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Validation of Goudriaan's model: A case study for maize

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Abstract

The crop micro-weather model of Goudriaan was tested, using data collected in a maize field during one day. The simulated results are described and validated with actual field measurements, which were carried out, over the maize crop canopy, during the middle of the summer of 1986. Except for the soil heat flux, latent and sensible heat fluxes are simulated reasonably well. The model of Goudriaan overestimates the latent and sensible heat fluxes above the crop canopy by 9 and 10%, respectively, in comparison to the latent and sensible heat fluxes measured with the eddy correlation technique. The simulated fluxes can still be improved upon by a better incorporation of the effect of dewfall in the model. The canopy and soil temperatures were also estimated and described in relation to the observed data from the field. Root mean square error of the simulated soil temperatures at 1, 5, 10 and 20 cm depth were found between 0.30 K and 0.68 K. Further, sensitivity analysis of the model showed that the heat fluxes are more sensitive to soil than to crop parameters, for the same magnitude of variations. Among soil parameters, the soil surface resistance to evaporation has large influence on the latent heat and the sensible heat fluxes at soil surface; in addition it also has influence on the soil heat flux. The soil water stress has high influence on the daily net CO_2 assimilation as well as the latent and the sensible heat fluxes above the crop canopy.

Keywords: Micro-meteorological model, validation, sensitivity analysis, heat fluxes, soil parameters, maize canopy

Introduction

Various biological and physical crop models have been developed in the past two decades to predict the heat and mass exchange between the plants and the atmosphere under a certain set of conditions. However, there is still a gap between the modelling results and the observed behaviour of the canopy system to their natural environment. Perhaps, these discrepancies are mainly due to a lack of true mathematical relationships, describing the interaction, between the vegetation and surrounding environment. These simulation models draw our attention to the areas where there is a lack of knowledge and where scientific efforts should be made in future.

Crop canopies generate the heat and water vapour fluxes which influence the surrounding atmospheric conditions, but subsequently they also respond to these conditions. Simulation of crop micro-meteorology is an important tool to study the net result of these feedback mechanisms. Modelling of the crop canopy is done by many researchers in the past (Monteith, 1973; Shawcroft *et al.*, 1974; Waggoner, 1975; Norman, 1979). The clarity and usefulness of simulation models is sometimes improved by replacing the numerical solution of the various processes by more analytical approaches (de Wit & Penning de Vries, 1985). A good example of this is the development of multilayer micro-meteorological simulation programmes, originally formulated by Goudriaan (1977). In general, Goudriaan's model retain much of the scientific base, quality of the original, simplicity and much easier to use by those who did not develop them. These reasons could influence us to select this model for this study. In his simulation the exchange coefficient was calculated as the product of wind velocity and some mixing length hypothesis. The relative vertical turbulence intensity was assumed unity which is questionable specially near the top of the vegetation. Stigter *et al.* (1977) indicated the possibility of reducing the deviations between measurement and simulated profiles of air temperature and humidity after using the reduced value of relative vertical turbulence intensity inside the canopy. Hiramatsu *et al.* (1984) simulated the micro-meteorology of unstressed rice crop, grown in the saturated soil conditions, using the Goudriaan's model. But, they used some interpolated and smoothed input weather data to drive the model. They slightly changed the stability correction function to get better model results during night hours. Above study was mainly confined to the air temperature, water vapour, CO_2 flux and eddy diffusivity profiles within the rice crop canopy in relation to variation in the crop characteristics. However, the Goudriaan's model still remains to be tested for the different types of soil and crop canopy in various climates. With this aim, in the present paper, we have tested the model performance giving more emphasis on possible variation in the soil physical properties and its influence on the heat fluxes above and at bottom of the maize crop canopy.

Brief description of the model

The model developed by Goudriaan (1977) predicts the micro-weather as a function of the properties of plant, soil and of the weather conditions at fixed height above the canopy.

Feedback of plants or soil on their environment is included, for instance by shading, by the release of water vapour through transpiration and by the reduction of the wind velocity. The plant's own properties play a role in this feedback. They are considered as given parameters, though in fact they may have been partly influenced by the past meteorological conditions. Short term effects, such as plant water stress caused by increased transpiration, are incorporated in this model. In Goudriaan's model, not only micro-meteorological factors, that are directly important for the crop growth and development, are treated, but also those that play an important role in the development and spread of pests and diseases. An example is the leaf wetness duration.

The model consists of various complex submodels like that of radiation within crops (De Wit, 1965; Ross, 1975), energy and mass balance at the leaves and at the soil surface, photosynthesis, and wind and turbulence above, as well as inside, the crop canopy (Figure 1). The wind profile within the canopy was modelled as a simple exponential extinction with cumulative leaf area. The value of the extinction coefficient was based on simple first-order K theory. The parameter values that are needed in the submodels were almost exclusively taken from the available literature. But the structures of the submodels were specially developed in view of their compatibility and of an optimal balance between accuracy and simplicity.

In the energy and mass balances of the canopy, the partitioning of the absorbed radiant energy (R) into sensible heat (H), latent heat (LE) and photosynthesis (P) is calculated using the combination of following energy balance equations (Penman, 1948; Monteith, 1973).

$$R - P - H - LE = 0 \tag{1}$$

$$H = \frac{(T_l - T_a)\rho c_p}{r_{b,h}} \tag{2}$$

$$LE = \frac{(e_s(T_l) - e_a)\rho c_p}{\gamma(r_{l,v} + r_{b,v})} \tag{3}$$

$$e_s(T_l) = e_s(T_a) + s(T_l - T_a) \tag{4}$$

Where T_l and T_a are leaf and air temperatures, respectively. ρc_p is the volumetric heat capacity of the air. e_s is the saturated vapour pressure at air temperature and e_a is the actual vapour pressure. s is the slope of the saturated vapour pressure curve at air temperature and γ is psychrometric constant. $r_{b,h}$ and $r_{b,v}$ are boundary layer resistances to heat and water vapour, respectively. $r_{l,v}$ is leaf resistance to water vapour. Resistances for these fluxes are computed from the wind profile and given relationships for stomatal resistance. The profiles of temperature and vapour pressure are found by integration of the net fluxes over time for different canopy and soil layers. The plant water content, which feeds back on the stomatal resistance, is found by integration of calculated transpiration and water uptake from the soil. The partitioning of the available radiant energy at soil surface into sensible heat, latent heat and soil heat flux (G) is also computed. For a complete description and more detailed information about the model, the reader is referred to Goudriaan's monograph (1977).

Materials and methods

The experimental site was the "Sinderhoeve" near Wageningen (51° 59'N, 5°45'E) in the central part of The Netherlands. A one day detailed above and within canopy measurement programme was performed in a maize field on July 30, 1986. On the

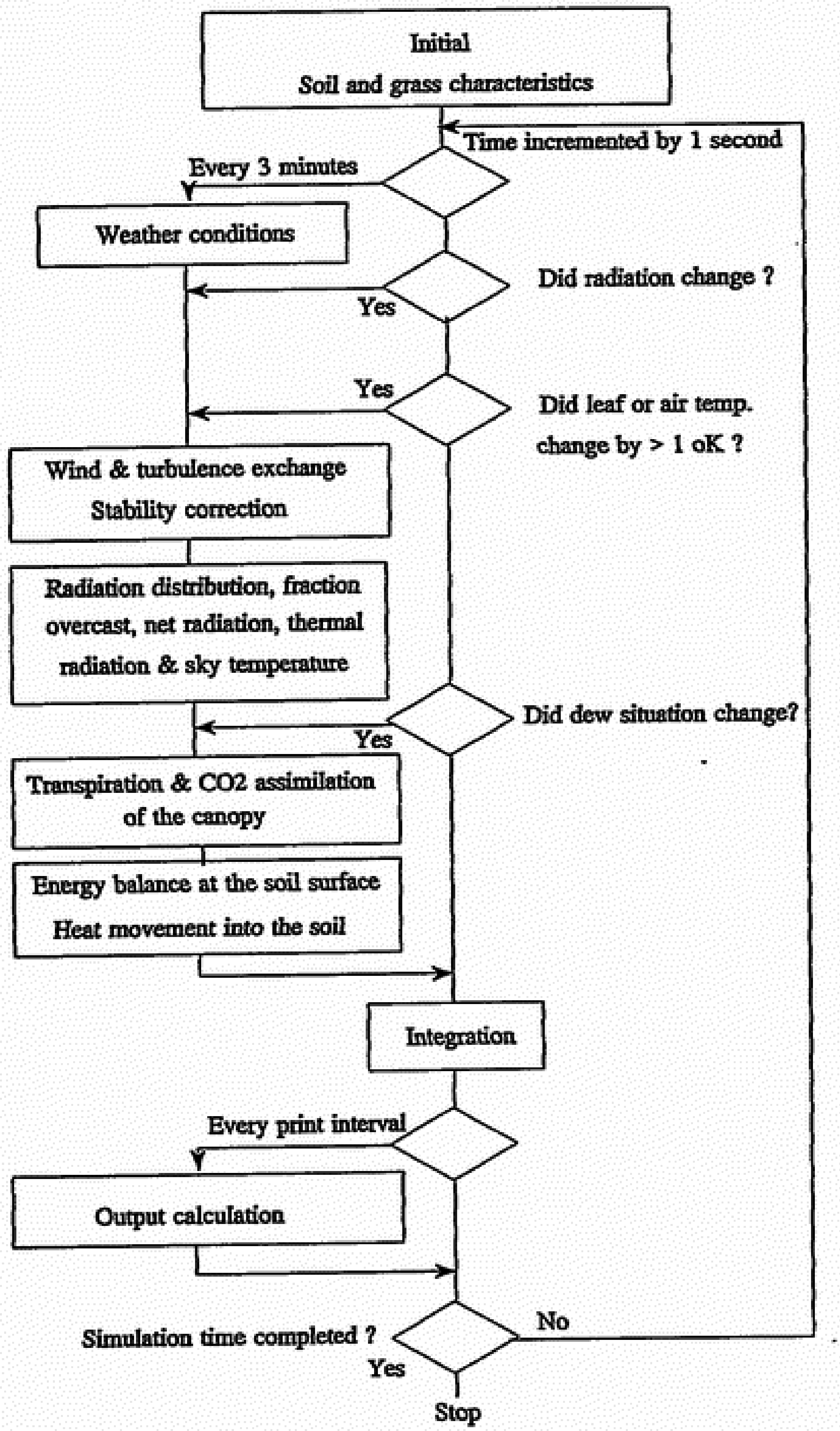

Figure 1. A diagram describing the different submodels used in micro-meteorological simulation model (after Goudriaan, 1977).

observation day the crop was at the end of its vegetative stage. The number of plants was 11 to 12 per square metre with a maximum leaf area index of 3.85 m^2m^{-2}. The crop experienced water stress during its vegetative stage (Jacobs & van Pul, 1990).

Two sets of meteorological data were collected: an 'input' set to run the model, and another to compare the model results. All time dependent data are averaged half hourly, i.e. the 12.25 hour value is actually the mean for the period 12.00-12.50 GMT. The following half hourly meteorological data were measured to run the model: (i) wind speed (ms^{-1}), vapour pressure (mbar), and air temperature (°C) at 2.75 m (reference level) above the soil surface and (ii) global and net radiation (Wm^{-2}) above the crop canopy. In another set, fluxes of sensible and latent heat above the canopy were measured by the eddy correlation technique to test the model results. Profiles of canopy and soil temperatures were also measured for comparison of results. The data were collected under a cooperative research project on crop evapotranspiration (Jacobs & Van Boxel, 1988; Jacobs & Van Pul, 1990).

The soil of the experimental site consisted of sand; a humic top soil had developed as a result of the addition of farmyard manure (Halbersma and Przybyla, 1986). The soil fraction smaller than 2 µm (clay) was 4% and the fraction larger than 50 µm (sand) was 78%. The volumetric heat capacity and thermal conductivity of the soil were taken from values derived by De Vries (1975). The soil water stress (–6.0 bar) was given as per measured soil moisture content in the soil profile. The top layer was partially dry as there was clear weather during the three days preceding the experiment. Hence soil surface resistance to evaporation was taken 800 sm^{-1} (Van de Griend & Van Boxel, 1989). Besides these input parameters, measured values of soil temperatures of each layer were given at the starting time of the simulation.

The crop physical parameters were taken either from the measured data from the field or from the available literature. Some measured parameters were (i) crop height (h) = 1.70 m; (ii) leaf area index (LAI)=3.85 m^2m^{-2}, and (iii) average leaf width 0.05 m. Drag coefficient (C_d) and relative turbulence intensity (i_w) were 0.2 and 0.6, respectively, (Shaw *et al.*, 1974), while scattering coefficients of leaves for near-infrared and visible radiation were taken as 0.85 and 0.2, respectively (Goudriaan,1977).

Results and discussion

The weather conditions at 2.75 m height for 211th day (30 July, 1986) given as input in the model, are shown in Figure 2a.

Diurnal variation of energy fluxes

Diurnal course of measured net radiation (R_n) together with the simulated values of latent heat (LE) and sensible heat (H) fluxes above the maize canopy are presented in Figure 2b. The peak of the total latent heat loss occurred later in the day than that of the total sensible heat loss. This small shift in time is mainly due to the increase of

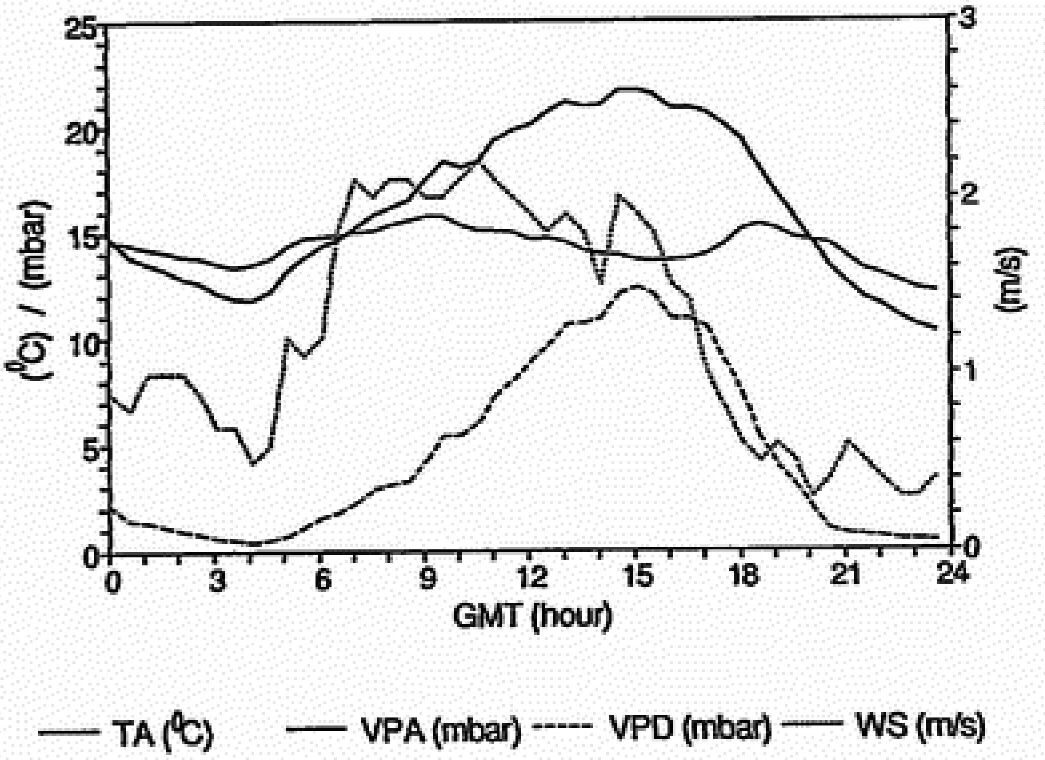

Figure 2a. Daily courses of weather conditions used in the case study. The scale for air temperature (TA), water vapour pressure in the air (VPA), vapour pressure deficit (VPD) are given on the left ordinate and for wind speed (WS) on the right ordinate. These conditions are measured at reference level (2.75 m height) above the maize crop in the field.

the vapour pressure deficit (VPD) during the afternoon (Figure 2a). The simulated net radiation at the soil surface, averaged from 05.25 hour till 17.25 hour, equalled 21% of the value above the canopy; this corresponds to an effective average extinction coefficient of 0.40 for total net radiation. The modelled soil heat flux (G) reached a peak of 82 Wm^{-2} at noon, which amounts to 17% of the total net radiation (R_n) above the canopy or 70% of the net radiation at the soil surface (R_{nsoil}) at that moment (Figure 2c). The sensible heat flux at the soil surface (HG) was always positive with a maximum value of 12 Wm^{-2}, which shows that the soil surface was warmer than the surrounding air inside the crop canopy, except around the time of sunset. This is common over partially dry soil surface caused by prevailing dry spell over the region. Further, the evaporative heat loss from the soil surface (LEG) reached a maximum value of 27 Wm^{-2} just in the afternoon; this is only 11% of the total water loss. Therefore, under the given circumstances (high radiation, and partially dry soil surface) soil evaporation took almost one tenth of the total water loss from the maize field. In a similar study, the soil evaporation was found about 30% of the total water loss from rice field during peak day hours (Hiramatsu *et al.*, 1984).

The canopy (leaf) temperature stayed 2-4°C below the air temperature during the inversion period, i.e. when atmosphere was stable (Figure 2d). Upon increase of the net radiation in the early morning, the inversion vanished and the leaf temperature started rising and a second steep increase occurred which can be explained by the disappearance of dew from the leaves. From about 08.00 hour till 10.00 hour the leaf temperature rose gradually with respect to air temperature till a steady difference of 1 to 1.5°C was reached, in spite of a two-fold variation in the net radiation. After

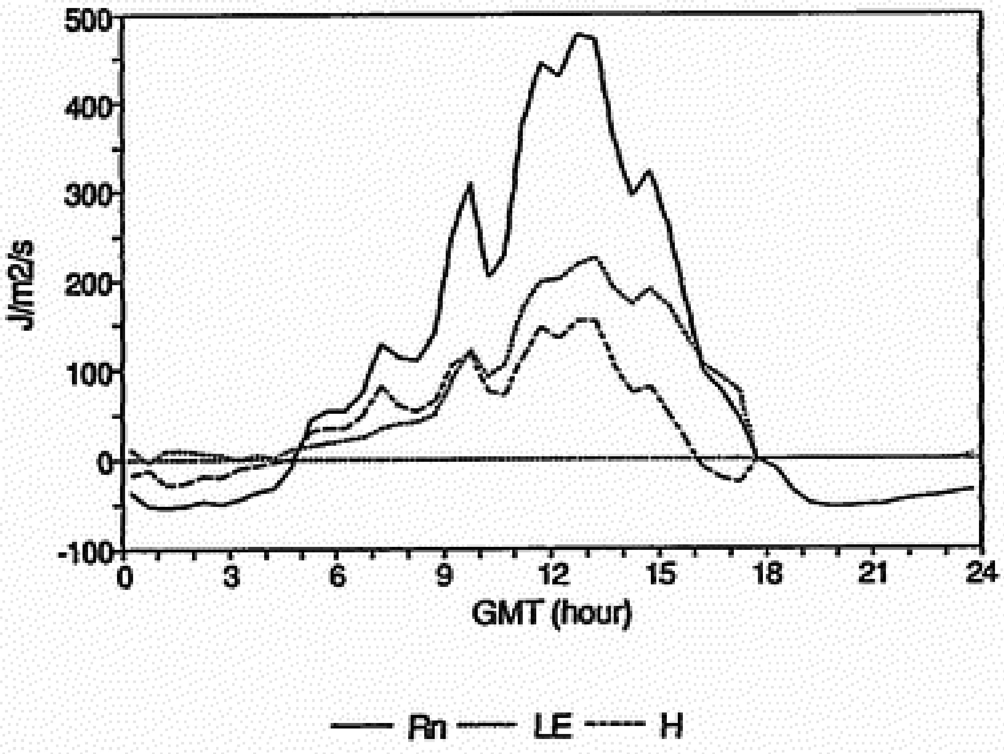

Figure 2b. Daily courses of net radiation (R_n) used in the study together with simulated latent heat flux (LE) and sensible heat flux (H) into the air above the canopy.

15.00 hour the leaf temperature dropped again. At 16.00 hour air, leaf and soil surface temperatures were almost equal, so that the sensible heat was zero and the buoyant forces disappeared. At about 20.00 hour the inversion situation started again.

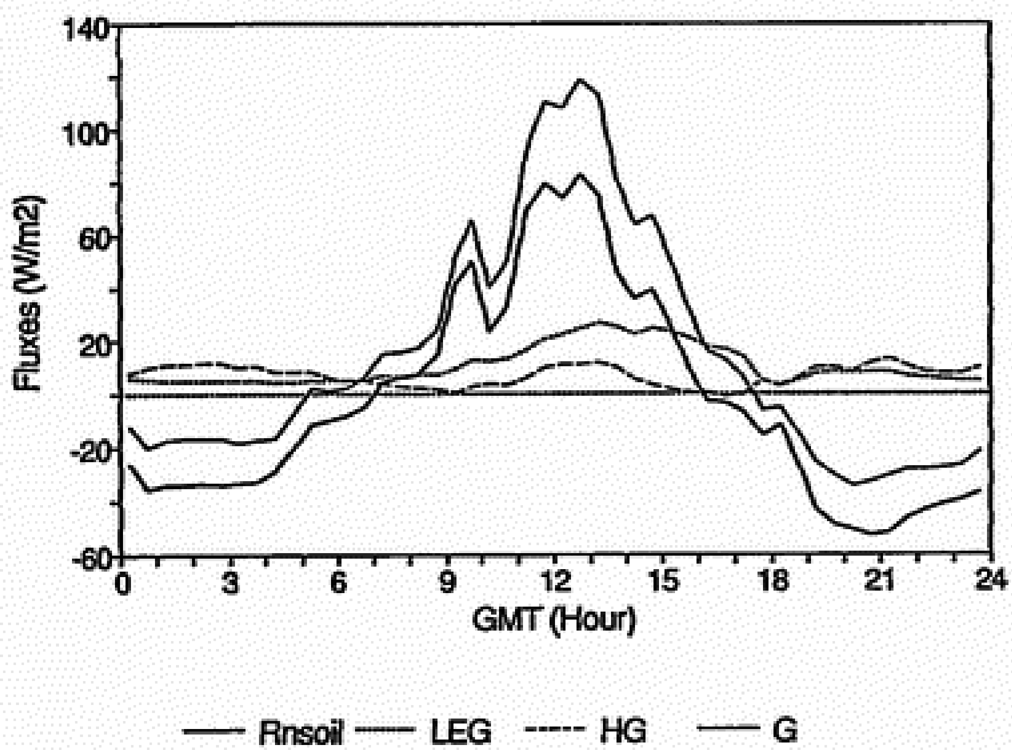

Figure 2c. Simulated energy balance at soil surface in maize field. R_{nsoil} is the net radiation just above the soil surface, LEG the latent heat loss from the soil to air, HG the sensible heat loss from the soil to the air and G the soil heat flux.

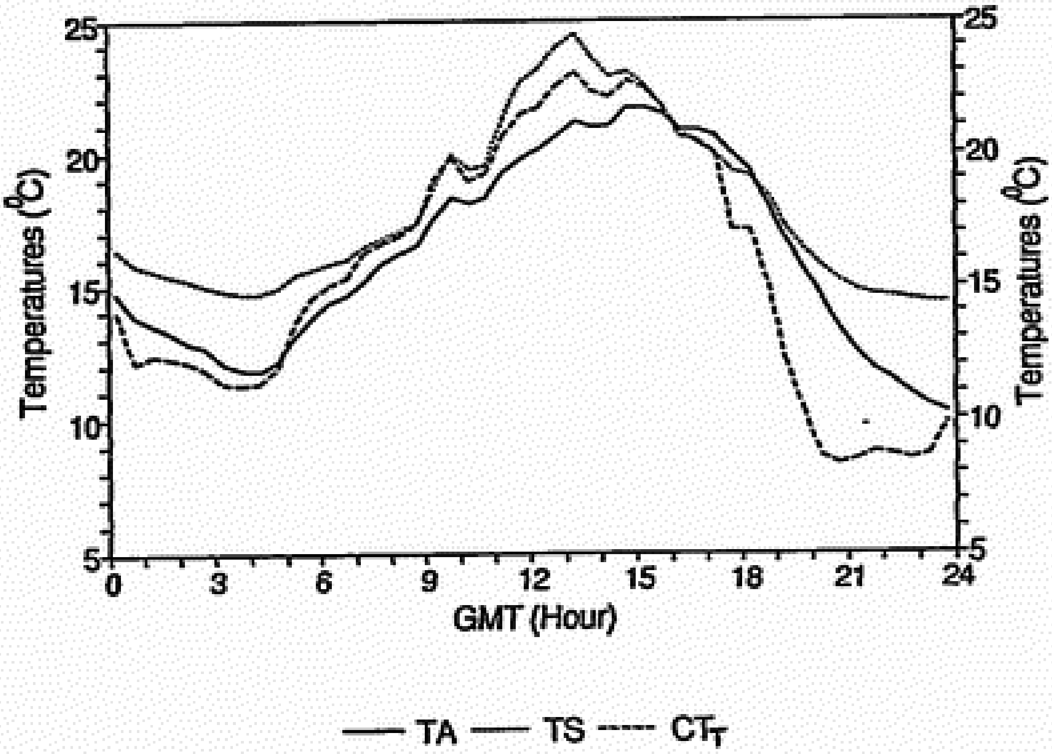

Figure 2d. Daily courses of some temperatures in the case study. The solid line is the air temperature, TA (forcing function), the dotted line is the simulated soil surface temperature, TS and the broken line is the simulated canopy temperature of the top canopy layer, CT_T.

The soil surface temperature remained always higher than the leaf and air temperatures with a maximum around 13.00 hour. However, the diurnal range of the soil surface temperature was less than the diurnal range of leaf and air temperature.

Validation of model

The model results for the latent heat flux (LE) are plotted against the measured latent heat flux above the maize canopy in Figure 3a. On average, the simulated values were 9% higher than the measured values (Table 1). In Figure 3b, model predictions of sensible heat flux (H) are plotted versus the measurement values for the complete cycle of the day. On average, the model overestimated the sensible heat flux by 10%. The discrepancy between model and measurement results (specially during morning time when both LE and H < 50 Wm^{-2}) might be due to dewfall, which reduces soil surface resistance to evaporation, not considered in the model.

The model calculations of the soil heat flux were compared with the measured values (Figure 3c). It seems that the simulation of the energy balance of the soil surface has some short comings, but since the energy fluxes at the soil surface do not exceed 25% of the total flux incident over top of the canopy, errors in this submodel are not likely to cause deviations in the aerial profiles of heat fluxes. Also, Camillo and coworkers (Camillo *et al.*, 1983; Camillo and Gurney, 1984, 1986) repeatedly experienced that it is difficult to model the soil heat flux correctly using the soil conductivity values described by De Vries (1975) for the different soil types. Similar problems were also reported by Van de Griend & Van Boxel (1989) in their study.

Table 1. Comparison of model results with measurements (No. of observations, N = 48).

Parameters	Regression line forced through the origin	Correlation coefficient (r)
Latent heat flux above canopy (LE)	LE(model) = 1.09LE(measured)	0.98
Sensible heat flux above canopy (H)	H(model) = 1.10H(measured)	0.95
Soil heat flux (G)	G(model) = 1.83G(measured)	0.96
Canopy temperature of top canopy layer (CT_T)	CT_T(model) = 0.99CT_T(measured)	0.95
Canopy temperature of middle canopy layer (CT_M)	CT_M(model) = 0.99CT_M(measured)	0.96
Canopy temperature of bottom canopy layer (CT_B)	CT_B(model) = 1.02CT_B(measured)	0.96
Soil temperatures at		
(a) 1 cm depth (ST_1)	ST_1(model) = 1.03ST_1(measured)	0.98
(b) 5 cm depth (ST_5)	ST_5(model) = 1.02ST_5(measured)	0.99
(c) 10 cm depth (ST_{10})	ST_{10}(model)= 1.01ST_{10}(measured)	0.95
d) 20 cm depth (ST_{20})	ST_{20}(model)= 1.01ST_{20}(measured)	0.89

Canopy temperatures in the top, middle and bottom layers of the canopy are plotted against time in Figure 4a, 4b and 4c, respectively. The root mean square error (RMS) of the simulated canopy temperatures varied between 1.2 K and 1.4 K. The soil temperatures at 1, 5, 10 and 20 cm depth were also simulated (Table 1 & Figure 5a to 5d). The simulated soil temperatures at various depths were matching well with

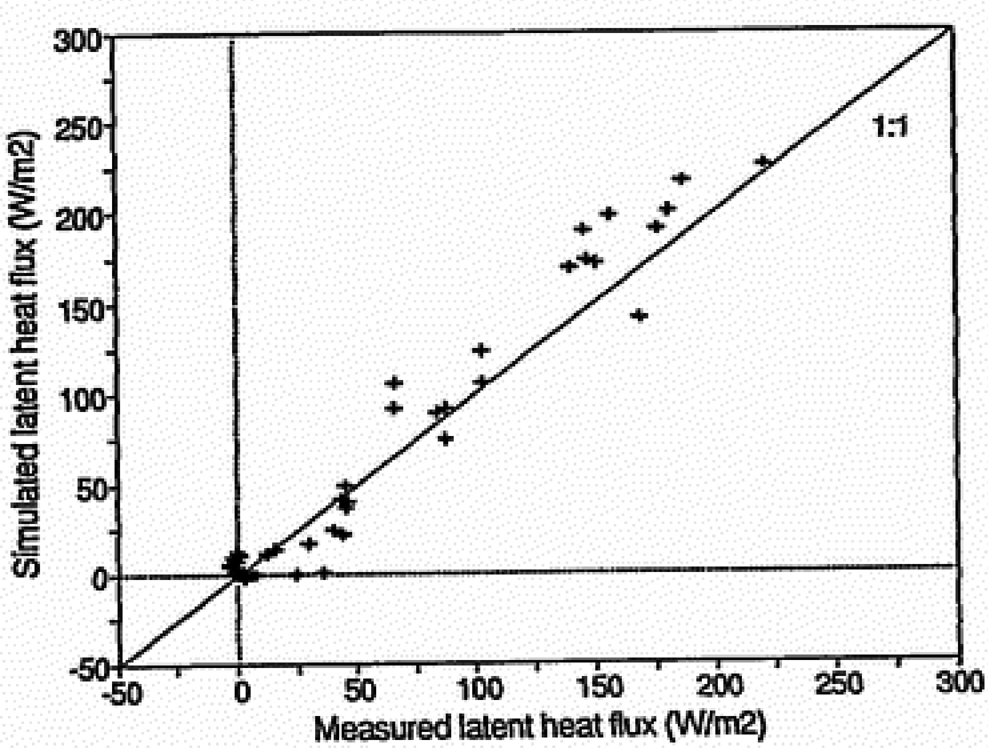

Figure 3a. Measured versus simulated latent heat flux above the maize canopy.

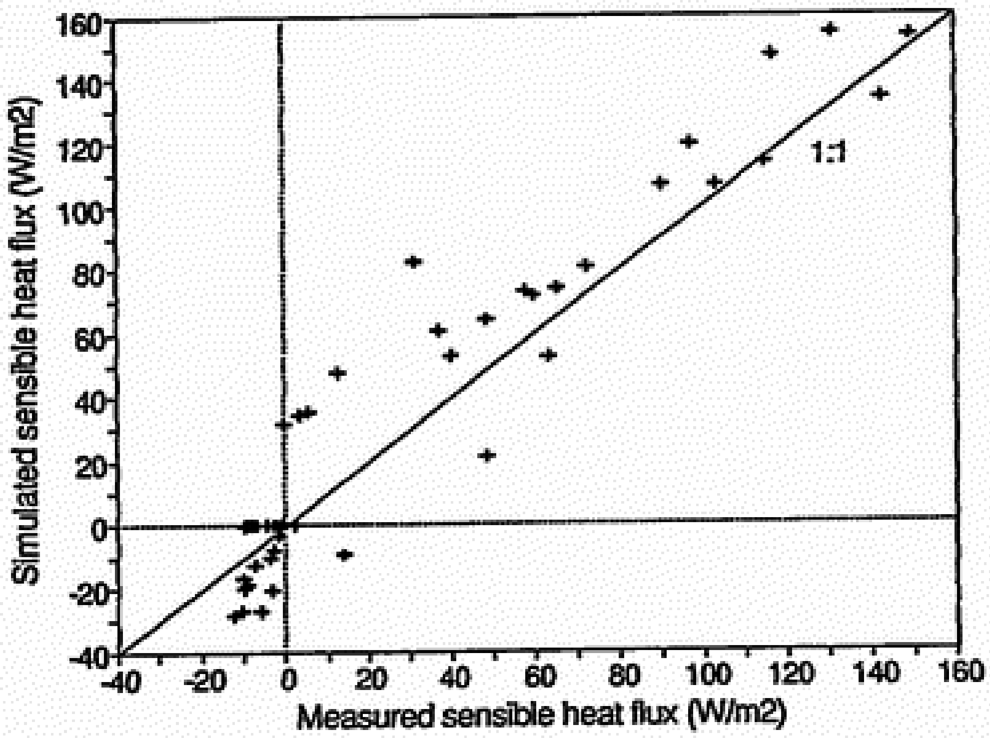

Figure 3b. Measured versus simulated sensible heat flux above the maize canopy.

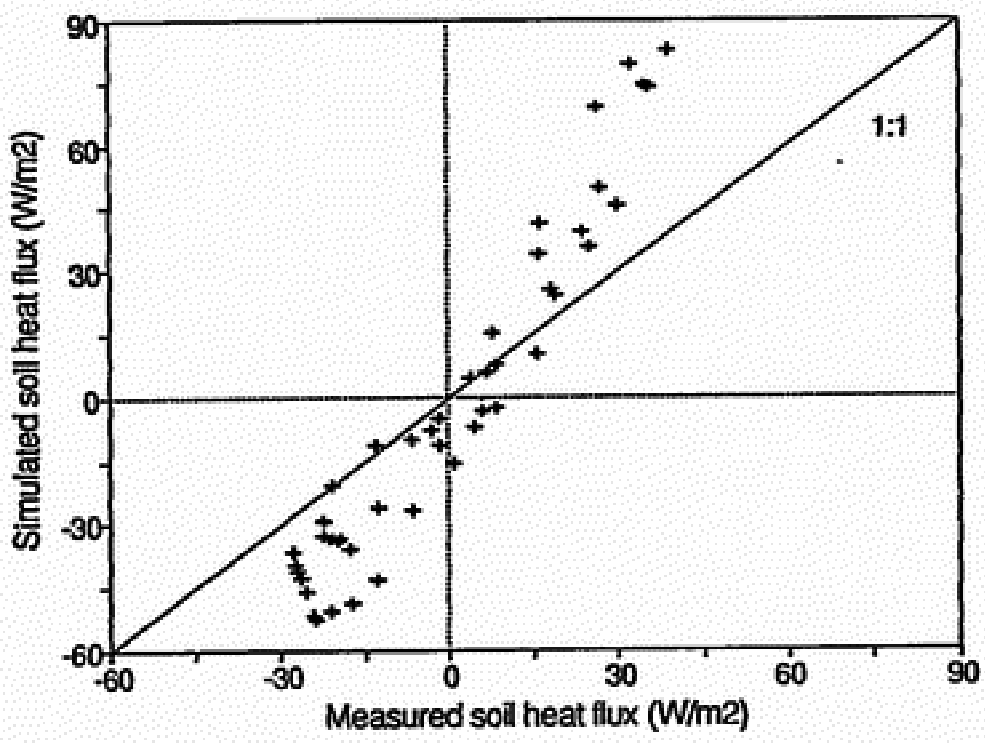

Figure 3c. Measured versus simulated soil heat flux in the maize field.

the measured data. However, deviation between simulated and measured soil temperatures may likely to increase after few days of simulation. The RMS of the simulated soil temperatures found 0.30 K at 20 cm depth and 0.68 K at 1 cm soil depth during 24 hours period of simulation. Similar result, in case of soil temperature at 2 cm depth, was reported by Stigter *et al.* (1977) using the data measured during the day time only under dry soil surface conditions.

Table 2. Standard input parameters value used in the model for standard run.

Input parameters	Unit	Value	Description
CROPHT	m	1.70	Height of the crop
DRAGC	–	0.20	Drag coefficient of leaves
RTUR	–	0.60	Relative turbulence intensity
LAI	m^2m^{-2}	3.85	Leaf area index
NUMLL	–	3	Number of layers inside the canopy
WIDTH	m	0.05	Average width of the leaves
DFACT	–	0.63	Ratio of zero plane displacement (d) and crop height (h)
Z_0	m	0.17	Surface roughness parameters
SCN	–	0.85	Scattering coefficient of leaves for near infrared radiation
SCV	–	0.20	Scattering coefficient of leaves for visible radiation
CO2REG	vpm	120	Internal regulatory CO_2 concentration
CO2EXT	vpm	345	External CO_2 concentration
CTRESW	sm^{-1}	2000	Cuticular resistance of leaves
VHCAP(1)	$Jm^{-3}K^{-1}$	$1.3*10^6$	Volumetric heat capacity of top soil
LAMBDA(1)	$Wm^{-1}K^{-1}$	0.6	Thermal conductivity of top soil
RESS	sm^{-1}	800	Soil surface resistance to evaporation
WSTSL	bar	–6.0	Water stress in the soil

Sensitivity analysis

A sensitivity analysis was performed to judge the importance of the input crop and soil variables for the behaviour of new version of the model. The sensitivity analyses to most of the input variables, except soil surface resistance to evaporation (RESS), were done in a similar way as it was done by Goudriaan (1977). Two kinds of output variables were distinguished. The first group contained the daily totals of CO_2 assimilation and various fluxes, and the second group contained diurnal CO_2 assimilation and the profile of heat fluxes and temperatures. First, the model was used to get a standard reference run using the standard input values (Table 2).

Crop properties

Table 3 shows the observed variations in the scattering coefficients for visible (SCV) and near-infrared radiation (SCN). The increase of SCV from 0.20 to 0.25 increases the availability of radiation for shaded leaves. This explains the 1% increase of the daily net CO_2 assimilation (DNCO2A). Daily latent heat flux (DLHFL) i.e. evapotranspiration also increased a little because of the relation between the stomatal opening and the net CO_2 assimilation (Goudriaan, 1977). A decrease in scattering coefficient for near-infrared radiation (SCN) from 0.85 to 0.80 slightly reduced the net CO_2 assimilation. The effect on heat fluxes was mixed for both scattering coefficients, but, of course, the CO_2 assimilation was more sensitive to the scattering coef-

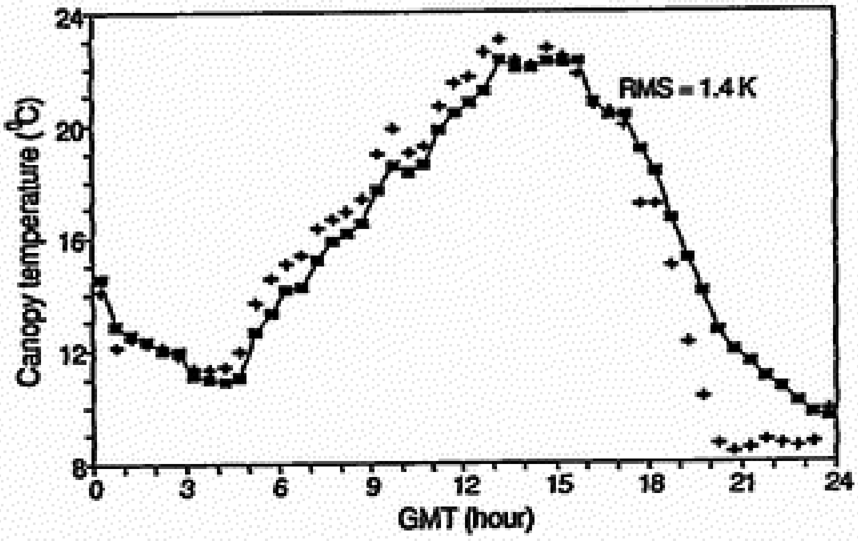

Figure 4a. Diurnal variation of measured (-■-) and simulated (+) temperature in the top layer of the canopy.

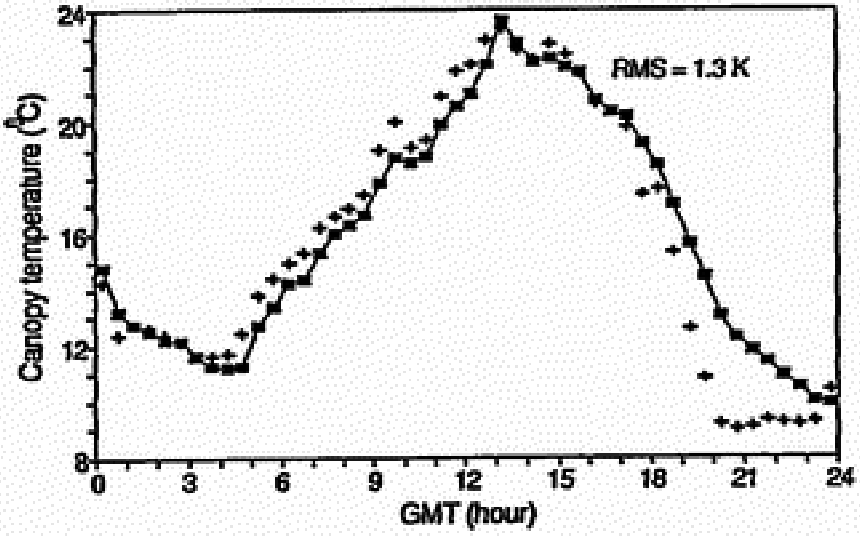

Figure 4b. Diurnal variation of measured (-■-)) and simulated (+) temperature in the middle layer of the canopy.

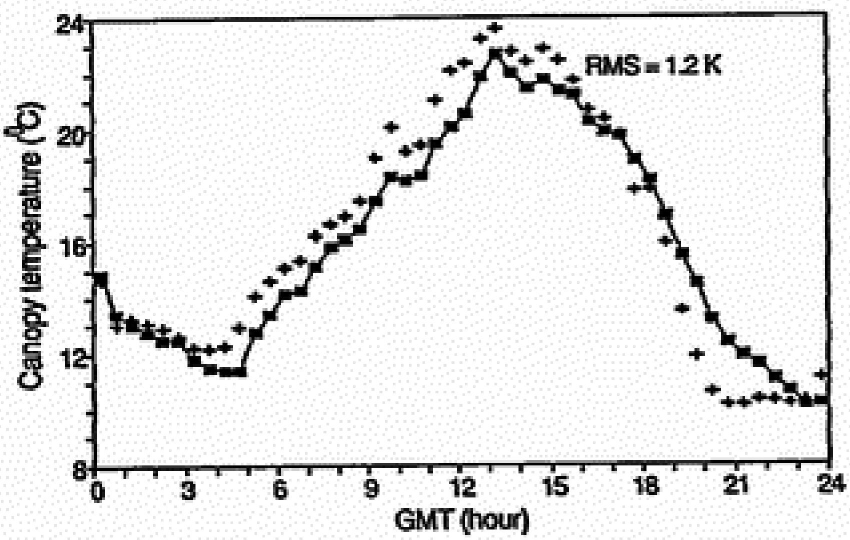

Figure 4c. Diurnal variation of measured (-■-)) and simulated (+) temperature in the bottom layer of the canopy.

ficient in the visible region. Decreasing cuticular resistance (CTRESW) and increasing internal regulatory CO_2 concentration (CO2REG) effected the net CO_2 assimilation. This indicates that a 1% change in evapotranspiration can be made by 5 vpm change in CO2REG and by 300 sm^{-1} in cuticular resistance. More than 10% increase or decrease in LAI reduces the daily net CO_2 assimilation by only 1%. The daily total CO_2 assimilation was adversely affected by higher LAI because of increased respiration (Goudriaan, 1977). Increasing the LAI results in decrease of the daily latent heat flux at soil surface (DLHFLB). Also, this increase in LAI decreases soil evaporation faster than it increases plant transpiration. Therefore, a 10% increase in LAI enhanced evapotranspiration by 1% only under partially dry soil surface conditions.

The sensitivity to the aerodynamic crop properties such as the drag coefficient (C_d) and the relative vertical turbulence intensity (i_w) was very small. These coefficients may vary by 50% before the daily fluxes were changed by 1%. Other important aerodynamic factors like zero plane displacement (d) and roughness length (z_0) could influence daily fluxes by 1%, if they were changed at least by 25%. However, this 25% variation is in a rather narrow range compared with the larger experimental errors that occur in their determination.

Soil properties

In Table 4 the results are presented for a run where volumetric heat capacity of the soil (VHCAP) and the soil conductivity for heat (LAMBDA) were kept for higher volumetric soil moisture content. This increase in LAMBDA and VHCAP caused 28% enhancement in the soil heat flux at 13.25 hour. Hence the value of G was highly sensitive to VHCAP and LAMBDA of the soil. Of course, the phase of the daily cycle of the soil heat flux (DSOILF) was hardly affected by the thermal properties of the soil.

In the next run the influence of the soil surface resistance to evaporation (RESS) was studied. When RESS is assumed to be zero, to represent top surface soil wetness, the evaporation from the soil was increased by more than 300%, which indicates enhancement in latent heat flux at the bottom of the crop canopy (LHFLB) from 11% to 33% of latent heat flux above the crop canopy (LHFL1). Besides this, the sensible heat flux at soil surface (SHFLB) became negative from sunrise to sunset, indicating that the soil surface was colder than the surrounding air which was contrary to the real field situation studied. On the other hand, when the RESS value was assumed to be very high to represent the very dry top soil, evaporation from the soil was stopped and the sensible heat as well as the soil heat flux were increased. The present study revealed that with 25% decrease in the value of RESS, the daily soil evaporation (DLHFLB) increased by 20%, which contributed to augment the daily total evapotranspiration loss (DLHFL) by 3%. The same 25% increase in the value of RESS, decreased the DLHFLB by 14%. But the daily sensible heat flux at soil surface (DSHFLB) was less affected: it increased or decreased by 7% only with the same 25% increase or decrease in the value of RESS. This 25% variation in RESS value is quite possible at field situations (sandy soil) due to sudden changes in weather conditions. Also, unlike LAI and other crop properties, the value of the

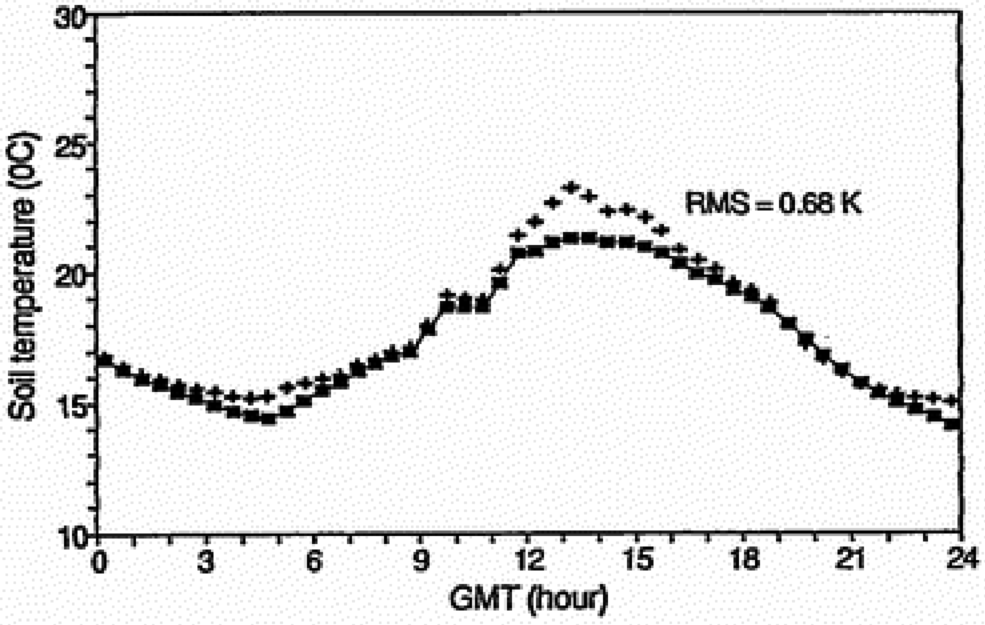

Figure 5a. Diurnal variation of measured (-■-) and simulated (+) soil temperature at 1 cm depth.

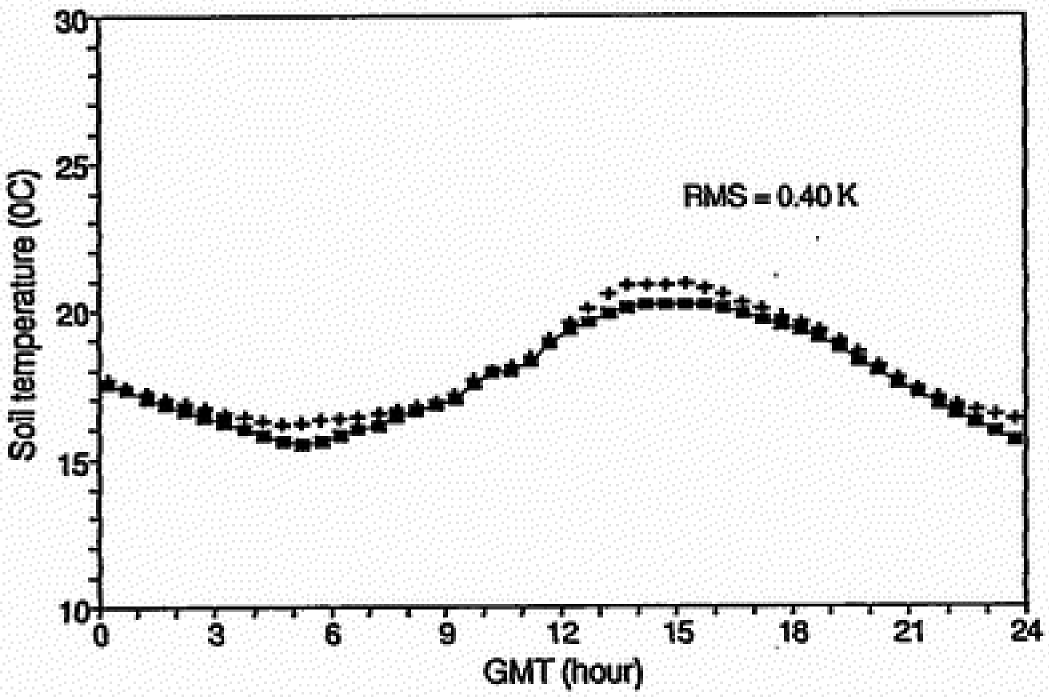

Figure 5b. Diurnal variation of measured (-■-) and simulated (+) soil temperature at 5 cm depth.

RESS even can vary considerably within a single day. Hence, it is very interesting to highlight the importance of the RESS, not only because of its large effect on different fluxes, but also, because of its possible frequent variation within a short period. Therefore, an error in the RESS value can lead to a drastic change in the simulated fluxes, particularly at soil surface.

The value of WSTSL was changed from –6.0 to –15.0 bar. This change resulted in a serious stomatal closure and consequently a depression in the net CO_2 assimilation and plant transpiration (Goudriaan, 1989). This depression, particularly in the plant

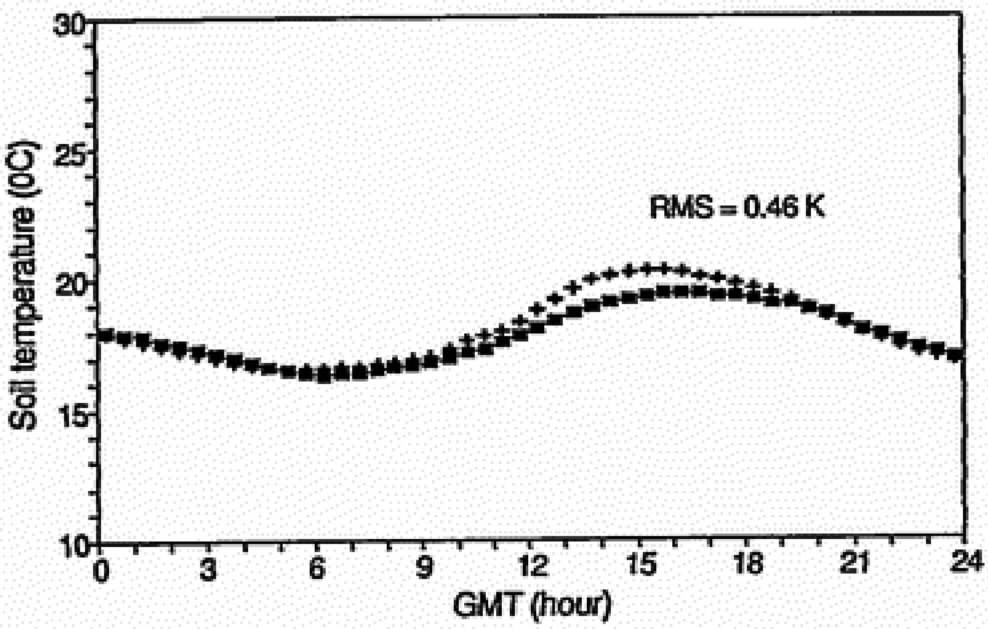

Figure 5c. Diurnal variation of measured (-■-) and simulated (+) soil temperature at 10 cm depth.

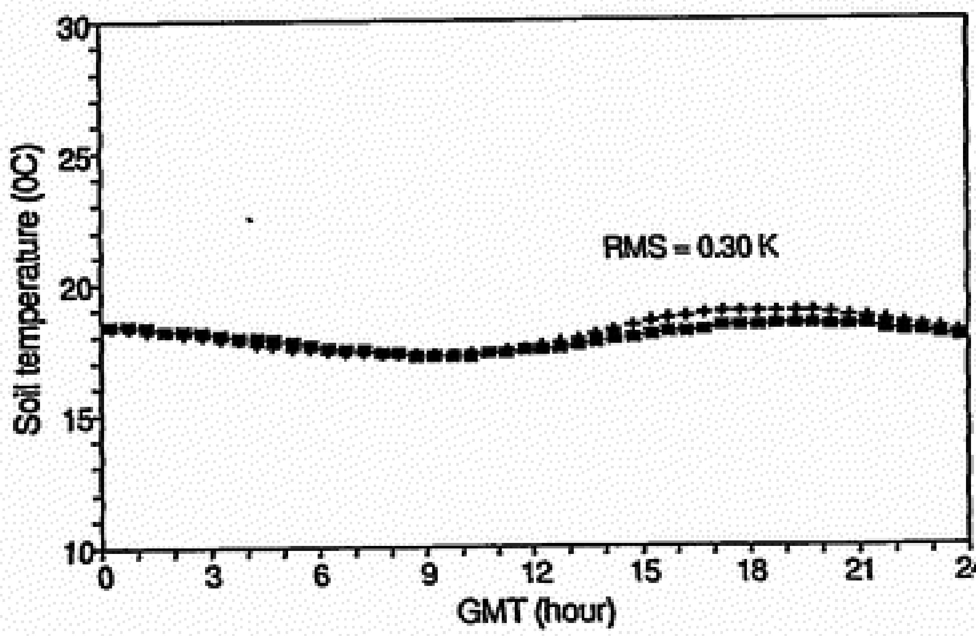

Figure 5d. Diurnal variation of measured (-■-) and simulated (+) soil temperature at 20 cm depth.

transpiration, was more pronounced during the afternoon periods due to the combined effect of water and temp- erature stresses. In contrast, when the soil water stress was reduced enough from –6.0 to –0.1 bar, the evapotranspiration and the net CO_2 assimilation were increased considerably but at the same time sensible heat flux was reduced. Our analysis showed that 15% increase or decrease in the soil water stress causes 4% increase or decrease in the CO_2 assimilation and about 2% increase or decrease in the evapotranspiration. But the same 15% increase or decrease in the soil water stress had the opposite effect by about 5% on daily sensible heat flux simulated above crop canopy (DSHFL).

Table 3. Influence of crop characteristics on daily and diurnal fluxes. The change with respect to the standard run is indicated by the arrow.

Variables	Unit	Standard run	SCV .20→.25	SCN .85→.80	CTRESW 2000→2220	CO2REG 120→150	LAI 3.85→3.45	3.85→4.25	d 1.07→1.36	Z_0 .17→.13
DNCO2A	kg CO_2ha^{-1}	420	426	419	422	399	417	417	417	420
DNARD	10^6Jm^{-2}	8.30	8.30	8.30	8.30	8.30	8.30	8.30	8.30	8.30
DLHFL	10^6Jm^{-2}	5.20	5.22	5.20	5.13	5.37	5.08	5.28	5.24	5.17
DSHFL	10^6Jm^{-2}	2.86	2.82	2.92	2.92	2.71	2.91	2.92	2.70	2.95
DLHFLB	10^6Jm^{-2}	0.92	0.93	0.90	0.92	0.91	0.97	0.88	0.86	0.93
DSHFLB	10^6Jm^{-2}	0.60	0.61	0.55	0.59	0.60	0.75	0.46	0.44	0.61
DSOILF	10^6Jm^{-2}	−0.27	−0.25	−0.33	−0.26	−0.27	−0.20	−0.40	−0.13	−0.32
	13.25 hour									
TNCO2A	kg co_2ha^{-1}	58	60	58	58	53	56	60	57	58
LHFL1	$Jm^{-2}s^{-1}$	225	227	225	223	230	218	231	228	225
SHFL1	$Jm^{-2}s^{-1}$	154	150	157	156	151	156	152	146	154
G	$Jm^{-2}s^{-1}$	74	75	71	75	74	80	70	80	75
LHFLB	$Jm^{-2}s^{-1}$	27	27	26	27	27	29	24	25	27
SHFLB	$Jm^{-2}s^{-1}$	12	13	10	12	12	07	18	09	12
CT_T	°C	23.0	23.0	23.1	23.0	23.0	23.0	23.0	23.6	23.0
TS	°C	24.5	24.6	24.2	24.5	24.5	25.0	23.9	25.1	24.4

Note:
DNCO2A : Daily net CO_2 assimilation
DLHFL : Daily latent heat flux above canopy
DLHFLB : Daily latent heat flux at bottom
DSOILF : Daily soil heat flux
LHFL1 : Latent heat flux above canopy
G : Soil heat flux
SHFLB : Sensible heat flux at bottom
TS : Soil surface temperature
DNARD :Daily net radiation
DSHFL : Daily sensible heat flux above canopy
DSHFLB : Daily sensible heat flux at bottom
TNCO2A : Net CO_2 assimilation
SHFL1 : Sensible heat flux above canopy
LHFLB : Latent heat flux at bottom
CT_T : Canopy temperature of top canopy layer

Table 4. Influence of soil properties on the daily and diurnal fluxes. The change with respect to the standard run is indicated by the arrow.

Variables	Standard run	LAMBDA 0.6→1.8 VHCAP(*10^6) 1.3→2.3	800→0	800→600	RESS 800→1000	800→10^6	−6.0→−0.1	−6.0→−5.0	WSTSL −6.0→−7.0	−6.0→−15.0
DNCO2A	420	421	421	420	420	418	486	438	402	289
DLHFL	5.20	5.20	6.66	5.33	5.10	4.54	5.64	5.32	5.08	4.31
DSHFL	2.86	2.69	2.16	2.80	2.90	3.29	2.36	2.72	3.00	3.85
DLHFLB	0.92	0.89	2.81	1.10	0.79	0.00	0.90	0.92	0.92	0.94
DSHFLB	0.60	0.52	0.02	0.54	0.63	0.86	0.61	0.60	0.59	0.57
DSOILF	−0.27	−0.10	−1.04	−0.34	−0.22	−0.04	−0.29	−0.27	−0.26	−0.23
	13.25 hour									
TNCO2A	58	58	59	58	58	58	78	63	54	37
LHFL1	225	218	282	230	222	202	263	235	217	177
SHFL1	154	139	128	151	155	163	112	143	162	206
G	74	95	43	72	76	88	72	74	75	76
LHFLB	27	22	94	33	23	00	26	27	27	28
SHFLB	12	03	−08	10	13	19	13	12	12	11
CT_T	23.0	22.9	22.9	23.0	23.0	23.1	22.4	22.9	23.1	23.7
TS	24.5	23.0	21.3	24.2	24.7	25.6	24.3	24.4	24.5	24.7

Note:

DNCO2A : Daily net CO_2 assimilation
DLHFL : Daily latent heat flux above canopy
DLHFLB : Daily latent heat flux at bottom
DSOILF : Daily soil heat flux
LHFL1 : Latent heat flux above canopy
G : Soil heat flux
SHFLB : Sensible heat flux at bottom
TS : Soil surface temperature
DNARD : Daily net radiation
DSHFL : Daily sensible heat flux above canopy
DSHFLB : Daily sensible heat flux at bottom
TNCO2A : Net CO_2 assimilation
SHFL1 : Sensible heat flux above canopy
LHFLB : Latent heat flux at bottom
CT_T : Canopy temperature of top canopy layer

Conclusions

We have shown in this paper that Goudriaan's model simulated the latent heat and sensible heat fluxes well over a maize crop canopy. This particular result is also supported by Hiramatsu *et al.* (1984) in their study over a rice crop. It is likely to get better agreement between measured and simulated fluxes by incorporating the effect of drainage / dripping due to dew in the model. The model is more sensitive to soil than crop parameters for the same magnitude of variations, particularly for short periods of simulation. Among soil properties, the soil surface resistance to evaporation has a higher influence on latent and sensible heat fluxes at soil surface, whereas variations in soil water stress are more sensitive to latent and sensible heat fluxes above the crop canopy as well as to daily net CO_2 assimilation. Hence, it must be emphasized that these soil characteristics should be estimated with great care during an experiment.

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