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Micrometeorology of Shelter Belts and Forest Edges [and Discussion]

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Micrometeorology of shelter belts and forest edges

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The micrometeorological effects of shelter belts are briefly summarized, paying particular attention to the similarity framework that is used to bring order to the empirical data. Stretching downwind from the top of a shelter belt is a turbulent wake. This spreads and reaches the ground at about eight heights out, more or less depending on the properties of the incident wind profile. Closer to the fence is a quiet zone where the wind is less turbulent. Turbulent transport of scalars is suppressed in the quiet zone and enhanced in the wake zone.

Much less information is available on shelter in the lee of forest edges. It appears that a similar pattern of quiet zone and wake zone is found there, but the pattern is much shortened. However, windspeed continues to increase over a longer distance as a deeper layer of air adjusts progressively to the roughness change. Shelter belts whose width is comparable to their height are transitional cases, but too little information is available to chart the transition.

1. Introduction

Shelter belts and forest edges are common features of the rural landscape, but, although shelter belts are usually planted deliberately to modify microclimate, forest edges occur naturally or are accidents of forest planted for wood production, wildlife protection or other ends. It is therefore hardly surprising that micrometeorological changes in the lee of shelter belts have been studied extensively, both at full scale and on models (see reviews by van Eimern *et al.* (1964), Heisler & DeWalle (1988) and McNaughton (1988)), although the effects of forest edges have received far less attention.

That is not to say that everything is known about the micrometeorology of thin shelter belts. The models developed to calculate flows about windbreaks (Plate 1971; Counihan *et al.* 1974; Hagen *et al.* 1981; Wilson 1985) have been only partly successful. Our knowledge remains mostly empirical and, being empirical, has gaps in areas where suitable measurements have not been made. The microclimate of forest edges is less well understood. Few observations have been made and there have been even fewer attempts to develop aerodynamic theory (Bergen 1979).

The purpose of this paper is first to summarize our knowledge of the micrometeorology of thin windbreaks, paying particular attention to the way that the empirical information has been organized by using similarity principles, and the physical interpretations that have been developed to underpin these results. The discussion is then extended to forest edges and wide shelter belts by using principles established in the study of thin windbreaks as a guide. Even so, this discussion is more a summary of our ignorance than of our knowledge.

2. Thin shelter belts

Similarity laws

To a large extent the history of our understanding of shelter aerodynamics and microclimate is the history of the development of similarity laws. These laws specify which experiments may be properly compared and how data obtained by models can be applied at full scale. Knowledge has advanced by the accumulation of empirical results, but it is only by the similarity laws that such information gains generality.

As currently understood, the similarity law for any dimensionless aerodynamic property P states that, for a long windbreak standing on uniform, level ground, any experimental map of $P(x/h, z/h)$ will be the same in every case where the parameters h/z_0, h/L, ϕ and α are the same. Here h is the height of the barrier, z_0 is the roughness length characterizing the shape of the mean wind profile in the open, L is the Monin–Obukhov length, ϕ is the visual porosity of the barrier, and α is the angle between the mean wind vector and the normal to the barrier. The Monin–Obukhov length is given by

$$L = -kgH/\rho_a c_p Tu_*^3, \qquad (1)$$

where k is the von Kármán constant, g is the acceleration due to gravity, H is the sensible heat flux density, ρ is the density of air, c_p is the specific heat of air at constant pressure, T is ambient absolute temperature and u_* is the friction velocity in the open. That is

$$P = f_P(x/h, z/h, h/z_0, h/L, \phi, \alpha), \qquad (2)$$

where $f_P(\dots)$ is a universal function for the property P.

The property P in equation (1) can be any one of many ratios. It might be the horizontal wind speed, u, normalized by the horizontal wind speed measured at the same level in the open, u_0. Equally, u might be normalized by wind speed at fence-top height in the open, u_h, or by some other parameter with dimensions of wind speed such as the friction velocity, u_*. Other examples of P are the scaled standard deviation of the vertical wind velocity, σ_w/u_*, and the local shear stress, $\overline{u'w'}/u_*^2$, where w is the vertical wind velocity and the primes indicate deviations from the mean.

The pattern of changes in concentration, Δs, of some scalar quantity, s, which is transported by the wind, can also be described in this way if a suitable concentration scaling parameter, s_*, can be identified. Thus

$$\Delta s/s_* = f_s(x/h, z/h, h/z_0, h/L, \phi, \alpha), \qquad (3)$$

where s might be temperature, humidity, CO_2 concentration or the concentration of some pollutant. If the boundary conditions governing the absorption or release of s are complex then still more parameters might need to be introduced.

With four parameters required to specify each two-dimensional map of each property, a great many maps could be drawn, so very many experiments would be required to provide sufficient data. Nor is this the end to our difficulties, for equation (2) is known to be incomplete. The structure of many windbreaks is not fully expressed by a single porosity value, for porosity might vary with height (Wilson 1987): the nature and size of the openings influences the turbulence close in the lee of the barrier (Perera 1981), and the sheltered field may not be uniform. In some instances where tall shelter belts block the wind beneath a shallow inversion, the height of the inversion could be important. I ignore these possibilities and assume a long, uniformly porous barrier standing on a uniform field. Unless otherwise noted, I also assume $\alpha = 0$.

Effects of shelter belts on the mean wind

In the agricultural literature 'the shelter effect' is usually described in terms of reduction of wind speed near the ground. Most measurements have been made with cup anemometers, which are insensitive to wind direction. This has led to confusing results in the area of complex flow close behind denser barriers. Confusion is the greater because in early field studies wind reductions were compared for shelter belts where upwind conditions of roughness, topography or other obstacles were not similar (Heisler & DeWalle 1988). Recommendations given in most agricultural textbooks and farm advisories that medium porosity windbreaks ($\phi = 0.3$–0.5) are best for crop shelter, are still based on the work of Naegeli (1946, cited by van Eimern *et al.* (1964)) who studied dissimilar shelter belts by using cup anemometers.

Cup anemometers do not detect the reverse flows that occur within the recirculating eddies ('rotors') that form near dense barriers. Such eddies occupy a separation bubble extending as far as $17h$ downwind of models in smooth-floored wind tunnels and low turbulence (Petryk & Brundrett 1967, cited by Bradshaw & Wong (1972)). Baltaxe (1967), working in a smooth-floored wind tunnel with a trip wire to ensure a turbulent boundary layer observed a large recirculating eddy that extended to about $11h$ downwind and a smaller corner eddy close in the lee of the barrier. With higher turbulence levels in a boundary-layer wind tunnel ($h/z_0 = 100$), Raine & Stevenson (1977) found the recirculating eddy extended to $8h$, and a similar-length eddy was found by Ogawa & Diosey (1980) behind a solid fence in the field ($h/z_0 = 140$) in near-neutral conditions. Fewer observations of the upwind rotor have been made, although Tanaka *et al.* (1954) observed reversed flow at $x/h = 0.6$ in the field in front of a solid board fence (h/z_0 unknown). Figure 1 is a sketch of the situation. One significance of the main lee rotor is that its length is a useful horizontal scale for the entire pattern of lee-side wind reduction. Also, flow within this zone retains different turbulent characteristics, even when the rotor is replaced by bleed flow through a more porous fence.

Reversed flow within rotors can be detected with directional anemometers. Perera (1981) measured a series of vertical velocity profiles near a solid barrier in a wind tunnel ($h/z_0 = 110$). Some of his results are shown in figure 2. Notable features of these profiles are the very strong shear zone close to the top of the barrier ($x/h = 1.25$) and the reversed flow near the ground detected at $x/h = 1.25$ and 5.

More porous barriers allow more air to pass through them, so the displacement flow over the top is reduced. The recirculating eddies, which are a feature of the flow behind dense barriers, retreat downwind, become confined to a shallower layer near the ground, become intermittent and finally vanish (Tanaka *et al.* 1954). Recirculating eddies are weak or absent for ϕ greater than about 30% (van Eimern *et al.* 1964).

There seems to be no entirely satisfactory set of data describing the effect of porosity on relative wind velocity. Figure 3 is a representation of relative wind speed at $z/h = 0.25$ behind barriers of various porosities, based on two data sets. The data of Perera (1981), with $h/z_0 = 110$, were used to plot behaviour near the barrier, and those of Raine & Stevenson (1977) with $h/z_0 = 100$, for larger distances and for $\phi = 0.5$ at all distances. The curves were drawn so that relative wind speeds behind barriers of all porosities are nearly equal at larger distances, as observed by Hagen & Skidmore (1971) and Raine & Stevenson (1977), and so that the wind behind denser barriers remains slower, as expected from theory (Counihan *et al.* 1974; Wilson

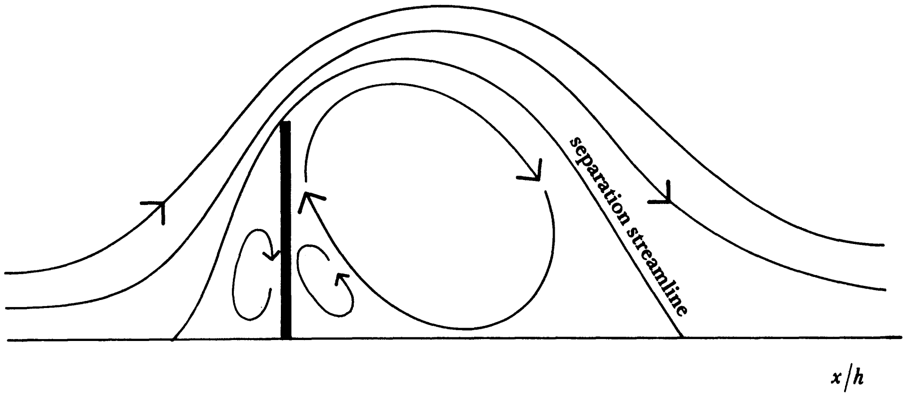

FIGURE 1. Sketch of the flow streamlines about a thin, solid barrier standing normal to a wind blowing from left to right. The horizontal scale is variable, decreasing as h/z_0 increases. For $h/z_0 = 100$ the separation streamline reaches the ground plane at about $x/h = 8$ downwind of the barrier.

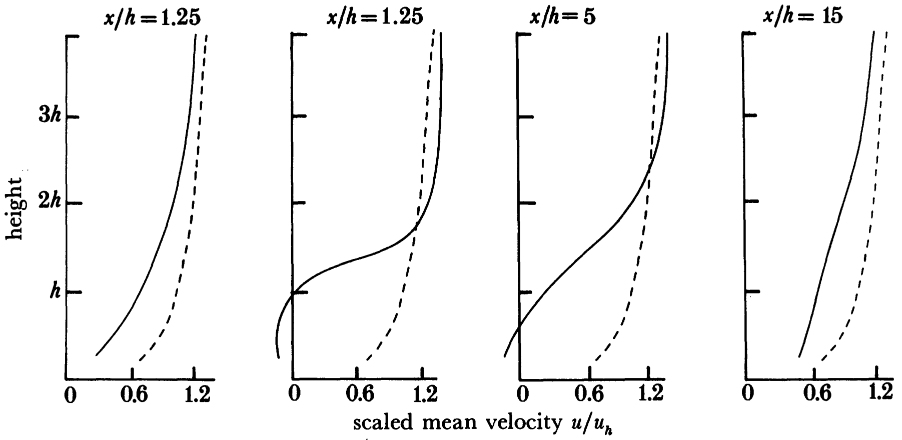

FIGURE 2. Vertical profiles of the mean wind velocity at several distances behind a thin solid barrier in a wind tunnel with $h/z_0 = 110$. The undisturbed profile is indicated by a dotted line in each panel. Values have been normalized by using the wind speed in the open, u_h, at height h. (Adapted from Perera (1981).)

1985). Results measured close to barriers are sensitive to the structure of the barrier and height of the measurement.

The pattern of wind reduction also depends on the turbulence of the oncoming wind. Generally, the more turbulent the wind in the open the less is the protection offered by a windbreak (van Eimern *et al.* 1964). Wind is slowed less and over a smaller distance if h/z_0 is small or h/L is very negative as in unstable conditions. Results collated by Raine & Stevenson (1977) show that, with $\phi \approx 0.5$, relative wind speed, u/u_0, (where u_0 is the wind speed measured at the same height, in the open) at $x/h = 10$ increases from about 0.3 to 0.7 as h/z_0 decreases from greater than 10^4 to less than 40. Instability increases turbulence and has a similar effect, though it is less well documented. The only detailed study is by Seginer (1975), who worked with a porous fence in the field ($h/z_0 = 670$, $\phi = 0.50$). At $z/h = 0.25$ Seginer observed the relative wind speed to increase from 0.5, at $x/h = 10$ during neutral conditions, to 0.8 in very unstable conditions with $h/L = -1.5$. Meanwhile, the minimum relative wind speed increased from 0.33 at $x/h = 5$ to 0.53 at the closer position of $x/h = 3$.

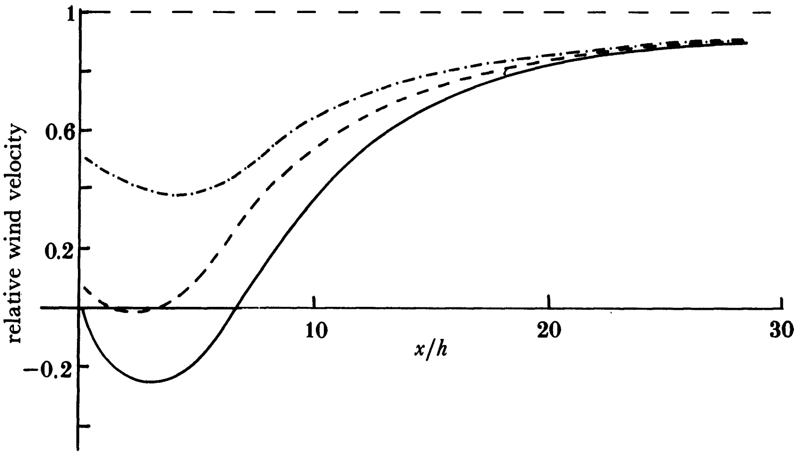

FIGURE 3. Horizontal profiles of the mean relative wind velocity at $z/h = 0.25$ behind barriers with $h/z_0 \approx 100$ and $\phi = 0$ (——), $\phi = 0.3$ (– – –) and $\phi = 0.5$ (· · · · ·). The curves are based on data of Raine & Stevenson (1977) and Perera (1981).

Effects of shelter belts on turbulence

So far, I have considered only the effects of windbreaks on the mean wind. This emphasis arises not so much because reduction of the mean wind speed is the most important effect of shelter, but because it is most easily measured; many more data are available for the mean wind than for any other meteorological element. Turbulence properties such as the shear stress, turbulent kinetic energy per unit mass of air, or the standard deviations of the three components of wind velocity have been less thoroughly explored. We might expect their patterns to stretch or contract, intensify or weaken in step with changes in the pattern of relative wind speed.

Besides its importance for physical understanding and modelling, turbulence is important because the eddies carry heat, vapour and other scalars across wind streamlines. Turbulence helps determine whether a crop near a shelter belt is warmed or coöled, dried or humidified. Turbulent transport depends, in general terms, on both the size and the energy of the turbulent motions, so it is instructive to examine these properties before going on to consider other features of shelter microclimate.

Raine & Stevenson (1977) used the term 'quiet zone' to describe the triangular region between a barrier and a line to the ground at $8h$ behind their barriers. This was the zone occupied by a recirculating eddy behind a solid barrier. Its shape remained much the same behind more porous barriers as bleed flow replaced the rotor. Not only was mean wind speed substantially reduced in the quiet zone, but the longitudinal fluctuations of the wind, σ_u/u_*, were reduced also, and the frequencies were higher (smaller eddies) there than in the open, as shown by the shapes of the spectra in figure 4. That is, energy is transferred from larger to smaller eddies on passing through the barrier.

The vertical fluctuations are reduced also. At $x/h = 2$ and $z/h = 0.5$, Hagen & Skidmore (1971) found σ_w/u_* was smaller in the filtered flow behind porous barriers ($\phi = 0.2$, 0.4 and 0.6) than upwind. Behind a solid barrier σ_w/u_* was larger, but recirculating eddies tended to trap scalars released within them (Sheih *et al.* 1978) so these increased w fluctuations do not necessarily signify enhanced transport of scalars away from the quiet zone.

Above the quiet zone lies a wake zone. Here, a large velocity gradient interacts with a large

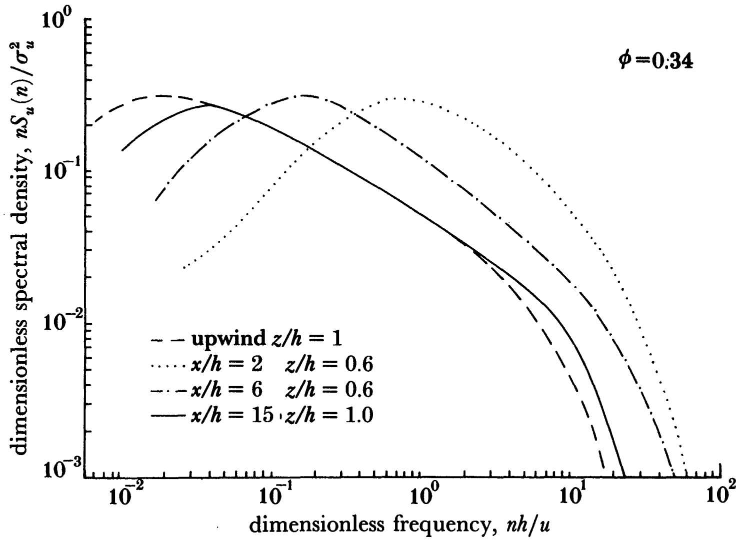

FIGURE 4. Normalized u spectra at positions in the quiet zone, near the edge of the quiet zone and within the wake zone behind a porous barrier ($h/z_0 = 100$, $\phi = 0.34$) in a wind tunnel. From Raine & Stevenson (1977).

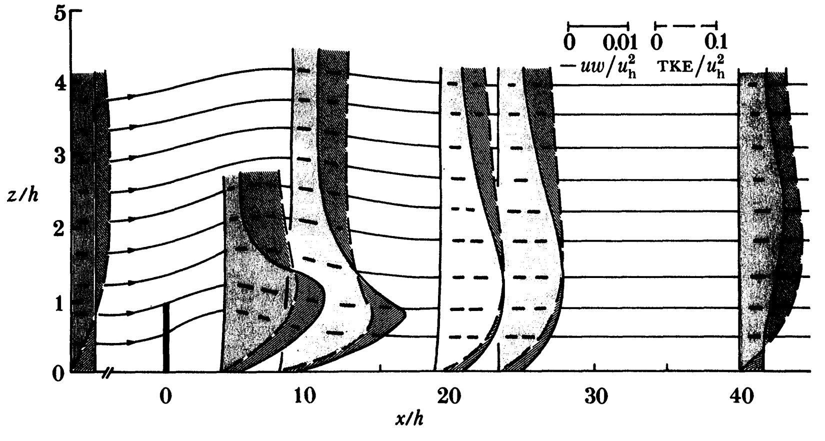

FIGURE 5. Scaled profiles of turbulent kinetic energy and shear stress in the lee of a windbreak ($h/z_0 = 600$, $\phi = 0.5$). From Finnigan & Bradley (1983).

downward momentum flux to produce a great deal of turbulence (Finnigan & Bradley 1983). This wake zone follows, and spreads about, a streamline close to the top of the barrier, reaching the ground beyond the quiet zone. Finnigan and Bradley have measured the distribution of momentum flux, $\overline{u'w'}$, and turbulent kinetic energy (TKE) behind a windbreak in the field ($h/z_0 = 600$, $\phi = 0.5$) in near-neutral stability conditions. Their results are shown in figure 5.

Though TKE is greatly increased in the wake, there are only minor changes in the shape of the u spectrum (figure 4). But Ogawa & Diosey (1980) show this is not true of the important w spectrum, where the peak is moved significantly towards lower frequencies (figure 6). Ogawa & Diosey explain this in terms of the differences between the u and w spectra of the incident wind and the size of the disturbances created by the barrier. In the open field, large eddies on the scale of the whole planetary boundary layer contribute energy to the u and v spectra, but not the w spectrum because vertical wind movements are limited by proximity to the ground. In neutral stability, $\sigma_u/u_* = 2.5$ and $\sigma_v/u_* = 1.9$ whereas σ_w/u_* is much smaller at 1.25, and peak frequency of the w spectrum is much higher than those of the u and v spectra (Panofsky 1985). The turbulence generated in the wake is at an intermediate frequency and its energy is shared among the three components. The effect is that the energy and the sizes of the w fluctuations are both increased in the wake, whereas the sizes of the u and v fluctuations are reduced. This general picture is supported by the data of Hagen & Skidmore (1971), showing that σ_w/u_* in the wake of their porous barriers is increased more than either σ_u/u_* or σ_v/u_*.

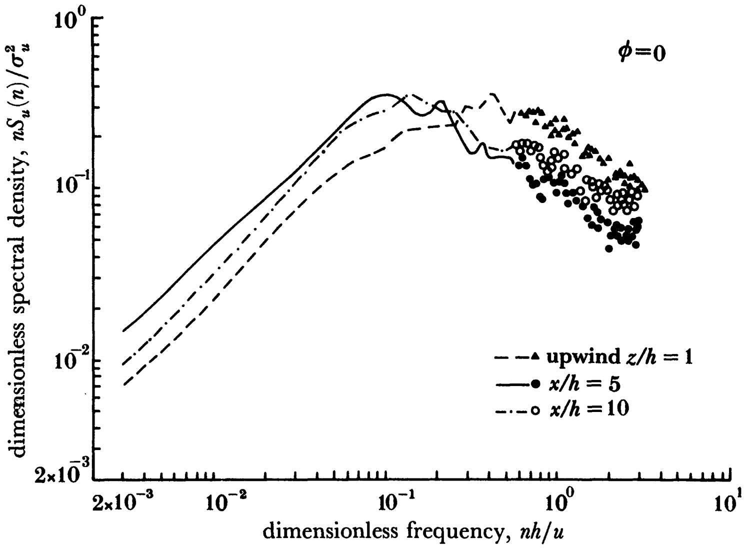

FIGURE 6. Normalized w spectra upwind and at two positions at $z/h = 1$ in the wake of a solid barrier in the field. From Ogawa & Diosey (1980).

Transport of scalars

These results suggest that turbulent transport of scalars is suppressed in the quiet zone and enhanced in the wake zone. That is, the concentration of some scalar, say temperature, is increased in the quiet zone and decreased in the wake zone if a uniform flux of that scalar (sensible heat) is released across the field. This expectation is most clearly confirmed by two experiments in which temperature changes were measured over dry fields. In these experiments the outgoing sensible heat flux, H, would have equalled the available energy, (R_n-G), and been nearly uniform across the field.

In the earlier experiment, Woodruff *et al.* (1959) measured temperature changes behind a dense, multi-row shelter belt. They reported: 'During the day the warm zones were located directly to the leeward of the windbreak and extended in height nearly to the top of it. Leeward extent generally was 5 to 10h. Cool zones... touched the ground between 4 and 8h leeward and beyond'. In the later experiment, Hagen & Skidmore (1971) obtained similar results. They measured temperature changes in the lee of four slatted fences over a field of clipped, dormant grass. They summarized their results in the diagrams reproduced here as figure 7. Again, conditions were warmer upwind near the barrier and cooler beyond 6h or 10h, depending on porosity. Though these results are in qualitative agreement, it is hard to compare the sizes of the temperature changes because they are not scaled.

McNaughton (1988) scaled the changes in equivalent temperature rises, ΔT_e, measured

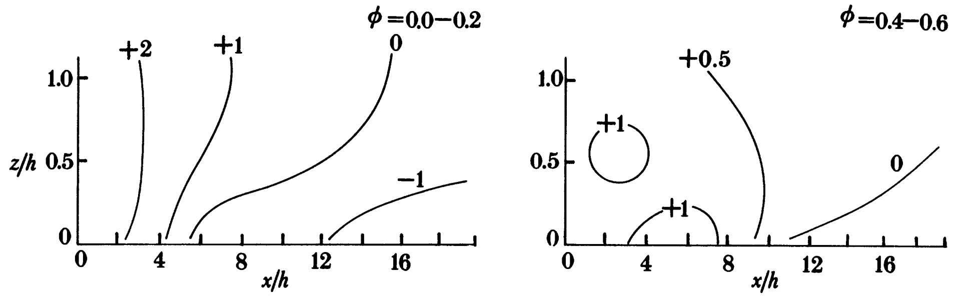

FIGURE 7. Schematic summary of temperature changes measured above a dry field of dormant stubble sheltered by barriers ($h/z_0 = 260$) of various porosities in neutral and unstable conditions. From Hagen & Skidmore (1971).

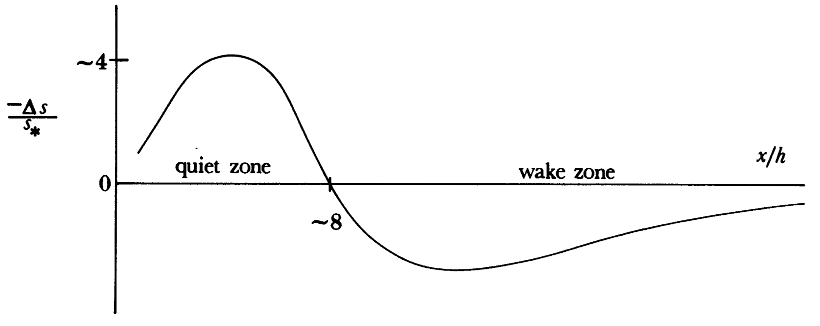

FIGURE 8. Scaled changes in concentration of a scalar, s, behind a barrier ($h/z_0 = 150$, $h/L = 0$, $\phi = 0.5$) in a field with a uniform scalar flux. The curve is drawn from experimental results to $x/h = 9$, and estimated beyond that point. From McNaughton (1988).

behind a fence standing in pasture ($h/z_0 = 150$, $\phi = 0.5$) in near-neutral conditions. The slope of the semi-log plot of the upwind profile of equivalent temperature,

$$T_{e_*} = k(\mathrm{d}T_e/\mathrm{d}\ln z), \tag{4}$$

was used as the scale temperature. Equivalent temperature, T_e, which is defined as $T+q\lambda/c_p$, where q is specific humidity and λ is the latent heat of vaporization of water, is a measure of the total heat content of the air. Its gradient over an open field is proportional to the total heat flux, $H+\lambda E$ where E is the evaporation rate. Available energy, $R_n - G$, would have been almost uniform across the grassed field, so these data are for the change in concentration of a scalar, Δs, with a uniform scalar flux, S, across the field, just as in the experiments of Woodruff *et al.* (1959) and Hagen & Skidmore (1971). McNaughton (1988) has combined results from all these sources to estimate the dimensionless rise in concentration of any scalar, $\Delta s/s_*$, at the ground behind a windbreak with $h/z_0 \approx 150$ and $\phi = 0.5$. In terms of equation (1), the curve shown in figure 8 represents the function $f_s(x/h, 0, 150, 0, 0.5, 0)$.

With the result shown in figure 8 the rise in concentration of any scalar in the lee of any similar barrier in neutral conditions can be estimated, provided the flux of that scalar is uniform across the field. McNaughton (1988) used the drawdown in CO_2 concentration at the surface of a uniformly photosynthesizing crop as an example. However, some fluxes will not be constant across the field. Notably, Miller *et al.* (1973) have reported an upward sensible heat flux from soybeans close behind a shelter fence on some occasions when the flux was directed downwards in the open. Though the total energy flux from a field may be reasonably uniform, the sensible and latent heat components may each be quite variable. However, some useful deductions can be made about the changes of temperature and humidity individually, as shown below.

Near shelter, as in many other situations, the two boundary conditions governing the surface energy balance are the energy conservation law

$$R_n - G = H + \lambda E, \tag{5}$$

and a model describing evaporation from the canopy, for which the Penman 'big leaf' is used:

$$E = \rho D / r_c, \tag{6}$$

where r_c is the canopy resistance and D is a linearized form of the saturation deficit

$$D = q^*(T_0) + s(T - T_0) - q, \tag{7}$$

where $q^*(T_0)$ is the saturation specific humidity at the mean ground temperature, T_0, and $s^* = \mathrm{d}q^*/\mathrm{d}T$ at $T = T_0$.

These boundary conditions were used by McNaughton (1976) to analyse advection downwind of a change in surface properties. There it was shown that the temperature and humidity changes could be calculated from independent solutions for the distributions of equivalent temperature and saturation deficit, provided $(R_n - G)$ was constant. It was also shown that D depends on a new similarity parameter, $p \equiv r_c u_* / (1+\epsilon)$, where $\epsilon = s^*\lambda / c_p$. Similar analysis shows that r_c must appear in the same dimensionless form here, so the similarity law for changes in the scaled saturation deficit, $\Delta D/D_*$, about a windbreak must include this new parameter and take the form

$$\Delta D/D_* = f_D(x/h, z/h, p, h/z_o, h/L, \phi, \alpha), \tag{8}$$

where D_* is calculated from the slope of the undisturbed profile of D. The flux associated with D, $\rho_a \overline{w'D'}$, is equal to $(\epsilon H - \lambda E)$ so D_* is zero when the upwind Bowen ratio equals $1/\epsilon$ (McNaughton 1983). That is, ΔD is zero so D is unchanged behind shelter when evaporation is at the equilibrium rate, $E_r = \epsilon(R_n - G)/\lambda(1+\epsilon)$.

If ΔD and ΔT_e are known then ΔT and Δq can each be found separately from

$$\Delta T = (\Delta T_e + \lambda \Delta D / c_p)/(1+\epsilon) \tag{9}$$

and

$$\lambda \Delta q / c_p = (\epsilon \Delta T_e - \lambda \Delta D / c_p)/(1+\epsilon). \tag{10}$$

Some idea of f_D can be gained by studying limiting cases. At one extreme the surface is wet, with $p = 0$. Then D_o is zero so D/D_* is also zero everywhere at the ground and $f_D(x/h), 0, 0, \ldots)$ will be zero also. At the other extreme the surface is dry so $p \rightarrow \infty$. Then the flux of D, $\overline{w'D'}$, is constant across the field, because $\lambda E = 0$ and H is constant, being equal to $(R_n - G)$. Then f_D must equal f_s, whose form is already known. At intermediate values of p one expects the distinctions between wake zone and quiet zone to be preserved so the general shape of f_D should remain fairly constant as p increases from 0 to ∞. That is, one expects the amplitude of $\Delta D/D_*$ to increase with increasing p, but the shape of f_D to remain more or less fixed. As a first approximation one can write

$$\Delta D/D_* = g(p) f_s(x/h, 0, h/z_o, h/L, \phi, \alpha), \tag{11}$$

where $g(p)$ is a function of p that increases monotonically from 0 to 1 as p increases from 0 to ∞. There are no experimental assessments of $g(p)$.

If the distribution of D at the ground is known, then the evaporation rate can be found from (6). The equation can be shown to be

$$\Delta E/(E_{eq}-E_i) = (1/p)f_D, \tag{12}$$

where E_{eq} is the equilibrium evaporation rate, $\epsilon(R_n-G)/\lambda(1+\epsilon)$, and E_i is the evaporation rate in the open field. Now $(E_{eq}-E_i)$ may be either positive or negative, depending on whether the saturation deficit overhead is larger or smaller than near the ground. The evaporation rate from a uniform crop can either be increased or decreased in the quiet zone, with changes of opposite sense in the wake zone.

In the important agricultural case of protection of irrigated crops from dry winds, evaporation will be depressed in the quiet zone and enhanced in the wake zone. Unfortunately, there is little usable information on the size of the evaporation changes. In one study it was found that the amount by which the upwind evaporation rate exceeded the equilibrium rate from soybeans in the open was halved behind shelter (Miller *et al.* 1973; McNaughton 1983). A semicircular fence was used in this experiment and measurements were made at only one point in the centre, so it is difficult to generalize this result to other windbreaks. Enhanced evaporation in the wake zone has not been noted in the field. Old ideas that only reduced evaporation could be associated with reduced wind speed have not led experimentalists to search for such an effect.

3. Shelter by a forest edge

Similarity laws

It might be expected that the microclimate in the lee of a forest edge would resemble that behind a thin windbreak, but as well as the obvious similarities there are important differences. These differences can be introduced by considering the set of similarity variables for this new situation.

Suppose that the upwind forest is extensive, with equilibrium profiles of wind speed, turbulence properties and temperature developed above it. That is to say, there exists a layer where Monin–Obukhov similarity holds and profile shapes are governed by a new set of the parameters z_0, u_* and L, appropriate to the forest and different from those far downwind of the forest edge. This extends the list of similarity parameters by three beyond those given in equation (2). In addition, a description is needed of the distribution of the foliage with height within the canopy, both in the interior of the stand and at the forest margin, because both of these can affect the emerging wind.

Fortunately, not all of the new parameters are independent of those identified for thin shelter belts. The roughness length for the forest is closely related to forest height, so perhaps only tree height need appear on the list of scale lengths. Similarly, the friction velocity over the forest is related to that over the shorter vegetation (which I call 'grass') far from the boundary because both are coupled to the same larger-scale winds. The foliage density of the forest canopy replaces the porosity used for narrow windbreaks (though in both cases a single value is usually inadequate). Only the new sensible heat flux over forest is largely unrelated to that over 'grass', so a new value of L is needed. In the first approximation, the number of similarity variables, which was already large, is here increased only by another one.

For windbreaks stretching across a uniform field I use u_*, u_h or u_0 as convenient velocity

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scales; 'convenient' because they can be measured easily in the open field nearby. A suitable 'open' location may not exist upwind of a forest, and there is a question as to how far one must go downwind to re-establish 'open' conditions. If the chief interest is in the more obvious microclimatic effects close to the forest edge then the friction velocity measured over the forest is probably the most practical scale velocity, though such a change in scale velocity will make it difficult to compare results for thin shelter belts with results for forest edges. For example, it becomes difficult to talk about variables regaining their values in the open.

Wind flow in the lee of a forest edge

A solid, backward-facing, rectangular step constructed of smooth materials has been studied in the wind tunnel by Bradshaw & Wong (1972). They found that a recirculating eddy forms immediately downwind of such a step, with the eddy extending to $6h$ downwind. This is about one third the length recorded behind thin barriers in similar conditions. Above the recirculating eddy lay a turbulent wake similar to that found behind thin windbreaks. Forest edges differ from this model because forests are both rough and permeable.

Forests create more drag and generate more turbulence than do the smoother 'grass' fields found upwind of thin windbreaks. The equilibrium value of σ_w/u_*, measured in neutral conditions a little way above the canopy, equals 1.25 in either case, but u_* over the forest may be more than double that over 'grass'. This enhanced turbulence should further shorten the distance at which the wake reaches the ground behind a forest edge, so the quiet zone is expected to be very much shorter behind a forest edge than behind a thin shelter belt.

The permeability of forests allows the wind to penetrate downwards into the canopy a little way before the forest edge. Where this penetration begins seems to depend particularly on whether or not the forest wall is densely foliated. Measurements of mean wind speed near a forest edge have been made by Raynor (1971) and Fritschen *et al.* (1969, cited in Fritschen (1985)), in coniferous forests, and by Meroney (1968, 1970) in a forest of plastic 'trees' in a smooth-floored wind tunnel. Meroney observed that wind speed increased above and within the forest canopy over the last $10h$ to the edge. In coniferous forest Fritschen observed acceleration over the last few heights to the edge and Raynor, whose forest had a dense wall of foliage at its edge, recorded very little acceleration of the wind beneath the canopy right to the edge (figure 9).

There is little information on the effect of this wind penetration on the flow in the corner between the forest wall and the ground. Intermittent recirculating eddies at the edges of forest clearings $1h$ and $2.7h$ wide have been observed by Bergen (1975, 1979) using smoke as a tracer, but there are no accounts of rotors in the lee of simple forest edges. In the wind tunnel M. R. Raupach (personal communication, 1988) has observed an intermittent recirculating vortex, about $2h$ or $3h$ long, immediately in the lee of a model canopy made of nylon fibres (Finnigan & Mulhearn 1978). This is the only direct clue as to the length of the quiet zone in the lee of forest edges.

As mentioned above, it is difficult to talk of the 'recovery' (to what?) of the mean wind downwind of a forest edge. Gash (1986) found that the wind sped up fairly rapidly over heath to about $20h$ downwind of a forest edge, then increased more slowly to at least $70h$ (figure 10). A similar result was obtained in the wind tunnel by Mulhearn (1978) for wind speed increase after a step from stone chips to a smooth floor. Mulhearn did tests both with the downwind floor section level with the upwind floor, so the reference height for the wind profile downwind

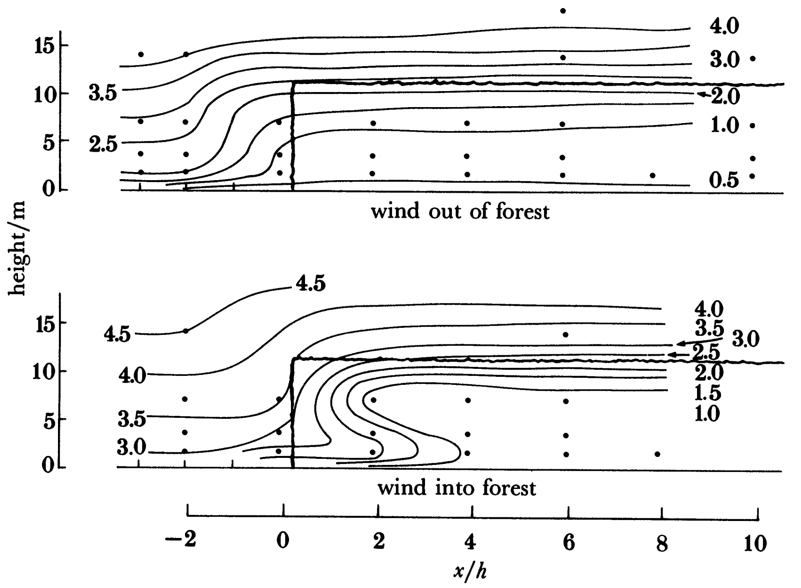

FIGURE 9. Wind speed isolines at the edge of a coniferous forest. The wind out of the forest accelerates over only the last few heights. The wind into the forest penetrates to about $6h$ as a sub-canopy jet. From Raynor (1971).

was lower than upwind and with the downwind floor raised to eliminate the step. By $20h$ downwind both wind speed and shear stress were similar behind the two models. These results suggest that the immediate effect of the step is past by $20h$, but that the wind continues to accelerate over a longer distance as a deeper layer of the atmosphere adjusts to the change of surface roughness. It is probably this two-stage adjustment, together with the lack of a reference windspeed in the open, that underlies the debate, reported by van Eimern *et al.* (1964), on whether narrow shelter belts provide more or less wind reduction at larger distances than wide forests.

Turbulence downwind of a forest edge

There are no measurements of turbulence characteristics in the quiet zone in the lee of a forest edge. We might expect small-scale turbulence from the wakes of individual trees and branches to be carried into this zone from the forest, but these eddies, being small, would be inefficient in the transport of scalars.

In the wake zone behind thin barriers a large amount of TKE is produced by interaction of a strong velocity gradient and a large downward momentum flux. The velocity gradient is weaker in the wake behind a forest edge because the wind has already been slowed over the forest. Shear production of TKE should be less important behind a forest edge. On the other hand, turbulence from above the forest canopy is carried into the wake zone, and this turbulence will decay progressively as the air moves downstream. Although the terms of the budget of TKE will be different, the absolute level of turbulence is another question. Whatever the answer, it appears that wake turbulence decays faster behind forest edges than behind thin barriers. Gash (1986) found that σ_w/u_* settles to its equilibrium value by $x = 20h$ at $z = h/3$ whereas, in a similar location behind a thin fence, σ_w/u_* was still about 50% more than the upstream value in measurements by Hagen & Skidmore (1971).

The most far-ranging effect of a forest is the increased gustiness of the horizontal wind, σ_u. Large eddies in the outer part of the planetary boundary layer over the forest become

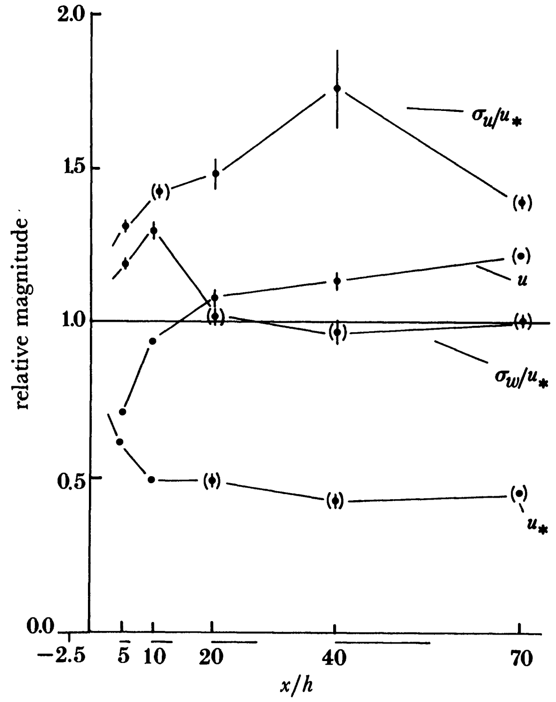

FIGURE 10. Horizontal profiles of wind speed, u, friction velocity, u_*, and scaled standard deviations of the horizontal and vertical wind fluctuations, σ_u/u_* and σ_w/u_*, respectively, measured at $z/h = \frac{1}{3}$ over heath in the lee of a forest edge. Bars on the x/h axis represent the range of distances accepted in finding each average point. Adapted from Gash (1986).

conditioned to its rough surface. These large eddies contribute mainly to the horizontal fluctuations, σ_u, and σ_v, because vertical movements are restricted by proximity to the ground, and they adjust slowly to the smaller roughness of the downwind area (Beljaars 1987; Hojstrup 1981). Gash's results (figure 10) illustrate the point, showing that σ_u/u_* is still far from its equilibrium value at $70h$ from the forest edge, even though σ_w/u_* and u_* are fully adjusted by $20h$ (Gash 1986).

Effects on temperature and humidity

The number of similarity variables needed to describe the changes in temperature and humidity near a forest edge is unmanageably large. The forest and grass surfaces have their own separate energy budgets, so new temperature and humidity scales must be added to the growing list of similarity variables. Conditions in the quiet zone will reflect the temperature and humidity of the air flowing out from the trunk space beneath the forest canopy, and these conditions must be represented in addition to the fluxes above the canopy. This illustrates the limitations of an empirical approach to problems of this complexity; with so many dimensions it becomes impractical to collect enough experimental data to flesh out the similarity skeleton. Without dynamical transport models to provide interpretation, experimental results remain merely anecdotal.

In the present case there are very few anecdotes. Geiger (1966) reported that almost no measurements had been made of the microclimate of forest edges and the situation seems to have changed little since. Geiger reports some measurements made by W. Ludi and H. Zoller, of air temperatures at 10 cm above ground at the time of the daily maximum at the southern

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(sunny) edge of a forest. They measured a temperature of 18.4 °C some 20 m into the forest, 22.2 °C at the forest edge, possibly in the quiet zone, 20.0 °C at 35 m from the edge, possibly in the wake zone, and 21.6 °C at 100 m where recovery towards open conditions might be expected. Forest height was not given in Geiger's summary.

It remains to be asked how conditions downwind of wide shelter belts or forest strips whose width is neither very large nor very small compared with their height might vary between the two extremes that we have examined. To discuss this we must look briefly at the flow about the leading edge of a forest, i.e. the field-to-forest transition.

The field-to-forest boundary

When the wind arrives at a solid step it is deflected upwards and accelerates over the top in much the same way that the wind is deflected by a thin, solid barrier. A similar corner eddy forms in front of the step and the flow separates at the top edge and reattaches further downwind. A recirculating eddy occupies the separation bubble.

This pattern is modified at a forest edge where the wind can move through the trunk space as well as upwards through the canopy. Usually the space beneath the tree crowns is more open than the upper canopy, so the wind penetrates further there and forms a jet. An example is shown in figure 9, from Raynor (1971). After some distance an 'equilibrium' wind speed profile becomes established within and above the forest. Meroney (1968, 1970) observed equilibrium wind speed profiles after about $20h$ from the leading edge of his plastic forest in the wind tunnel, whereas in coniferous forests Naegeli (1953, cited by van Eimern *et al.* (1964)), Raynor (1971) and Fritschen (1985) found the 'equilibration' distance to be $8.5h$, $6h$ and $3h$, respectively. Gash (1986) also found that u, $\overline{u'w'}$, σ_u/u_* and σ_w/u_* measured at 13.5 m above ground in a 10 m forest were well adjusted at $12h$ downwind.

These results show a rapid adjustment that is substantially complete by about $10h$ from the forest edge. Slower adjustment continues for some distance as the new internal boundary layer develops over the forest and the increased surface drag is felt at higher and higher levels. An indication that this larger-scale adjustment is incomplete at $40h$ is given by the low value of σ_w/u_* over the forest relative to that over the heath measured by Gash (1986); at equilibrium, both values should be the same at about 2.5.

A separation bubble forms on the top of solid steps and this probably still exists within the upper part of denser canopies. The evidence for this is indirect; windthrow of forest trees sometimes occurs not at the very edge of a clearing but in the zone from a few heights to about $10h$ downwind. Somerville (1980) gives some particularly striking examples and notes that damage starts right at the edge only for very open stands. M. R. Raupach (personal communication, 1988) has observed an intermittent recirculating eddy and large turbulence intensities in the upper part of a model canopy in this zone. Cionco (1985) reported that smoke released at ground level in unstable conditions rides up and over a leading forest edge, to penetrate the canopy some 10–$20h$ downstream.

Overall, the flow is complex for about the first $10h$ from a forest edge, often with a jet in the trunk space and probably an intermittent rotor above and within the upper canopy. Beyond that the flow reattaches and a new, raised profile develops as the whole planetary boundary layer adjusts to the increased surface drag.

Temperature and humidity conditions within the canopy appear to settle down in a shorter distance. The data of Fritschen (1985) and Miller (1980) show that even at the leading edge

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the temperature and humidity in the upper canopy are within 1 °C and 0.1 kPa of their final values. This is as expected because the temperature and humidity at canopy-top height (approximately 10 m) in the open are closely coupled to the values overhead in the bulk of the planetary boundary layer. Conditions in a forest canopy are similarly linked to overhead conditions because of the large roughness (McNaughton & Jarvis 1983). The new forest energy balance becomes established almost immediately.

Shelter belts with width comparable to height

Wide shelter belts with widths comparable to their height are transitional cases between extensive forests (width $\gg h$) and thin windbreaks (width $\ll h$). In these cases the new similarity variable W/h must be considered, where W is the width of the strip of trees. Unfortunately, there appears to be no new information on this subject since the review by Van Eimern *et al.* (1964). I can do no more than comment on a few points raised in that review and suggest some possible points to consider in further work.

The performance of wide shelter belts of rectangular cross section will bridge the two extremes of forest edges and thin windbreaks. One might ask the range of widths over which the transition takes place is. Van Eimern *et al.* (1964) are necessarily vague on this point because the sources quoted were not in agreement. For belts up to a few tree-heights wide, they find the prevailing opinion to be that wide belts give similar shelter to narrow belts of similar porosity. To these observations, based on reduction of the mean, I can add the comment that the patterns of temperature change measured by Hagen & Skidmore (1971) behind a thin barrier are qualitatively similar to those measured by Woodruff *et al.* (1959) behind a 10-row shelter belt about $4h$ wide.

A point of interest is the remark attributed by Van Eimern *et al.* (1964) to N. P. Woodruff and A. W. Zing that 'quite different conditions of flow supervene if the width of belts is considerably greater than their height'†. That is, there is a suggestion of a sudden change in the nature of the flow rather than a smooth transition. If so then this probably relates to the question of whether the flow, which may separate intermittently at the leading edge, has reattached before the step back down to grass. Bradshaw & Wong (1972), talking of flows about solid models where two separations occur, say that the length of the second separation region depends strongly on the inclination of the separation streamline from the first separation. All of this is very vague and amounts to no more than a few points to consider when planning future experiments on the micrometeorology of wide shelter belts.

4. Conclusion

Similarity methods have served well in the study of thin windbreaks. A great deal of information has been organized so that our understanding of the micrometeorological effects of simple shelter belts on level ground is quite good, if far from complete. However, this empirical approach is well stretched, with four or more major similarity parameters to set for each experimental map.

The present attempt to extend the similarity analysis to forest edges and wide shelter belts is largely unsuccessful, both because the number of dimensions is increased and, more

† The bibliographic reference is in error; the paper referred to does not contain this remark.

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especially, because the amount of empirical data is much less. Expense and logistical difficulties in working with arrays of instruments spanning forest edges means that the large amounts of requisite information will not be gathered easily. Little work has been done in wind tunnels. The alternative route for progress lies in the development and testing of dynamical transport models. This seems more feasible.

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Discussion

M. H. Unsworth (*Department of Physiology and Environmental Science, University of Nottingham, U.K.*). The influence of shelter on evaporation rate may be because of decreased wind speed or because of altered saturation deficit. Is it possible to generalize to indicate the relative importance of these terms?

K. G. McNaughton. One of the conceptual errors in the past has been to relate the spatial pattern of changes in evaporation near shelter to changes in relative wind speed. The error arises because in open fields wind speed and turbulent diffusivities are simply related; a change in wind speed with time leads to a proportional change in diffusivity. Near shelter the changes in wind speed with position are not simply related to change in eddy diffusivity. It is the turbulent transport properties of the wind that are important.

A useful way of looking at shelter is to regard the changes in size scales and energies of the turbulent motions as changing the coupling between the saturation deficit at the ground and that overhead. I have used this approach in an earlier paper (McNaughton 1988). The surface saturation deficit in the quiet zone is more decoupled from the saturation deficit overhead than it is in the open, whereas conditions in the wake are more coupled. The effect of these changes in coupling on the local surface evaporation rate will depend on the saturation deficit of the air overhead: whether it is larger or smaller than the equilibrium evaporation rate. Equation (12) of this paper is an alternative statement of the same result.

M. R. Raupach (*CSIRO, Canberra, Australia*). The vortices observed by smoke visualization behind model forest trailing edges, i.e. in the wind tunnel, are highly intermittent, unlike those behind a solid barrier. Recirculation only appears systematically for 20–30% of the time. Would Dr McNaughton please comment on this?

K. G. McNaughton. I rely on Dr Raupach's data here, so I accept the experimental facts as he outlines them. The use I make of this information is to estimate the size of the quiet zone in the lee of a forest edge. I expect this to be much smaller behind a forest edge than behind a thin shelter belt, because the geometry of the step seems to favour a smaller quiet zone and because the wind over forests is more turbulent than winds over fields near shelter belts. Dr Raupach's observation of a recirculating eddy behind his model canopy of only $2h$ or $3h$ downwind extent is my only measure of this. Its intermittency, but probably not its size, depends on the canopy density.

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