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Leaf wetness within a lily canopy

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A wetness duration experiment was carried out within a lily field situated adjacent to coastal dunes in the Netherlands. A within-canopy model was applied to simulate leaf wetness in three layers, with equal leaf area indices, within the canopy. This simulation model is an extension of an existing model. It appeared that in most cases leaf wetness started in the uppermost layer followed by the middle and bottom layer, respectively. The same occurred during the early morning drying process. Just after sunrise the upper layer started to dry, followed by the middle and bottom layer, respectively. The longest leaf wetness duration occurred in the bottom layer. The calculated leaf wetness durations were within 10 minutes of the results obtained using a leaf wetness sensor.

1. Introduction

Rain, fog, drizzle, mist and dew are meteorological phenomena that cause leaf wetness, i.e. free liquid water on plant leaves. Leaf wetness affects plant growth and plant life (Wallin 1967), but can also offer free water to plants and small animals in deserts (Evenari et al. 1982; Zangvill 1996) and support the development of fungal spores (Aylor 1986). When water is deposited on leaves for critical periods and temperatures are appropriate, fungal and other pathogens can develop that can be extremely harmful for the health of plant canopies. Such diseases are often controlled by fungicide sprays. Given increasing environmental awareness and the high cost of fungicides, there is now a need to curb excessive use of chemical control measures. Reliable estimates of leaf wetness duration can help decision-making and thus maximise the efficiency of fungicide use. Simulation models can be used in combination with leaf wetness sensors in crop protection systems. Previous research on leaf wetness duration has been carried out by Pedro & Gillespie (1982a, 1982b), Barr & Gillespie (1987), Wittich (1995), Hubert & Itier (1990), Jacobs et al. (1994) and Luo & Goudriaan (2000).

Dew is the main process responsible for the leaf wetness. It can occur by dewfall, the process during the night where water is extracted from the atmospheric water reservoir, dew rise, the process where soil water evaporates during the night and is intercepted by the canopy, and by guttation, an internal plant process (Garratt & Segal 1988). The distribution of dew within a canopy is not homogeneous and changes in time depending on the weather and on the leaf distribution and architecture of the plant canopy (Jacobs & Nieveen 1995). Wetness usually starts in the upper levels of the canopy if the dewfall dominates. Drying also starts in the upper canopy due to direct irradiation after sunrise. The longest wetness period is expected in lower canopy levels. Water dripping from leaves or draining along stems at night can accumulate liquid water in the lower canopy levels, which may enhance wetness duration.

Lilies (*Lilium spp.*) are a very important export product in the Netherlands. The crop can be damaged by the fungal pathogen *Botrytis elliptica*, which causes disease. The disease symptom, brown spots on the leaves, not only affects the growth of the plant, it hinders the ability to bring them to market. To cause 100% infection *Botrytis elliptica* requires at least 24 hours of leaf wetness at a temperature of 20 °C (Van den Ende et al. 2000). Thus a reliable early warning system for this disease would be most welcome to lily growers.

The objectives of this paper are to achieve a better insight into the dew forming process during the night in different layers within a lily canopy and to study the early morning drying process in different layers within the canopy. A relatively simple physical model was developed to simulate the wetting and drying processes and a field experiment was carried out to verify this model.

2. Theory

The model used in the present study is an extension or a variant of the model presented by Pedro & Gillespie (1982a). The main difference is that Pedro & Gillespie's model was derived for the top layer of a crop, while our model can be applied to every layer within a canopy. If we take an arbitrary layer within a canopy, the energy budget of that layer is:

$$\Delta Q_l^* + \Delta H_l + \Delta \lambda_v E_l = 0 \quad (1)$$

where ΔQ_l^* is the absorbed net radiation within this layer, ΔH_l is the released sensible heat and $\Delta \lambda_v E_l$ is the released latent heat within that layer. For simplicity the energy storage and metabolic energy terms within this layer have been neglected since most of the time these terms are relatively small.

The model assumes the net radiation, Q^*, available, either by measurement or by estimation, for example as proposed by Pedro & Gillespie (1982a, 1982b). Within the canopy the net radiation flux is attenuated and we assume that attenuation follows the relationship proposed by Lowry (1989):

$$Q_l^*(L(z)) = Q^* e^{-(0.622L - 0.055L^2)} \quad (2)$$

where $L(z)$ is the integrated leaf area from the top, h, of the canopy to the height z within the canopy. The absorbed net radiation, ΔQ_l^*, within the layer is:

$$\Delta Q_l^* = Q_l^*(L_t) - Q_l^*(L_b) \quad (3)$$

where L_t and L_b are the integrated leaf area from the top of the canopy to the top and the bottom of that layer, respectively.

The released sensible heat, ΔH_l, in the layer is simulated as:

$$\Delta H_l = -2\alpha(T_l - T_a)(L_b - L_t) \quad (4)$$

where T_l is the mean leaf temperature in that layer, T_a the mean ambient air temperature of that layer and α is the convective heat transfer coefficient of a one-sided leaf in this layer. A factor 2 in Eq. (4) appears since both sides of the leaves are involved in the heat exchange process.

The convective heat coefficient, α, is calculated using the dimensionless Nusselt number, Nu, for forced convection (Gates 1980):

$$Nu = \frac{\alpha D}{\lambda} = 0.664 Pr^{0.333} Re^{0.5} \quad (5a)$$

where D is a characteristic leaf diameter, λ is the molecular heat conductivity of air, Pr the Prandtl number and Re the Reynolds number defined as (Gates 1980):

$$Pr = \frac{\nu}{a} \text{ and } Re = \frac{uD}{\nu} \quad (6a)$$

where u is mean wind speed, ν is the kinematic viscosity and a the thermal diffusivity of still air.

Under free convection the convective heat transfer coefficient, α, is also calculated from the Nu number (Gates 1980):

$$Nu = \frac{\alpha D}{\lambda} = 0.50 Gr^{0.25} \quad (5b)$$

where Gr the Grashof number is defined as (Gates 1980):

$$Gr = \frac{g\beta(T_l - T_a)D^3}{\nu^2} \quad (6b)$$

where g is the gravity and β the coefficient of thermal expansion. For a gas the thermal expasion coefficient equals $\beta = 1/T_{abs}$ where T_{abs}, is the absolute air temperature. Forced convection is taken when $Gr < 0.1\,Re^2$ (Gates 1980). In the present model a distinction was made between forced and free convection since under light wind conditions free convection can occur very frequently.

The released latent heat, ΔLE_l, in the layer is simulated as (Pedro & Gillespie 1988):

$$\Delta LE_l = -2\frac{0.622}{p}\rho\lambda_v\alpha'(e_{sl} - e_a)(L_b - L_t) \quad (7)$$

where p is air pressure, ρ is the density, λ_v is the latent heat of vaporization, α' is the convective mass exchange coefficient, e_{sl} is the saturated vapour pressure at leaf level, and e_a is the vapour pressure of the ambient air. From a similarity analogy between heat and mass it can be shown that (Gates 1980):

$$\frac{\alpha}{\alpha'} = \left(\frac{a}{D_i}\right)^{0.667} = Le^{0.667} = 0.93 \quad (8)$$

with D_i the molecular mass diffusivity and Le, the Lewis number.

In the present model both the wind profile within the canopy and the air temperature profile must be known. The wind profile within the canopy was derived by extrapolating the wind speed measured at a reference height to canopy height via a log-linear profile and then, applying the within canopy extinction wind speed profile as suggested by Goudriaan (1977):

$$u(L) = u_c \exp\left(-M\frac{L}{LAI}\right) \quad (9)$$

with u_c, the wind speed at canopy height, LAI the one-sided leaf area index of the canopy and M an extinction coefficient for momentum depending on the canopy architecture. For our agricultural crop with erectophile leaves M has a value of about 0.3 (see, for example, Goudriaan 1977).

During the evening, and around sunrise and sunset, the air within the canopy is well mixed and results in a within canopy temperature profile that is more or less constant with height (Jacobs et al. 1992). In the present study the air temperature at two heights within the canopy was measured and the within-canopy air temperature was simulated by a linear profile.

Combining Eqs (1), (4) and (7) and by using Penman's elimination procedure, we obtain:

$$e_{sl} - e_a = (e_{sa} - e_a) - s(T_l - T_a) \qquad (10)$$

where s is the slope of the vapour pressure saturation curve, and thus derive the temperature difference between leaf and ambient air, $\Delta T = T_l - T_a$, which equals the equation:

$$\Delta T = \frac{\Delta Q_l - 2\frac{0.622}{p}\alpha'(e_{sa} - e_a)(L_b - L_t)}{2\alpha(L_b - L_t) + 2s\frac{0.622}{p}\alpha(L_b - L_t)} \qquad (11)$$

Following Pedro & Gillespie (1982a), dew is accumulated when $T_a > T_l$ and the amount of dew is calculated using Eq. (7). The cessation of dew occurs when all accumulated free water is evaporated.

Dew water on leaves is not distributed equally over the leaves but in drops of irregular sizes (Butler 1985; Leclerc et al. 1985; Hubert & Itier 1995). During evaporation the surface of the drop contact with the leaves remains more or less constant, and the drop height decreases (Butler 1985; Leclerc et al. 1985; Hubert & Itier 1995). In the present model we assumed that a certain percentage of leaf was covered by water drops and that drying only took place from these wet spots.

3. Experimental set-up

The experiments were carried out between June and September 1996 at a coastal experimental site of the Dutch Bulb Institute, Lisse, Netherlands (52°23′ N, 4°30′ E, 3.5 m m.s.l.). The lily cultivar was Connecticut King (*Lilium Liliaceae Erythronium americanum*). The experimental site was surrounded by other lily fields. The lilies were planted in rows about 0.4 m apart with 67 plants m^{-2}. During the experimental period the mean crop height was 0.35 m with a leaf area index of 3.6, and a characteristic leaf dimension of D = 0.06 m. The underlying soil was sand and the mean water table was at a depth of about 0.5 m.

A 4-m mast was placed in the centre of the field between two rows of lilies. Two aspirated psychrometers (Pt100; locally made), with an accuracy better than 0.05 K, were mounted at a height of 1.5 and 3 m. Wind speed was measured at 4 m using locally made cup anemometers with a stall speed of 0.2 m s^{-1} and a distance constant of 0.90 m. At the top of the mast at 4 m, two global radiometers (CM 10; Kipp & Zonen, Delft, Netherlands) measured the incoming and outgoing short wave radiation. A net radiometer (LVX055; Schulze Drake, Berlin, Germany) was placed at 1.5 m. Two infrared thermometers (KT15; Heimann, Wiesbaden, Germany) were placed at 1.5 m and measured leaf temperature at the top of the canopy. One sensor faced south while the other faced north.

Within the canopy, air temperature was measured with Pt100 resistance thermometers (locally made) at 0.08 and 0.28 m. Relative humidity was measured, with capacitive relative humidity sensors (HMP45AC; Vaisala, Helsinki, Finland) at the same height. A resistance grid measured the leaf wetness (237 wetness sensing grid; Campbell Scientific Inc., Logan, USA) 0.07 m above the ground. From other studies it appeared that this grid mimics well the wetness of real leaves (Jacobs et al. 2005).

Soil temperature was measured (Pt100; locally made) at depths of 5, 30, 130, 340 and 750 mm. Soil heat flux was estimated at 30 and 50 mm depth with soil heat plates (WS 31-Cp; TNO, Delft, The Netherlands). The variables were sampled every minute using a portable logger (21X; Campbell Scientific Inc., Logan, Utah) and stored as 10-min averages.

4. Results and discussions

Two nights were chosen for analysis: a typical representative dewy night, 26–27 August 1996, and a night with little dew, 14–15 September 1996. The foliage area distribution, a, is shown in Figure 1 in a dimensionless form. The foliage area distribution is the one-sided area of the leaves per unit volume and was obtained by the leaf tracing technique proposed by Kvet & Marshall (1971).

Figure 2 presents the most important meteorological variables responsible for the dew formation process for 26–27 August. Around 21 UTC (UTC = local summertime –2h) the dry and wet bulb temperatures were nearly equal, which meant that dewfall was expected and would continue until about 9 UTC.

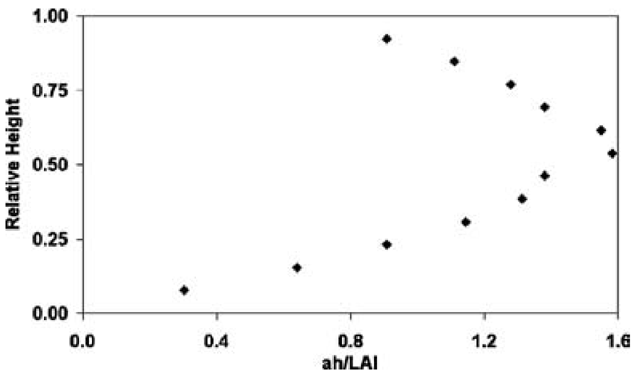

Figure 1. *The non-dimensional leaf area distribution, ah/LAI, as a function of the non-dimensional height, z/h, for August 1996. The horizontal axis has been scaled with the leaf area index, LAI, so that the area under the curve with respect to the y-axis equals 1.*

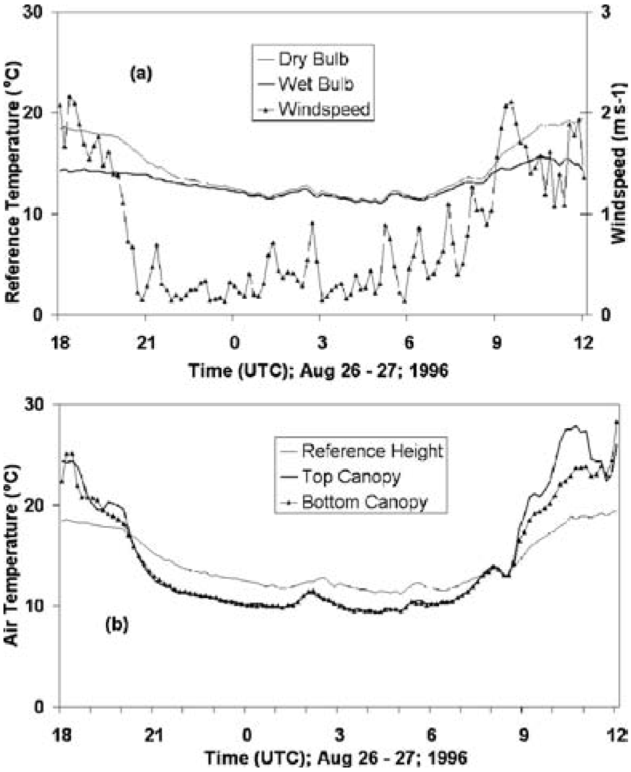

Figure 2. *The course of the most important meteorological variables during the selected heavy dew night of 26–27 August 1996. Local summertime is UTC + 2h.*

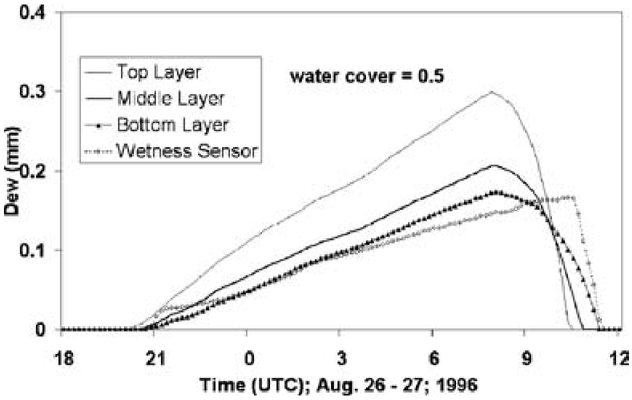

Figure 3. *The course of the accumulated dew amounts during the night of 26–27 August 1996, for the three layers with equal leaf area index of 1.2. Local summertime is UTC + 2h.*

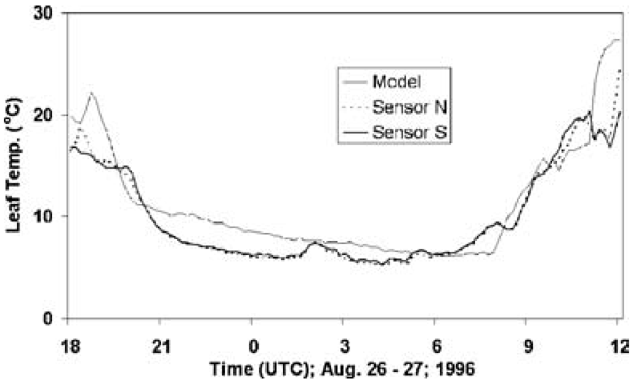

Figure 4. *The course of the measured and simulated leaf temperatures of the top layer during the selected night of 26–27 August 1996. Local summertime is UTC + 2h. Sensor S faced south while sensor N faced north.*

During this period the wind speed was low, which favours the dewfall process.

The lily canopy was divided into three layers, (top, centre and bottom), with equal leaf area indices of 1.2. From visual observations it appeared that the drop coverage of the leaves was about 50%, which agrees with water drops on the leaves with a contact angle of about 90° (see for example Beysens 1995). In the model simulations this coverage value was used for the drying process. The lily crop consists of relatively stiff stems and leaves, thus water redistribution was little-affected by draining and dripping caused by the fluttering of the leaves (Jacobs & Nieveen 1995). Accordingly, the model calculations were not corrected for these effects.

Figure 3 presents the accumulated dewfall simulations and early morning drying results, together with the results of the wetness sensor (in arbitrary units). The data suggest that the top layer collects most of the dew and the lowest layer within the canopy receives the least dew. In addition, dewfall appears to start earliest in the top layer, followed by the centre and then the bottom layer. The wetness sensor was located at 7 cm and the results of this sensor can be best compared with the accumulated dew within the bottom layer. The leaf wetness sensor results compare well with the dew accumulation of the bottom layer except that the wetness results show a small time lag of the order of a few minutes. The reason for this small lag is that the leaf wetness sensor consists of an electrical resistance grid covered with a porous latex paint. It takes some time for the accumulated free water on the sensor to infiltrate into the porous paint layer at the onset of dew formation and, at the end of the drying period, to diffuse out of the paint layer into the ambient air. Also the leaf wetness sensor indicates the presence only of free water and the output signal cannot provide the accumulated amount of dew on the sensor.

The simulations suggest that the shortest leaf wetness duration occurred in the top layer of the canopy, while the longest wetness duration occurred in the bottom layer. This is different from what was found earlier within a maize canopy. Jacobs et al. (1994) found for a maize canopy that the wetting as well as drying process was nearly equal for all layers within the canopy.

Two infrared thermometers were directed to the leaves of the top layer of the canopy to help measure the upper temperatures of the upper leaves in this layer. One sensor faced south while the other faced north. In Figure 4 the output of both sensors are plotted together with the simulated mean leaf temperature of

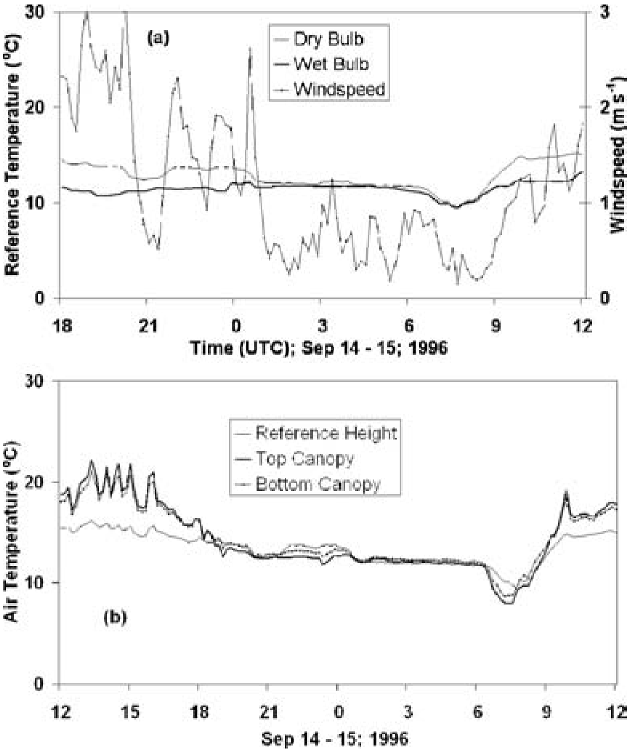

Figure 5. *The course of the most important meteorological variables during the second selected very low dew night of 14–15 September 1996. Local summertime is UTC + 2h.*

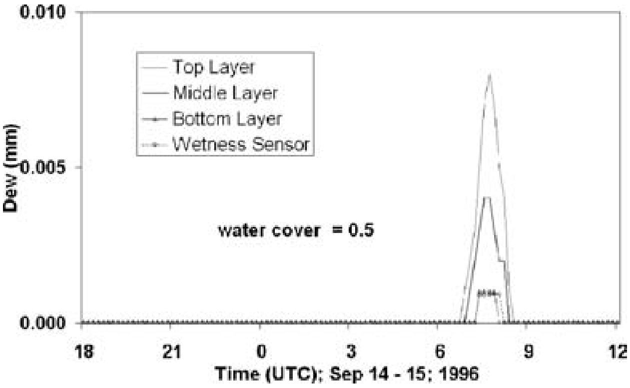

Figure 6. *The course of the accumulated dew amounts during the night of 14–15 September 1996, for the three layers with equal leaf area index of 1.2. Local summertime is UTC + 2h.*

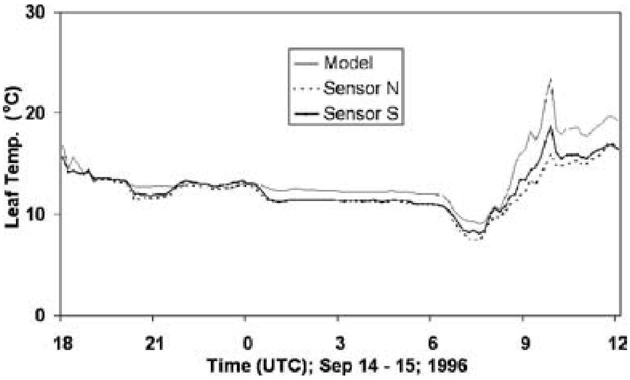

Figure 7. *The course of the measured and simulated leaf temperatures of the top layer during the selected night of 14–15 September 1996. Local summertime is UTC + 2h. Sensor S faced south while sensor N faced north.*

the top layer. Both measured leaf temperatures were nearly equal, especially during the night. The simulated values were about 2 K higher than the measured ones for most of the night. A difference must be expected since the upper leaves cool primarily by long wave radiative losses. During daytime the opposite can be expected since the incoming short wave radiation will heat the upper leaves. Indeed Figure 3 clearly shows this behaviour.

Figure 5 shows the most important meteorological variables for the dry night (13–14 September). To observe or to simulate a nearly dewless night correctly is also very important, since after such a night no spraying measures need to be executed. This night was windier and dryer than the 26–27 August. The dry and wet bulb temperatures at reference height were close enough to cause dewfall only for a short interval. The calculated and measured dew results are plotted in Figure 6. The accumulated dew during this night was very low and the calculated accumulated dew amount in the lowest layer mimicked the measured value well. The model performed well for both dew and nearly dewless conditions.

The measured and simulated leaf temperatures of the top layer are plotted in Figure 7. The characteristics are similar to those for Figure 4, but the difference between modelled and measured results are smaller, probably due to higher wind speeds and consequently better mixing during this night.

Table 1. *The wetness periods simulated with the model compared to the measured wetness periods as measured using the leaf wetness sensor.*

Date	Bottom Layer			Wetness Sensor		
1996	Start	End	Duration	Start	End	Duration
Aug						
26–27	21:50	9:50	12:00	21:50	10:00	12:10
Sep						
1–2	20:50	11:30	14:40	21:00	11:30	14:30
2–3	21:30	10:00	12:30	21:40	10:10	12:30
4–5	2:10	10:10	8:00	2:20	10:30	8:10
14–15	7:10	8:10	1:00	7:10	8:10	1:00
15–16	21:30	10:20	12:50	21:30	10:30	13:00

In total six nights were simulated (main results provided in Table 1). The calculated leaf wetness duration for the bottom layer agrees to within 10 minutes (the averaging time of the system) with the measured results obtained using a simple resistance grid instrument.

5. Conclusions

In this paper leaf wetness duration and meteorological variables were quantified within a lily crop canopy. We used model calculations to improve our understanding of the physical mechanisms controlling the exchange mechanism of water vapour to and from the plant canopy. The following main conclusions can be drawn from our study:

(a) Leaf wetness duration in the bottom layer was well-simulated by the multi-layer model. The simulated wetness durations agree with the observations made with the electrical grid leaf wetness instrument within twice the data averaging time.
(b) Agreement between model simulations and observations was good for both periods of dew formation and dry periods.
(c) The model results suggest that the leaf wetness period first begins at the top of the canopy and from there penetrates into the canopy, while drying also starts at the top of the canopy.
(d) The model simulations suggest that the longest leaf wetness duration occurs at the bottom of the canopy. Thus lower parts of the canopy may be most sensitive to fungal diseases and, if a wetness sensor is used, it should be placed within the lower canopy.

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