Mausam, (1997), **48**, 1, 15-22

551.511.6 : 551.510.522 (213.5)

Turbulent kinetic energy balance in the atmospheric surface layer over a tropical region

B. PADMANABHAMURTY and PIALI CHAKRABORTY

School of Environmental Sciences
Jawaharlal Nehru University, New Delhi
(Received 8 May 1995, Modified 23 April 1996)

सार — भारत में जोधपुर के आस-पास धरातल की सतह पर प्रक्षुब्ध गतिज ऊर्जा बजट की विभिन्न अवधियों का पता लगाया गया और प्रमाणित सादृश्य संबंधों से उनकी तुलना की गई है । जिन अवधियों को जाँच के लिए चुना गया उनमें से अधिकांश अवधियों की सामान्य अस्थिर परिस्थितियों में प्रक्षुब्ध उत्पादन और विसरण सन्तुलित रहा है ।

ABSTRACT. The various terms of the turbulent kinetic energy budget in the surface layer over Jodhpur, India have been worked out and compared with established similarity relations. The turbulent production and dissipation tend to balance under moderately unstable conditions for most of the runs considered for investigation.

Key words — Turbulent energy budget, Components, Similarity relations, Balance.

1. Introduction

Turbulent kinetic energy is an important parameter used to study the turbulence characteristics of the surface boundary layer. Turbulence is produced by buoyancy and mechanical eddies and dissipated into heat by molecular viscosity. The turbulent kinetic energy budget equation depicts the production as well as the loss terms and using this it can be determined whether the boundary layer will become more turbulent or turbulence will decay in the boundary layer. The turbulent kinetic energy budget under horizontally homogeneous conditions can be expressed by,

$$- \; uw\frac{\delta U}{\delta z} + \frac{g}{T}w\theta - \frac{1}{2}\frac{\delta wq^2}{\delta z} - \varepsilon - \frac{1}{\rho}\frac{\delta pw}{\delta z} = 0 \qquad (1)$$

If all terms on the left hand side of the equation are normalized by multiplying by kz/u_*^3, the equation reduces to,

$$\phi_n - z/L - \phi_t - \phi_\varepsilon + I = 0 \qquad (2)$$

where I is the imbalance comprising the pressure term.

The first term (ϕ_n), 'shear production', denotes the rate of production of energy by the interaction of Reynold's stress with the mean strain rate. The second term (z/L) denotes 'buoyant production'. The third term (ϕ_t) denotes 'turbulent transport' or the divergence of the turbulent flux of kinetic energy. The fourth term (ϕ_ε) is the 'dissipation rate'. The fifth term (I) represents 'Pressure transport'.

The budget of turbulent kinetic energy and the variation with height of the dissipation have been discussed by various authors, though some disagreement exists about the energy balance. Hess and Panofsky (1966), based on wind records of two days over the Brookhaven tower, New York, tentatively concluded that in equilibrium, shear production and energy dissipation are not very different from each other, even under highly unstable conditions. The change from rough to smoother terrain however, produced a state of non equilibrium in which dissipation was much greater than production. Busch and Panofsky (1968) analyzed data from field stations at Round Hill and found that for $|z/L| < 0.5$, the dissipation balances the mechanical and buoyant production when turbulence is in equilibrium. Fichtl and Mcvehil (1970) concluded that under unstable conditions the dissipation balances shear production and thus total production exceeded dissipation.

Wyngaard and Cote (1971) made a complete study of the TKE balance in the surface boundary layer. They observed that under stable conditions, dissipation balanced shear production, while turbulent transport and buoyant production were of secondary importance. Under unstable conditions, dissipation slightly exceeded the total production and energy was also lost at a substantial rate due to upward transport by turbulence. Bradley *et al*. (1981) measured the relative magnitude of components of the TKE budget in the range $-0.4 < z/L < 0$. They found that the dissipation rate balanced total production. The turbulent energy flux decreased in magnitude, but remained positive as the stability condition approached neutrality.

2. Site and data

MONTBLEX was the first planned experiment to probe the atmospheric boundary layer processes over the monsoon trough region. The core program of the experiment included setting up of towers at 4 stations representing different meteorological regimes of the monsoon trough. Data from the tower erected at Jodhpur has been selected for the present study. Jodhpur (26° 18′ N, 73°04′ E) is situated near the western limit of the monsoon trough. It marks a region of dry convective processes. The 30 m tower is situated next to a cropped field with a grassland on the other side. The overall area around the tower site is open. This station was found to have more extensive and continuous data compared to the other three stations. The tower had booms fitted at six levels (1, 2, 4, 8, 15, and 30 m). The booms can be partially rotated on the vertical and horizontal axis so that they can be oriented towards the prevailing wind simultaneously ensuring horizontality. At Jodhpur, fast response instrument like the Sonic anemometer was installed at a height of 4 m whereas, the Gill anemometer was installed at a height of 15 m.

In the present study, slow as well as fast response data from the tower at Jodhpur were collected for two different periods during the summer monsoon of 1990- onset period and mid-monsoon period. The slow data was sampled once every minute whereas, the fast response was recorded for 15 min sampling period at hourly interval at the rate of 8 Hz (Rudrakumar *et al*. 1991). The entire MONTBLEX data set for four months was scrutinized in order to select those days which meet the conditions required for the present study. The runs selected are those which satisfy following conditions:

(*i*) Presence of both, slow data as well as fast data.

(*ii*) Days having the maximum number of runs with both Sonic as well as Gill anemometer data were used so that turbulence characteristics at 4 m as well as 15 m could be analyzed.

(*iii*) All observations used were taken under no rainfall conditions. This condition is necessary for testing the similarity relations which require uniform weather conditions during each run.

(*iv*) Observations on totally overcast days were rejected, to avoid having runs with mostly neutral conditions. This was done in order to be able to analyze a wide spectrum of stability conditions.

(*v*) Runs having minimum errors and spikes were selected and as far as possible the erroneous data sets were rejected.

102 runs (51 runs at each level) of 15 min duration, each consisting of around 7,200 data points for each parameter were analyzed at the 4 m as well as 15 m levels. The weather conditions during the onset period runs mainly consisted of clear skies and low winds. During mid-monsoon period for most of the runs, the sky was partly cloudy with moderate winds.

3. Method of analysis

List of symbols used

g = acceleration due to gravity

k = Von Karman constant (0.4)

U = Mean wind speed

u, v, w = Longitudinal, lateral and vertical fluctuations of wind

θ = Temperature fluctuation

$u_* $ = Frictional velocity = $[(uv)^2 + (vw)^2]^{\frac{1}{4}}$

$\zeta = z/L = -(kgw\theta z) / (Tu_*^3)$

ϕ_n = Normalized wind shear = $(kz/u_*)\,\partial U/\partial z$

ϕ_t = Normalized turbulent transport

= $(kz/2u_*^3)\,\partial(wq^2)/\partial z = T.T\ (q)$

ϕ_ε = Normalized turbulent energy dissipation rate

ϕ_{tw} = Vertical velocity variance

= $(kz/2u_*^3)\,\partial(w^3)/\partial z = T.T\ (w)$

$q^2 = u^2 + v^2 + w^2$

B D = Businger-Dyer relations

The non dimensional wind shear (ϕ_n) is expressed as $(kz/u_*)\,\partial U/\partial z$, where u_* has been determined from eddy correlation method which is a direct method of determination of fluxes. For this method, in order to obtain all significant high frequency contributions, the ratio of the path length of the instrument to the height above the ground should be less than 0.08, which is satisfied in the case of the Gill as well as Sonic anemometer (Brook 1974). Time series were generated for all the variables in each run and the fluctuations were computed by subtracting the mean from the instantaneous values. The covariances of the fluctuations have been determined by averaging the products of the appropriate fluctuations. The mean wind speed gradient, $\partial U/\partial z$, has been computed using curve fit method. As the profiles of wind are more linear with respect to ln (z) than z, second order polynomials in ln (z) were fitted to five levels of wind speeds and differentiated for each gradient computation. Similarly, for the term z/L the covariances have been computed by eddy correlation method.

In most studies carried out so far, the normalized turbulent transport term ϕ_t [$T.\ T\ (q)$ in the Figs. 3(a&b)] has been inferred as an out of balance term. Wyngaard and Cote (1971) estimated it from the difference in wq^2 between two levels and the result was taken as ϕ_t at the mid-point of ln z of the two levels. Brook (1974) evaluated ϕ_t using a flux-gradient relation for q. He compared this method with the one used by Wyngaard and Cote (1971) and the results were not strongly correlated as the latter measures the average ϕ_t over the layer considered whereas Brook's method estimates the point value of ϕ_t. McBean and Elliott (1975) used a single height of measurements of wind components and deduced the turbulent flux divergence from z/L dependence of the vertical and horizontal components of energy separately. In the present study, ϕ_t has been evaluated using the following expression,

$$\phi_t = (k/2u_*^3)\,\partial(\overline{wq}^2)/\partial\,(\ln z)$$

$$\simeq (k/2u_*^3)\,[(\overline{wq^2})_{z2} - (\overline{wq^2})_{z1}]/\ln(z2/z1) \quad (3)$$

z/L dependence of the turbulent energy flux and transport of turbulent energy and vertical velocity variance has also been studied. The vertical velocity variance ϕ_{tw} [$T.\ T\ (w)$ in the Figs. 3(a&b)] is the contribution from the w component to the turbulent transport and is computed in a similar manner as ϕ_t, but taking only the w component into account.

$$\phi_{tw} \approx (k/2u_*^3)\,[(w^3)_{z2} - (w^3)_{z1})]/\ln(z2/z1) \quad (4)$$

The normalized dissipation ϕ_ε has been computed from values of ε derived from the inertial subrange portion of the one dimensional velocity spectrum plotted against k. In the inertial subrange portion, the velocity spectrum is described by the equation,

$$S_u(k) = a\,\varepsilon^{2/3}\,k^{-5/3} \quad (5)$$

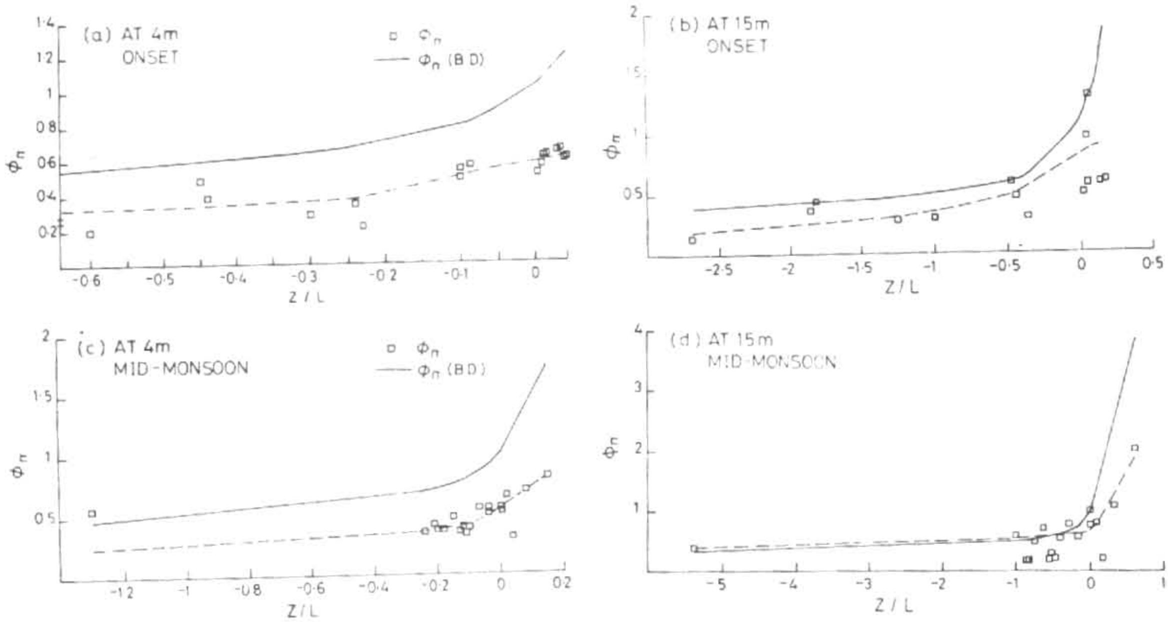
Lumley and Panofsky (1964) reviewed the various estimates of 'a' and concluded that 'a' lies in the range 0.45 to 0.50. In the present study a value of 0.5 has been used for 'a'.

The pressure transport term could not be computed due to lack of pressure sensors.

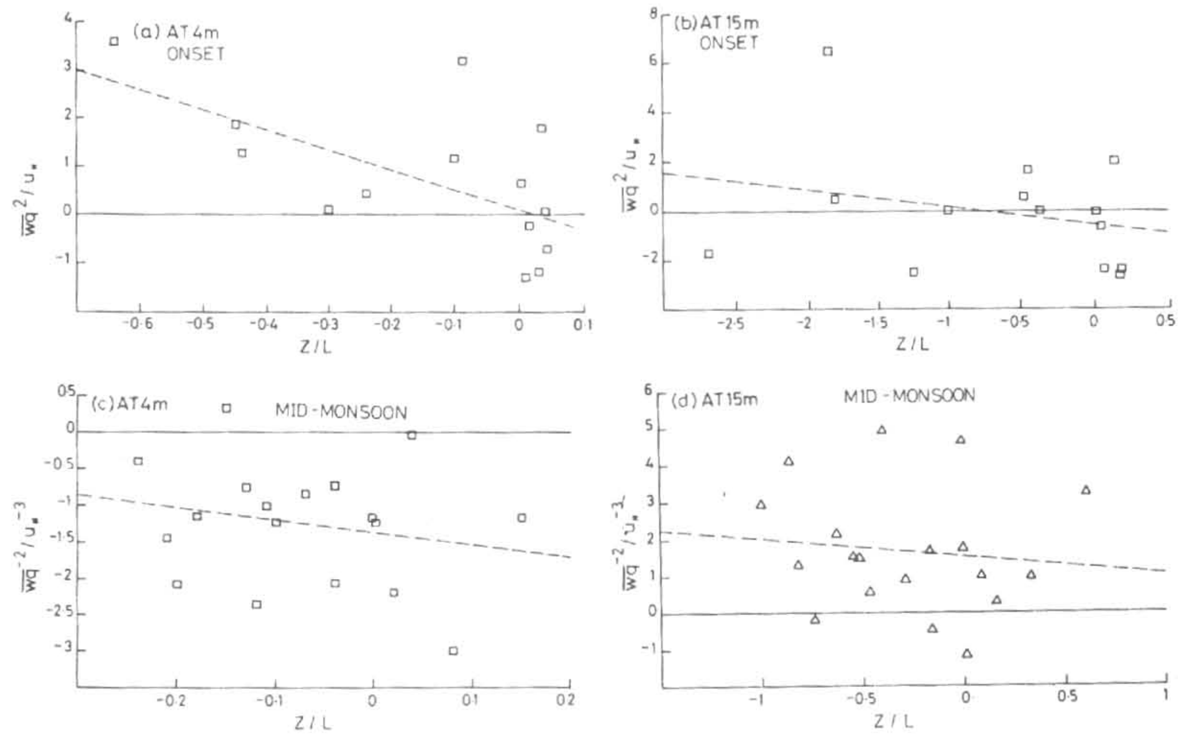
4. Results and discussion

4.1. *Non-dimensional wind shear (ϕ_n)*

The non-dimensional wind shear was determined for the 4 m as well as 15 m level. During the onset period [Figs. 1(a&b)] the variation of ϕ_n with z/L shows an overall trend similar to that reported in studies conducted in extra-tropical regions (Businger *et al.* 1971, Carl *et al.* 1973, Korrell *et al.* 1982). The magnitude of ϕ_n however, is different from other results. ϕ_n is less under unstable conditions, as compared to



Figs. 1(a-d). Variation of ϕ_n with *z/L* at (a) 4 m & (b) 15 m during the onset period and (c) 4m & (d) 15 m during the mid-monsoon period

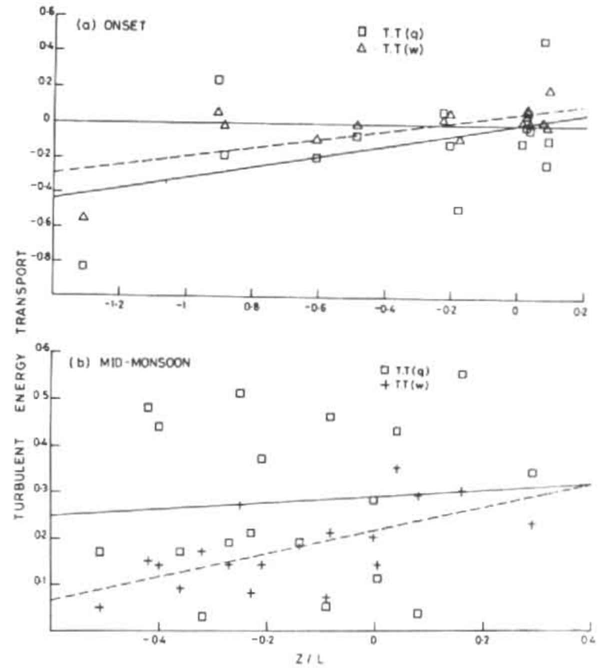


Figs. 2(a-d). Variation of turbulent energy flux with *z/L* at (a) 4 m & (b) 15 m during the onset period and (c) 4 m & (d) 15 m during the mid-monsoon period stable conditions, due to increased mixing under unstable conditions. The results of the present study have been compared with the Businger-Dyer equations. During the onset phase, the ϕ_n values give a correlation of 0.64 at the 4 m level and 0.45 at the 15 m level. The difference with the Businger-Dyer relations (referred to as B D) increases as stability increases. Under stable conditions the Businger-Dyer relation predicts a much faster rate of increase of ϕ_n with stability than shown by the present results. At the 4m level, under neutral conditions, the magnitude of ϕ_n is below the hypothetical value of 1 which pertains to the logarithmic law of wind. This could be attributed to terrain irregularities as the value of ϕ_n is less than 1 in accelerating air or when air flows from rough to smoother terrain or *vice versa* (Panofsky and Dutton, 1984). At the 15 m level too, the magnitude of ϕ_n is less than 1 [Fig.1 (b)].

During the mid monsoon phase too at the 4 m level the value of ϕ_n is less than 1 [Fig.1 (c)]. At the 15 m level [Fig.1 (d)], the magnitude of ϕ_n at $z/L =$ 0, is close to 1, confirming the logarithmic law of wind. The results show a correlation of 0.65 at the 4 m level and 0.8 at the 15 m level with the Businger-Dyer relations. The deviation from BD is less than that for the onset phase. At 15 m for unstable conditions the magnitude of ϕ_n shows very close convergence with the Businger-Dyer relations. In this case too, the deviations from the Businger-Dyer relations increase with stability. At the 15 m level, under unstable conditions, ϕ_n approached the constant value of 0.3.

4.2. *Turbulent transport* (ϕ_t)

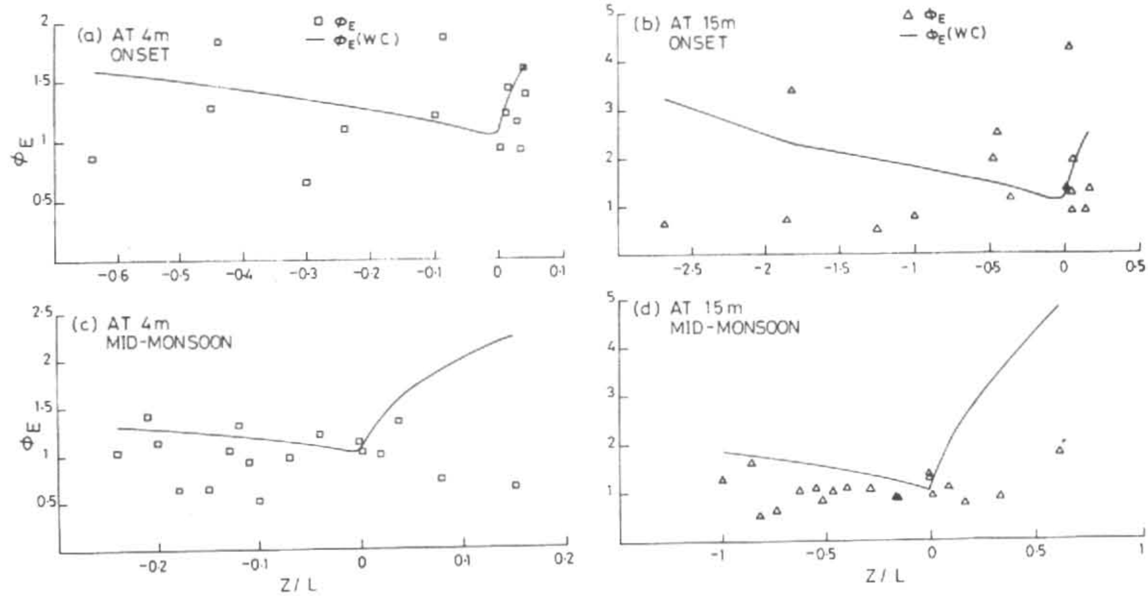
Turbulent transport could not be determined accurately with the present data set as different fast response instruments were used at the 4 m and 15 m levels. However, an attempt was made to quantify this term using the Gill and Sonic anemometer data. The computations using two level data actually give an estimate of the average flux divergence over the 4-15 m layer, rather than the point value of ϕ_t. The variation of the dimensionless turbulent energy flux (wq^2/u_*^3) with stability for the onset period has been plotted in Figs. 2(a&b). For the 4 m as well as the 15 m level, wq^2/u_*^3 tends to zero under neutral conditions. This is similar to the observations of Bradley *et al.* (1981). The dimensionless turbulent energy flux



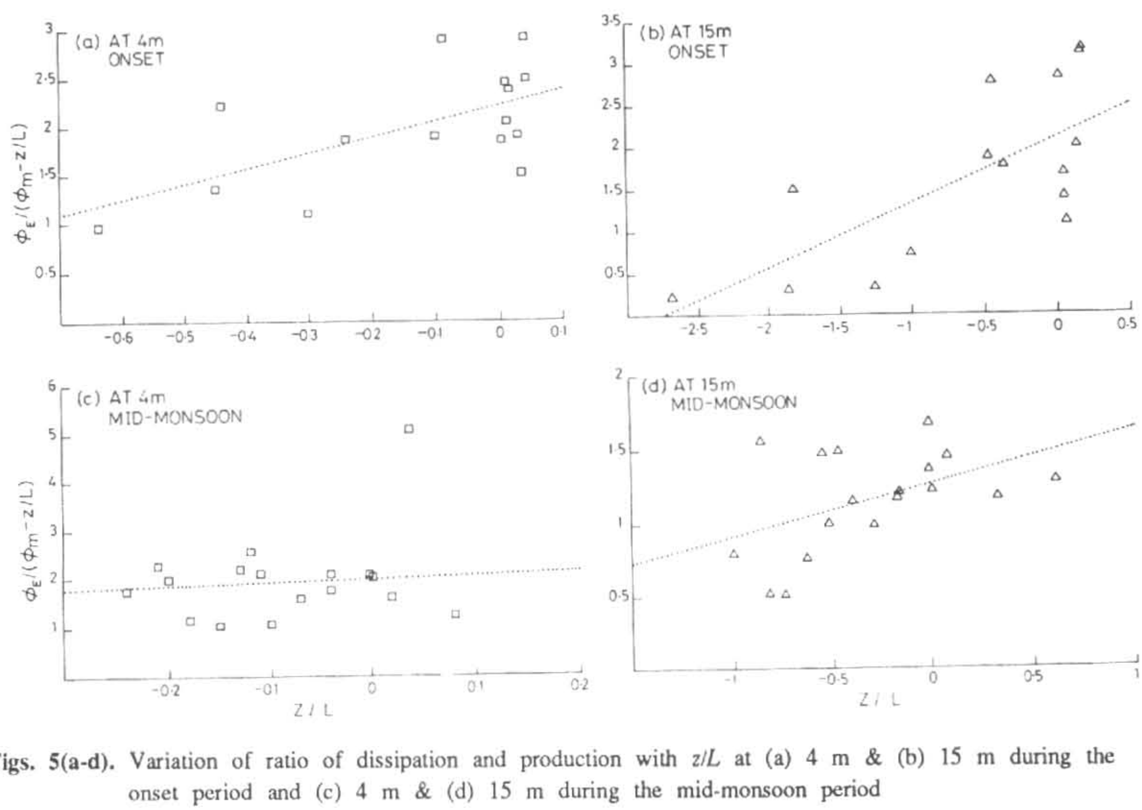
Figs. 3(a&b). Variation of turbulent energy transport with *z/L* for the (a) onset period and (b) mid-monsoon period

is positive for almost all unstable cases. The overall variation of wq^2/u_*^3 with stability seems to show almost the same trend as some other studies (Bradley *et al.* 1981, McBean and Elliott 1975). At 15 m turbulent energy flux does not show much variability with stability, whereas, at 4 m the variability is much more. The turbulent energy flux is positive for most of the unstable cases at the 15 m. At both levels the data exhibits a lot of scatter. This scatter is due to the fact that sometimes the contribution from the horizontal components add to that of the vertical component and sometimes subtract from it. The variation of turbulent energy flux during the mid monsoon period [Figs. 2(c&d)] is somewhat different. At the 4 m level the turbulent energy flux is negative under all stability conditions. The data shows a large amount of scatter. At the 15 m level, the turbulent energy flux is positive for almost all the stability conditions. The scatter in this case is less than that at 4 m. The contrasting behaviour at the two levels could be due to some advection from the surrounding areas.

The variation of transport of turbulent energy (ϕ_t) and vertical velocity variance (ϕ_{tw}) with stability have been plotted in Figs. 3 (a & b). The data shows a lot



Figs. 4(a-d). Variation of ϕ_E with z/L at (a) 4 m & (b) 15 m during the onset period and (c) 4 m & (d) 15 m during the mid-monsoon period



Figs. 5(a-d). Variation of ratio of dissipation and production with z/L at (a) 4 m & (b) 15 m during the onset period and (c) 4 m & (d) 15 m during the mid-monsoon period of scatter which precludes any similarity relationships. The scatter is probably due to the short averaging time and the approximations used in deriving the component. The scatter is also caused by the large uncertainty associated with third moments. The vertical component of turbulent transport shows less scatter as the effect of large scale eddies associated with horizontal components also contributes to the scatter in the total turbulent transport. This trend has been reported in other studies too (Bradley *et al.* 1981, Wyngaard and Cote 1971).

During the onset phase, the turbulent transport is negative under unstable conditions and tends to zero under neutral conditions. This implies a gain of turbulent energy from higher levels. The difference between ϕ_t and ϕ_{tw} is very less. During the mid monsoon phase, the scatter in ϕ_t is very large. The flux divergence is positive for all stability conditions, which signifies loss of turbulent energy to higher levels. In contrast to the onset phase, ϕ_t does not tend to zero under neutral conditions but has a value $\approx$ 0.3. Hogstrom (1990) reported a value of 0.25 under neutral conditions and attributed this to 'inactive turbulence' and suggested a modified similarity formulation for the neutral surface layer. Under unstable conditions, there is large difference between ϕ_t and ϕ_{tw} suggesting that most of the contribution is due to the horizontal components. As the instability increases the contribution from the smaller frequencies or large scale motion associated with horizontal components increases (McBean and Elliott 1975).

4.3. *Turbulent energy dissipation* (ϕ_ε)

The variation of ϕ_ε with stability has been compared with the results of Wyngaard and Cote (1971) which have been referred to as WC [Figs. 4(a-d)]. During the onset phase the deviation from WC increase with instability at the 4 m as well as at the 15 m level. The scatter is relatively less for the near neutral conditions. Overall the results for the onset phase give a low correlation of + 0.17 and + 0.26 with WC at 4 m and 15 m respectively. At both heights ϕ_ε tends to be close to the hypothetical value of 1 under neutral conditions. The trend is somewhat different during the mid-monsoon phase. The convergence to WC is quite close for moderately unstable conditions whereas, the deviations are more for the stable conditions. At the 15 m level ϕ_ε values from the present study tend to be lower than the WC values. The correlation with the WC values is 0.19 at 4 m and 0.34 at 15 m level. Under neutral conditions at 4 m as well as 15 m level, the normalized dissipation rates approach a value of 1.

4.4. *Turbulent energy balance*

The balance between turbulent energy production and dissipation for the onset and mid monsoon phase have been shown in [Figs. 5(a-d)]. During the onset period, at 4 m dissipation and production almost balance each other under unstable conditions. Therefore over this range, the turbulent transport and pressure term can be expected to balance each other. As the stability increases, dissipation tends to exceed production. This is more or less in accordance with the observations of Wyngaard & Cote (1971) and Caughey & Wyngaard (1979) whose results indicate an excess of dissipation over production under near neutral and moderately unstable conditions with a balance being reached with increasing instability. At the 15 m level the trend is similar with a balance between production and dissipation being achieved under moderately unstable conditions at $z/L \approx -1.5$. Dissipation exceeds production as stability increases. Under highly unstable conditions ϕ_ε tends to be less than production. A somewhat different trend is observed at the 4 m level during the mid-monsoon phase when dissipation almost always tends to exceed production. As even the turbulent transport term over the 4-15 m layer, indicates a loss during this period, it seems to signify an important role for the pressure transport term.

Hogstrom (1990) observed that dissipation exceeds production under near neutral conditions and attributed this to the fact that inactive turbulence is imported to the surface layer from the upper parts of the boundary layer by pressure transport and partly dissipated in the surface layer. McBean and Elliott (1975) found the pressure flux divergence to be larger (but opposite in sign) than the divergence of turbulent energy flux. At the 15 m level a balance between dissipation and production is achieved under moderately unstable conditions ($z/L \approx -1$). The excess of dissipation over production increases as stability increases.

5. Conclusions

Under unstable conditions, during all phases of the monsoon, the values of ϕ_n at the 15 m level, show closer convergence with the Businger-Dyer relation than at the 4 m level. Under stable conditions for all periods, the ϕ_m values show a much slower rate of increase with stability than that predicted by the Businger-Dyer relation. It thus appears that the Businger-Dyer relationships do not hold good under Indian monsoon conditions. The variation of ϕ_t with stability shows a lot of scatter which precludes any similarity relationship. During the onset phase, ϕ_t is negative under unstable conditions and tends to zero under neutral conditions. During the mid-monsoon phase ϕ_t is positive for all stability conditions and has a value = 0.3 under near neutral conditions. The ϕ_ε values have been compared with the results of Wyngaard and Cote (1971) or WC. During the onset phase, the deviations from WC increase with instability, whereas, for the mid-monsoon period, the deviations increase with stability. During both periods, under neutral conditions ϕ_ε is close to unity.

During the onset (4 m and 15 m) and the mid-monsoon (15 m) period, turbulent dissipation and production balance each other under moderately unstable conditions. Dissipation tends to exceed production with increase in stability. This is in accordance with results of studies conducted at extra-tropical sites. A somewhat different trend is observed at the 4 m level during the mid monsoon period, when, dissipation almost always tends to exceed production. There are certain inherent limitations in this study. The runs available for analysis were only of 15 min duration which may have introduced some inaccuracies in the results. ϕ_t was determined using two different instruments and direct measurements of ϕ_ε were not available.

Acknowledgement

The authors acknowledge Department of Science and Technology, Govt. of India, New Delhi for providing the MONTBLEX data.

References

Bradley, E.F., Antonia, R.A. and Chambers, A.J., 1981, "Turbulence Reynolds Number and the Turbulent Kinetic Energy Balance in the Atmospheric Surface Layer", *Bound. Layer Meteor.*, **21**, 183-197.

Brook, R.R., 1974, "A Study of Wind Structure in an Urban Environment", Met Study No. 27, Australian Government Publishing Service, Canberra.

Busch, N.E. and Panofsky, H.A., 1968, "Recent Spectra of Atmospheric Turbulence", *Quart. J. R. Met. Soc.*, **94**, 132-148.

Businger, J.A., Wyngaard, J.C., Izumi, Y. and Bradley, E.F., 1971, "Flux-Profile Relationships in the Atmospheric Surface Layer", *J. Atmos. Sci.*, **28**, 181-189.

Carl, D.M., Tarbell, T.C. and Panofsky, H.A., 1973, "Profiles of Wind and Temperatures from Towers over Homogeneous Terrain", *J. Atmos. Sci.*, **30**, 788-794.

Caughey, S.J. and Wyngaard, J.C., 1979, "The Turbulent Kinetic Energy Budget in Convective Conditions", *Quart. J. R. Met. Soc.*, **105**, 231-239.

Fichtl, G.H. and McVehil, G.E., 1970, "Longitudinal and Lateral Spectra of Turbulence in the Atmospheric Boundary Layer at the Kennedy Space Center", *J. Appl. Meteor*, **9**, 51-63.

Hess, G.D. and Panofsky, H.A., 1966, "The Budget of Turbulent Energy near the Ground", *Quart. J. R. Met. Soc.*, **92**, 277-280.

Hogstrom, U., 1990, "Analysis of Turbulence Structure in the Surface Layer with a Modified Similarity Formulation for Near Neutral Conditions", *J. Atmos. Sci.*, **47**, 1949-1972.

Korrell, A., Panofsky, H.A. and Rossi, R.J., 1982, "Wind Profiles at the Boulder Tower", *Bound. Layer Meteor.*, **22**, 297-312.

Lumley, J.L. and Panofsky, H.A., 1964, "The Structure of Atmospheric Turbulence", Interscience, New York, 239 p.

McBean, G.A. and Elliott, J.A., 1975, "The Vertical Transports of Kinetic Energy by Turbulence and Pressure in the Boundary Layer", *J. Atmos. Sci.*, **32**, 753-766.

Panofsky, H.A. and Dutton, J.A., 1984, Atmospheric Turbulence, Wiley, New York, 397 p.

Rudrakumar, S., Srinivasan, H.P., Srikrishna, R., Ameenullah, S. and Prabhu, A., 1991, "Available Tower Data from MONTBLEX 90", *IJ.S.C.*, **91**, MD1.

Wyngaard, J.C. and Cote, O.R., 1971, "The Budgets of Turbulent Kinetic Energy and Temperature Variance in the Surface Layer", *J. Atmos. Sci.*, **28**, 190-201.