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A preliminary analysis of tower micrometeorological data during December 1978 at Visakhapatnam

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ABSTRACT. Temperature and wind data collected at seven levels over the micrometeorological tower at Visakhapatnam Steel Plant site during December 1978 were analysed. Variation of frictional velocity (u_*), mean wind speed ($\bar{u}$), ratio of frictional velocity to mean wind speed, momentum eddy diffusivity (K_M) standard deviation of horizontal wind speed (σ_u), power law coefficients during the day were studied. Stability parameters like stability ratio (SR), non-dimensional wind shear (ϕ_M) and Richardson number (R_i) were computed. Rates of production of mechanical and buoyant energies and rate of dissipation of turbulent kinetic energy were also computed to arrive at the turbulent energy budget.

1. Introduction

Micrometeorological studies with tower data, although rare, have been made earlier by Rao *et al.* (1965), Narayanan *et al.* (1971, 1972) and Shirvaikar *et al.* (1970), Adiga *et al.* (1980) at Thumba and Tarapur respectively. In 1978 meteorological data began to be taken over a 64 m tower at the steel plant site at Visakhapatnam. Wind, temperature and humidity measurements have been made continuously at 2, 4, 8, 16, 32, 48, 64 metre heights on the tower. This paper describes the findings made by the author while studying one month data record of December 1978.

2. Data and site description

The topographic map of steel plant site along with location of tower can be seen in Fig. 1. The site is more or less flat and open except for small mounds in the southwest and eastnortheast at distances of 5 and 10 km respectively. Temperatures were recorded by bead type thermisters shielded from direct radiation with proper calibration and exposure. Wind speed and direction were recorded by electrical contact cup anemometers and Selswyn wind vanes. Accuracies of wind speed, wind direction and temperature are 1 kt, 5° and 0.15°C respectively.

3. Analysis of data

3.1. *Frictional velocity*

A rough estimate of frictional velocity u_* can be obtained by assuming a logarithmic profile relationship of the form :

$$\bar{u} = \frac{u^*}{k} \ln \frac{z}{z_0} \tag{1}$$

where u is the mean wind speed at height z, k is Von Karman constant (0.4) and z_0 the roughness length. The atmospheric surface layer tends to be neutrally stratified during high wind conditions due to intense mixing. Hence using Eqn. (1) for two heights and subtracting one from the other, a relationship of the form :

$$u_2 - u_1 = \frac{u_*}{k} \ln \frac{z_2}{z_1} \tag{2}$$

can be obtained where the wind speeds, u_1 and u_2 correspond to heights z_1 and z_2 respectively. The frictional velocities with 2 and 4 m, 4 and 8 m, 8 and 16 m, 16 and 32 m, 32 and 48 m, 48 and 64 m level winds were computed separately and the mean frictional velocity was found for the hour. Mean hourly frictional velocities in the month of December are shown in Fig. 2. Also are plotted in Fig. 2 the mean wind speed in the layer of 64 m and the ratio $u_*/\bar{u}$. The figure reveals that u_* has a semidiurnal oscillation with the crests

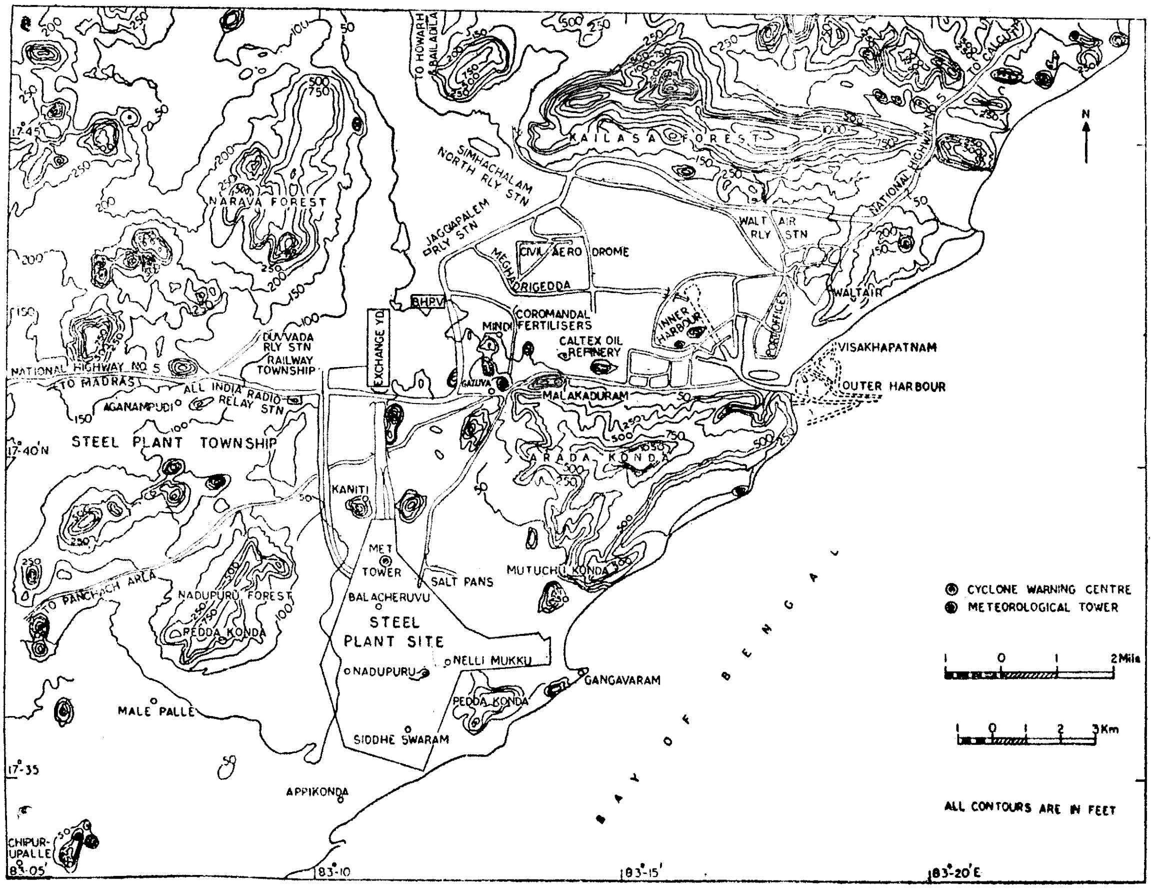

Fig. 1

(0500 & 1700 hr) and troughs (1000 and 2200 hr) separated exactly by 12 hr. Unlike u_*, $\bar{u}$ has only diurnal oscillation with a peak in the mid-afternoon at 1500 hr and lowest value at 2200 hr. The ratio $u_*/\bar{u}$ also exhibited, similar to u_*, semidiurnal oscillation with peaks at 0500 and 2300 hr and the troughs at 0200 and 1300 hr.

3.2. *Momentum eddy diffusivity* (K_M)

Under neutral conditions :

$$\partial \bar{u}/\partial z = u_*/kz$$

$$u_*^2 = \tau/\rho = K_M\,(\partial \bar{u}/\partial z)$$

$$(\partial \bar{u}/\partial z)^2 = \frac{u_*^2}{k^2 z^2} = K_M\;\frac{\partial \bar{u}}{\partial z}\;\frac{1}{k^2 z^2}$$

$$\therefore K_M = (k^2 z^2\,\partial \bar{u}/\partial z) \qquad \text{(gradient method)}$$

$$\text{or } K_M = k u_* z \qquad \text{(Bulk Method)} \qquad (3)$$

When the terrain features are to be incorporated this equation becomes :

$$K_M = k u_* (z + z_0) \quad \text{(Bulk method)} \qquad (4)$$

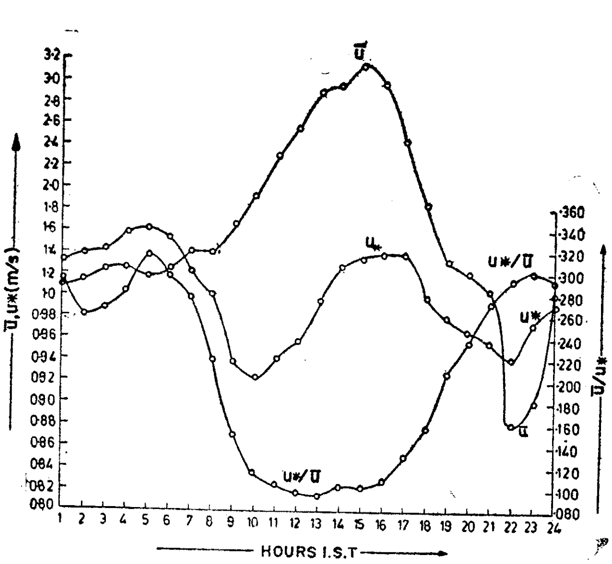

Fig. 2. Hourly variation of u_*, $\bar{u}$ and $u_*/\bar{u}$

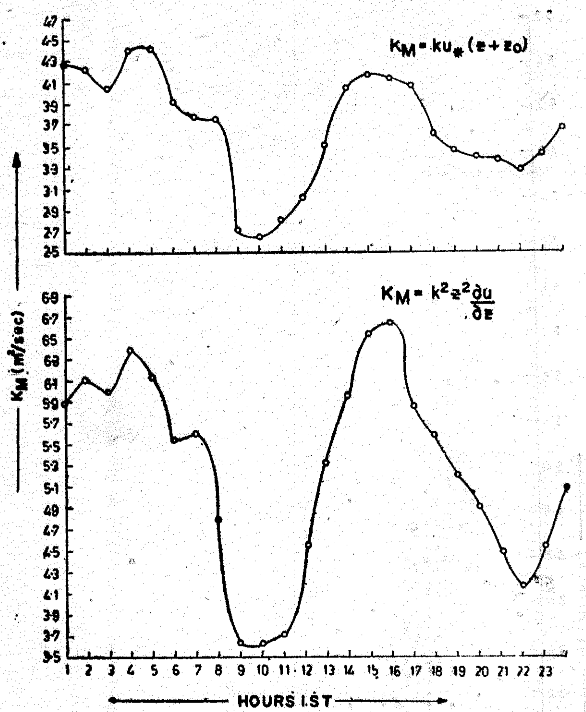

Fig. 3. Variation of K_M by Gradient and Bulk methods

In the present analysis z_0 was evaluated from Eqn. (1) by substituting the value of u_*. z_0 values were calculated for 2-4 m, 4 and 8 m, 8-16 m, 16-32 m, 32-48 m, 48-64 m and all the values were averaged to yield mean value of z_0 for the hour. These values were utilised to compute K_M by Eqn. (4). In this z is taken as 32 m, the middle value of the heights of observations.

To determine K_M by Eqn. (3) z is considered as 32 m and $\partial u/\partial z$ is the gradient of wind speed between 64 and 2 m levels.

Variation of K_M during the day by both methods is shown in Fig. 3. K_M has diurnal variation. Values of K_M by gradient method are always higher than Bulk method. From 1100 hr it increases to 1600 hr and decreases till 2200 hr and again increases in the night attaining a secondary peak at 0400 hr. The first peak in the day is due to free convection coupled with sea breeze and the second peak in the night appears to be due to forced convection due to land breeze. The maximum values of K_M by gradient and Bulk methods are 4.41×10^5 and 1.94×10^5 cm²/sec respectively. Haltiner and Martin (1951) gave the value of K_M considering it as the coefficient of eddy diffusivity of matter in the vertical, K_z, of the order of 5×10^4 cm²/sec corresponding to average turbulence and 5×10^3 cm²/sec corresponding to stable conditions. It can thus be seen that the present values of K_M ($=K_z$) are higher than the extra tropical values reported by Haltiner and Martin (1951).

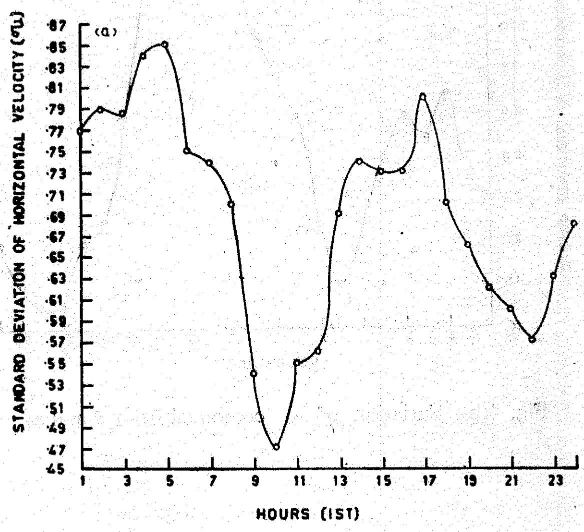

Fig. 4(a). Variation of σ_u computed from u_*

3.3. *Intensity of turbulence*

Wind direction in strong winds varies little with height within the lowest 150 metres. The standard deviation of horizontal wind is a function of frictional velocity $\sigma_u = f(u_*) = Cu_*$. The constant, C, has a value between 2 and 3 (Panofsky 1975). The author has taken a value of 2.5 in this paper.

The standard deviation (σ_u) can be found out alternatively as $\sigma_u = \bar{u}/k \log (z/z_0)$. In cases of strong convection this formula leads to systematic underestimates.

With frictional velocity the standard deviation, σ_u, increases from 1000 hr attaining a peak value at 1700 hr and decreases further reaching a lowest value at 2200 hr. It again increases attaining a peak higher than the daytime one at 0500 hr. This also shows exactly a semi-diurnal oscillation of 12 hr for it is simply a function of u_* (Fig. 4a).

By the second method σ_u increases from 0800 hr reaches a peak at 1600 hr, decreasing further to a lowest value at 2200 hr and attains another peak at 0300 hr. Although this exhibits two troughs and crests the phase differences are varying. Further magnitudes of σ_u by this method are always 50 per cent of the former (Fig. 4 b).

3.4. *Law of variation of wind with height*

Wind profile in the lowest 150 metres follows a logarithmic law in strong winds (Panofsky 1975, Tennekes 1973). This can be extended upto

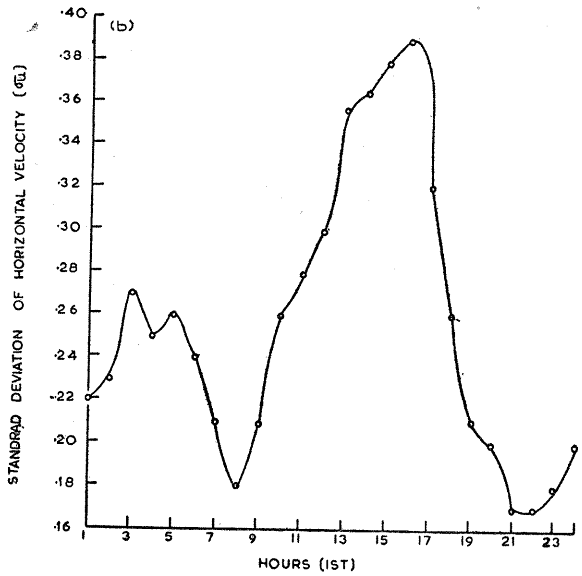

Fig. 4(b). Variation of σ_u computed from $\bar{u}$ and z_0

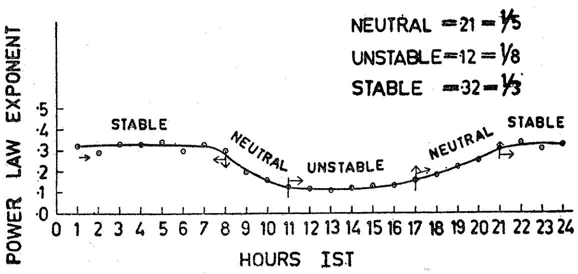

Fig. 5. Variation of power law exporent during a day

300 metres or even more (Sutton 1952) by approximating a power law of the form :

$$u_2 = u_1 \, (z_2/z_1)^p \qquad (5)$$

where u_1 and u_2 refer to wind speeds at levels z_1 and z_2 respectively and p is an exponent. The best estimate for $p = 1/\ln^2(\overline{z}/z_0)$ where $\overline{z}$ is the geometric mean height in the interval over which the law is to be fitted. In the case of strong heat convection p is decreased by an amount in a known way on the relative production of convective and mechanical turbulence.

The mean power law exponent for the levels 2-4, 4-8, 8-16, 16-32, 32-48 and 48-64 metres with corresponding z_0 was computed for each hour and averaged over a month and the variation can be seen in Fig. 5. The exponent for unstable, neutral and stable conditions came out to be 1/8, 1/5 and 1/3 respectively. These are slightly different than those reported earlier (Sutton 1952, Padmanabhamurty and Gupta 1979).

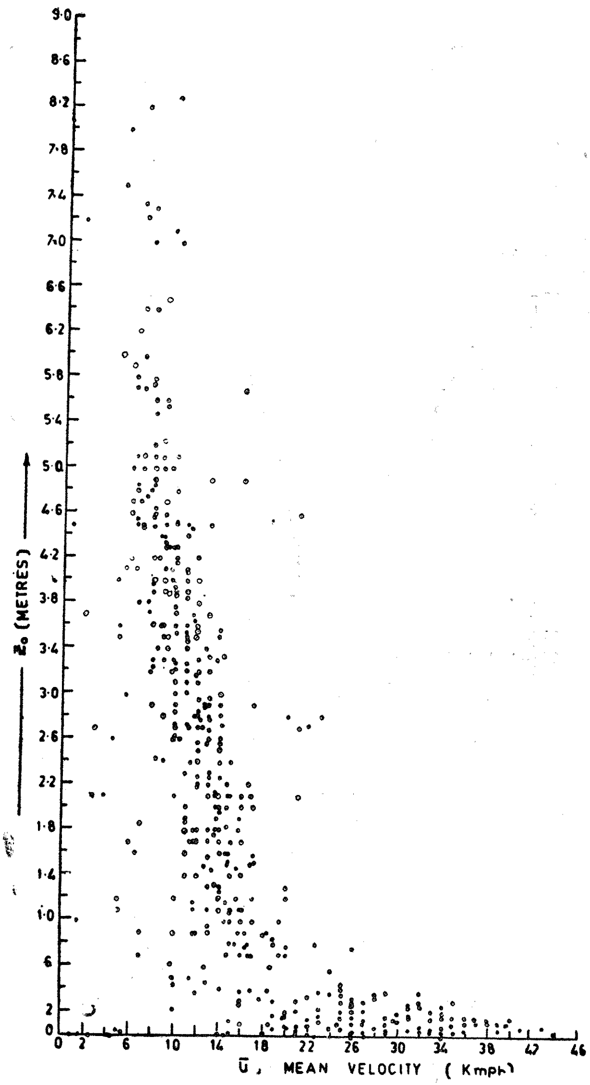

Fig. 6. Variation of z_0 with $\bar{u}$

3.5. *Roughness parameter* z_0

z_0 is calculated from Eqn. (1) after evaluating the value of u_* from two level wind observations. Thus,

$$z_0 = z/\exp\,(k\bar{u}/2.303u_*) \qquad (6)$$

Values of z_0 from each level wind data and for each hour were found out and averaged. A plot of z_0 against Richardson number did not give any encouraging result indicating that z_0 is independent of stability. However a plot of z_0 against $\bar{u}$ (mean velocity) suggests that at low winds (<2 kmph) z_0 is independent of $\bar{u}$ and as the wind speed increases z_0 decreases and depends on wind speed (Fig. 6).

3.6. *Stability parameters*

Stability ratio, a simplified parameter which is quite satisfactory to indicate stability (Munn 1966) is calculated as :

$$SR = \frac{T_2 - T_1}{\bar{u}^2} \times 10^5 \;\; (^\circ\mathrm{C\,sec^2/cm^2}) \qquad (7)$$

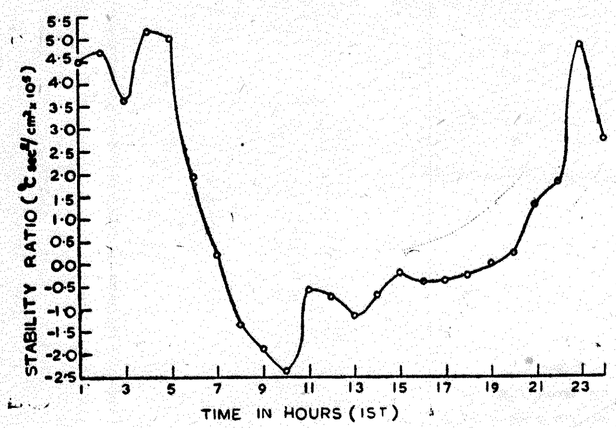

Fig. 7. Hourly variation of stability ratio

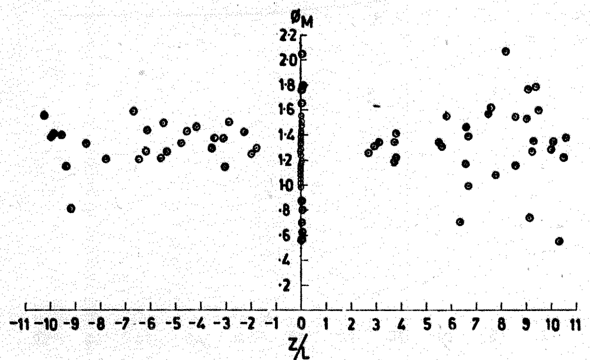

Fig. 9. Variation of ϕ_M and z/L

where T_1 and T_2 are temperatures at two levels and u is the wind speed at a mean level of the two. Stability ratios for the levels 2-4, 4-8, 8-12, 12-16, 32-48 and 48-64 metres were worked out and averaged for each hour. The mean hourly stability ratio is shown in Fig. 7. Negative values indicate instability and positive values stability. At Visakhapatnam instability exists from 0800 hr to 1800 hr during the day even in winter period.

Another stability parameter ϕ_M, the non-dimensional wind shear, is computed from:

$$\phi_M = (\partial \bar{u}/\partial z) \,/\, (u_*/kz) \tag{8}$$

ϕ_M is a universal function of z/L where L is the Monin–Obukhov length in the surface layer defined as:

$$L = \frac{-u_*^3}{(kg/T)\,(H/\rho c_p)} \tag{9}$$

where g is gravitational acceleration, T absolute temperature, ρ air density, c_p, specific heat of air at constant pressure and H, flux of sensible heat. H is computed from two level winds and temperatures:

$$H = -\frac{\rho\, c_p k^2 (u_2 - u_1)(\theta_2 - \theta_1)}{(2.303 \log z_2/z_1)^2} \tag{10}$$

where θ_1 and θ_2 are potential temperatures. Since the levels under consideration are close actual temperatures used instead of potential temperatures as this will not result in significant difference.

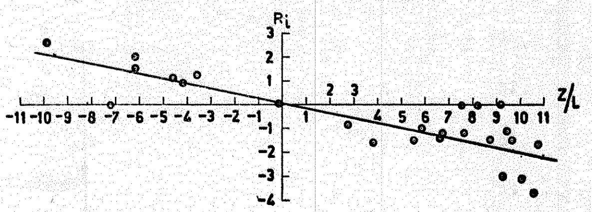

Fig. 8. Variation of z/L vs Ri

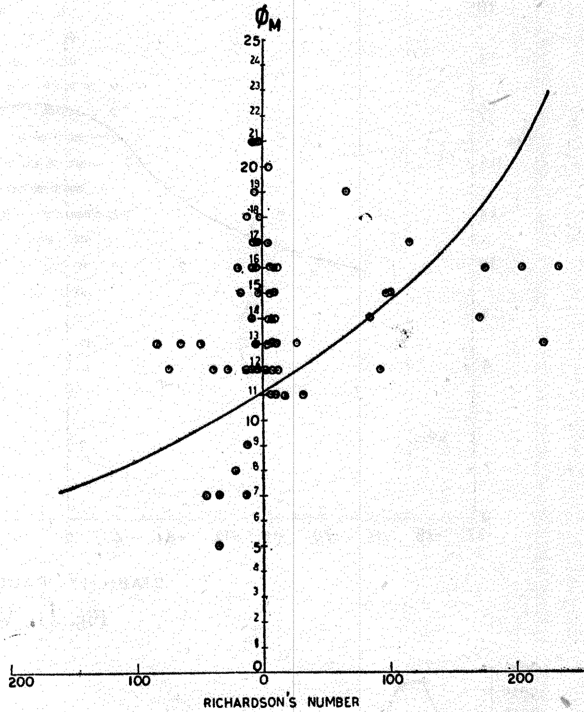

Fig. 10. Variation of ϕ_M vs Richardson's Number

Richardson's number which is a measure of stability is also a unique function of z/L (Paulson 1970, Oke 1970, Panofsky 1973, 1974). Therefore, ϕ_M also should be a unique function of R_i.

Richardson's number is calculated from the two level wind and temperature data as:

$$R_i = \left(\frac{g}{\theta'}\right)\left(\frac{\partial \theta}{\partial z}\right) \Big/ \left(\frac{\partial u}{\partial z}\right)^2 \tag{11}$$

where θ is potential temperature and θ' is the mean potential temperature of the two levels in question. As in the computation of heat flux, H, here too actual temperatures are used.

Fig. 8, the plot of z/L against R_i shows a linear relationship. In unstable air $z/L=0=R_i$. Under stable conditions (R_i +ve) z/L decreases and under very unstable condition z/L increases. This points out that R_i varies linearly with height either in unstable or stable conditions but for the sign (Panofsky 1974). Variation of ϕ_M against z/L may be seen in Fig. 9. No relationship could be established. The relationship between ϕ_M and R_i shown in Fig. 10, also supports Businger *et al.* (1971) and Brook (1974).

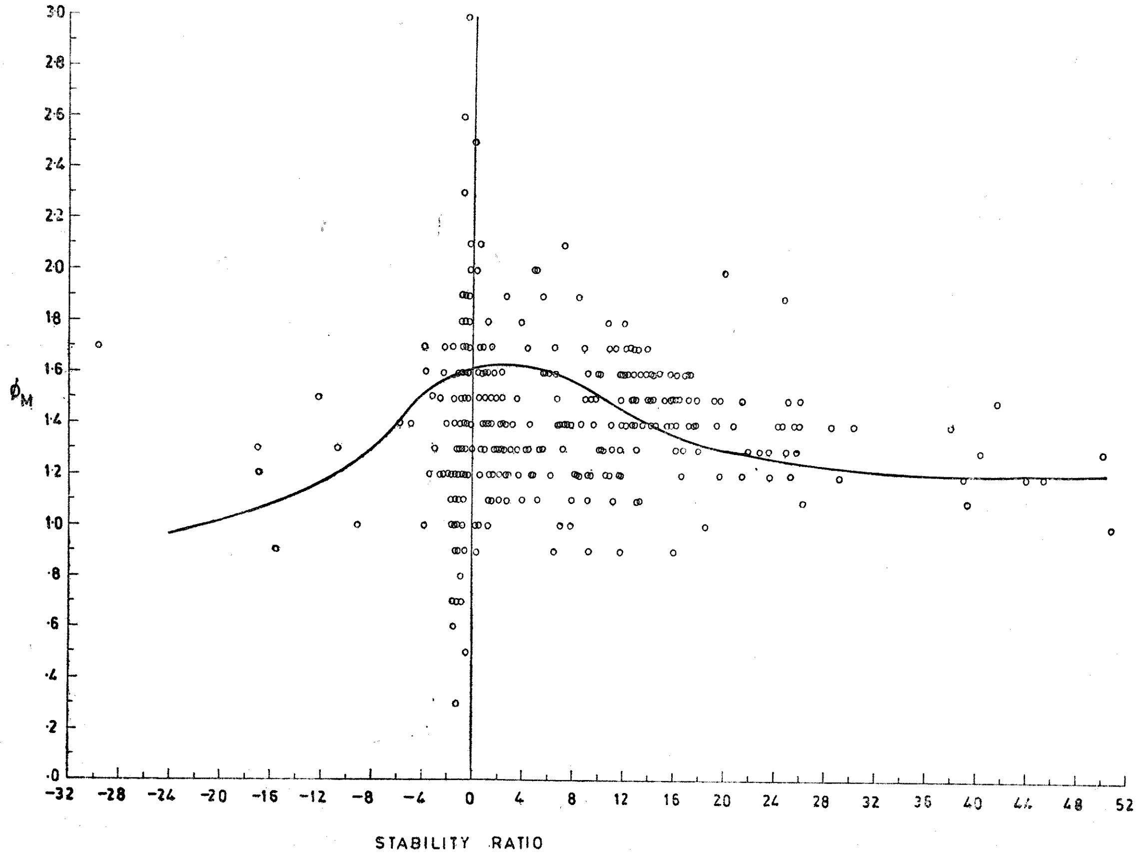

Fig. 11. Variation of ϕ *vs* SR

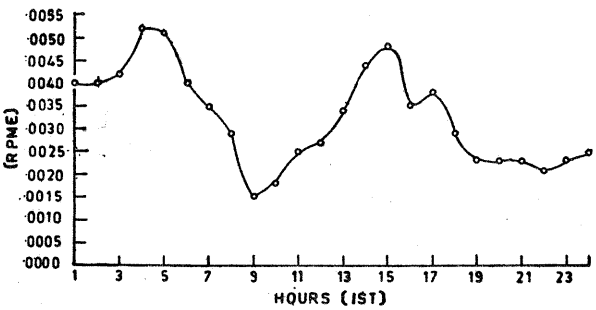

Fig. 12. Variation of rate of production of mechanical (RPME) energy

The relationship between ϕ_M and SR is shown in Fig. 11. As SR increases on the positive side (more stable) or on the —ve side (more instability) ϕ_M decreases. The decrease in the former case is more gradual than in the latter. This is of the same form of ϕ_M with R_i suggested by Businger *et al.* (1971).

3.7. *Rate of production of mechanical energy (RPME)*

The rate of production of mechanical energy includes a term $\partial \bar{u}/\partial z$ and is given as :

$$u_*^2 (\partial \bar{u}/\partial z) \tag{12}$$

$\partial \bar{u}/\partial z$ is simply approximated as $(\bar{u}_2 - \bar{u}_1)/\triangle z$ where $\bar{u}_2$ and $\bar{u}_1$ are the wind speeds and $\triangle z$ the height difference between these levels. Stearns (1971) discussed the representativeness of this formulation and found to be of good accuracy. The most difficult part of the mechanical production term to evaluate is the friction velocity u_*. u_* was evaluated according to Eqn. (2) as well as $\partial \bar{u}/\partial z$ from the two level wind observations. The values of RPME for each pair of successive levels of wind observations were averaged every hour over the whole month. The hourly variation of RPME is shown in Fig. 12. The variation of RPME is more or less semi-diurnal with peaks at 0400 and 1500 hr and troughs at 0900 and 2200 hr. It can be seen that in the early morning and early night RPME is low.

3.8. *Rate of dissipation of viscous forces*

Kolmogorov (1941 a, b, c) suggested that there exists a range of wave members, K in which the spectrum of turbulent kinetic energy $\phi(K)$ is described by :

$$\phi(K) = a\epsilon^{2/3} K^{-5/3} \tag{13}$$

where a is a universal function. With the assumption of Taylor's (1938) hypothesis of frozen turbulence Lumley and Panofsky (1964) have shown :

$$\epsilon = \frac{n^{5/2}}{\bar{u}} \left\{ \frac{S_u(n)}{a} \right\}^{3/2} \tag{14}$$

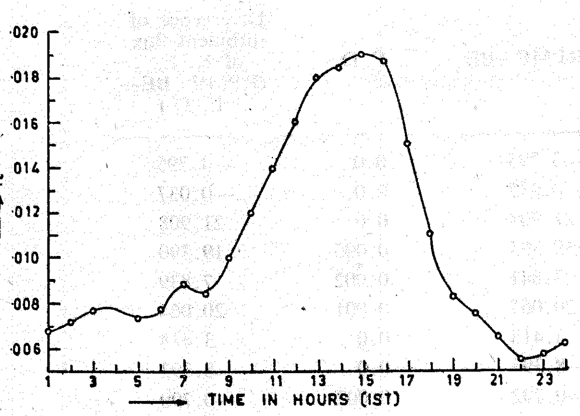

Fig. 13. Frequency variation(n)

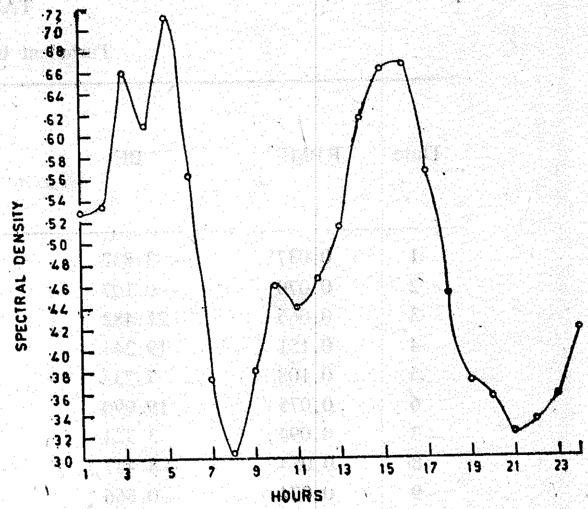

Fig. 14. Variation of spectral density

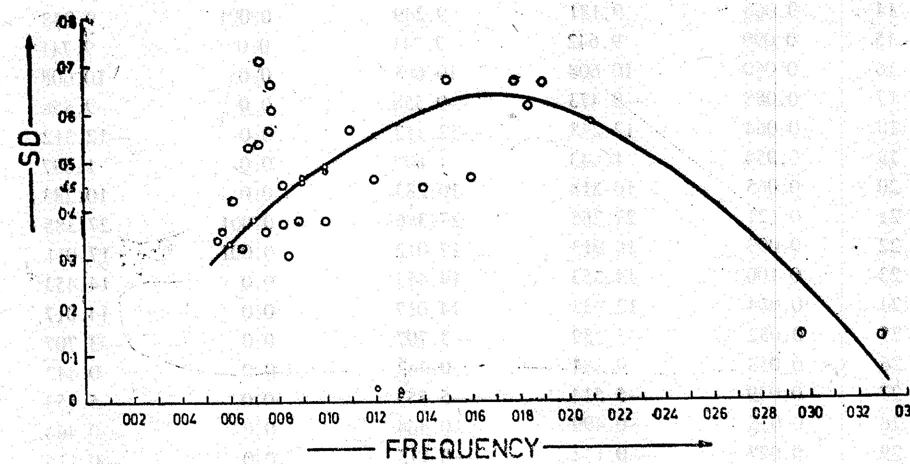

Fig. 15. Relation between n and spectral density

where $S_u(n)$ is the one dimensional spectral ordinate of the longitudinal component at frequency n. There now exists numerous measurements at spectra of wind speed or of the longitudinal component of the wind vector. There is little disagreement about the behaviour of these spectra at high frequencies. For frequencies n, exceeding about $0.2\bar{u}/z$, the classical Kolmogorv spectrum provides a satisfactory fit for the spectral densty, $S(n) = 0.15\,(\epsilon\bar{u})^{2/3}\,n^{-5/3}$, where ϵ is the energy dissipation rate which can be estimated by:

$$\epsilon = 0\cdot 16\bar{u}^3/\{z \ln^3 (z/z_0)\} \qquad (15)$$

The diurnal variation of frequency may be seen in Fig. 13. The frequencies are higher during the day reaching a peak at 1500 hr and a minimum around 2200 hr. Fig. 14 shows the spectral density during the day, which also exhibits a semi-diurnal variation. The peaks of spectral density are occurring at 0500 hr and 1600 hr (the former being higher) and the troughs at 0800 hr and 2100 hr. Fig. 15 shows the relationship between spectral density and frequency. The spectral density is at its peak value of 0.64 when the frequency is 0.017. As the frequency increases further the spectral density decreases in magnitude. At lower frequencies than 0·64 also spectral density decreases with frequency (Davenport 1961).

3.9. *Turbulent kinetic energy budget*

Neglecting horizontal gradients and assuming horizontal homogeneity the turbulent energy equation can be written as:

$$\frac{\partial \bar{e}}{\partial t} = u_*^2 \frac{\partial \bar{u}}{\partial z} + \frac{g}{\rho c_p}\frac{H}{T} - \frac{\partial \overline{e'w'}}{\partial z} - \frac{1}{\rho}\frac{\partial}{\partial z}\overline{w'p'} - \epsilon \qquad (16)$$

TABLE 1

Turbulent Energy Budget

Date	RPME	BE	RPME+BE	E. D.	Divergence of turbulent flux of K. E. (RPME+BE—E. D.)
1	0.037	—3.832	—3.795	0.0	—3.795
2	0.070	—0.107	—0.037	0.0	—0.037
3	0.066	21.482	21.908	0.0	21.908
4	0.151	19.244	19.395	0.005	19.390
5	0.108	7.733	7.841	0.002	7.839
6	0.075	19.990	20.065	0.001	20.064
7	0.094	3.324	3.418	0.0	3.418
8	0.054	—8.447	—8.393	0.0	—8.393
9	0.074	—0.866	—0.792	0.002	—0.790
10	0.083	2.781	2.864	0.001	2.863
11	0.059	2.391	2.450	0.0	2.450
12	0.048	0.187	0.235	0.0	0.235
13	0.085	14.120	14.205	0.0	14.205
14	0.068	9.181	9.249	0.001	9.248
15	0.099	9.642	9.741	0.0	9.741
16	0.060	10.608	10.608	0.0	10.608
17	0.085	—9.473	—9.558	0.0	—9.558
18	0.064	—12.248	—12.312	0.0	—12.312
19	0.054	1.643	1.697	0.0	1.697
20	0.065	10.218	10.283	0.0	10.283
21	0.121	27.265	27.386	0.001	27.385
22	0.099	16.913	17.012	0.001	17.011
23	0.100	14.353	14.453	0.0	14.453
24	0.084	13.933	14.017	0.0	14.017
25	0.052	—3.759	—3.707	0.0	—3.707
26	0.058	0.384	0.442	0.0	0.442
27	0.039	—5.514	—5.553	0.0	—5.553
28	0.035	—0.499	—0.464	0.0	—0.464
29	0.027	—0.142	—0.115	0.0	—0.115
30	0.006	0.0	0.006	0.0	0.006
31	0.009	0.0	0.009	0.0	0.009

RPME=Rate of Production of Mechanical Energy, B. E.=Buoyant Energy, E. D. =Energy Dissipation.

This is the form of the turbulent energy equation most studied in the atmospheric boundary layer. No consensus on the importance of all terms is found in the literature, but it is generally accepted that except under special circumstances $\partial \bar{e}/\partial t=0$. Taylor (1952), Robinson (1953), Mc Cormick (1954), Hess and Panofsky (1966), Record and Cramer (1966), Fichtl (1968), Wyngaard and Cote (1971) and McBean *et al.* (1971) have made studies of turbulent energy budget with instrumented data over towers of varying heights. With the present set up of equipment it is not possible to evaluate e' and w' hence the terms containing these parameters are not evaluated. Also they are least well determined and often has been inferred as an out of balance term. The turbulent kinetic energy equation can be written as:

$$0 = u_*^2 \frac{\partial \bar{u}}{\partial z} + \frac{g}{\rho c_p} \frac{H}{T} - \epsilon - \frac{\partial \overline{e'w'}}{\partial z} - \frac{1}{\rho} \frac{\partial}{\partial z} \overline{w'p'} \quad (17)$$

or

$$u_*^2 \frac{\partial \bar{u}}{\partial z} + \frac{g}{\rho c_p} \frac{H}{T} - \epsilon = \frac{\partial \overline{e'w'}}{\partial z} - \frac{1}{\rho} \frac{\partial}{\partial z} \overline{w'p'} \quad (18)$$

(i) (ii) (iii) (iv) (v)

where,

(i)—Rate of production of mechanical energy,
(ii)—Rate of production of buoyant energy.

(iii)—Rate of dissipation of turbulent kinetic energy,

(iv)—Divergence of turbulent flux of kinetic energy and

(v)—Contribution to the turbulent kinetic energy by pressure field.

The contribution to the turbulent kinetic energy by the pressure field is negligible as the areal considerations are small. Therefore the out of balance of the terms on the left hand side is equivalent to divergence of turbulent flux of kinetic energy. Table 1 shows the daily turbulent budget for the month of December. It may be seen that divergence of turbulent flux of kinetic energy is more than energy dissipation indicating that the atmosphere at Visakhapatnam, even in December, is turbulent.

4. Conclusions

(1) u_*, $u_*/\bar{u}$ and σ_u exhibited semi-diurnal oscillation but $\bar{u}$ showed diurnal variation.

(2) The momentum eddy diffusivity, K_M came out to be 4.41×10^5 cm²/sec and 1.94×10^5 cm²/sec by gradient and bulk methods respectively.

(3) The exponents of power law came out to be 1/8, 1/5 and 1/3 during unstable neutral and stable atmospheric conditions.

(4) Roughness parameter, z_0, did not show any relation with R_i. But relationship between z_0 against u suggests that at low wind speeds (< 2 kmph) it is independent of $\bar{u}$ but as the wind increases z_0 decreases.

(5) z/L showed a linear relationship with R_i. R_i varied linearly with height. Relationship is found to exist between ϕ_M on one hand and R_i and SR on the other.

(6) The rate of production of mechanical energy also showed semi-diurnal oscillation with low values in the early mornings and early night. The diurnal variation of frequencies show peak value at 1500 hr and minimum around 2200 hr.

(7) Spectral density also showed semi-diurnal variation. The relationship between spectral density and frequency suggests that the former is at its peak value of 0.64 when the latter is 0.017. As the frequency increases further, spectral density decreases. At frequencies lower than 0.64 also spectral density decreases with frequency.

(8) Turbulent energy budget indicates that the divergence of turbulent flux of kinetic energy is more than energy dissipation.

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