Results and Discussion

4.1 Wind Profile: Wind profile at Kharagpur during onset, mid and end monsoon season are represented in Exhibits 1.1 a, b, and c. It can be seen from the exhibit that the wind velocities were significantly reduced from onset to end phase. Maximum wind speed of about 7 m/s recorded at 30 m height during onset phase was reduced to near 2 m/s during end phase of monsoon at the same height. All the observations show typical logarithmic wind profiles in the surface boundary layer.

Wind shears between different levels are presented in the Exhibits 4.2 a and b. As expected, higher wind shears were observed between 1 m and 2 m followed by 1 m and 4 m. During the onset phase the shear was maximum up to 1.3 m²/s around 2030 IST on 9th of June. Decrease of wind shear with increase of height from ground can be seen from 4.2 b. The value of $\partial U/\partial Z$ rarely exceeds 0.2 m²/s at 2 m and above.

4.2 Frictional Velocity: The frictional velocity computed using the Sonic and Gill anemometers are presented in the Exhibit 4.3. Higher values of $U^*$ have been obtained from sonic anemometer observations compared to Gill anemometer. This difference may be due to lower height of Sonic anemometer (8 m) compared to Gill anemometer (15 m) at Khargapur.
Exhibit 4.1 Wind profile at Khargapur during (a) onset (b) mid phases of monsoon
Exhibit 4.1 (c) Wind profile at Khargapur during end phase of monsoon
Exhibit 4.2 (a) Wind shear between different heights during MONTBLEX (Khargapur)
Exhibit 4.2 (b) Wind shear between different heights during MONTBLEX (Khargapur)
Exhibit 4.3 Frictional velocity at 8 m and 15 m level at Kharagpur during MONTBLEX
Padmanbhamurty and Jain (1999) also reported such difference. This shows that the shearing stress is more at the lower level and fluxes in the SBL are not constant with height. Results of the fluxes in the study pointing to the same direction. Frictional velocity at 8 meters varied between 0.033 to 0.39 m and that of 15 m varied between 0.01 to 0.4. Lower values of $U^*$ are obtained during stable conditions. This is probably due to the lower wind speed at night at Kharagpur during these days.

The frictional velocity at Kharagpur has been normalised with height ($z$) and mean wind speed ($U$) and shown in the Exhibit 4.4. The relationship derived from above exercise is given below:

$$U^* = 0.4367 \left( \frac{U}{z} \right)$$

From the exhibits 4.4, it can be seen that during the nocturnal conditions (run number 6 to 11), the magnitude of $U^*z/U$ became minimal. This may be due to the effect of stability in this scaling parameter. Since there were not many night time observations available for analysis, further analysis was restricted.

Correlation between frictional velocity at 8m height and surface layer forcing ($du/dz$) shows different trends during day time and night time. Exhibit 4.5 a and b show the above correlation during daytime and night time respectively. Relation between $U^*$ at 15 m level and corresponding level wind shear are given in Exhibit 4.6 a and b. Trends are similar at both the levels. This agrees with the surface layer similarity relationships established elsewhere.

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Exhibit 4.4 Normalised frictional velocity with mean wind and observation height
Exhibit 4.5 a Correlation between $U_\star (8m)$ and windshear during daytime

Exhibit 4.5 b Correlation between $U_\star (8m)$ and windshear during night time
Exhibit 4.6 a Correlation between $U_\cdot$ (15m) and windshear during daytime

Exhibit 4.6 a Correlation between $U_\cdot$ (15m) and windshear during night time
Non-dimensional wind shear calculated using observed values and similarity functions (Dyer, 1974, Högström, 1988) showed good agreement. Exhibits 4.7 a and 4.8a show the variation of non-dimensional wind shear during the different phases of monsoon. It can be seen that the similarity function was always slightly underestimated. The differences were apparent during high wind shear conditions. This is evident in Exhibit 4.7 b. also. During the extreme conditions, the similarity function appears to be inaccurate.

The trend was similar at 15 m also. The similarity function was unable to reproduce the $\phi_m$ during higher wind shear conditions. The correlation graph at 15 m level did not give a clear picture. This may be due to wide scatter of calculated non-dimensional wind shear.

Daytime variations of $U_*$ at different phases of monsoon can be seen in Exhibits 4.9 a, b and c. It could be seen that during the daytime the frictional velocity increases with time till after noon. Maximums $U_*$ is normally obtained at noon hours. It can be observed from the Exhibits 4.9 a, b, c that the values of $U_*$ decreased slightly from onset to end phase of monsoon.
Exhibit 4.7 a. Variation of non-dimensional wind shear during MONTBLEX, Kharagpur (8 m level)

Exhibit 4.7 b. Correlation between nondimensional wind shear computed and similarity function (8 m level)
Exhibit 4.8 a. Variation of non dimensional wind shear during MONTBLEX, Kharagpur (15 m level)

Exhibit 4.8 b. Correlation between nondimensional wind shear computed and similarity function (15 m level)
Exhibit 4.9a. Diurnal variation of frictional velocity during onset phase of monsoon
Exhibit 4.9 b. Diurnal variation of frictional velocity during mid phase of monsoon
Exhibit 4.9c. Diurnal variation of frictional velocity during end phase of monsoon
Exhibit 4.10 Variation of Roughness length ($Z_0$) during different phases of monsoon
At the end monsoon phase, the inverse relation of $U_r$ and measurement height, found in earlier phases could not be seen at 1130 observations. The trend was same on 11th, 14th, and 15th of September. This might be due to very low wind speeds experienced during end phase of monsoon (probably due to absence of monsoonal winds/airmass and increased atmospheric turbulence near the ground.)

4.3 Roughness Length ($Z_o$): Roughness (length) parameter computed using Kharagpur data is presented in the Exhibit 4.10. Values obtained from 8 m levels are more scattered and higher than 15 m observation. This might be due to lower measurement height. Most values, however, were less than 0.5 m. These results are more or less agreeing with the observations from elsewhere (Royal Aeronautical Society; 1972, Deacon; 1953).

It can be seen from the Exhibit 4.10 that the parameter shows slight increase in its value from onset to end of the monsoon season. Probably, after rainfall, the height of the vegetation around the observation tower might have increased and caused higher roughness. Many studies (Kung; 1953, Chamberian; 1966, Plate; 1971; Royal Aeronautical Society; 1972) suggested higher value of $Z_o$ with taller vegetation. Attempts to find out the roughness parameter from the wind profiles, did not yield good results. It may be due to high wind shear immediate to the surface.

During night time, roughness length computed using 15 m level data shows minimum values. Although $Z_o$ computed from Sonic...
anemometer (8m) shows lower values during night time, the magnitude was not so low as compared to those computed from Gill anemometer. Diurnal variation of \(Z_0\) at 8m and 15 m levels are given in the Exhibit 4.11. It can be seen that the diurnal variation of \(Z_0\) at 15 m level is much more than 8 m. This variation may be in accordance with development of mixing in surface boundary layer.

4.4 Drag Coefficient (\(C_D\)): Drag coefficient computed for 8 m and 15 m are shown in the Exhibit 4.12. While examining the results, definite correlation observed between wind speed and \(C_D\). Some increasing trend of \(C_D\) from onset phase to end of monsoon has been observed. As explained earlier, this could be due to increase of vegetation height after rainfall. The magnitudes of drag coefficients at Kharagpur are in conformity with other studies (Garratt; 1977).

4.5 Turbulent Kinetic Energy (TKE): Turbulent kinetic energy per unit mass at Kharagpur is shown in Exhibit 4.13. TKE at 8 m level shows slightly higher magnitude compared to 15 m levels during most of the time. Higher magnitude of TKE was observed during day time also with higher and larger variation between 8 m 15 m. Maximum value of TKE observed was more than 0.7 m²/s². As expected, at stable surface layers TKE was very less; one or two orders lesser than that of daytime. During mid and end monsoon phase, TKEs are comparatively lower than onset phase. This may be due the low insolation and subsequent low longwave emissions from the earth's surface.
Exhibit 4.11 Diurnal variation of roughness length at 8m and 15 m heights during onset phase of monsoon
Exhibit 4.12 Variation of drag coefficient at 8m and 15 m levels during various phases of monsoon at Kharagpur
Exhibit 4.13 Variation of Turbulent kinetic energy during different phases of monsoon at Kharagpur
Diurnal variation of TKE during onset, mid and end monsoon phases are given in Exhibit 4.14. In a normal day TKE reaches its maximum during mid day hours. As indicted by Viswanadham et al. (1977), high fluctuation in TKE can be observed at Kharagpur within micro time limits.

To determine the dissipation rate of TKE ($\varepsilon$), two methods are adopted. As explained in chapter 3, determination from the $5/4$ slope of energy spectrum did not give good results. In the plot of energy spectrum (Exhibits 4.15 a, b, and c), the inertial sub-range was too short to identify. This may be a typical phenomenon of tropical convective condition, where the gap between energy generation and dissipation is negligible. The dissipation rate $\varepsilon$ was found by using surface layer relationships and given in the Exhibit 4.16. Diurnal variation of $\varepsilon$ follows a definite trend, minimum during night and maximum during the mid day hours. Occasionally some observations show very low rate. This may be due to the prevailing micrometeorological conditions.

4.6 Mixing Layer (ML) Height ($Z_l$): Mixing layer height calculated using Rossby number similarity function has been shown in the Exhibit 4.17. Although results shows typical day time development and decay of ML, it can be seen that the mixing layer calculated using 15 m observation is always less compared to 8 m observation. This is basically due to the lower magnitude of frictional velocity at 15 m level. When compared with available observed values of $Z_l$, the 15 m level set of data shows better
Exhibit 4.14. Diurnal variation of TKE during (a) onset, (b) mid (c) end phases of monsoon
Exhibit 4.15 (c) Vertical velocity spectra during stable condition

Exhibit 4.15 (d) Temperature spectra during stable condition
Exhibit 4.15 (a) Horizontal velocity spectra during stable condition

Exhibit 4.15 (b) Horizontal velocity spectra during stable condition
Exhibit 4.16 TKE dissipation rate at different phases of monsoon, Kharagpur
Exhibit 4.17 Computed mixing layer height (Rossby number similarity function) during different phases of monsoon at Kharagpur
correlation. Since the available SODAR data was limited, this cannot be taken as a definite conclusion.

Diurnal variation of mixing layer heights during onset, mid and end phases of monsoon are given in the Exhibit 4.18 a, b, and c. It can be seen from the above exhibits the typical development of mixing layer during daytime. Maximum mixing heights were obtained during onset phase of monsoon. Magnitudes of maximum mixing heights of other phases were significantly lower than the onset phase. Climatological averages of mixing heights also show same trend. This decrease may be due to continuous low insolation during monsoon period because of cloud cover and comparatively lower temperature of earth's surface during mid and end phases. Study of Padmanbhamurty and Jain (1999) is also shows similar results.

4.7 Momentum and Heat fluxes: Momentum and heat fluxes calculated using eddy correlation method is presented in this section.

Momentum flux obtained using 8 m and 15 m level are given in the Exhibit 4.19. As can be seen those maximum values were obtained during mid monsoon phase. Except in the beginning, the fluxes computed at 8 m and 15 m levels closely follow the same trend. Variation of the flux computed, however, was much larger than 10% during this study. As per the definition, the variations of the fluxes within the surface boundary layer ought to be within...
Exhibit 4.18. Diurnal variation of mixing heights during (a) onset, (b) mid, and (c) end phases of monsoon
Exhibit 4.19 Momentum heat flux computed at 8 m and 15 m levels during different phases of monsoon.
10%. Difference in the observation might be due to different types of instruments, high transfer rate of latent heat energy, etc.

Daytime variation of momentum fluxes during onset, mid and end phases of monsoon are given in the Exhibits 4.20 a, b, and c. It can be seen that the direction of fluxes was changing during daytime. These fluctuations were noticed mostly during active monsoon days.

Sensible heat flux computed during the monsoon period is given in the Exhibit 4.21. It can be seen that the fluxes at 15 m are much below than the expected values. This may be due to the failure of sensor at this level. While examining the reasons, it was observed that magnitudes of thermal fluctuations obtained from the fast temperature sensors were very low. Hence for further analysis this data set were not considered. Maximum sensible heat flux of about 100 w/m² was obtained during this study period. Diurnal variation of sensible heat flux during onset period is given in the Exhibit 4.22. The results are not very clear during nighttime, especially during early hours of the day.

4.8 Atmospheric Stability Classification

Stability of atmosphere during the selected observation period computed by different methods is presented here.

Pasquill's stability classification: The cloud cover data were available only for 0830 IST, 1730 IST, 2030 IST and 2330IST.
Exhibit 4.20 Day time variation of momentum flux during (a) onset, (b) mid, and (c) end monsoon phases
Exhibit 4.21. Sensible heat flux at 8 m and 15 m levels at Kharagpur during MONTBLEX
Exhibit 4.22 Diurnal variation of sensible heat fluxes during onset monsoon phase
Atmospheric stability of corresponding runs are calculated and presented. Wind speed at 10 m.height has been derived from the best-fit logarithmic curve of observed wind profile of the corresponding time.

Table 4.1

<table>
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<th>Date</th>
<th>Time (IST)</th>
<th>Stability class</th>
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<td>2</td>
<td>9th June</td>
<td>0830</td>
<td>Neutral (D)</td>
</tr>
<tr>
<td>5</td>
<td>9th June</td>
<td>1738</td>
<td>Neutral (D)</td>
</tr>
<tr>
<td>6</td>
<td>9th June</td>
<td>2032</td>
<td>Slightly stable (E)</td>
</tr>
<tr>
<td>15</td>
<td>12th June</td>
<td>0830</td>
<td>Slightly unstable (C)</td>
</tr>
<tr>
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<td>1730</td>
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</tr>
<tr>
<td>18</td>
<td>12th June</td>
<td>2030</td>
<td>Slightly stable (E)</td>
</tr>
<tr>
<td>23</td>
<td>20th July</td>
<td>0830</td>
<td>Neutral (D)</td>
</tr>
<tr>
<td>26</td>
<td>20th July</td>
<td>1730</td>
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<tr>
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<td>1730</td>
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</tr>
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<td>36</td>
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<td>2130</td>
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<td>37</td>
<td>18th August</td>
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<td>1730</td>
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<td>0830</td>
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</tr>
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<tr>
<td>56</td>
<td>15th October</td>
<td>0830</td>
<td>Neutral (D)</td>
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It can be seen that from the above table, unstable classes are very few. This may be because of the selected hours are low insolation periods (due to lack of cloud data). As per above results, neutral stability classes predominate the season. More than high cloud cover (or low net radiation) the higher wind speeds lead to get these results in this method. As per the classification, higher the wind speed tends the atmosphere to be towards neutral.

**Slade"d Method:** The stability classification based on standard deviation (σθ) of wind direction is summarised in the following table. Standard deviation for wind direction at 10 m height has been derived from a best fit curve of σθ of 1m, 4 m, and 30 m. Vertical profile of σθ for typical unstable, stable and neutral timings are shown in Exhibit 4.23. Following table summarises the results of stability classification using standard deviation of winds.

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<th>k6121130</th>
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<td>14.2</td>
<td>16.0</td>
<td>14.8</td>
<td>19.0</td>
<td>32.7</td>
<td>44.8</td>
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<tr>
<td>4</td>
<td>6.0</td>
<td>6.7</td>
<td>9.1</td>
<td>7.7</td>
<td>13.7</td>
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<td>20.1</td>
<td>30.7</td>
</tr>
<tr>
<td>30</td>
<td>0.1</td>
<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

| Stability Class | F | F | F | F | F | F | E | E |

<table>
<thead>
<tr>
<th>Height (M)</th>
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<th>k6090830</th>
<th>k6091130</th>
<th>k6091430</th>
<th>k6091738</th>
<th>k6092032</th>
<th>k6120030</th>
<th>k6121030</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.9</td>
<td>31.1</td>
<td>31.5</td>
<td>30.8</td>
<td>15.1</td>
<td>17.8</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.3</td>
<td>8.6</td>
<td>7.6</td>
<td>8.9</td>
<td>6.2</td>
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<td>1.0</td>
<td>0.9</td>
<td>0.7</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

| Stability Class | F | F | E | E | E | F | F | F |

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Exhibit 4.23 Vertical profile of standard deviation of wind direction during onset phase of monsoon
It can be seen from the above table that the atmosphere is stable irrespective of the time. Standard deviation of wind direction never exceeded 5°. Most of the time it was even less than 2.5°. Probably the homogeneity of area around the monitoring tower might be one of the reasons for low σ₀ along with intensity of monsoonal airflow near the ground. Even if we consider σ₀ of 4 m wind direction, most of the time σ₀ was between 5° and 10°, i.e. as per Slade’s classification it is neutral stability class. Only at two instances it exceeded 15° (0830 and 1130 of 12th June), i.e. moderately unstable conditions.

As expected, higher variation in wind direction was observed at 1m level. Maximum of 44.8° is observed at 1130 hours on 12th June. Minimum of 8.3° also reported in the same day at 0330 hours.

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Richardson Number: The Richardson number has been calculated at four levels, 2m, 4m, 8m, and 15m. Temperature and wind speed differences were derived from above and below levels of height considered. Wide variations in the results are noticed. Maximum wind shears were obtained during the onset phase and least at end phase of monsoon. Due to very low wind shear with some data sets, the computed values of Ri were too high in these cases (As can be seen from the equation, the wind shear is in the denominator). For convenience of drawing, these high values were omitted from the graph data file.

Ri obtained at each run is given in the Exhibit 4.24. It can be seen from above exhibit that most of the values are very close to zero. Ri values were positive very near to the ground (2 m level) in all the cases irrespective of phase and time. This is due to an inversion very near to ground. Most of the records show higher temperatures at 4 m level than at 1 m level. This trend was observed throughout the observation period (Exhibit 4.25). Temperatures at other levels were always lower than 4 m level. Since the temperature observations were limited to 30 m other low-level inversions could not be identified with this data set.

The reason for this inversion could be the uniform vegetative covers around the observation tower. Lower temperature near the ground may be due to evapotranspiration from grass cover and subsequent cooling just under the 1 m level boom. The positive values of Ri indicate the stable layer very close the ground.
Exhibit 4.24 Variation of Richardson Number at 2m, 4m, 8m, and 15 m above ground level
Exhibit 4.25 Temperature profile near ground during MONTBLEX at Kharagpur
In the present study most of the $R_i$ values lie between -10 to 1. More scatter of $R_i$ can be seen at the end of monsoon season compared to the onset phase. As indicated earlier, this is mainly due to very low wind shear during end of the monsoon season compared to onset phase. According to sign of $R_i$, the atmosphere was unstable near the ground (at least up to 30 m) irrespective of time. Basically, the sign of the $R_i$ is fully dependent on the temperature profile. So long as inversions are not there, the $R_i$ will be negative. On many occasions, it can be seen from the Exhibit 4.24 that the $R_i$ exceeds critical value 0.25, which represents purely mechanical turbulence.

The diurnal variation of $R_i$ at the onset and mid monsoon phases has been presented in the Exhibit 4.26 a and b. Since data beyond day time were not available for end monsoon phase, that could not be evaluate in this study.

In the onset phase of monsoon, minimum values (absolute) of $R_i$ were obtained during night time. After sunrise, $R_i$ increased considerably due to convective forcing. But later in the day, this growth subsided and reached its minimum later in the day. Some trend was observed in mid monsoon season also.

For application to air pollution studies, stability of atmosphere based on wind at 10 m level, for $R_i$ near to 10 m (i.e. 8 m) is considered for comparison. It could be noted that $R_i$ (8m) was negative almost all the time. Based on that it can be concluded that the atmosphere was unstable. If air pollution computations are based on this parameter alone, it could lead to large errors in the
Exhibit 4.26 Diurnal variation of Richardson Number at 2m, 4m, 8m, and 15m above ground level during (a) onset and (b) mid phases of monsoon
results. Simple examples of errors that could occur in air quality modelling due to stability miscalculation have been discussed later in this chapter.

These results indicate that, even in rural areas, the mechanical turbulence dominates very near the ground, which also controls the temperature profile. It can be concluded from the above study that vertical temperature profile up to a height of lower level inversion will be required for correctly estimating the $R_i$ for air pollution studies.

Monin - Obukhov similarity parameter $\zeta$ ($\zeta = R_i$ when $R_i < 0$ and $\zeta = R_i/(1-5R_i)$ when $R_i = 0 < 0.2 < R_i$) plotted (Exhibit 2.27) against non dimensional wind shear at 8 m and 15 m exhibited the typical pattern of the curve obtained in other boundary layer studies (Izumi, 1971).

**Obukhov Length (L):** Obukhov Length computed using the eddy velocities is analysed. Very low eddy heat flux ($w'\theta'$) during the experimental period lead to large magnitudes of $L$. The values obtained at 15 m show larger variations.

Variations of the stability parameter obtained under various run conditions are given in Exhibit 2.28. Most of the values are near zero. This can be justified for the sky was cloudy, i.e. near neutral. As expected, most values obtained during day time were negative. Whereever the night time observations were there, variations from negative to positive (and also positive to negative) could also be seen in the exhibit.
Exhibit 4.27 Plot of M-O similarity function against nondimensional wind shear at (a) 8 m and (b) 15 m levels
Exhibit 2.28 Variation of the stability parameters under various run conditions during MONTBLEX, Kharagpur
Correlation between $z/L_8$ and $z/L_{15}$ is presented in the Exhibit 4.29. It could be seen in the exhibit that the plots are in either first or third quadrant. This shows that, as per the sign of the parameter, $L_8$ and $L_{15}$ have good agreement. Only on few occasions it shows different results. This may be due to errors in the observations. Magnitudes of $z/L$ were higher at 8 m level compared to that of 15 m. This may be due to the higher mechanical turbulence near ground.

Diurnal variations of $z/L$ for onset and mid monsoon phases are given in the Exhibit 4.30. Large variation of $z/L$ can be seen during daytime compared to night time. This may be due to higher turbulence during high insolation hours.

In Exhibit 4.31 a and b, the $z/L$ was plotted against $U^*$ at 8 m and 15 m level. Both the graphs show same trend. Maximum frictional velocities were obtained during neutral conditions. In diabatic conditions frictional velocities were less compared to neutral conditions. Higher frictional velocity during near neutral conditions is mainly due to higher wind speeds at these timings.

Non dimensional wind shear has been calculated using the Businger – Dyer similarity relationship and presented in Exhibit 4.32 a and b. Value of above parameter computed using onsite wind shear also can be seen in the exhibit. At 8 m level the relationship over all shows good agreement and comparable with other studies elsewhere (Businger et al, 1971; Carl et al, 1973; School of Environmental Sciences, JNU)
Exhibit 4.29. Correlation between $-z/L$ at 8 m and 15 m levels during MONTBLEX, Kharagpur
Exhibit 2.30 Diurnal variation of $z/L$ during (a) onset phase (b) mid phases of monsoon
Exhibit 4.31 Variation of frictional velocity with $z/L$ (a) at 8 m level and (b) 15 m levels
Exhibit 4.32 Non dimensional wind shear as function of \(-z/L\) at (a) 8 m and (b) 15 m levels
Korrell et al, 1982). In unstable atmosphere, the magnitudes of $\phi_m$ were less than the values obtained in the Businger - Dyer similarity relationships established at other places. Higher differences in magnitude of $\phi_m$'s at lower end of $z/L$ were observed at Kharagpur. In stable atmosphere $\phi_m$ values shows better agreement compared to that of unstable conditions. Under neutral conditions, magnitude $\phi_m$ was very close to hypothetical value 1.

At 15 m level, computed value of $\phi_m$ was high compared to that of 8 m. Due to high fluctuation in $\phi_m$ magnitude, it is difficult to draw a meaningful conclusion from this set of data. As in the case of 8m level, overall the trends are almost similar to that of other studies. The deviation of $\phi_m$ from wind shear of similarity relationship may be attributed to typical terrain features of MONBLEX site.

Relationship with the stability parameter and turbulent kinetic energy at 8m and 15 m level can be seen in the Exhibit 4.33 a and b. At 8 m level, lowest TKE are observed during stable conditions. Higher energy obtained near neutral levels. Further decrease in $z/L$ shows lower value of TKE. At 15 m level, TKE was comparatively less than that of 8m. Higher eddy velocities near ground due to surface friction might be the reason for this difference. This plot of 15 m level also exhibits similar behaviour of 8 m level.

Convective Velocity Scale ($w_c$): The diurnal variation of convective velocity scale at 8 m level can be seen in the Exhibit 4.34.
Exhibit 4.33 Plot between $z/L$ and turbulent kinetic energy at (a) 8 m and (b) 15 m levels
Exhibit 4.34 Diurnal variation of convective velocity scale during onset and mid phases of monsoon
The parameter attains its peak during late noon and minimum (negative values) during night time. The negative values are due to the $H_0$, the sensible heat flux term in the equation.

The slow increase during the morning hours and rapid decrease of the velocity scale at Kharagpur was similar to that of other field programmes (O’Neill and Wangara). High magnitude of $w$ during the onset phase indicates the high mixing layers with vigorous heating at ground. During the mid monsoon period, the magnitudes of $w$ were not as high as at onset. This may be indicative of low heating of ground (may be due to high moisture levels in the soil).

### 4.9 Relation among Stability Parameters

A comparison of Stability parameters such as Richardson Number ($R_i$), Obukhov Length ($1/L$ or $z/L$), Turner and Slade’s classification was made. Standard deviation (Slade’s method) of wind direction at 8 m level did not yield good results. Results obtained under different schemes are compiled in the following table. For getting insight into $R_i$ behaviour, $R_i$ (2m), $R_i$ (4m), and $R_i$ (8 m) are included in the table. Night time observations are shaded in the table for easy identification.

<table>
<thead>
<tr>
<th>Time</th>
<th>k6090530</th>
<th>k6090830</th>
<th>k6091130</th>
<th>k6091430</th>
<th>k6091738</th>
<th>k6092032</th>
<th>k6120030</th>
<th>k6120130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turner</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Turner($\sigma_0$)</td>
<td>F</td>
<td>F</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>D</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>$R_i$ (2m)</td>
<td>0.30</td>
<td>0.25</td>
<td>0.13</td>
<td>0.06</td>
<td>0.11</td>
<td>0.07</td>
<td>0.11</td>
<td>0.46</td>
</tr>
<tr>
<td>$R_i$ (4 m)</td>
<td>-0.039</td>
<td>0.036</td>
<td>0.028</td>
<td>-0.009</td>
<td>0.017</td>
<td>-0.020</td>
<td>-0.064</td>
<td>-0.114</td>
</tr>
<tr>
<td>$R_i$ (8 m)</td>
<td>-2.95</td>
<td>-2.90</td>
<td>-1.19</td>
<td>-0.52</td>
<td>-0.87</td>
<td>-3.19</td>
<td>-5.70</td>
<td>-2.58</td>
</tr>
<tr>
<td>$z/L$</td>
<td>0.007</td>
<td>-0.229</td>
<td>-0.237</td>
<td>-0.122</td>
<td>-0.002</td>
<td>0.097</td>
<td>0.068</td>
<td>0.201</td>
</tr>
</tbody>
</table>

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As can be seen in the above table, \( \sigma_0 \) method did not provide good result. Failure of this method might be due to:

- Strong influence of monsoonal current that supercedes the local factors
- Uniform fetch around the site that resulted homogeneity of the terrain
- Height considered for determining the \( \sigma_0 \)
From the data sets at the site, it is understood that there were few days with very little or no monsoon winds. Even during those days also $\sigma_0$ did not increase up to 15° to represent the unstable conditions.

Uniform surface roughness due to the homogeneity around site might have reduced the gustiness of wind and wind direction becomes steady at 10 m height and hence the low values of $\sigma_0$. This direction of thought lead to third point, the height considered for measurement. It can be noted from the Table 4.2 that $\sigma_0$ of 1 m and 4 m wind direction has recorded high values during daytime. At rural location such as Kharagpur site, $\sigma_0$ determined at 10 m height may not truly represent the atmospheric stability, at least for air pollution studies.

Gifford (1976) used $R_i$ (2 m) to compare the stability class. As indicated earlier, at Kharagpur, an inversion exists all the time very close to ground (4 m), hence the $R_i$ becomes positive in all cases. Such cases, adopting $R_i$ based on 2 m will lead to erroneous results. Although $R_i$ at 4 m level shows some different result, most of the time it is did not yield correct result. The temperature profile did not indicate any low level inversion during night time, which resulted negative $R_i$ at 4 m and 8 m levels. It can be concluded that $R_i$ may not be the right option to determine stability at Kharagpur site.

The maximum variation in the results was obtained from Pasquill’s classification using net radiation as well as the Obukhov criteria $(z/L)$. Since the cloud cover data was limited to few hours in a
day, Stability determination was limited to few observations. As such the Pasquill classification system will not allow unstable conditions during night time and stable conditions during day time. This inherent advantage of Pasquill classification system is that it always exhibits the variations in stability conditions. One main drawback noticed with this scheme is the sudden jump of stability classes just after sun set. Prevailing low wind speeds point to stable class F or G just one hour after an unstable class of C. In windy conditions this may not happen. And also this scheme will not produce neutral conditions during dusk or dawn timings.

Although magnitude of $z/L$ did not attain the hypothetical value zero for neutral stability, but on many occasions value was very close to zero. Golder (1972) has suggested a conversion nomogram for determining the Pasquill’s stability class from $1/L$. In general better agreement can be seen among Pasquill scheme and Obukhov length. This can be taken as efficacy of Pasquill scheme to determine the atmospheric stability with routine measurements.

To highlight the importance of atmospheric stability in air pollution modelling, an illustration using SCREEN ver 3.0 has been presented. Meteorological parameters on 12th of June 1990 at 0830 IST, are used for simulation. Two sets of emission characteristics are used to assess the influence of source height. These emission characteristics are given below:

<table>
<thead>
<tr>
<th>Source</th>
<th>Source II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack height (m)</td>
<td>60</td>
</tr>
<tr>
<td>Volume flow rate (m$^3$/Sec)</td>
<td>78.5</td>
</tr>
</tbody>
</table>

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Wind speed at 8m level was 1.59 m and atmospheric temperature was 33 °C. As per the results of stability classification, (a) Pasquill method is ‘slightly unstable’, (b) Slade’s method (σ₀) is ‘slightly stable’, (c) Ri indicate (2m) ‘moderately stable’ and (d) Obukhov length is ‘extremely unstable’. Gifford (1976), and Golder (1972) finding are used to convert the Ri and 1/L to have a common platform.

The simulated concentration of SO₂ is given in the Exhibit 4.35 for source I. It can be seen from above exhibit that large variation of concentration can be due to variations in the determination of stability. The maximum concentration obtained in each condition is tabulated below:

<table>
<thead>
<tr>
<th>Stability</th>
<th>Distance (km)</th>
<th>Maximum concentration (μg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on net radiation</td>
<td>3.5</td>
<td>36</td>
</tr>
<tr>
<td>Based on σ₀</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Based on Rᵢ</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Based on Obukhov length</td>
<td>0.8</td>
<td>83</td>
</tr>
</tbody>
</table>

From above table it can be observed the effect of stability in air quality simulation. Variations in end results may be of the order of 400 percent.
Exhibit 4.35 Downwind concentration distribution of pollutant from an elevated (60 m) stack under various stabilities
Down wind concentration of pollutants from a very tall (275 m) stack (source II) under various atmospheric stabilities obtained by different schemes are shown in Exhibit 4.36. It could be seen from the exhibit that significance of stability is much more prominent in elevated stacks. Maximum concentration the pollutant under various conditions is given below.

<table>
<thead>
<tr>
<th>Stability</th>
<th>Distance (km)</th>
<th>Maximum concentration (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on net radiation</td>
<td>10.4</td>
<td>56</td>
</tr>
<tr>
<td>Based on $\sigma_0$</td>
<td>41.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Based on $R_i$</td>
<td>41.3</td>
<td>0.0049</td>
</tr>
<tr>
<td>Based on Obukhov length</td>
<td>1.2</td>
<td>199</td>
</tr>
</tbody>
</table>

Compared to Source I, the variation is much higher with Source II. Basically the stability affects the air quality simulation in many ways, and are as follows:

- Determination of wind speed at stack level, which is a function of stability.
- Selection of diffusion parameters, i.e. $\sigma_y$ and $\sigma_z$ which are a function of stability.
- Plume rise, which is again dependent on stability as well as wind speed at stack height.
- Dilution of plume that is indirectly proportional of wind speed at stack height.

Screen 3 model uses the power law to determine the wind speed at stack height. Power law coefficient varies 0.07 to 0.55 for A to F stability classes. Depending on the value of power law coefficient, the wind speed will vary and hence the plume rise and the...
Exhibit 4.36 Downwind concentration distribution of pollutant from an elevated (275) stack under various stabilities
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dilution. Given below the plume rise obtained during different conditions used in this study.

<table>
<thead>
<tr>
<th>Stability</th>
<th>Maximum plume height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(stack height + plume rise)</td>
</tr>
<tr>
<td>Based on net radiation (C)</td>
<td>60+231</td>
</tr>
<tr>
<td>Based on $\sigma_0$ (E)</td>
<td>60+80</td>
</tr>
<tr>
<td>Based on $R_1$ (F)</td>
<td>60+59</td>
</tr>
<tr>
<td>Based on Obukove length (A)</td>
<td>60+244</td>
</tr>
</tbody>
</table>

One can notice the significant differences in plume rise between stable and unstable cases. These are mainly due to the Brigg's plume rise formulae for unstable and stable atmospheric conditions. Again during unstable condition itself, the final values differ due to the difference in wind speed estimated at stack level and also due to the diffusion coefficients.

Another point to be noticed is large differences in the location of maximum concentration. Since this study considered only level terrain, these differences are due to the nature of the plume, i.e. looping during unstable conditions and fanning during stable condition. During fanning conditions, plume travels long distance before touching the ground. In practical cases, the stability is likely to change within the distance, especially due to water bodies or large urban areas and hence the predictions become appropriate.

It can be concluded from the above session that the stability determination is one of the most important parameter in the air quality modelling. Since air pollution modelling is being widely used in our country for environmental impact assessment of
proposed industries or expansion of industries, decision-makers are heavily dependent on output of air quality predictions. Inaccurate results might lead to wrong decisions and hence severe environmental consequences.

Central Pollution Control Board (CPCB) recommended few methods to determine the stability for which two methods are analysed in this study, i.e. the insolation based method (Pasquill's) and wind direction fluctuations method (Slade's). As can be seen the results using Slade's method are not very encouraging. Significant variations in stability classes and serious deviations in end results suggest an in depth study is required to establish the realistic method under Indian conditions.

4.10 Simulation of Vertical Profiles

Eddy diffusivity coefficient was computed using wind and temperature profile, and turbulent fluctuations. Exhibits 4.37 a and b show the variation of these coefficients at 8m and 15 m levels.

It can be that the magnitudes of eddy momentum coefficient are consistently higher at 15 m level during mid day. Due to this, the diurnal variations were high at 15 m compared to 8 m level.

Eddy heat coefficients at 8 m and 15 m show similar pattern throughout the study season. As in the case of momentum flux, the magnitude of $K_h$ at 15 m level was higher than that of 8m. But during end monsoon, the values were much lower than in other
Exhibit 4.37 Eddy exchange coefficient at Kharagpur during MONTBLEX (a) momentum flux (b) heat flux
phases. The neutral condition relationship, $K_h = 1.35 K_m$ is not observed at Kharagpur.

Result of vertical profile of the eddy diffusivity under neutral condition is comparable with the results of other studies. The simulated profile of 9th June is given in the Exhibit 4.38. Maximum magnitude of $K_v$ was obtained around 300m level. As expected from the physical reasoning, highest magnitude of $K_v$ is likely to be obtained at a few hundred meters above constant flux layer (O'Brien J J, 1970).

The simulated profile is agreeing with the empirical relationships established earlier for the first 500 metres, but it deviates at higher levels. Other studies also confirmed this deviation (Shir, 1973, Jia-Yeong, 1987).

The vertical profiles of wind and temperate simulated using surface measurements are discussed in his section. The numerical simulation was initiated with available minisonde data at Kharagpur. The minisonde data was supplemented by the radio sonde date of Calcutta.

The simulation produces the temperature and wind fields of June 12th and August 18th of 1990. Numerical integration was limited due to the absence of continuous data.

Diurnal variation of temperature (12th June) can be seen in the Exhibit 4.39. The contours of temperatures are drawn at an interval of 1°C. The model could simulate a typical profile of
Exhibit 4.38 Vertical eddy diffusivity ($K_v$) profile under neutral atmospheric condition
Exhibit 4.39. Diurnal variation of simulated potential temperature profile on 12th June 1990
temperature. Maximum temperatures could be seen at all the levels just after noon. The development of turbulence and vertical movement of parcels can be visualised in the plot. Rise in temperatures can be noticed after 9 O’clock in the morning. The peak temperature was recorded around 1400 hrs and then reduces slowly. But this rate of decrease was slow compared with the rate of increase of temperature.

Minimum temperatures at higher levels appear to be lagging. It can be seen from the exhibit that the minimum values were recorded after sun rise even up to 0800 hrs, except at ground level.

The model simulation could not produce temperature inversions during both the days up to the height of 2000 m. This might be due to strong monsoonal winds or the inversion might not been strong during these days.

A comparison between observed and simulated temperature at 30 m level is shown in Exhibit 4.40. It can be seen that the model has underestimated the temperature at this level, although model has reproduced the trend. The validation at higher levels could not be studied due to non-availability of data.

Horizontal wind field simulated on 18th August 1990 by the model is given in the Exhibits 4.41 and 4.43.

North south component of the wind is given in the Exhibit 4.41. It can be seen that maximum wind component (5-6 m/s) is around 1500-200 m level. The simulated wind field component is
Exhibit 4.40 Comparison of observed and simulated temperature at 30 m level
Exhibit 4.41. Diurnal variation of simulated u-wind profile on 18th August 1990
compared with available doppler sodar. Since sign of doppler sodar data was opposite to normal meteorological convention wind filed, the sign has changed for comparison.

The analysis shows the modelled value of v are underestimated at higher elevations (more than 800 m) and overestimated at lower levels (Exhibit 4.42). Magnitudes of v at middle layers, however, were comparable with observed field. This may be due to adaptation of the lower resolution at higher levels while computing.

East-west component of wind field simulated on 18th August 1990 is given in the Exhibit 4.43. The magnitude of u component was less compared to v component. Reversal of u wind could be observed during some part of the day, which indicates southerly winds and or good agreement with the observed wind pattern. The simulated u-wind field has been compared with Doppler sodar data.

The scatter between observed and simulated winds is shown in Exhibit 4.44. From the exhibits it can be seen that the model has overestimated at lower wind components compared to the Doppler Sodar observations. On further analysis of the wind speeds recorded by the Sodar and tower data at 30 m level, it was found that the Sodar data was much lower.

The mean wind field generated from the u and v components is given in the Exhibit 4.45. Definite pattern of wind speed could not be observed in the simulation. Wind speed was below 6m/s at any
Exhibit 4.42 Scatter plot between observed and simulated u-wind on 18th August, Kharagpur
Exhibit 4.43. Diurnal variation of simulated v-wind profile on 18th August 1990
Exhibit 4.44 Scatter plot between observed and simulated v-wind on 18th August, Kharagpur
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point of time within the simulated period. This shows good agreement with synoptic observation of Calcutta. Simulation shows less variation in wind speed with time between 1000 - 2000 meter levels. As in the case of three-dimensional modeling studies (Potty et al., 1997), this one dimensional model also fail to simulate low level wind maxima.

It is noticeable that the model has simulated change in wind speed around 1m/s within an hour of time on many occasions during the simulation period. In pollution dispersion studies, these changes are very important, especially at 500 - 800 m level, since the plume rise and initial dilution of the plume depend on this factor.

Although overall performance of the model is good, scientific evaluation of the model could not be carried out due to lack of dependable data. As explained in the earlier chapter, the model uses many similarity functions for computational practicability and filling the gap of observed data. Deviation from the similarity functions lead to erroneous results. As discussed in the earlier sections of this chapter, during the extreme stability conditions, the observed values are deviate more from the similarity relationships. Further studies using data of other than monsoon seasons will help to understand the deviations in better way.
Exhibit 4.45. Diurnal variation of mean wind profile on 18th August 1990