The turbulence kinetic energy budget in convective conditions

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SUMMARY

Data from the 1973 Minnesota atmospheric boundary layer experiment are used to investigate details of the turbulence kinetic energy budget in convective conditions. Surface layer results are presented in nondimensional form and compared with conclusions from earlier Kansas data. Above the surface layer the terms are nondimensionalized using mixed layer similarity length and velocity scales and compared with indications from other recent experiments.

1. INTRODUCTION

The Minnesota atmospheric boundary layer experiment was carried out in late summer 1973 by the Meteorological Research Unit (MRU), RAF Cardington, in association with the Air Force Geophysics Laboratory (AFGL), Cambridge, Mass. The site chosen was at the southern edge of an extremely flat, square-mile section of farmland in northwestern Minnesota (48°34′N 96°51′W) and was surrounded by essentially featureless terrain for about 10 km. Measurements of vertical profiles of wind velocity and of transport of heat and momentum were made by AFGL from a 32 m tower. Simultaneous measurements of these parameters at five levels between 61 and 1219 m were made by the MRU, employing turbulence probes attached to the tethering cable of a large (1300 m³) kite balloon. Full details of measurement techniques and data reduction procedures can be found in the data report by Izumi and Caughey (1976). The results of an analysis of eleven seventy-five-minute runs in convective conditions have been reported by Kaimal et al. (1976) and by Caughey and Kaimal (1977). It is the purpose of this paper to investigate details of the turbulence kinetic energy budget using data from a selection of these runs.

A good deal of progress has been made in the specification of relative magnitudes (and dependence on stability) of some of the terms in the turbulence kinetic energy budget equation (see, e.g., Wyngaard and Coté 1971). These authors measured directly the production of turbulence energy by both wind shear and buoyancy, the vertical transport of turbulence, and the rate of dissipation. Thus the substantial residual (or imbalance) observed in their results can be attributed either to the vertical transport of pressure fluctuations (which was not measured) or to experimental difficulties such as horizontal inhomogeneity, although in view of the nature of the site this second possibility seems unlikely. Conclusions from more recent experiments have tended to confirm the existence of the imbalance quantity and have more closely identified this with pressure transport divergence (McBean and Elliott 1975; Champagne et al. 1977). Only a small number of attempts to measure the budget equation quantities above the surface layer have been reported. Instrumented aircraft have been used to estimate directly some of the terms, by,
e.g., Zubkovski and Koprov (1970) and Lenschow (1970, 1974). In all these studies the rate of dissipation of turbulence kinetic energy was estimated from the velocity component spectral densities in the inertial subrange rather than directly measured. Results from these experiments indicate substantial variations in the relative importance of the turbulence kinetic energy budget components through the boundary layer. Rayment (1973) has reported tethered balloon measurements of the turbulence dissipation rate ($\varepsilon$) to about 1 km altitude, although mixed layer and surface layer similarity scales are not available for these data. Rayment and Caughey (1977) have demonstrated that the relative magnitudes of the balance equation terms at 91 m are significantly different from those at the surface. The Minnesota data will be examined within the surface layer similarity framework for comparison with the Kansas experiment conclusions (Wyngaard and Coté 1971) and within the mixed layer similarity scheme to gain some insight into the behaviour of the balance equation terms through the boundary layer depth.

2. INSTRUMENTATION AND AVAILABLE DATA

Details of the instrumentation are given in the data report by Izumi and Caughey (1976) so only a brief outline is included here. The profile and turbulence sensors employed by AFGL were mounted on a 32 m tower. The balloon tethering point was about 90 m ESE of the tower. Two-axis sonic anemometers placed at 1, 2, 4, 8, 16 and 32 m on the tower were used for measuring horizontal winds whilst quartz crystal thermometers measured mean temperatures at 0.5 m in addition to the heights listed above. Wind component and temperature fluctuations were obtained with three-axis sonic anemometers at 4 and 32 m on the tower. Five MRU turbulence probes were employed for the balloon-borne measurements, distributed across a maximum height range from 61–1219 m. During all runs the sky was almost cloud-free with only occasional patches of cirrus visible around the horizon. Details of the runs considered here are listed in Table 1.

<table>
<thead>
<tr>
<th>Run</th>
<th>Date (Sept. 1973)</th>
<th>$z_i$ (m)</th>
<th>$w_e$ (m s$^{-1}$)</th>
<th>$u_e$ (m s$^{-1}$)</th>
<th>$-L$ (m)</th>
<th>Turbulence probe heights (m)</th>
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<tr>
<td>2A1</td>
<td>10</td>
<td>1250</td>
<td>2.00</td>
<td>0.45</td>
<td>41.7</td>
<td>61, 305, 610, 914, 1219</td>
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<tr>
<td>2A2</td>
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<td>1615</td>
<td>2.23</td>
<td>0.45</td>
<td>38.0</td>
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<tr>
<td>3A1</td>
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<td>2310</td>
<td>2.41</td>
<td>0.37</td>
<td>24.0</td>
<td>61, 152, 305, 457, 610</td>
</tr>
<tr>
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<td>11</td>
<td>2300</td>
<td>2.06</td>
<td>0.32</td>
<td>24.3</td>
<td>61, 152, 305, 457, 610</td>
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<tr>
<td>5A1</td>
<td>15</td>
<td>1085</td>
<td>1.35</td>
<td>0.18</td>
<td>7.1</td>
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</tr>
<tr>
<td>6A1</td>
<td>17</td>
<td>2095</td>
<td>2.43</td>
<td>0.24</td>
<td>5.7</td>
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<tr>
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<td>2035</td>
<td>2.21</td>
<td>0.23</td>
<td>6.4</td>
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<td>1.77</td>
<td>0.26</td>
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<td>7C1</td>
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<td>1020</td>
<td>1.95</td>
<td>0.28</td>
<td>8.8</td>
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<tr>
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<td>1140</td>
<td>1.89</td>
<td>0.30</td>
<td>13.1</td>
<td>61, 152, 305, 457, 610</td>
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<tr>
<td>7D1</td>
<td>19</td>
<td>1225</td>
<td>1.38</td>
<td>0.25</td>
<td>13.5</td>
<td>61, 152, 305, 457, 610</td>
</tr>
</tbody>
</table>

3. CHARACTERISTICS IN THE UNSTABLE SURFACE LAYER

Under the assumptions of horizontal homogeneity and zero mean vertical velocity the equation that describes the budget of turbulence kinetic energy is

$$\frac{\partial}{\partial t}(E) + u'u' \frac{\partial u'}{\partial z} + v'w' \frac{\partial v}{\partial z} \frac{1}{T'} w'T' + \left[ \frac{\partial}{\partial z} \left( \frac{1}{\rho} w' \rho' \right) + \frac{\partial}{\partial z} (w'E) \right] + \varepsilon = 0$$

(1)

where $u'$, $v'$, $w'$, $T'$ and $\rho'$ represent departures from the mean of longitudinal, lateral and
vertical components of air motion, of temperature, and of pressure, respectively; \( \rho \) is the air density; \( E \) represents the total turbulence kinetic energy, \( \frac{1}{2}(u'^{2} + v'^{2} + w'^{2}) \). Overbars represent time averages; \( \langle \bar{u}, \bar{v} \rangle \) are the mean longitudinal and lateral components of air motion; \( g \) is the acceleration due to gravity; and \( T \) the absolute temperature.

The parameter \( \varepsilon \) represents the rate of dissipation of turbulence kinetic energy to heat by viscous forces. Except during transitional periods in the turbulence regime, the local rate of change of turbulence energy \( \langle \partial E/\partial t \rangle \) is expected to be generally small compared with the other terms. This generally was the case in the Minnesota experiment, e.g. in runs 6B1 and 7D1 (which were closest to the evening transition to stable conditions) the time derivative terms at 4 m were of order \( 2 \times 10^{-4} \text{m}^2 \text{s}^{-3} \), considerably smaller than the other terms in Eq. (1). At higher levels in the boundary layer this term was more significant but still generally negligible compared with the others.

In the convective surface layer, wind shear plays an important role and the controlling parameters for turbulence in this region, under the Monin–Obukhov (M–O) similarity hypothesis, are the height, \( z \), \( \tau_0 \) (the surface stress, \( = -\rho \langle u' w' \rangle_0 \)), \( Q_0 \) (surface temperature flux, \( = \langle w'T' \rangle_0 \)) and the buoyancy parameter, \( g/T \). The scaling velocity is \( u_\ast \) \( (= (\tau_0 / \rho)^{\frac{1}{2}}) \) and dimensionless groups formed with these parameters are expected to be universal.

![Energy Balance Terms, z/L vs. z/L](image)

**Figure 1.** Nondimensionalized terms in the energy equation as functions of \( z/L \) in the unstable surface layer. The full line in the upper half of the figure represents buoyancy production \( (z/L) \).

- **Solid circles:** mechanical production, \( -\phi_m = (kz/\rho_u^2)u'w' \langle \partial \bar{u}/\partial z \rangle \).
- **Dashed line:** the Kansas \( \phi_m \) relation, \( \phi_m \approx (1 - 15z/L)^{-\frac{1}{2}} \).
- **Solid triangles:** turbulence transport, \( \phi_t = (kz/\rho_u^2) \partial \langle \frac{1}{2} w'(u'^{2} + v'^{2} + w'^{2}) \rangle / \partial z \), the full line through these data represents \( -z/L \).
- **Open circles:** dissipation rate, \( \phi_d = k \varepsilon / \rho_u^2 \), with the relation \( \phi_d = (1 + 0.75z/L)^{\frac{1}{2}} \) through the data.

The dash–dot line in the upper half of the figure represents the residual, identified here with the pressure transport term \( (kz/\rho_u^2) \partial \langle w'p'(\rho) \rangle / \partial z = \phi_p \).
functions of $z/L$, where $L$ is the Monin-Obukhov length, $= -Tu^3_*/(kgQ_o)$ ($k$ is von Kármán's constant). Following Wyngaard and Coté (1971) the terms in Eq. (1) may be nondimensionalized with the factor $kz/u^3_*$.

Terms 2 and 3 in Eq. (1) describe the production of turbulence energy through shearing forces with the second of these usually negligible in the surface layer. The normalized shear production thus reduces to

$$
(kz/u^3_*) w'w' \frac{\partial u}{\partial z} = -(kz/u^*_*^*) \frac{\partial u}{\partial z} = -\phi_m \sim -(1-15z/L)^{-4/3},
$$

where $\phi_m$ is the nondimensional wind shear (see, e.g., Businger et al. 1971). For consistency in applying this expression $k$ has been taken as 0.35 (for a recent discussion of possible forms of the $\phi_m$ relation and the sensitivity to the choice of $k$ see Yaglom, 1977). The stress value at 4 m has been used to calculate $u_*$ and, clearly, for the shear production term to normalize to $\phi_m$ at higher levels within the surface layer, the local stress, $-u'w'(z)$, must approximate $u^2_*$. This was true at 32 m in many of the Minnesota runs, but in others (i.e. 3A2, 6A1, 6A2, 6B1 and 7C1) the stresses at this level greatly exceeded those at 4 m (see Kaimal et al. 1976) and these data have been excluded from this analysis. Figure 1 shows good agreement between the present data and the $\phi_m$ curve based on the Kansas results (Businger et al. 1971). The buoyancy production term $(-g/\rho)w'T'$ normalizes simply to $\phi_b = z/L$ and is indicated by the solid line in the upper half of Fig. 1.

The dissipation rate, $\varepsilon$, was estimated from the inertial subrange level of the vertical velocity spectrum, with the universal constant, $a_\nu$, in the Kolmogorov expression for the one-dimensional horizontal wind speed spectrum, taken as 0.5. Wyngaard and Clifford (1977) have recently demonstrated that serious errors in high-frequency spectral properties may arise from a fluctuating convection velocity. Errors in $\varepsilon$ could in certain circumstances reach 15%; however for the present data this effect was calculated to be negligibly small. In normalized form the dissipation rate is represented by $\phi_\varepsilon$ and this shows a generally increasing value with increasing instability. A fairly good fit to the data is obtained with the relation $\phi_\varepsilon = (1 + 0.75^2 z/L)^{4/3}$, i.e. a somewhat higher value for the constant is required than the 0.5 determined from the Kansas data.

The turbulence transport term ($\phi_p$) was estimated from the total turbulence kinetic energy values available at 32 and 4 m. The gradient was estimated by simple differencing and the approximation assumed to apply at the mid-point in $z$, i.e. 18 m (this procedure differs insignificantly from fitting the data to ln $z$ and applying the gradient at the mid-point in ln $z$).

This term appears as a loss in the surface layer (see Fig. 1), indicating an export of turbulence energy out of the layer. In the range 0 < $z/L$ < 1 the data suggest $\phi_p \sim -z/L$, i.e. equal in magnitude to buoyancy production, which indicates that turbulence generated by buoyancy forces in the surface layer is transported out of this region and not dissipated locally. As neutral conditions are approached both turbulence transport and buoyancy production tend to become small, denoting a trend towards balance between mechanical production and dissipation. With increasing instability a large residual (imbalance) appears which probably reflects the importance of the unmeasured pressure transport term $(-kgQ_o^3/\rho_0) \frac{\partial (1/\rho)w'p'}{\partial z}$ in Eq. (1).

While pressure transport remains the least well-understood term in the turbulence energy budget, we can describe the broad features of its behaviour in the unstable surface layer. The covariance $w'p'$ vanishes at a rigid surface, but at a wavy water surface it can be positive (representing an energy flux from the waves to the air) or negative (energy flux from the air to the waves). The measurements of McBean and Elliott (1975) show that $\bar{w}'p'$ is negative just above a heated surface. These negative $\bar{w}'p'$ values are consistent with positive $p'$ in downdraughts, and negative $p'$ in updraughts. Their measurements were
at one height, 5.8 m, and they inferred the vertical gradient by assuming M–O similarity, plotting results from several runs against \( z/L \), and using the relationship \( \frac{\partial}{\partial z} (w'p') = \frac{1}{L} \frac{\partial (w'p')}{\partial (z/L)} \).

Their results indicate that \( w'p' \) becomes increasingly negative as \(-z/L\) increases, or that pressure transport is a gain in the unstable surface layer. The magnitude of this gain was not well determined due to scatter, but was of the order of the residual (imbalance) in our results.

Ascribing the total imbalance \( (\phi_p) \) to this term gives the following relations for the stability dependence of the budget equation components, for \( 0 < z < -L \):

\[
\begin{align*}
\phi_m &= (1 - 15z/L)^{-1} \\
\phi_b &= z/L \\
\phi_v &= -z/L \\
\phi_e &= (1 + 0.75|z/L|^{1/3})^{3/4} \\
\phi_p &= (1 - 15z/L)^{-1} - (1 + 0.75|z/L|^{1/3})^{3/4}.
\end{align*}
\]

For \( z > -L \) the turbulence transport term becomes less than \(-z/L\) with the implication that at these heights turbulence generated through buoyancy forces begins to be dissipated locally. The conclusions from Minnesota therefore generally confirm the Kansas results, although some revision of the value of the constant in the \( \phi_e \) expression seems necessary.

In concluding this section we mention some implications of the accumulating evidence (Lumley and Panofsky 1964; Busch 1973; Panofsky et al. 1977; Kaimal 1978) that horizontal wind fluctuations in the unstable surface layer do not follow M–O similarity. The data of Panofsky et al. (1977) support their hypothesis that \( u'^2 \) and \( v'^2 \) are instead influenced strongly by the large, convectively driven eddies which extend to the top of the PBL. They suggest that, as a result, the horizontal wind fluctuations in the very unstable surface layer scale with \( w_* = (|g|/T)Q_o z_i^{1/4} \), the velocity scale of these eddies \( z_i \) is the boundary layer depth.

Consider now the limiting case of free convection (zero mean wind). As pointed out by Businger (1973), within the surface layer there are local mean winds due to these large, convective eddies. These local mean winds would be expected to persist for periods of the order of \( z_i/w_* \), and cause local wind shears, local Reynolds stress, and therefore local production of turbulence kinetic energy. Since on the average there is zero stress and zero wind shear in this case, these local wind shears must be randomly oriented, and this 'production' is, of course, formally a part of the turbulence transport term. But since this 'production' depends on \( z_i \) and on the surface roughness length, \( z_0 \), it cannot be M–O similar. Furthermore, it seems likely that this will induce departures from M–O similarity in the pressure transport and dissipation terms as well. We would expect these departures to be larger (at fixed \( z/L \)) for cases with more intense large-scale convective eddies and larger local stresses; that is, for cases with larger \( w_* \) and \( z_0 \). Although at this point we cannot estimate quantitatively these departures, they are possible contributors to the observed variations from experiment to experiment in some of the M–O similarity functions in the turbulence energy budget.

4. Characteristics of the Mixed Layer

The mixed layer is considered as that region of the convective boundary layer in which the structure of turbulence is insensitive to the surface stress \( (\tau_0) \) and the height above the surface \( (z) \). The boundary layer depth, \( z_i \) (taken as the height of the lowest inversion base), emerges as a controlling parameter (Kaimal et al. 1976) so that the scaling
velocity for this layer is \( w_\ast = (z_i Q_0 g/T)^{1/4} \). Dimensionless groups formed with \( w_\ast \) and \( z_i \) are expected to be functions only of \( z/z_i \). All terms in the energy equation have therefore been nondimensionalized by \( w_\ast^2/z_i \).

Three of the eleven runs in convective conditions (2A1, 2A2 and 5A1) were found to exhibit marked directional wind shear, with changes in wind direction between the surface layer and centre region of the mixed layer of about +10° for runs 2A1 and 2A2 and −15° for run 5A1. The origin of this wind shear is unknown but may possibly be related to baroclinic effects. All other runs exhibit negligible wind shear in the mixed layer. However, since 6B1 and 7D1 occur near the evening transition when turbulence levels were changing, these runs have been excluded from the analysis. Additionally, examination of the profiles of the turbulence kinetic energy revealed a considerable degree of scatter in the data to the extent that estimation of the gradients was difficult. A simple differing scheme was therefore employed and the gradient assigned to the mean height. For runs 6A1 and 6A2 the scatter was such that extraction of the gradients was not considered meaningful. This scatter in the third moments most probably arises from inadequate averaging time, and this effect becomes more severe the higher the level (Wyngaard et al. 1974). It would

Figure 2. Components in the energy equation nondimensionalized with the mixed layer similarity scales \( w_\ast \) and \( z_i \), plotted against \( z/z_i \). The full lines are simply drawn through the data points.

- Stars: \( (-g/T)w^T \) \( z_i/w_\ast^2 \)
- Solid circles: \( \frac{\partial}{\partial z}(w \partial u/\partial z + v \partial w/\partial z) \) \( z_i/w_\ast^2 \)
- Solid triangles: \( \partial \{4w(u^2 + v^2 + w^2)\} \) \( z_i/w_\ast^2 \)
- Open circles: \( \varepsilon /w_\ast^2 \)
- Dashed line: Residual
appear that further improvements in the specification of third-moment behaviour will only result from spatial measurements over long distances, which should be free from diurnal trends that inevitably contaminate long-term fixed point measurements.

Shown in Fig. 2 are available data for runs with small wind shear in the mixed layer. Dissipation rate estimates fall off steadily with height to become generally less than $w_f^3/z_f$ above 0.1 $z_f$. The asymptotic surface layer prediction, written in mixed layer notation, is $\varepsilon z_f/w_f^3 \sim 0.66$, and this appears to fall near the lower bound to the data above about $\sim 0.2z_f$. Normalized shear production in these runs decreases rapidly with height becoming essentially negligible above $\sim 0.3z_f$. This occurs although stress values at the higher levels were of the same order as, and in some cases greater than, mean surface values. Only rather sketchy information exists on the behaviour of the turbulence transport term, which appears to decrease from about unity at $\sim 0.01z_f$ (i.e. in approximate balance with normalized buoyancy production) to become negative above $\sim 0.3z_f$. The change in sign at around this level in the convective boundary layer is supported by aircraft observations which show the crossover point varying between 0.2 and 0.5 $z_f$ (see, e.g., Lenschow 1974; Pennell and LeMone 1974). Normalized buoyancy production falls steadily with height and shows signs of becoming a loss in the region above 0.5-0.6 $z_f$.

Above about 0.2 $z_f$ the indications are that both turbulence transport and shear production are small and although the data exhibit significant scatter it would appear that the budget is imbalanced. It is considered unlikely that other factors such as advection, non-stationarity or other terms (ignored in Eq. (1)) could account for this. One possible explanation is, however, that the dissipation rates in this region are erroneously high. Approximate balance would be achieved with $\varepsilon z_f/w_f^3$ averaging $\sim 0.4$ to 0.5 in this region, rather than the $\sim 0.6$ to 1.0 range observed.

Consideration of the turbulence energy budget integrated over the planetary boundary layer (PBL) supports the possibility of erroneously high $\varepsilon$ values. The transport terms integrate to zero, and our results indicate that layer-integrated dissipation exceeds integrated buoyant production by roughly a factor of two. This difference, if real, would represent shear production, but in view of our results would have to occur above our measurement heights; furthermore, this shear-produced energy would have to be exported downwards to mid-regions, evidently by pressure transport. This situation seems unlikely. While there are yet no direct measurements of pressure transport above the surface layer, Deardorff’s (1974) 3-D model calculations do give some insight into its behaviour. His computational grid was fine enough to resolve most of the energy-containing range of turbulence in mid-regions of the PBL, so that his calculated $\overline{w'p'}$ profiles should be representative there. He found negative $\overline{w'p'}$ in mid-regions, with magnitudes decreasing with increasing $z/z_f$. This indicates that pressure transport is a loss in mid-regions, but its magnitude is small compared to dissipation. Thus these results do not support the notion that our substantial mid-region energy budget imbalance is due to gain from pressure transport.

Our dissipation rates aloft were inferred from the vertical velocity spectrum in the interval 0.1 to 1.0 Hz, which we assumed was in the inertial subrange (the spectral slope in this region was, to a good approximation, $-5/3$). Figure 3 indicates that these mid-layer $\varepsilon z_f/w_f^3$ values increase with $-z_f/L$, implying that the energy budget imbalance under very convective conditions is appreciable. (Note that runs 2A1, 2A2 and 5A1 have the smallest dimensionless dissipation rates although they possess significant mid-layer shear production.) This again suggests the possibility that our $\varepsilon$ values have systematic errors. Perhaps the $w$ spectrum in the range 0.1 to 1.0 Hz (wavelengths from 100 to 10 m for $\bar{a} = 10$ m s$^{-1}$) was not truly inertial because it was too near the spectral region directly influenced by the small-scale convective elements. This could lead to a stability-dependent error in $\varepsilon$ of the form suggested in Fig. 3. However, it should be emphasized that the Minnesota vertical velocity power
spectra do not exhibit any noticeable distortion in the resolved inertial subrange region
(private communication, J. C. Kaimal) and thus the above discussion must be regarded as
largely speculative. For the three runs (2A1, 2A2, 5A1) with significant directional wind
shear, the shear production term averages ≈ 30–50% of the mid-layer $\varepsilon$. These figures in-
dicate that shear production can be surprisingly large in mid-layer, even under convective
conditions.

5. Concluding Remarks

These results have shown that in the unstable surface layer all terms in the energy
budget are substantial. Turbulence kinetic energy generated through buoyancy forces is
transported out of the layer and the dissipation rate can be regarded as approximating the
sum of mechanical production and the residual, identified here with the unmeasured
pressure term. This partitioning appears to hold up to $\sim 0.02 z_i$. By $\sim 0.1 z_i$ all terms have
decreased substantially, more particularly the shear production which, generally speaking,
is now quite small. The relative magnitudes of the terms at this height relate quite well to
those found at 91 m ($\sim 0.1 z_i$) from the observations reported by Rayment and Caughey

Our results indicate the need for improved understanding of several aspects of the
turbulence energy budget in convective conditions. The possible dependence of the surface
layer energy budget on $z_i$ and $z_0$, and its implied departure from Monin–Obukhov similarity,
merit further study. Our finding that shear production can be large at mid-levels even in
very convective conditions, presumably because of baroclinic effects, points to the need
for further study of the structure of the baroclinic PBL. Additionally, our large values for
mid-region dissipation and the budget imbalance there suggest a need for further investiga-
tion. It would be very useful to be able to probe more deeply into the inertial subrange, and
to be able to measure pressure transport directly, above the surface layer in the convective
planetary boundary layer.

Further studies of the convective boundary layer are also required to add more detail
in the region above 0.5z, and in particular to investigate the influence of entrainment on the terms. It appears from the experience gained in Minnesota that 75-minute averaging periods, even in wind speeds of ~10 m s⁻¹ (equivalent to a spatial average over ~45 km) is insufficient to give stable estimates of the third moments at the higher levels in the boundary layer. Future experimental work should therefore involve the use of instrumented aircraft to record these quantities from long flight paths over uniform terrain, coupled with multilevel balloon (or tower) observations of the mean flow and lower-order moments.

REFERENCES


Rayment, R. 1973 An observational study of the vertical profile of the high frequency fluctuations of the wind in the atmospheric boundary layer, Boundary-Layer Met., 3, 284-300.


Wyngaard, J. C. and Coté, O. R. 1971 The budgets of turbulent kinetic energy and temperature variance in the atmospheric surface layer, Ibid., 28, 190-201.

