes and corresponding wavelengths for 12 data sets is shown in Table 7. It is not clear why the secondary peak was not seen for 1400–1500 h (LST) on 14 February 1992.

The spectral plots of longitudinal and vertical components for typical nighttime conditions on 15 February 1992 at 0300–0400 h (LST) are shown in Figs 11

Table 7. Summary of spectral analysis

Date	Time LST		Mean $m\,s^{-1}$	St. Dev $m\,s^{-1}$	Max. amp. $m^2\,s^{-2}$	Wave length km	Sec. max. $m^2\,s^{-2}$	Wave length km	z/L
11 October 1991	1900–2000	u	0.15	0.07	0.001	1.00			1150.22
		v	− 0.19	0.13	0.010	0.01			
		w	− 0.04	0.05	0.001	0.10			
		T	24.65	0.36	0.030	0.20			
13 November 1991	1000–1100	u	0.78	0.51	0.200	0.80	0.17	1.2	− 3.29
		v	− 0.23	0.63	0.200	0.70	0.10	1.2	
		w	− 0.10	0.39	0.060	0.20	0.04	1.2	
		T	19.73	0.63	0.090	0.90			
13 November 1991	1600–1700	u	0.32	0.35	0.030	0.40	0.03	0.9	− 1.91
		v	− 0.02	0.27	0.040	0.70	0.02	1.1	
		w	− 0.03	0.15	0.010	0.10	0.01	0.8	
		T	21.76	0.69	0.060	0.60			
13 November 1991	2300–2400	u	0.17	0.24	0.030	0.80	0.001	1.2	100.84
		v	− 0.02	0.17	0.010	1.00	0.002	1.2	
		w	− 0.01	0.11	0.010	0.20	0.004	1.0	
		T	15.60	0.92	0.300	0.80			
24 January 1992	2200–2300	u	0.25	0.08	0.001	0.70			1664.64
		v	0.07	0.05	0.010	0.80			
		w	0.00	0.02	0.001	1.02			
		T	6.74	0.24	0.010	0.50			
25 January 1992	0430–0530	u	0.46	0.27	0.030	0.90			22.29
		v	− 0.03	0.29	0.020	0.90			
		w	− 0.10	0.15	0.010	0.10			
		T	7.15	0.55	0.070	0.90			
14 February 1992	1200–1300	u	2.47	1.12	0.490	0.07	0.43	1.0	− 0.63
		v	2.45	1.36	0.650	0.20	0.50	1.0	
		w	0.20	0.70	0.240	0.06	0.05	1.0	
		T	14.62	0.59	0.060	0.10			
14 February 1992	1400–1500	u	2.34	1.13	0.380	0.20			− 0.49
		v	2.19	1.47	1.400	0.90			
		w	0.10	0.72	0.290	0.08			
		T	16.63	0.46	0.030	0.07			
14 Febuary 1992	1500–1600	u	2.03	1.25	0.010	1.00			− 0.21
		v	0.17	0.67	0.200	0.10			
		w	− 1.30	0.20	0.400	0.80			
		T	30.16	0.65	0.050	0.10			
14 Febuary 1992	1900–2000	u	0.99	0.47	0.850	0.20			1.95
		v	0.53	0.47	0.090	0.30			
		w	0.06	0.33	0.040	0.20			
		T	13.90	0.27	0.030	0.20			
14 February 1992	2000–2100	u	1.01	0.45	0.080	0.50	0.10	1.1	2.67
		v	0.59	0.48	0.100	0.20	0.10	1.0	
		w	0.07	0.31	0.050	0.10	0.01	1.2	
		T	3.50	0.34	0.030	0.10			
15 February 1992	0300–0400	u	1.05	0.48	0.150	0.30	0.15	0.9	1.98
		v	0.52	0.45	0.100	0.20	0.05	0.9	
		w	0.06	0.38	0.070	0.20	0.06	0.9	
		T	9.04	0.38	0.010	0.30			
15 February 1992	0500–0600	u	1.18	0.51	0.150	0.40			1.39
		v	0.65	0.53	0.160	0.60			
		w	0.09	0.41	0.060	0.10			
		T	7.80	0.17	0.005	0.20			

and 12. These spectra also show primary and secondary peaks but with lower magnitudes. The secondary peak corresponds to a wavelength of 0.9 km for both longitudinal and vertical spectra; however, the primary peak is at 0.3 km for the longitudinal component and at 0.2 km for the vertical component. Out of the nighttime test runs listed in Table 7, three have both the primary and the secondary peaks. The secondary peaks during nights could be due to gravity waves.

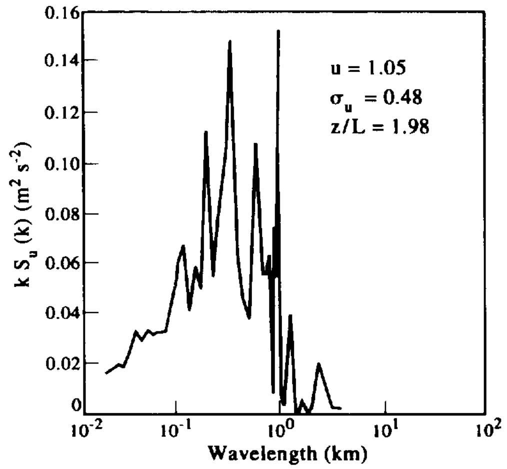

Fig. 11. Spectra of longitudinal turbulence at 0300–0400 LST on 15 February 1992 at a height of 4 m.

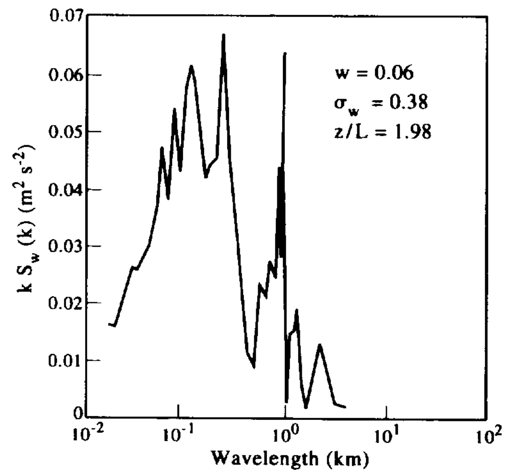

Fig. 12. Spectra of vertical turbulence at 0300–0400 LST on 15 February 1992 at a height of 4 m.

5. CONCLUSIONS

The low wind speed observations were classified broadly into daytime (convective) and nighttime (stable) conditions. The Monin–Obukhov length scale, L, was used to determine stability parameter, z/L. The results show that the variances of longitudinal, σ_u, lateral, σ_v, and vertical, σ_w, velocity fluctuations normalized by the friction velocity do not have appreciable variation for wind speeds greater than 1 m s^{-1}. For $U \geqslant 1$ m s^{-1}, the average values of ratios σ_u/u_*, σ_v/u_* and σ_w/u_* were 2.08, 1.83 and 1.18, respectively, for day cases, whereas the corresponding values for night cases are 1.90, 1.59 and 1.27, respectively. For mean wind speed less than 1 m s^{-1}, these ratios were significantly different between day and night. The mean ratios (σ_i/u_*, $i = u, v, w$) were 2.47, 2.72, 1.55 for daytime and 4.44, 4.25, 1.79 for nighttime, respectively. The scatter plot of these ratios σ_i/u_* showed far less scatter for $U \geqslant 1$ m s^{-1} and appreciable scatter for $U < 0.3$ m s^{-1}. Increased values are believed to be due to free convection in the daytime and presence of internal gravity waves in the nighttime in combination with appreciable reduction in the frictional effects. The Monin–Obukhov similarity theory appears to work well for stable conditions and $U \geqslant 1$ m s^{-1}. More (substantial) observations are needed for a definite and clear understanding for very low wind speeds.

The analysis of turbulence intensities reveals that there is not much variation with wind speed for $U > 1$ m s^{-1}. The average values of intensities have been found to be large when winds become very low, especially during the daytime. Further, the Taylor's "frozen turbulence" hypothesis may not be valid for the range of $U < 1$ m s^{-1}. Normalized standard deviations and turbulence intensities for near-neutral conditions compare well with the observations from three other sites.

Observations of the spectral plots of the data indicate that larger eddies dominate during the nighttime (about 200 m) as compared to those during the day (about 100 m). In the presence of moderate convection, secondary maxima are observed in the spectra, the corresponding wavelength being of the order of 1 km. These secondary maxima are observed occasionally in the night and this could be due to the breaking of internal gravity waves.

Acknowledgements—This research was supported by the Division of International Programs, National Science Foundation under grant INT-9008926.

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