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MEASUREMENT OF SCALAR TRANSPORT IN A MODEL PLANT CANOPY

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SUMMARY Scalar dispersion from a plane source within a model plant canopy is examined, using heat as a tracer. The budgets for turbulent energy ($\frac{1}{2}\overline{q^2}$), temperature variance ($\overline{\theta^2}$), vertical heat flux ($\overline{w\theta}$) and streamwise heat flux ($\overline{u\theta}$) are shown to be similar in the following sense: large local production maxima occur for each entity near the top of the canopy, with up to half of this local production accounted for by downward turbulent transport into the lower part of the canopy, where the budgets are balances between transport and molecular dissipation (for q^2 and θ^2) or pressure terms (for $\overline{u\theta}$ and $\overline{w\theta}$). Spectral results show unexpected upwards momentum flux ($\overline{uw}$) at high frequencies within the canopy, in opposition to the average (all-frequency) downwards $\overline{uw}$.

1 INTRODUCTION

The behaviour of scalar transport above and within plant canopies has been of increasing interest for understanding and predicting the mean concentration fields, variances and turbulent fluxes of biologically active scalars (water vapour, heat, CO_2, NH_3, etc.), and also the dispersion and interception of particulates (airbourne pollen, fungal spores, fertilizers, pesticides, etc.). The turbulent flow within and above a canopy is not well understood, the conditions being complicated by the extreme roughness of the surface, the influence of canopy-element wakes and waving of the canopy elements (Raupach and Thom, 1981).

Modelling efforts have centred around the first-order diffusion equation based on flux gradient assumptions (e.g., Legg and Long, 1975). This approach has proved inadequate for such problems as counter-gradient transport within the canopy (Bradley et al., 1984). A theoretical approach which can potentially account for counter-gradient transport is that of higher-order closure. Wilson and Shaw (1977) describe a simple, one-dimensional, second-order closure model for momentum transport only. Models for scalar transport are under development in the Division of Environmental Mechanics and elsewhere. Part of this development is a critical examination of second-moment budgets within the canopy, especially the scalar variance and scalar flux budgets, in order to test whether the common parameterizing assumptions used in the atmospheric planetary boundary layer (e.g., Wyngaard, 1981) need modification for canopy flows. This paper is a preliminary report of an experimental investigation of second-moment budgets within a canopy; here we concentrate on the turbulent energy, scalar variance and scalar flux budgets, the tracer being passive heat released from a plane source at about 3/4 of the canopy height.

2 EXPERIMENTAL ARRANGEMENT

The experiment consisted of a model canopy placed in the Pye Laboratory wind tunnel (an atmospheric boundary layer simulation tunnel with a working section of length 11 m, width 1.8 m and height 0.65 m). Figure 1 shows the arrangement. The roof of the working section was adjusted for zero pressure gradient. The canopy consisted of a 3 m section of floor with aluminium strips of height (h) 60 mm, width 10 mm and thickness 0.2 mm, placed in a staggered array with 60 mm cross-stream and 40 mm streamwise spacing. Upstream of the crop, the flow was developed over a 5.2 m section of 15 mm road gravel placed on a raised surface so that its zero-plane displacement (d) matched, as closely as possible, that estimated *a priori* for the crop (d = 50 mm). The whole working section floor was

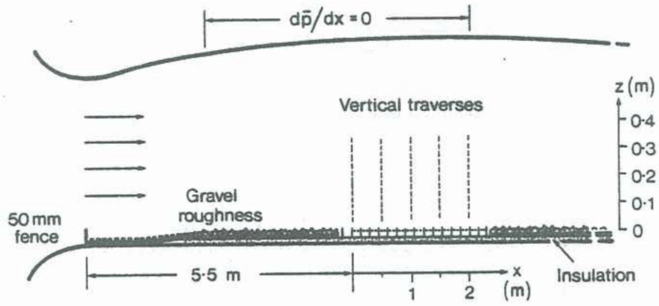

Figure 1 Experimental arrangement in the wind tunnel, with expanded vertical scale.

thermally insulated. Position coordinates (x = streamwise, z = vertical) are defined so that x = 0 at the source leading edge, and z = 0 on the ground surface beneath the canopy.

The tracer was passive heat, supplied by an array of 1 mm diameter nichrome wires stretched across the tunnel, 20 mm apart, between the rows of canopy elements. The source height (z_s) was 50 mm (i.e., coincident with the *a priori* estimate of d); the fetch of source was 2.2 m, commencing 0.3 m downwind of the crop leading edge (see Figure 1). A total power of 1 Kw was used, yielding a source power per unit area of 275 W m^{-2}. At the operating wind speed, the heat was nonbuoyant (the Monin-Obukhov stability parameter $(z-d)/L$ was -3×10^{-4} at $z-d = 100$ mm).

Streamwise ($U = \overline{U} + u$) and vertical ($W = \overline{W} + w$) wind components were measured with a specially developed triple hot wire probe (Legg et al., 1983), whose angle of acceptance of ±75° allowed accurate measurements in turbulent intensities of up to 0.7 (encountered frequently in the canopy). This is in contrast to the conventional X-probe, whose acceptance angle of less than ±45° allows accurate measurements in turbulent intensities of up to about 0.3 only. The temperature ($\Theta = \overline{\Theta} + \theta$) was measured using a 0.12 µm Pt resistance wire placed close to the triple hot wire probe. Vertical traverses consisting of 20 levels were made, within the canopy and up to a height of 400 mm, at x = 0, 0.53, 1.06, 1.55 and 2.03 m. The wind and temperature signals were low pass filtered at 1 KHz and digitized at 2 KHz; 20 s of continuous data were recorded at each measurement point.

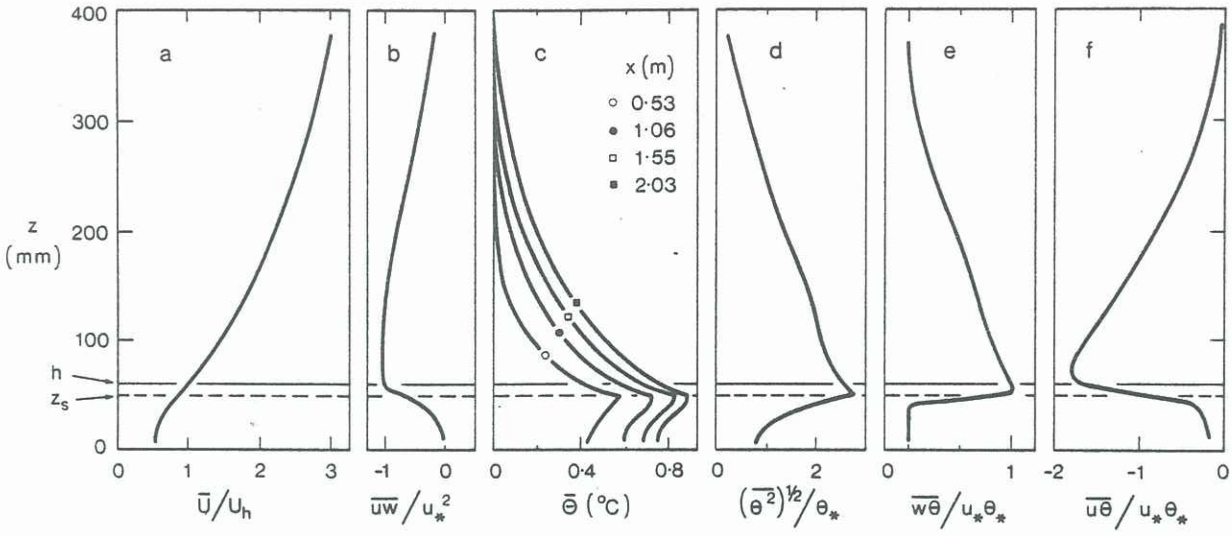

Figure 2 Profiles at x = 2.03 m of (a) $\overline{U}/U_h$; (b) $\overline{uw}/u_*^2$; (c) $\overline{\Theta}$ (note extra x values); (d) σ_θ/θ_*; (e) $\overline{w\theta}/u_*\theta_*$; (f) $\overline{u\theta}/u_*\theta_*$.

Figure 2 shows $\overline{U}$, $\overline{uw}$, $\overline{\Theta}$, $\sigma_\theta (=(\overline{\theta^2})^{\frac{1}{2}})$, $\overline{w\theta}$ and $\overline{u\theta}$ at x = 2.03 m. To indicate the streamwise development of the thermal layer, $\overline{\Theta}$ is shown for all x-stations. Normalizing parameters are the mean wind speed U_h at crop height, U_h = 3.5 m s^{-1}; the friction velocity u_* (defined as $(-\overline{uw})^{\frac{1}{2}}$ in the constant-stress layer), u_* = 1.02 m s^{-1}; and the friction temperature θ_* (defined so that $u_*\theta_* = Q/\rho c_p$, Q being the source power per unit area, ρ the density and c_p the specific heat of air), θ_* = 0.23 K. The profiles in Figure 2 are averages over two points within a "unit cell" of the canopy, which were chosen (after extensive study of horizontal variability within several "unit cells") as representative of the horizontally averaged flow within the canopy. Therefore, the data in Figure 2, and in subsequent figures, can be considered as averaged over the small-scale horizontal variability inherent in the canopy structure (Raupach and Shaw, 1982).

3 RESULTS: WIND FIELD

The wind profile (Figure 2a) shows considerable damping within the canopy as expected, but the near-floor value of 0.5 U_h is rather higher than for most measurements in field crops. This value was confirmed using a miniature sonic anemometer (Legg et al., 1983). The open nature of the model canopy allows significant penetration of large gust structures to floor level, giving the high $\overline{U}$.

When plotted logarithmically, the wind profile above the canopy departs from a logarithmic profile below 100 mm, the velocity being greater than predicted. This observation agrees well with others made over rough surfaces (Raupach et al., 1980).

The shear stress profile (Figure 2b) shows a reasonable constant-stress layer from the top of the canopy to about 120 mm. The rapid drop-off within the canopy shows that almost all the momentum absorption occurs (by form drag) in the top half of the canopy. The shear-stress profile yielded a measurement of the zero-plane displacement (d) by the centre-of-pressure method (Thom, 1971; Jackson, 1981); the result, d = 45 mm, confirmed our *a priori* estimate of 50 mm to be acceptable.

Area preserving $\overline{uw}$ cospectra, for three heights within and one just above the canopy, are shown in Figure 3. The expected downwards momentum transfer is observed for frequencies (n) below about 100 Hz, but at higher frequencies, momentum is transferred upwards. The crossover occurs at a length scale ($n\overline{U}$) of the order of the canopy element spacing. The relative magnitude of the high-frequency upward momentum-transfer depends on z, with the shape of the cospectrum just above the canopy approaching that usually observed in the surface layer. This phenomenon was also observed by the first author in atmospheric data measured over a very rough suburban surface (Coppin, 1979).

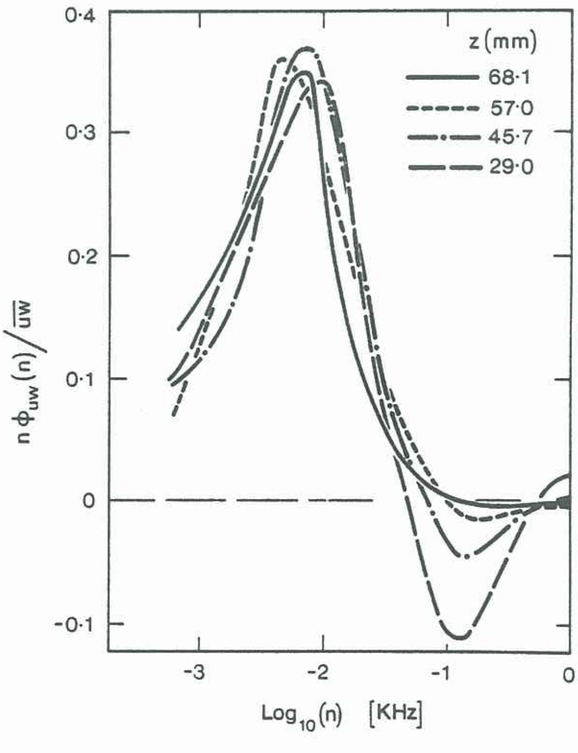

Figure 3 Cospectrum of $\overline{uw}$.

Figure 4 presents measurements (at x = 2.03 m) of the dominant terms in the budget for turbulent energy, $\frac{1}{2}\overline{q^2} = \frac{1}{2}(\overline{u^2} + \overline{v^2} + \overline{w^2})$:

$$\frac{1}{2}\frac{\partial \overline{q^2}}{\partial t} = 0 = -\overline{uw}\frac{\partial \overline{U}}{\partial z} - \overline{U}\frac{\partial \overline{uw}}{\partial z} - \frac{1}{2}\frac{\partial \overline{wq^2}}{\partial z} - \frac{\partial \overline{wp}}{\partial z} - \varepsilon \quad (1)$$

I II III IV V

Here p is the fluctuating kinematic pressure and ε the dissipation rate for $\frac{1}{2}q^2$. Terms due to large-scale mean horizontal inhomogeneity have been ignored (they were negligible by measurement). The terms in (1) are conventional (I = shear production, III = turbulent transport, IV = pressure transport, V = dissipation) except for II, which is a *wake production* term accounting for the conversion of mean to turbulent kinetic energy by form drag on the canopy elements (Raupach and Shaw, 1982). The pressure term IV was not measured.

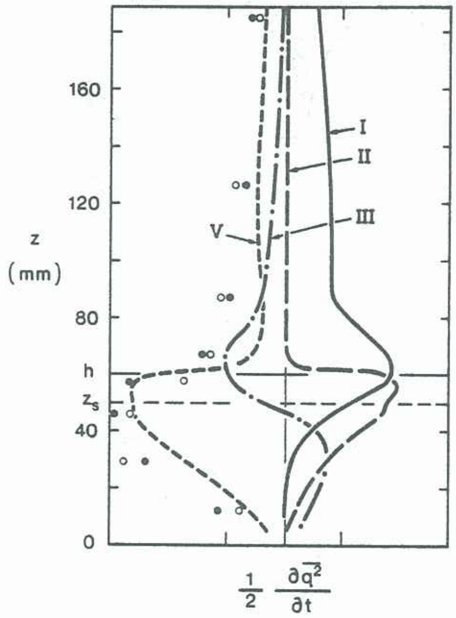

Figure 4 The budget at x = 2.03 m of $\overline{q^2}/2$, Equation (1). o, dissipation from u spectrum; •, from w spectrum.

Dissipation was computed both by residual (as - I - II - III) and from the inertial subrange spectral densities of u and w, assuming a Kolmogorov constant of 0.5. (A discernable -5/3 law was present in both spectra, despite the complication of wake production of turbulent energy at high frequencies.)

Shear production and wake production both have strong peaks, of comparable magnitude, near z = h. Unlike an equilibrium surface layer, where production is approximately balanced by dissipation, there is a significant downwards transport of turbulent energy into the canopy, this term being a loss near z = h of about one third of the combined production terms. The dissipation term has a large maximum in the top half of the crop but remains significant in the lower half. In summary, most of the turbulent energy is produced in the vicinity of the top of the canopy, but about a third of this is transported downwards to be dissipated at lower levels. These general features agree remarkably well with the second-order closure predictions of Wilson and Shaw (1977).

The residual and spectral measurements of ε show fair agreement within the canopy, but in this region it is doubtful whether one can assume an inertial subrange with a Kolmogorov constant of 0.5. Therefore, this agreement cannot yet be taken as significant. Above the canopy, however, there is a discrepancy of a factor of two between the two measurements of ε, which we believe to be greater than can be accounted for by plausible experimental errors. If the discrepancy is, in fact, real, it implies significant pressure transport in the $\overline{q^2}/2$ budget for z between about h and 2h, such that pressure transport is a gain that roughly balances the loss due to turbulent transport. Incidentally, Bradley et al. (1981) found a similar balance in the unstable atmospheric surface layer, at heights far greater than the roughness height.

4 RESULTS: SCALAR FIELD

Figure 2c shows the streamwise development of $\overline{\Theta}$. Below the source, equilibrium is quickly reached and $\overline{\Theta}$ increases uniformly with x. Above the source, the plume continues to spread upward; the centre of action of the plume rises to 100 mm at x = 2.03 m. Figures 2d, e and f show, respectively, normalized profiles of σ_θ, $\overline{w\theta}$ and $\overline{u\theta}$, each of which peaks strongly at the source height. The value of $\overline{w\theta}$ just above z_s is within 5% of source strength $Q/\rho c_p$, confirming the reliability of the $\overline{w\theta}$ measurements. There is a small downwards $\overline{w\theta}$ below the source, accounting for the progressive warming within the canopy ($z \leq z_s$) with increasing x (see Figure 2c). However, $\overline{w\theta}$ remains positive just below the source, probably because of the vertical spreading of the source caused by heat conduction through the metal elements. For $z \lesssim h$, the profiles of $\overline{w\theta}$, $\overline{u\theta}$ and σ_θ are all qualitatively different.

Figure 5 shows the budgets (at x = 2.03 m) of $\overline{\theta^2}/2$, $\overline{w\theta}$ and $\overline{u\theta}$. In the absence of large-scale horizontal inhomogeneity (which was, in fact, negligible) these take the conventional forms

$$\frac{1}{2}\frac{\partial \overline{\theta^2}}{\partial t} = 0 = -\overline{w\theta}\frac{\partial \overline{\Theta}}{\partial z} - \frac{1}{2}\frac{\partial \overline{w\theta\theta}}{\partial z} - \varepsilon_\theta \quad (2)$$

I II III

$$\frac{\partial \overline{w\theta}}{\partial t} = 0 = -\overline{w^2}\frac{\partial \overline{\Theta}}{\partial z} - \frac{\partial \overline{ww\theta}}{\partial z} - \overline{\theta\frac{\partial p}{\partial z}} \quad (3)$$

I II III

$$\frac{\partial \overline{u\theta}}{\partial t} = 0 = -\overline{uw}\frac{\partial \overline{\Theta}}{\partial z} - \overline{w\theta}\frac{\partial \overline{U}}{\partial z} - \frac{\partial \overline{uw\theta}}{\partial z} - \overline{\theta\frac{\partial p}{\partial x}} \quad (4)$$

Ia Ib II III

where ε_θ is the molecular dissipation rate for $\frac{1}{2}\overline{\theta^2}$, and where molecular dissipation has been neglected in (3) and (4). The terms III in each equation (the dissipation term ε_θ in (2), and the pressure terms in (3) and (4)) were found by residual.

All of these budgets show similar features. Production (term I) is highest between z_s and h. There is significant downward transport into the canopy, causing turbulent transport (term II) to act as a loss, in the region of intense production, of a significant fraction (around half) of the locally produced $\overline{\theta^2}/2$, $\overline{w\theta}$ or $\overline{u\theta}$. This fraction is destroyed (by molecular dissipation or pressure-gradient interaction, as appropriate) in the lower part of the canopy. The pattern observed here is shared also with the $\overline{q^2}/2$ budget. (Note that $\overline{u\theta}$ is negative; we interpret "loss" as "returning $\overline{u\theta}$ to zero", or as "decreasing $|\overline{u\theta}|$".)

5 DISCUSSION

The result that downward transport of turbulent energy is significant over rough surfaces is not new. Maitani (1979) reviews several sets of data that show this effect for plant canopies. Laboratory investigations by Andreopoulos and Bradshaw (1981) and Raupach (1981) confirm the effect; Raupach found that the ratio of turbulent transport to production near the top of the roughness was a smooth function of roughness density (his roughness elements were 6 mm cylinders with unity aspect ratio), varying from zero for a smooth wall to about -0.3 for the surface of maximum roughness. The new component of the present work is the extension to scalar transport (in particular, the $\overline{\theta^2}/2$, $\overline{w\theta}$ and $\overline{u\theta}$ budgets), for the case of extreme roughness. Here turbulent transport of $\overline{\theta^2}/2$, $\overline{w\theta}$ and $\overline{u\theta}$ near the top of the canopy is a loss of up to half the local production. Obviously, this finding should be interpreted with care; for example, it is probably true only when the (mean) source height z_s coincides approximately with the mean level of momentum absorption, which is the zero-plane displacement d according to the centre-of-pressure hypothesis (Thom, 1971; Jackson, 1981). We designed our experiment to ensure $z_s \approx d$, but this approximate equality also holds for many natural surfaces, such as plant canopies of moderate to high density. We expect our results for the $\overline{\theta^2}/2$, $\overline{w\theta}$ and $\overline{u\theta}$ budgets within and just above the canopy to be a guide to the behaviour of these budgets for field crops, at least in near-neutral conditions; furthermore, the general findings should be similar for scalars other than heat, provided $z_s \approx d$.

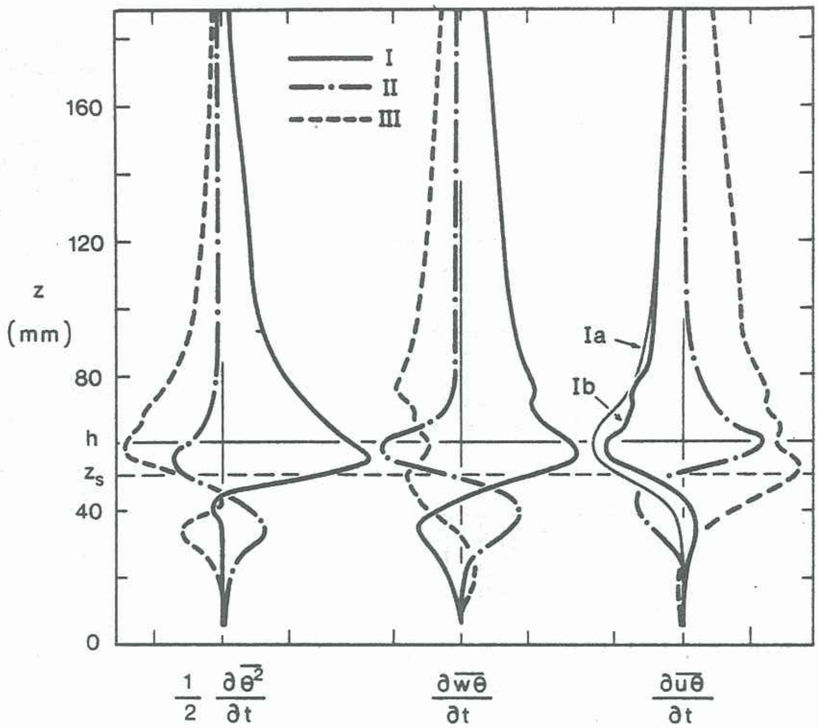

Figure 5 The budgets at x = 2.03 m of (a) $\overline{\theta^2}/2$, Equation (2); (b) $\overline{w\theta}$, Equation (3); (c) $\overline{u\theta}$, Equation (4).

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