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11.1

WIND SPEED AND AIR TEMPERATURE CHARACTERISTICS WITHIN A DENSE VEGETATION CANOPY

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1. INTRODUCTION

Air movement as well as the air temperature just above and within a row crop canopy is characterized by complex interactions of the air mass above and within the canopy. The air characteristics far above a horizontally homogeneous canopy behaves two-dimensionally. In the vicinity of the top of the canopy, in the so-called roughness layer, the state of the flow becomes more complex. Large deviations from the spatially averaged mean value can occur due to direct sensing of individual roughness elements by the flow. Here, the mean flow becomes essentially three-dimensional and spatially very variable. As a rule of thumb, we may expect that the vegetation layer lies between $0 < z < (d + z_o)$ and the roughness layer between $(d + z_o) < z < (d + 20\ z_o)$, where d is the displacement height and z_o is the roughness length. Within the canopy, between the roughness elements, this three-dimensional behaviour will be enhanced, since there the flow is completely disturbed by canopy elements.

During daytime there is a strong intrusion of air from above to the canopy air space due to the passage of so-called coherent structures. This means there is a strong coupling between the flow from above and within the canopy. During night-time a different process can take place. Through radiative cooling at the top of the canopy the above flow stabilizes. However, through cooling at the top and heat from the soil the within-canopy flow destabilizes.

It is our purpose here to delineate some of the characteristics of canopy flows. In particular our objectives are: first, to examine the governing scaling parameters of the within-canopy wind speed and air temperature profiles; second, to investigate the type of within-canopy transport mechanism during daytime and night-time.

2. THEORY

Under a steady state and a thermally stratified atmosphere, the wind speed profile and the temperature profile near the earth's surface in the surface layer ($z > d+20\ z_o$) can be adequately described by the profiles:

$$\begin{aligned} u(z) &= (u^*/k)\{\ln((z-d)/z_o) - \Psi_m((z-d)/L)\} \\ T(z)-T(d+z_o) &= (T^*/k)\{\ln((z-d)/z_o) - \Psi_h((z-d)/L)\} \end{aligned} \qquad (1)$$

where u(z) and T(z) are the mean wind speed and mean air temperature, respectively, at height z, d is displacement height, z_o is roughness length, u* is the friction velocity, T* is the scaling temperature defined by $T^* = -\overline{w'T'}/u^*$, k = 0.4 is Von Karman's constant, L is Obukhov's stability length scale and Ψ_m and Ψ_h are stratification correction functions for momentum and heat, respectively.

During daytime the within-canopy processes are dominated by the large eddy exchange mechanism (Finnigan and Raupach, 1987; Jacobs et al., 1992). Under these conditions it is to be expected that an appropriate within-canopy scaling velocity and scaling temperature will be equal to the above-canopy friction velocity, u*, and scaling temperature, T*, respectively. During night-time with strong wind conditions, the exchange mechanism is also expected to be dominated by the above-canopy flow regime, and the velocity and temperature regime is expected to scale with u* and T*, respectively.

At night under low wind speed conditions, however, a decoupling between the above and within-canopy processes develops. Then, within the canopy a free convection state occurs in which free convection cells are generated by the relatively warm canopy floor (Jacobs et al., 1992). Above the top of the vegetation, the air is stabilized by radiative cooling and thus the unstable vegetation layer is capped and thereby decoupled from the above-canopy region.

At night within a canopy, the crop height and the buoyancy flux at the floor are the two variables important to this free convection state. Combining these scales yields a free convective velocity scale, w*, and a free convective temperature scale, θ*, (Tennekes & Lumley, 1972):

$$\begin{aligned} w^* &= [(h\ g/T)\ \overline{(w'T')_o}]^{1/3} \\ \theta^* &= -\ \overline{(w'T')_o}]/w^* \end{aligned} \qquad (2)$$

where, g is gravity, h is canopy height and $\overline{(w'T')}_o$ the kinematic heat flux at the soil surface. An appropriate estimate at night-time for the kinematic heat flux at the floor is $\overline{(w'T')}_o \sim q_s/(\rho c_p)$, where q_s

is the soil heat flux at the ground and (ρc_p) the volumetric heat capacity of air, since during nighttime most of the soil heat flux at the base of a reasonable dense canopy is transformed into sensible heat (Garrat & Segal, 1988).

3. MATERIALS AND METHODS

A detailed turbulence and within-canopy experiment was carried out at the pilotfarm Sinderhoeve (51°59'N, 5°45'E) during two weeks in July, 1986. Only instruments important for this study will be discussed here.

Above the crop, the mean wind profile was measured with cup anemometers at eleven heights above the ground. The above-canopy wind profiles were used to calculate the two surface characteristics: d and z_0. The mean temperature and moisture were measured at 2 levels at heights 2.0 and 4.0 m with aspirated psychrometers. At a height of 4.5 m, a 3-D sonic anemometer (Kaijo Denki, model DAT-310) and an additional fast-response thermometer and a Lyman-α humidiometer were installed. These instruments provide data about the above-crop thermal stratification.

Within the canopy, at 0.25 D between the rows, the mean wind speed profile was estimated with hot-sphere anemometers at heights above the ground: 0.1, 0.2, 0.3, 0.4, 0.7, 1.0 and 1.4 m. Moreover, within the canopy, at 0.25 D between two rows, the mean temperature profile was estimated with fast-response thermometers at heights above the ground: 0.0, 0.1, 0.2, 0.3, 0.5, 0.7, 1.0 and 1.4 m. The thermometers were based on the thermocouple principle.

A 1-D sonic anemometer (Kaijo Denki, model PAT-110) plus an additional fast-response thermometer and a Lyman-α humidiometer were installed at a height of 0.7 m inside the canopy to measure the within-canopy transport of heat and water vapour.

The maize crop (Zea Mays L., cv Vivia) was planted in rows 0.75 m apart with plants 0.11 m apart in the row. The rows were orientated NNE-SSW. During the present experiments, the crop was at the end of the vegetative state, and had a height, h, of 1.70 m and a one-sided plant area index, PAI, of 3.6.

The fast-response thermometers were sampled at 5 Hz. All other fast-response instruments were sampled at 10 Hz, while all slow-response instruments were sampled at 1 Hz. The signals were carried to a mobile measurement van, about 100 m from the instruments. Here, the unconditioned data were dumped on a digital magnetic tape for later analysis.

4. RESULTS

Two days with quite different weather regime have been selected for a detailed analysis. July 29 was a windy day with intermittent cloudiness while July 30 was a moderate fine day with less wind and a more regular irradiation pattern.

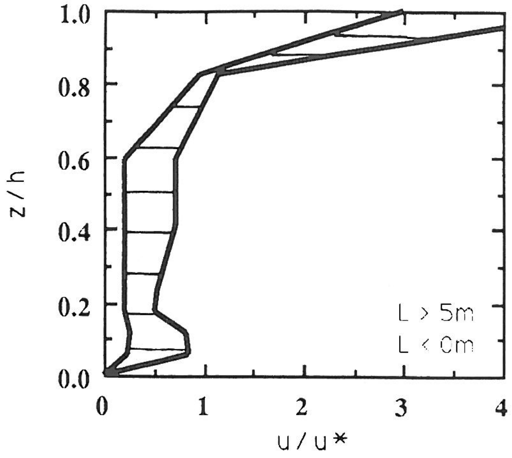

Fig. 1. The envelope of the wind profiles within the corn canopy under neutral and unstable thermal stratifications.

In figure 1 the envelope has been depicted between which the 30 minutes means of the within-canopy wind speed profiles fit. The data have been selected for a thermal stratification range (L > 5 m and L < 0 m). The heights have been nondimensionalized with the height of the canopy, and the wind speeds have been nondimensionalized with the friction velocity, u*. It can be concluded from this result that the dimensionless profiles are more or less similar in shape under near-neutral and unstable stratification and scale well with the above-canopy friction velocity, u*.

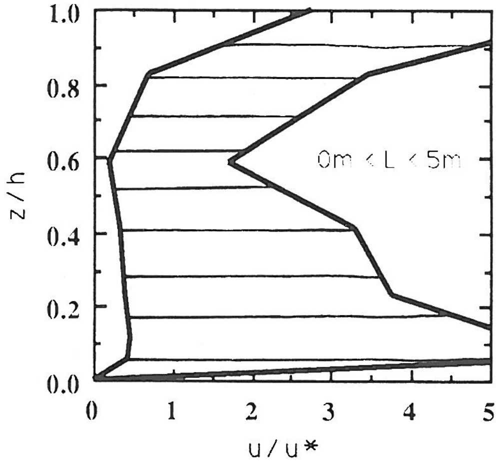

Fig. 2. The envelope of within-canopy wind speed profiles under extreme above-canopy stable conditions (0 m < L < 5 m).

In figure 2, the envelope has been given for mean wind speed profiles selected for above-canopy very stable conditions (0 m < L < 5 m). These situations occur during the nights, when the top of the canopy cools by radiation losses while at the floor of the canopy the air is forced by the soil heat flux. Under these conditions, the within-canopy air is statically unstable and decoupled from the above-canopy region. Within the canopy, and in particular in the lower region of the canopy, a free convection state occurs in which free convection cells are generated by the relatively warm canopy floor. This result shows that the envelope is extremely wide under very stable conditions, which suggests that then the above-canopy friction velocity, u*, is not a suitable scaling parameter for within-canopy processes.

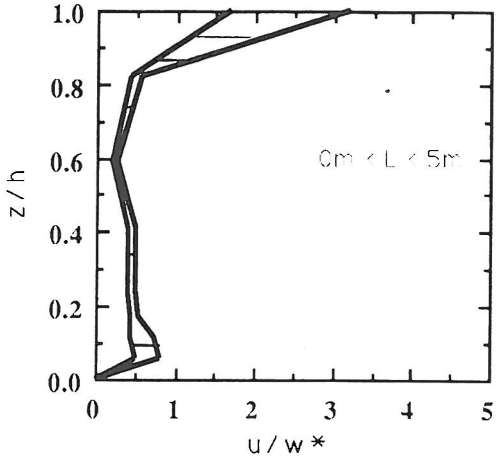

Fig. 3. The envelope of within-canopy wind speed profiles under extreme above-canopy stable conditions (0 m < L < 5 m).

In figure 3, the same night-time results have been nondimensionized with the free convection scale, w*. From this result it can be inferred that, under above-canopy very stable stratification, the within-canopy free convection scaling velocity, w*, is indeed a much better scaling parameter than the above canopy friction velocity scale, u*.

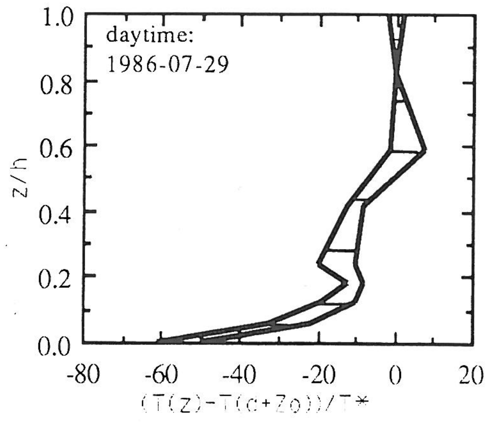

Fig. 4. The envelope of the within-canopy air temperature profiles during daytime.

The result depicted in figure 3 also reveals that the absolute wind speed profiles under above-crop very stable conditions show a clear minimum at a height of z/h = 0.6. This suggests that the free convection height is more or less restricted to this level; below z/h = 0.6 the free convection states dominates; above this height the wind speed forcing from above the canopy dominates. It is interesting to note that the height z/h = 0.6 coincides with the maximum of the plant area distribution.

In figure 4, the envelope has been plotted in which the day-time profiles of the dimensionless temperature difference occur, $(T(z)-T(d+z_0))/T^*$. Here, the day-time temperature profiles are nondimensionalized with the scaling temperature, T*. The procedure has been executed in the same way as it follows from general theory for the above canopy state. In the present study, the displacement height and roughness length have been assumed to be $d = 0.75h$ and $z_0 = 0.25(h-d)$, respectively. This means that the height, $d+z_0$, agrees well with an inside canopy level of $z = 1.4$ m. It can be inferred from the results of figure 4 that the dimensionless profiles for a particular day are similar in shape under above-canopy neutral and unstable stratification and scale well with the above-canopy scaling temperature, T*.

In figure 5, the results have been plotted for calm night-time situations when the above canopy stratification was stable (5m > L > 0m) and the wind speed was low ($u(10m) < 2\ ms^{-1}$). Here, the profiles of the temperature difference, $(T(z)-T(d+z_0))/\theta^*$, have been non-dimensionalized with the free convection temperature scale θ*. It can be inferred from this result that the dimensionless profiles are more or less similar in shape under above-canopy stable stratification and scale well with the within-canopy free convection temperature scale, θ*.

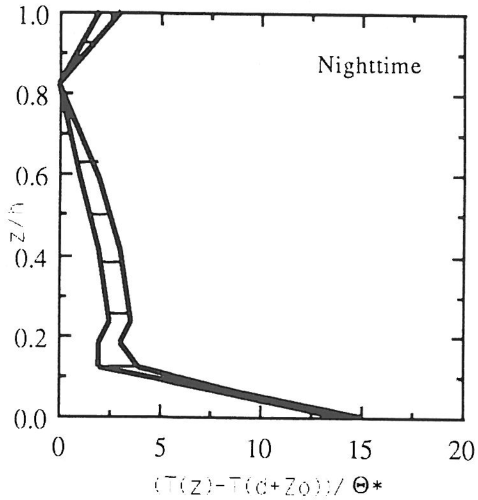

Fig. 5. The envelope of the within-canopy night-time temperature profiles.

During night-time, the above-crop wind speed drops with a resulting decrease in the friction velocity, u*, while the within-canopy free convection velocity, w*, will be of increasing importance. Jacobs et al. (1992) found that within the above-canopy thermal stability range of 0 m < L < 5 m, the within-canopy wind speed profile scales excellently with the free convective velocity scale. From figure 6 it is shown that this situation agrees with periods when the convective velocity scale, w*, exceeds the friction velocity scale, u*.

It is of interest to find out if, when the free convective scale, w*, dominates, the within-canopy state agrees with the often used criteria based on the Grashof and Reynolds numbers:

Free convection: $Gr > 16\, Re^2$

Forced convection: $Gr < 0.1\, Re^2$ (3)

Mixed convection: $16 Re^2 < Gr < 0.1 Re^2$.

Here, the Grashof number is $Gr = a\, g\, \Delta T\, h^{*3}/\nu^2$ (g is gravity, a = 1/T is the thermal expansion coefficient, h* is characteristic length scale and ν is kinematic viscosity) and the Reynolds number is $Re = u^* h^*/\nu$. The length scale $h^* = d + z_0$ was chosen.

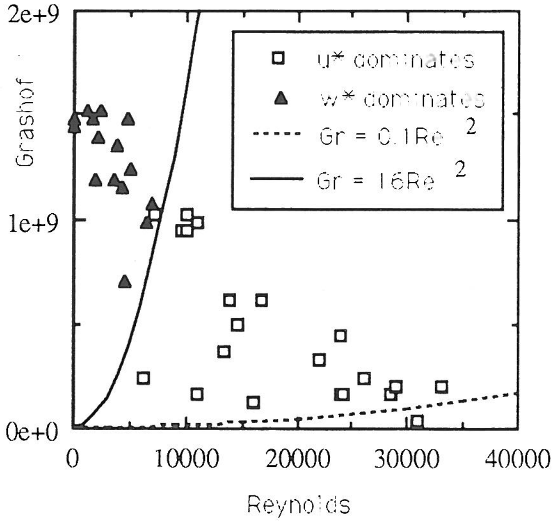

Fig. 6. The Grashof number ($Gr = ag\, h^{*3} \Delta T/\nu^2$) vs. the Reynolds number ($Re = u^* h^*/\nu$).

In figure 6 these criteria as well as the results for the selected nights have been plotted. From these results it can be observed that, when the convective velocity scale exceeds the friction velocity the above criteria (3) indicate a free convection state within the canopy. Moreover, it can be concluded that during all other night-time situations the criterion of eqs. (3) indicate a mixed convection state. It must be noted, however, that under night-time strong wind conditions the forced convection state can be reached easily.

5. CONCLUSIONS

From the foregoing results the following main conclusions can be drawn:

1) In most stratification states (L > 5m and L < 0m) the within-canopy mean wind profiles can excellently be scaled by the above-canopy friction velocity, u*, or by a mean above-canopy reference wind speed. This means that above-canopy and within-canopy flow is strongly coupled.

2) Under above-canopy very stable stratification (0m < L < 5m) a decoupling between the above-canopy and within-canopy flow occurs. Here, the within-canopy free convective flow is mainly forced by the soil heat flux at the floor of the canopy. The height of the convective cells are restricted by the top layer of the canopy where long-wave energy losses cause a strong thermal temperature inversion. The height of the free convection region coincides with the maximum of the plant density distribution.

3) During unstable stratification states (daytime) the within-canopy mean temperature profiles can be scaled well by the above-canopy scaling temperature, T*. This also means that under these conditions, above-canopy and within-canopy flow is strongly coupled.

4) During nights with less wind, a decoupling between the above-canopy and within-canopy flow occurs. Here, the within-canopy free convective flow is forced by the soil heat flux at the floor of the canopy. Under these conditions, the within-canopy temperature profiles scale well with the free convective within-canopy temperature scale, θ^*.

5) The criteria of eqs. (3) apply well for the within-canopy heat transport process to distinguish the convection type. The boundary between the free convection and mixed convection states can also be found by comparing the above-canopy friction velocity and the within-canopy free convective velocity scale.

6) In modeling transport processes within a plant canopy, the present results suggest that during daytime hours nearly always mixed convection dominates while during nocturnal hours, when w* > u*, the free convection dominates.

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