Secondary Wind Speed Maxima Inside Plant Canopies

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ABSTRACT

It is noted that wind profiles measured in forest and crop canopies normally contain a secondary maximum or a region of very small shear beneath the level of greatest foliage density. One-dimensional models utilizing a turbulent transport coefficient cannot predict a reversed velocity gradient and, as a result, profile analyses normally imply coefficients that are unrealistic or nonsensical. Examination of the equation for the local rate of change of Reynolds stress $\overline{u'w'}$ shows that the velocity gradient can reverse in sign if the divergence of the turbulent transport of stress is of opposite sign and exceeds in magnitude the pressure-velocity gradient correlation. Direct measurements of the turbulent transport of $\overline{u'w'}$ in corn (*Zea mays* L.) indicate that its value is considerably larger than in the air layers above and show that stress is transported downward from the upper parts of the vegetation. A one-dimensional model of canopy flow which solves the equations for momentum, Reynolds stress and the three components of turbulent kinetic energy, without relating the stress to the mean velocity gradient, predicts a weak secondary maximum in the wind profile for a corn canopy.

1. Introduction

Mean wind speeds have been observed to increase to varying degrees in the lower portions of a variety of plant stands. The effect appears to be most noticeable within forest canopies having a trunk space relatively free of branches where air movement is less restricted (Fig. 1). Fons (1940), Bergen (1971) and Oliver (1971, 1975), for example, recorded definite maxima in mean wind speed within the trunk space of pine forests with minimum speeds approximately in the region of greatest foliage density. Likewise, a local maximum was noted in a wind profile within a Japanese larch plantation, after needle fall, by Allen (1968). Landsberg and James (1971) show evidence of the wind increasing within an orange plantation and within a spruce forest, while Geiger (1965) shows the effect in both a thin fir stand and a mature oak forest. The presence of an understory appears to decrease the relative magnitude of the canopy wind maximum or eliminate it completely (Reifsnyder, 1955).

Lemon et al. (1970) discuss their observations of the same phenomenon in a tropical rain forest and suggest that this feature is unique to forest wind profiles setting them apart from agricultural crops within which, they say, wind speeds tend to decrease monotonically with decreasing height. There is evidence, however, that a small increase in wind speed occurs in the lower part of some wheat (Legg and Long, 1975) and corn canopies (Allen, 1975), and other reports have shown observed wind speeds nearly constant with height in the lower part of corn (Uchiyama and Wright, 1964) and a bean crop (Thom, 1971). Fig. 2 illustrates three of these profiles and it is apparent that the feature is less pronounced in such canopies. This is probably a result of a more uniform vertical distribution of vegetation.

A difficulty arises in explaining the phenomenon under discussion because it implies that, in canopies of large and uniform horizontal extent, a portion of the canopy exists in which momentum is transported (downward) in the direction of increasing mean wind speed. One-dimensional models of canopy flow utilizing a flux-gradient relationship cannot predict a reversal in the velocity gradient and attempts to calculate a turbulent diffusivity using the momentum balance approach (Wright and Brown, 1967) can result in nonsensical values if the wind shear reverses in direction (Legg and Long, 1975) or complex, S-shaped profiles of diffusivity (Thom, 1971). Others (e.g., Landsberg and James, 1971) have not considered the analysis of the wind profile in the lower parts of the canopy because of this problem.

For this reason, Monteith (1973) has proposed that secondary wind maxima are probably a consequence of horizontal advection rather than vertical transfer of momentum through the main foliage layer. Similarly, Allen (1968) concluded that observed wind

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measuring winds within spruce on sloping terrain, have discounted this effect because their wind maximum was apparent regardless of wind direction.

Finally, Oliver (1971) found the wind speed maximum in pine to increase with increasing instability, as indicated by a Richardson number measured above the forest. He proposed that the effect is associated with convective activity, such that plumes leaving the upper canopy draw up air from within the trunk space increasing the scalar wind speed in that region. It should be recognized that the observed dependence upon stability does not in itself imply that the phenomenon thus described is the major cause of the wind maximum. Reifsnyder (1955) has also compared wind profiles in forest stands under lapse and inversion conditions and has concluded that the secondary maximum, while still existing, is not as sharply defined under inversion conditions. In corn, Uchijima and Wright (1964) found no significant thermal effects although their measurements were made during both superadiabatic and inversion conditions.

It has been concluded that no single proposal provides adequate explanation for the phenomenon under all situations, although each may be an important contributory factor under the appropriate conditions. Further, the proposals imply that one-dimensional models cannot adequately represent this feature of canopy flow. It is the purpose of this report to show that, within a more suitable framework, increased wind speeds within the lower portions of vegetative canopies can be accounted for by one-dimensional vertical transport of momentum through the denser upper foliage.

2. Air flow within vegetation

Under steady-state conditions the air flow within vegetation is represented by a balance between the rate
of change of momentum flux and the drag force of the plant parts per unit volume (Saito, 1964). When horizontal advection can be neglected, this balance is usually written

$$\frac{\bar{u}'w'}{dz} = -C_d A \bar{u}^2$$

(1)

where $\bar{u}'w'$ is the Reynolds stress, $C_d$ an effective drag coefficient for the plant parts, $A$ the vegetation surface area per unit volume and $\bar{u}$ the horizontal wind speed. The overbar signifies either 1) a spatial average over a horizontal distance large compared with distances between canopy elements and with the largest scales of motion contributing to the momentum transport, or 2) a combination of a spatial average over a horizontal distance large compared with distances between canopy elements and a time average that is large compared with the time scales of the momentum transport. Experimental measurements of flow statistics, on the other hand, are usually made at a fixed location with temporal averaging and the two procedures may not yield the same results if the nature of the vegetation is such that significant spatial variations in the flow occur.

Since the soil surface is a sink for momentum, (1) implies that the Reynolds stress must be negative throughout the depth of the canopy and increase in magnitude with height monotonically. It does not impose any such restriction upon the shape of the mean wind profile.

Eq. (1) cannot be solved without further information concerning the turbulent transport. Most frequently in canopy flow modeling a flux-gradient model is assumed such that

$$\frac{\bar{u}'w'}{dz} = -K_m \frac{\partial \bar{u}}{\partial z}$$

(2)

where $K_m$ is a turbulent transport coefficient which sensibly can take only positive finite values if the fluid is to be diffusive. This step imposes a restriction upon the form of the wind profile because the wind gradient can now take only values that are opposite in sign to that of the Reynolds stress and the mean wind speed must increase monotonically from zero at the soil surface. This limitation arises because of the imposition of the flux-gradient model and is not implied by the basic flow equation.

The flux-gradient model has been used extensively in boundary layer work but suffers from several fundamental objections (Lumley and Panofsky, 1964), some of which become especially critical when the theory is applied to canopy flow. Legg and Monteith (1975) have pointed out that flow statistics change rapidly with height in the canopy region and characteristic distances over which flow properties can be considered to be changing at a uniform rate can be smaller than appropriate scales of the transporting mechanism. It is unlikely, therefore, that a realistic transport model could be constructed incorporating a turbulent diffusivity. Thurtell (personal communication) has demonstrated that the apparent diffusivity for a quantity transported to or from an elevated horizontal plane is dependent upon the height of that plane. This is equivalent to Taylor's (1959) "illogical conception" in which the apparent diffusivity for material emitted from a point source is dependent upon the location of that source as well as local flow conditions. In a plant canopy in which the sinks for momentum, and the sources or sinks of heat and water vapor, are distributed over a finite vertical distance, and not necessarily in the same manner, one should not expect to be able to develop a consistent transport theory based upon a flux-gradient relationship.

An alternative to parameterizing the Reynolds stress in the above fashion is to develop a dynamic equation for the stress (e.g., Hinze, 1959). Incorporating the Boussinesq approximations, neglecting terms involving molecular viscosity and the pressure transport term (Mellor, 1973), and assuming horizontal homogeneity, neutral buoyancy and steady-state conditions, this equation is

$$\frac{\partial \bar{u}'w'}{\partial t} = -\frac{\partial \bar{u}'w'}{\partial z} \frac{\partial \bar{u}}{\partial z} + \rho' \left( \frac{\partial \bar{u}}{\partial z} + \frac{\partial \bar{w}}{\partial x} \right)$$

(3)

The first term on the right-hand side of (3) represents the shear production of stress due to the interaction of the turbulent field and the mean velocity gradient. The generation of the triple velocity product contained in the second term is the contribution to the rate of change of stress due to the net turbulent transport of stress from other regions. The final term contains correlations between fluctuations in kinematic pressure $\rho$ and fluctuating velocity gradients, and acts to decrease the absolute value of the Reynolds stress by reducing the correlation between velocity components (Hinze, 1959). This process is related to the tendency to "return to isotropy" represented in the normal stress budget equations by similar pressure-velocity gradient correlations. The presence of the vegetation does not introduce any additional term or terms into the tangential stress budget equation when the stress is defined according to the averaging procedure previously described, although it may do so on a local scale in the vicinity of individual plants or plant parts.

In the lower atmosphere but above any region occupied by vegetation or other obstructions to the flow, the Reynolds stress changes only slowly with height compared with changes in the mean wind
speed and its derivative (constant stress layer). For this reason, it is expected that the divergence of the turbulent transport of stress does not contribute significantly to the Reynolds stress budget. Thus, under steady-state conditions, the stress will be determined by an approximate balance between the rate of shear production and the rate of destruction by the pressure-velocity gradient correlation. If the pressure-velocity gradient correlation acts to decrease the absolute value of the Reynolds stress, it must be opposite in sign from that of the stress. This being the case, examination of (3) shows that the mean wind gradient must also have opposite sign to the stress requiring that momentum be transported in a downgradient direction.

The situation is somewhat different inside a region occupied by vegetation in a way that can significantly influence the relationship between the mean wind gradient and the Reynolds stress. This arises because the rate of transport of momentum decreases with height from a maximum at the top of the canopy to only a small fraction of this value at the soil surface if the foliage is reasonably dense. Momentum is generally absorbed most strongly in the upper part of the vegetation (see, e.g., Shaw et al., 1974) and the Reynolds stress decreases rapidly with decreasing height in this region. Consequently, the triple velocity product representing the turbulent transport of stress will be considerably larger inside the canopy than above, and will result in a net transport of Reynolds stress from the upper part of the canopy to lower regions. Thus, except in the upper levels, the second and third terms on the right-hand side of (3) will be of opposite sign to each other, and if the magnitude of the term involving the stress transport exceeds that of the pressure-velocity gradient correlation, i.e., if

\[
\frac{\partial \bar{u}' \bar{w}'}{\partial z} > \rho \left( \frac{\partial \bar{u}'}{\partial z} + \frac{\partial \bar{w}'}{\partial x} \right),
\]

it is seen that the mean wind gradient can reverse in direction and produce a secondary maximum in the wind profile.

A secondary wind maximum is therefore allowed by the existence of the triple velocity correlation but the identification of this mechanism is, of course, not proof that it is responsible for the wind profile bulges actually observed in plant canopies. No direct measurements have been made of all of the terms in the Reynolds stress budget equation in such an environment, but evidence is presented to indicate that within a corn crop (Ze a mays L.), the gradient of the triple velocity product can be at least comparable in magnitude with estimates of the pressure-velocity gradient term. It is expected that in forest canopies with a more open structure below a denser crown, the criterion expressed by the inequality (4) will be more readily satisfied since stress will be transported downward more easily.

A similar argument could be presented based upon the equation for turbulent kinetic energy since viscous dissipation acts only in the direction of converting kinetic energy into internal energy. However, the balance of turbulent kinetic energy in a plant canopy is complicated somewhat by the presence of a term representing the generation of turbulent energy in the wakes behind obstacles to the flow. The action of this mechanism makes the argument a little less certain.

It can also be seen that the stability of the air, particularly in the lower levels, will influence the magnitude of the triple velocity term by inhibiting or promoting the vertical exchange of all transportable quantities, and would probably affect the magnitude of the profile bulge in the manner observed (Oliver, 1971; Reifsnyder, 1955).

Since net momentum transport is directed downward at all levels, countergradient transport exists in a region where the wind gradient reverses and a diffusivity defined by (2) has no physical significance. It is suggested that larger scales of motion transport momentum downward to the regions where the profile bulge is observed, while smaller scales transport momentum upward according to the local gradient. This mechanism has also been proposed by Legg and Long (1975) but no cospectral estimates have yet been presented in direct support of this belief.

It is noted that in the situation described, in which the mean wind decreases with height, the mechanical production of stress due to the interaction of the turbulent field and the mean velocity gradient changes sign and tends to create stress in the opposite direction to that of the existing stress. The shear production of turbulent kinetic energy must also be negative in this region and represents an exchange of energy from the turbulence to the mean flow. This is not found, in general, in the atmosphere free of the influence of obstructions to the flow such as vegetation.

3. Direct measurements

To compute the divergence of the transport of stress directly it is necessary to measure the quantity \( \bar{u}' \bar{w}' \bar{w}' \) at more than one height but, to the author's knowledge, no data have yet been presented that permit this computation within a plant canopy. Direct measurements at a single height have been made, however, of the triple velocity products \( \bar{u}' \bar{w}' \bar{w}' , \bar{u}' \bar{w}' \bar{v}' \) and \( \bar{u}' \bar{w}' \bar{v}' \) from tape recorded data collected during an experiment inside a corn crop at Elora, Canada. Details of the experiment were reported by Shaw et al. (1974). The measurements were made using a directionally sensitive hot-film anemometer at a height of 1.8 m when the crop was approximately 2.8 m tall.
Mean velocities, covariances and triple velocity products were computed without filtering from analog instrument signals previously stored on magnetic tape using an FM tape recorder. During the computation a coordinate transformation was applied to make the mean values of the vertical and transverse velocities equal to zero.

Table 1 presents the results of the computations for six consecutive 15 min runs made on 8 October 1971. They are shown in nondimensional form using the above-canopy friction velocity $u_\infty$, defined by $u_\infty^2 = -\overline{u'w'}/(h)$, where $h$ is the canopy height, for normalization. The triple velocity products representing the transports of the tangential stress and the normal stresses were positive and negative, respectively, indicating a downward and downgradient transport in each case.

The average normalized $\overline{u'w'/w'}$ at the measurement height was 0.64. It is estimated that this is approximately two orders of magnitude larger than the same quantity in the “constant stress” layer but well away from the surface of the vegetation, at least under neutral conditions. Furthermore, since the soil surface does not act as a sink for $u'w'$ as it does for momentum, the triple velocity product must decrease to zero at the bottom of the canopy and the stress transported downward from above and from the upper part of the vegetation must converge within the lower portions of the vegetation. Because of the limited vertical extent of this region, it is expected that the divergence of the transport of stress will reach values that are much larger than in the layers well above. The average value for this term of the stress budget for the region below the measurement height in the crop was calculated, in nondimensional form, as

$$\frac{h}{u_\infty^2} \frac{du'w'w'}{dz} = 0.99. \quad (5)$$

It does not appear to be feasible to measure the pressure-velocity gradient correlation at the present time, for comparison with the transport term, but the following section contains estimates of the budget terms predicted from a canopy flow model that incorporates the stress and turbulent kinetic energy equations (Wilson and Shaw, 1976). The measured transport and average transport divergence values provide some evidence for the validity of the model.

Table 1 also includes data for the transport of the components of (twice) the turbulent kinetic energy per unit mass. The mean value of $-1.91$ for $\overline{\theta^2 / u_\infty^2}$, where $\overline{\theta^2} = u'^2 + v'^2 + w'^2$, is somewhat larger than measurements made at close to neutral stability in the surface boundary layer by Garratt (1972), Banke and Smith (1973), Wyngaard and Coté (1971) and McBean and Elliot (1975) as interpreted by the latter authors. In addition, the value measured in the canopy implies a downward transfer of turbulent kinetic energy while the reports listed above generally indicate a net upward transport. The divergence of the transport will also be much larger within the vegetation since the kinetic energy is transported into a shallow layer. It is expected, therefore, that the divergence of the transport of turbulent energy would be an important term to the total budget of turbulent kinetic energy.

4. Model predictions

A canopy flow model has been described by Wilson (1975) and by Wilson and Shaw (1976) in which five equations are solved: the budget equations for mean momentum (1), the Reynolds stress (3), and each of the three components of turbulent kinetic energy, for the same five unknown quantities under steady-state, horizontally homogeneous conditions. The turbulent kinetic energy equations are those shown by Hinze (1959) with an additional term in the equation for the longitudinal component to account for the generation of turbulence due to the flow separation around plant parts.

In order to solve the equation set it is necessary to parameterize the higher order terms generated, including the triple velocity products and the pressure-velocity gradient correlations of interest here.
Generally, the parameterization schemes followed those described by Mellor (1973) with a gradient diffusion model being used for the transport of the tangential and normal stresses. A length scale is required for this and for each of the other submodels and was prescribed as a function of the density and drag properties of the vegetation and the height above the surface such that the length \( l \) is continuous and assumes the maximum possible value allowed by

\[
\begin{align*}
  l &= 0, \quad z = 0 \\
  l &\leq \alpha/(C_d A), \quad 0 < z < h, \\
  |dl/dz| &\leq k, \quad z > 0
\end{align*}
\]

where \( \alpha \) is a constant and \( k \) the von Kármán constant assumed equal to 0.4. The effective drag coefficient \( C_d \) and the constant \( a \) were chosen to obtain the best fit to observed canopy flow data (Shaw et al., 1974). Other constants were set by requiring the model to reproduce the observed structure of the constant stress layer. Models formulated in this manner have been successful in predicting various properties of the surface boundary layer (e.g., Mellor, 1973) and it was assumed that the same relationships could be applied to the airflow inside the vegetation.

Numerical techniques were used to solve the equation set on a linear height grid with 40 intervals, half of which were located within the canopy. Boundary conditions were specified at the soil surface and at twice the canopy height \( h \).

It is appreciated that a gradient diffusion model is not entirely adequate for the transport of the tangential stress since \( u'w' \) becomes constant in magnitude immediately above the surface of the vegetation whereas this quantity is certainly transported downward into the canopy from higher levels. In partial answer to this problem, smoothing was applied to the gradient of the stress in the calculation of \( u'w' \). The effect was to allow the transport to reduce to zero at some height above the vegetation rather than at \( h \) and to smooth out the otherwise large positive peak in the divergence of \( u'w'/w' \) near the top of the vegetation. The influence of this action was rather minor in the lower half of the vegetation and had little effect on the relative magnitudes of the budget terms.

Figs. 3 and 4 show the predicted profiles of mean longitudinal velocity and Reynolds stress, using plant area measurements for a corn crop, and their comparison with hot-film anemometer measurements (Shaw et al., 1974). The mean wind profile has the same general form as those measured in corn and other agricultural crops illustrated in Fig. 2. It exhibits a relatively constant mean wind in the lower third of the canopy and contains a weak secondary maximum that is quite similar to those observed in corn and wheat.

The magnitudes of the three terms in the Reynolds stress equation are shown in Fig. 5. The height interval through which the velocity gradient reverses sign corresponds to that in which the predicted divergence of the stress transport exceeds in magnitude the pressure-velocity gradient correlation although both assume quite small values in the lower portion of the canopy. It is noted that through the same interval the shear production reverses sign, tending to create stress in the opposite direction from that of the existing stress.

The predicted \( u'w'/w' \) and hence its divergence are smaller than observations reported in the previous section. Since the crop had deteriorated somewhat by the time anemometer signals were recorded for the triple velocity measurements, it is appropriate to compare observed and predicted values of the normalized \( u'w'/w' \) at the height at which \( u'w' \) was the same proportion of the above-canopy stress. Thus,
observed and computed values of $\overline{u'w'}/\overline{u_w^2}$ averaged 0.64 and 0.44, respectively, at the height at which $\overline{u'w'}/\overline{u_w^2}$ was $-0.66$. This suggests that the model does not, at least, overestimate the magnitude of the transport term but empirical modification to force $\overline{u'w'}/\overline{u_w^2}$ to match observed values does not appear to be justified.

5. Summary and conclusions

Doubt has been cast upon the usefulness of one-dimensional models of transport in the air layers of plant canopies because of their reliance on gradient diffusion theory. The difficulty is illustrated when the theory is applied to the vertical transport of horizontal momentum since mean wind profiles frequently exhibit a bulge, or regions of very small wind shear, in their lower levels which lead to unrealistic or nonsensical values of apparent diffusivity. The intent of this report is to show that, within a more suitable framework, this feature of canopy flow can indeed be explained by the application of a one-dimensional model.

Examination of the equation for the local rate of change of Reynolds stress shows that countergradient transport of momentum can occur if the divergence of the transport of stress is of opposite sign and exceeds in magnitude the pressure-velocity gradient correlation. This latter term tends to destroy Reynolds stress but in the lower canopy its effect is offset by the net influx of stress from higher levels. Normally the turbulent transport $\overline{u'w'}/\overline{u_w}$ has negligible effects upon boundary layer flow but direct measurements inside corn indicate that its influence is appreciably larger, and it is suggested that, in canopies with a relatively open structure near the bottom, it leads to the development of the familiar secondary wind maximum.

A mathematical model of canopy air flow, which solves the budget equation for Reynolds stress as well as the equations for mean horizontal momentum and the three components of turbulent kinetic energy, indicates that a secondary wind maximum, or at least a region of small wind shear, is to be expected in a canopy having relatively small leaf population beneath a denser crown. Higher order terms in the stress and turbulent energy equations were modeled in the manner described by Mellor (1973) for an environment free of obstructions to the flow. If the assumption can be made that these schemes are valid for canopy flow, the results of the flow model support the argument proposed in the previous paragraph. Presumably, large scales of motion transport momentum directly from above the vegetation to the relatively open lower levels. A gradient diffusion model in which the transport of momentum is related directly to the local wind gradient cannot account for such a phenomenon.

It is not suggested that two- or three-dimensional effects such as blow-through and those of isolated clearings or thermal influences are unimportant; canopy inhomogeneities and buoyancy effects will influence the flow but should be considered as supplemental to a basic regime that already includes increased wind speeds near the surface.

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