Simulation and measurement of leaf wetness formation in paddy rice crops

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Simulation and measurement of leaf wetness formation in paddy rice crops

LUO Weihong

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This thesis contains results of a research project of the Department of Theoretical Production Ecology, Wageningen Agricultural University. The research project was part of the 'Simulation and Systems Analysis for Rice Production' (SARP) - Project, which was a collaborative project of the Department, together with over 16 national agricultural research centers in Asia, the International Rice Research Institute (IRRI), Los Baños, the Philippines and the DLO-Research Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen. The SARP-project was partly financed by the Directorate General for International Cooperation of the Dutch Ministry of Foreign Affairs.

Propositions

1. The contribution of guttation to leaf wetness in paddy rice crops can be as important as dew.
This thesis

2. Shielding nocturnal net radiative loss is a feasible method for experimentally distinguishing dew from guttation.
This thesis

3. When windspeed is below 1 m s^{-1}, dew formation mainly depends on nocturnal net radiative loss and vapour pressure deficit.
This thesis

4. In the tropics, daily leaf wetness duration is linearly related to the time of onset of wetness.
Huber, L. and Gillespie, T.J., 1992. Modeling leaf wetness in relation to plant disease epidemiology. Annu. Rev. Phytopathol., 30: 553-557 and this thesis

5. To estimate dew formation, air humidity and nocturnal net radiation have to be observed at least hourly.
This thesis

6. The dewball is a new and simple instrument that allows easy estimation and observation of daily dew duration.
This thesis

7. Lack of information about the stratification condition above a canopy is one of the main causes of the estimation error for dew formation.
This thesis

8. Simplifying a complex model is as important as improving the accuracy of a simple model.

9. On one hand tradition is the main convergent force of a society, on the other hand it can also be the main constraint of the development of the society.

10. Human rights are sold for the biggest market share.

11. Facts speak louder than eloquence.

Propositions associated with the Ph.D. thesis of LUO Weihong:
Simulation and measurement of leaf wetness formation in paddy rice crops.

Wageningen, November 27, 1996.

灌溉水稻叶表面液态水形成的模拟与观测

罗卫红

Dedicated to my family

Abstract

Simulation and measurement of leaf wetness formation in paddy rice crops

The study described in this thesis focuses on a quantification of leaf wetness formation in paddy rice crops based on insight in the physical processes of the formation of leaf wetness. For this purpose, experimental research was conducted in a tropical paddy rice field.

A shielding (nocturnal net radiative loss) experiment was designed to investigate the dependence of dew formation on nocturnal net radiative loss. A simple method was developed to estimate dew amount and duration using the nightly total net radiative loss. The shielding experiment unexpectedly provided a feasible method for experimentally distinguishing dew from guttation. For a better understanding of the characteristics of the formation of leaf wetness in paddy rice crops, warm water flooding both in the paddy rice field and in a phytotron was conducted to investigate the effects of water temperature on dew formation and guttation. The experimental data indicated an optimum paddy water temperature of 30°C for rice leaf guttation. The effect of water temperature on dew formation depended on the weather condition above the canopy, especially the thermal stratification condition, net radiation and vapour pressure deficit. A simple device, the dewball, was designed to observe dew formation and to determine its threshold value of nocturnal net radiative loss from top leaves. This was shown to be a simple and accurate method for estimating daily dew duration on top leaves. The possibility of using the mean diurnal patterns of weather variables to estimate dew formation was analysed by comparing the dew estimated using a simulation model to the measured results. This helped to understand to what extent the diurnal patterns will give as good an estimate of dew formation as when the observed hourly weather data are used. Based on the observation results on the dewball and the results of the shielding experiment, a simple approach to estimate daily dew duration on top leaves of the paddy rice crops was formulated and its potential applications to plant protection were discussed.

Keywords: dew, guttation, net radiative loss, vapour pressure deficit, stratification condition, diurnal pattern.

Preface

The work reported in this dissertation was funded by the 'Simulation and System Analysis for Rice Production' (SARP) project which was financed by The Netherlands' Ministry for Development Cooperation (DGIS). The idea for this research was formed during my first visit to the Department of Theoretical Production Ecology of the Wageningen Agricultural University (TPE-WAU) and DLO-Research Institute for Agrobiology and Soil Fertility (AB-DLO, then CABO) (from January to July, 1990). The experimental instruments were prepared with the help of the Department of Meteorology of WAU (M-WAU) (from September to December, 1993). The field experimental work was done at the International Rice Research Institute (IRRI) in the Philippines (from December, 1993 to April, 1994). The phytotron experiment was conducted at the Department of Agronomy of WAU (A-WAU) (September, 1995). The experimental data analysis, simulation and writing-up started during my third visit to Wageningen (from August to October, 1994). The work was finalized during my fourth visit to Wageningen. I gratefully acknowledge the supports given by AB-DLO, TPE-WAU, IRRI, M-WAU and A-WAU through the SARP project. I also thank my home institute the Zhejiang Agricultural University (ZAU) for granting me such extended oversea study leave. Thanks to Prof. Wang Zhaoqian, the SARP-ZAU team supervisor, Prof. Pang Zhengchao and Prof. Huang Shoubo for providing moral support.

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Contents

List of symbols and abbreviations

Symbol	Description	Unit
D	vapour pressure deficit at 1.5 m above the ground	kPa
D_{min}	minimum vapour pressure deficit	kPa
DEW	dew amount	mm
DEW_{di}	simulated dew amount using the mean diurnal pattern of weather variables	mm
$DEW_{di}(T_a)$	simulated dew amount using the mean diurnal pattern of air temperature	mm
DEW_{hi}	simulated dew amount using the observed hourly data of all weather variables	mm
DEW_{oi}	measured dew amount	mm
DEWT	dew duration	hour
$DEWT_{di}$	simulated dew duration using the mean diurnal patterns of weather variables	hour
$DEWT_{hi}$	simulated dew duration using the observed hourly data of all weather variables	hour
$DEWT_{oi}$	measured dew duration	hour
e_a	actual vapour pressure at 1.5 m above the ground	kPa
f	the ratio of the exposed period to night length	–
LAI	leaf area index	–
L_n	thermal net radiation	$W\ m^{-2}$
Q	global radiation	$W\ m^{-2}$
Q_e	daily total extraterrestrial radiation	$MJ\ m^{-2}$
Q_0	solar constant (1367)	$W\ m^{-2}$
Q_{total}	daily total global radiation	$MJ\ m^{-2}$
r_a	resistance for water vapour and heat transfer or	$s\ mm^{-1}$ or $s\ m^{-1}$
RH	relative humidity	–
R_n	net radiation	$W\ m^{-2}$
R_{nt}	total nocturnal net radiative loss	$MJ\ m^{-2}$
$R_{n,thresh}$	threshold nocturnal net radiative loss for dew formation	$W\ m^{-2}$
$R_{nt,thresh}$	threshold total nocturnal net radiative loss for dew formation	$MJ\ m^{-2}$

s	slope of the saturation vapour pressure curve at air temperature	$kPa\ K^{-1}$
T_a	air temperature at 1.5 m above the ground	^oC
$T_{abs,air}$	absolute air temperature at 1.5 m above the ground	K
$T_{abs,s}$	absolute temperature of the canopy	K
t_h	local standard time	hour
$t_{h,sset}$	local standard time of sunset	hour
T_{wc}	critical paddy water temperature for dew formation	^oC
u	wind speed	$m\ s^{-1}$
VPD	vapour pressure deficit	kPa
α	surface effective albedo	–
β	solar height	degree
σ	Stefan-Boltzmann constant ($=5.67\times10^{-8}$)	$W\ m^{-2}\ K^{-4}$
ε	emissivity of the canopy (=0.95) (also used for the absorptivity of the canopy)	–
λE	latent heat flux	$J\ m^{-2}\ s^{-1}$
ρc_p	volumetric heat capacity of the air	$J\ m^{-3}\ K^{-1}$
γ	psychrometric constant	$kPa\ K^{-1}$
φ	latitude	degree
δ	declination of the sun with respect to the Equator	degree
θ	zenith angle on the dewball	degree
τ_a	atmospheric transmissivity	–

Chapter 1

Introduction

Leaf wetness, its role in agriculture and its causes

The duration of leaf wetness is of prime importance to the incidence of fungal diseases in plants (Ingold, 1978; Rotem et al., 1978; Yarwood, 1978; Eisensmith et al., 1982; Dainello and Jones, 1984; Jones, 1986; Lacey, 1986). The development and germination of spores and their infection of susceptible host tissues takes place only under specific conditions of temperature and wetness (Hearn, 1958; Wallin, 1963). Also, leaf wetness plays a role in the deposition of acidic air pollutants on plants (Schuepp, 1989; Janssen and Romer, 1991).

Leaf wetness is usually caused by rain, fog, dew, overhead irrigation and water exuded by the leaves themselves, known as guttation. On rain-free and/or fog-free days, dew formation and guttation are the only contributors to leaf wetness if no overhead irrigation is applied. Dew formation on leaf (or crop) is a result of radiative cooling of the leaf (crop) surface and subsequent condensation of water vapour on it. Guttation is a physiological phenomenon and often occurs during nights when the soil is both warm and moist at or near field capacity (Long, 1958; Hughes and Brimblecombe, 1994). Dew and guttation often occur together (during night). The duration of leaf wetness caused by both dew and guttation as a whole can be monitored by leaf wetness sensors. For the validation of dew formation simulation models, however, it is necessary to distinguish between the dew and guttation. The water of guttation is exuded only at the edge of the leaves in large drops which are generally about 2 mm in diameter and sometimes reach 3 mm diameter before trickling down the leaf surface (Long, 1958; Hughes and Brimblecombe, 1994). Dew droplets, on the other hand, rarely grow larger than 1 millimeter and are spread fairly evenly over the leaf surface (Long, 1958; Hughes and Brimblecombe, 1994). Therefore, it is easy to distinguish between dew and guttation visually or qualitatively, but not instrumentally or quantitatively.

Measurement of leaf wetness

Many instruments have been devised for the observation and measurement of dew (but none for the measurement of guttation), some by observation of the deposition of droplets upon a standard surface such as the Tylor dew meter (Tylor, 1956), some by directly weighing an object or plant upon which dew is forming such as the Hirst dew balance (Hirst, 1954) and the Jennings and Monteith dew balance (Jennings and Monteith, 1954), and some other by using a variety of sensors which expand when wet and contract when dry (e.g. the lamb-gut sensor of the Wallin-Polhemus recorder) to record the wetness amount and/or duration (Wallin, 1963). Most recent sensors that measure leaf wetness are electrical impedance grids (Gillespie and Kidd, 1978; Weiss and Lukens, 1981; Weiss et al., 1988). An extended review on electronic instruments for leaf wetness measurements was given by Jones (1986). A simple approximate method of measuring dew is to weigh the amount of water absorbed by pieces of filter or blotting paper of known area and weight, which have been carefully and firmly pressed on to a leaf surface. When guttation occurs together with dew this method measures the total surface water. Up to now, however, there is still no standard instrument for wetness observation and measurement.

Estimation of leaf wetness

The lack of standard instruments as well as the required instrumentation and time for leaf wetness observation and measurement have stimulated the efforts to develop models to estimate leaf wetness. Many studies on leaf wetness estimation have been focused on estimating leaf wetness caused by dew. Only a few studies have paid attention to guttation (Long, 1958; Hughes and Brimblecombe, 1994). Leaf wetness estimation models so far can be classified into three categories: 1) models involving the indirect assessment of wetness duration, i.e. using the duration of high relative humidity above a certain threshold, 2) multiple regression models, and 3) physical simulation models based on an energy balance approach. The level of 90% relative humidity has been widely used as a threshold value in models of the first category. High correlations were found between the duration of wetness as recorded and the duration of relative humidity above 90% (Smith, 1956; Preece and Smith, 1961; Wallin, 1962; Jensen and Boyle, 1966; Krause et al., 1975; Sutton et al., 1984; Vincelli and Lorbeer, 1988; Wilks and Shen, 1991). The duration of dewpoint depression (i.e. the difference between air temperature and dewpoint) that was lower than a threshold value was also used to indicate wetness duration (Huber and Gillespie, 1992). The multiple regression models use readily available climatic data such as relative humidity, wind speed, and minimum temperature to derive a regression equation for dew duration prediction (Crowe et al., 1978). The models using one or more other weather variables to assess the wetness (the first category) and the multiple regression models are site- and season-specific and can only assess the wetness duration at the top of a canopy. These shortcomings can be overcome by the physical models.

The physical models for dew formation simulation are based on the energy balance of a leaf. Dew formation in crops is a result of radiative loss of heat from the crop surface and transfer of water vapour from the warmer air to the cooler surface. The water vapour transferred to the crop surface may come from the atmosphere (dewfall) or from the soil (distillation) (Monteith, 1957) by means of molecular diffusion and turbulent transfer processes. The physical base of dew formation on surfaces can be described by the Penman-Monteith combination equation (Monteith and Unsworth, 1990) for latent heat loss (λE):

$$\lambda E=(sR_n+\rho c_p D/r_a)/(s+\gamma) \quad \text{or} \quad \lambda E=s/(s+\gamma)(R_n+\rho c_p D/sr_a) \tag{1.1}$$

in case of a wet surface, e.g. when the stomatal resistance is zero. In this equation s is the slope of the saturation vapour pressure curve at air temperature, γ is the psychrometric constant, ρc_p is the volumetric heat capacity of the air, r_a is the boundary layer resistance to water vapour and heat, R_n is the net radiation and D is the vapour pressure deficit. Dew onset occurs when $\lambda E < 0$ and dew ends as soon as the calculated condensation accumulated during the night is consumed by an equivalent amount of evaporation, usually in the next morning. The accumulated amount of condensed water at sunrise is the daily dew amount (mm) and the period between the onset and the ending of dew is the daily dew duration (hour).

The physical models for dew formation simulation can be classified into two categories: *single layer energy balance models*, which simulate dew formation at top leaves or other plant organs such as fruit, and *multilayer models*, which simulate the dew formation at different levels inside homogeneous canopies. Representative single layer models and multilayer models were proposed by Pedro and Gillespie (1982 a,b) and Goudriaan (1977), respectively. Pedro and Gillespie's model simulates the dew duration on a single leaf by using micrometeorological data as well as standard weather station data. Their model has been applied to several new crops and new sites by several authors (Gillespie and Barr, 1984; Bass et al., 1991; Lhomme and Jimenez O, 1992; Scherm and Van Bruggen, 1993). Goudriaan's multilayer MICROWEATHER model gives the dew amount and duration at different layers of crop canopies. The MICROWEATHER model was validated for a rice canopy (Hiramatsu and Maitani, 1984) and a maize canopy (Singh and Jacobs, 1995). An extended review of dew formation simulation models can be found in Huber and Gillespie (1992). However, simulated dew formation practically always deviates from measured results. This deviation might be attributed to measurement errors, both of dew formation and of relevant weather data, but also to that the model structure deviates from reality. Within a canopy, the net loss by radiation is accompanied by sensible and latent heat transfer not only between the cooler crop surface and the warmer air above but also between the crop surface and the warmer soil beneath the canopy. Dew formation in crops is, therefore, governed not only by the meteorological conditions over the canopies but also by soil moisture and temperature beneath. Thus, dew formation within a canopy is a very complex micrometeorological process.

When its measurement is not available, dew formation must be estimated. Hourly weather data are needed to run a dew formation simulation model. In places where there are only non-automatic weather stations, only daily values of weather data are routinely reported. Then, hourly data have to be estimated from the diurnal patterns of weather variables. Before adapting the diurnal patterns of weather variables to estimate dew formation, the possibility of using the mean diurnal patterns of weather variables derived from observed hourly weather data to estimate dew formation has to be investigated so as to know whether the diurnal patterns will give as good an estimate of dew formation as when using the observed hourly weather data.

Paddy rice crops: a special situation

The amount of dew formed on a surface depends on how much nocturnal net radiation is partitioned into latent heat. The main difference of the environment of paddy rice crops from that of dry land crops is that soil moisture is not a limitation due to the water layer in the paddy rice field. Hence, compared to dry land crops the formation of leaf wetness in paddy rice canopies possesses the following two characteristics: 1) instead of soil temperature, it is water temperature that plays an important role in dew formation and 2) guttation may contribute much more water to leaf wetness. Understanding quantitatively these two characteristics and how much nocturnal net radiation is partitioned into latent heat is essential for an accurate estimation and measurement of leaf wetness in the paddy rice crops. The physical simulation models however, can only estimate the wetness caused by dew and not by guttation. Because there is no phase change of water as guttation occurs, estimates of total leaf wetness using the energy balance approach cannot account for leaf wetness from guttation. Unfortunately, up to this date no wetness sensor can distinguish between dew and guttation. Therefore, it is necessary to visually distinguish the dew from guttation when validating a physical leaf wetness model.

Objective and approach

The main objective of the present study was to explore a simple and accurate method for the estimation of dew formation based on insight in the physical base of the formation process of leaf wetness in paddy rice crops. For this purpose, the following field experiments were conducted in a tropical paddy rice field: 1) a shielding experiment, i.e. covering the experiment plots at sunset and removing the cover at 03:00 or 04:00 or 05:00 in the next morning, for investigating how the dew formation depends on nocturnal net radiation and how much nocturnal net radiation is partitioned into latent heat; 2) a warm water flooding experiment for investigating the effect of water temperature on dew formation and the interaction of water temperature in dew formation with the meteorological conditions above the rice canopy. During both experiments mentioned above, a new device (a glass ball) was designed and installed in the field for investigating the possibility of developing a simple and accurate method for dew formation observation and estimation at top leaves. In addition to the field experiments, a pot experiment with warm water flooding in a phytotron was carried out for investigating the effect of water temperature on rice leaf guttation. The Penman-Monteith combination equation was used to estimate the dew formation and the potential dew amount to analyse the measured dew formation data (dew amount and dew duration). Hourly weather data were collected at the experimental site, not only for the purpose of dew formation estimation but also for deriving their diurnal patterns. These diurnal patterns are useful to derive diurnal courses of weather variables from daily values in dew formation estimation. Both the observed hourly weather data and the diurnal courses of weather variables derived from the diurnal patterns were used to run the MICROWEATHER model (Goudriaan, 1977). The model results were compared with the observed dew data to investigate the possibility of using the estimated diurnal courses of weather variables instead of observed hourly weather data to estimate dew formation in crops.

Outline of the thesis

The dependence of dew formation on nocturnal net radiative loss is discussed in Chapter 2 based on results of a shielding experiment in a tropical paddy rice field. Shielding nocturnal net radiative loss, as an experimental spin-off, is not only helpful in understanding its immediate effect on dew formation but also to estimate the guttation rate. In Chapter 3, the effect of water temperature on dew formation and guttation is described based on results of warm water flooding experiments both in the paddy rice field and in a phytotron. The interaction of water temperature with the meteorological conditions above the rice canopy is also analysed in Chapter 3. A threshold value of nocturnal net radiation for dew formation and its dependence on other weather variables was derived based on the dew formation observations on the dewball and in the rice crop itself (Chapter 4). Both the diurnal courses of weather variables derived from the observed hourly weather data and the observed hourly weather data were used to run the MICROWEATHER model for simulating dew formation. The model results were compared with the observed dew data to investigate the possibility of using the estimated diurnal courses of weather variables to estimate the dew formation (Chapter 5). Experimental findings of the present study are summarized in Chapter 6. Based on the results of Chapters 2 and 4, a simple method for estimating daily dew duration on top leaves is formulated and its potential applications to plant protection are discussed (in Chapter 6). A general discussion on problems in physical dew formation simulation models and leaf wetness observation, on the requirements for using the physical models and on further research needs is also given in Chapter 6.

Chapter 2

Dew formation in rice crops as affected by different exposure duration to nocturnal net radiative loss

Abstract In order to understand how nocturnal net radiative loss affects dew formation, a shielding experiment was carried out in a rice field at the International Rice Research Institute during 16 nights in February, March, and April 1994. Four plots (with an area of 4×5 m^2 for each) in the field were used to measure the dew formation. During each night, two of the four plots were covered using black plastic sheets from sunset (about 18:00) till 03:00 or 04:00 or 05:00 of the next day. The other two plots were used as control (without cover). The results showed that shielding the nocturnal net radiative loss resulted in almost the same relative reduction of dew amount and duration in the rice canopy. At crop height, dew duration after sunrise ranged between 1.4 and 3.4 hours and it was reduced between 0 and 2 hours by shielding. Both amount and duration of dew were found to be highly correlated with the total net radiative loss (R_{nt}) during the night. These correlations were further improved by introducing the minimum value of water vapour pressure deficit into the regressions. These improved equations gave a more accurate estimation of dew formation than the energy balance approach did. The latent heat released by dew formation at crop height was about half of the total nocturnal net radiative loss (both expressed as per leaf area). The threshold value of R_{nt} for dew formation was about -0.24 MJ m^{-2} per night during the experimental period. Guttation by the rice plants, as one of the crop surface wetness contributors, supplied as much water to the leaf surface of the paddy rice crop as dewfall did.

Introduction

Leaf wetness is an important factor in plant disease epidemics and also for the deposition of acidic air pollutants on plant surfaces. It provides the free water that is essential to the development of many foliar bacterial and fungal plant pathogens (Wallin, 1963) and may enhance the deposition of the pollutants (Janssen and Romer, 1991; Hughes and Brimblecombe, 1994). For instance, leaf wetness is required by all rice blast (which is one of the most severe diseases in rice) epidemic forecasting models and systems (Uehara et al., 1988; Manibhushanrao and Krishan, 1991; Kim and Kim, 1991; Horino, 1992).

Dew, as a main contributor of the leaf wetness, normally occurs during night time as a result of radiative loss of heat from the leaf surface and transfer of water vapour to it. Thus, nocturnal net radiative loss plays an important role in the dew formation process. Nocturnal net radiative loss is a direct or indirect input of many dew formation simulation models using the energy balance approach (e.g. Pedro and Gillespie, 1982a,b; Jacobs et al., 1990; Wittich, 1995). Its effect on dew formation was theoretically studied by comparing it with model output or by sensitivity analyses (Scherm and Van Bruggen, 1993).

The amount of dew formed on a surface depends on how much nocturnal net radiation is partitioned into the latent heat. Simulated dew formation practically always deviates from measured results. This deviation might be attributed to measurement errors, both of dew formation and of relevant weather data, but also to the model structure that deviates from reality. The objective of this study was to experimentally investigate how the dew formation depends on nocturnal net radiative loss and how much nocturnal net radiative loss is partitioned into latent heat. The understanding of these factors is essential for both accurate dew formation estimation and its simplification.

Materials and methods

Site, treatment and crop

The experiment was carried out at the International Rice Research Institute (IRRI), Los Baños (14°11'N, 121°15'E, 20.0 m), Philippines during 16 rain-free nights (22-24, 28 February, 1, 3-4, 28, 30-31 March, and 1-2, 6-9 April) in 1994 (dry season in the wet tropics). Global radiation, net radiation, air temperature, air humidity, and wind speed over rice canopies in four 4×5 m^2 plots and their water temperatures (at 0.05 m below the water surface) were automatically monitored. All aerial sensors were mounted on four tripods each of which was set up at the center of one of the four plots. To avoid disturbance of the rice canopies, a walk board was installed between the tripod and the edge of the field. The four plots were built at the center part of a 25×50 m^2 paddy rice field. To measure the total amount of dew during the whole night, two plots were kept continuously open without cover (control treatment). The other two plots were covered with a sheet of 4×5 m^2 black plastic from sunset (18:00) till 03:00 or 04:00 or 05:00 of the next day to create different levels of nocturnal net radiative loss. The plastic cover was supported at a height of 2.5 m above the ground by a wooden frame. The removal of the cover was achieved rolling the plastic. In this way, two exposure durations to nocturnal net radiative loss were generated per night.

The rice variety used in the experiment was IR72. The experiment was done in the period of crop development from tillering to dough ripe stage. Crop height H, leaf area index LAI, and canopy extinction coefficient for photosynthetic active radiation PAR were measured once a week.

Instrumentation

An ES230 Li-Cor pyranometer, REBS net radiometer (model Q-6), and RM Young Wind Sentry anemometer were used to measure global radiation, net radiation, and wind speed, respectively. The manufacturer's calibrations were used. Air and paddy water temperature and air humidity were measured with copper-constantan thermocouples and copper-constantan thermocouple psychrometers which were self-made and calibrated in the Meteorology Department of Wageningen Agricultural University. All sensors were connected to a CR10T data logger and a AM416 multiplexer (Campbell Scientific). The sampling interval was two seconds for all the elements mentioned above except wind speed for which the sampling interval was ten seconds. All outputs were hourly averaged.

The dew amounts at H, 2/3H, and 1/2H (where H is the crop height) were measured by weighing blotting paper installed before sunset. In February, a circular blotting paper with diameter of 9 cm was used as a substitute leaf for dew formation, with two replicas at each height. In March and April, the same kind of paper was used to collect the dew with five replicas at each height. The blotting paper was installed horizontally, attached to erect bamboo sticks. The blotting paper was weighed three times during each observation day, i.e. before sunset, before removing the cover, and around sunrise (06:00). The dew amount was calculated as the weight increment of the blotting paper divided by the area of the blotting paper. Thus the unit of the dew amount was 'millimeter per leaf (or blotting paper) area'. The onset and disappearance of dew was visually observed. The dew duration was calculated as the period between the onset and the disappearance moments, expressed in hours.

Guttation

During the 16 experimental nights, dew never occurred in the covered plots before the cover was removed. But the blotting papers did gain weight due to leaf

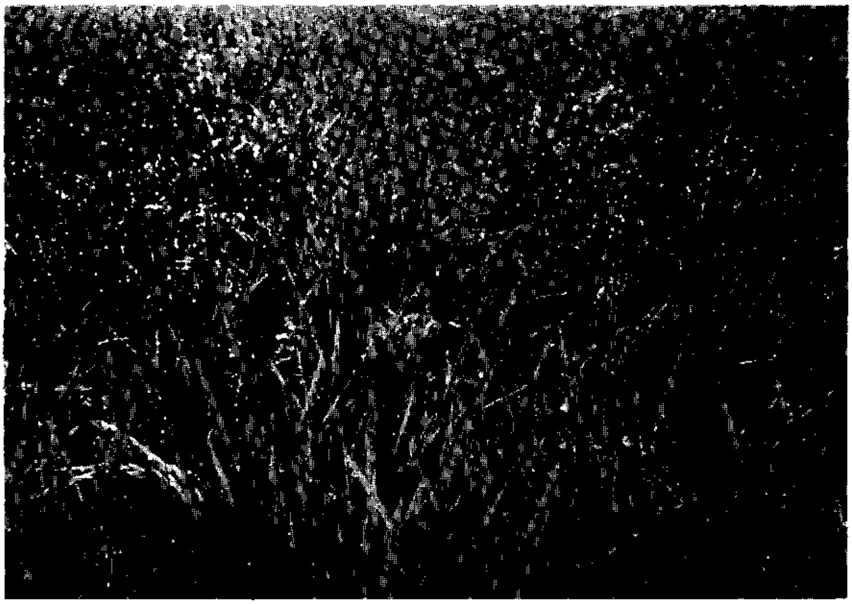


Fig. 2.1. Leaf guttation in a paddy rice field. The picture was taken in early morning. The white dots that suspend along the leaf edge are the guttation drops.

guttation (Fig. 2.1). To distinguish the dew amount from the guttation water, the mean guttation rate for each night was estimated by dividing the weight increment of the blotting paper at the moment just before cover removal by the time duration after sunset. With this guttation rate (expressed in mm per hour per leaf area), the guttation amount at any moment in a night was estimated. Therefore, the dew amount in the control plots was estimated by deducting this guttation amount from the total weight increment of the blotting paper.

Results and discussion

Effects of shielding nocturnal net radiative loss on dew amount

Shielding nocturnal net radiative loss resulted in a large reduction of dew amount in the rice canopy (Fig. 2.2) because no dew occurred in the canopy during the covered period. For the canopy as a whole (including data at 1/2H, 2/3H and H during the 16 nights), the relation between dew amount around sunrise with and

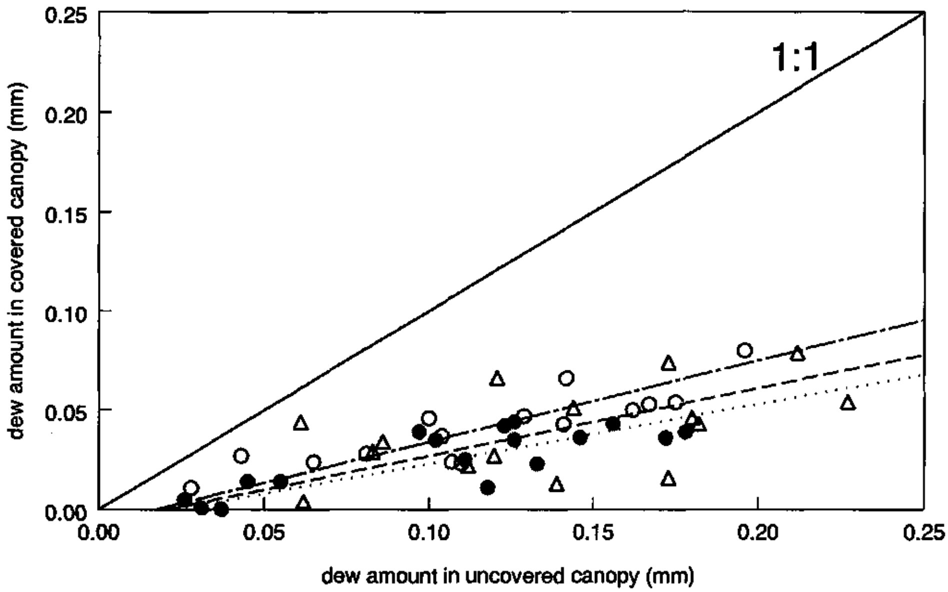


Fig. 2.2. Relation between dew amount (mm) with cover and without cover. The symbols are measured data at crop height H, 2/3H and 1/2H during 5, 5 and 6 days for the removal moment at 03:00 (o), 04:00 (Δ) and 05:00 (•), respectively. The lines are the regression relationships for the removal moment at 03:00 (— · —), 04:00 (– – –) and 05:00 (· · · · · ·), respectively.

without cover was about linear (Fig. 2.2). The accumulated dew amounts at sunrise in the cover canopy were about 41%, 34% and 30% of that in the control canopy for removal moment at 03:00, 04:00 and 05:00, respectively. Although the time intervals of the three removal moments were the same (1 hour), the difference between the percentages with removal moment at 03:00 and 04:00 (7%) was larger than that with removal moment at 04:00 and 05:00 (4%). This was partly caused by the difference of net radiation between 03:00 and 04:00 (–142.9 kJ m^{-2}) and that between 04:00 and 05:00 (–81.9 kJ m^{-2}) (Table 2.1). On average, the dew amount at the upper layer of the canopy (H and 2/3H) was more sensitive to the removal moment than that at 1/2H (Fig. 2.3).

Effects of shielding nocturnal net radiative loss on dew duration

As expected, dew duration with cover was much shorter than that without cover. On average for all observed nights and heights, the dew duration with cover was

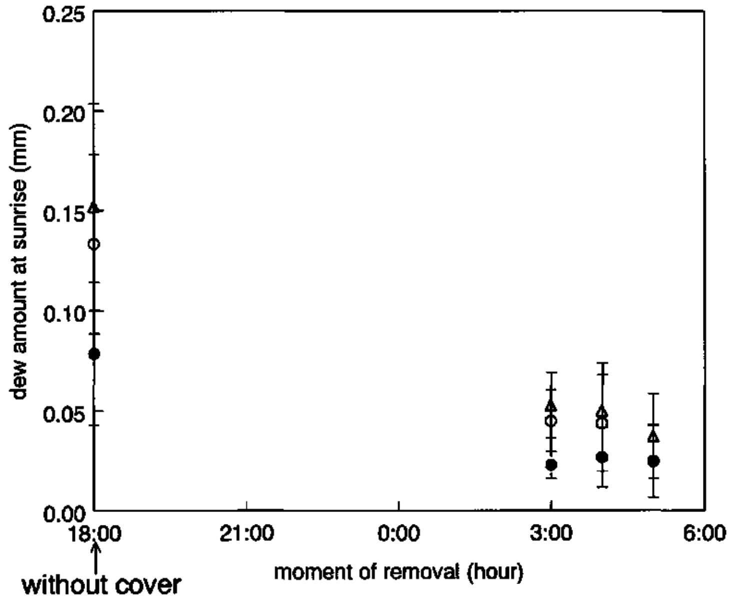


Fig. 2.3. Relation between dew amount (mm) at sunrise and the time of removal. The symbols are mean values of dew amount measured during 16, 5, 5 and 6 days for the removal time at 18:00 (without cover), 03:00, 04:00 and 05:00, respectively, and the vertical lines are error bars. The open dots (o), the open triangles (Δ) and the closed dots (•) are the mean values of dew amount measured at crop height H, 2/3H and 1/2H, respectively.

Table 2.1. Net radiative loss (R_n, kJ m^{-2}) between the moment of removal and sunrise and its percentage of the nightly total of R_n .

Moment of removal	R_n	Difference	Percentage	Difference
03:00	−363		22.8%	
		−143		7.7%
04:00	−220		15.1%	
		− 82		5.7%
05:00	−138		9.4%	

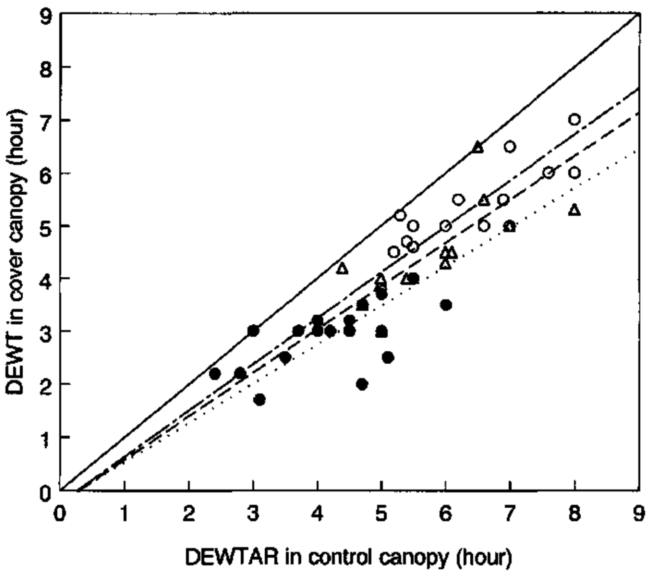


Fig. 2.4. Relation between dew duration (DEWT, hour) in the cover canopy and the dew duration in the uncovered canopy counted after the moment of removal (DEWTAR, hour) in each cover treatment. The symbols are measured data at crop height H, 2/3H and 1/2H during 5, 5 and 6 days for the removal moment at 03:00 (o), 04:00 (Δ) and 05:00 (•), respectively. The lines are the regression relationships for the removal moment at 03:00 (– · –), 04:00 (– – –) and 05:00 (· · · · ·), respectively.

about 46%, 36% and 25% of that without cover for the removal moment at 03:00, 04:00 and 05:00, respectively. The correlation between total dew duration with cover and that without cover was rather weak. Counted after the removal moment however, a good correlation existed between the dew duration with cover and that without cover (Fig. 2.4). The value of the regression slope was 0.87, 0.82 and 0.74 for the removal moment at 03:00 (r^2=0.77 and standard error SE=0.51 hour, $P<0.05$, df=14), 04:00 (r^2=0.56 and SE=0.76 hour, $P<0.05$, df=14) and 05:00 (r^2=0.60 and SE=0.6 hour, $P<0.05$, df=17), respectively, i.e. after the moment of removal, the gap between the dew duration with and without cover was only 13%, 18% and 26% for the removal moment at 03:00, 04:00 and 05:00, respectively.

The dew duration at the three observed heights (1/2H, 2/3H and H) had a similar dependence on the removal moment (Fig. 2.5). At crop height, dew duration after sunrise ranged between 1.4 and 3.4 hour and it was reduced between

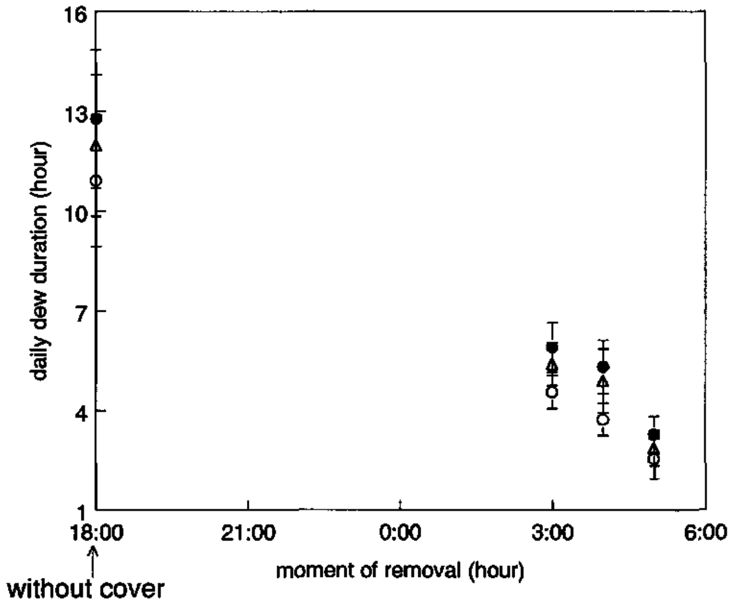


Fig. 2.5. Relation between daily dew duration (hour) and the time of removal. The symbols are mean values of daily dew duration observed during 5, 5 and 6 days for the removal moment at 03:00, 04:00 and 05:00, respectively, and the vertical lines are error bars. The open dots (o), the open triangles (Δ) and the closed dots (•) are the mean values of daily dew duration observed at crop height H, 2/3H and 1/2H, respectively.

0 and 2 hours by shielding. This indicates that dew at crop height disappeared soon after sunrise irrespective of the duration of its formation. This is because the solar radiation increased rapidly after sunrise. The drying could take longer in cloudy conditions.

Effects of nocturnal net radiative loss on dew formation

To see the direct effect of nocturnal net radiative loss on dew formation (both dew amount and duration), total nocturnal net radiative loss (R_{nt}) was calculated based on the hourly observed data. During the experimental period, R_{nt} had a larger range than usual, because the shielding generated two levels of accumulated nocturnal net radiative loss during a night. Good correlations existed between R_{nt} and dew amount and dew duration at crop height H as well as 2/3H and 1/2H (Figs. 2.6 (a) and 2.7 (a), Table 2.2). The higher values of r^2 for dew duration, as shown in Fig.

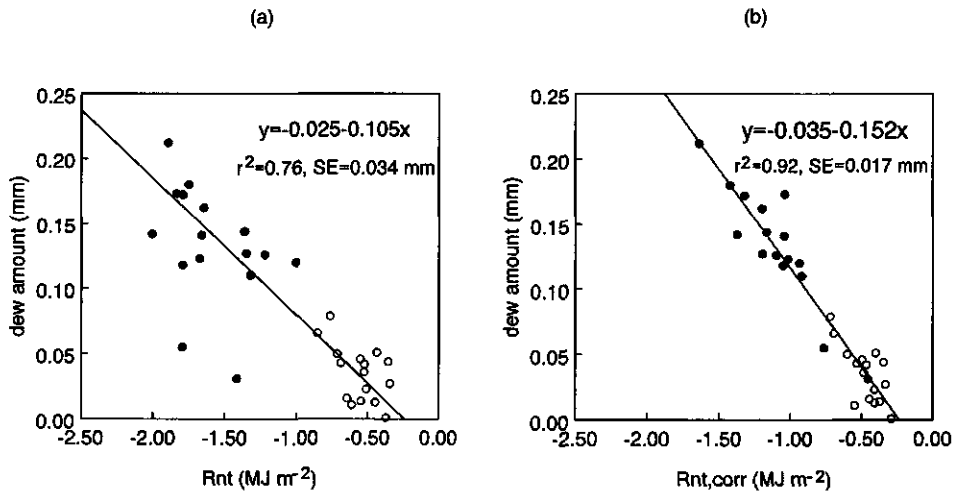


Fig. 2.6. Relation between dew amount formed at crop height and (a) total nocturnal net radiative loss (R_{nt}, MJ m^{-2}), and (b) the corrected R_{nt} ($R_{nt,corr} = R_{nt}+2.6 \cdot f \cdot D_{min}$, where D_{min} is the nightly minimum vapour pressure deficit in kPa, 2.6 is an empirical coefficient with a unit of MJ m^{-2} kPa^{-1} and f is the ratio of the exposed period to night length (12 hours)). The open dots (o) and the closed dots (•) are dew amounts measured at crop height in the cover and control canopies, respectively. The solid lines are the regression relationships.

2.7 (a) and Table 2.2, implied that during the experimental period, the effect of nocturnal net radiative loss was more direct on dew duration than on dew amount. This is because both R_{nt} and dew duration depend immediately on the duration of the exposed period.

In the regression equations between dew amount and R_{nt} and dew duration and R_{nt} (Figs. 2.6 (a) and 2.7 (a), Table 2.2), a threshold value of R_{nt} for dew formation appeared. The level of this threshold R_{nt} was determined as –0.24 and –0.13 MJ m^{-2} for amount and duration, respectively. It is remarkable that these threshold levels were not the same. This can be explained by the fact that the relation between dew amount and dew duration is not linear. A very small amount of dew can be present for a considerable duration.

Assuming the canopy extinction coefficient for nocturnal net ıadiative loss is the same as that for PAR which was about 0.5 during the experimental period, the slope of the regression line in Fig. 2.6 (a) shows that at crop height, the

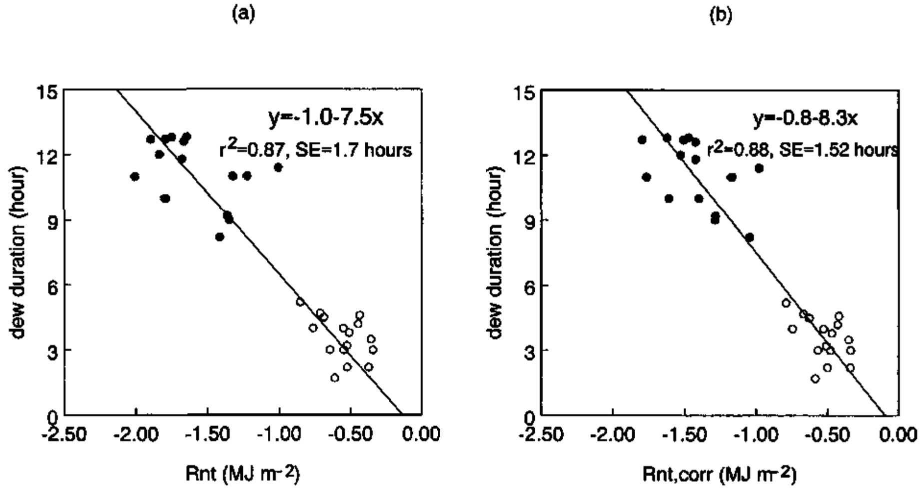


Fig. 2.7. Relation between dew duration at crop height and (a) the total nocturnal net radiative loss (R_{nt}, MJ m^{-2}), and (b) the corrected R_{nt} ($R_{nt,corr} = R_{nt}+1.0 \cdot f \cdot D_{min}$, where D_{min} is the nightly minimum vapour pressure deficit in kPa, 1.0 is an empirical coefficient with a unit of MJ m^{-2} kPa^{-1} and f is the ratio of the exposed period to night length (12 hours)). The open dots (o) and the closed dots (•) are dew duration at crop height in the cover and control canopies, respectively. The solid lines are the regression relationships.

condensation energy in dew formation had supplied about 51% of the total nocturnal net radiative loss (both expressed as per leaf area).

The good correlations between the dew amount, the dew duration at crop height and the total nocturnal net radiative loss (Figs. 2.6 (a) and 2.7 (a)) show a possibility to directly estimate the dew amount and dew duration using the nightly total net radiation data, at least under stable weather conditions such as during the dry season in the tropics.

Effect of water vapour pressure deficit (D) on dew formation

In addition to nocturnal net radiative loss, vapour pressure deficit is another important weather variable that affects dew formation (Scherm and Van Bruggen, 1993). To assess the effect of vapour pressure deficit on dew formation, total night (D_t), mean night (D_{mean}) and nightly minimum vapour pressure deficit (D_{min}) were

Table 2.2. Summary of the regression results between dew formation and total nocturnal net radiative loss (R_{nt} expressed in MJ m^{-2})(df=31, p<0.05)*.

Height	Equations	r^2	SE	Unit
H	$DEW = -0.025 - 0.105R_{nt}$	0.76	0.034	[mm]
	$DEW = -0.035 - 0.152R_{nt,corr,dew}$	0.92	0.017	[mm]
	$DEWT = -1.0 - 7.5\ R_{nt}$	0.87	1.70	[hour]
	$DEWT = -0.8 - 8.3\ R_{nt,corr,dewt}$	0.88	1.52	[hour]
2/3H	$DEW = -0.025 - 0.111R_{nt}$	0.73	0.039	[mm]
	$DEWT = -1.0 - 8.24\ R_{nt}$	0.88	1.78	[hour]
1/2H	$DEW = -0.025 - 0.067R_{nt}$	0.66	0.028	[mm]
	$DEWT = -1.0 - 8.7\ R_{nt}$	0.88	1.91	[hour]

* H, DEW, DEWT and R_{nt} are the crop height, dew amount (mm), dew duration (hour), and nightly total net radiative loss, respectively. $R_{nt,corr,dew}$ and $R_{nt,corr,dewt}$ are the corrected R_{nt} for dew amount and dew duration, respectively. $R_{nt,corr,dew} = R_{nt} + 2.6 \cdot f \cdot D_{min}$ and $R_{nt,corr,dewt} = R_{nt} + 1.0 \cdot f \cdot D_{min}$, where 2.6 and 1.0 are empirical coefficients with a unit of MJ m^{-2} kPa^{-1}, f is the ratio of exposed period (12, 3, 2 and 1 hour for the control canopy and cover canopies with removal moment at 03:00, 04:00 and 05:00, respectively) to night length (12 hours) and D_{min} is the nightly minimum vapour pressure deficit (kPa) at 1.5 m above the ground.

calculated based on the hourly observed data. The exposed fraction of the night, f, calculated as the ratio of the exposed period to night length (12 hours), was taken into account because no dew occurred in the cover canopy during the shielding period. The value of f was 1, 0.25, 0.167 and 0.083 for the control canopy and the cover canopies with removal moment at 03:00, 04:00 and 05:00, respectively. According to the experimental data, however, there was only a weak direct relation between fD_t or fD_{mean} or fD_{min} and dew amount or duration. This means that vapour pressure deficit interacted with the nocturnal night radiative loss as was proved by the increase of r^2 and the decrease of SE for multilinear regressions of dew amount (DEW) at crop height to R_{nt} and fD_{min} (r^2=0.92, SE=0.017 mm) and dew duration (DEWT) at crop height to these two weather variables (r^2=0.88, SE=1.57 hour). The multilinear regression expression for dew amount or duration is:

$$\text{DEW or DEWT} = a + b\,R_{nt} + c \cdot f \cdot D_{min} \tag{2.1}$$

where a, b and c are regression coefficients. Eq. (2.1) can be simplified as a single regression equation by introducing a variable defined as corrected total nocturnal net radiative loss:

$$R_{nt,corr} = R_{nt} + (c/b) \cdot f \cdot D_{min} \tag{2.2}$$

Therefore,

$$\text{DEW or DEWT} = a + b\,R_{nt,corr}$$

Based on the observed data, the values of a and c/b was determined as –0.035 mm and 2.6 for dew amount and –0.8 and 1.0 for dew duration when R_{nt} is in MJ m^{-2} and D in kPa. The relations between DEW and DEWT and $R_{nt,corr}$ are shown in Figs. 2.6 (b) and 2.7 (b). The value of c/b in Eq. (2.2) for dew amount (2.6) was higher than that for dew duration (1.0). This indicates that vapour pressure deficit had a stronger effect on dew amount than on dew duration.

Relation with the Penman-Monteith combination equation

Compared to the Penman-Monteith combination equation for latent heat loss (Eq. (1.1)), the ratio c/b in Eq. (2.2) must be $(\rho c_p/s r_a)\Delta t$ for dew amount when R_{nt} instead of R_n is used. In this study, Δt is night length (12 hours). Taken s as 0.2 kPa K^{-1} and r_a as 50 s m^{-1}, the average value of $(\rho c_p/s r_a)\Delta t$ is about 2.2, which is the same order of magnitude as observed (2.6). The correlation of dew amount (at crop height) with the corrected total nocturnal net radiative loss (r^2=0.92, SE=0.017 mm) appeared to be better than that with the values simulated by the energy balance approach (r^2=0.80, SE=0.033 mm). The correlation between dew duration and R_{nt} was already much better (r^2=0.87, SE=1.7 hours) than that between the observed and the fully simulated dew duration (r^2=0.80, SE=2.27 hours). It has to be noted that these regression equations are season- and site-specific. In these multilinear regressions, the measurements at 1/2H and 2/3H were not included because of absence of radiation and vapour pressure deficit measurements inside the canopy.

Guttation

In our experiment, guttation by the rice plants was quite heavy (Fig. 2.1) and its rate depended on the crop development stage. The guttation rate decreased from 0.026 mm per hour at tillering to 0.003 mm per hour at the dough ripe stage. At the rate of 0.026 mm hour^{-1} the guttation water exuded from the rice leaf reached as much as 0.31 mm per night which was more than the maximum dew amount (0.27 mm per night) measured during the experimental period. These results indicate that guttation, as one of the crop surface wetness contributors, can supply as much water to the rice crop surface as dewfall. For short grass, Hughes and Brimblecombe (1994) found that guttation was of the same importance as dewfall. So far, no surface wetness sensor exists that can distinguish guttation from dew. It is necessary to find a way to estimate the guttation rate. The shielding experiment was not designed for this purpose, but it supplied a feasible method for the guttation rate estimation.

In the paddy rice canopy, the difference between guttation and dew drops was easily visible because guttation drops were much bigger than dew drops. They were suspended along the leaf edge whereas dew drops were distributed homogeneously on both sides of the leaf surface. Guttation does not contribute to the leaf wetness at the top of the canopy. Inside the canopy however, it might contribute to the leaf wetness in the same way as precipitation, i.e. the lower layer of the canopy could intercept the guttation drops. Therefore, the contribution of guttation to leaf wetness in paddy rice can not be ignored.

Conclusions

From the obtained results, the following conclusions could be extracted:

- At the top of the rice canopy, the condensed energy was about half of the nightly total net radiative loss, both expressed as per leaf area.
- At crop height, dew duration after sunrise ranged between 1.4 and 3.4 hours. Shielding reduced it by between 0 and 2 hours.
- The threshold value of total nocturnal net radiative loss for dew formation was on average about –0.24 MJ m^{-2} per night during the experimental period.
- Accumulated nocturnal net radiative loss provides a means to directly estimate the dew duration and amount.
- When the nightly minimum value of water vapour pressure deficit was included into the regression, the regression equation gave a more accurate estimation of

dew formation at the top of the rice canopy than an energy balance approach did.

- As an experimental spin-off, shielding nocturnal net radiative loss was not only helpful in understanding its immediate effect on dew formation but also to estimate the guttation rate.
- The contribution of guttation to leaf wetness in paddy rice was similar to dew.

Chapter 3

Effects of altering water temperature on leaf wetness in paddy rice crops

Abstract Leaf wetness on rain-free days is caused by dew formation and guttation. The effect of paddy water temperature on these two processes in rice crops was investigated by a field experiment in the tropics and a phytotron experiment, respectively. A micrometeorological model was used to analyse the dew formation data. The experimental data indicated an optimum paddy water temperature for rice leaf guttation of about 30°C. The simulation analysis results showed that dew amount increases with water temperature and is highly sensitive to the stratification condition above the canopy. Under a stable stratification condition, the dew amount increased about 4 times faster with water temperature than under neutral conditions. However, when the water temperature was high enough to generate an unstable stratification condition, the effect of water temperature on dew formation in the rice canopy almost disappeared. The critical water temperature for onset of dew depends not only on the stratification condition, but also on the nocturnal net radiation and vapour pressure deficit. A comparison of the measurements of guttation water with the total amount of water on leaves in the middle of the rice canopy showed that the guttation water amount was at least half of it. Therefore, guttation, as a contributor to leaf wetness in paddy rice crops, is of similar importance as dew formation.

Introduction

Leaf wetness in crops has been studied because of its importance for plant pathogen activity. On rain-free days, the components of leaf wetness are dew condensed on leaves and guttation exuded from the leaves.

Hughes and Brimblecombe (1994) suggested that guttation is controlled by soil moisture, but that soil temperature acts as a regulator when moisture is not limiting. As a contributor of the leaf wetness, guttation might be ignored in dry land crops due to limiting soil moisture. In a paddy rice crop, however, soil moisture is not a limitation for guttation. The amount of guttation water will depend on paddy water temperature.

So far, only a few experimental investigations on dew formation in dry land crops such as wheat (Burrage, 1972), dry beans (Weiss et al., 1989), corn (Jacobs et al., 1990) and barley (Jacobs and Nieveen, 1995) have been reported, probably for lack of instrumentation and time to do the dew formation measurements. Most of the dew formation studies focus on estimating dew amount and/or dew duration by means of the energy budget approach. Models for simulating dew formation in crops reported so far can be classified into two categories: single leaf models and multilayer models. Representative single leaf models and multilayer models were proposed by Pedro and Gillespie (1982a,b) and Goudriaan (1977), respectively. Pedro and Gillespie's model simulates the dew duration on a single leaf by using micrometeorological data as well as standard weather station data. Their model has been applied to several new crops and new sites by several authors (Gillespie and Barr, 1984; Bass et al., 1991; Lhomme and Jimenez O, 1992; Scherm and Van Bruggen, 1993). Goudriaan's multilayer MICROWEATHER model gives the dew amount and duration at different layers of the crop canopy. The MICROWEATHER model was validated for a rice canopy (Hiramatsu et al., 1984) and a maize canopy (Singh and Jacobs, 1995). Dew formation in crops is a result of radiative loss of heat from the crop surface and transfer of water vapour to it. The water vapour transferred to the crop surface may come from the atmosphere (dewfall) or from the soil (distillation) (Monteith, 1957) by means of molecular diffusion and turbulent transfer processes. Within a canopy, the net loss by radiation is accompanied by sensible and latent heat transfer not only between the cooler crop surface and the warmer air above but also between the crop surface and the warmer soil beneath the canopy. Dew formation in crops is, therefore, governed not only by the meteorological conditions over the canopies but also by soil moisture and temperature beneath. In a paddy rice field, soil moisture is not a limitation and water temperature must play an important role in dew formation in the rice canopy.

The objectives of this study are: 1) to investigate the effect of water temperature on dew formation and guttation in rice crops; 2) to investigate the interaction of water temperature in dew formation with the meteorological conditions above the canopy. To achieve these two objectives, two experiments, one with a rice crop in a tropical field and one in a phytotron with a pot experiment, were carried out. The MICROWEATHER model was used to analyse the observed dew formation data. Then the model was used to evaluate the effect of water temperature on dew formation under different meteorological conditions above the rice canopy.

Materials and methods

Site and treatments

The field experiment was carried out at the International Rice Research Institute (IRRI) (14°11'N, 121°15'E, 20.0 m), Philippines during seven nights in March, 1994. Three plots (with an area of 4×5 m^2 for each) were linked by two 5 m long narrow canals and used for treatment. Warm water from a hot spring flowed into the first plot and from there on to the second and third, respectively. One other plot with an area of 4×5 m^2 was flooded with nonhot water and used as a control. In this way, four levels of water temperature were obtained among the four plots. The warm water treatment began before sunset and ended around 08:00 the next morning. Global radiation, net radiation, air temperature, air humidity, and wind speed over four rice canopies in the three treatment plots and a control plot and water temperature in the four plots were automatically monitored. The four plots were situated at the center part of a 25×50 m^2 paddy field and were isolated from the other parts of the field by earth bands with a width of 0.2 m. All sensors were mounted on four tripods which were set up at the center of each of the four plots, respectively. To avoid disturbing the rice canopies, a walk board was installed between the tripod and the edge of the field. Within 1000 m around the experimental field, there were no high buildings and tall trees. The experimental field was surrounded by other rice fields.

The experiment in the phytotron was carried out in the Agronomy Department of Wageningen Agricultural University, the Netherlands during three nights i.e. 11–12, 14–15, and 18–19 September, 1995. Rice plants were planted in eight plastic pots with four plants in each of them. Three waterbaths with water temperature constantly controlled at 20, 30, and 40°C respectively were installed in the phytotron. The number of pots put into the waterbath with water temperature of 20, 30, and 40°C was 2, 3, and 3, respectively. In the phytotron, the dark period was set at 13 hours per night and air temperature was constantly controlled at 20 and 30°C during dark and light period, respectively.

Crop and instrumentation

The rice variety used in the field was IR72 and that used in the phytotron was Awini. In the field, the development stage of the crop varied from heading to flowering during the experiment period. The crop height and leaf area index

(LAI) were measured once a week. In the phytotron, the plant height was 0.5 m and the plants were at tillering development stage.

In the field, dew amount was measured just above crop height (H), 2/3H, and 1/2H inside the canopies by weighing blotting paper installed before sunset. The blotting paper with diameter of 9 cm was installed horizontally by attaching it to an erect bamboo stick and in five replicas at each height. Care was taken that the papers installed just above crop height did not touch the crop leaves. Therefore, the measurements at this height were dew only. Dew duration on leaves was visually observed.

Guttation in the phytotron was measured in the same way as for the dew amount in the field. The blotting paper used to collect the guttation with five replicas was attached to the upper part of the leaves by using paper clips.

Model

Goudriaan's MICROWEATHER model (1977) was chosen in this study for it is a multi-layer model that suits the situation of this study. In this model, in the energy and mass balance of the canopy, the partitioning of the absorbed net energy (R_n) into sensible heat and latent heat (λE) is calculated using the Penman-Monteith combination equations for the leaf energy balance (Monteith and Unsworth, 1990). The partitioning of the available radiation energy at soil or water surface into sensible heat, latent heat and soil heat flux is also computed. The onset of dew occurs when the net flux of latent heat for a canopy layer becomes negative. The dew amount during a night is calculated by integration of the net flux of latent heat over time for different canopy layers.

In order to understand the dew formation measurements, potential dew amount during a night was estimated. The potential dew amount was estimated using the Penman-Monteith combination equation by assuming a water vapour pressure deficit of 0 kPa in the air above at a height of 1.5 m:

$$\lambda E = s\, R_n / (s + \gamma)$$

where s is the slope of the saturation vapour pressure curve at air temperature, γ is the psychrometric constant, and R_n is the net radiation at leaf surface. Dew amount is expressed per leaf area, also the net radiation must be expressed per leaf area. This was done by multiplication with the extinction coefficient.

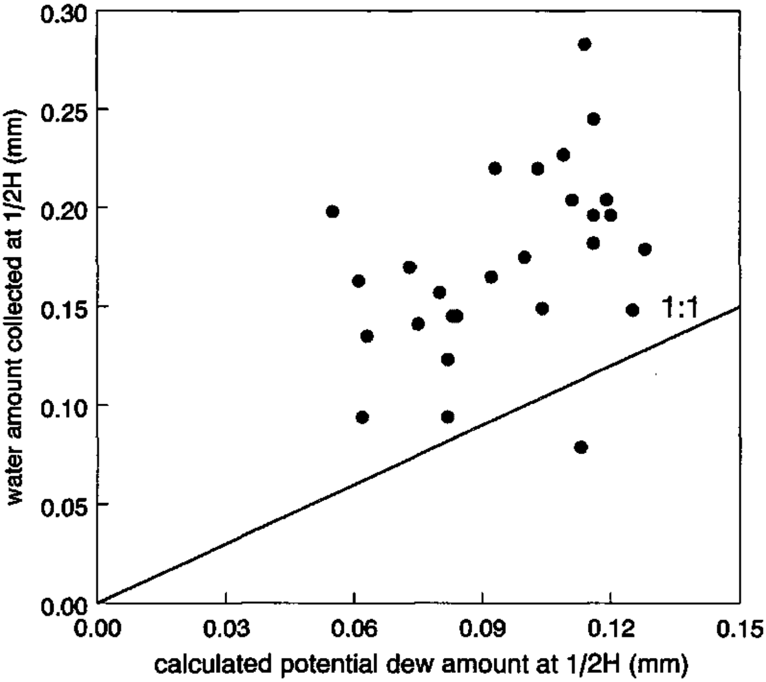


Fig. 3.1. Relation between water amount (mm per leaf area) collected in the middle of the rice canopy (•) and the calculated potential dew amount (mm per leaf area) at 1/2 crop height (H).

Results

The amount of water collected inside the rice canopies using the blotting paper consisted of both dew and guttation. This is proved by the fact that during most of the experimental nights, the amount of water (mm per leaf area) collected in the middle of the rice canopy (1/2H) was more than the calculated potential dew amount (mm per leaf area) at 1/2H (Fig. 3.1). Hence, the excess water collected by the blotting paper must have been guttation.

The effect of water temperature on guttation

Hughes and Brimblecombe (1994) found a positive effect of soil temperature at 10 cm depth on the diameter of guttation drops on grass and a negative effect of

Table 3.1. Guttation* measured in pot planted rice crops** irrigated by water of altering temperature in a phytotron.

Water temperature (°C)	Date (day/month/year)			3 day average
	11–12/09/95	14–15/09/95	18–19/09/95	
20	0.032	0.030	0.009	0.024
30	0.044	0.049	0.020	0.037
40	0.025	0.020	0.005	0.017

* The guttation data in this table have a unit of 'mm per leaf area'.

** The variety of the rice crop was *Awini*, the crop was 50 cm high and at tillering development stage.

soil moisture tension. Our experiment carried out in the phytotron showed that the total amount of nocturnal guttation increased with water temperature from 20 to 30°C and decreased strongly again to 40°C (Table 3.1). This implies that the optimum water temperature for guttation was around 30°C. This result gives an indication of what we can expect under field conditions, even though the circumstances are quite different. During the field experimental period, the leaf area index (LAI) of the rice crop was about 5. The total guttation amount in the field crop canopy can be estimated as 0.120, 0.185, and 0.085 mm per ground area for a water temperature of 20, 30, and 40°C, respectively (Table 3.1) assuming that the guttation amount per leaf area in the phytotron crop is the same as that in the field crop. These values are more than half of the total water amount collected in the middle of the field canopies using blotting paper. Therefore the guttation amount can easily have been at least as much as the dew amount formed in the field canopies.

Model analysis for dew formation simulation

It is difficult to distinguish quantitatively dew from guttation in the total water amount collected by blotting paper inside the rice canopies. However, the dew amount can be estimated from the energy balance using the meteorological data observed above the rice canopy. Dew formation simulated by the MICROWEATHER model was very sensitive to the assumed stratification

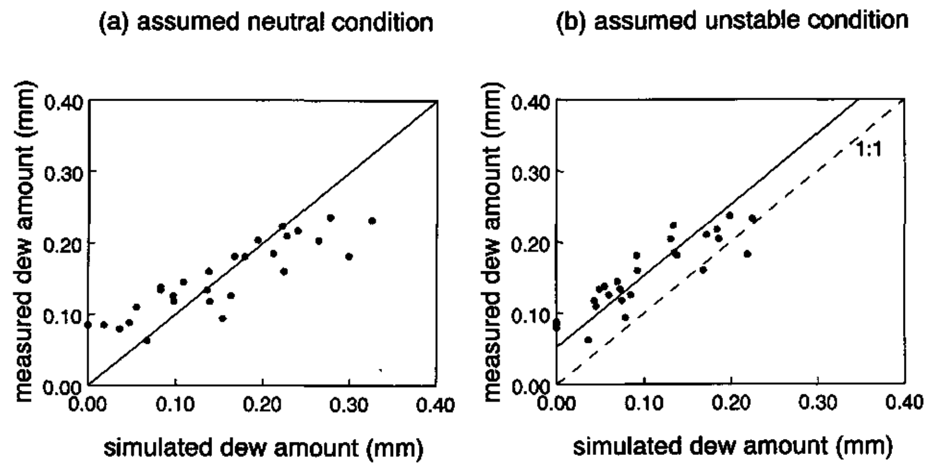


Fig. 3.2. Relation between measured and simulated dew amount (mm) at crop height: (a) under neutral condition and (b) under unstable condition. The solid lines are regression relationship (y=x for neutral condition, y=0.05+x for unstable condition).

condition above the rice canopy. In this study, the stratification conditions were characterized by the inverse of the aerodynamic resistance (r_a) between crop and reference height (1.5 m above the ground). The values of $1/r_a$ used in this study were imposed as 100, 20, and 2 mm s^{-1} for a typical unstable, neutral, and stable condition, respectively. Compared to the dew amount measured at around sunrise at crop height, the model results for unstable (r^2=0.82, standard error SE=0.033 mm) and neutral (r^2=0.76, SE=0.049 mm) stratification conditions correlated well with the measurements (Figs. 3.2 (a) and (b)) while those for stable conditions extremely overestimated the dew amount (not shown). This might be attributed to that the imposed value of $1/r_a$ for stable conditions was impossible in reality when the paddy water temperature was much higher than the air temperature above the canopy (e.g. the situations in the warm water treatment plots) (Figs. 3.3 (a) and (b)). In the warm water treatment plots, the high water temperature generated a very unstable within-canopy stratification which transferred the heat from the warm water to the whole canopy, hence destroyed the stable stratification above the canopy.

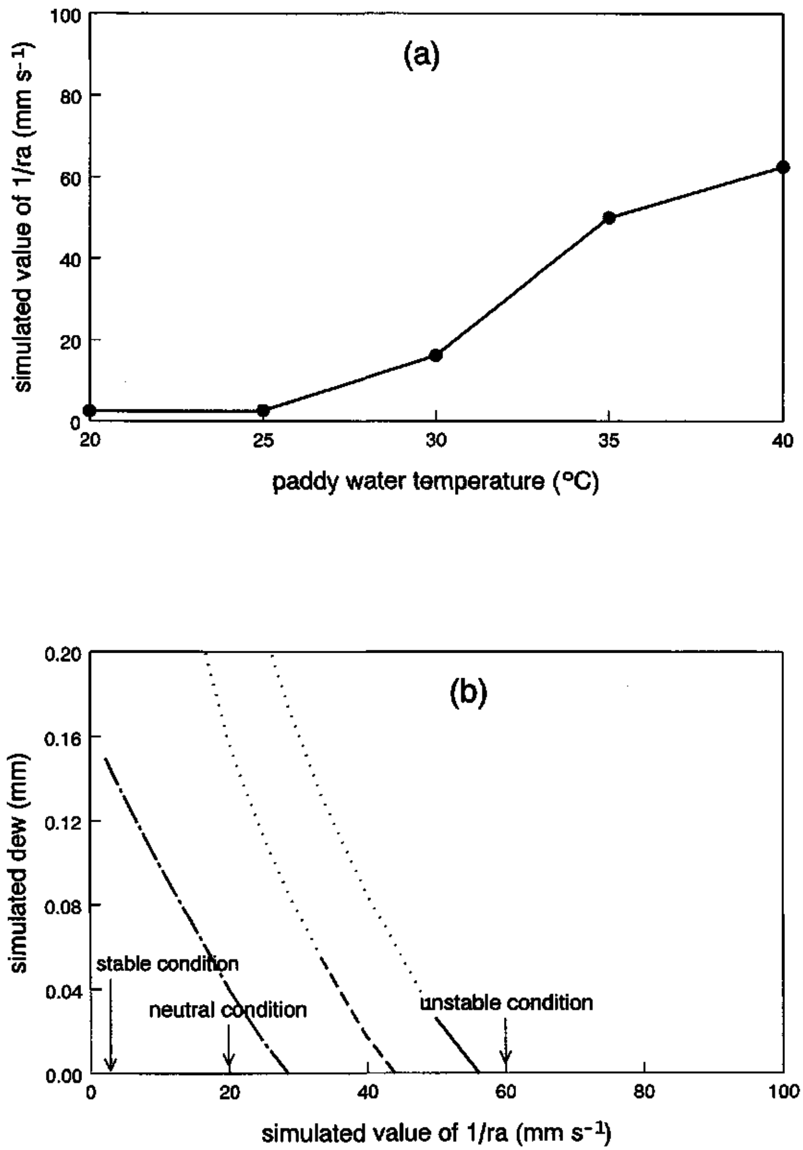


Fig. 3.3. Relation of the inverse of the simulated resistance between the canopy and the reference height (1.5 m above the ground) ($1/r_a$, mm s^{-1}) to (a) the paddy water temperature (°C); and (b) the simulated dew amount (mm). The lines in (b) are simulated dew amount accumulated for 12 hours at a water temperature of 25°C (— - —), 35°C (– – –), and 45°C (——), respectively for possible regions of $1/r_a$ in reality and that for impossible regions of $1/r_a$ in reality (········).

The effect of water temperature on dew formation

During a typical quiet and clear tropical night (with a wind speed of 1 m s^{-1}, a nocturnal net radiation of -40 W m^{-2} and an air temperature of 25°C), the simulated dew amount increased with paddy water temperature (Fig. 3.4). Dew amount per night increased about 0.004, 0.01 and 0.04 mm per 1°C increase of water temperature under unstable, neutral and stable stratification conditions, respectively. During the field experiment period, the water temperature in the control plot was about 25°C and that in the warm water treatment plots varied between 34 and 39°C (Fig. 3.4) and the corresponding values of $1/r_a$ estimated by the model were about 2.5, 50 and 60 mm s^{-1}, respectively (Fig. 3.3 (a)). If the vapour pressure deficit was 0.1 kPa during the typical quiet and clear tropical night, the simulated dew amount at the middle of the control canopy was 0.148 mm per night and that at the middle of the treatment canopies was 0 mm per night, i.e. no dew occurred (Fig. 3.3 (b)). This indicates that no dew occurs when the water temperature is high enough to generate an unstable stratification condition.

Simulation analysis of the effects of meteorological conditions on the role of water temperature in dew formation in paddy rice crops

The role of water temperature in dew formation in paddy rice crops is modified by meteorological factors such as water vapour pressure deficit, nocturnal net radiation and the stability of the air layer above the canopies. These effects of the meteorological factors on the role of water temperature in dew formation can be analysed using a simulation model. The simulated effect of paddy water temperature on dew formation depended strongly on the stratification conditions above the canopy (Fig. 3.4). For the warm water treatments, it was impossible for the stable stratification condition to occur due to the high water temperature (Fig. 3.3 (a)). Therefore, only neutral and unstable conditions were studied in this section.

Dew formation occurs only when the water temperature is higher than a certain value (Fig. 3.4) which is called the critical water temperature for the onset of dew. The difference between this critical water temperature (T_{wc}) and the air temperature at the reference height (T_a) for the onset of dew was found to depend on all three meteorological factors mentioned above. During a quiet night with a wind speed of 1 m s^{-1}, a water vapour pressure deficit of 0.1 kPa, and a neutral stratification above a closed rice canopy (LAI=6), the difference between T_{wc} and T_a for onset of dew at the middle of the canopy (T_{wc}-T_a)

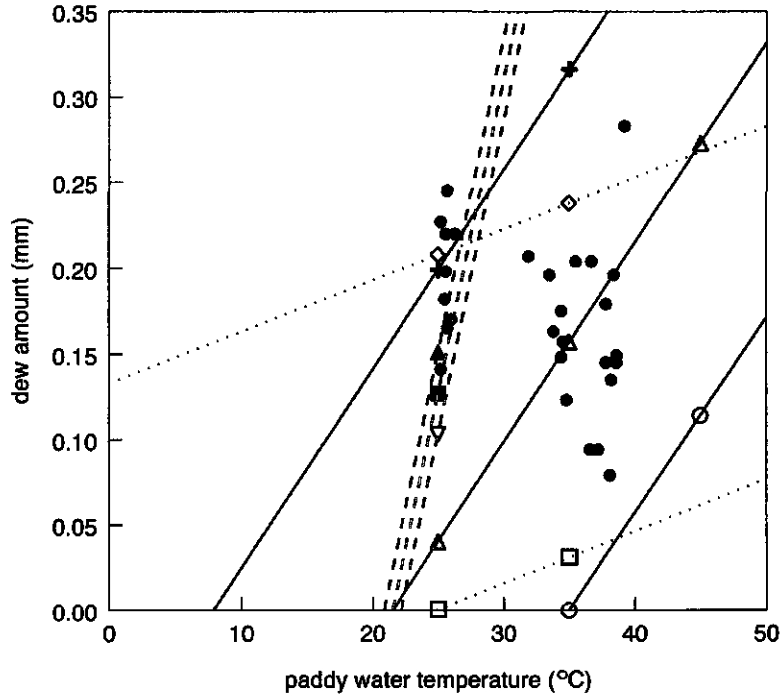


Fig. 3.4. Relationship between dew amount in the middle of the rice canopy and water temperature. The closed dots (●) are water amount collected at sunrise in the middle of the rice canopy. The lines are simulated dew amount under a neutral (——; ✚: VPD=0.0 kPa; Δ: VPD=0.1 kPa; ○: VPD=0.2 kPa), stable (– – –; ▲: VPD=0.1 kPa; ■: VPD=0.2 kPa; ∇: VPD=0.3 kPa), and unstable (·······; ◊: VPD=0.0 kPa; □: VPD=0.05 kPa) stratification condition, respectively during a typical quiet and clear tropical night with a constant nocturnal net radiation of –40 W m^{-2}, an air temperature at 1.5 m of 25°C, and a wind speed of 1 m s^{-1}.

increased 4°C per 10 W m^{-2} less negative nocturnal net radiation (Fig. 3.5). Given the same meteorological conditions mentioned above and a constant nocturnal net radiation of -40 W m^{-2}, the value of (T_{wc}–T_a) increased 13°C per 0.1 kPa increase of the water vapour pressure deficit (Fig. 3.6). Under an unstable stratification condition, the value of (T_{wc}–T_a) was extremely sensitive to the water vapour pressure deficit and nocturnal net radiation (Figs. 3.5 and 3.6). These results indicate that under unstable and neutral stratification conditions, the critical water temperature for the onset of dew was highly

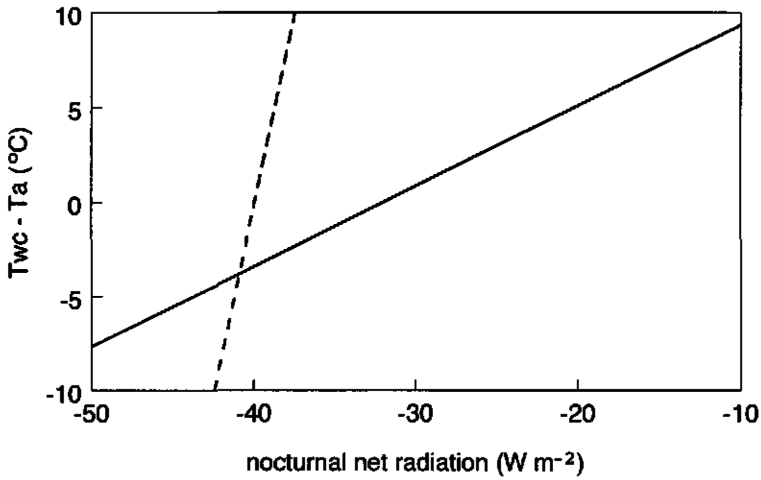


Fig. 3.5. Relationship between (T_{wc}–T_a)(the difference between critical water temperature (T_{wc}, °C) and air temperature (T_a, °C) at the height of 1.5 m above the ground) and the nocturnal net radiation (W m^{-2}) for a closed rice canopy (LAI=6) under a certain weather condition: wind speed u=1 m s^{-1}, air temperature T_a=25°C, water vapour pressure deficit VPD=0.1 kPa for neutral condition (——) and 0.05 kPa for unstable condition (– – –).

sensitive to both nocturnal net radiation and water vapour pressure deficit. Dew formation only occurred when the water vapour pressure deficit was less than 0.06 kPa for a value of (T_{wc}–T_a) below 10°C, due to the strong exchange of heat and vapour between the canopy and the air layer above.

Discussion and conclusions

Water temperature affects not only dew formation but also guttation in paddy rice crops. The optimum water temperature for rice leaf guttation was about 30°C. Towards higher temperatures, guttation decreased again with water temperature. For any meteorological condition, dew amount in the rice crops increased with water temperature. However, when the water temperature was high enough to generate an unstable stratification condition even above the canopy, the effect of water temperature on dew formation almost disappeared.

The measured data indicated that the guttation water in the field canopies must have been at least as much as the dew amount. Therefore, guttation, as a

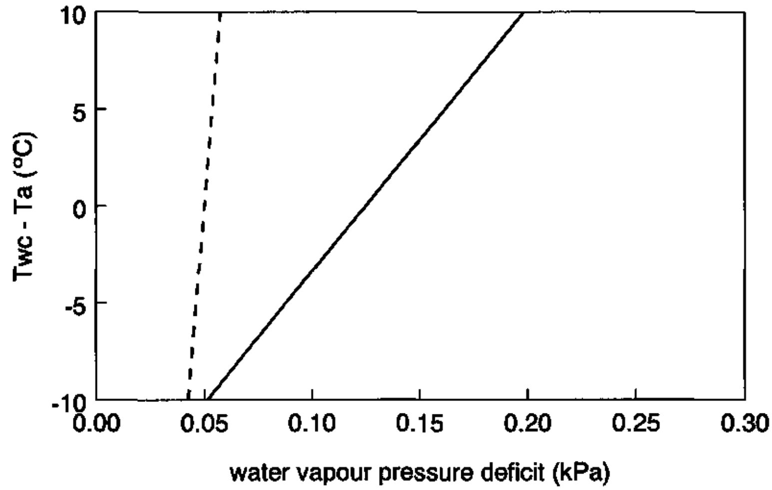


Fig. 3.6. Relationship between (T_{wc}−T_a)(the difference between critical water temperature (T_{wc}, °C) and air temperature (T_a, °C) at the height of 1.5 m above the ground) and the water vapour pressure deficit (kPa)for a closed rice canopy (LAI=6) under a certain weather condition: wind speed u=1 m s^{-1}, air temperature T_a=25°C, and nocturnal net radiation R_n= −40 W m^{-2} for both neutral condition (——) and unstable condition (− − −).

contributor to leaf wetness in paddy rice crops, cannot be ignored.

Nocturnal net radiation, as a driving force, significantly affects dew formation under all stratification conditions, especially under unstable and neutral conditions. Under unstable and neutral stratification conditions, dew formation is also highly sensitive to vapour pressure deficit, i.e. the measurement of air humidity must be very accurate for a proper dew formation estimation. Under a neutral condition, 0.03 kPa measurement error of water vapour pressure deficit could cause a dew formation estimation error of 0.05 mm per night (Fig. 3.4) which equals to the standard errors between the measured and the simulated dew amount (SE=0.05 mm). Therefore, deviations of the measured dew amount from the simulated one, as shown in Fig. 3.2 (a), can easily be caused by measurement errors of air humidity. Under a stable stratification condition, water vapour pressure deficit has little effect on dew formation but water temperature becomes very important. Hence, in addition to nocturnal net radiation, water temperature also plays a very important role in dew formation in the rice canopy. However, when the water temperature reaches a value much higher than the air temperature above the canopy, the stratification condition will be modified from stable via neutral to unstable conditions. Under neutral stratification conditions, the effect of water temperature was less and under unstable conditions its effect almost disappeared.

During a quiet and clear tropical night with a wind speed of 1 m s^{-1}, a nocturnal net radiation of –40 W m^{-2}, an air temperature of 25°C, and a water vapour pressure deficit of 0.1 kPa, simulated dew amount at middle of crop height decreased with the inverse of the aerodynamic resistance $1/r_a$ (Fig. 3.3 (b)). It should be noted that no dew occurred when $1/r_a$ was larger than 57, 44, and 29 mm s^{-1} for a water temperature of 45, 35, and 25°C, respectively. This result indicates that the heat and vapour exchange between the canopy and the air layer above is too strong to permit any condensation in the canopy when the inverse of the resistance between the canopy and the reference height is larger than a critical value, i.e. a neutral or stable stratification condition in the lower atmosphere is needed for dew formation in the canopy. According to the simulation analysis in this study, dew formation is highly sensitive to the stratification condition above the canopy. This complication might also be a cause for the deviation of the measured dew amount from the simulated one. However, the good agreement between the dew amount measured at crop height and the result simulated for the assumed neutral condition (Fig. 3.2 (a)) indicates that without information about the stratification condition above a canopy, assuming a neutral condition may give a reasonable estimation of the dew formation in the canopy. The assumed stable condition extremely overestimated the dew formation not only for the treatment canopies, but also for the control canopy (Fig. 3.3 (a)). The MICROWEATHER model tended to simulate a stable condition during all night. In reality, such a stable condition was probably periodically broken by gusts.

Chapter 4

The dewball: a simple instrument to determine the threshold value of nocturnal net radiative loss for dew formation

Abstract The threshold value of nocturnal net radiative loss for dew formation in rice crops and its dependence on other weather variables were investigated in a field experiment in a tropical paddy rice field during 23 nights from February to April, 1994. The onset and end of dew were visually observed both on the top leaves of the rice crop and on a glass sphere, the "dewball", installed in the field at 1.0 m above the ground. The threshold value of total nocturnal net radiative loss ($R_{nt,thresh}$) for dew formation on the ball was determined based on the maximum zenith angle reached by dew formation on the ball surface during a night. The $R_{nt,thresh}$ was found to be linearly related to the minimum nightly value of vapour pressure deficit. This linear relationship and the Penman-Monteith equation (an energy balance approach) were used to estimate both the moment of dew onset and dew duration on the ball. These estimated results agreed well with the observed results. These results showed that for the estimate of the moment of dew onset and nightly dew duration on the ball, the linear relationship between the threshold value of total nocturnal net radiative loss for dew formation and vapour pressure deficit could be as accurate as the Penman-Monteith equation. The observed dew duration was well correlated with both the observed and the estimated moment of dew onset on the ball. During most of the nights, dew occurred on the top leaf surface almost at the same moment that dew reached the zenith angle of 60° on the ball. The linear relationship between the observed daily dew duration on the top leaf surface of the rice crop and the estimated moment of dew onset at the zenith angle of 60° on the ball gave a much more accurate estimation of dew duration on the top leaf surface of the rice crop than the Penman-Monteith combination equations did.

Introduction

Dew, as a main contributor of leaf wetness, has been studied for its importance in plant pathogen activities. Dew formation in crops can either be estimated using the energy balance approach or be measured using special instruments and techniques. A few experimental measurements of dew amount or duration profiles in crops such as wheat (Burrage, 1972), dry beans (Weiss et al., 1989), corn (Jacobs et al., 1990) and barley (Jacobs and Nieveen, 1995) have been reported. The measurement of dew formation in crops has been done mainly for scientific purposes, for instance model validation, due to its large demand of time and instruments. Therefore, there is a great need for good methods to estimate dew formation. Pedro and Gillespie (1982a,b) developed a single-layer model to estimate dew formation on leaf surface using micrometeorological data as well as standard weather data. Goudriaan (1977) developed a multilayer model (MICROWEATHER) which can simulate the distribution of dew formation at different levels in a canopy.

Daily dew duration is composed of two parts, night dew duration and dew duration after sunrise. According to Huber and Gillespie (1992), in the tropics the wetness period ends each morning at approximately the same time irrespective of when rainfall occurred during the previous afternoon. Daily leaf wetness duration is therefore linearly related to wetness start time. A simple but accurate estimation of dew onset and night dew duration is essential for a simple and accurate estimation of daily dew duration. The shielding nocturnal net radiative loss experiment showed that a threshold value of nocturnal net radiative loss exists for dew formation in paddy rice crops (see Chapter 2). The existence of a threshold value of nocturnal net radiative loss and the linear relation between daily leaf wetness duration and wetness start time suggest a simple way to estimate daily dew duration. However, the threshold value will be dependent on weather conditions such as air humidity and wind speed. The objectives of this study were to experimentally investigate 1) the quantitative relationship between the threshold nocturnal net radiative loss for dew formation and the pertinent weather variables, and 2) the possibility to estimate time of dew onset and daily dew duration using this relationship.

Materials and methods

Site and crop

The experiment was carried out at the International Rice Research Institute (IRRI) (14°11'N, 121°15'E, 20.0 m), Los Baños, Philippines during 23 nights from February to April, 1994. Global radiation, net radiation, air temperature, air humidity, and wind speed over a rice canopy, at 1.5 m above the ground and water temperature in the rice field were automatically monitored. All aerial sensors were mounted on a tripod which was set up at the centre of a 4×5 m^2 plot situated at the centre part of a 25×50 m^2 paddy rice field. Within 1000 m around the experimental field, there were no high buildings or tall trees. The experimental field was surrounded by other rice fields.

The rice variety used in the experiment was IR72. The crop was in the tillering stage at the beginning of the experiment and reached the dough ripe stage by the end. Crop height and leaf area index (LAI) were measured once a week.

Dewball and dew formation observation

Dew formation was observed on the surface of a white glass sphere, the 'dewball', that had a diameter of 0.25 m. The dewball was installed in the rice field at 2 m west of the tripod to avoid shadow by the tripod in the morning. The 'north pole' of the ball was at 1.0 m above the ground. Before the dewball was installed in the field, the following preparations had been done. First, the ball was fully filled with packing foam through the opening at its bottom to avoid heat exchange within the ball. Second, the 'equator' and the 'north' and 'south poles' of the ball were marked as well as latitudinal circles every 10 degrees, using red plastic tape with a width of about 2 mm. Thus the upper hemisphere of the ball was divided into 9 strips with a width of 10 degrees for each strip. Then the ball was fixed on a vertical wooden post.

After sunset dew formation on the ball surface was visually observed. If dew was already present at that moment, the zenith angle of the outer edge reached by the dew was recorded together with the observation time as the first record of the night. The second visual observation was made when the dew reached a new 10° border, so that the second record was more accurate. After sunset, the visual observation was stopped after at least two records were made. Observations were resumed at sunrise (presumably the dew had reached the maximum zenith angle) and afterwards until the whole ball dried.

When the dew was heavy, it flowed from the north pole down to the lower part of the ball. The flow traces could be easily distinguished from the locally condensed dew drops. Therefore, this did not disturb the dew onset observation. During the drying period, however, it was impossible to distinguish the flowing water from the dew drops. Fortunately, the whole ball dried soon after sunrise and the difference between the drying moments of the eastern and western parts of the ball was normally less than half an hour. Therefore, the moment that the whole ball had become dry was used as the time of dew cessation for all latitudes of the ball surface, i.e. the dew duration at a certain latitude of the dewball surface was defined as the period between the moment of dew onset at this latitude and the moment that the whole ball had become dry.

Also the timing of dew onset and end on the leaves at the top of the rice crop were visually observed for validation purposes.

Estimation of critical level of net radiative loss

Dew formation was estimated by using the Penman-Monteith combination equations for the surface energy balance (Monteith and Unsworth, 1990). During the night, net radiation only consists of thermal radiation exchange between the surface and the atmosphere. Assuming a uniform effective sky temperature, the net radiative loss of an inclined surface depends on its zenith angle (θ) as

$$R_n = R_{n0}(1 + \cos\theta) / 2 \qquad (4.1)$$

where $R_{n,0}$ is the net radiative loss of a horizontal surface. This equation was also applied to the dewball.

The position of the outer fringe of dew formation was used as an estimate for the maximum value of zenith angle θ, and could thus be used to estimate the lower boundary value of net radiative loss below which dew formation could no longer occur. This level of net radiation was the critical threshold level. In the further analysis, this critical level was found to depend on other weather variables, and in particular on the vapour pressure deficit.

Results and discussion

Threshold value of total nocturnal net radiative loss ($R_{nt,thresh}$) for dew formation on dewball

Based on the experimental data, it was found that a good correlation existed between $R_{nt,thresh}$ (MJ m^{-2}) and the minimum value of the water vapour deficit, D_{min} (kPa), at 1.5 m above the ground (Fig. 4.1):

$$R_{nt,thresh} = -2.5\ D_{min} \tag{4.2}$$

The slope of Eq. (4.2) has a unit of MJ m^{-2} kPa^{-1}, i.e. the $R_{nt,thresh}$ becomes 0.25 MJ m^{-2} more negative with 0.1 kPa increase of the D_{min}. It is to be expected that the value of this slope depends on the wind speed: the stronger the ventilation, the higher this slope will be. The Penman-Monteith combination equation for latent heat loss for a wet surface (Eq.(1.1)) is used to analyse this dependence. The critical level of net radiative loss occurs when

$$R_n = -\ \rho c_p D/(s r_a) \tag{4.3}$$

where s is the slope of the saturation vapour pressure curve at air temperature, ρc_p is the volumetric heat capacity of the air, r_a is the boundary layer resistance to water vapour and heat, R_n is the net radiative loss and D is the vapour pressure deficit. Compared to Eq. (4.3), the slope in Eq. (4.2) must be $(-\rho c_p/(s r_a))\Delta t$ for the $R_{nt,thresh}$, where Δt is night length (12 hours). Taken s as 0.2 kPa K^{-1}, r_a is found to be about 100 s m^{-1}. This is quite a large value, probably because the wind speed is low whenever dew is formed first.

Moment of dew onset and nightly dew duration on dewball

In the tropics, daily leaf wetness duration is linearly related to wetness start time (Huber and Gillespie, 1992). Therefore, an accurate estimation method of daily dew duration should give an accurate estimate of the moment of dew onset and night dew duration. To investigate the possibility of using the critical level of net radiation to estimate the moment of dew onset and night dew duration, it was assumed that dew onset occurred when total nocturnal net radiative loss became more negative than the threshold value of total nocturnal net radiative loss ($R_{nt,thresh}$) estimated using Eq. (4.2). These results were compared with both the observed and the estimated results using the Penman-

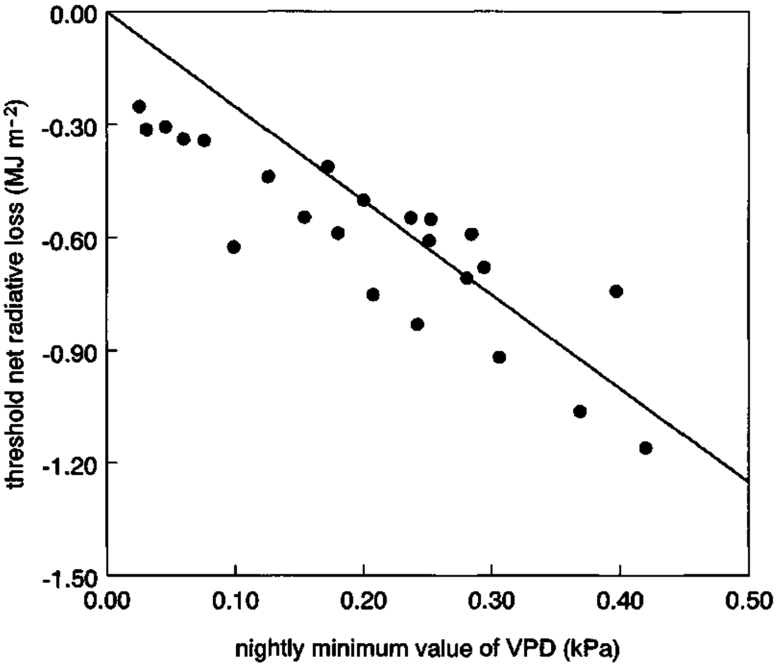


Fig. 4.1. Relation between the threshold value of total nocturnal net radiative loss ($R_{nt,thresh}$ in MJ m^{-2}) for dew formation on dewball and the nightly minimum value (D_{min}) of vapour pressure deficit (VPD in kPa) at 1.5 m above the ground. The symbols are observed data. The solid line is the regression relationship ($R_{nt,thresh} = -2.5\ D_{min}$, df=22, $p<0.05$, $r^2=0.76$, SE=0.17 MJ m^{-2}).

Monteith equation. Since dew cover on the ball might reach its maximum zenith angle at the moment when the minimum value of vapour pressure deficit during a night occurred, it is reasonable to assume that Eq. (4.2) can be generalized for any moment during the night. Then, Eq. (4.2) can be rewritten in a general format:

$$R_{n,thresh} = -57.9D \tag{4.4}$$

where $R_{n,thresh}$ is the threshold value of nocturnal net radiative loss for dew onset (in W m^{-2}) and D is the vapour pressure deficit in kPa. The slope of Eq. (4.4) has a unit of W m^{-2} kPa^{-1}. A good correlation was found between the

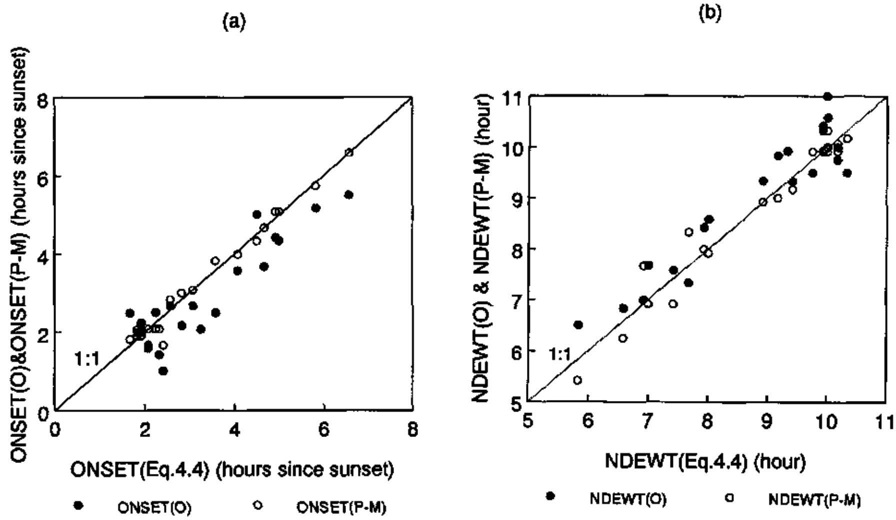


Fig. 4.2. (a): Relations between the moment of dew onset on dewball observed (ONSET(O), expressed in hours since sunset (18:00), Y axis) and estimated using the Penman-Monteith equation (ONSET(P–M), Y axis) and that estimated using the threshold value of nocturnal net radiative loss (ONSET(Eq.4.4), X axis) (df=22, $p<0.05$, between ONSET(O) and ONSET(Eq4.4): $r^2=0.81$, SE=0.71 hour; between ONSET(P–M) and ONSET(Eq.4.4): $r^2=0.95$, SE=0.33 hour; between ONSET(O) and ONSET(P–M): $r^2=0.85$, SE=0.63 hour) and; (b): relations between the nightly dew duration on dewball observed (NDEWT(O), Y axis) and estimated using the Penman-Monteith equation (NDEWT(P–M), Y axis) and that estimated using the threshold value of nocturnal net radiative loss (NDEWT(Eq.4.4), X axis) (df=22, $p<0.05$, between NDEWT(O) and NDEWT(Eq.4.4): $r^2=0.89$, SE=0.50 hour; between NDEWT(P–M) and NDEWT(Eq.4.4): $r^2=0.95$, SE=0.32 hour; between NDEWT(O) and NDEWT(P–M): $r^2=0.86$, SE=0.58 hour).

observed results (ONSET(O), NDEWT(O)) and the estimated results using both Eq. (4.4) (ONSET(Eq.4.4), NDEWT(Eq.4.4)) and the Penman-Monteith equation (ONSET(P–M), NDEWT(P–M)) (Fig. 4.2). For the moment of dew onset, the values of r^2 and SE were 0.81 and 0.71 hour for the correlation between the observed and the estimated results using Eq. (4.4), 0.85 and 0.63 hour for the correlation between the observed and the estimated results using the Penman-Monteith equation, and 0.95 and 0.33 hour for the correlation between the estimated results using Eq. (4.4) and the Penman-Monteith equation, respectively (Fig. 4.2 (a)). For night dew duration, the values of r^2 and

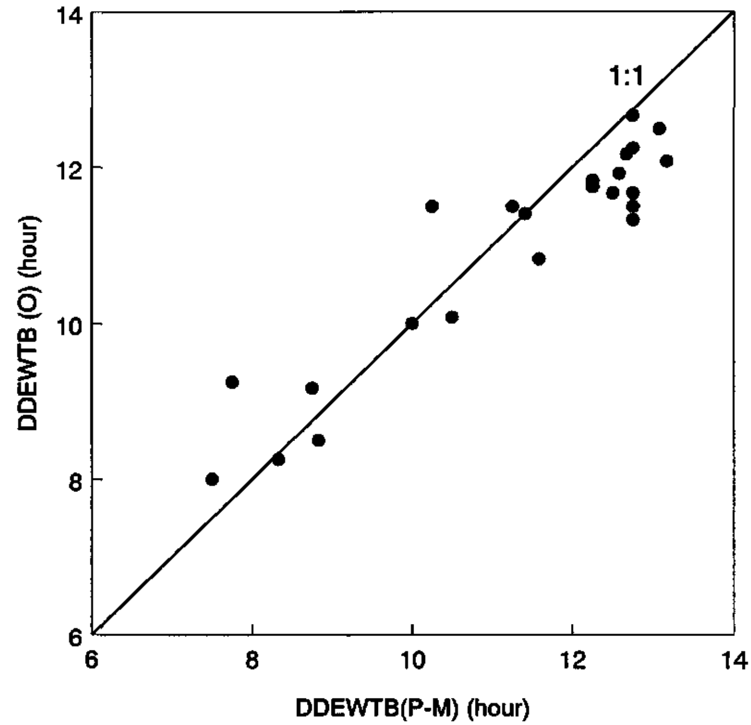


Fig. 4.3. Relation between the daily dew duration on dewball observed (DDEWTB(O)) and estimated using the Penman-Monteith equation (DDEWTB(P–M)). The symbols are observed daily dew duration on dewball. The solid line is the regression relationship (y=x, df=22, $p<0.05$, $r^2=0.85$, SE=0.78 hour).

SE were 0.89 and 0.50 hour for the correlation between the observed and the estimated results using Eq. (4.4), 0.86 and 0.58 hour for the correlation between the observed and the estimated results using the Penman-Monteith equation, and 0.95 and 0.32 hour for the correlation between the estimated results using Eq. (4.4) and the Penman-Monteith equation, respectively (Fig. 4.2 (b)). These results showed that for the estimate of the moment of dew onset and nightly dew duration on dewball, Eq. (4.4) could be as accurate as the Penman-Monteith equation.

Daily dew duration on dewball

Eq. (4.4) can not directly give daily dew duration estimation. Thus, daily dew duration on dewball (DDEWTB) was estimated using the Penman-Monteith equation. The estimated result agreed well with the observed result (r^2=0.85, SE=0.78 hour) (Fig. 4.3). So did the estimated time of dew onset (r^2=0.85, SE=0.63 hour) (Fig. 4.2 (a)). However, there was no correlation between the estimated and the observed moment of drying of dew on the dewball in the next morning. This was caused by the fact that the dew formed on the ball flowed down during heavy dew nights. During the experimental period, the dew ball dried within 1.25 to 2.67 hours after sunrise, i.e. the contribution of the dew period after sunrise to the total dew duration was quite small compared to the nightly dew period. Hence, the high correlation between the estimated and the observed dew duration still existed in spite of the fact mentioned above. These results indicate that dew duration is more dependent on the time of dew onset. This was proved by the high correlation between the observed daily dew duration and the observed time of dew onset on dewball (r^2=0.84, SE=0.68 hour) (Fig. 4.4). The same linear relationship was found between the observed daily dew duration on dewball and the time of dew onset estimated using Eq. (4.4) as well as the Penman-Monteith equation with a slightly lower r^2 =0.83 and higher SE=0.72 hour (Fig. 4.4):

$$DEWT = 14.57 - 1.1t_0 \tag{4.5}$$

where DEWT is the daily dew duration on dewball, t_0 is the moment of dew onset expressed as hours since sunset, 14.57 (hours) and 1.1 are regression coefficients. The estimation of daily dew duration can be done using Eq. (4.4) combined with Eq. (4.5). The coefficient 1.1 in Eq. (4.5) is not 1.0. This indicates that the moment of dew onset or nightly dew period has a slight effect (10%) on the dew period after sunrise, i.e. the dew period after sunrise will be six minutes longer or shorter if the moment of dew onset is one hour earlier or later. This result further confirms that the contribution of the dew period after sunrise to the total dew duration is quite small compared to the nightly dew period (see Chapter 2).

Daily dew duration at the top of the leaf surface of the rice crop

A high correlation also existed between the observed daily dew duration and the moment of dew onset on the top of the leaf surface of the rice crop (r^2

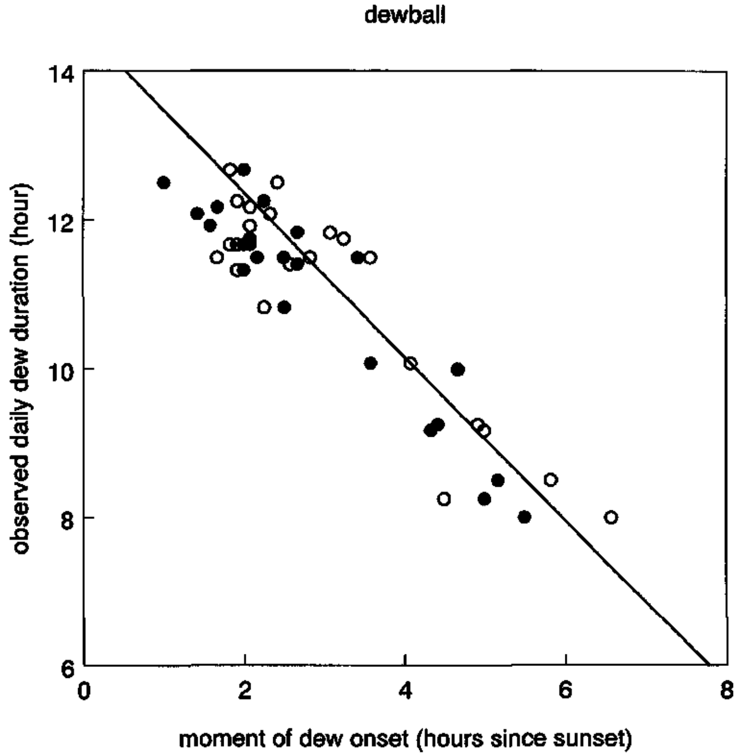


Fig. 4.4. Relation of the observed daily dew duration on dewball (Y axis) to the moment of dew onset on dewball observed (●)(ONSET(O), X axis) and estimated using the threshold value of total nocturnal net radiative loss for dew formation (o)(ONSET(Eq.4.4), X axis). The solid line is the regression relationship ($y=14.57-1.1x$, df=22, $p<0.05$, for ONSET(O): $r^2=0.84$, SE=0.68 hour; for ONSET(Eq.4.4): $r^2=0.83$, SE=0.72 hour).

=0.90, SE=0.51 hour) (Fig. 4.5). During the field observations, it was found that for most of the observation nights dew occurred on the top leaf surface of the rice crop almost at the same moment when dew reached the zenith angle of 60° on dewball. The moment of dew onset at the zenith angle of 60° on dewball (ONSETE(60)) during each experimental night was estimated using Eq. (4.4). It was found that Eq. (4.5) applied to the relationship between the observed daily dew duration on top leaf surface of the rice crop and the estimated moment of dew onset at the zenith angle of 60° on dewball using Eq. (4.4), and gave a much more accurate estimate of daily dew duration on top leaf surface of the

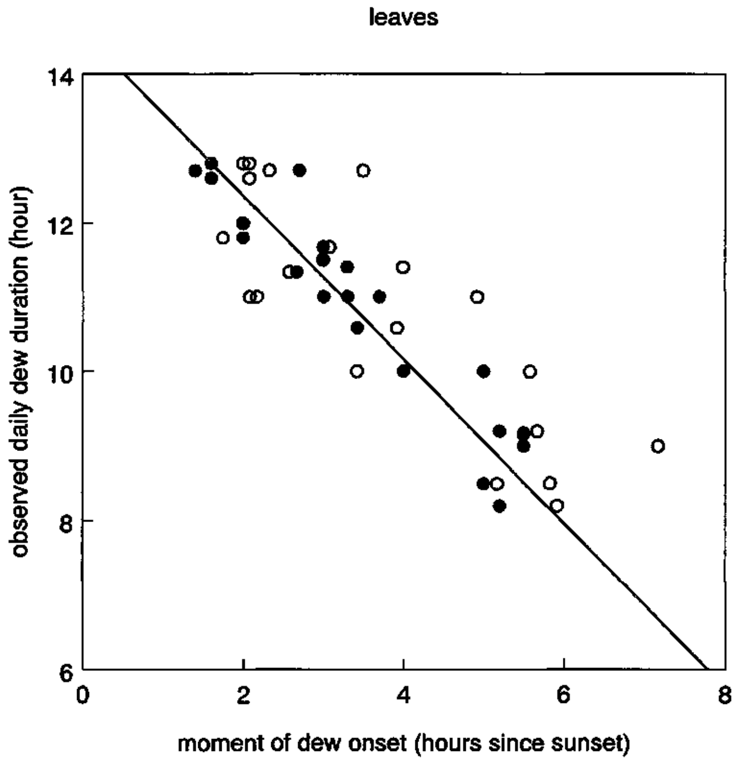


Fig. 4.5. Relation of the observed daily dew duration on top leaf surface of the rice crop (Y axis) to the observed moment of dew onset on the leaf surface (•)(ONSET(O), X axis) and the estimated moment of dew onset at zenith angle of 60° on dewball using the threshold value of total nocturnal net radiative loss for dew formation (o)(ONSETE(60), X axis). The solid line is the regression relationship ($y=14.57-1.1x$, df=22, $p<0.05$, for ONSET(O): $r^2=0.90$, SE=0.51 hour; for ONSETE(60): $r^2=0.76$, SE=1.07 hours).

rice crop (r^2 =0.76, SE =1.07 hours) (Fig. 4.5) than the Penman-Monteith combined equations did (r^2 =0.49, SE =2.24 hours). Eqs. (4.4) and (4.5) gave quite an accurate estimation of daily dew duration even though wind speed, which is one of the important weather variables affecting dew formation, was not included into the equations. This might be attributed to the fact that wind speed was always very low during dew nights. Although Eqs. (4.4) and (4.5) are site- and season-specific, the linear relationship between the threshold value of total nocturnal net radiative loss and vapour pressure deficit and between the daily dew duration and the time of dew onset will be maintained if the weather conditions are quite stable.

Conclusions

According to the obtained results, the following conclusions can be extracted for dry season in the tropics:

- The threshold value of total nocturnal net radiative loss for dew formation linearly depended on vapour pressure deficit.
- For most of the experimental nights, dew occurred on the top leaf surface almost at the same moment when dew reached the zenith angle of 60° on the dewball. This indicates that the dewball can be a useful device for dew formation observation.
- A linear relationship existed between daily dew duration and the moment of dew onset.
- Daily dew duration on dewball and on top leaf surface of the rice crop can be simply estimated using the combination of Eqs. (4.4) and (4.5). These equations gave a much more accurate estimate of daily dew duration on top leaves of the rice crop than the Penman-Monteith combination equations did.

Chapter 5

Analysis of the possibility of using diurnal patterns of weather variables in estimating dew formation in a tropical paddy rice field

Abstract When dew formation cannot be measured, it must be estimated. Existing dew formation simulation models need hourly weather data as input. However, hourly weather data are not available at places where there is no automatic weather station. In this case, the diurnal pattern of weather variables might be used to run the simulation model. In order to investigate the possibility of using diurnal patterns of weather variables to estimate dew formation, a field experiment was carried out at the International Rice Research Institute (IRRI) (14°11'N, 121°15'E, 20.0 m), Los Baños, Philippines from February to April, 1994. The mean diurnal patterns of weather variables were derived based on the observed hourly data. Both the observed hourly weather data and the estimated diurnal patterns of weather variables were used to run a simulation model based on an energy balance approach. The observed hourly weather data gave the best estimation of dew formation at crop height. Replacing observed by estimated diurnal patterns of wind speed and air temperature gave the second and third best estimation, respectively, whereas that of water vapour pressure and the calculated nocturnal net radiation resulted in large estimation errors. The results of a Wilcoxon signed rank test confirmed that it is possible to use the estimated diurnal pattern of air temperature and wind speed but not that of air humidity and nocturnal net radiation to estimate dew formation.

Introduction

Dew, as a main contributor of leaf wetness, has been studied for its importance in plant pathogen activities and in the deposition of pollutants on leaves. Dew formation in crops can be either estimated using the energy balance approach or measured using special instruments and techniques. Dew formation must be estimated when its measurement is not available. Pedro and Gillespie (1982a, b) developed a single-layer model to estimate dew formation on leaf surface using microclimate data as well as standard weather data. Goudriaan (1977) developed a multilayer model (MICROWEATHER) which can simulate the distribution of dew formation at different levels in a canopy. Hourly weather data are needed to run the dew formation simulation models. Applications of dew formation simulation models are limited in places where there are only non-automatic weather stations because only daily weather data are routinely reported by the non-automatic weather stations. Studies on diurnal patterns of weather variables (Parton and Logan, 1981; Peterson and Parton, 1983; Wann et al., 1985; Reicosky et al., 1989) provide a possibility of estimating hourly values from daily ones. However, the question whether the estimated diurnal pattern will give as good an estimate of dew formation as when using the observed hourly weather data has to be answered before adapting the diurnal pattern of weather variables to estimate dew formation. The objective of this study was to answer this question through field experiments and simulation analysis.

Materials and methods

Site and measurements

The experiment was carried out in a rice field at the International Rice Research Institute (IRRI) (14°11'N, 121°15'E, 20.0 m), Los Baños, Philippines from 7 February to 11 April, 1994. Within 1000 m around the experimental field, there were no high buildings or tall trees. The experimental field was surrounded by other rice fields. Dew amount at crop height was measured using a circular blotting paper with diameter of 90 mm and dew duration at the same height was visually observed during 23 rain-free nights. Five replicas of the circular blotting paper were weighed and installed horizontally at crop height by attaching them to five vertical bamboo sticks, respectively before sunset and were weighed again at sunrise in the next morning. Global radiation, net radiation, air temperature, air humidity, and wind speed over the rice canopy, at 1.5 m above the ground and water temperature in the rice field were automatically monitored. All aerial sensors were mounted on a tripod which was set up at the centre of a 4×5 m^2 plot situated at the centre part of a 25×50 m^2 paddy rice field.

The rice variety used in the experiment was IR72. The crop was from tillering to dough development stage from the beginning to the end of the experiment. Crop height and leaf area index (LAI) were measured once a week.

Derivation of diurnal patterns and calculation of relative variations of weather variables

Derivation of diurnal patterns

The mean diurnal patterns of weather variables (global radiation Q, net radiation R_n, air temperature T_a, relative humidity RH, vapour pressure e_a, vapour pressure deficit VPD and wind speed u) were derived by means of curve fitting.

The diurnal time course for global radiation should be related to true solar time. The difference between local standard time and true solar time was determined by plotting observed global radiation values versus the calculated values of the sine of solar height:

$$\sin\beta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos(2\pi(t_h-(12+\Delta t))/24) \quad (5.1)$$

where β, φ, δ, t_h, and Δt are solar height, latitude, declination of the sun, local standard time in hours, and time difference (in hours) between local standard time and true solar time, respectively. The relationship between measured radiation and computed sine of solar height will exhibit a loop if the value of Δt is not correct. A correct Δt will produce a linear relation between the measured radiation and the computed $\sin\beta$. In this way, Δt was determined to be 0.05 hour for IRRI.

Generally, the equations for global radiation Q (W m^{-2}) (Ross, 1975) and day time net radiation R_n (W m^{-2}) can be written as:

$$Q = Q_0\tau_a\sin\beta\exp(A/\sin\beta) \quad (5.2)$$

$$R_n = L_n + (1-\alpha)Q \quad (5.3)$$

where Q_0 is the solar constant with a value of about 1367 W m^{-2}, τ_a and α are the atmospheric transmissivity and the surface effective albedo, respectively, L_n is the thermal component of the net radiation, and A is an empirical coefficient of about −0.12.

The nocturnal net radiation L_n, was calculated using the Swinbank (1963) formula:

$$L_n = L\downarrow - L\uparrow$$

$$L\downarrow = \varepsilon\sigma T_{abs,air}^{4}\,(1.0 - (1.0 - 9.35\times10^{-6}\times T_{abs,air}^{2})(Q_{total}/Q_e))$$

$$L\uparrow = \varepsilon\sigma T_{abs,s}^{4}$$

where $L\downarrow$ is the absorbed net radiation from the sky, $L\uparrow$ is the outgoing thermal radiation from the canopy, ε (=0.95) is the emissivity of the canopy (also used for the absorptivity of the canopy), σ (=5.67×10^{-8} W m^{-2} K^{-4}) is the Stefan-Boltzmann constant, $T_{abs,air}$ and $T_{abs,s}$ are the absolute air temperature at 1.5 m above the ground and the absolute canopy temperature, respectively, Q_{total} is the daily total global radiation and Q_e is the daily total extraterrestrial radiation.

Vapour pressure deficit was calculated from the observed hourly data of air temperature and vapour pressure. The mean diurnal patterns of air temperature, relative humidity, vapour pressure, vapour pressure deficit and wind speed were directly derived by means of curve fitting.

Calculation of relative standard error of estimate (RSE)

To compare the day by day variation of the diurnal patterns of weather variables, a term, RSE, is defined for describing the relative deviation of the actual diurnal patterns (of air temperature, vapour pressure, vapour pressure deficit, wind speed and nocturnal net radiation) from the mean ones:

$$RSE = ((\Sigma(y_i - y_{mean})^2)/n)^{1/2} / (y_{max} - y_{min})$$

where y_i is the observed hourly value, y_{mean} is the average value of y_i during the experimental period (n days), and y_{max} and y_{min} are the average values of daily maximum and minimum during the experimental period (n days).

Simulation and methods of error analysis and test of significance

First, the mean diurnal patterns of weather variables derived from the observed hourly data were used to run the MICROWEATHER model. Then, these model results were compared with the observed dew data as well as with the model results using observed hourly data of all weather variables. The significance of the differences in estimation error between using the mean diurnal patterns and the observed hourly data of weather variables was tested using the Wilcoxon signed rank test (Hollander and Wolfe, 1973).

Simulation

In the MICROWEATHER model (Goudriaan, 1977), dew formation is estimated by using the Penman-Monteith combination equations for surface energy balance (Monteith and Unsworth, 1990). The mean diurnal pattern of air temperature (T_a), vapour pressure (e_a), vapour pressure deficit (VPD), wind speed (u) and the calculated nocturnal net radiation (R_n), respectively as well as different combinations of the diurnal pattern of these weather variables were used to run the model.

Error analysis and test of significance

The observations of dew formation during the 23 nights could be regarded as independent cases by i=1,2,3,...,23. The root mean square error RMSE was calculated as:

$$RMSE = ((\Sigma(DEW_{si} - DEW_{oi})^2)/n)^{1/2} \qquad \text{for dew amount}$$

and

$$RMSE = ((\Sigma(DEWT_{si} - DEWT_{oi})^2)/n)^{1/2} \qquad \text{for dew duration}$$

where DEW_{si} and $DEWT_{si}$ are simulated dew amount and duration of night i, DEW_{oi} and $DEWT_{oi}$ are the observations of dew amount and dew duration of night i, and n=23 is the number of observation nights.

The Wilcoxon signed rank test (Hollander and Wolfe, 1973) was used to test the significance of the differences in estimation error between using the *observed* hourly data of all weather variables and the *estimated* diurnal pattern of weather variables. The differences in estimation error can be defined as:

$$\Delta DWO_i = (DEW_{hi} - DEW_{oi})^2 - (DEW_{di} - DEW_{oi})^2$$

$$\Delta DWTO_i = (DEWT_{hi} - DEWT_{oi})^2 - (DEWT_{di} - DEWT_{oi})^2$$

where DEW_{hi} and $DEWT_{hi}$ are the simulated results using observed hourly data of all weather variables, and DEW_{di} and $DEWT_{di}$ are the simulated results using the estimated diurnal pattern of weather variables. Under the null-hypothesis H_0: 'both, using the estimated diurnal pattern of weather variables and the observed hourly data of all weather variables (to run the MICROWEATHER model), predict the observations equally well', ΔDWO_i (or

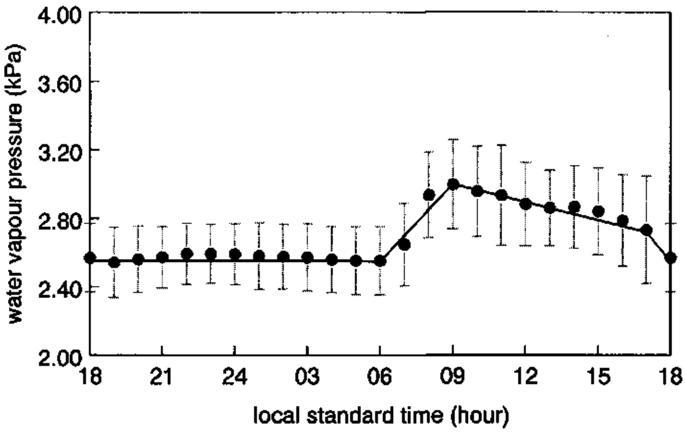


Fig. 5.1. Mean diurnal time course of water vapour pressure. The symbols are the average values of measured data during the experimental period. The solid line is the regression fitting curve. The vertical lines are the error bars.

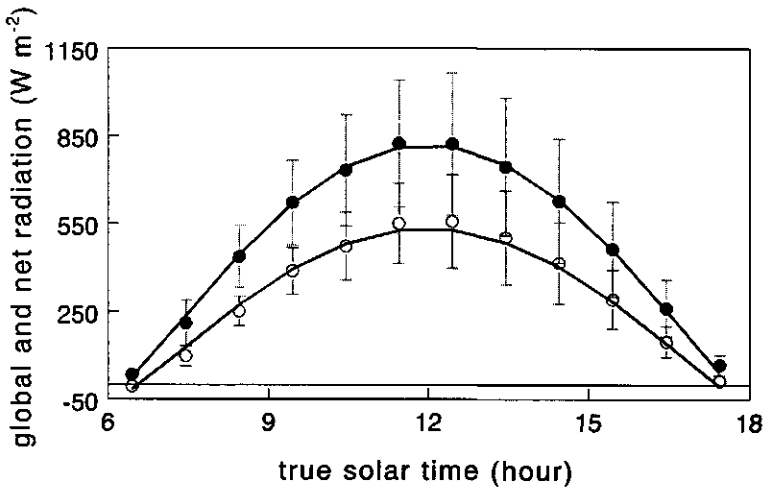
$\Delta DWTO_i$) is positive or negative with equal probability 0.5 if no zero values of ΔDWO_i (or $\Delta DWTO_i$) occur. A one-sided 'Large Sample Approximation' test was performed (at level α=0.05) since what we were interested in was if the estimated diurnal pattern of the weather variable(s) gives worse estimation of dew formation than the observed hourly data of all weather variables (Hollander and Wolfe, 1973).

Results and discussion

Mean diurnal time courses of weather variables and their relative variations

During the night, water vapour pressure was rather stable and could be considered as constant. After sunrise, water vapour pressure increased and reached its daily maximum value at about 3 hours after sunrise (e.g. around 09:00) (Fig. 5.1). 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 (Figs. 5.2 (a) and (b)). Nocturnal net radiation gradually became less negative from sunset to sunrise by 8 W m^{-2} (Fig. 5.3),

(a)



(b)

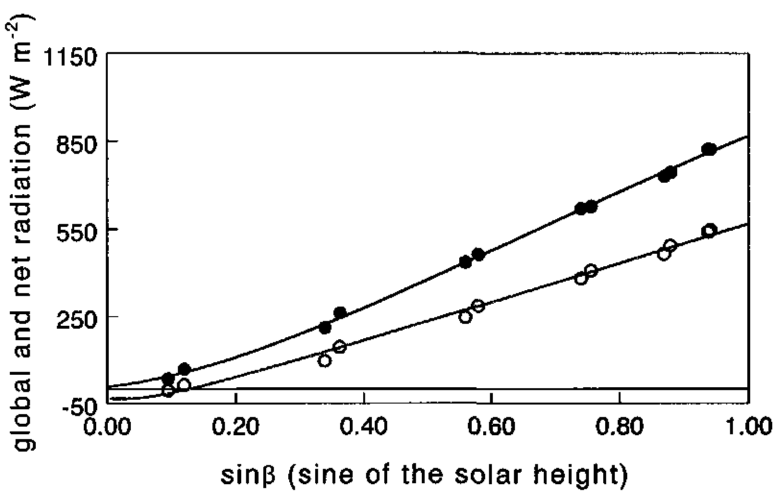


Fig. 5.2. (a) Mean diurnal time courses of global radiation (Q) and day time net radiation (R_n); and (b) the relations between Q and R_n and sinβ (sine of the solar height). The symbols are the average values of measured global radiation (•) and net radiation (o) during the experimental period. The solid lines are the regression fitting curves. The vertical lines are the error bars.

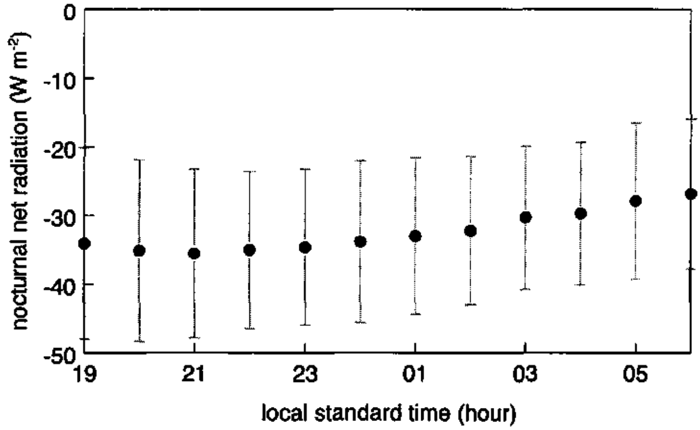


Fig. 5.3. Mean diurnal time course of nocturnal net radiation. The symbols are the average values of measured nocturnal net radiation during the experimental period. The vertical lines are the error bars.

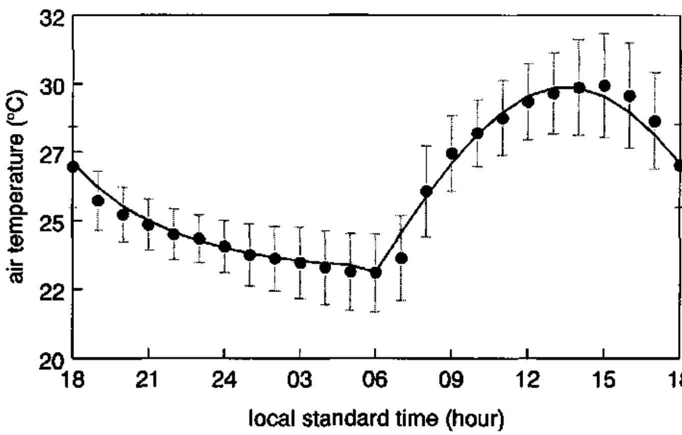


Fig. 5.4. Mean diurnal time course of air temperature. The symbols are the average values of measured air temperature during the experimental period. The solid line is the regression fitting curve. The vertical lines are the error bars.

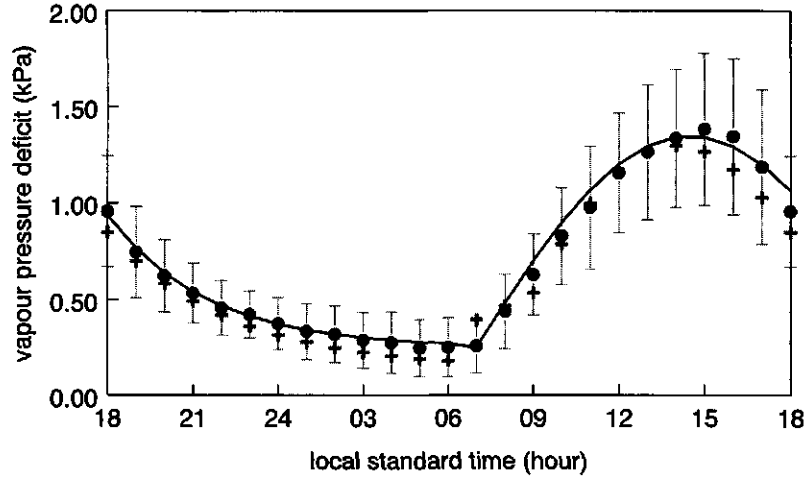


Fig. 5.5. Mean diurnal time course of vapour pressure deficit (VPD). The symbols are the average values of VPD calculated from the hourly data of air temperature and vapour pressure measured during the experimental period (●) and the VPD calculated from the mean diurnal patterns of air temperature and vapour pressure (✚). The solid line is the regression fitting curve. The vertical dash lines are the error bars (from ●).

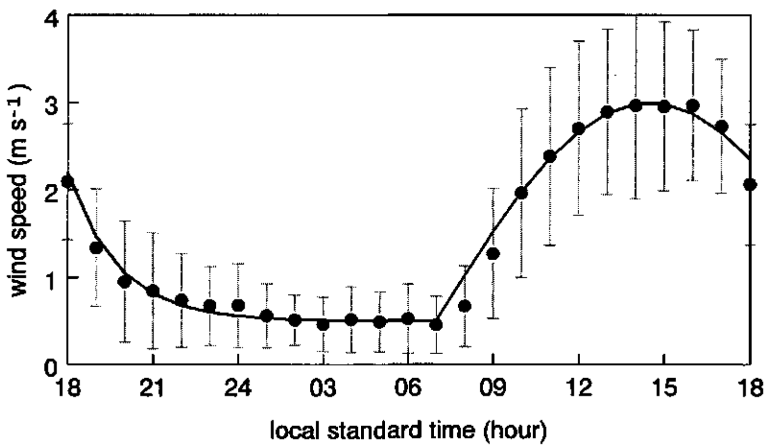


Fig. 5.6. Mean diurnal time course of wind speed. The symbols are the average values of measured wind speed during the experimental period. The solid line is the regression fitting curve. The vertical lines are the error bars.

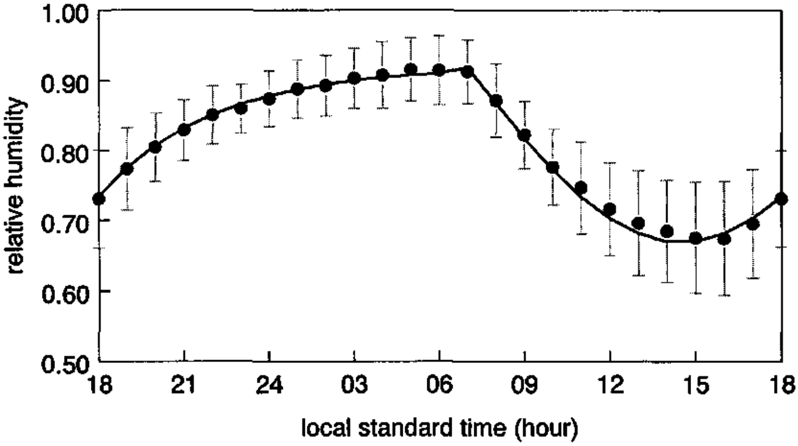


Fig. 5.7. Mean diurnal time course of relative humidity. The symbols are the average values of measured relative humidity during the experimental period. The solid line is the regression fitting curve. The vertical lines are the error bars.

Table 5.1. Relative standard error of estimate (RSE) of the diurnal patterns of weather variables.

Weather variable	Daily range of RSE (%)			Daily mean RSE (%)
air temperature	12.5	to	28.4	20.5
vapour pressure deficit	10.7	to	35.7	23.2
wind speed	11.0	to	42.5	26.8
water vapour pressure	37.0	to	68.5	52.8
nocturnal net radiation	119.0	to	161.0	140.0

concurrent with a decrease of air temperature (Fig. 5.4). Air temperature, vapour pressure deficit and wind speed reached their maximum values at about 13:30 and 14:30, 14:30, respectively and their minimum values at sunrise (Figs. 5.4 to 5.6). The amplitude of air temperature was about 6.5°C. Wind speed and vapour pressure deficit ranged between 0.5 and 3 m s^{-1} and 0.25 and 1.38 kPa, respectively. The diurnal pattern of relative humidity was opposite to that of air temperature but reached its minimum (0.68) at about 14:30 and maximum (0.92) at sunrise (Fig. 5.7). Its diurnal range was 0.24.

The relative standard error of the estimate RSE was the smallest for air temperature and largest for nocturnal net radiation (Table 5.1). This result indicates that the diurnal 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 5.2.

Table 5.2. Equations for averaged diurnal time course of weather variables*.

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

* β is the height of the sun, x is the time since sunset in hours, t_h is the local standard time (1 to 24 hour), $t_{h,srise}$ is the local standard time of sunrise and $t_{h,sset}$ is the local standard time of sunset; the items with subscripts $_{mean}$, $_{max}$ and $_{min}$ are the daily mean, maximum and minimum values, respectively.

Global radiation and net radiation

For the specific experimental site and season, τ_a, α, L_n and A in Eq. (5.2) and Eq. (5.3) were 0.72, 0.31, −32.0 W m^{-2}, and −0.12, respectively (Table 5.2). At night, Q is zero and R_n is equal to L_n. During daytime, L_n was set equal to the seasonal average nocturnal net radiation (−32 W m^{-2}). The effective albedo α in the expression for net radiation (Eq. (5.3)) consists of two parts: first the true albedo for shortwave radiation, which has a value of about 0.25 for most vegetated surfaces, and second a heating coefficient, which is caused by the increased thermal radiation as the incoming shortwave radiation and surface temperature rise (Davies and Buttimor, 1969). Assuming that the daily amplitude of surface temperature was the same as that of air temperature (about 6.5°C), the thermal radiative loss would be increased by about 40 W m^{-2}. Hence the heating coefficient is estimated at 0.05 (=40/840). The true surface albedo is decreased by this value from 0.31 to 0.26.

Air temperature, air humidity, and wind speed

The best fitting equation for mean diurnal time courses of air temperature, vapour pressure deficit and wind speed was a sine function for daytime and an exponential function for night (Figs. 5.4 to 5.6 and Table 5.2). As shown in Figs. 5.4 to 5.6, after sunset wind speed settled down much faster than air temperature and vapour pressure deficit. The mean pattern of daytime water vapour pressure (e_a), as shown in Fig. 5.1, was more difficult to approximate. In an approximation, it was divided into two parts: from sunrise to 09:00 when the maximum value occurred, and from 09:00 to sunset. The first part and the second part could be approximated by linear functions of time (Fig. 5.1 and Table 5.2).

The coefficients in the fitting equations for air temperature, relative humidity and vapour pressure deficit were related to daily maximum and minimum values whereas those for vapour pressure and wind speed were related to daily maximum and mean value, respectively, since only daily maximum vapour pressure (at 09:00) and mean wind speed are routinely reported by non-automatic weather stations. A minimum (or maximum) value was needed to derive the equation for the diurnal time course 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 5.2).

Comparison of the simulated dew formation to the observed result

Dew amount

The smallest value of root mean square error (RMSE=0.038 mm) was that between DEW_{hi} and DEW_{oi}. When the estimated diurnal pattern of weather variables was used instead, the value of RMSE between DEW_{di} and DEW_{oi} became larger (Table 5.3). Among all weather variables, substituting the observed wind speed by its mean diurnal pattern gave the smallest deterioration (RMSE=0.046 mm) and wind speed and temperature combined or VPD, u and T_a combined the second smallest (RMSE=0.047 mm). Substituting nocturnal net radiation R_n by its estimate gave a much larger deterioration (RMSE=0.111 mm). The mean diurnal pattern of vapour pressure also gave a large deterioration (RMSE=0.076 mm). The mean diurnal patterns of VPD and T_a combined (equivalent to those of e_a and T_a combined) gave better estimation of dew than those of e_a and T_a combined. This might be attributed to that the mean nocturnal VPD was constantly underestimated when the observed diurnal time course of e_a was substituted by its mean diurnal pattern (Fig. 5.5).

The Wilcoxon signed rank test showed that there was no significant deterioration of the simulation results in comparison to the observed dew data when the observed hourly time course of air temperature, wind speed and VPD were replaced by their mean diurnal patterns (Table 5.3). However, the difference between the observed and the simulated result using mean diurnal courses of any other weather variable or a combination was significantly different from that between the observed and the simulated result using observed hourly data of all weather variables. These results combined with the RMSE indicate that the time courses of air temperature, vapour pressure deficit and wind speed can be replaced by their mean diurnal patterns whereas those of net radiation and vapour pressure have to be observed and cannot be replaced by their mean diurnal patterns when the objective is to estimate dew amount.

Dew duration

The smallest RMSE (=2.1 hours) between the measured results and the simulated results was that between DEW_{hi} and DEW_{oi} and between $DEW_{di}(T_a)$ and DEW_{oi}. The combination of the mean diurnal pattern of T_a and u gave the second best result (RMSE=2.2 hours) whereas substituting the observed vapour pressure or nocturnal net radiation by their diurnal patterns resulted in a larger deterioration (Table 5.3). As expected, the Wilcoxon signed rank test showed that there was no significant deterioration of the simulation results in comparison to the observed data when the observed hourly time courses of air

Table 5.3. Summary of the results of error analysis and test of significance (α=0.05)*.

Input of weather data		Dew amount RMSE (mm)	Dew amount P	Dew duration RMSE (hour)	Dew duration P
hourly data for all variables		0.038	2.1		
T_a	diurnal pattern, hourly data for others	0.064	0.10**	2.1	0.22**
u	diurnal pattern, hourly data for others	0.046	0.22**	2.4	0.37**
e_a	diurnal pattern, hourly data for others	0.076	0.01	2.8	0.01
R_n	calculated, hourly data for others	0.111	0.00	2.8	0.13**
T_a and u	diurnal pattern, hourly data for others	0.047	0.23**	2.2	0.28**
T_a and e_a	diurnal pattern, hourly data for others	0.071	0.01	2.8	0.01
VPD and T_a	diurnal pattern, hourly data for others	0.066	0.10**	2.6	0.03
e_a and u	diurnal pattern, hourly data for others	0.135	0.00	3.4	0.03
T_a, e_a and u	diurnal pattern, hourly data for others	0.076	0.01	4.0	0.07**
VPD, T_a and u	diurnal pattern, hourly data for others	0.047	0.24**	3.1	0.15**
T_a, u and R_n	diurnal pattern, hourly data for others	0.096	0.00	3.3	0.08**
e_a, u and R_n	diurnal pattern, hourly data for others	0.128	0.01	4.0	0.01
T_a, e_a and R_n	diurnal pattern, hourly data for others	0.132	0.00	3.9	0.01
VPD, T_a and R_n	diurnal pattern, hourly data for others	0.104	0.00	2.8	0.04
T_a, e_a, u and R_n	diurnal pattern, hourly data for others	0.130	0.00	4.6	0.02
VPD,T_a, u and R_n	diurnal pattern, hourly data for others	0.081	0.00	2.6	0.05

* RMSE and r are the root mean square error and correlation coefficient between the simulated results using mean diurnal pattern of weather variables and observed data; T_a is air temperature, e_a is water vapour pressure, u is wind speed, R_n is nocturnal net radiation and VPD is vapour pressure deficit;

** The difference between the simulated dew (amount and duration) using the mean diurnal pattern(s) of weather variable(s) and the observed dew (amount and duration) is not significantly different from that between the simulated dew using the observed hourly data of all weather variables and the observed dew (P>α=0.05).

temperature and wind speed were replaced by their mean diurnal patterns (Table 5.3). This was still the case for net radiation, T_a, e_a and u combined, VPD, T_a, and u combined, and T_a, e_a and R_n combined but the level of similarity (P value in Table 5.3) was lower. These results combined with the temperature and wind speed instead of their observed hourly values to estimate dew duration. For vapour pressure or vapour pressure deficit or nocturnal net radiation this cannot be recommended.

Conclusions

The mean diurnal pattern of net radiation cannot be used to estimate dew formation because of its huge relative standard error of estimate (Table 5.1), neither can that of vapour pressure probably due to its large relative standard error of estimate (Table 5.1) as well as its less precise approximation by its mean diurnal curve equation (Fig. 5.1). The mean diurnal pattern of vapour pressure deficit with a small relative standard error of estimate can be used to estimate dew amount but not dew duration. This might be attributed to the good approximation for nocturnal VPD and overestimation for VPD in early morning by its mean diurnal curve equation (Fig. 5.5). The dew amount is directly affected by the nocturnal VPD while the dew duration is affected by both nocturnal and early morning values of VPD. The VPD has to be calculated from air temperature and humidity (vapour pressure or relative humidity). At places where there is no automatic weather station, only maximum vapour pressure or minimum relative humidity are routinely reported. In this case, VPD has to be calculated from the diurnal pattern of vapour pressure or relative humidity. Therefore, air humidity has to be observed to estimate both dew amount and duration.

Based on the obtained results, it can be concluded that in order to estimate both dew amount and duration, the diurnal time courses of air temperature and wind speed may be replaced by their mean diurnal patterns whereas those of air humidity and net radiation have to be observed. Further investigation is needed to check if the results are applicable to other seasons and sites.

Chapter 6

General discussion

On rain-free and/or fog-free days, dew formation and guttation are the only natural contributors to leaf wetness. The lack of standard instruments and the required instrumentation and time for leaf wetness observation and measurement have stimulated the efforts to develop models to estimate leaf wetness. Because empirical and regression models are usually season- and site-specific, much effort in the past two decades has been devoted to the development of physical simulation models for leaf wetness estimation caused by dew. Guttation, as a physiological phenomenon, cannot be estimated by physical models. The contribution of guttation to leaf wetness is minor compared to dew in dryland crops due to the limitation of soil moisture. In paddy rice crops, where soil moisture is not limited due to the water layer beneath the crops, the contribution of guttation to total leaf wetness cannot be ignored (Chapters 2 and 3). Thus, how to measure and estimate guttation by paddy rice leaves should be included into the study of leaf wetness in paddy rice crops. In spite of the common physical base of the dew formation simulation models, simulated dew formation often deviates from measured results. This deviation could be attributed to measurement errors, both of dew and relevant weather data, but also to that the model structure deviates from reality. The experimental findings in this study are helpful in understanding these reasons.

Experimental findings on the formation of leaf wetness in paddy rice crops

The importance of guttation

Long (1955, 1958) and Hughes and Brimblecombe (1994) suggested that guttation is controlled by soil moisture and that soil temperature acts as a regulator when moisture is not limiting. Hughes and Brimblecombe (1994) found a positive effect of soil temperature at 0.1 m depth on the diameter of guttation drops on grass and a negative effect of soil moisture tension.

Experimental results in this thesis indicated an optimum paddy water temperature for rice leaf guttation of about 30°C (Chapter 3). The measurements of Hughes and Brimblecombe (1994) showed that the amount of guttation water exuded by shortgrass leaves was similar in magnitude to that of dew. Experimental results in this study confirmed that this was also the case for paddy rice leaves (Chapter 3). They showed that guttation rate by the rice leaves depended on crop development stage, i.e. guttation rate decreased from 0.026 mm per hour at tillering to 0.003 mm per hour at the dough ripe stage (Chapter 2). These results indicate that on one hand, guttation, as a contributor to leaf wetness in paddy rice crops, is of similar importance as dew, thus, cannot be ignored; on the other hand, without valid experimental separation of dew from guttation, it is not possible to reliably validate physical models for simulating dew formation in paddy rice crops since dew and guttation often occur together (during night). Therefore, guttation can be a cause of dew measurement errors. As an experimental spin-off, shielding nocturnal net radiative loss (Chapter 2) could be a feasible method to estimate the guttation rate.

The dependence of dew formation on weather conditions

It is clear from inspection of Eq. (1.1), the Penman-Monteith combination equation for latent heat loss (Monteith and Unsworth, 1990) for a wet leaf surface, that the rate of vapour condensation from air to the surface increases linearly with the surface net radiative loss and decreases with the value of vapour pressure deficit. It also decreases with wind speed because the boundary-layer resistance, r_a, decreases with increasing wind. Experimental results in the present study indeed showed that dew formation on leaf surface linearly depended on nightly total net radiative loss. The nightly *minimum* value of vapour pressure deficit instead of nightly *mean* value had to be used, and wind speed played no role at all (Chapters 2 and 4). This indicates that the nightly minimum value of vapour pressure deficit has to be carefully measured. The Penman-Monteith equation (Eq. (1.1)), implies the existence of a threshold value of nocturnal net radiative loss for dew formation if vapour pressure deficit is not zero. This is confirmed by experimental results in this thesis (Chapters 2 and 4). The threshold value of net radiative loss for dew formation was mainly dependent on the value of vapour pressure deficit rather than on wind speed (Chapter 4). Experimental results in this study did not show any dependence of dew formation and the threshold value of net radiative loss on wind speed. This can be attributed to the fact that wind speed was low (below 1 m s^{-1}) and settled down soon after sunset during the experiment. For the experiment, a descriptive multiple linear regression equation for the relationship between dew formation (amount and duration) and the nightly total net radiative loss and the nightly minimum VPD (Eq. (2.1)) gave a better estimate of dew formation at crop height than a physical simulation model, in which the Penman-Monteith equation is used (Chapter 2). Simulation analysis showed that the physical simulation model is very sensitive to the vapour pressure deficit (Scherm and Van Burgeon, 1993; Chapter 3) and to the stratification condition above the canopy (Chapter 3). Therefore, deviations of measured dew amounts from the simulated ones can often be caused by measurement errors of air humidity and by the lack of information on the stratification condition above the canopy. Comparison between the simulated dew under different assumed stratification conditions and the measured results revealed that the smallest simulation deviation occurred when a neutral stratification condition was assumed (Chapter 3). Van Zyl and De Jager (1987) also showed that estimates of maximum evapotranspiration for wheat, obtained from the Penman-Monteith equation, was not improved by adjusting them for atmospheric stability. This indicates that without knowledge about the stratification condition above a canopy, assuming a neutral condition may be reasonable for estimating the dew formation in the canopy.

The importance of night dew duration

Daily dew duration includes night dew duration and dew duration after sunrise. Huber and Gillespie (1992) have indicated that in the tropics the wetness period ends each morning at approximately the same time irrespective of when rainfall occurred during the previous afternoon. Experimental results in this study showed that this was also the case for dew duration (Chapters 2 and 4). The contribution of night dew duration to daily dew duration was much larger than that of dew duration after sunrise (Chapter 2). The moment of dew onset (or night dew duration) had a slight effect (10%) on the dew duration after sunrise (Eq. (4.5), Chapter 4). Daily leaf wetness (or dew) duration is therefore linearly related to wetness start time (or dew onset) in the tropics if the wet period, once started, is not interrupted by a dry period until sunrise. Hence, it is important to accurately estimate night dew duration for an accurate estimation of daily dew duration.

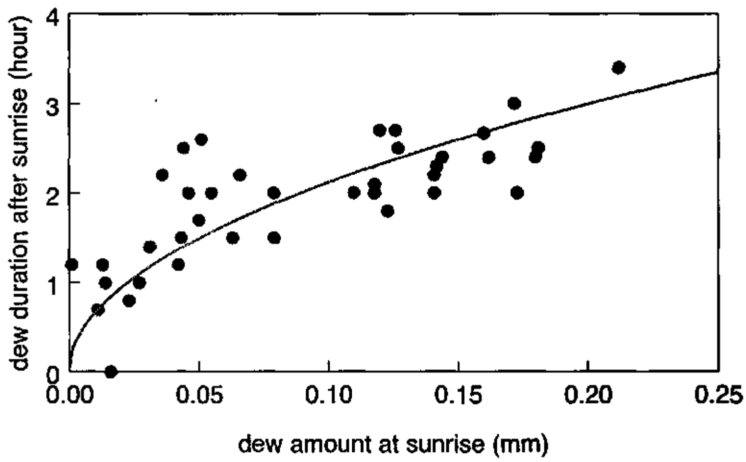


Fig. 6.1. Relation between dew duration (hour) after sunrise and dew amount (mm) collected at sunrise at crop height (H) in tropical paddy rice crops. The symbols are measured data at crop height during both the shielding and the warm water flooding experiments (Chapters 2 and 3). The solid line is the regression relationship (see Eq. (6.1), df=37, $P<0.05$, $r^2=0.71$, SE=0.49 hour).

The relation between dew duration after sunrise and daily dew amount

Dew duration after sunrise (DEWT(after sunrise), hour) was found to be dependent on the dew amount collected at sunrise (DEW, mm) on the top leaf surface according to experimental results in this study (Fig. 6.1):

$$\mathrm{DEWT(after\ sunrise)} = 6.7(\mathrm{DEW})^{0.5} \tag{6.1}$$

where 6.7 and 0.5 are regression coefficients. They are expected to change with weather type and latitude. The higher the latitude or the more cloudy the weather after sunrise, the closer Eq. (6.1) will be to a linear relationship. In temperate areas, dew duration after sunrise will give more contribution to daily dew duration than in tropics.

The dewball: a simple instrument to estimate daily dew duration

According to observations in this study, dew occurred on top leaves of the rice crops at the same moment that dew reached the 60° zenith angle on the dewball. This finding, combined with the linear relationship between the threshold value of nocturnal net radiative loss and the vapour pressure deficit (Eq. (4.4)) and the relation between the daily dew duration on top leaf surface and the moment of dew onset (Eq. (4.5)) based on the observations of dew formation on the dewball (Chapter 4), suggests a simple method to estimate daily dew duration on top leaves of the rice crops. The procedures using this simple method can be summarized as follows if hourly data of nocturnal net radiation, air temperature and humidity are available:

1) Calculate the values of nocturnal net radiative loss at zenith angle 60° ($R_n(60)$) according to Eq. (4.1);
2) Calculate the threshold value of nocturnal net radiative loss for dew formation ($R_{n,thresh}$) according to Eq. (4.4);
3) Determine the moment of dew onset and night dew duration on top leaves and draw the curves of $R_n(60)$ and $R_{n,thresh}$ in the same time course graph. Dew onset occurs when the time course of $R_n(60)$ first crosses that of $R_{n,thresh}$. The night dew duration is the period between the moment of dew onset and sunrise;
4) Calculate daily dew duration: daily dew duration can either be directly calculated using Eq. (4.5) or indirectly using the combination of Eqs. (2.1) and (6.1), i.e. calculate the daily dew amount (the amount at sunrise) according to Eq. (2.1) (Chapter 2) and use this value to calculate the dew duration after sunrise according to Eq. (6.1). Daily dew duration is the sum of the night dew duration obtained in step 3) and the dew duration after sunrise.

It should be noted that this method assumes that dew, once starts, is not interrupted by a dry period until sunrise, i.e. it gives a maximum estimate of night dew duration and daily dew duration for top leaves. For the general condition where the dew period may be interrupted by dry periods during a night, the energy balance approach would be more reliable for estimating daily dew duration. For estimating dew formation inside a paddy rice crop, a physical multilayer model has to be used.

Requirements for dew formation estimation using an energy balance approach

Since empirical multiple regression models (e.g. Crowe et al., 1978) are season- and site-specific, many physical leaf wetness models using an energy balance approach have been developed in the past two decades (Goudriaan, 1977; Monteith and Butler, 1979; Butler, 1980; Thompson, 1981; Pedro and Gillespie, 1982a,b). Despite much effort and the common physical base of the energy balance approaches, no existing simulation model can be applied without test or calibration due to the parameterization and the complication of the processes involved in the simulation model. This is why at a specific site, a simple regression relationship between dew formation and some key weather factors (such as Eqs. (2.1) and (4.5)) gives a better estimate of dew formation at top leaves than a physical model. The key weather factors, however, can only be found when the energy balance of the leaves or crops is fully understood. Dew formation estimation should be improved by calibration of the parameters used in a physical model. To do this kind of calibration, the requirements for dew formation estimation using an energy balance approach have to be inspected.

To run a physical dew formation simulation model, hourly weather data (net radiation, air temperature, air humidity and wind speed), leaf temperature and boundary-layer resistance for heat and vapour between the leaf and the surrounded air are needed. The boundary-layer resistance can be derived through the wind speed at the leaf surface and the characteristic leaf dimension. The leaf temperature can be either eliminated from the Penman-Monteith combination equations by assuming that the saturation vapour pressure is a linear function of temperature or found by iteration within a computer program (Monteith and Unsworth, 1990). The wind speed at the leaf surface can be estimated through its standard profile with or without an adjustment for atmospheric stability when observation of wind speed profile is absent (Goudriaan, 1977; Monteith and Unsworth, 1990). Some models use the standard logarithmic profile of wind speed with atmospheric stability adjustment (Goudriaan, 1977) while others use the power law without atmospheric stability adjustment (Pedro and Gillespie, 1982b). The present study showed that assuming a neutral stratification condition gave a reasonable estimate of dew formation in paddy rice crops (Chapter 3). For the conditions where hourly weather data are not available, this thesis has shown that it is possible to use the estimated mean diurnal patterns of air temperature and wind speed but not of air humidity and net radiation to estimate dew formation in dry season of the wet tropics (Chapter 5). This may be attributed to the fact that the dew formation simulation model is very sensitive to air humidity and net radiation (Scherm and Van Burgeon, 1993) but not to air temperature (Monteith and Unsworth, 1990). According to Scherm and Van Burgeon (1993), the model is also sensitive to wind speed. The wind speed during the experimental dew nights however, settled down to a low value (less than 1 m s^{-1}) soon after sunset. In this case, wind speed has little effect on dew formation.

Potential applications of the simple method for dew formation estimation to plant protection

Plant disease is a combined function of a virulent pathogen, a susceptible host, and a favourable environment (weather), the so-called 'disease triangle' (Johnson, 1989). Among the weather factors, particularly the duration of wetness, stands out as dominant (Jones, 1986). Quantifying leaf wetness duration is essential for all rice blast epidemic forecasting models and systems (Uehara et al., 1988; Manibhushanrao and Krishan, 1991; Kim and Kim, 1991; Horino, 1992). Examples and detailed literature review of using leaf wetness in other crop or fruit disease forecasting models and systems were given by Jones (1986) and Huber and Gillespie (1992). Measuring or simulating leaf wetness is difficult due to extreme spatial variability over very short distances in a crop as well as over large distances at regional scale (Huber and Gillespie, 1992). Measurements or simulations of dew duration at top leaves, however, are relatively reliable. Therefore, dew duration at top leaves can be used as a reference for leaf wetness in plant disease forecasting and the simple method for estimating daily dew duration at top leaves presented in this thesis may be useful for this purpose. The simple method can provide a data set of maximum daily dew duration on top leaves for plant disease epidemic forecasting models or systems. By calibrating the coefficients in the equations for different areas, the simple method can also provide a data set for mapping the leaf wetness caused by dew, which is useful as a tool for geophytopathology (Weltzien, 1983).

Future research needs

Experimental work and simulation analysis reported in this thesis have laid the groundwork for further studies on measurement and estimation of leaf wetness in paddy rice crops in the following aspects:

Guttation measurement and estimation

The dependence of guttation rate on crop development stage was shown in Chapters 2 and 3. Because the amount of guttation cannot be directly measured since no existing wetness sensor can distinguish guttation from dew, an indirect way to estimate the guttation rate has to be figured out. Although shielding nocturnal net radiative loss is a feasible method to measure and estimate guttation (Chapter 2), further research is still needed to explore a simple but reliable method for estimating guttation.

Estimation of the contribution of guttation to leaf wetness

The importance of guttation in leaf wetness of paddy rice crops was shown in Chapter 3. Further research has to be done to find out how to include it into the estimation of total leaf wetness duration. Guttation started around sunset and continued throughout the night in the tropics according to the observations in this study. If the wetness duration caused by guttation is also divided into night duration and the duration after sunrise, the night duration will be the night length and the duration after sunrise can be estimated in the same way as dew duration after sunrise (Eq. (6.1)) by the nightly amount of guttation. Guttation, however, affects leaf wetness inside the canopy much more than at the top since it occurs at the edge of leaves. Therefore, the wet period after sunrise inside canopy caused by guttation should be observed and also estimated using a physical multilayer model.

Extend the simple method for estimating the daily dew duration on top leaves

Before applying the simple method to other crops and sites, more experiments have to be conducted for several calibrations. First, it is needed to identify the zenith angle (60° for tropical paddy rice) on the dewball where dew occurred at the same moment as on top leaves. This angle may be different in other crops and areas. Secondly, the dependence of the threshold nocturnal net radiative loss on wind speed has to be specified. It is expected that the higher the wind speed, the larger the coefficient (57.9) in Eq. (4.4) (Chapter 4). A table or a graph of its dependence on wind speed can be made based on more observations in other crops and areas. Thirdly, the coefficients in the other equations involved in the simple method (Eqs. (2.1), (4.5) and (6.1)) may also be different from crops and areas, and thus, have to be calibrated.

Undoubtedly, more topics can be found that are needed to explain and understand the leaf wetness problem. The formation and disappearance of leaf wetness is a complicated process which cannot be solved by a simple major scientific breakthrough. Rather, several small steps will lead to a gradual improvement in our understanding and predictive ability. The experimental findings and simulation analysis in this study give insights in the process of the formation of leaf wetness in paddy rice crops. Understanding this process is essential for an accurate estimation of leaf wetness in paddy rice crops. This study not only shows that guttation, as a contributor to leaf wetness, is of similar importance as dew, and, therefore, cannot be ignored in paddy rice crops (Chapters 2 and 3), but it also provides a solution for guttation measurement and estimation (Chapter 2). The effort to find a simple method for estimating daily dew duration on top leaves resulted in the dewball (Chapter 4) and in using the results of the shielding experiment (Chapter 2). The simplicity and the physical base of these simple methods for estimating daily dew duration indicate their potential application in plant disease epidemiology and geophytopathology.

Summary

Leaf wetness is a crucial environmental parameter in most plant disease epidemic forecasting models and systems. On rain-free and/or fog-free days, dew formation and guttation are the only natural contributors to leaf wetness. In dryland crops where guttation is limited due to the limitation of soil moisture, dew is the main cause of leaf wetness. The present study focuses on understanding the formation of leaf wetness in paddy rice crops. Soil moisture there is not limited because of the water layer beneath the crops, so the contribution of guttation to leaf wetness may not be ignored (Chapters 2 and 3). The objective of this study was to explore a simple and accurate method for the estimation of dew formation, based on insight in the formation process of leaf wetness in paddy rice crops.

Dew formation in crops is a result of radiative loss from the crop surface and transfer of water vapour from the warmer air to the cooler surface. The water vapour condensed onto the crop surface may come from the atmosphere or from the soil (or water in the paddies). A shielding experiment was designed to investigate the dependence of dew formation on nocturnal net radiative loss (Chapter 2). The latent heat released by dew formation was about half of the nightly total net radiative loss. The experimental data showed the existence of a threshold nocturnal net radiative loss for dew formation. Above this threshold level, both amount and duration of dew were linearly correlated with the nightly total net radiative loss. These correlation were further improved by including the nightly minimum (not the mean value) of vapour pressure deficit into the regressions. The improved equations provide a simple method to directly estimate the dew formation at top leaves using the data of nightly total net radiative loss and minimum vapour pressure deficit. Moreover, the shielding experiment unexpectedly provided a feasible method for experimentally distinguishing dew from guttation.

Guttation is a physiological phenomenon that is regulated by soil (or water in paddy rice crops) temperature provided soil moisture is not limiting. For a better understanding of the characteristics of the formation of leaf wetness in paddy rice crops, warm water flooding experiments were conducted both in the paddy rice field and in a phytotron to investigate the effect of water temperature on dew formation and guttation (Chapter 3). The experimental data indicated an optimum paddy water temperature for rice leaf guttation of about 30°C. During both the shielding and the warm water flooding experiments, it was found that

guttation by the rice plants supplied as much water to the rice leaf surface as dewfall did (Chapters 2 and 3). Simulation analysis showed that the dependence of dew formation on paddy water temperature will be affected by weather conditions above the rice canopy, especially the thermal stratification condition, vapour pressure deficit and net radiative loss (Chapter 3). For any weather condition, dew amount in the rice crops will increase with paddy water temperature. However, when the water temperature is high enough to generate an unstable stratification condition even above the canopy, the effect of water temperature on dew formation will almost disappear. Lack of information about the stratification condition above the canopy may cause an estimation error about the dew formation. Comparison between the observed and simulated dew amount at crop height, however, indicated that without information about the stratification condition above a canopy, assuming a neutral condition may give a reasonable estimate of dew formation. Nocturnal net radiative loss, as a driving force, significantly affects dew formation under all stratification conditions, especially under unstable and neutral conditions. Under unstable and neutral stratification conditions, dew formation is also highly sensitive to vapour pressure deficit, i.e. the measurement of air humidity must be very accurate for a proper dew formation estimation.

Due to the lack of standard instruments and the demand of manpower and instrumentation for dew formation observation and measurement in crops, there is a great need for alternative good methods to estimate dew formation. A simple device, the dewball, was designed to observe dew formation and to determine the threshold value of nocturnal net radiative loss for dew formation on top leaves (Chapter 4). This was shown to be a simple and accurate estimation method. This threshold ($R_{nt,thresh}$) was determined based on the maximum zenith angle reached by dew formation on the dewball surface during a night. The $R_{nt,thresh}$ was found to be linearly related to the nightly minimum vapour pressure deficit. During the experimental period, it was found that dew often occurred on the top leaves almost at the same moment that dew reached the zenith angle of 60° on the dewball. These experimental findings laid the groundwork for developing a simple method of estimating daily dew duration on top leaves of rice crops (Chapters 4 and 6).

When dew formation cannot be measured, it must be estimated. Existing dew formation simulation models need hourly weather data as input. However, hourly weather data are not available at places where there is no automatic weather station. In this case, standard diurnal patterns of weather variables might be used to run the simulation model. To investigate this possibility, the mean diurnal patterns of weather variables were derived based on the hourly weather data collected at the experimental site. Then the possibility of using the mean diurnal patterns of weather variables to estimate dew formation was analyzed by comparing the simulated dew to the measured results (Chapter 5). The results of this study showed that it is possible to use the mean diurnal pattern of air temperature and windspeed but not air humidity and nocturnal net radiation. The latter two variables always have to be measured at least hourly to estimate dew formation.

Based on the results of Chapters 2 and 4, a simple approach to estimate daily dew duration on top leaves of the paddy rice crops was formulated and its potential applications to plant protection were discussed (Chapter 6).

Samenvatting

Bladnat is een essentiële omgevingsparameter voor de meeste modellen en systemen voor de prognose van plantenziekte epidemieën. Op dagen zonder regen of mist zijn dauwvorming en guttatie de enige natuurlijke bronnen van bladnat. Bij gewassen in droge gebieden waar guttatie beperkt wordt door een laag bodemvochtgehalte is dauw de voornaamste oorzaak van bladnat. De voorliggende studie is gericht op het begrijpen van de vorming van bladnat bij paddy rijst. Daar is geen beperking van bodemvocht wegens de aanwezigheid van de waterlaag onder het gewas, zodat de bijdrage van guttatie aan bladnat niet veronachtzaamd mag worden (Hoofdstukken 2 en 3). De doelstelling van deze studie was een eenvoudige en nauwkeurige methode te vinden voor de schatting van dauwvorming, gebaseerd op inzicht in het vormingsproces van bladnat bij paddy rijst.

Dauwvorming bij gewassen is een gevolg van stralingsverlies vanaf het gewasoppervlak en overdracht van waterdamp vanuit de warme lucht naar het koele oppervlak. De waterdamp die op het gewasoppervlak is gecondenseerd kan zowel van de atmosfeer als van de bodem (of het water in de rijstvelden) afkomstig zijn. Een overkappingsproef werd opgezet om na te gaan hoe dauwvorming van het nachtelijke netto stralingsverlies afhangt (Hoofdstuk 2). De latente warmte die bij dauwvorming vrij komt bleek ongeveer de helft van het nachtelijke stralingsverlies te bedragen. De experimentele gegevens toonden aan dat er voor dauwvorming een drempelwaarde is aan het nachtelijke stralingsverlies. Boven deze drempelwaarde waren zowel de hoeveelheid als de tijdsduur van dauw lineair gecorreleerd aan het totale nachtelijke netto stralingsverlies. Deze correlatie werd nog verbeterd door het nachtelijke minimum (niet de gemiddelde waarde) van het dampdrukdeficit in de regressie te betrekken. De verbeterde vergelijkingen verschaffen een eenvoudige methode om direkt de dauwvorming op de bovenste bladeren te schatten, uitgaande van het totale nachtelijke stralingsverlies en de minimumwaarde van het dampdrukdeficit. Bovendien gaf het overkappingsexperiment onverwacht een werkbare methode om experimenteel dauw van guttatie te onderscheiden.

Guttatie is een fysiologisch verschijnsel dat gereguleerd wordt door de temperatuur van de bodem (of van water bij paddy rijst) mits bodemvocht niet limiterend is. Voor een beter begrip van de karakteristieken van bladnat bij paddy rijst werden bevloeiingsproeven met warm water uitgevoerd, zowel in het veld als in het fytotron, ten einde het effekt van watertemperatuur op dauwvorming en guttatie te bestuderen (Hoofdstuk 3). De experimentele gegevens gaven aan dat bij rijst de optimale watertemperatuur voor guttatie op ca 30 °C ligt. Zowel bij het overkappingsexperiment als bij het warmwater bevloeiingsexperiment werd gevonden dat guttatie door de rijstplanten net zoveel water naar het bladoppervlak bracht als dauwvorming (Hoofdstukken 2 en 3). Een simulatieanalyse gaf aan dat de afhankelijkheid van dauwvorming van watertemperatuur beïnvloed werd door de weersomstandigheden boven het rijstgewas, in het bijzonder door de thermische stratificatie, het dampdrukdeficit en het netto stralingsverlies (Hoofdstuk 3). Ongeacht de weersomstandigheden zal de hoeveelheid dauw in de rijstgewassen toenemen met de paddy watertemperatuur. Echter, zodra de watertemperatuur hoog genoeg is om een onstabiele stratificatie te veroorzaken, zelfs boven het gewas, zal het effekt van watertemperatuur op de dauwvorming vrijwel geheel verdwijnen. Gebrek aan informatie over de stratificatietoestand boven het gewas kan een schattingsfout veroorzaken betreffende de dauwvorming. Vergelijking tussen de waargenomen en gesimuleerde hoeveelheid dauw op gewashoogte toonde echter aan dat zonder informatie over de stratificatietoestand boven het gewas, toch een redelijke schatting van de dauwvorming verkregen kan worden door een neutrale stratificatie aan te nemen. De nachtelijke netto straling als drijvende kracht beïnvloedt de dauwvorming aanzienlijk, ongeacht de stratificatie, maar vooral bij onstabiele en neutrale omstandigheden. Bij onstabiele en neutrale omstandigheden is de dauwvorming ook erg gevoelig voor het dampdrukdeficit. Voor een goede schatting van de dauwvorming moet de luchtvochtigheid daarom heel nauwkeurig worden gemeten.

Wegens gebrek aan standaardinstrumenten, en ook wegens het grote beslag op manuren en instrumentatie voor waarneming van dauw in gewassen, is er een grote behoefte aan alternatieve methodes om dauwvorming te schatten. Een eenvoudig apparaat, de dauwbol, werd ontworpen om dauwvorming waar te nemen en om de drempelwaarde van het nachtelijke stralingsverlies te bepalen voor dauwvorming op de bovenste bladeren te bepalen. Dit bleek een eenvoudige en nauwkeurige schattingsmethode te zijn (Hoofdstuk 4). De drempelwaarde ($R_{nt,thresh}$) werd berekend uitgaande van de maximum zenith-hoek die de dauwvorming gedurende de nacht bereikte op het oppervlak van de dauwbol. Gevonden werd dat de $R_{nt,thresh}$ lineair samenhing met de laagste waarde van het dampdrukdeficit gedurende de nacht. Gedurende de experimentele periode werd ook gevonden dat dauwvorming op de bovenste bladeren vaak op het zelfde moment begon als wanneer de dauw een zenith-hoek van 60 graden bereikte op de dauwbol. Deze experimentele resultaten vormden de basis voor de ontwikkeling van een eenvoudige methode om de dagelijkse dauwduur te schatten voor de bovenste bladeren van rijst (Hoofdstukken 4 en 6).

Wanneer dauwvorming niet gemeten kan worden, moet het worden geschat. Bestaande dauwvormingsmodellen gebruiken uurlijkse weersgegevens als input. Echter, uurlijkse weersgegevens zijn niet beschikbaar op plaatsen waar geen automatisch weerstation is. In dat geval zouden standaard dagelijkse patronen van het tijdsverloop van de weersgrootheden wellicht gebruikt kunnen worden om het simulatiemodel te voeden. Om deze mogelijkheid te onderzoeken zijn de gemiddelde dagelijkse weerspatronen bepaald, uitgaande van uurlijkse waarnemingen op de proeflokatie. Vervolgens is de mogelijkheid om de gemiddelde dagelijkse weerspatronen te gebruiken voor de schatting van dauwvorming nagegaan door de gesimuleerde hoeveelheid dauw te vergelijken met de gemeten hoeveelheden (Hoofdstuk 5). De resultaten van deze studie toonden aan dat het mogelijk is om de gemiddelde weerspatronen van luchttemperatuur en windsnelheid te gebruiken in plaats van de uurlijkse waarnemingen, maar niet die van luchtvochtigheid en van nachtelijke nettostraling. Deze twee grootheden moeten tenminste uurlijks worden gemeten om dauwvorming te kunnen schatten.

Op basis van de resultaten van de Hoofdstukken 2 en 4 is een eenvoudige benadering uitgewerkt om dagelijkse duur van de dauw te schatten voor de bovenste bladeren van paddy rijst, en zijn de mogelijke toepassingen ervan bij de gewasbescherming besproken (Hoofdstuk 6).

小结

叶片表面液态水(持续时间)是大多数植病流行预测模型或系统所需的关键环境参数.在无雨无雾的天气里,叶片表面液态水的自然来源是露和吐水.在旱地作物中,因土壤水分有限,吐水受到限制,露是叶片表面液态水的主要来源.本研究着眼于灌溉水稻叶片表面上液态水的形成.由于水层的存在,稻田土壤水分不受限制,所以吐水的贡献不能忽视(第2,3章).本研究的目的是在了解叶片表面液态水形成机理的基础上,探索简便而精确的估计露形成的方法.

作物表面上露的形成是表面辐射冷却至空气露点温度以下的结果.凝结在作物表面上的水汽来自于大气或土壤(或水稻田中的水层).因此,本研究设计了一覆盖试验以确定夜间作物表面净辐射对露形成的直接影响(第2章).结果表明,形成于灌溉水稻叶片上的露量所释放的潜热相当于作物表面夜间净辐射总量的一半.观测结果还表明,对露在作物表面的形成,存在着一个临界夜间净辐射值.当夜间净辐射总量超过这一临界值时,作物表面的露量和露持续时间与夜间净辐射总量成线性关系.若在这些线性关系中加入夜间饱和水汽差的最小值(而不是平均值),这种多元线性回归关系则可以更精确地估计露量和露持续时间.此外还发现,覆盖也是一种行之有效的区分露和吐水的试验手段.

吐水是一种生理现象.当土壤水分不受限制时,植物吐水受土温(在稻田里则是水温)的调节.本研究在田间及人工气候室内进行了热水灌溉试验(第3章),以便更好地了解灌溉稻叶片上液态水形成的特点.结果表明,吐水的最佳水温是30°C.在覆盖及热水灌溉两试验中都发现,吐水对灌溉水稻叶片表面液态水的贡献与露的贡献一样大(第2,3章).模拟分析结果表明,水温对露形成的影响依水稻冠层上方的气象条件,特别是层结条件,饱和水汽压差及夜间净辐射不同而异(第3章).在任何气象条件下,灌溉稻冠层中的成露量都随水温升高而增加.但当水温高至足以使冠层上方空气层结变为不稳定时,水温对成露的影响就不复存在.因此,缺乏空气层结观测资料将

会导致露量和露持续时间估计上的误差.但在比较冠层顶部露量的实测结果与模拟结果时发现,在无层结资料时,假设层结为中性可得到较为合理的露量估计值.作为驱动变量,夜间作物表面净辐射在任何层结条件,特别是在不稳定和中性条件下,对成露都有显著影响.在不稳定及中性层结条件下,露的形成对饱和水汽压差高度敏感.因此,为得到合理的露量估计值,空气湿度的观测必需很精确.由于露的观测缺乏标准仪器且需要大量的人力物力,因而很需要有好的方法来估计露量和露持续时间.为此,本研究设计了一种简便装置,即露球,来观测露的形成及确定水稻冠层顶部成露所需的夜间净辐射临界值(第4章).结果表明这是一种简单而又精确的估计成露的好方法.根据夜间露在露球上所能达到的最大天顶距角可以确定成露所需的夜间净辐射临界值.试验结果表明,这一临界值与夜间最小饱和水汽压差成线性相关.试验还发现,露出现在叶片上的起始时间与其出现在露球上60度天顶距角的相同.这一试验研究中的新发现为探索水稻冠层顶部露持续时间的简便估计方法奠定了基础(第4,6章).

在缺乏露的观测资料或观测很难时,就要对其进行估计.现有的露模拟模型都需要每小时的气象观测资料(作为输入).但在没有自动气象站的地区,则缺乏每小时的气象观测资料.在这种情况下,每小时的气象要素值也许可以用气象要素的标准日变化曲线来估计.为了解用标准日变化曲线代替每小时实测值是否能得到同样好的模拟结果,本研究首先根据试验点每小时实测的气象资料确定出各要素的平均日变化曲线.然后分别用日变化曲线和每小时实测气象资料运行模型,并将模型估计出的露量和露持续时间与实测结果进行比较分析(第5章).结果表明,可用气温和风速的平均日变化曲线代替其每小时实测值运行模型,而不能用空气湿度和夜间净辐射.因此,为了精确估计露的形成,必需对空气湿度和净辐射两要素进行至少每小时一次的观测.

最后,在第2和4两章的基础上,提出了一种估计灌溉水稻冠层顶部叶片表面每日露持续时间的简便方法,并就本试验研究的新发现及提出的这一简便方法在植物保护方面的应用进行了讨论.

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