PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Stand Overstorey Processes [and Discussion]

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Stand overstorey processes

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Typical turbulent eddies in a plant canopy are coherent over much of the canopy depth, making gradient-diffusion theory inappropriate for describing the vertical transfer of scalars and momentum. A better description of scalar transfer is obtained by regarding the canopy as an assembly of source elements (individual leaves), each releasing a plume of scalar material into the turbulent flow. The contrasting behaviours of the plume from each leaf in the near and far fields (or small and large travel times, in comparison with the turbulence time scale) account naturally for observed phenomena such as counter-gradient fluxes within the canopy. With two hypotheses, this paradigm yields a simple, analytic expression for the scalar concentration profile corresponding to a given source density in the canopy, effectively replacing gradient-diffusion theory.

1. Introduction

The microclimate of a plant canopy is determined largely by the source distributions and concentration fields for several biologically significant scalar entities: heat, water vapour and CO_2 in particular. For an arbitrary scalar entity, let us denote the source density profile by $S(z)$ (with a sink being a negative S) and the mean concentration profile by $C(z)$, where z is the height above ground. Physical and physiological processes at the scale of individual leaves or other source elements control S, whereas C is determined by the way that the scalar released from the source profile S is mixed by the turbulent wind field through the air within and above the canopy. The S and C profiles are often coupled in the sense that S depends on C as well as other environmental or physiological parameters. For example, S for water vapour and heat depends on leaf irradiance, aerodynamic resistance, stomatal resistance and saturation deficit, according to the combination equation for evaporation from a single leaf; the last of these parameters involves the water vapour and heat concentrations (humidity and temperature).

Having recognized that such coupling exists, progress is best made by first treating separately the leaf-scale processes that control S and the turbulent transfer that controls C. This paper concerns the turbulent transfer. (Leuning (this symposium) considers the leaf-scale exchange of energy, heat and water vapour.) For simplicity, consideration is mainly (but not entirely) restricted to steady conditions in an extensive, uniform, level canopy, so that advection is negligible and the scalar conservation equation reduces to

$$S(z) = \mathrm{d}F/\mathrm{d}z, \quad F(z) = F_g + \int_0^z S(z)\,\mathrm{d}z, \tag{1}$$

where $F(z)$ is the vertical scalar flux density and F_g the scalar flux density from the ground at $z = 0$.

Turbulent transfer in canopies has often been described by a gradient-diffusion assumption:

$$F(z) = -K(z)\,\mathrm{d}C/\mathrm{d}z, \tag{2}$$

where the eddy diffusivity $K(z)$ is assumed to be a property of the turbulent motions. Equation (2) is very successful in certain turbulent flows, for example in the atmospheric surface layer well above the underlying rough surface or plant canopy, where K is a function of height, turbulent velocity scale and atmospheric stability. However, efforts to quantity K in the canopy environment have met with no general success. In fact, $K(z)$ within a canopy is so erratic that equation (2) is not a practical description of the turbulent transfer process at all. This is shown by several lines of evidence (Legg & Monteith 1975; Raupach 1988*a*), the most dramatic being observations of frequent counter-gradient fluxes, or negative K values, for heat, water vapour and CO_2 within a pine forest (Denmead & Bradley 1985, 1987).

Equation (2) is obtained by regarding canopy transfer as essentially similar to vertical transfer in the atmospheric surface layer well above the surface. A better abstraction is to regard the canopy as a collection of a vast number of scalar source elements, or tiny chimneys, puffing out plumes of scalar material. To explore this view, it is necessary to consider the process of dispersion from each source element by using Lagrangian principles: that is, by finding statistics of the motion of the wandering fluid elements that carry the scalar. Because a Lagrangian analysis requires knowledge of the turbulent wind field which is responsible for the dispersion, §2 of this paper summarizes some basic features of turbulence in a canopy. Sections 3 and 4 outline the hypotheses and some results of an analytic Lagrangian theory for scalar transfer, summarizing from a complete description by Raupach (1988*b*). Section 5 returns to the idea of coupling between S and C, and shows how the theory can be applied.

2. Turbulence structure in level, uniform canopies

It is sometimes said that canopy turbulence is very complex. Reasons for complexity are certainly easy to find. Two that are often advanced are that the turbulence structure is heterogeneous both vertically and horizontally on the scale of individual plants, and that the flow is a combination of the lowest part of a shear-driven boundary layer and the wakes of a series of obstacles. However, neither horizontal heterogeneity nor the presence of wakes contributes significantly to the vertical transfer (Raupach *et al.* 1986). The important features of the turbulence, as far as vertical scalar transfer is concerned, are quite simple and have a well-defined behaviour in many canopies. In support of this notion, figures 1–3 present a collection of wind turbulence statistics drawn from a recent review (Raupach 1988*a*). The data come from seven different canopies: two forests, two corn crops and three wind-tunnel model canopies (see table 1). The streamwise, lateral and vertical components of the instantaneous wind vector are written as u, v and w, with overbars and primes denoting time averages and fluctuations from them, respectively. The normalizing scales are the canopy height h and the friction velocity u_*. All the data are from single vertical profiles, positioned to avoid obvious interference from nearby canopy elements. However, more detailed measurements in two of the canopies (WT strips and Moga, see table 1) showed that this intuitively sensible positioning strategy provided a reasonable estimate of a truly horizontally averaged profile.

A common flow structure is evident, even though the canopies vary widely (for example, h varies by a factor of 400, u_* by more than 10 and the area index by nearly 20). There is strong shear in the mean wind $\bar{u}(z)$ (figure 1*a*) near the canopy top, with weaker shear both above and below this level. The standard deviations σ_u and σ_w (figure 1*c*, *d*) are approximately

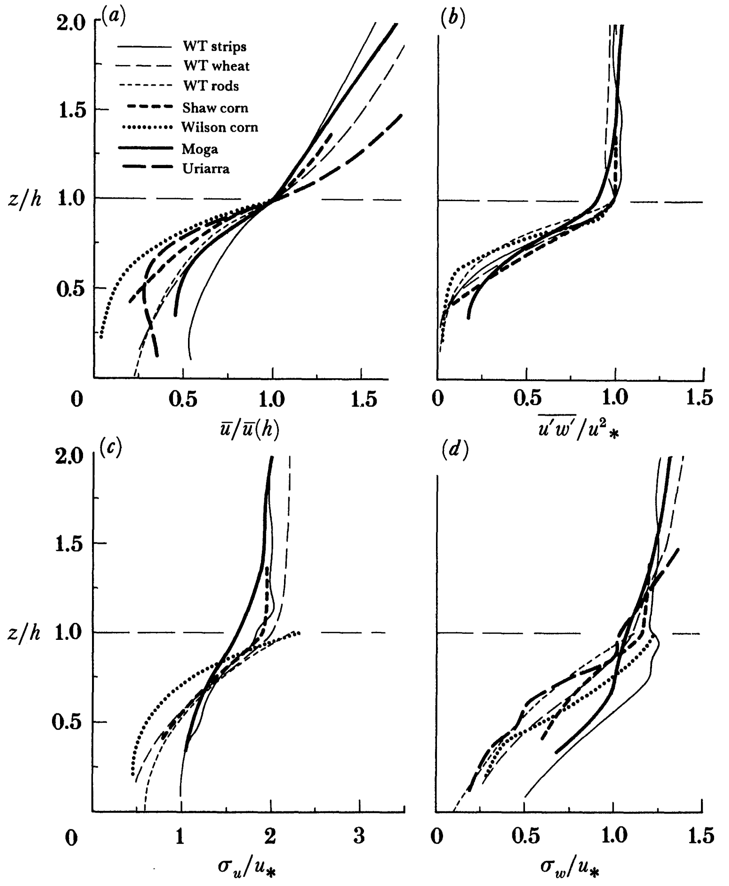

FIGURE 1. Profiles with height z of (*a*) $\bar{u}$, (*b*) $\overline{u'w'}$, (*c*) σ_u and (*d*) σ_w for canopies listed in table 1.

TABLE 1. PHYSICAL AND AERODYNAMIC PROPERTIES OF SEVEN CANOPIES IN FIGURES 1–3

(WT denotes wind tunnel. Sensors: C, cup anemometer; F, split-film servo-driven anemometer; X, X-configuration hot-wire anemometer; T, coplanar triple hot-wire anemometer; S1, single-dimension (vertical) sonic anemometer; S3, three-dimensional sonic anemometer. [a] denotes manuscript in preparation.)

canopy	site	reference	h	leaf area index	$\bar{u}(h)/u_*$	sensors mean	sensors turbulence
strips	WT	Raupach *et al.* (1986)	60 mm	0.23	3.3	T	T
wheat	WT	Finnigan, Brunet and Raupach[a]	47 mm	0.50	4.1	T	T
rods	WT	Seginer *et al.* (1976)	19 cm	1.0	5.0	X	X
corn	Elora	Shaw *et al.* (1974)	260 cm	3.0	3.6	C	F
corn	Elora	Wilson *et al.* (1982)	225 cm	2.9	3.2	C, F	F
forest (eucalypt)	Moga	Raupach, Brunet and Finnigan[a]	12 m	1.0	2.9	C, S3	S3
forest (pine)	Uriarra	Denmead & Bradley (1987)	16, 20 m	4.0	2.5	C	S1

constant above the canopy but attenuate rapidly with depth within the canopy. The shear stress $\overline{u'w'}$ (figure 1*b*) is constant above the canopy but attenuates even more rapidly within the canopy than σ_u and σ_w. The u and w skewnesses Sk_u and Sk_w are both significant, with Sk_u greater than 0 and Sk_w less than 0 within the canopy (figure 2). This indicates that the strongest turbulent events are gusts: energetic, downward incursions of air into the canopy space from

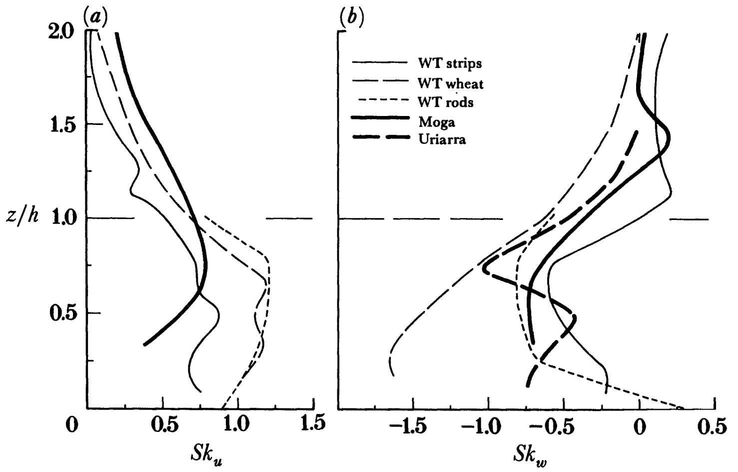

FIGURE 2. Profiles with height z of (*a*) Sk_u and (*b*) Sk_w for canopies listed in table 1.

the faster-moving flow above. Other types of analysis (see Finnigan & Raupach 1987) show that the gusts are responsible for most of the momentum transfer and are highly intermittent: typically, more than half the momentum transfer occurs in events occupying only about $\frac{1}{20}$ of the time. The gusts are also large structures, as shown by the turbulence length scales L_u and L_w (figure 3), which are found from the single-point (Eulerian) u and w time scales with a frozen-turbulence hypothesis. Near $z = h$, $L_u \approx h$ and $L_w \approx h/3$. Therefore typical canopy eddies (of which gusts form the most energetic and active part) are coherent over streamwise and vertical distances of order h. The phenomenon of 'honami', or wind waves on grass or cereal canopies, provides striking visual evidence for gusting motions on this scale.

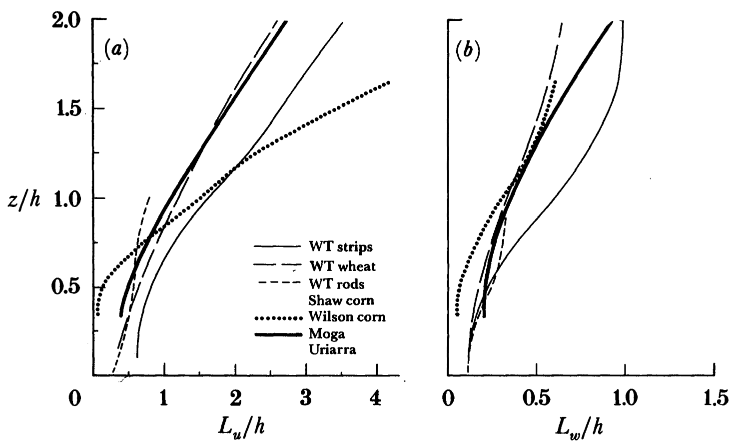

FIGURE 3. Profiles with height z of (*a*) L_u and (*b*) L_w for canopies listed in table 1.

A further attribute of canopy turbulence implied by such large, coherent motions is persistence, or the tendency of air moving in a particular direction to keep going for a while. For vertical motion, the timescale over which persistence acts is the Lagrangian timescale for vertical velocity, T_L (defined below). Scale arguments (Corrsin 1963) show that $T_L \approx L_w/\sigma_w$. This implies, from the data in figures 1 and 3, that $T_L \approx 0.3\ h/u_*$ within the canopy (with a scatter of about 30 %, except very close to the ground where the scatter is larger and the likely

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behaviour is $T_L \rightarrow 0$ as $z \rightarrow 0$). A more direct determination of T_L from dispersion measurements gives a similar conclusion (Legg *et al.* 1986).

Figures 1–3 indicate that a clear picture is available of the main features of canopy turbulence, at least for near-neutral flow in canopies of moderate area density (the conditions for most of these data). Clearly, large variations in area density and strong departures from neutrality have significant effects on the turbulence: for example, strong stable stratification above a temperate forest canopy in winter leads to substantially reduced turbulence intensities within the canopy (Thurtell 1988), and similar effects are likely in dense tropical rainforest (see discussion in Shuttleworth (this symposium)). Nevertheless, the present picture of canopy turbulence provides an adequate basis on which to proceed.

I turn now to the far-reaching consequences of persistence for scalar transfer in canopies. A Lagrangian analysis is necessary because persistence is an attribute of fluid particle motion, rather than of velocities at fixed points in space. Therefore for the rest of this paper it is assumed that the turbulent velocity field is known.

3. Lagrangian analysis of scalar transfer

Provided that the Reynolds number is large enough, the transfer of a scalar released from a point source in a turbulent flow is statistically equivalent to the dispersion of an ensemble of marked fluid particles that pass through that point and thereafter carry the scalar. To find the ensemble-averaged behaviour of the scalar cloud, or the time-averaged behaviour of the plume from a steady source in a steady flow, it suffices to assume that the marked particles all move independently and to consider a single, typical particle only. Let $Z(t)$ be the height and $W(t) = \mathrm{d}Z/\mathrm{d}t$ the vertical Lagrangian (fluid-particle-following) velocity of this particle. Then, if unit mass of scalar is released from an instantaneous point source at $z = z_0$ at $t = t_0$, the ensemble-averaged concentration field is equal to the particle *transition probability* $P(z, t; z_0, t_0)$. This is the conditional probability density that $Z(t) = z$, given that $Z(t_0) = z_0$; that is, $P\,\mathrm{d}z$ is the probability that a particle with a trajectory passing through the source at time t_0 will pass at a later time t through a height element $\mathrm{d}z$, located at z.

It is easy to quantify the dispersal of a scalar in one dimension (say the vertical) from an instantaneous point release (say at $z = 0$, $t = 0$) into steady, homogeneous turbulence. The scalar cloud depth is given by the standard deviation of $Z(t)$, $\sigma_Z(t) = [Z(t)^2]^{\frac{1}{2}}$ (where bold square brackets denote an ensemble average). Taylor (1921) derived the classic result

$$\frac{\mathrm{d}\sigma_Z^2}{\mathrm{d}t} = 2\sigma_w^2 \int_0^t r_L(s)\,\mathrm{d}s, \tag{3}$$

where $r_L(s)$ is the autocorrelation function of W at time-lag s, defined by $r_L(s) = [W(t)\,W(t+s)]/\sigma_w^2$. The most important characteristic of $r_L(s)$ is its integral time scale T_L, the integral of $r_L(s)$ from $s = 0$ to $s = \infty$. This was introduced above as the time-scale over which $W(t)$ is persistent (or has 'memory'). According to (3), the cloud depth has two different types of behaviour in the limits of small and large relative travel time t/T_L, known as the near-field and the far-field limits, respectively:

$$\sigma_Z(t) \rightarrow \sigma_w t \qquad (t/T_L \rightarrow 0, \quad \text{near field}), \tag{4a}$$

$$\sigma_Z(t) \rightarrow (2\sigma_w^2 T_L t)^{\frac{1}{2}} \qquad (t/T_L \rightarrow \infty, \text{ far field}). \tag{4b}$$

In the near field, persistence causes $W(t)$ to differ only a little from $W(0)$ and the particle trajectories $Z(t)$ to depart only a little from straight lines, so the cloud depth grows linearly with t. In the far field, on the other hand, persistence no longer has influence and $Z(t)$ behaves as a random walk; the cloud depth grows as $t^{\frac{1}{2}}$, as for a diffusion process in a homogeneous medium. It can be shown (Durbin 1983) that in the far field, but not in the near field, the transition probability P obeys the diffusion equation

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial z}\left(K_f(z)\,\frac{\partial P}{\partial z}\right), \tag{5}$$

where $K_f(z) = \sigma_w^2(z)\,T_L(z)$ is the far-field eddy diffusivity (with the z dependence vanishing in homogeneous turbulence). Hence the dispersion is *diffusive* in the far field but *non-diffusive* in the near field.

In a canopy, the scalar concentration $C(z)$ at any point of observation includes contributions from all upwind source elements, so the fluid particles carrying the scalar have a vast range of travel times encompassing both the near and far fields. The near-field contribution is mainly due to source elements within a streamwise distance $\Delta x = \bar{u}T_L \approx h$. The implications can be explored by considering a hypothetical canopy in which the scalar source density $S(z)$ has a realistic profile with height, but the wind field is idealized as a homogeneous turbulent flow (Raupach 1987). Despite this drastic simplification (all height variation in the velocity field and all velocity skewnesses have been removed) this simple model accounts for many of the observed features of scalar transfer in canopies: the erratic behaviour of the eddy diffusivity $K(z)$, the important part played by turbulent transport in the budget for vertical scalar flux, and the existence of counter-gradient fluxes in some circumstances. In essence, persistence causes near-field scalar plumes (those with $t < T_L$) to be narrower and therefore more concentrated than they would be if far-field diffusion operated at all travel times, so they put 'bumps on the C profile' (a phrase attributable to G. W. Thurtell). The bumps have the effect of decoupling the local gradient $\mathrm{d}C/\mathrm{d}z$ from the local vertical scalar flux density $F(z)$. This makes equation (2) unusable because $K(z)$ depends very strongly on the source density $S(z)$. If the bumps are locally strong enough, they induce gradient reversal and a counter-gradient flux; an example appears later, in figure 6.

4. A practical Lagrangian approach: localized near-field theory

Although qualitatively helpful, the homogeneous-turbulence analysis involves too many idealizations to aspire to quantitative predictions. One possible quantitative approach is the random-flight method, in which an ensemble of particle trajectories is constructed by solving a stochastic differential equation for $W(t)$ on a computer with random-number methods (see Raupach (1988*a*) for a brief review of the literature). There are three significant difficulties with this type of calculation: the stochastic equation for $W(t)$ has been difficult to prescribe in a general and physically consistent way; the calculations require substantial computing power and are stochastically noisy; and the numerical complexities obscure physical insight. Even if the first difficulty is resolved, the second makes random-flight calculations an insufferable burden for, say, a canopy microclimate model which must also give due weight to other important physical processes such as leaf–air and soil–air transfer, radiation exchange and so on. However, I find the last objection the most telling.

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It is possible to develop a more direct, analytic Lagrangian theory for scalar transfer in canopies; the following outline draws from a full account by Raupach (1988*b*). The aim is to find the scalar mean concentration profile $C(z)$ resulting from a spatially extensive source with source density $S(z)$, placed in vertically inhomogeneous turbulence with prescribed profiles $\sigma_w(z)$ and $T_L(z)$. The theory requires two assumptions, both exact in the limit of weak inhomogeneity but adequate approximations in real, inhomogeneous canopy turbulence: (I) scalar dispersion in the far field obeys a diffusion equation like equation (5); and (II) near-field or persistence effects can be calculated by assuming the turbulence to be locally homogeneous. Assumption (II) motivates the label 'localized near-field theory' for this approach.

The transition probability P for marked particles emanating from a particular source element is decomposed into two parts, a far-field, diffusive part P_f and a near-field, non-diffusive part P_n:

$$P = P_f + P_n, \tag{6}$$

where P_f satisfies equation (5) and where P_n is the difference between the true P and the diffusive P_f. By assumption *I*, $P \rightarrow P_f$ and $P_n \rightarrow 0$ at large travel times, $(t-t_0)/T_L \rightarrow \infty$. Hence P_n may be regarded as a correction accounting for the non-diffusive nature of the dispersion in the near field. This correction is large only for $(t-t_0)/T_L \lesssim 1$, a modest range of travel times in which marked particles do not, on average, spread vertically very far from the height z_0 of the marking source element. Therefore, to calculate P_n, it is reasonable to assume that the turbulence is homogeneous with properties $\sigma_w = \sigma_w(z_0)$ and $T_L = T_L(z_0)$, which is assumption (II). Because both P and P_f are known in homogeneous turbulence, as outlined above, it is easy to find P_n. Once P_n is determined, the complete, inhomogeneous-turbulence solution for $P = P_f + P_n$ is available because P_f is merely the solution of equation (5) with the appropriate far-field diffusivity $K_f(z) = \sigma_w^2(z)\, T_L(z)$ for the inhomogeneous flow.

Having established P (which equals the mean concentration field for an instantaneous source of unit mass), one adds the contributions from all source elements to obtain the concentration $C(z)$ resulting from the spatially extensive canopy source. It is convenient to break C into diffusive and non-diffusive parts, as for P in equation (6). For the case where advection is negligible and equation (1) holds, the solution is:

$$C(z) = C_f(z) + C_n(z), \tag{7}$$

$$C_f(z) = C(z_R) - C_n(z_R) + \int_z^{z_R} \frac{F(z)}{K_f(z)}\,dz, \tag{8}$$

$$C_n(z) = \int_{-\infty}^{\infty} \frac{S(z_0)}{\sigma_w(z_0)} \left[k_n\!\left(\frac{z-z_0}{\sigma_w(z_0)\; T_L(z_0)}\right) + k_n\!\left(\frac{z+z_0}{\sigma_w(z_0)\; T_L(z_0)}\right)\right] dz_0, \tag{9}$$

with $C(z_R)$ a given reference concentration well above the canopy, and k_n a 'near-field kernel function' described below. The flux density $F(z)$ is given directly by equation (1), and involves no near-field correction.

The structure of this solution is quite simple. The diffusive term C_f is familiar as the C profile generated in the canopy by the gradient-diffusion assumption, equation (2), with $K(z) = K_f(z) = \sigma_w^2(z)\, T_L(z)$, a known property of the turbulence. The non-diffusive term C_n involves k_n, the 'near-field kernel function', which is the integral of P_n over all travel times. Therefore k_n represents the near-field contribution at height z for a plane source of unit strength at a single height z_0 in the canopy, which contributes marked particles of all travel times to

$C(z)$. Figure 4 shows $k_n(\zeta)$, which is approximated very closely by the function $-0.399\ln(1-e^{-|\zeta|})-0.156\,e^{-|\zeta|}$ (where the argument ζ is a measure of the height interval $z-z_0$, made non-dimensional with the turbulent length scale $\sigma_w(z_0)\,T_L(z_0)$ at the source). Because k_n is the near-field contribution for a unit plane source at z_0, the complete near-field term $C_n(z)$ is the convolution of k_n with the source density $S(z_0)$, as in equation (9). Two k_n terms arise because an extra, image flow and source are introduced below $z = 0$ to ensure that there is no flux through the ground of the scalar from the elevated sources represented by S. A scalar flux density F_g at the ground makes no near-field contribution to C (provided that $T_L \rightarrow 0$ as $z \rightarrow 0$, which is true close to the underlying surface in a boundary layer, and is also likely to hold close to the floor of the canopy). Instead, the entire concentration contribution from F_g appears in the C_f term, equation (8), via the contribution of F_g to $F(z)$.

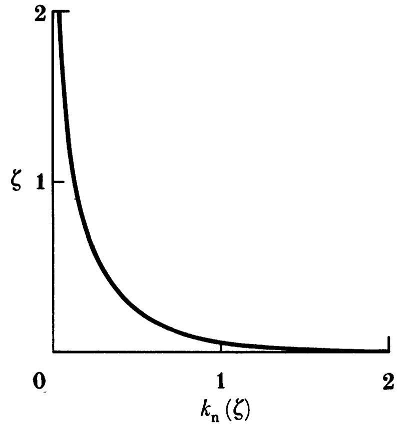

FIGURE 4. The near-field kernel function $k_n(\zeta)$, for $\zeta > 0$. The function is symmetric in ζ.

To show the nature of the solution in practice, figure 6 presents profiles of C, C_f, C_n and the vertical flux density, F, for two source densities, S, typical of daytime heat and water vapour source distributions in forest canopies. The assumed profiles $\sigma_w(z)$ and $T_L(z)$, which were guided by the data in figures 1–3, are shown in figure 5. In both $S(z)$ profiles, the upper peak represents the heat or water vapour emitted by the dense foliage in the crown and accounts for 90% of the overall scalar flux density from the canopy, $F_* = F(h)$; the lower peak, accounting for the remaining 10% of F_*, represents the source due to the understorey and underlying ground. The difference between the two profiles is in the spread of the upper peak, which is sharp in case A but more vertically diffuse in case B. Several features are noteworthy.

1. The main small-scale structure in $C(z)$ is imparted by C_n, which tends to induce peaks in C at the heights of peaks in S. By comparison, C_f has a much smoother profile which reflects little of the shape of S and serves mainly to set the large-scale variation in C.

2. The local peaks in C_n can be strong enough to cause a gradient reversal in $C(z)$ just below a peak in $S(z)$, as in case A. Because $F(z)$ is positive, this situation represents a counter-gradient flux.

3. The detailed shape of $C(z)$ is very sensitive to $S(z)$, because of the small-scale structure due to C_n. For example, a minor increase in the spread of the upper peak in $S(z)$ causes the counter-gradient flux observed in case A to disappear in case B.

For simplicity, the localized near-field theory has been described here for non-advective

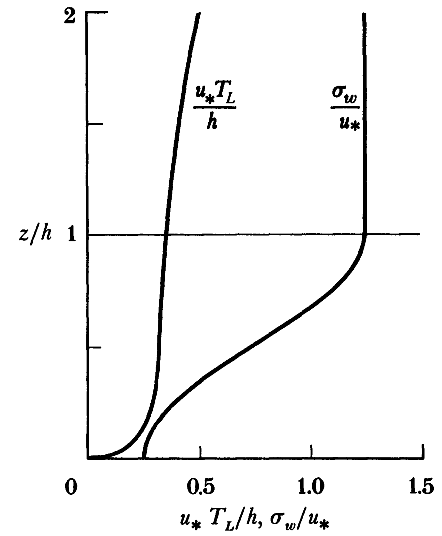

FIGURE 5. Assumed profiles of σ_w and T_L for predictions of concentration profiles in figure 6.

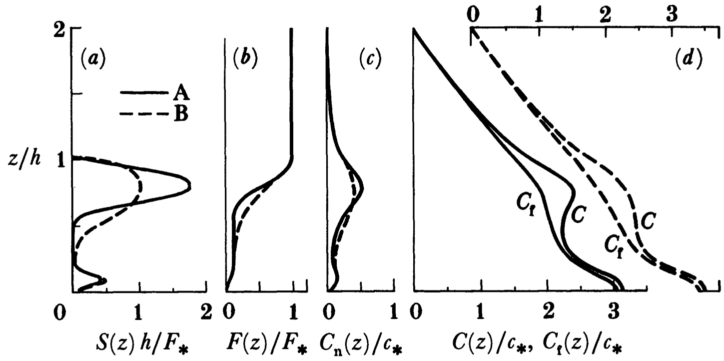

FIGURE 6. (*a*) Source density profiles for cases A and B; (*b*) flux densities $F(z)$ from equation (1); (*c*) near-field concentration contributions $C_n(z)$ from equation (9); (*d*) far-field and total concentrations $C_f(z)$ and $C(z)$, from equations (7) and (8). Profiles of σ_w and T_L as in figure 5. Normalizing flux and concentration scales are $F_* = F(h)$ and $c_* = F_*/u_*$, respectively.

conditions in which the scalar conservation equation reduces to equation (1). The theory also applies in advective conditions, with no change except that C_f is no longer given by equation (8) but instead by the solution to a diffusion equation with advection included. The only restriction is that the theory is inaccurate where streamwise change is very rapid, for example within a few canopy heights of the leading edge of a canopy.

Assumptions (I) and (II) of the theory have been tested (Raupach 1988*b*) by comparisons between localized near-field and random-flight predictions of $C(z)$, showing that both assumptions are adequate approximations in typical canopy turbulence. One consequence of assumption (II) is that the localized near-field theory makes no direct reference to the skewness of the canopy turbulence, because unskewed, homogeneous turbulence is used for calculating P_n and k_n. A separate series of random-flight experiments showed that the effect of skewness on $C(z)$ is small (at least for $-Sk_w \lesssim 1$, which is typically true) so the neglect of skewness is justified.

5. Application to the canopy microclimate

Canopy source or sink densities for scalars such as heat, water vapour and pollutants are generally concentration dependent, as indicated in the introduction. Therefore a practical description of scalar transfer must include the possibility that S depends on C as well as other, externally specified parameters, such as the leaf boundary layer and stomatal resistances r_b and r_s, or the leaf area density α. For example, S for a pollutant being deposited on a canopy may be specified by

$$S(z) = \alpha\rho(C_s - C(z))/(r_b + r_s), \tag{10}$$

where ρ is the air density and C_s the concentration at deposition sites which for this example are within the stomata. (For deposition, S is negative.) In the case of coupled heat and water vapour transfer, (10) would be replaced by some form of the combination equation for evaporation from a leaf.

It is usually convenient to consider the canopy as a collection of a small number of layers with specified r_b, r_s, α, and so on. To indicate the approach, suppose that the canopy and the air just above it are divided into N layers, with C_i, S_i, Δz_i and z_i being the average concentration, source density, thickness and height of layer i. The top height coincides with a reference level z_R above the canopy (the height of a weather station, say) at which a reference concentration C_R is known by measurement. The problem is to find S and C in the various canopy layers. Considering first a hypothetical scalar tracer which is released uniformly in layer j with a source density s (so that $S_i = s$ when $i = j$ and $S_i = 0$ otherwise), the resulting hypothetical concentration profile c_i defines a 'dispersion matrix'

$$D_{ij} = \frac{c_i - c_R}{s\Delta z_j}, \tag{11}$$

which is the concentration (relative to the reference level) produced in level i by a unit source in level j. The matrix D_{ij} is a function only of the turbulence structure in the canopy (specifically, $\sigma_w(z)$ and $T_L(z)$) and can be calculated from the localized near-field theory using equations (7)–(9). The dimension of D_{ij} is that of aerodynamic resistance (inverse velocity). In fact, if the transfer is entirely diffusive, then D_{Nj} is the familiar aerodynamic resistance between levels j and N from gradient-diffusion theory, the integral of $1/K_f(z)$ from z_j to z_N (Thom 1975). However, because the concentration is actually the sum of a diffusive and a non-diffusive term, from equation (7), turbulent flux densities in the canopy are not driven by concentration differences alone and no analogy with Ohm's law applies to D_{ij}, in contrast to the aerodynamic resistance in gradient-diffusion theory.

Once D_{ij} has been found, $C(z)$ for an arbitrary $S(z)$ (this time for the real scalar) can be written by using the principle of linear superposition, which enables the concentrations resulting from separate sources or separate layers to be summed. Introducing a relation $S(C)$ between the local source density and concentration, we have:

$$C_i - C_N = \sum_{j=1}^{N} S_j(C_j) D_{ij} \Delta z_j, \tag{12}$$

which is a set of N equations relating C to S. Once $S(C)$ is specified on a single-leaf basis, and thence for each layer, the N equations can be solved for C and S. Usually, the $S(C)$ relation is linear, as in equation (10), and the equations can be solved algebraically.

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6. Concluding discussion

What has been outlined is a simple multi-layer approach to scalar transfer in canopies, using an analytic Lagrangian theory for turbulent dispersion. The key physical process is the persistence of the turbulent motions, which makes the turbulent transfer non-diffusive so that no simple gradient-diffusion relation holds. Because the theory is Lagrangian, wind information is required: specifically, profiles of vertical velocity standard deviation $\sigma_w(z)$ and Lagrangian time scale $T_L(z)$. Existing data are sufficient to establish these profiles quite closely in many cases.

This kind of multi-layer approach appears to contrast strongly with a single-layer or 'big-leaf' approach, which treats the entire canopy as a single transferring surface endowed with bulk aerodynamic and stomatal resistances. However, we may unify the two approaches by noting that equation (12) reduces to a single-layer model if $N = 1$ (when D_{ij} reduces to a single element akin to an aerodynamic resistance). When is a multi-layer approach necessary? One answer is whenever the microclimatic variations within the canopy are significant, either in their own right or through their influence on the overall scalar flux density F_* between the canopy and the atmosphere. Examples include the re-evaporation of intercepted rainfall, which is controlled almost entirely by turbulent transfer between various parts of the canopy and the flow above; partitioning of evaporation between the ground, understorey and overstorey; analysis of the surface temperature distribution in the canopy, and thence of the relation between radiative measurements of the bulk canopy temperature and the bulk heat flux density; and understanding the sink distribution within the canopy of deposited pollutants, as well as the overall pollutant deposition rate.

A further potential application is in the area of measurement. The connection between the source profile $S(z)$ and the concentration profile $C(z)$ is much tighter in reality than it appears to be if gradient-diffusion transfer is the only operating mechanism (compare the extent to which the profiles $C(z)$ and $C_f(z)$ reflect the source profile $S(z)$ in figure 6). This raises the possibility that measurements of concentration profiles, with measurements or inferences of $\sigma_w(z)$ and $T_L(z)$, can be used to infer $S(z)$. The inference of $S(z)$ from $C(z)$ was attempted some years ago (see, for example, Legg & Monteith 1975) by using gradient-diffusion transfer theory, but abandoned at that time because contradictory results were often obtained. The reason for the contradiction is now clear, and a fresh look at the idea seems worthwhile.

I am grateful to my colleagues Dr J. J. Finnigan and Dr Y. Brunet for many discussions and for the use of data from as yet unpublished joint work; also to Dr O. T. Denmead and Dr I. Webster for lively comments on draft manuscripts. I would also like to acknowledge the indirect influence of Dr G. W. Thurtell. Although I have not had the benefit of much direct interaction with him, it was he who first saw intuitively that counter-gradient fluxes are possible within canopies.

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Discussion

J. A. CLARK (*School of Agriculture, University of Nottingham, U.K.*). Dr Raupach shows that the profiles of concentration and wind speed are affected by the near-field contributions. These appear to extend to about $1\frac{1}{2}$ times the canopy height; a layer in which profile and Bowen ratio measurements have 'traditionally' been regarded as most accurate. Does this mean that much of the historical data on fluxes derived from measurements above forest and rough crops (e.g. maize) are suspect?

M. R. RAUPACH. The near-field concentration contribution does extend to about $1\frac{1}{2}$ times the canopy height, but the effect on Bowen ratio measurements near the canopy top will be small provided the distributions of heat and water vapour sources in the canopy are roughly coincident. However, if the two source distributions are markedly different then the near-field contributions to the temperature and humidity profiles will reflect this, leading to different values of K for the two entities above the canopy and errors in the Bowen ratio technique.

Because heat and water vapour sources in canopies are fairly similar in dry canopies with full cover we do not need to discard the historical Bowen ratio data in most cases. This is supported by observed agreement between profile and eddy correlation Bowen ratios close to the top of the canopy at Uriarra Forest. However, the kinds of situation in which trouble might be expected include cases where free surface water is available in part of the canopy (wet forests or rice paddies, for example), or very sparse canopies where much of the heat source is at the ground surface but the water vapour source is elevated.

P. G. JARVIS (*Department of Forestry and Natural Resources, University of Edinburgh, U.K.*). In the model that Dr Raupach described he has referred to treating the tree canopy as a series of

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levels. I would like to ask if this is appropriate for tree canopies, as opposed to crop canopies or grassland, because, in tree canopies, the distribution of the foliage is markedly non-uniform. The foliage is grouped into crowns, and where the trees are widely spaced the crowns do not touch. This occurs in many stands, especially the widely spaced agro-forestry stands now becoming more prevalent. Also, the distribution of leaf area density is also very non-uniform within the crowns, as I and my co-workers have shown in Sitka spruce and radiata pine. As a result of these two levels of foliage grouping, we have concluded that layer models are inappropriate for the calculation of water and CO_2 exchanges by trees. How does such non-conformity affect his Lagrangian model?

M. R. Raupach. Although the geometry of plant canopies can be complex, especially for forests, one should not become overwhelmed by the complexity. Two factors allow us to introduce some simplification. Firstly, the small-scale clumpiness of canopies (say, up to the scale of a tree crown, or about one canopy height in sparse canopies) will affect the near-field concentration, C_n, far more than the far-field term, C_f. The result is that, as one moves away from a clump of vegetation, the bumps on the C profile imparted by C_n will spread out more. The C profile through the canopy therefore changes locally in response to the proximity of clumps of vegetation, but does not change its large-scale form because this is determined by C_f.

Secondly, the variation of turbulence properties (such as σ_w, eddy fluxes, and so on) is quite mild even in fairly sparse canopies, as shown by both wind-tunnel and field data. I refer particularly to the experiment in Moga forest, Australia, where sonic anemometers on a horizontal line gave similar turbulence data except in the case of an anemometer placed within a tree crown. This suggests that estimates of horizontally averaged turbulence properties in canopies can be obtained from single-point measurements, provided that one avoids obvious interference, as any sensible micrometeorologist would. The tree spacing at Moga is of the same order as the canopy height, so such a conclusion would extend to this kind of spacing.

B. Gardiner (*Forestry Commission Northern Research Station, Roslin, U.K.*). What is the applicability of the new approach Dr Raupach has described to a vector quantity such as momentum where one would regard trees as a sink rather than a source?

M. R. Raupach. Momentum is not a conserved property of a wandering fluid particle because it is transferred by pressure as well as viscous forces. Although it is tempting to think of trees as sources of mean momentum deficit that spreads in the way I have outlined for scalars, more work is needed before this approach can be made rigorous.

W. J. Shuttleworth (*NERC Institute of Hydrology, Wallingford, U.K.*) 1. Dr Raupach's paper makes no mention of leaf boundary layer resistance: is this introduced through the effective value of the source distribution? If so it presumably means this requires an assumed form for the in-canopy windspeed.

2. I noticed Dr Raupach's predicted profiles for the bottom of the canopy were similar to the 'far-field' (K-theory) approximation: does this mean Dr Black (this symposium) is adequately correct in assuming this for understorey modelling?

M. R. Raupach. 1. Yes, leaf boundary layer resistance enters the determination of source density through an equation such as (10), and a wind profile is therefore needed to specify boundary-layer resistance.

2. The predicted profiles near the ground have little near-field contribution, and therefore approximately obey far-field diffusion dynamics, because I have assumed that the Lagrangian time-scale T_L tends to 0 at the ground surface. This implies K-theory is valid very close to the ground. However, the suggestion that $T_L \rightarrow 0$ as $z \rightarrow 0$ is a guess that is neither confirmed nor invalidated by the available data, so more experimental work is needed on this point.

J. M. Crowther (*Department of Physics and Applied Physics, University of Strathclyde, U.K.*). Ms A. M. Brown and I have been doing flow-visualization experiments at Rivox Forest, southern Scotland, in which we used a smoke-generator just below the top of a Sitka spruce canopy. We observed that the smoke plume was strongly influenced by vertical gusts of wind, sometimes being taken tens of metres above top of canopy (12 m) and sometimes being drawn down into the canopy for 10 s or more. These events can be accompanied by vertical wind-speeds of ± 2 to ± 4 m s^{-1} and occur very frequently, perhaps about one every 30–60 s or so. Dr Raupach's model seems to suggest a plume being drawn out horizontally and gradually spreading, which seems quite unlike the observations we have made. Can his model cope with this situation in which the vertical excursions of the plume cover several crop heights?

M. R. Raupach. The key parameter distinguishing near-field from far-field dispersion is travel time, not downwind distance from a source. The theory does not involve plumes spreading gradually downwind, but rather the vertical spread in time arising from a sequence of releases at successive instants from point sources. Hence the horizontal drift is not of basic importance. The very interesting observations that Dr Crowther describes would seem to be consistent with the notion that the persistence time, T_L, is large. I wonder if his data could be used to estimate T_L?

R. Leuning (*Division of Forestry and Forest Products, CSIRO, Canberra, Australia*). Does Dr Raupach think there is a unique relation between the concentration profile and distribution of source and sinks?

M. R. Raupach. If the relation between the source density S and the local concentration C is linear (as in equation (10), for example) then the system of equations determining both S and C in a multi-layer canopy model is also linear and a unique solution is assured. In most cases, the $S(C)$ relation is either linear or can be linearized; an example is the local combination equation that specifies the water vapour and heat source densities.

F. di Giovanni (*Department of Geography, University of Hull, U.K.*). Firstly, in connection with the near-field difficulties Dr Raupach mentioned, what is his opinion of the modifications by Aylor *et al.* (1981) to gradient-flux theory to account for threshold speed of release and enforced impaction efficiencies for particles in canopies, and are there any connections with his work?

Secondly, I was interested to see the modelled sources in the forests Dr Raupach has studied as being, effectively, line sources. Does he think any improvement would come from treating individual trees or plants as volume sources or sinks?

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M. R. Raupach. The work of Aylor *et al.* (1981) is mainly aimed at determining the release (source) and deposition (sink) properties of spores. These are clearly important – perhaps dominant – for spore dispersal; but both are outside the topic I have considered, which is the transfer process between release and deposition. All I can say is that gust-dominated spore release, which Aylor *et al.* (1981) consider, makes for a more complicated source density than I have dealt with.

As to the question of line or volume sources, I actually treat the source as spatially continuous. Line or point elements only appear as building blocks from which the complete canopy behaviour is found by summation. Whether this is justifiable, given the heterogeneous nature of real canopies, is the subject of the question raised by Professor Jarvis, and considered in my reply.

J. B. Stewart (*NERC Institute of Hydrology, Wallingford, U.K.*). Does Dr Raupach's theory explain the discrepancy, originally found by Alasdair Thom, between fluxes estimated from gradients measured at small distances above a forest canopy and the measured fluxes at the same height?

M. R. Raupach. The discrepancy is built into this theory through the forms assumed for σ_w and T_L just above the canopy. The data suggest that the product $\sigma_w^2\, T_L$, the far-field eddy diffusivity, is almost constant in the layer $h \lesssim z \lesssim 2\,h$ (h is canopy height and z height above ground). Hence the diffusivity in this layer is greater than that expected from classical surface-layer theory, which for neutral conditions would be proportional to $z-d$, where d is zero-plane displacement. There is also some near-field contribution to concentration profiles above $z \approx h$. The effect of the departure of the diffusivity $\sigma_w^2\, T_L$ from proportionality with $z-d$ is to cause the discrepancy Dr Stewart cites, whereas the observed difference in the discrepancies for heat, water vapour and momentum can be accommodated by considering the different source–sink distributions for these entities and the consequent difference in the near-field contributions to the profiles.

H. A. R. de Bruin (*Department of Physics and Meteorology, Agricultural University, Wageningen, The Netherlands*). The picture of turbulence within a vegetation layer I have had so far, is that it is non-local and that much of the transfer of heat, atmospheric scalars, etc. takes place during short events, but that first-order closure applies at other times, with no counter-gradient fluxes. I understand that the measurements of turbulence by Denmead & Bradley (1985) confirm this picture. This markedly differs from the description Dr Raupach has presented. Can he comment on this?

M. R. Raupach. The transfer is non-local in two senses: firstly, it does not obey local gradient-diffusion theory because of the large-scale nature of the turbulence, and secondly, the energy that maintains the turbulence in the canopy is generated mainly above or near the top of the canopy, and then transported downwards by large turbulent transport terms in second moment budgets such as that for turbulent energy.

The first of these is applicable in both homogeneous and inhomogeneous turbulence and is therefore independent of inhomogeneity, whereas the second is fundamentally linked to inhomogeneity because it involves height gradients of triple velocity moments. The observations of scalar transfer behaviour, including counter-gradient fluxes and the large turbulent transport term in the scalar flux budget, can all be accounted for by a homogeneous-turbulence theory (see Raupach 1987). This suggests that the fundamental factor operating is the large-scale nature of the turbulence, or persistence, and that the inhomogeneity is secondary. The transfer in this picture still occurs in short events and is still compatible with Denmead & Bradley's observations at Uriarra Forest.

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