Estimating dew formation in rice, using seasonally averaged diel patterns of weather variables

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Abstract

If dew formation cannot be measured it has to be estimated. Available simulation models for estimating dew formation require hourly weather data as input. However, such data are not available for places without an automatic weather station. In such cases the diel pattern of weather variables might be used to run the simulation model. To investigate the possibility of using diel patterns of weather variables to estimate dew formation, a field experiment was carried out from February to April 1994 at the International Rice Research Institute (IRRI), Los Baños, Philippines. The seasonally averaged diel patterns of weather variables were derived from hourly records. Both the hourly recorded weather data and the seasonally averaged ('mean') diel patterns derived from these weather variables were used to run a simulation model based on an energy-balance approach. Hourly recorded weather data as input gave the best estimation of dew formation at crop height. Substituting the hourly records of wind speed and air temperature by their mean diel patterns gave slightly worse but still acceptable dew estimates, as confirmed by a Wilcoxon signed rank test. This test showed that for water vapour pressure and nocturnal net radiation, however, the substitution of actual values by mean diel patterns resulted in unacceptably large estimation errors.

Additional keywords: simulation model, micrometeorology, leaf wetness

Introduction

Dew as a main contributor to leaf wetness has been studied for its importance in phytopathology (Wallin, 1963; Jones, 1986) and in the deposition of pollutants on leaves (Schuepp, 1989; Janssen & Romer, 1991). Dew formation in crops can be either

estimated using the energy-balance approach, or measured using special instruments and techniques. Dew formation has to be estimated if records are not available. Pedro & Gillespie (1982a, b) developed a single-layer model to estimate dew formation on leaf surfaces, using microclimate data as well as standard weather data. Goudriaan (1977) developed a multi-layer model (MICROWEATHER) that simulates the distribution of dew formation at different levels in a crop canopy. Hourly weather data are required to run the dew formation simulation models. Such models can only be used in places with weather stations where the diel weather data are routinely recorded by hand. Studies on diel patterns of weather variables (Parton & Logan, 1981; Peterson & Parton, 1983; Wann *et al.*, 1985; Reicosky *et al.*, 1989) provide a possibility of estimating hourly values from daily ones. However, before adopting the diel pattern of weather variables to estimate dew formation, the question needs to be answered whether the estimated diel pattern will give as good an estimate of dew formation as hourly recorded weather data. The objective of this study was to answer this question through field experiments and simulation analysis.

Materials and methods

Experimental site and measurements

The experiment was carried out in the period 7 February – 11 April 1994 in a 25 × 50 m paddy rice field at the International Rice Research Institute (IRRI) (14°11′N, 121°15′E, 20.0 m a.s.l.), Los Baños, Philippines. In a 1000-m radius around the experimental field there were no high buildings or tall trees. Other paddy fields surrounded the site.

To measure the amount of dew formed at crop height, blotting-paper discs with a diameter of 90 mm were used as artificial leaves. The discs were attached horizontally at crop height to an erect bamboo stick and placed in the field before sunset. Dew was measured at five locations. To avoid the artificial leaves to become saturated with dew, per location five discs were pinned together, using two paper clips. The discs remained in the field until the next morning and were weighed three times: (1) before sunset, (2) at the time of dew onset, and (3) around sunrise (06:00 h). The total amount of dew formed per unit leaf area (kg m^{-2} or millimetre) was calculated as the weight increment of the discs, divided by the one-sided area of one disc. The time dew appeared and the time it disappeared were recorded visually. After sunset, the rice leaves were sensed every 15 minutes for the presence of dew until dew was detected. The same procedure was followed after sunrise to detect the time of drying up of the leaves. Dew duration was calculated as the time interval (hours) between the moment dew appeared and the moment it disappeared. The observations were made on 23 rain-free nights during the experimental period.

Global radiation (at 2.5 m above the paddy water surface), net radiation, air temperature, air humidity (at 1.5 m above the paddy water surface), wind speed (at 2.0 m above the paddy water surface) over the rice canopy, and paddy water temperature (at 0.05 m below the water surface) were recorded automatically. All aerial sensors were

mounted on a tripod that was set up in the centre of a 4 × 5 m plot situated in the middle of the experimental paddy rice field. The recording interval was 2 seconds for all weather variables except for wind speed, which was recorded every 10 seconds. All data were hourly averaged.

The rice variety IR72 was used. During the experimental period the crop passed through the development stages 'tillering' (22 February 1994) to 'dough ripe' (6 April 1994).

Diel patterns and relative variations of weather variables[1]

The seasonally averaged diel patterns of the weather variables global radiation (Q), net radiation (R_{net}), air temperature (T_a), relative humidity (RH), vapour pressure (e_a), vapour pressure deficit (D) and wind speed (u) were derived by means of curve fitting.

The diel pattern of global radiation is related to true solar time. The sine of solar height (β) can be calculated with the equation:

$$\sin\beta = \sin\varphi \ \sin\delta + \cos\varphi \ \cos\delta \ \cos\{2\pi [t_h - (12 + \Delta t)] / 24\} \qquad (1)$$

where
β = solar height,
φ = latitude,
δ = declination of the sun,
t_h = local standard time, and
Δt = difference (in hours) between local standard time and true solar time.

For Los Baños Δt was calculated from the difference between local longitude (121.25°E) and the standard local time longitude (120°E), and was determined to be about 0.08 hours.

Generally, the equations for global radiation (Q) (Ross, 1975) and daytime net radiation (R_{net}) can be written as:

$$Q = Q_o \ \tau_a \sin\beta \exp(A / \sin\beta) \qquad (2)$$

and

$$R_{net} = L_{net} + (1 - \alpha) \ Q \qquad (3)$$

where
Q_o = solar constant (about 1367 W m^{-2}),
τ_a = atmospheric transmissivity,
α = surface effective albedo,
L_{net} = thermal component of net radiation,
A = empirical coefficient of about –0.12.

[1] For symbols and abbreviations used see Appendix.

The fluctuation of nocturnal net long-wave radiation (L_{net}) was calculated using the Swinbank (1963) formula, in which L_{net} depends on cloudiness through a variable called C:

$$L_{net} = L\downarrow - L\uparrow$$

$$L\downarrow = \varepsilon\, \sigma\, T^4_{abs,air}\, [1 - (1 - 9.35 \times 10^{-6}\, T^2_{abs,air})\, C\,]$$

$$L\uparrow = \varepsilon\, \sigma\, T^4_{abs,air}$$

where

$L_{\downarrow}$ = downward thermal radiation from the sky,
$L_{\uparrow}$ = upward thermal radiation from the canopy,
ε = emissivity of the canopy (0.95) (also used for the absorptivity of the canopy),
σ = Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and
$T_{abs,air}$ = absolute air temperature at 1.5 m above the paddy water surface.

In this study no observations on cloudiness were made. C, as an indicator of cloudiness, was therefore calculated from the equation:

$$C = Q_{total} / Q_e$$

where

Q_{total} = daily total global radiation, and
Q_e = daily total extraterrestrial radiation, thus assuming that nocturnal cloudiness did not differ from daytime cloudiness.

Vapour pressure deficit (D) was calculated from the observed hourly data of air temperature and vapour pressure. The mean diel patterns of air temperature, relative humidity, vapour pressure, vapour pressure deficit and wind speed were summarized in the form of simple equations fitted to the hourly data available over the experimental period, and thus represent one specific seasonally averaged diel pattern for each weather variable. The equations used for this purpose are given in Table 2.

Relative standard error of estimate

To compare the day by day variation of the diel patterns of weather variables, the relative standard error (RSE) was used to describe the relative deviation of actual diel patterns – of air temperature, vapour pressure, vapour pressure deficit, wind speed and nocturnal net radiation – from the mean ones. RSE is a 'daily weighted' measure to express deviation of estimated from recorded values of weather variables used as inputs in the MICROWEATHER model (Goudriaan, 1977). RSE was calculated with the equation:

$$RSE = [(\sum(w_i - w_{mean})^2 / 552\,]^{1/2} / (w_{max} - w_{min}) \qquad (4)$$

where
w_i = recorded hourly value of the weather variable concerned (w),
w_{mean} = average value of w_i during the experimental period (23 days),
w_{max} = average value of the daily maximum of w during the experimental period,
w_{min} = average value of the daily minimum of w during the experimental period,
i = subscript for the index number of the hourly value of the weather variable and
552 = the total number (24 × 23) of hourly values during the 23-day period considered.

Simulation, error analysis and test of significance

In the MICROWEATHER model (Goudriaan, 1977) dew formation is simulated by the Penman-Monteith combination equation for the surface energy balance (Monteith & Unsworth, 1990). First, the mean diel patterns of weather variables derived from the observed hourly data were used as inputs to the MICROWEATHER model. Then, model predictions of amount and duration of dew were compared with the recorded dew data as well as with model predictions using recorded hourly data of all weather variables. The statistical significance of difference in model predictions between using the two types of weather variables, i.e., their estimated mean diel patterns on the one hand and their actually observed hourly values on the other, was tested using the Wilcoxon signed rank test (Hollander & Wolfe, 1973). Measured and estimated mean diel patterns of the weather variables air temperature, vapour pressure, vapour pressure deficit, wind speed and the calculated nocturnal net radiation, were used in different combinations as input to the model, ranging from all weather variables recorded to all weather variables estimated.

Error analysis and test of significance

The data on dew formation measured during the 23 nights are regarded as independent observations by i = 1, 2, 3,..., 23. The root mean square error (RMSE) between simulated values, using seasonally mean diel patterns of weather variables, and recorded data of amount of dew and dew duration was calculated as follows:

$$RMSE = [\sum(\hat{y}_i - y_i)^2 / 23]^{1/2}$$

where
$\hat{y}_i$ = amount of dew or dew duration predicted (by simulation),
y_i = amount of dew or dew duration recorded,
i = the index number of the night of observation, and
23 = total number of observation nights.

The Wilcoxon signed rank test (Hollander & Wolfe, 1973) was used to test the statistical significance of the differences in estimation error between using the actual hourly data of all weather variables as input versus using the estimated diel patterns of weather variables as input. The difference in estimation error for amount of dew or dew duration (Δy_i) was defined as:

$$\Delta y_i = (\hat{y}_{a,i} - y_i)^2 - (\hat{y}_{e,i} - y_i)^2$$

where

i = the index number of y recorded,
a,i = subscripts indicating the actual weather variables used to predict y, and
e,i = subscripts indicating the estimated diel patterns of weather variables used to predict y.

Under the null-hypothesis: 'it makes no difference whether the mean diel pattern of weather variables or their actually observed hourly values are used as input for the MICROWEATHER model', Δy_i will have equal probability to be either positive or negative. A one-sided 'Large Sample Approximation' test was done at the 95% significance level (Hollander & Wolfe, 1973) to detect any statistically significant effect of the kind of input weather data.

Results and discussion

Mean diel fluctuations of weather variables and their relative variation

During the night, vapour pressure varied little and was therefore considered as constant. After sunrise, however, water vapour pressure increased and reached its daily maximum at about 3 hours after sunrise (around 09:00 h) (Figure 1). Global radiation and daytime net radiation varied with the sine of the height of the sun up to maximum values of about 840 W m^{-2} and 630 W m^{-2}, respectively (Figure 2 A and B). Nocturnal net radiation (between sunset and sunrise) gradually became less negative by 8 W m^{-2} (Figure 3), concurrent with a decrease in air temperature (Figure 4). Air temperature, vapour pressure deficit and wind speed reached their maximum at about 13:30 h, 14:30 h and 14:30 h, respectively, and their minimum at sunrise (Figures 4–6). The diel range of air temperature was about 7 °C. Wind speed and vapour pressure deficit ranged from 0.5 to 3 m s^{-1} and from 0.25 to 1.38 kPa, respectively. The diel

Table 1. Relative standard error of deviations of recorded diel patterns of weather variables from means.

Weather variable	Symbol	Relative standard error[1]	
		Daily range	Daily mean
		(%)	
Air temperature	T_a	12.5 – 28.4	20.5
Vapour pressure deficit	D	10.7 – 35.7	23.2
Wind speed	u	11.0 – 42.5	26.8
Water vapour pressure	e_a	37.0 – 68.5	52.8
Nocturnal net radiation	R_{net}	119.0 – 161.0	140.0

[1] For explanation of relative standard error (RSE) see text.

Table 2. Equations for mean diel patterns of weather variables[1].

Equation	Variable	Unit
During daytime		
$Q = 981.0 \sin\beta \exp(-0.12/\sin\beta)$	global radiation	[W m^{-2}]
$R_{net} = -32.0 + 0.69Q$	net radiation	[W m^{-2}]
$T_a = T_{min} + (T_{max} - T_{min}) \sin[\pi(t_h - 6.0)/15]$	air temperature	[°C]
$RH = RH_{max} - (RH_{max} - RH_{min}) \sin[\pi(t_h - 7.0)/15]$	relative humidity	[–]
$u = 0.5 + 2.0(u_{mean} - 0.5) \sin[\pi(t_h - 7.0)/15]$	wind speed	[m s^{-1}]
$e_a = e_{max} + 0.15\ (t_h - 9.0)$ (if: $6 \le t_h \le 9$)	water vapour pressure	[kPa]
$e_a = e_{max} - 0.035(t_h - 9.0)$ (if: $9 < t_h \le 18$)	water vapour pressure	[kPa]
$D = D_{min} - (D_{max} - D_{min}) \sin[\pi(t_h - 7.0)/15]$	vapour pressure deficit	[kPa]
During night time[2]		
$T_a = T_{min} + (T_{max} - T_{min}) \sin[\pi(t_{h,sset} - 6.0)/15]\exp(-x/4.0)$	air temperature	[°C]
$RH = RH_{max} - (RH_{max} - RH_{min}) \sin[\pi(t_{h,sset} - 6.0)/15]\exp(-x/4.0)$	relative humidity	[–]
$u = 0.5 + u_{mean}\exp(-x/1.8)$	wind speed	[m s^{-1}]
$e_a = e_{max} + 0.15(t_{h,srise} - 9.0)$	water vapour pressure	[kPa]
$D = D_{min} - (D_{max} - D_{min}) \sin[\pi(t_{h,sset} - 7.0)/15] \exp(-x/3.5)$	vapour pressure deficit	[kPa]

[1] For symbols see Appendix. Symbols with subscripts 'mean', 'max' and 'min' are daily mean, maximum and minimum values, respectively.

[2] No curve was fitted for nocturnal net radiation.

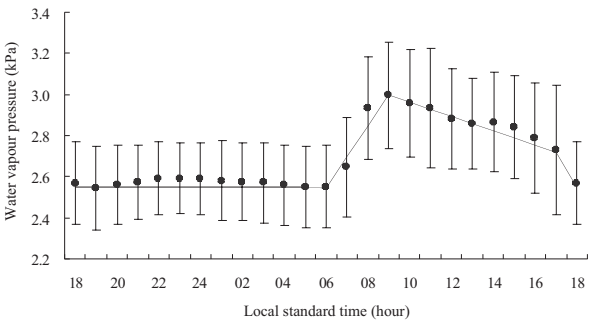

Figure 1. Mean diel pattern of water vapour pressure. Average values of data recorded during the experimental period (•) and regression curve fitted to the data (solid line). For the regression equations see Table 2. The vertical lines are the standard error bars.

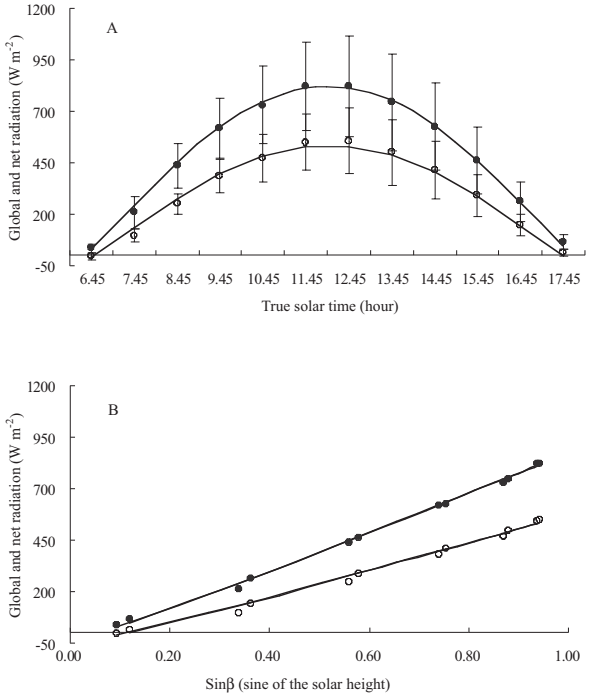

Figure 2. A. Mean diel patterns of global and net radiation. B. The relations between global or net radiation and sinβ (sine of the solar height). Average values of global radiation (•) and average values of net radiation (o), both recorded during the experimental period, and regression curves fitted to the data (solid lines). For the regression equations see Table 2. The vertical lines are the standard error bars.

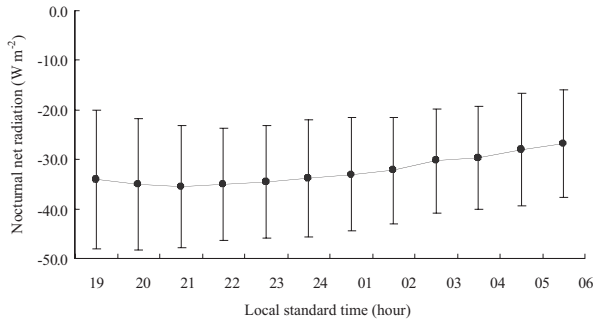

Figure 3. Mean pattern of nocturnal net radiation recorded during the experimental period (•). The vertical lines are the standard error bars.

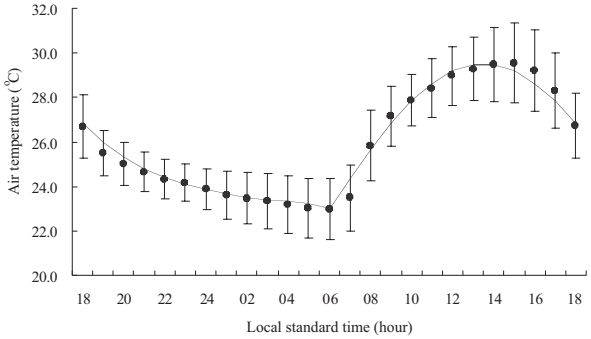

Figure 4. Mean diel pattern of air temperature. Average values of air temperature recorded during the experimental period (•) and regression curve fitted to the data (solid line). For the regression equations see Table 2. The vertical lines are the standard error bars.

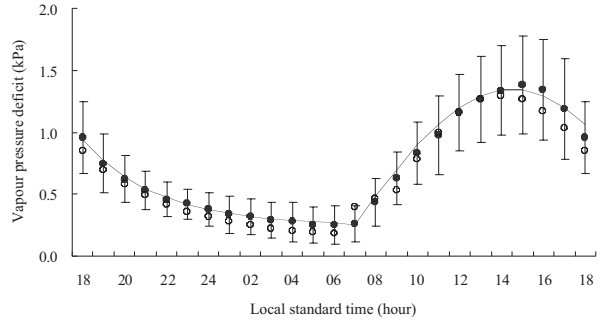

Figure 5. Mean diel pattern of vapour pressure deficit. Average values of vapour pressure deficit calculated from the hourly data of air temperature and vapour pressure recorded during the experimental period (•) and vapour pressure calculated from the mean diel patterns of air temperature and vapour pressure (o). Regression curve fitted to the data (solid line). For the regression equations see Table 2. The vertical lines are the standard error bars for •.

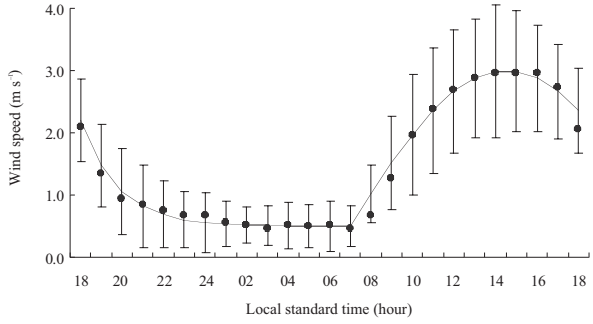

Figure 6. Mean diel pattern of wind speed. Average values of wind speed recorded during the experimental period (•) and regression curve fitted to the data (solid line). For the regression equations see Table 2. The vertical lines are the standard error bars.

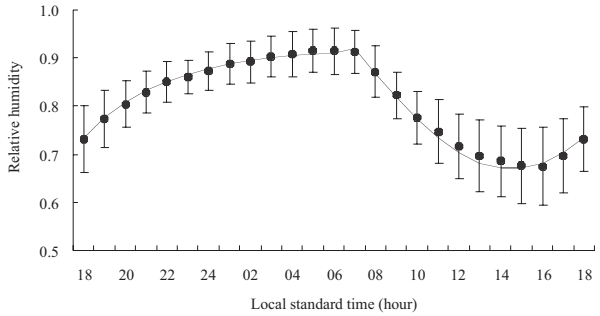

Figure 7. Mean diel pattern of relative humidity. Average values of relative humidity recorded during the experimental period (•) and regression curve fitted to the data (solid line). For regression equations see Table 2. The vertical lines are the standard error bars.

pattern of relative humidity was opposite to that of air temperature but reached its minimum (0.68) at about 14:30 h and maximum (0.92) at sunrise (Figure 7). Its diel range was 0.24.

The relative standard error of the estimate (RSE) was smallest for air temperature and largest for nocturnal net radiation (Table 1). This indicates that the diel patterns of air temperature, vapour pressure deficit and wind speed were much more stable than those of vapour pressure and nocturnal net radiation.

All equations derived for the weather variables are listed in Table 2.

Global radiation and net radiation

For the specific experimental site and season, τ_a, α, L_{net} and A in Equations 2 and 3 were 0.72, 0.31, –32.0 W m^{-2}, and –0.12, respectively (Table 2), according to the curves fitted to the observed hourly data. At night, $Q = 0$ and $R_{net} = L_{net}$. During daytime, L_{net} was set equal to the seasonal average nocturnal net radiation (–32 W m^{-2}). The apparent albedo (α) in the equation for net radiation (Equation 3) consists of two parts: (1) the true albedo for short-wave radiation, which has a value of about 0.23 for most vegetation surfaces, and (2) a heating coefficient, which is caused by the increased thermal radiation as the surface temperature rises due to the absorption of incoming short-wave radiation (Davies & Buttimor, 1969). Assuming that the diel range of surface temperature was the same as that of air temperature (about 7 °C), the thermal radiation loss would be increased by about 40 W m^{-2} at maximum solar height. So the heating coefficient can be estimated at 0.05 (= 40/840). The observed apparent albedo was 0.31, and so the short-wave albedo is estimated at about 0.26, which is slightly higher than the generally accepted value of 0.23.

Air temperature, air humidity and wind speed

The best fitting descriptive equation for the mean diel patterns of air temperature, vapour pressure deficit and wind speed was a sine function during daytime and an exponential function for the nights (Figures 4–6 and Table 2). After sunset, wind speed settled down much faster than air temperature and vapour pressure deficit (Figures 4–6). The mean pattern of daytime water vapour pressure (e_a) (Figure 1) was more difficult to approximate. In an approximation it was divided into two parts: (1) from sunrise to 09:00 h, when the maximum was reached, and (2) from 09:00 h to sunset. The two parts could be approximated by linear functions of time (Figure 1 and Table 2).

The coefficients in the descriptive equations for air temperature, relative humidity and vapour pressure deficit were expressed in daily maximum and minimum values whereas those for vapour pressure and wind speed were expressed in daily maximum and mean values, respectively, since only daily maximum vapour pressure (at 09:00 h) and mean wind speed are routinely recorded by non-automatic weather stations. A minimum (or maximum) value was needed to derive at the equation for the diel pattern of wind speed since the equation was not linear. The minimum wind speed was set equal to the seasonal average minimum (0.5 m s^{-1}) (Table 2).

Comparison of simulated and observed dew formation

Amount of dew

The measured and simulated daily amounts of dew at crop height are shown in Figure 8. Root mean square error (RMSE) between measured and simulated results was smallest (0.038 mm) when hourly observed weather variables were used in the model. With mean diel patterns of weather variables, RMSE became larger (Table 3). Of all

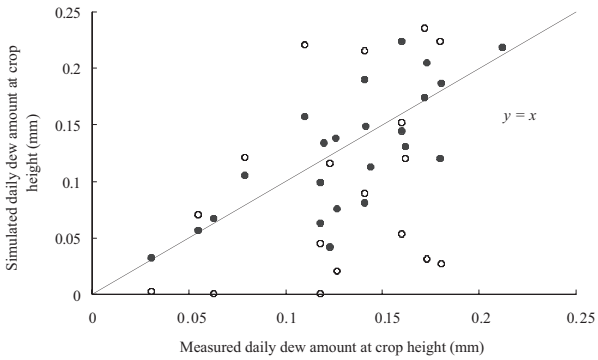

Figure 8. Comparison of measured and simulated daily amount of dew. Simulation results using hourly weather records (•) and simulation results using the daily curve of weather variables as input for the MICROWEATHER model (o).

Table 3. Root mean square error (RMSE) values between recorded and simulated dew (amount and duration). The weather variables used in the simulation were hourly observed except the ones mentioned, which were replaced by their diel patterns. Summary of results of error analysis and test of statistical significance.

Hourly recorded weather variables[1]	Amount of dew		Dew duration	
	RMSE (mm)	P[2]	RMSE (hour)	P
All variables	0.038		2.1	
All variables except T_a	0.064	0.10*	2.1	0.22*
All variables except u	0.046	0.22*	2.4	0.37*
All variables except e_a	0.076	0.01	2.8	0.01
All variables except R_{net}	0.111	0.00	2.8	0.13*
All variables except T_a and u	0.047	0.23*	2.2	0.28*
All variables except T_a and e_a	0.071	0.01	2.8	0.01
All variables except D and T_a	0.066	0.10*	2.6	0.03
All variables except e_a and u	0.135	0.00	3.4	0.03
All variables except T_a, e_a and u	0.076	0.01	4.0	0.07*
All variables except D, T_a and u	0.047	0.24*	3.1	0.15*
All variables except T_a, u and R_{net}	0.096	0.00	3.3	0.08*
All variables except e_a, u and R_{net}	0.128	0.01	4.0	0.01
All variables except T_a, e_a and R_{net}	0.132	0.00	3.9	0.01
All variables except D, T_a and R_{net}	0.104	0.00	2.8	0.04
All variables except T_a, e_a, u and R_{net}	0.130	0.00	4.6	0.02
All variables except D, T_a, u and R_{net}	0.081	0.00	2.6	0.05

[1] For symbols see Appendix.

[2] * = The difference between simulated dew (amount and duration), using mean diel pattern(s) of weather variable(s), and recorded dew (amount and duration) is not statistically different (95% significance level) from that between simulated dew, using recorded hourly data for all weather variables, and recorded dew.

weather variables, recorded wind speed (u), when substituted by its mean diel pattern, resulted in the lowest RMSE (0.046 mm), and wind speed and temperature (T_a) combined or water vapour deficit (D), u and T_a combined, in the lowest but one RMSE (0.047 mm). Substituting nocturnal net radiation (R_{net}) by its estimate resulted in a much higher RMSE (0.111 mm). Also the mean diel pattern of vapour pressure (e_a) resulted in a high RMSE-value (0.076 mm). The mean diel patterns of D and T_a combined – theoretically equivalent to those of e_a and T_a combined – resulted in a better estimation of dew than those of e_a and T_a combined. This might be attributed to the fact that the mean nocturnal value of D was constantly underestimated if the recorded diel pattern of e_a was substituted by its mean diel pattern (Figure 5).

The Wilcoxon signed rank test showed that when the observed hourly patterns of air temperature, wind speed and vapour pressure deficit were substituted by their diel patterns, there was no statistically significant increase in RMSE of the simulation results compared with the recorded dew data (Table 3). However, the difference between the recorded data and the simulation results using mean diel patterns of any other weather variable or a combination, was significantly larger than that between the observed and the simulation results using observed hourly data of all weather variables. These results combined with the RMSE indicate that the diel patterns of air temperature, vapour pressure deficit and wind speed can be substituted by their mean diel patterns whereas those of net radiation and vapour pressure have to be recorded, and cannot be substituted by their mean diurnal patterns. In the worst cases of Table 3 the RMSE for amount of dew was similar in magnitude to the absolute amount of dew, which varied between 0.1 and 0.2 mm.

Dew duration

Recorded and simulated daily dew duration at crop height are shown in Figure 9. RMSE between measured and simulated results was lowest (2.1 hours) when hourly measured weather variables were used in the model. Substituting T_a by its mean diel pattern did not affect the result. The combination of mean diel pattern of T_a and u resulted in the second best result (RMSE = 2.2 hours) whereas substituting measured vapour pressure or nocturnal net radiation by their diel patterns resulted in a lower RMSE-value (Table 3). As for amount of dew, the Wilcoxon signed rank test showed that the RMSE of the simulation results was not significantly lower than that of the measured data if the recorded hourly time courses of air temperature and wind speed were substituted by their mean diel patterns (Table 3). Neither was this the case for R_{net}, T_a, e_a and u combined, for D, T_a and u combined, and for T_a, e_a and R_{net} combined, although the level of similarity (P-value in Table 3) was lower. These results combined

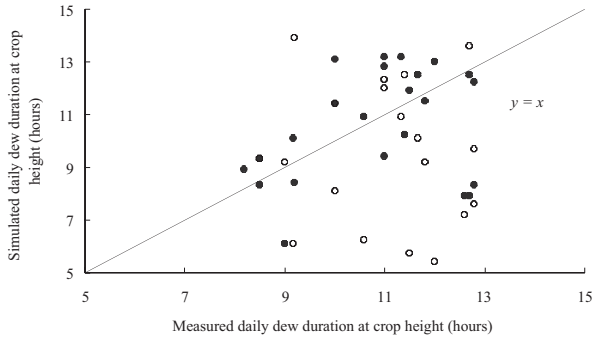

Figure 9. Comparison between measured and simulated daily dew duration. Simulation results using hourly weather records (•) and simulation results using the daily curve of weather variables as input for the MICROWEATHER model (o).

with the RMSE suggest that for estimating dew duration it is possible to use the mean diel patterns of air temperature and wind speed instead of their measured hourly values. For vapour pressure or vapour pressure deficit or nocturnal net radiation this substitution cannot be recommended.

Overview

Mean diel pattern of net radiation nor that of vapour pressure can be used to estimate dew formation, as is shown by both the large relative standard errors of estimate (Table 1), and their less precise approximation by the mean diel curve equation (Figure 1). Remarkably, the mean diel pattern of vapour pressure deficit can be used to estimate amount of dew but not dew duration. This may be attributed to a good approximation of nocturnal vapour pressure deficit (D) in contrast to an overestimation of D early in the morning (Figure 5). Nocturnal D has to be calculated from air temperature and humidity (vapour pressure or relative humidity), so the amount of dew is directly affected by nocturnal D whereas dew duration is affected by nocturnal as well as early-morning D. Where no automatic weather station is present, only maximum vapour pressure or minimum relative humidity are routinely recorded. In that case, D has to be calculated from the diel pattern of vapour pressure or relative humidity. Therefore, air humidity records are required to estimate amount of dew as well as dew duration. The mean diel pattern of wind speed can be used to estimate amount as well as duration, which may be attributed to the fact that wind speed during the experimental nights was very low: less than 1 m s^{-1}. At low wind speed levels, free convection takes over from forced convection.

Based on the results obtained it can be concluded that to estimate amount of dew and dew duration, the diel patterns of air temperature and wind speed may be substituted by their mean diel patterns whereas for air humidity and net radiation hourly values have to be used. Further research will be needed to see whether these results are also valid for other seasons and sites.

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Appendix

List of abbreviations and symbols

Abbreviation/ symbol	Description	Unit
A	empirical coefficient for diel pattern of global radiation	[–]
C	cloudiness	[–]
D	vapour pressure deficit	[kPa]
e_a	actual vapour pressure at 1.5 m above the paddy water surface	[kPa]
L_{net}	thermal net radiation	[W m^{-2}]
Q	global radiation	[W m^{-2}]
Q_e	daily total extraterrestrial radiation	[MJ m^{-2}]
Q_o	solar constant (1367)	[W m^{-2}]
Q_{total}	daily total global radiation	[MJ m^{-2}]
RH	relative humidity	[–]
RMSE	root mean square error of dew variable	[mm] or [hour]
R_{net}	net radiation	[W m^{-2}]
RSE	relative standard error of diel pattern	[–]
T_a	air temperature at 1.5 m above the paddy water surface	[°C]
$T_{abs,air}$	absolute air temperature at 1.5 m above the paddy water surface	[K]
$T_{abs,s}$	absolute temperature of the canopy	[K]
t_h	local standard time (1–24 h)	[hour]
$t_{h,srise}$	local standard time of sunrise	[hour]
$t_{h,sset}$	local standard time of sunset	[hour]
u	wind speed	[m s^{-1}]
w	weather variable	[*]
x	time since sunset	[hours]
y	dew variable	[mm] or [hour]
α	surface effective albedo	[–]
β	solar height	[degree]
σ	Stefan-Boltzmann constant (= 5.67×10^{-8})	[W m^{-2} K^{-4}]
ε	emissivity of the canopy (= 0.95) (also used for the absorptivity of the canopy)	[–]
φ	latitude	[degree]
δ	declination of the sun with respect to the equator	[degree]
Δt	time difference between local standard time and true solar time	[hour]
τ_a	atmospheric transmissivity	[–]

* Depending on the weather variable concerned.