STREAMWISE HEAT FLUX BUDGET IN THE ATMOSPHERIC SURFACE LAYER

E. F. BRADLEY

CSIRO Division of Environmental Mechanics, Canberra, A.C.T., 2600, Australia

and

R. A. ANTONIA, A. J. CHAMBERS

Department of Mechanical Engineering, University of Newcastle, N.S.W., 2308, Australia

(Received 28 October, 1981)

Abstract. Atmospheric surface-layer measurements of terms in the equation for the streamwise heat flux confirm previous results in both laboratory and atmosphere that the temperature-pressure gradient correlation acts as a sink, approximately equal in magnitude to the production term. The measured viscous dissipation term is independent of stability and represents less than 10% of the production term over the range of experimental stability conditions. Models for the temperature-pressure gradient correlation are compared with the measurements.

1. Introduction

Budgets of the horizontal and normal heat fluxes and of the Reynolds shear stress have been measured in both the laboratory (e.g., Antonia and Danh, 1978) and atmospheric boundary layer (Wyngaard, Coté, and Izumi, 1971, hereinafter referred to as WCI). The measurements of Antonia and Danh (1978) were made downstream of a sudden increase in surface heat flux. Well downstream of the change, the temperature-pressure gradient correlation, obtained by difference, was effectively balanced by the terms representing the production of the thermometric heat flux $\overline{u\theta}$ and $\overline{w\theta}$ (u and w are velocity fluctuations in the streamwise and normal directions, respectively, θ is the temperature fluctuation). In the budget for the kinematic Reynolds shear stress $\overline{uw}$, the pressure-rate of strain correlation, also obtained by difference, was found to be approximately equal to the production term for $\overline{uw}$. Similar results were obtained for the budgets of $\overline{u\theta}$, $\overline{w\theta}$, and $\overline{uw}$ in a turbulent round jet (w is the radial velocity fluctuation for this particular flow) with a co-flowing external stream (Antonia and Prabhu, 1978). Both the boundary layer and jet were only slightly heated so that temperature acted as a passive marker of these flows. WCI measured budgets of $\overline{uw}$, $\overline{u\theta}$, and $\overline{w\theta}$ in the homogeneous atmospheric surface layer (Kansas experiment) over a wide range of stability conditions. They found that the flux divergence terms were small and, by invoking local isotropy to neglect the viscous 'dissipation' terms, inferred that the terms containing the pressure fluctuation were in balance with the production terms.

In this paper we focus our attention on the budget of $\overline{u\theta}$, primarily because direct measurements of part of the viscous dissipation term are available from experimental data obtained in the atmospheric surface layer (Bradley *et al.*, 1981a, hereinafter referred

Boundary Layer Meteorology **23** (1982) 3–15. 0006–8314/82/0231–0003$01.95.

to as I). The budget of $\overline{\theta^2}$, reported in I, indicated good balance between production and dissipation of $\overline{\theta^2}$ for near-neutral conditions. For moderately unstable conditions, however, the production was about 40% larger than the measured (isotropic) dissipation. Speculatively, it was suggested that the imbalance might be attributed to a slight inequality between $\overline{(\partial\theta/\partial x)^2}$, $\overline{(\partial\theta/\partial y)^2}$, and $\overline{(\partial\theta/\partial z)^2}$, although the turbulent Reynolds number and turbulent Péclet number were large enough to expect equality of these three quantities. The budget of $\overline{u\theta}$ provides, through the measurement of the correlation $\overline{(\partial u/\partial x)(\partial\theta/\partial x)}$ between velocity and temperature derivatives, another opportunity to check local isotropy. The transport or flux divergence term and the production terms are directly measured. The temperature-pressure gradient term, obtained by difference, is compared with models proposed by Donaldson (1973) and by Lumley and Khajeh-Nouri (1974).

2. Experimental Arrangement

A description of the site, instrumentation and experimental techniques has been given in I. The surface at the Bungendore (New South Wales, Australia) field site of the CSIRO Division of Environmental Mechanics consisted of a young wheat crop, about 0.12 m high. The fetch varied between 330 and 400 m for the wind direction sector (W–NW) used for the measurements.

The horizontal heat flux was measured at two heights (usually 2 and 4 m or 2.5 and 5 m) by two 3-axis sonic anemometers, each equipped with a 25 μm platinum wire thermometer. These anemometers were mounted on the same mast but on independent carriages so that their heights could be varied between 1.5 and 5.5 m†. The anemometers also provided measurements of $-\overline{uw}$ ($\equiv U_*^2$, where U_* is the friction velocity) and $\overline{w\theta}$ ($\equiv U_* T_*$, where T_* is the friction temperature). Values of $-\overline{uw}$ and $\overline{w\theta}$ were used in the determination of the Monin-Obukhov length L ($\equiv -TU_*^3/\kappa g\overline{w\theta}$, where T is the mean potential temperature of the air, g is the acceleration due to gravity and κ is the von Kármán constant, here taken equal to 0.4).

Vertical gradients of the horizontal wind speed U and temperature T, required for the production terms, were measured using miniature cup anemometers and aspirated wet and dry bulk platinum resistance thermometers mounted on a mast set 15 m to the north of the sonics mast.

The velocity and temperature derivatives, required for the dissipation term, were obtained using a pair of vertical wires (Wollaston, 90% Pt–10% Rh) set about 1 mm apart. The hot wire (2.5 μm diam, 0.8 mm length) and cold wire (0.6 μm diam, 0.8 mm length) were mounted at a height of 4 m on a mast set 5 m to the south of the sonics mast. The hot wire was operated by a DISA 55M10 constant temperature anemometer while the cold wire was operated with a constant current circuit at a current of 0.1 mA. The frequency response (−3 dB) of the 0.6 μm wire was estimated to be approximately 3 kHz at 6 m s^{-1}. The maximum Kolmogorov frequency f_K ($\equiv U/2\pi\eta$, where η is the Kolmo-

† This height was sufficiently smaller than the fetch to avoid any upwind inhomogeneity.

gorov microscale) corresponding to this speed was about 2.7 kHz so that the frequency response of the wire was judged to be adequate to cover the experimental frequency range of interest. As the lengths of the wires were comparable with η, no wire length correction was applied.

Signals from the sonic anemometers were filtered at 5 Hz and recorded digitally on magnetic tape at 15 Hz. The signals were subsequently analysed to determine various statistics of u, w, and θ and, in particular, the momentum and heat fluxes in the triple moment $\overline{uw\theta}$ required to determine the dominant transport term in the $\overline{u\theta}$ budget. Fluctuating wire voltages and their derivatives were recorded on a four-track FM tape recorder (HP2960A) at a speed of 381 mm s^{-1}. These voltages were subsequently digitized for processing at $2f_K$, after low-pass filtering with cut-off set at f_K (in the range 0.6–2.7 kHz). A record duration of 15 min was used in the reduction of signals from both sonic and wire anemometers.

3. Heat Flux Budget: Results and Discussion

The transport equation for $\overline{\theta u_i}$ can be written (e.g., Corrsin, 1953) for a rectangular Cartesian co-ordinate system as

$$\frac{\partial \overline{\theta u_i}}{\partial t} + U_k \frac{\partial}{\partial x_k} (\overline{\theta u_i}) = - \overline{u_i u_k} \frac{\partial T}{\partial x_k} - \overline{\theta u_k} \frac{\partial U_i}{\partial x_k} - \frac{\partial}{\partial x_k} (\overline{u_k \theta u_i})$$
$$- \overline{\theta \frac{\partial p}{\partial x_i}} + \overline{\alpha u_i \nabla^2 \theta} + \overline{\nu \theta \nabla^2 u_i} \tag{1}$$

where U_i and u_i are the mean and fluctuating velocities, respectively, and p is the kinematic pressure fluctuation. The last two terms on the right of (1) may be approximated, if it is assumed that the kinematic viscosity ν and thermal diffusivity α are equal (viz., the Prandtl number $Pr = \nu/\alpha = 1$), by

$$\overline{\alpha u_i \nabla^2 \theta} + \overline{\nu \theta \nabla^2 u_i} = -2\nu \overline{\frac{\partial \theta}{\partial x_k} \frac{\partial u_i}{\partial x_k}} + \nu \frac{\partial^2}{\partial x_k^2} \overline{\theta u_i}\,. \tag{2}$$

Under stationary conditions and with the assumption of horizontal homogeneity, (1) can be simplified when $i = 1$ (streamwise direction; the subscript notation is dropped and, as is common, u_i and x_i are replaced by their components u, v, w, and x, y, z) to

$$\overline{w\theta} \frac{\partial U}{\partial z} + \overline{uw} \frac{\partial T}{\partial z} + \frac{\partial}{\partial z} (\overline{uw\theta}) + \overline{\theta \frac{\partial p}{\partial x}} + 2\nu \overline{\frac{\partial \theta}{\partial x_k} \frac{\partial u}{\partial x_k}} = 0\,. \tag{3}$$

The second term on the right of (2) is expected to be negligible, in comparison with the first two terms in (3), partly because of the large Reynolds number in the atmospheric surface layer and because no systematic variation of $\overline{u\theta}$ with height was detected in the present experiment. The first term on the right of (2) can only be neglected if local isotropy is involved since the vector $\overline{(\partial\theta/\partial x_k)(\partial u_i/\partial x_k)}$ would then be zero†. This term has been retained here since we have an opportunity to measure the x component of this vector and compare it with its locally isotropic value. When (3) is multiplied by $\kappa z/U_*^2 T_*$,

$$\phi_M - \phi_H + \frac{\kappa z}{U_*^2 T_*}\frac{\partial}{\partial z}(\overline{uw\theta}) + \frac{\kappa z}{U_*^2 T_*}\overline{\theta\frac{\partial p}{\partial x}} + \frac{2\nu\kappa z}{U_*^2 T_*}\overline{\frac{\partial\theta}{\partial x_k}\frac{\partial u}{\partial x_k}} = 0 \tag{4}$$

where $\phi_M \equiv (\kappa z/U_*)(\partial U/\partial z)$ is the dimensionless wind shear and $\phi_H \equiv (\kappa z/T_*)(\partial T/\partial z)$ is the dimensionless temperature gradient. The distributions of ϕ_H and ϕ_M, as a function of z/L, were found (Bradley *et al.*, 1981a, b) from the least-square fits to the present data ($z/L \le 0$):

$$\phi_M = 1.06(1 - 15z/L)^{-1/4} \tag{5}$$

and

$$\phi_H = -1.04(1 - 9z/L)^{-1/2}\,. \tag{6}$$

The stratification and shear production terms $-\phi_H$ and ϕ_M are of the same sign and their ratio $-\phi_H/\phi_M$ can be identified with the turbulent Prandtl number, here equal to 0.98 when $z/L = 0$. Note that ϕ_M, as given by (5), differs only slightly from the expression of WCI, who used a value of unity for the constant outside the circular brackets. However, they found a value of 0.74 instead of 1.04 for the corresponding constant in (6).

The turbulent transport term was calculated from the measured values of $\overline{uw\theta}$ at the two sonic heights, z_1 and z_2, with the logarithmic approximation used by Wyngaard *et al.* (1974), viz.,

$$\frac{\kappa z}{U_*^2 T_*}\frac{\partial}{\partial z}(\overline{uw\theta}) = \frac{\kappa}{U_*^2 T_*}\,\frac{(\overline{uw\theta})_{z_2} - (\overline{uw\theta})_{z_1}}{\ln\dfrac{z_1}{z_2}}\,, \tag{7}$$

the value of the derivative being taken at the geometric mean height $(z_1 z_2)^{1/2}$.

Values of the transport term are shown in Figure 1. It appears that in the moderately unstable region, the term is slightly positive. Bearing in mind the sign convention used here, this represents a gain. With approach to neutrality, however, transport appears to become a loss. WCI found essentially the same behaviour, although their crossover occurred around $-z/L = 0.3$, whereas in the present data it occurs closer to $-z/L = 0.1$. Scatter is large in both sets of data, but both would support an estimate of $(\kappa z/U_*^2 T_*)\,\partial(\overline{uw\theta})/\partial z$ of between 0.1 and 0.2 for $-z/L > 0.1$, and thus a small fraction of the $\overline{u\theta}$ budget for moderately unstable conditions. The gradient production terms ϕ_M and $-\phi_H$ are shown in Figure 1 as functions of z/L for comparison.

Some indication of the reliability of the data in Figure 1 may be gained from measurements obtained in the series of 'comparison' runs in which the two sonics were set at

† While the expectation that $\partial^2\overline{\theta u_i}/\partial x_k^2$ is negligible seems reasonable (the measurement of this term would be subject to relatively large experimental uncertainty), the assumption of local isotropy is worth testing for reasons given later in this section.

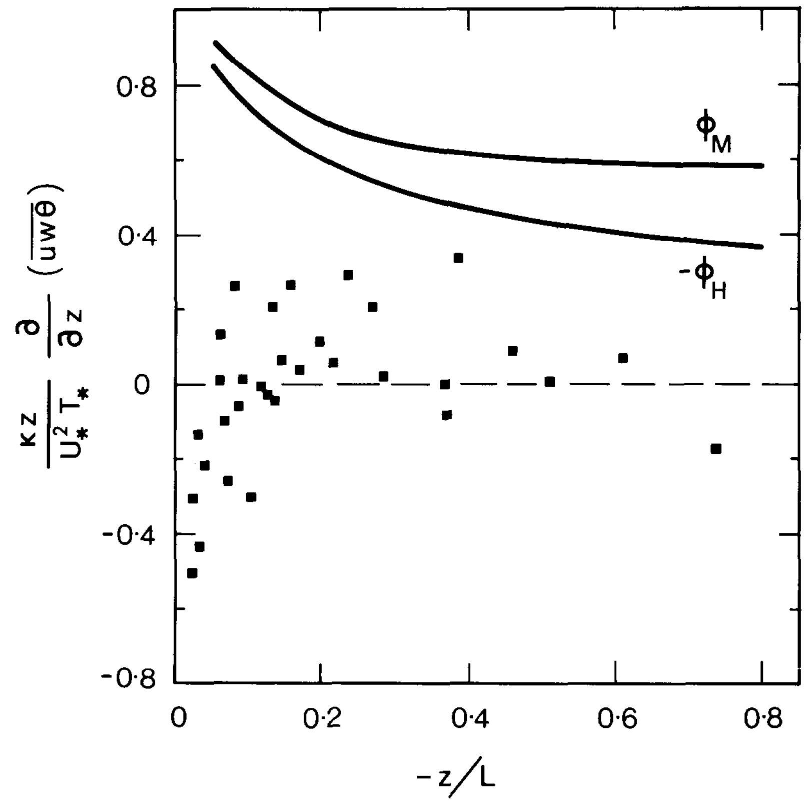

Fig. 1. Dimensionless turbulent transport term in $\overline{u\theta}$ budget. Wind shear and stratification production rates are shown for comparison.

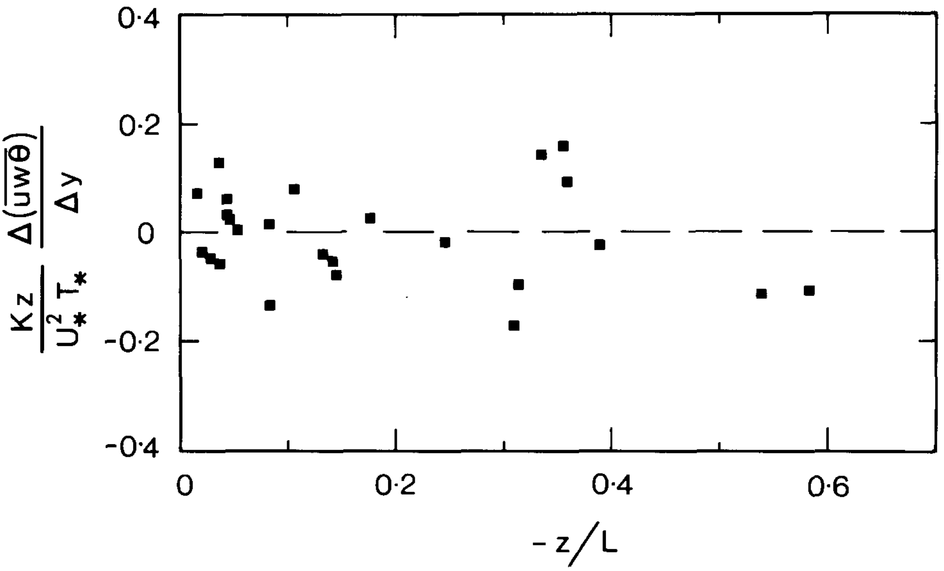

Fig. 2. Comparison, in similar terms to Figure 1, of the difference between $\overline{uw\theta}$ measured by two sonic anemometers set 5 m crosswind at 3 m height.

the same height, 3 m, and separated by 5 m crosswind. (Other results from this 'comparison' series are given in Bradley *et al.*, 1981a, b and in Antonia *et al.*, 1981). For proper comparison with the divergence data of Figure 1, taking account of the possible effect of scaling parameters, we present in Figure 2 values of $(\kappa z/U_*^2 T_*)\Delta(\overline{uw\theta})/\Delta y$, where $\Delta(\overline{uw\theta})$ is the difference between the values of this triple moment given by the two instruments (always in the same order) and Δy, their crosswind separation. Neither systematic difference nor stability dependence is evident, confirming that the divergences indicated in Figure 1 have a geophysical rather than instrumental origin.

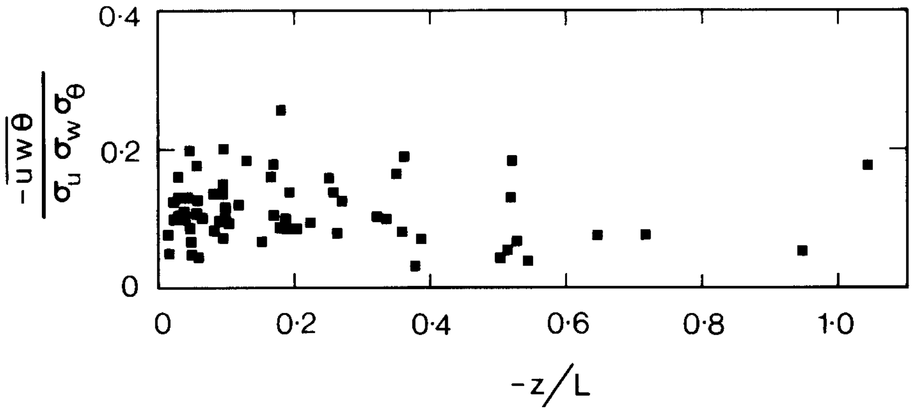

Fig. 3. Third-order moment $\overline{uw\theta}$ normalized by standard deviations of individual fluctuations.

The average value of $\overline{uw\theta}/\sigma_u\sigma_w\sigma_\theta$ (Figure 3), where σ_α denotes the standard deviation of the fluctuation α, is approximately -0.10 (WCI indicate a value of -0.15 as representative of moderately unstable conditions). This value is considerably smaller than the upper bound given by extending Schwarz's inequality to third-order moments (e.g., André *et al.*, 1976). WCI have already pointed out that, under moderately unstable conditions, $\overline{w^2\theta}$ is only about 20% of its maximum value; tighter bounds for $\overline{w^2\theta}$ may be found using inequalities derived by Lumley (1974).

The viscous term in (3), which is zero by local isotropy, can be re-written as $6\nu\overline{(\partial\theta/\partial x)(\partial u/\partial x)}$ if we make the (perhaps crude) assumption that

$$\overline{\frac{\partial u}{\partial x}\frac{\partial \theta}{\partial x}} \simeq \overline{\frac{\partial u}{\partial y}\frac{\partial \theta}{\partial y}} \simeq \overline{\frac{\partial u}{\partial z}\frac{\partial \theta}{\partial z}}. \tag{8}$$

Strictly, each term in (8) is zero by local isotropy but (8) allows an estimate of the departure from local isotropy to be made. The viscous term can be re-written

$$6\,\frac{\kappa z \nu}{U_*^2 T_*}\,\overline{\frac{\partial u}{\partial x}\frac{\partial \theta}{\partial x}} = \frac{6}{(45)^{1/2}}\,R\left(\frac{\kappa z \varepsilon}{U_*^3}\right)^{1/2}\left(\frac{\kappa z N}{U_* T_*^2}\right)^{1/2}\left(\frac{\nu}{\alpha}\right)^{1/2}, \tag{9}$$

where the correlation coefficient R is defined by

$$R = \frac{\overline{(\partial u/\partial x)(\partial \theta/\partial x)}}{\left[\overline{(\partial u/\partial x)^2}\;\overline{(\partial \theta/\partial x)^2}\right]^{1/2}}$$

and $\overline{(\partial u/\partial x)^2}$ and $\overline{(\partial\theta/\partial x)^2}$ in (9) have been replaced by their isotropic values, i.e.,

$$\overline{\left(\frac{\partial u}{\partial x}\right)^2} = \frac{\varepsilon}{15\nu}$$

and

$$\overline{\left(\frac{\partial \theta}{\partial x}\right)^2} = \frac{N}{3\alpha},$$

where ε and N, the averaged dissipations of the turbulent kinetic energy per unit mass and of $\overline{\theta^2}$, can be calculated using local isotropy. We assume equality of ν and α for consistency with approximation (2). Measurements of the relative magnitude of terms of the turbulent kinetic energy budget (Bradley *et al.*, 1981b) indicated local balance between ε and production over the range $0 < -z/L < 0.4$, viz., $\kappa z\varepsilon/U_*^3 \simeq \phi_M - z/L$. Measurements in *I* of the $\overline{\theta^2}$ budget indicated that $-\phi_H \simeq 1.4(\kappa zN/U_*T_*^2)$ over the range of moderately unstable conditions. Since the magnitudes of the terms involving ε and N on the right of (9) are of order unity and therefore comparable with the magnitude of the production terms in (3), the magnitude of R is a good indicator of the left side of (9).

The correlation coefficient R has been calculated for a number of runs over the available stability range in which the hot and cold wires were about 1 mm apart†. The results, Figure 4, indicate that R is negative and approximately independent of z/L. Although the magnitude of R is small, it is not negligible, as local isotropy would imply.

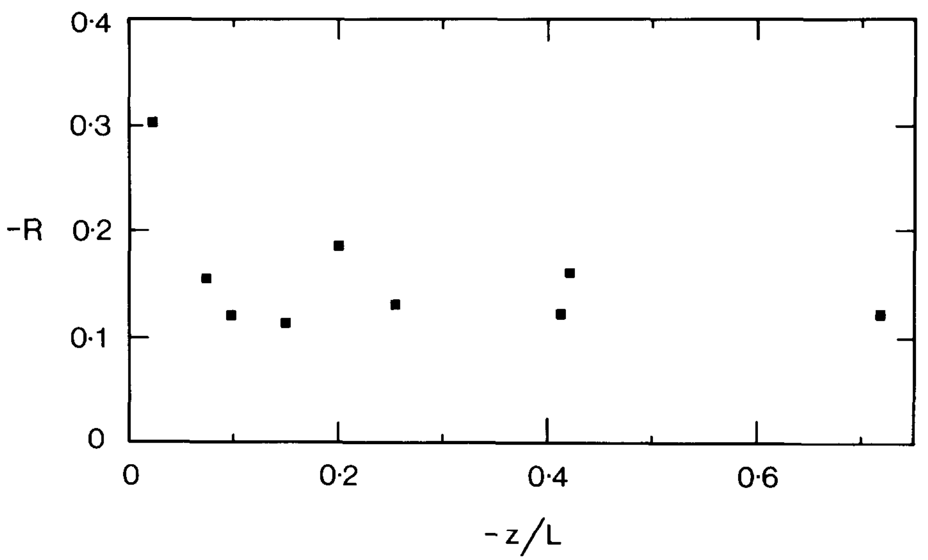

Fig. 4. Correlation coefficient R between velocity and temperature derivatives (see Equation 9).

† The contamination of the hot-wire signal by temperature was removed using the procedure outlined by Antonia *et al.* (1975).

Its non-zero value may reflect a departure from isotropy of the fine structure of the velocity and temperature fields. A more likely possibility is that the ramp structure of temperature (Antonia *et al.*, 1979a) with its associated, though less distinct and inverted, longitudinal velocity ramp (e.g., Phong-anant *et al.*, 1980) may contribute to the non-zero value of the correlation. The contribution would be primarily the result of the instantaneously large (and negative) correlation that would occur at the upwind end of the ramp; the sudden decrease in θ is accompanied by a relatively less sudden increase in u.

From the measurements of Tavoularis and Corrsin (1981a, b) in a quasi-homogeneous turbulent shear flow with a uniform mean temperature gradient, a value of about 0.21‡ can be inferred for the magnitude of the correlation coefficient between $\partial w/\partial x$ and $\partial\theta/\partial x$. However, these authors indicated that in their experiment neither the velocity nor the temperature field was locally isotropic, possibly because of insufficiently large turbulent Reynolds and Péclet numbers. The present atmospheric experiments do not suffer from this limitation (the turbulent Reynolds number for the data in Figure 4 falls in the range 2000–8000) and the non-zero value of R cannot be explained in this fashion. Although the velocity-temperature ramp model seems a plausible explanation, direct confirmation

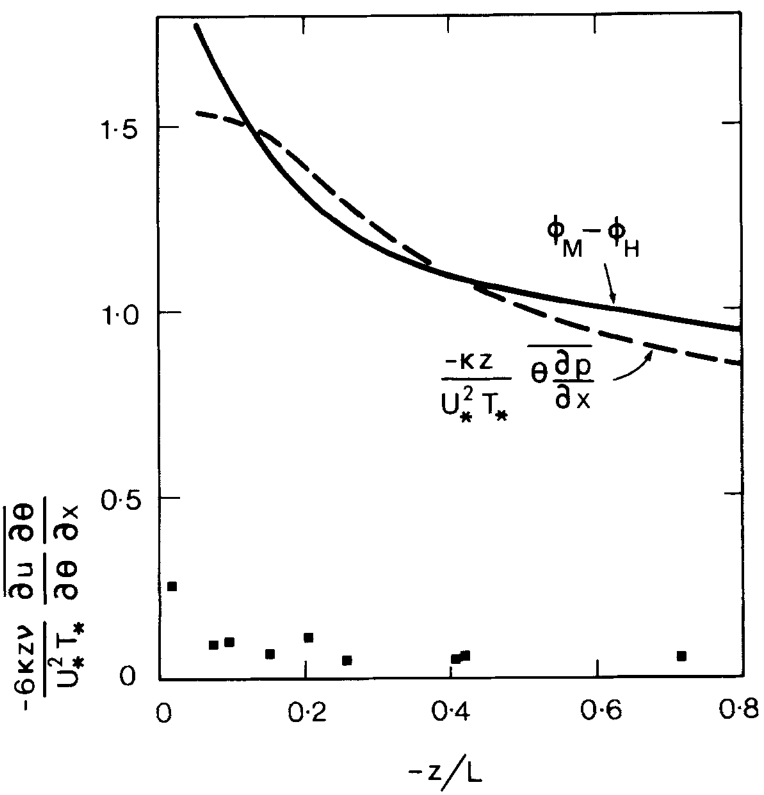

Fig. 5. Total production, viscous dissipation and temperature-pressure gradient terms in $\overline{u\theta}$ budget.

‡ The measured values of $\overline{(\partial w/\partial x)^2}$ and $\overline{(\partial\theta/\partial x)^2}$ were used for this estimate.

of local isotropy, perhaps by high-pass filtering the derivative signals (e.g., Antonia *et al.*, 1979b), would be desirable.

The magnitude of the viscous term, obtained from (9) using isotropic estimates for ε and N, is small (Figure 5) and approximately independent of z/L. Its average value is about 0.08, which represents about 5% of the production term $(\phi_M - \phi_H)$ at $-z/L = 0.1$. The temperature-pressure gradient term shown in Figure 5 was obtained (by difference) after assuming a constant value (0.08) for the viscous dissipation and allowing approximately for the stability variation of the transport term (Figure 1).

4. Comparison with Models

It is of interest to compare the resulting temperature-pressure gradient term with models for this term that have been proposed and used in calculations of turbulent shear flows. Donaldson (1973) assumed that

$$\overline{p\frac{\partial\theta}{\partial x}} = -\frac{\overline{q^2}^{1/2}}{\Lambda}\overline{u\theta} \tag{10}$$

where $\overline{q^2} = \overline{u^2} + \overline{v^2} + \overline{w^2}$ and Λ is related to an integral length scale of the turbulence. With the assumption that $\overline{p\partial\theta/\partial x} \simeq -\overline{\theta\partial p/\partial x}$ in conditions of spatial surface homogeneity and using experimental values for $(\overline{q^2})^{1/2}$ and $\overline{u\theta}$, a distribution of Λ/z can be

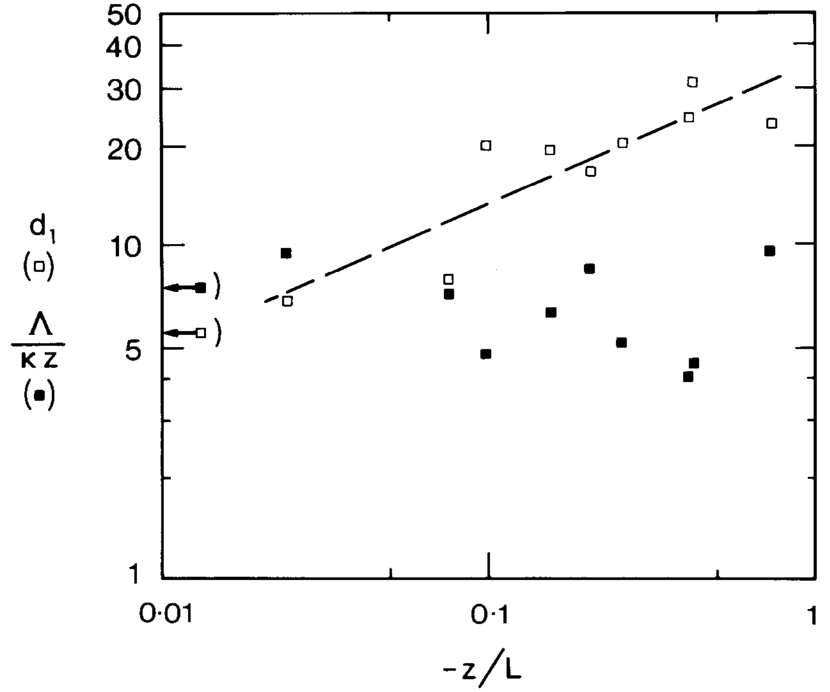

Fig. 6. Dimensionless scaling parameters $\Lambda/\kappa z$ and d_1 used in models of the temperature-pressure gradient correlations. Arrows indicate the approach-to-neutral values of both parameters. The broken line is a least-squares fit to the d_1 data.

obtained. Values of $\Lambda/\kappa z$, shown in Figure 6, indicate approximate independence on $-z/L$, with an average value of about 7. For comparison, the $\overline{u\theta}$ budget measured by Antonia and Danh (1978) in a turbulent boundary layer well downstream of a sudden increase in surface heat flux indicated that $\Lambda \simeq 2\kappa z$. The difference between laboratory and atmospheric values of $\Lambda/\kappa z$, derived from (10), may be partly attributed to different values of the structure parameter $a_1 = U_*^2/\overline{q^2}$ (see below) and of the ratio $-\overline{u\theta}/\overline{w\theta}$ ($\equiv -\overline{u\theta}/U_*T_*$) between these two flows.

The laboratory measurements indicated a value of about 1.5 for $-\overline{u\theta}/\overline{w\theta}$ in the logarithmic region. Figure 7 illustrates its variation with stability for the present experiment. The strong increase of $-\overline{u\theta}/\overline{w\theta}$ with the approach to neutrality was noted by Wesely *et al.* (1970) and by WCI, whose empirical fit to the Kansas data is shown on the figure. WCI suggest a near-neutral value of $-\overline{u\theta}/\overline{w\theta} \approx 3$, whereas the considerably larger number of near-neutral runs by Wesely *et al.* (1970) and in the present data, while scattered, indicate a value between 4 and 5 as $-z/L \to 0$.

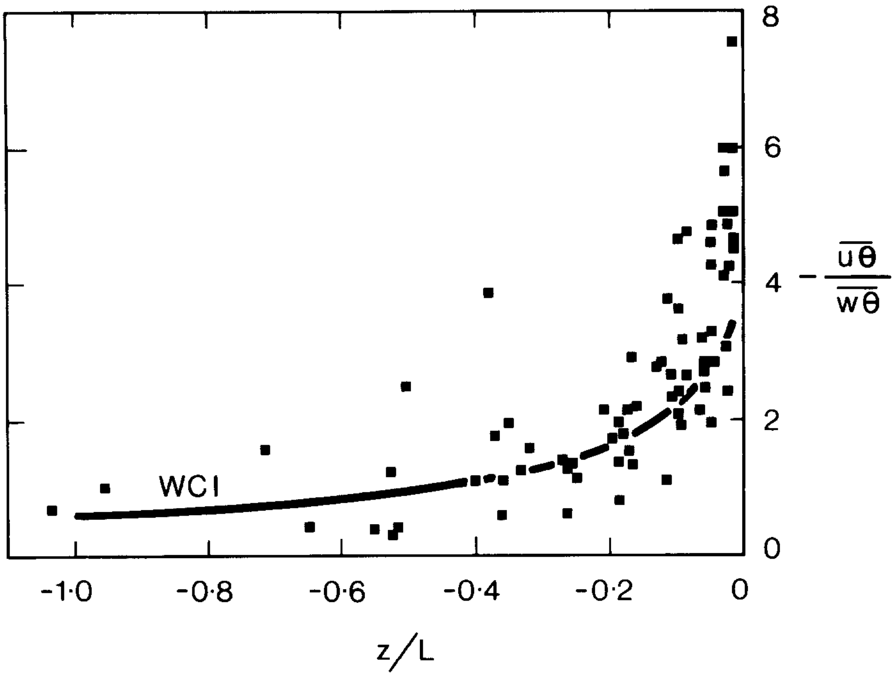

Fig. 7. Ratio of streamwise and vertical components of heat flux. The empirical distribution of WCI is also shown.

Wyngaard *et al.* (1974) applied the closure techniques of Lumley and Khajeh-Nouri (1974) to model the atmospheric boundary layer. In particular, $\overline{\theta \partial p/\partial x}$ was approximated by

$$\overline{\theta \frac{\partial p}{\partial x}} = d_1 \frac{\overline{\theta u}}{\tau} \tag{11}$$

where $\tau \equiv \overline{q^2}/\varepsilon$ is a turbulence relaxation time (or life-time of the energy-containing eddies) actually set by the model, which includes equations for $\overline{q^2}$ and ε. (Note that τ could also be identified with a life-time of temperature fluctuations such as that given by the ratio $\overline{\theta^2}/N)$†. Wyngaard *et al.* (1974) set the value of d_1 by requiring their model to reproduce the observed structure of the surface layer when z approaches, but remains larger than, the roughness length z_0. For $z/L \to 0$, they took values $\phi_M \to 1$, $-\phi_H \to 0.74$, $\overline{q^2}/U_*^2 \to 7.5$, $-\overline{\theta u}/U_* T_* \to 3$ and $\varepsilon\kappa z/U_*^3 \to 1$, resulting in a value for d_1 of 4.4. For the present experiments as $z/L \to 0$, $\phi_M \simeq \varepsilon\kappa z/U_*^3 \to 1.06$, $-\phi_H \to 1.04$ and $-\overline{\theta u}/U_* T_* \to 4.5$. The near-neutral value of $\overline{q^2}/U_*^2$ is approximately 12.5, implying a value for a_1 of 0.08 in agreement with results by Bradley and Antonia (1979) obtained from atmospheric surface layer data over both land and ocean. The resulting value of d_1 is 5.5 (similarly $\Lambda/\kappa z = 7.6$ as $z/L \to 0$). Launder's (1978) tabulated values of d_1‡, obtained for both laboratory and atmospheric flows, fall in the range 5–10. The measurements of Antonia and Danh (1978) indicate a value for d_1 of about 8.

Values of d_1 calculated directly from (11), using experimental values of ε, are also shown in Figure 6 with the near-neutral value as derived above. Clearly, d_1 increases significantly with increasing instability, a behaviour which is consistent with the dependence of a_1 on z/L since (10) and (11) yield

$$d_1 = \frac{1}{7}\,\frac{U_*^3}{\kappa z \varepsilon}\,a_1^{-3/2}$$

where the numerical factor is the average value of the ratio $\Lambda/\kappa z$ (Figure 6). The increase of d_1 with $-z/L$ reflects mainly the decreases (Bradley and Antonia, 1979) of a_1 with $-z/L$ since the ratio $\kappa z \varepsilon/U_*^3$ does not vary significantly with $-z/L$ (Bradley *et al.*, 1981b). The stability dependence of d_1 should be included in any calculation of the turbulent boundary layer in which the temperature-pressure gradient correlation is modelled according to (11). It should, however, be noted that although (11) or (10) only account for the contribution of what has been called 'turbulence interactions' to the temperature-pressure gradient correlation, pressure fluctuations may also arise from mean strain and gravitational effects. Gibson and Launder (1978) noted that it is the ground effect, or modification of the fluctuating pressure field by the presence of the surface, that is responsible for the qualitatively different effects of buoyancy observed in the earth's boundary layer and in turbulent free shear flows.

5. Concluding Remarks

Production, transport and dissipation terms in the budget for the streamwise heat flux have been estimated experimentally after making a number of simplifying assumptions.

† In this connection, these time scales were incorrectly defined (inverted) in the nomenclature to I, which led to an error in Equation (20) of Antonia *et al.* (1981). This did not affect the results or conclusions in that paper, but the authors regret any confusion which may have resulted.

‡ Note that Launder defines τ as $\overline{q^2}/2\varepsilon$ instead of $\overline{q^2}/\varepsilon$.

The transport term indicates a loss as neutral conditions are approached but a gain when $-z/L$ is greater than about 0.1. This trend is similar to that obtained by WCI for the Kansas experiment. The magnitude of the transport term for both the present and Kansas experiments is small compared with that of the total production. The viscous dissipation estimate provided in the paper can at best be regarded as a rough test for local isotropy. The magnitude of this estimate is such that approximate equality between total production and the temperature-pressure gradient correlation must be considered reasonable. Use of Equation (10) to model this latter correlation suggests a constant value of the ratio $\Lambda/\kappa z$, independent of stability. In contrast, the use of Equation (11) yields a significant stability variation for the dimensionless parameter d_1. Such variation should be included in computer models of the temperature-pressure gradient correlation.

Acknowledgements

The authors thank Dr S. Rajagopalan and Messrs A. J. Bryan and B. R. Satyaprakash, who assisted with the experiment and reduction of data. They are also grateful to Drs M. R. Raupach and J. Finnigan for their comments on the manuscript. R. A. A. and A. J. C. gratefully acknowledge the support of the Australian Research Grants Committee.

References

André, J. C., De Moor, G., Lacarrère, P., and du Vachat, R.: 1976, 'Turbulence Approximation for Inhomogeneous Flows: Part I. The Clipping Approximation', *J. Atmos. Sci.* **33**, 476–481.

Antonia, R. A. and Danh, H. Q.: 1978, 'A Local Similarity Model for the Heat Flux Equation in a Turbulent Boundary Layer', *Int. J. Heat Mass Transfer* **21**, 1002–1005.

Antonia, R. A., Prabhu, A., and Stephenson, S. E.: 1975, 'Conditionally Sampled Measurements in a Heated Turbulent Jet', *J. Fluid Mech.* **72**, 455–480.

Antonia, R. A., Chambers, A. J., and Bradley, E. F.: 1981, 'Temperature Structure in the Atmospheric Surface Layer. II. The Budget of Mean Cube Fluctuations', *Boundary-Layer Meteorol.* **20**, 293–307.

Antonia, R. A., Chambers, A. J., Friehe, C. A., and Van Atta, C. W.: 1979a, 'Temperature Ramps in the Atmospheric Surface Layer', *J. Atmos. Sci.* **36**, 99–108.

Antonia, R. A., Chambers, A. J., Phong-anant, D., and Rajagopalan, S.: 1979b, 'Properties of Spatial Temperature Derivatives in the Atmospheric Surface Layer', *Boundary-Layer Meteorol.* **17**, 101–118.

Bradley, E. F. and Antonia, R. A.: 1979, 'Structure Parameters in the Atmospheric Surface Layer', *Quart. J. Roy. Meteorol. Soc.* **105**, 695–705.

Bradley, E. F., Antonia, R. A., and Chambers, A. J.: 1981a, 'Temperature Structure in the Atmospheric Boundary Layer. I. The Budget of Temperature Variance', *Boundary-Layer Meteorol.* **20**, 275–292.

Bradley, E. F., Antonia, R. A., and Chambers, A. J.: 1981b, 'Turbulent Reynolds Number and the Turbulent Kinetic Energy Balance in the Atmospheric Surface Layer', *Boundary-Layer Meteorol.* **21**, 183–198.

Corrsin, S.: 1953, 'Remarks on Turbulent Heat Transfer', *Proc. Iowa Thermo. Symp.* **5**, State University of Iowa, Iowa City.

Donaldson, C. du P.: 1973, 'Construction of a Dynamic Model of the Production of Atmospheric Turbulence and the Dispersal of Atmospheric Pollutants', in *Workshop on Micrometeorology*, American Meteorological Society, 313–390.

Gibson, M. M. and Launder, B. E.: 1978, 'Ground Effects on Pressure Fluctuations in the Atmospheric Boundary Layer', *J. Fluid Mech.* **86**, 491–511.

Launder, B. E.: 1978, 'Heat and Mass Transport', in P. Bradshaw (ed.), *Topics in Applied Physics*, Springer-Verlag, p. 231.

Lumley, J. L.: 1974, 'On Third-Order Mixed Moments', *Phys. Fluids* **17**, 1127–1129.

Lumley, J. L. and Khajeh-Nouri, B.: 1974, 'Computational Modeling of Turbulent Transport', *Adv. Geophys.* **18A**, 169–192.

Phong-anant, D., Antonia, R. A., Chambers, A. J., and Rajagopalan, S.: 1980, 'Features of the Organized Motion in the Atmospheric Surface Layer', *J. Geophys. Res.* **85**, 424–432.

Tavoularis, S. and Corrsin, S.: 1981a, 'Experiments in Nearly Homogeneous Turbulent Shear Flow with a Uniform Mean Temperature Gradient. Part I', *J. Fluid Mech.* **104**, 311–347.

Tavoularis, S. and Corrsin, S.: 1981b, 'Experiments in Nearly Homogeneous Turbulent Shar Flow with a Uniform Mean Temperature Gradient. Part II', *J. Fluid Mech.* **104**, 349–367.

Wesely, M. L., Thurtell, G. W., and Tanner, C. B.: 1970, 'Eddy Correlation Measurements of Sensible Heat Flux Near the Earth's Surface', *J. Appl. Meteorol.* **9**, 45–50.

Wyngaard, J. C., Coté, O. R., and Izumi, Y.: 1971, 'Local Free Convection, Similarity, and the Budgets of Shear Stress and Heat Flux', *J. Atmos. Sci.* **28**, 1171–1182.

Wyngaard, J. C., Coté, O. R., and Rao, K. S.: 1974, 'Modelling the Atmospheric Boundary Layer', *Adv. Geophys.* **18A**, 193–211.