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The dependence of canopy layer turbulence on within-canopy thermal stratification

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ABSTRACT

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Transport properties near the Earth's surface are strongly influenced by the thermal stratification of the atmosphere. Until now, no distinction has been made between thermal stability parameters within and above a plant canopy, and it has been usual to classify canopy transport processes in terms of above-canopy stability parameters only. The question arises, however, whether such parameters adequately describe within-canopy properties because it is often the case that thermal stratification differs considerably between air layers above and below the top of the canopy. In the present study, two within-canopy thermal stratification parameters have been defined and tested to determine whether they yield additional information about canopy turbulence. It appears that a within-canopy bulk Richardson number provides useful information under low-wind nocturnal conditions. Strongly unstable conditions inside dense canopies commonly occur at night when the air layers above the canopy are very stable, resulting in a decoupling between the above- and within-canopy regions. A local within-canopy Obukhov length proved to be less useful, perhaps because the sensible heat flux within the canopy was nearly always directed upwards, regardless of the temperature gradient. A penetration length scale, defined for daytime conditions only, was of the order of the height of the canopy. This suggests that the height of the canopy is a suitable length scale for within-canopy processes.

INTRODUCTION

Thermal stratification within a dense plant canopy often differs considerably from that just above a canopy. During the daytime, the mean air temperature profile above a plant canopy is unstable, mainly due to a surplus of incoming short-wave radiation which is largely absorbed in the upper region of the stand. For the same reason, and because the shaded ground surface beneath tends to remain cool, an inversion develops within the canopy layer.

During the nocturnal period, the opposite is observed. Mainly because of the loss of long-wave radiation, the above-canopy stratification becomes stable, while the within-canopy stratification often shows a clearly unstable stratification due to the supply of heat from the soil (Hosker et al., 1974; Jacobs and Van Boxel, 1991).

Because the two layers have opposing stratification, it could be assumed that the exchange processes of heat, mass and momentum differ between the two regions. On the other hand, it could be argued that thermal stratification defined in terms of mean temperature gradients has direct influence only on the small-scale motions, and that large scales are governed by some bulk temperature difference between the vegetation and the air aloft. If the large scales are dominant, it might still be possible to define a single stability parameter for both above- and within-canopy exchange processes.

In the atmospheric surface layer well above the vegetation layer ($z \gg d+z_0$), Monin–Obukhov similarity theory provides a satisfactory treatment to the influence of stability on turbulence structure. In this region, the dimensionless ratio $(z-d)/L_{\mathrm{out}}$, where L_{out} is the above-canopy Obukhov length, is effective in explaining changes in the atmospheric properties resulting from thermal stratification.

Within-canopy processes have been less extensively investigated and the question arises whether the same stability parameters derived from above-canopy data can be used. Based on a study of wind flow in a deciduous forest, Shaw et al. (1988) found that turbulence levels inside the forest rapidly diminished as the ratio h/L_{out}, where h is the tree-top height, became increasingly more positive. However, considerable scatter in the data existed, especially under fully leafed conditions, and it is possible that specific effects of canopy level stratification are important.

This paper reports an analysis of the behavior of within- and above-canopy vertical wind fluctuations under various states of thermal stratification. The data were obtained during a detailed outdoor experiment within and above a maize crop at an experimental pilot farm located in the center of the Netherlands.

EXPERIMENTAL SETUP

In addition to a continuous measurement program in which the fluxes of heat, mass and momentum were studied above a maize crop (Jacobs and Van Boxel, 1988), a more detailed turbulence experiment was carried out at the pilot farm Sinderhoeve (51°58′N, 5°42′E) during 2 weeks in July 1986. Above the crop, the mean wind profile was measured with cup anemometers at 11 levels, and the mean temperature and moisture profiles were measured at two levels with aspirated psychrometers. At a height of 4.5 m, a three-dimensional sonic anemometer (Kaijo Denki type DAT-310), an additional fast-response thermometer and Lyman-α humidity sensor were installed. A Funk net radiometer was erected 6 m above the ground.

Within the crop, mean wind speed and temperature profiles were measured with hot-sphere anemometers (Stigter et al., 1977) and fine-wire thermocouples (Van Asselt et al., 1991), respectively, at heights above the ground of 0.1, 0.2, 0.3, 0.4, 0.7, 1.0 and 1.4 m. Moreover, a one-dimensional sonic anemometer (Kaijo Denki type PAT-110) oriented to measure the vertical component of the wind, an additional fast-response thermometer and Lyman-α humidity sensor were installed at a height of 0.7 m.

The maize crop (*Zea mays* L., cv. Vivia) was planted in rows 0.75 m apart with plants separated by 0.11 m within the row. The dimensions of the experimental site were 250 m × 300 m. The fetch to height ratio for the data used in the present paper was at least 40:1. The experimental site was surrounded by agricultural fields, among which mainly maize was grown. During the detailed turbulence experiment, the crop growth had reached the end of the vegetation state, had a height of 1.70 m and a one-sided leaf area index of 3.6.

Signals from the instruments were routed to a mobile van about 100 m from the measurement site. Fast-response instruments were sampled at a rate of 10 Hz, while the slow-response instruments were sampled at 1 Hz. The unconditioned data were recorded on digital magnetic tape for analysis at a later time. Additional details concerning the measurement techniques are provided in Jacobs and Van Boxel (1991).

RESULTS

In the scattergram of Fig. 1, a comparison has been made between the above-canopy standard deviation of the vertical wind component $\sigma_{\mathrm{w,out}}$ and the within-canopy value $\sigma_{\mathrm{w,in}}$. The statistics are 30 min averages. Data are presented in four classes: daytime ($R_n > 0$, where R_n is the above-canopy net radiation) for low wind speeds ($u^* < 0.35$ m s^{-1}) and strong wind conditions ($u^* > 0.35$ m s^{-1}), and night-time conditions ($R_n < 0$) for low and strong wind speeds. Lines through the origin with slopes of 0.15 and 0.24 have been drawn for guidance in evaluating the relationship between $\sigma_{\mathrm{w,in}}$ and $\sigma_{\mathrm{w,out}}$. The particular choice of these lines has been made to ensure that the bulk of the daytime measurements lie within the envelope of these lines. The unbiased line through the daytime points, however, has a slope of 0.22.

The results clearly show that a distinct difference exists between daytime and night-time situations, and low and strong wind speed conditions. Of special interest is the observation that the standard deviation of vertical velocity inside the canopy does not continue to decrease as the above-velocity variations diminish to small values. Under low-wind-speed and low-turbulence conditions, generally at night-time, we continued to measure significant vertical velocities inside the canopy and, in fact, found periods when $\sigma_{\mathrm{w,in}}$ exceeded $\sigma_{\mathrm{w,out}}$.

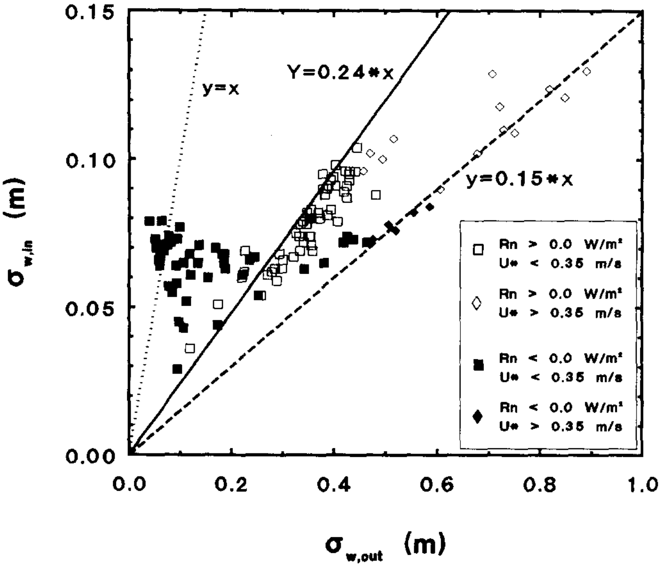

Fig. 1. A comparison between the standard deviation of vertical velocity above the canopy, $\sigma_{\mathrm{w,out}}$, and within canopy (at $z=0.4\,h$), $\sigma_{\mathrm{w,in}}$. Open symbols, $R_{\mathrm{n}}>0$; solid symbols, $R_{\mathrm{n}}<0$; diamonds, $u^*>0.35$ m s^{-1}; squares, $u^*<0.35$ m s^{-1}.

Let us define a bulk Richardson number, $\mathrm{Ri}_{\mathrm{in}}$, for the within-canopy thermal stratification

$$\mathrm{Ri}_{\mathrm{in}}=\frac{g \quad T(z_2)-T(z_1)}{T[u(z_1)-u(Z_2)]^2}(z_2-z_1) \qquad (1)$$

where we have selected the heights $z_2=1.4$ m and $z_1=0.0$ m. In Fig. 2, the ratio between the two standard deviations, $\sigma_{\mathrm{w,in}}/\sigma_{\mathrm{w,out}}$, has been plotted versus this within-canopy stability parameter. Most of the data points cluster around the near-neutral $\mathrm{Ri}_{\mathrm{in}}=0$ state. Only during the low-wind-speed nighttime situations, when $\mathrm{Ri}_{\mathrm{in}}$ became large and negative (locally unstable), did there exist a clear dependence on this stability parameter. The ratio increased more or less linearly with increasingly negative values of the stability parameter, yielding a linear regression of $\sigma_{\mathrm{w,in}}/\sigma_{\mathrm{w,out}}=-0.0133\,\mathrm{Ri}_{\mathrm{in}}+0.243$ ($r=0.93$ and $N=126$).

Another possible way to characterize the within-canopy thermal state is to define a local within-canopy Obukhov stability length

$$L_{\mathrm{in}}=-\frac{\kappa T u_{\mathrm{in}}^{*3}}{g(\overline{w'T'})_{\mathrm{in}}} \qquad (2)$$

where, u_{in}^* and $(\overline{w'T'})_{\mathrm{in}}$ are the local within-canopy friction velocity and sensible heat flux, respectively, κ is Von Karman's constant, T is the temperature

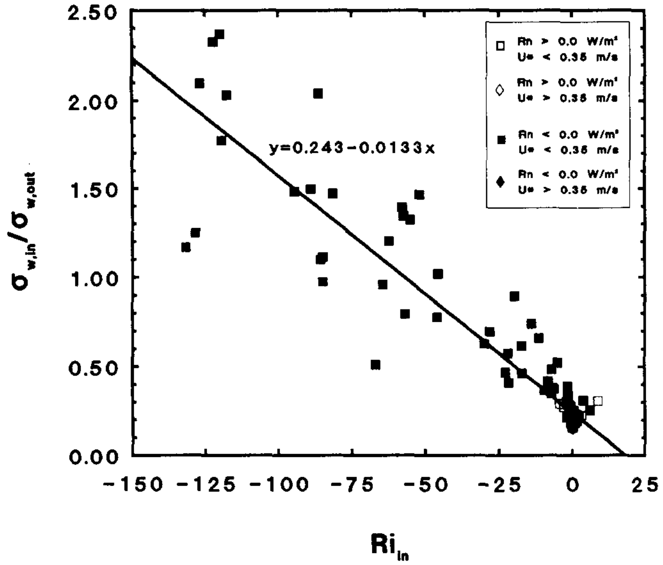

Fig. 2. The ratio of the within-canopy vertical velocity standard deviation ($\sigma_{w,in}/\sigma_{w,out}$) versus the within-canopy Richardson number (Ri_{in}). The symbols are the same as in Fig. 1.

and g is gravity. Since the sonic anemometer located at 0.7 m was undirectional, measuring only the vertical wind, it was necessary to estimate u^*_{in} from $\sigma_{w,in}$. For the adiabatic surface layer, it is commonly reported that $\sigma_{w,in}/u^*$ is of the order of 1.3 (e.g. Haugen et al., 1971), but smaller ratios have been calculated from observations in plant canopies (Shaw et al., 1974, 1988) and in the present study it is assumed that $u^*_{in} = c\sigma_{w,in}$, where $c = 1$. Equation (2) is very sensitive to errors in the u^*_{in} assessment. That is why periods with very low values of u^*_{in} ($u^*_{in} < 0.01$ m s^{-1}) have been ignored in the present analysis.

In Fig. 3, the ratio $\sigma_{w,in}/\sigma_{w,out}$ versus h/L_{in} has been plotted. It can be seen that the new graph differs considerably from the previous one. The parameter L_{in} is nearly always negative as a result of the fact that, during daytime, the short-wave radiation load within the canopy maintained an upward sensible heat flux despite a weak canopy layer inversion. During the night-time, the sensible heat was again upward due to the soil heat flux and latent heat flux by dew formation (Jacobs et al., 1991). For fine days, only during the transient period after sunrise was the within-canopy sensible heat flux downward, reversing the sign of the stability parameter. Occasionally, a downward within-canopy sensible heat flux also occurred during unsettled weather with strong wind conditions.

When the vertical velocity standard deviations ratio is plotted (as in Fig. 4) against the quantity h/L_{out}, where L_{out} is the Obukhov length calculated from above-canopy fluxes, the result is nearly a mirror image of Fig. 3. This is because of the reversal in the sign of the stability parameter between within-

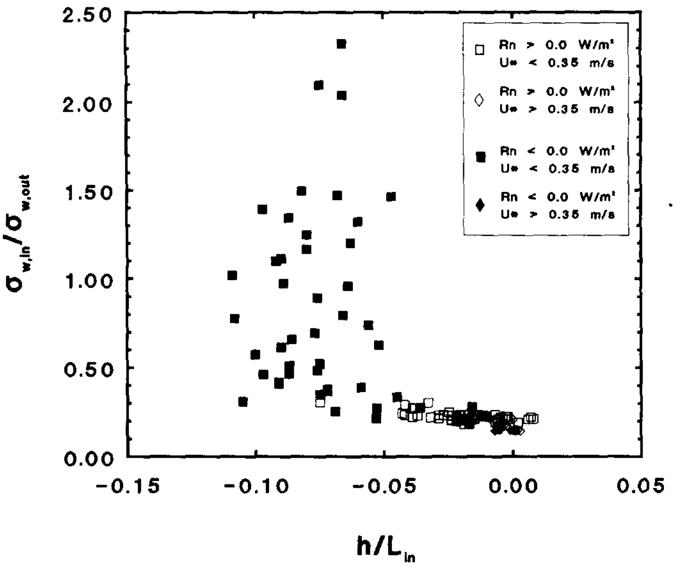

Fig. 3. The ratio of the within-canopy vertical velocity standard deviation, $(\sigma_{w,in}/\sigma_{w,out})$ versus h/L_{in}, where L_{in} is the local within-canopy Obukhov length scale at 0.4 h. The symbols are the same as in Fig. 1.

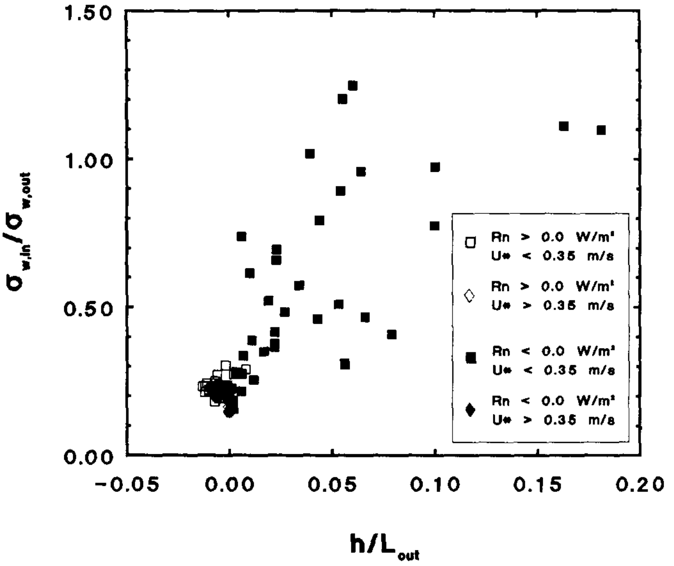

Fig. 4. The ratio of the within- to above-canopy vertical velocity standard deviations $(\sigma_{w,in}/\sigma_{w,out})$ versus h/L_{out}, where L_{out} is the above-canopy Obukhov length (four points $h/L_{out} > 0.20$). The symbols are the same as in Fig. 1.

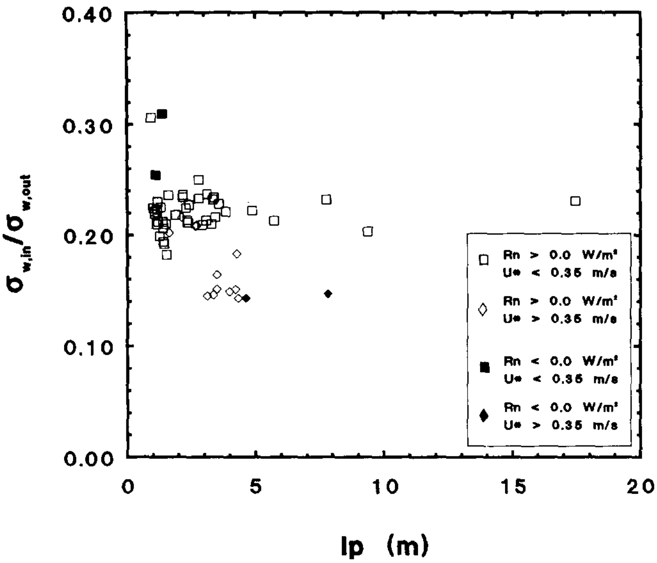

Fig. 5. The ratio of the within- to above-canopy vertical standard deviations ($\sigma_{w,in}/\sigma_{w,out}$) versus the penetration depth l_p (three points $l_p > 20$ m). The penetration depth is defined as $l_p = \sigma_{w,out}/N$, where N is the Brunt–Vaisala frequency. The symbols are the same as in Fig. 1.

and above-canopy layers during night-time low-wind conditions. Unlike the results of Fig. 3, however, low-wind daytime observations tend to depart little from neutral stability.

During the daytime, a weak inversion usually existed within the canopy, suggesting that eddies from above the crop might, to some extent, be prevented from penetrating into the canopy. The extent to which a stable temperature profile inhibits penetration into the canopy should depend on the within-canopy inversion. To examine this possibility, we define a penetration length scale, $l_p = \sigma_{w,out}/N$, where N is the Brunt–Vaisala frequency (Tennekes and Lumley, 1972). For those cases when the canopy temperature profile indicates a stable stratification, the ratio $\sigma_{w,in}/\sigma_{w,out}$ has been plotted in Fig. 5 versus this penetration length scale, l_p. The results suggest that no dependence exists and that stable temperature gradients in the canopy, which are observed mostly during the daytime, have little or no influence on canopy turbulence levels.

DISCUSSION AND CONCLUSIONS

The ratio of the standard deviations of vertical velocity measured within and above the canopy behaves differently between daytime and night-time (Fig. 1). During night-time, in low-wind conditions, vertical velocity fluctuations are maintained within the canopy despite decreasing turbulence levels above, which suggests that a decoupling occurs between the above- and within-canopy regions. This nocturnal state under low-wind-speed conditions is the result of radiation cooling at the canopy top and the presence of the soil beneath which stays relatively warm at night. This situation could be compared with the convective atmospheric boundary layer (Driedonks, 1982), with the difference that the thickness of the within-canopy well-mixed layer remains virtually constant, whereas the daytime boundary layer grows. However, when there is a strong wind speed above the canopy, the coupling between both regions is recovered. Figure 1 also reveals that during the daytime most $\sigma_{\rm in}/\sigma_{\rm out}$ ratios lie between 0.15 and 0.24, where there is a clear tendency for the ratio to decrease with increasing wind speed.

The constancy of the $\sigma_{\rm w,in}$ values during calm nights can also suggest other internal causes, such as drainage, edge effects or mechanical movement of the maize. During these nocturnal periods, however, the above-canopy wind speed fell to values far below 1 m s^{-1}, consequently mechanical movements of the relative stiff maize plant elements must be excluded. Moreover, the terrain itself is extremely flat (sloping less than 0.2%) and was surrounded by fields with the same conditions. Consequently, drainage or edge effects have to be ignored as well.

Decoupling between layers is most usual when the lower atmosphere is stable. At night, the upper layer may be stable above the canopy, thus exhibiting little turbulence, but what turbulence does occur should be easily passed to the unstable layer below.

Major variations in the ratio $\sigma_{\rm w,in}/\sigma_{\rm w,out}$ occur during the nocturnal conditions described above, while a within-canopy Richardson number ($\mathrm{Ri}_{\rm in}$) accounts for these variations quite well (Fig. 2). During the daytime and night-time with strong wind speeds, when $\mathrm{Ri}_{\rm in}$ is positive or near neutral, the ratio $\sigma_{\rm w,in}/\sigma_{\rm w,out}$ scatters around the numerical value 0.2.

As an alternative representation of canopy layer stability, the local Obukhov length is less successful than the Richardson number. The ratio $\sigma_{\rm w,in}/\sigma_{\rm w,out}$ shows large scatter for numerical values of $h/L_{\rm in}$ less than -0.05 (night-time with low wind speeds) while, for values of $h/L_{\rm in}$ greater than -0.05, this ratio tends to approach a constant value of 0.2. A primary difference between the Obukhov length and the bulk Richardson number is that the former is based on a measurement of turbulent heat flux, while the latter is determined by the temperature difference between two levels. For the data we collected in the maize canopy, temperature gradients more clearly distinguish between daytime and night-time, even though such gradients are the opposite of those measured above the crop, while the heat flux remains mostly positive regardless of whether the stand is under radiative gain or loss. This inability of the local Obukhov length to separate day and night observations by sign is the likely reason for the poorer results shown in Fig. 3 compared with those of Fig. 2.

The results of Fig. 4 appear to be in sharp contrast to those of Shaw et al. (1988), in which forest turbulence activity was seen to decline sharply with the onset of nocturnal conditions. It is not obvious why the maize and forest results differ so greatly, but it is clear that the mechanism maintaining vertical velocity variance at night in the maize was not operative in the forest.

The penetration depth, l_p, is always larger than 1 m and remains mostly within an order of magnitude of the canopy height. This suggests that the canopy height must be an appropriate length scale for within-canopy processes (Jacobs and Van Boxel, 1988; Raupach, 1988). Since no clear relationship was found between the penetration depth and the ratio of within- and above-canopy variances, the length scale of the downdrafts is judged to be much larger than the height of this canopy. It is likely that canopy layer stability affects the small eddies only and will provide resistance to these eddies as they try to enter deep into the canopy.

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