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Nighttime exchange processes near the soil surface of a maize canopy

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Abstract

The exchange process in the lower region of a maize canopy is analyzed for two nights. It appears that during calm nights a free convection state develops in the lower region of the canopy. Convective heat is released at the soil's surface and transported directly to the higher portion of the canopy. The released sensible heat at the soil's surface can be easily calculated by applying the Nusselt number for free convection.

At night thermal energy is also released through cooling of the canopy. The released heat from the stored canopy heat is of the same order of magnitude as all other energy terms. Conversely during daytime for most agricultural crops this energy term is of minor importance in comparison to the other energy terms.

The formation of dew at night is an important process. A maximal possible estimate of dew accumulation for a particular night can easily be made by using the potential dew. The potential dew can be deduced more accurately by taking into account the released heat stored in the plant canopy.

1. Introduction

A concise knowledge of the energy exchange between a crop canopy and the crop environment is of importance in agricultural management. This is specially important during nighttime and the early morning because it is then that the crop is mostly wet and sensitive to the development of certain foliar diseases (Van der Walle, 1978; Gillespie

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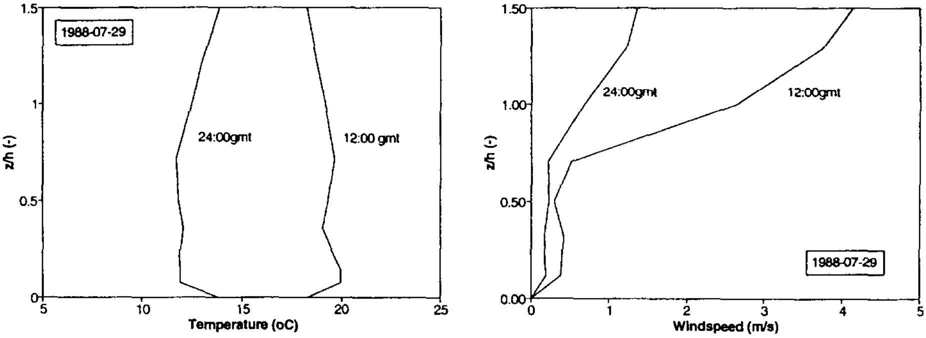

Fig. 1. Typical examples of temperature and windspeed profiles within and just above a canopy.

and Sutton, 1979) and plant pathogens whose spores or cells require a free water film to germinate activity (Royle and Butler, 1986).

During daytime there usually exists a strong coupling between the above-canopy weather regime and the within-crop state. Then the above-canopy exchange mechanism dominates the within-canopy exchange mechanism (Goudriaan, 1989; Jacobs et al., 1992, 1994; Raupach, 1988; Seginer et al., 1976; Shaw et al., 1989). During nighttime, however, when the above-canopy wind regime drops, only a weak coupling between both mechanisms by downdraught penetration occurs. Now, the coupling is reduced since the above-canopy state becomes thermally stable by long wave radiative cooling at the top of the canopy while the within-canopy state becomes thermally unstable by supply of heat from the soil. In particular, a free convective state develops in the lower region of the vegetation where the foliage density is less. In fact the lower part of the vegetation architecture is often very sparse and can then be considered as a free enclosure. A free convective state is a state where the turbulence is mainly generated by thermal production. In an earlier paper Jacobs et al. (1994) showed that a free convective state within a maize canopy occurs when the above-canopy Obukhov stability length scale, L, exceeds the value of $L > 0$. They also showed that if $L > 0$ the above canopy friction velocity is no longer an appropriate within-canopy velocity scale, and that under these conditions a within-canopy free convection scale should be used (see below). An illustration of typical daytime and nighttime temperature and windspeed profiles within and just above a canopy is shown in Fig. 1. Clearly is shown the sign reversal in the temperature profile from daytime to nighttime.

During the nocturnal period it is interesting to understand the behaviour of various terms in the energy budget equation, because it is not always clear which term of the energy balance dominates. During the day, however, the energy budget is mainly ruled by the short wave radiation load; a high or low irradiation load immediately affects all other terms.

Here we examine the various energy terms at nighttime with respect to their importance in the energy budget. The moisture flux at the top as well as at the soil surface of the canopy will be analyzed. Attention will also be given to the potential dew and a suggestion will be proposed to a more concise definition of this quantity.

2. Theory

We start from the surface energy budget, in which we take non-radiative fluxes directed away from the surface, and radiative fluxes directed towards the surface as positive. For a canopy, the canopy energy budget is then given by (e.g. Garratt, 1992),

$$R_n = H + LE + G + \mathrm{d}S \tag{1}$$

where R_n is the above-canopy net radiative flux (positive daytime; negative nighttime), H and LE the sensible and latent heat fluxes, respectively, above the canopy, G the soil heat flux at the canopy floor, and dS the change of heat storage of the canopy.

For a closed canopy, the nocturnal surface energy balance at the soil surface is given by (Garratt and Segal, 1988),

$$0 = H(0h) + LE(0h) + G \tag{2a}$$

where $H(0h)$ and $LE(0h)$ are the sensible and latent heat fluxes at the soil floor, respectively. Here, it is assumed that at the soil's surface the outgoing long wave radiation from the soil balances the incoming long wave radiation from the vegetation and air aloft. This assumption, however, is correct only for a very dense vegetation with no gaps. For most agricultural canopies, at daytime as well as at nighttime, there will be a net radiation flux, $R_n(0h)$, at the soil's surface, which is not negligible (Brown and Covey, 1966; Impens and Lemeur, 1969). That is why in the present study the energy balance at the interface soil air is taken as:

$$R_n(0h) = H(0h) + LE(0h) + G \tag{2b}$$

It is difficult to estimate directly the convective fluxes, $H(0h)$ and $LE(0h)$, at the soil surface. In order to make an assessment of the sensible heat flux at the soil surface the following procedure is suggested for calm nighttime conditions. During calm nights when the wind drops, a free convection state can develop at the canopy floor (Leclerc et al., 1991; Jacobs et al., 1992). Free convection will dominate the exchange mechanism if the dimensionless Rayleigh number, Ra, exceeds the criterion (Monteith, 1980; Gates, 1980; Kreith and Bohn, 1986; Jacobs et al., 1994):

$$\mathrm{Ra} > 16\mathrm{Re}^2 \tag{3a}$$

where

$$\mathrm{Ra} = \frac{l^3 g \beta \Delta T}{\nu^2}\mathrm{Pr}; \quad \mathrm{Re} = \frac{ul}{\nu} \tag{3b}$$

and l is a characteristic length scale, g is gravity, β is the expansion coefficient, ΔT the temperature difference between soil surface and ambient air, u a velocity scale, ν the kinematic viscosity and Pr the Prandtl number defined as $\mathrm{Pr} = \nu/a$, where a is the thermal diffusivity of still air. If this expression is applied to the free enclosure in the lower part of a row canopy, the length scale l is the width of the row distance. For a surface, the dimensionless heat transfer can be expressed by the Nusselt number,Nu, defined as (e.g. Kreith and Bohn, 1986):

$$\mathrm{Nu} = \frac{H(0h)l}{\lambda \Delta T} \tag{4}$$

where λ is the heat conductivity of still air. For a flat surface, if $\mathrm{Ra} > 10^7$, the latter expression is the same as (e.g. Jakob, 1950):

$$\mathrm{Nu} = 0.14\mathrm{Ra}^{1/3} \tag{5}$$

Finally for the sensible heat flux at the soil surface under free convective conditions, $H(0h)$, is found:

$$H(0h) = \frac{0.14\lambda}{l}\mathrm{Ra}^{1/3}\Delta T \tag{6a}$$

If we substitute Eq. (3b) for the Rayleigh number we see that the length scale, l, disappears from the equation:

$$H(0h) = 0.14\rho c_\mathrm{p}\frac{a}{\nu}(g\beta a)^{1/3}\Delta T^{4/3} \tag{6b}$$

An important parameter for the above exchange mechanism is the friction velocity, u_*, defined as:

$$u_* = \sqrt{-\overline{u'w'}} \tag{7}$$

This velocity parameter is also important in the within-canopy exchange mechanism. Jacobs et al. (1994) showed that u_* is also important for the within-canopy exchange mechanism, but is not appropriate as soon as the within-canopy free convective velocity scale, w_*, exceeds the above canopy friction velocity u_*. The within-canopy free convective velocity, w_*, is defined as (Tennekes and Lumley, 1972):

$$w_* = \left[\left(\frac{h_* g}{T}\right)\frac{H(0h)}{\rho c_\mathrm{p}}\right]^{1/3} \tag{8}$$

where ρc_p is the volumic heat capacity, h_* is a within-canopy length scale which agrees well with $h_* = d + z_\mathrm{o}$, where d is the displacement height and z_o the roughness length (Jacobs et al., 1994). Physically, w_* is a measure for the turbulent velocity scale under free convective conditions. h_* agrees well with the height where the maximum foliage area occurs, i.e. more or less the centroid of the zone of effective radiative cooling (Jacobs et al., 1994). In fact, this height seems to be a more appropriate length scale for canopy flow and appears to be also effective for sparse canopies (McNaughton and Van den Hurk, 1995).

An important nighttime process is the accumulation of dew within a vegetation canopy. For example in a plant canopy, dew is important for the development of all kind of fungal diseases which need free liquid water for germination activity. In agricultural practice, however, actual dew assessments are difficult to make. Monteith (1957) and Garratt and Segal (1988) suggested the use of the so-called potential dew. The potential dew is roughly the maximal possible dew amount which can occur within a particular canopy at night and the advantage of this quantity is that it can be estimated relatively easy. The potential dew, LE_p, equals the expression (Garratt and Segal, 1988):

$$LE_\mathrm{p} = \frac{s}{s+\gamma}(R_\mathrm{n} - G) \tag{9}$$

where s is the slope of the saturated vapour pressure and γ ($= 66$ Pa K^{-1}) is the psychrometric constant.

3. Materials and methods

A measurement programme in which the fluxes of heat, mass and momentum, and windspeed and temperature profiles were estimated above and within a maize crop canopy (Jacobs and Van Boxel, 1988), was carried out at the pilotfarm Sinderhoeve (51°59′ N, 5°45′ E) during two weeks in July, 1986. 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 experimental period, the crop was at the end of the vegetative state, had a height, h, of 1.70 m and a one-sided plant area index, PAI, of 3.6. The PAI is the sum of the leaf area index, LAI, and the stem area index, SAI.

Above the crop, the mean wind profile was measured with home-made cup anemometers (threshold speed 0.20 m s^{-1} and first-order response distance (66%) 0.90 m) at eleven heights above the ground of 1.7, 2.2, 2.85, 3.5, 4.25, 5.0, 6.0, 7.0, 8.0, 9.0 and 10 m. 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 (Van Asselt et al., 1991) and a Lyman-α humidiometer were installed. These instruments provide data about the displacement height, d, the roughness length, z_o, for the above-crop turbulent fluxes of momentum, heat and vapour.

Within the canopy, at 0.25D between two rows (where D is row distance), the mean temperature profile was estimated with unshielded fast-response thermocouples (Jacobs and McNaughton, 1994) at heights above the ground: 0.0, 0.1, 0.2, 0.3, 0.5, 0.7, 1.0 and 1.4 m. In addition, within-canopy absolute windspeeds were measured with hot-sphere anemometers (Stigter et al., 1976) at the same levels. The hot-sphere anemometers are very suitable for measuring low windspeeds (measuring range 0.02–2.0 m s^{-1}; accuracy 0.005 m s^{-1}).

A 1-D sonic anemometer (Kaijo Denki, model PAT-110) with a pathlength of 0.20 m plus an additional fast-response thermometer and a Lyman-α humidiometer were installed at a height of 0.7 m ($= 0.4h$, where h is canopy height) inside the canopy to measure the within-canopy transport of heat and water vapour.

The soil heat flux was measured at depths of 20 and 30 mm by flux plates (TNO transducer type WS 31-Cp). To obtain correct values for the soil heat flux at surface level ($0h$) corrections were carried out for the heat capacity of the soil (Fritschen and Gay, 1979) and for the flux plate dimensions and the ratio of the tranducer's conductivity and soil conductivity according to Philip (1969).

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 relayed to a mobile measurement van, about 100 m from the instruments. Here, the unconditioned data was saved on a digital magnetic tape for later analysis. Further details about measurement techniques are provided in Jacobs and Van Boxel (1988).

4. Results and discussion

Two successive nights (29–30–31 July, 1986) with different weather conditions were selected to analyze the energy budget in the lower region of the maize canopy. There had been rainfall of 5 mm on 28 July. In Fig. 2 the main characteristics of the weather during that period have been plotted to give a general impression of these conditions. From these data we see that the first night was windy until about midnight, where the above canopy windspeed at 4.5 m dropped from 6 $m s^{-1}$ to less than 1 $m s^{-1}$. During the windy period, the above canopy exchange mechanism also generates the within-canopy exchange mechanism and no free convective state within the canopy can develop. A strong wind near the earth's surface at night is unusual and because we intend to analyse the nighttime free convective state within a canopy this windy period was excluded from the present analysis.

In order to get an impression of the behaviour of the energy fluxes above and below the canopy during the nocturnal period these fluxes have been plotted in Fig. 3. Moreover, Fig. 3 shows the change of heat storage in the canopy, dS. It has been estimated according to $dS = C_A(\Delta T/\Delta t)$, where C_A is the heat capacity of the canopy per unit ground area ($C_A = 4 \times 10^4$ $J m^{-2} K^{-1}$) and $(\Delta T/\Delta t)$ the mean temperature change of the canopy. From the results plotted in Fig. 3, it can be inferred that in the beginning of the first night, due to the strong wind condition, there was a clear coupling between all energy fluxes. It can also be inferred that the above-canopy sensible heat flux changes sign faster than the latent heat flux. This characteristic is often observed after a rainy period where the top soil is relatively wet (see e.g. De Bruin, 1982). This is expected since the stomates are closed at night and since there is a strong wind, there should not be any dew, thus $LE = 0$. At the first midnight (0 GMT, 29 July) the wind drops and the coupling becomes weak between above and within-canopy convective processes. During the calm periods of both nights the above-canopy fluxes of heat and water vapour are very low due to the build-up of a temperature inversion above the canopy. This also means that the above-canopy radiative loss must be mainly compensated by the soil heat flux and the change of heat storage of the canopy. Besides that, it can be inferred that during nighttime the change of the heat storage term of the canopy is of the same order of magnitude as the other dominant energy terms, consequently, the heat storage term cannot be neglected in the total energy budget.

On a night when a free convective state dominates in the lower part of the canopy, the free convective velocity scale, w_*, exceeds the above-canopy friction velocity, u_*. In Fig. 4 for the two selected days both turbulent velocity scales have been plotted along with the Obukhov stability length scale. This result demonstrates that during calm nights the within-canopy velocity scale, w_*, dominates, hence that this velocity scale determines the within-canopy turbulence (Jacobs et al., 1992, 1994).

During the convective period it is important to know how the available energy at the soil surface, $\boldsymbol{R}_n(0h) - \boldsymbol{G}(0h)$, which equals the sensible heat and latent heat at the soil surface, $\boldsymbol{H}(0h) + \boldsymbol{LE}(0h)$, behaves in comparison to the sum of the convective fluxes, $\boldsymbol{H}(0.4h) + \boldsymbol{LE}(0.4h)$, at the top of the free enclosure of the canopy. The difference between the fluxes at both levels gives insight into the heat as well as moisture change within the lower region of the canopy. The soil heat flux, $\boldsymbol{G}(0h)$, was measured. For the

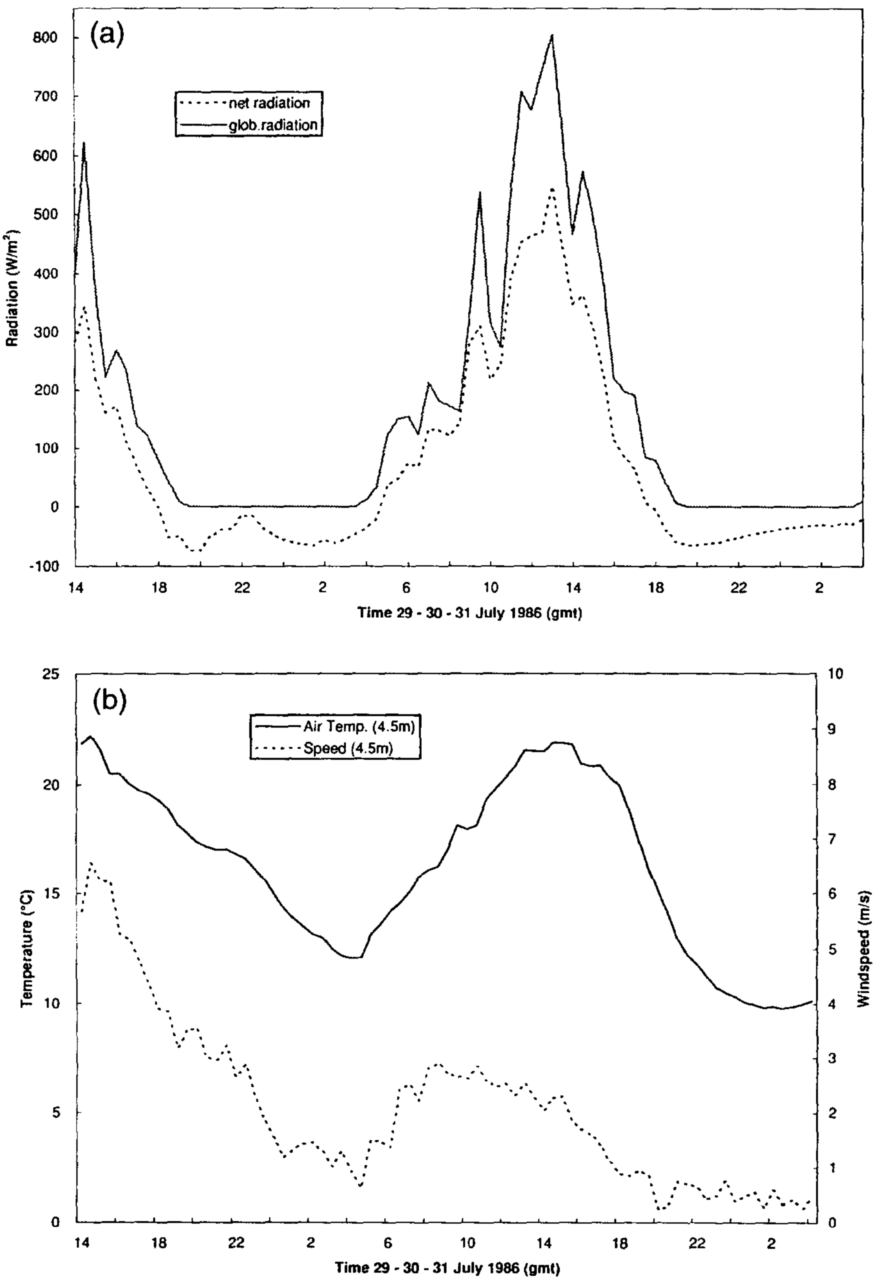

Fig. 2. General weather conditions during the two consecutive days. The net radiation was measured at 4.0 m above the soil, all other measurements were taken at 4.5 m.

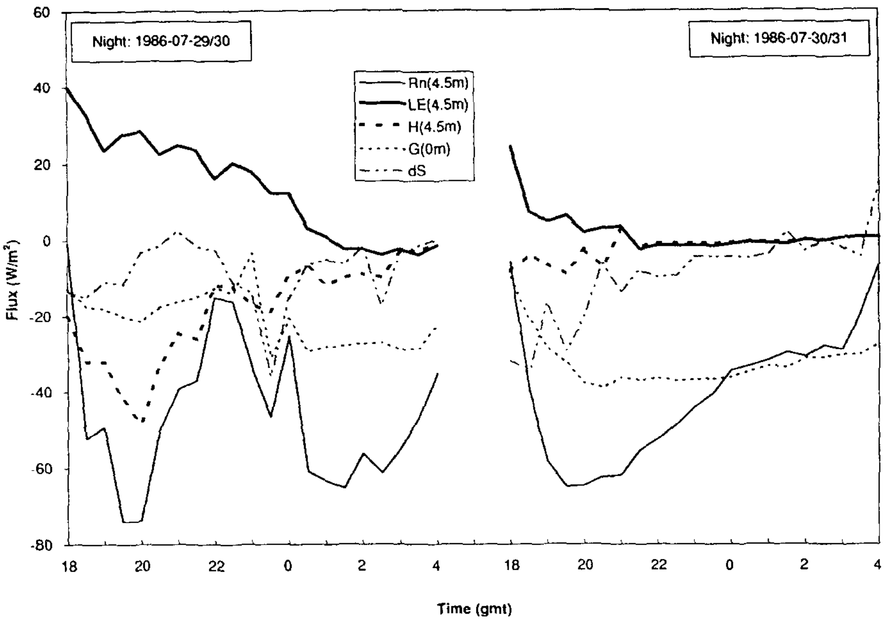

Fig. 3. Above and below energy fluxes during quiescent conditions. Night 29–30 July left-hand frame, night 30–31 July right-hand frame.

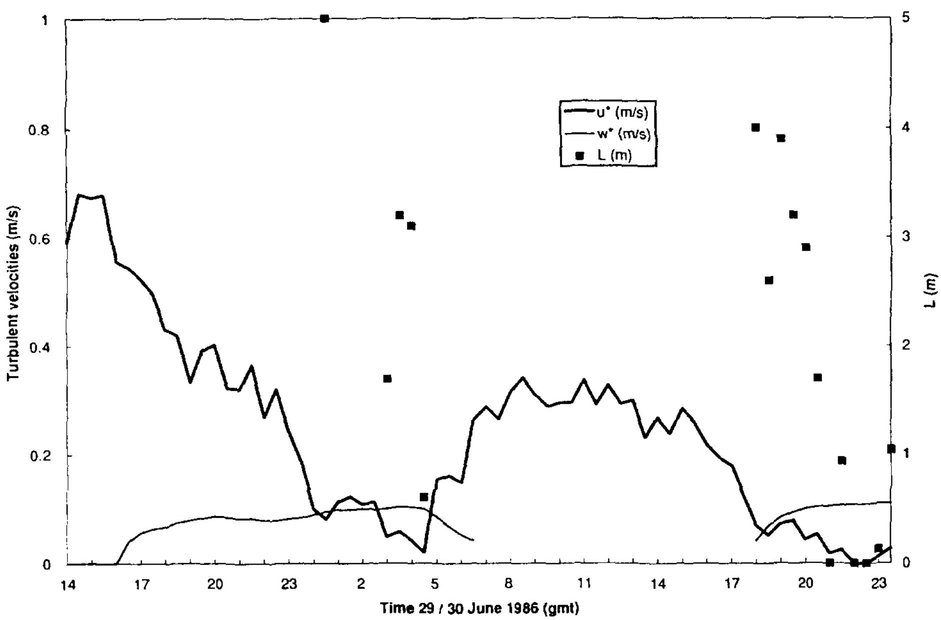

Fig. 4. The course of the friction velocity, u_*, measured at 4.5 m height, the free convective velocity scale, w_*, during the two selected days and the above-canopy Obukhov length during the quiescent conditions.

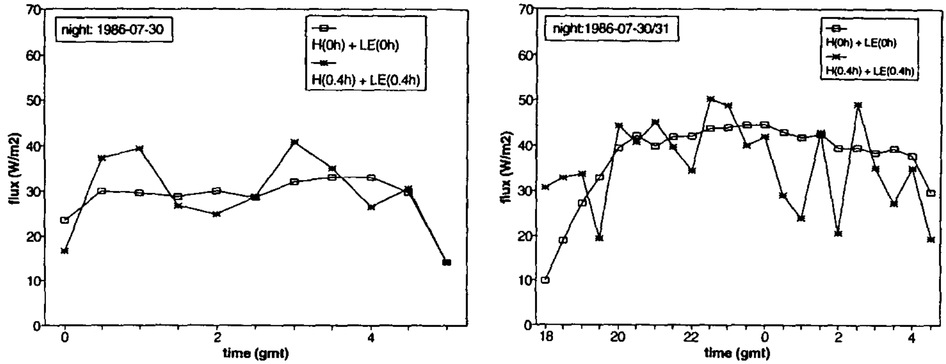

Fig. 5. The course of the total convective heat flux ($H + LE$) at the ground beneath the canopy ($0.0h$) and at $0.4h$.

assessment of the net radiation flux, $R_n(0h)$, at the bottom of the soil, the following procedure is followed. During an earlier experiment, attention was focused on the extinction of short, long and net radiation within the canopy (Jacobs et al., 1989). For a maize crop the following simple extinction relation for net radiation was found for nighttime conditions:

$$R_n(L') = R_n e^{(-\alpha L')} \tag{10}$$

where $R_n(\mathrm{PAI}')$ is the net radiation at a depth of the canopy with a cumulative plant area index L' and α is an extinction coefficient with a numerical value of 0.58. This numerical value agrees reasonable with that found, for example, by Brown and Covey (1966) and Impens and Lemeur (1969) who found $\alpha = 0.53$ and $\alpha = 0.50$, respectively. From Eq. (10) we can show that at the bottom the net radiation is $R_n(0h) = 0.13 R_n$. Here this relation has been applied for the assessment of the net radiation at the soil surface.

In Fig. 5 for both nights the course of the total convective flux, $H + LE$, has been plotted for near the ground ($0h$) as well as for the $0.4h$ level. From this result it can be inferred that the total convective flux is, approximately, constant with height within the enclosure. This means that the sum of sensible and latent heat released at the canopy floor is directly transported to the higher region of the canopy, and in addition, that the change of heat and liquid water storage in the lower layer of the canopy is of minor importance as well. The latter is to be expected since most of the foliage is located in the upper half of the canopy. It also can be seen from Fig. 5 that at the soil surface the convective fluxes scatter less then those at about half the canopy height. This result, however, is introduced partly artificially since the estimated soil heat flux at the top soil is in reality measured at 0.05 m depth after being corrected for the change of heat capacity in the slab of soil above. Consequently, this 'dampening' effect is introduced by the soil flux correction procedure. On the other hand during nighttime, the eddy-correlation technique is subjected to large errors especially within a canopy. In addition, it must be expected that at the top of the enclosure a higher scatter in the fluxes is more likely since even under above-canopy stable states an occasional gust can penetrate into

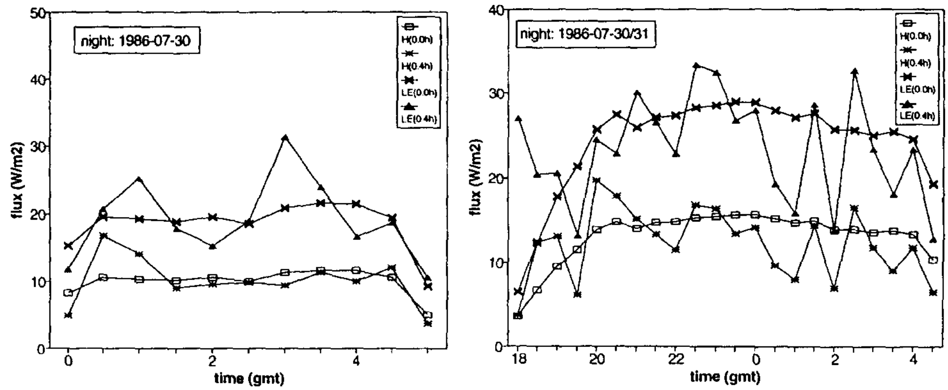

Fig. 6. The sensible and latent heat flux at the ground beneath the canopy (0.0h) and at 0.4h. The convective fluxes at the level 0.4h were directly measured by the eddy correlation technique.

the canopy. These gusts affect the fluxes at the top of the enclosure, but, will hardly ever affect the soil heat flux.

The sensible heat flux at the soil air interface, $H(0h)$, can be calculated according to Eqs. (6a) and (6b). It is interesting to compare these results with those measured directly with the eddy correlation technique at half the canopy height $H(0.4h)$. From the energy budget Eq. (2b), the latent heat flux at the soil surface, $LE(0h)$, can be estimated and can be compared with the measured results at the top of the within-canopy enclosure, $LE(0.4h)$. The results for both nights have been plotted in Fig. 6. This result suggests that for both nights the sensible heat flux at the soil surface more or less agrees with the heat flux at the top of the canopy enclosure. A linear regression for both nights showed the unbiased relation $H(0.4h) = 0.94H(0h)$, with a standard error of estimate of 4 W m^{-2}. Roughly speaking also the same result can be observed for the latent heat fluxes. Here, the linear regression showed the relation $LE(0.4h) = 0.96LE(0h)$, with a standard error of estimate of 7 W m^{-2}.

For model calculations it is often interesting to know how the Bowen ratio, $\beta_0 = H/LE$ behaves. This is not only interesting for the above-canopy partitioning of the available energy but this is also interesting for the partitioning of the available energy at the floor of the canopy. That is why in Fig. 7 a scattergram of $H(0.4h)$ versus $LE(0.4h)$ has been plotted for both nights. Moreover, in this scattergram the unbiased linear regression line has been depicted with the result: $Y = 0.6X$ (correlation coefficient, $r = 0.85$; number of points, $N = 42$; standard error of estimate, see = 3.3 W m^{-2}) i.e. the Bowen ratio has an average value of 0.6. From this scattergram we conclude that for both selected nights the latent heat at the soil floor is roughly twice the sensible heat flux. In fact this Bowen ratio for the soil surface is quite high. For example Massman (1992) showed that a value around $\beta_0 \approx 0.5$ can only occur when the surface resistance of the soil is very low which means that the soil must be wet. In our case the selected period was preceded by a rainy and cloudy spell from which the soil was indeed wet.

To be sure of the accuracy of this high Bowen ratio number near the soil surface a second independent technique was employed to check this ratio. Schmidt developed a

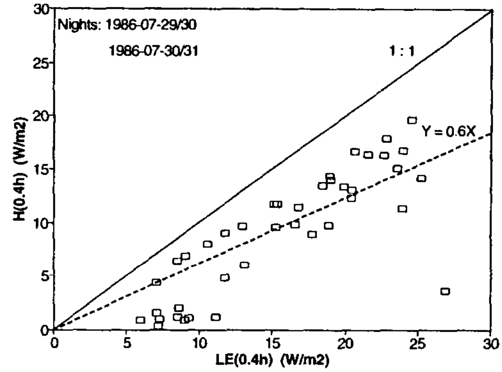

Fig. 7. Sensible heat flux plotted against latent heat flux. The slope of the regression through the origin being the Bowen ratio, $\beta_{0.4h} = H/LE$, at a height of $0.4h$. The fluxes are measured by the eddy correlation technique.

theory in 1918 for partitioning the net radiation into sensible and soil heat flux at bare soil (Schmidt, 1918). He found the simple expression:

$$r = \frac{G(0h)}{H(0h)} = \frac{1}{\rho c_p}\sqrt{\frac{C_s \lambda_s}{K_H}} \tag{11}$$

where λ_s is the conductivity of the soil, C_s the volumetric heat capacity of the soil and K_H is the exchange coefficient for heat in the air. At the canopy floor we can apply this equation after finding an adequate expression for the turbulent exchange coefficient. For an enclosure in which the air is turbulent a simple expression for this coefficient is (Raupach et al., 1989):

$$K_H = w_* h_* \tag{12}$$

where w_* and h_* are turbulent velocity and length scales, respectively. As mentioned earlier, the length scale equals the expression, $h_* = d + z_0$, which during the experimental period agreed the numerical value $h_* = 1.4$ m. Finally for the Bowen ratio near the canopy floor is found:

$$\beta_0 = \frac{-1}{r\left(\frac{R_n}{G}e^{-\alpha L'} - 1\right) + 1} \tag{13}$$

where R_n/G is the ratio between the above canopy radiation and soil heat flux. For nighttime situations the numerical value of this ratio ranges between 1 and 1.5. In Fig. 8 both partitioning functions r and β_0 are depicted versus the free convective velocity, w_*. During nighttime it appeared (see also Fig. 4) that the free convective velocity had a numerical value around 0.12 $m\,s^{-1}$, which means that the Bowen ratio had a numerical value between 0.6 and 0.7, which is in good agreement with the results presented in Fig. 7.

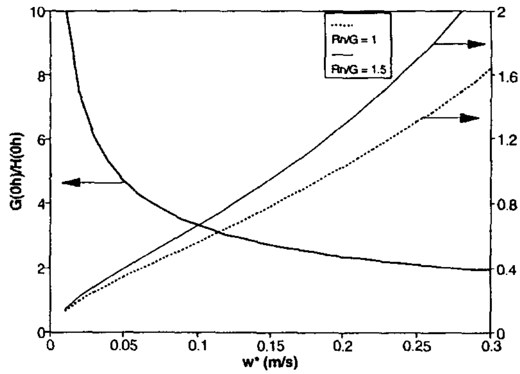

Fig. 8. The calculated partitioning between the soil heat flux and sensible heat flux and the consequent Bowen ratio at the soil's surface versus the free convective velocity scale, w_*.

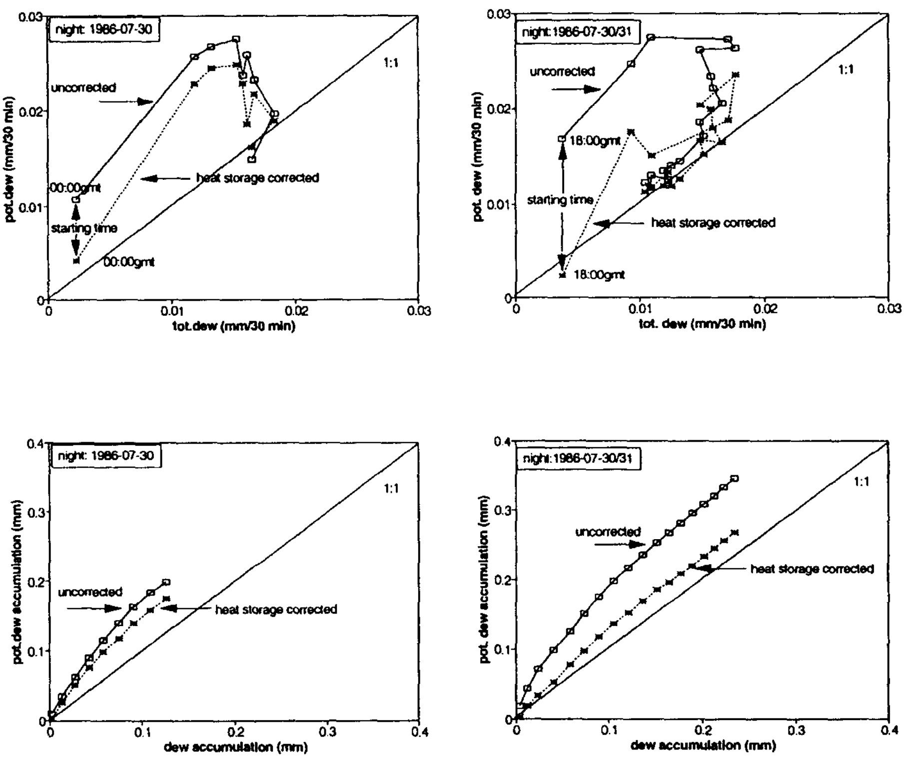

Fig. 9. The potential dew versus the actual total dew (dewrise plus dewfall), and, the potential dew corrected for heat storage versus the actual total dew.

In our experiments the total dew (sum of dewfall and dewrise) has been measured by the eddy correlation technique within (dewrise) and above (dewfall) the canopy and offers the possibility to make a comparison between the actual and potential dew amounts. In Fig. 9 for both nights the dew rate as well as the accumulated dew has been depicted. From this result we see that the potential dew almost always exceeds the actual dew. The graphs with the accumulated dew amounts show that at the start of dew formation the potential dew deviates from the 1:1 line and that after a while the results are shifted parallel to the 1:1 line. The reason for this behaviour originates from the original definition of the potential dew (Eq. (9)). In this potential dew definition no account has been taken of the energy storage in the canopy. Due to the temperature decrease of the canopy, stored energy is released which will reduce the maximum possible dew amount. In Fig. 9 the potential dew has also been depicted after correcting for the released energy storage according to:

$$LE_p = \frac{s}{s+\gamma}(R_n - G - \mathrm{d}S) \tag{14}$$

The result of this correction is that the potential dew still exceeds the actual total dew, but, is closer to the 1:1 line, which means that the potential dew definition (Eq. (14)) is closer to the realistic actual dew.

5. Conclusions

From the foregoing the following main conclusions can be drawn:

1. Near the bottom of the canopy during low wind conditions at night, a region exists where a free convective state develops.
2. In this region the released convective energy is directly transported from the soil surface to the upper region of the canopy.
3. The sensible heat at the floor of the canopy can be easily assessed by applying the Nusselt number for free convection for a flat plate.
4. In the plant canopy the heat storage term is of the same order of magnitude as all other important energy terms. Consequently, the heat storage term of the canopy cannot be neglected during nighttime.
5. The so-called potential dew is a physically sound assessment for the maximum possible dew amount. The definition of the potential dew can considerably be improved by taking into account the released heat storage within the canopy.

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