MICROWEATHER
Simulation Model,
Applied to a Forest

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ABSTRACT

The microweather is simulated as a function of properties of plant and soil, and of weather conditions at some height above the vegetation. The extinction and reflection coefficients of visible, near-infrared and thermal radiation are separately calculated by simplified equations, based on a more detailed submodel. The obtained partitioning of radiant energy over plant organs and soil surface is used to calculate transpiration or evaporation, sensible heat loss, heat storage and photosynthesis as influenced by specific plant proper- ties, and by conditions of air and soil. The stomatal resistance is affected by photosynthesis, CO_2 concentration and plant water status. Temperature and humidity profiles in air and soil are found by integration of net fluxes. The turbulent exchange inside the canopy is influenced by aerodynamic and geomet- ric vegetation properties which also serve to calculate the zero plane displa- cement and roughness length for the above-canopy profiles. These are based on a logarithmic wind profile, corrected for stability effects. Model outputs are fluxes from vegetation and soil surface, rates of CO_2 assimilation, profiles of air conditions, of radiation and of dew. The total simulation period only extends over one or two days.

Additional index words: Energy exchange, radiation balance, transpiration.

INTRODUCTION

The objective of this microweather simulation model is to explain the microweather as a function of the properties of the plants (trees) and soil, and of the weather conditions at some height a- bove the forest. The simulation period is limited to a few days. Therefore the term microweather is preferred to microclimate. The model has been based upon a simulation model for the microweather in maize, as described by Goudriaan (1977). The experimental eva- luation of the maize microweather model was given in Stigter *et al.* (1977). In this paper the modifications, necessary for adaption to a forest situation will be described. An attempt at an experimental evaluation will be made, using experimental results collected in Jädraås by the Swedish Coniferous Forest Project.

MODEL OUTLINE

The model can be characterized as dynamic, deterministic, continuous in time, stratified in height and driven solely by the weather conditions at its upper boundary. It is homogeneous in the horizontal dimensions. An outline of the model is given in Table 1.

Table 1. Outline of the microweather simulation model.

Input	Submodels	Output (both current values and daily totals or averages)
Meteorological parameters above the forest	Radiation: long wave or thermal, visible, near infrared	Total fluxes from vegetation and soil surface
Plant characteristics	Turbulence and wind above and inside	Rates of CO_2 assimilation
Soil characteristics	canopy	Profile of air conditions
	Leaf assimilation and transport	Profiles of radiation
		Profiles of dew
	Balances at the soil surface	
	Heat movement in the soil	

INPUTS

The required inputs consist of three main groups: the weather conditions above the forest, the plant characteristics and the soil characteristics. The weather conditions are the driving forces, whereas the plant and soil characteristics range among the model parameters. The determination of the parameter values is done before and separated from the actual simulation exercises. Thereby calibration of model parameters by comparison between simulation and experimental data is avoided. The model parameters are estimated from independent experiments.

The required weather conditions are the daily runs of air temperature, air humidity, wind speed, net radiation and/or incoming global radiation. Averages of 10-minute periods give enough resolution in time. The height of the weather measurements, the height of the forest and the distribution of leaf area density with height are needed. For the forest situation the trunk and branch densities are also required as they intercept radiation, store heat and interfere with the air movements.

The stomatal behaviour (leaf resistance) as a function of internal
(leaf) and external (air) conditions is of great importance for
the total transpiration. The photosynthesis-light response
curve of the individual leaves is required to simulate the
total CO_2-assimilation of the canopy.

Soil characteristics that must be known are thermal conductivi-
ty and heat capacity. The soil water regime is not simulated
because it is assumed always to be at field capacity.

METHODS

The temperature profile in the soil is simulated with the
energy balance at the soil surface as driving force, using a
finite difference method in the bulk soil. This method
is also used for simulating the profiles in the air. The
layers of air inside the canopy exchange heat and mass with
the leaves and the trunks, and with the adjacent layers. A
total of three layers in the canopy space appears to provide
sufficient accuracy. The net fluxes of heat and mass are
integrated with respect to time and soon reach a steady state.
A bypassing method is used to reduce the disastrous effect of
the small time constant on the execution time (Goudriaan, 1977).

The computer language used was CSMP for the original maize
model, but the forest model has been translated into FORTRAN
and subsequently into SIMP.[1] (Lohammar, 1979).

SUBMODELS

A concise description of the submodels is given in Stigter *et
al*. (1977), and a more extensive one, including a discussion of
the underlying theories, can be found in Goudriaan (1977). Here
I shall only discuss the modifications of the model for adapta-
tion to the coniferous forest. A list of changed parameter
values is given in Table 2. The most important structural change
is the introduction of the trunks, first as an interceptor of radia-
tion, secondly as a store of heat, and thirdly as a store of water.
For radiation absorption it is assumed that the trunks absorb
just as much as needles at the same height per unit of intercep-
ting area. So no allowance is made for a difference in absorpti-
vity of the trunks in comparison to that of the needles, which
seems reasonable in view of their woody character. As an obvious
modeling advantage we can now draw upon the calculations already
made of the radiaton absorption by the needles. We only need the
trunk surface area per ground area. With a trunk width of 0.13 m,
a tree height of 20 m and a tree density of 0.04 m^{-2}, it is esti-
mated as 0.21 (taking only one side of the trunks, just as with
leaves). Since the LAI is close to 1.6, about 11 % of the total
radiation absorption by the stand can be attributed to the trunks.
No allowance is made for the decrease of trunk width with height,

[1]
  P.E. Jansson is kindly acknowledged for this tedious job.

as this effect is more or less compensated by branches, which have not been considered separately. The storage of heat in the trunks is simulated by a one-component first order exchange. Both average trunk temperature and trunk surface temperature are available as model outputs. In the heat balance of the trunks the latent heat loss (transpiration) is not considered, so that also condensation of water vapour on trunk surfaces is excluded. The leaves on the other hand, transpire and collect dew if their simulated temperature falls below the dewpoint.

Table 2. Comparison of parameters as used for maize and for the coniferous forest.

	Parameter	Maize (Goudriaan 1977)	Coniferous forest (Jädraås)	Unit
CROPHT	crop height	2.5	20	m
REFHT	ref. height	3.	26	m
EFF	light use efficiency	$17.2 \ 10^{-9}$	$8.3 \ 10^{-9}$	$kg \ CO_2 \ J^{-1}$ (visible)
HRES	dimension of soil element	0.05	0.3	m
LAI	leaf area index	3.73	1.56	$m^2 \ leaf/m^2$ ground
LAMBDA	soil heat conductivity	1.3	0.2	$J \ m^{-1} \ s^{-1} \ {}^oC^{-1}$
LAT	latitude	45.	60.8	-
RCO2I	internal CO_2 concentration	90.	300.	vpm
RESCW	cuticular resistance	2000.	5000.	$s \ m^{-1}$
RESS	soil "stomatal" resistance	0.	200.	$s \ m^{-1}$
SCN	scattering coefficient of leaves in the near-infrared (700-2500 nm)	0.85	0.576	-
SCV	scattering coefficient of leaves in the visible (400-700 nm)	0.2	0.156	-
VHCAP	volumetric heat capacity of the soil	$2. \ 10^6$	$1.5 \ 10^6$	$J \ m^{-3} \ {}^oC^{-1}$
WIDTH	width needles		0.002	m
WTRUNK	width trunk		0.13	m
WRESPL	resistance for stem water flow	$1. \ 10^7$	$1. \ 10^8$	$bar \ m^2 \ s \ kg^{-1}$

The boundary layer resistance of the air on the trunk surface is related to the windspeed and the width of the trunks by an equation given by Pearman *et al.* (1972):

$$r_b = 100 \ (w/u)^{0.5}$$

with w the width and u the windspeed. For the needles the same equation is used, so that r_b for the trunks is 8 times larger than for the needles (width needles = 0.002 m). The heat exchange between the trunk surface and the trunk body takes place across a wood resistance, calculated as one quarter of the trunk width divided by the wood conductivity (0.2 J m^{-1} s^{-1} $^\circ$C^{-1}).

As for the storage of water, it is assumed that the water content of the trunks is 60 % on a volume basis. Extraction of water leads to decreased water potential in the same way as for maize (here adequate data must still be inserted). The water content of needles is neglected in comparison to that of the trunks.

The zero plane displacement and roughness length, that are needed to calculate the logarithmic wind profile above the canopy and the friction velocity u*, are calculated from aerodynamic crop characteristics by a method given by Goudriaan (1977). The mixing length for turbulent exchange inside the stand is identified with a mean distance between the branches, estimated as 2.7 m.

In maize the leaf resistance r_l depends on the rate of net CO_2 assimilation in such a way that the CO_2 concentration in the stomatal cavity is regulated at about 120 vpm (Goudriaan and Van Laar, 1978). The data for Scots pine do not indicate such a relation (Hellkvist *et al.*,1977). In any case, the internal CO_2 concentration is much higher and is estimated at about 300 vpm, decreasing with 10 vpm per bar of water stress. This relation was used in this simulation exercise, but a better description is necessary.

The rate of net CO_2 assimilation is found from the absorbed visible radiation. The maximum net CO_2 assimilation reaches a maximum of about 10 kg CO_2 ha^{-1} hr^{-1} at a temperature of 15°C (Linder, 1977). The initial light use efficiency is 0.3 kg CO_2 m^2 s ha^{-1} hr^{-1} J^{-1} (8.3 10^{-9} kg CO_2 per J absorbed visible radiation).

The leaf transpiration rate, heat loss and temperature are found by solving the energy balance equation.

Table 3 lists some intermediate and output variables that are independent of the driving variables and do not change during the simulation. The sparseness of the stand causes a very rough surface and a relatively small zero plane displacement. As a consequence, the turbulent resistance ABTURR (r_a) is also very small, gradients of temperature and humidity remain small and stability correctons are usually negligible. A similar procedure is followed for the soil surface, taking into account the additional term of the soil heat flow. The undergrowth is treated as part of the soil surface, which is assigned a constant stomatal resistance of 200 s m^{-1}. The boundary layer resistance is simulated by a characteristic element size of 0.3 m and subsequent application of Pear-

man's equation.

Table 3. Some intermediate and output variables.

LMIX	mixing length	2.66	m
ALPHAK	extinction coefficient for wind in canopy	1.65	
D	zero plane displacement	8.51	m
ZNOT	roughness length	3.99	m
ABTURR*WINDR	turbulent resistance above canopy times windspeed at reference height	3.75	
USTAR/WINDR	friction velocity over windspeed at reference height	0.24	
ALB (overcast)	reflection coefficient for global radiation	0.093	

RESULTS

The results of three days (770809 - 770811) are available, one run with net radiation above the canopy as driving variable and one run with both net and global radiation as driving variables. In the first run the incoming global radiation is estimated on the basis of a priori known correlations between radiation data. Sometimes these relations are not sufficient as is most clearly seen in Fig 1 where simulated and measured net long wave radiation above the canopy is plotted. With both radiation inputs the agreement is much better, especially on the clear day (770809).
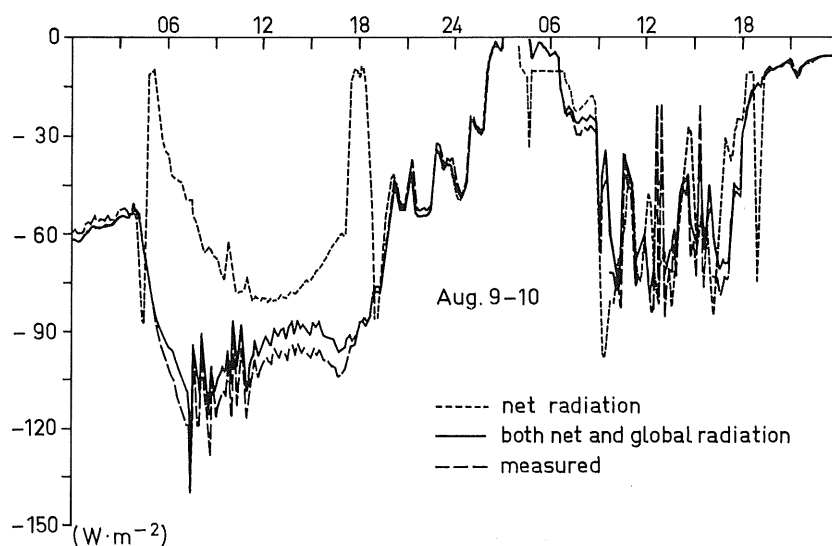

Figure 1. Measured net long wave radiation above the canopy, and simulated, once with only net radiation as driving variable and once with global radiation in addition.
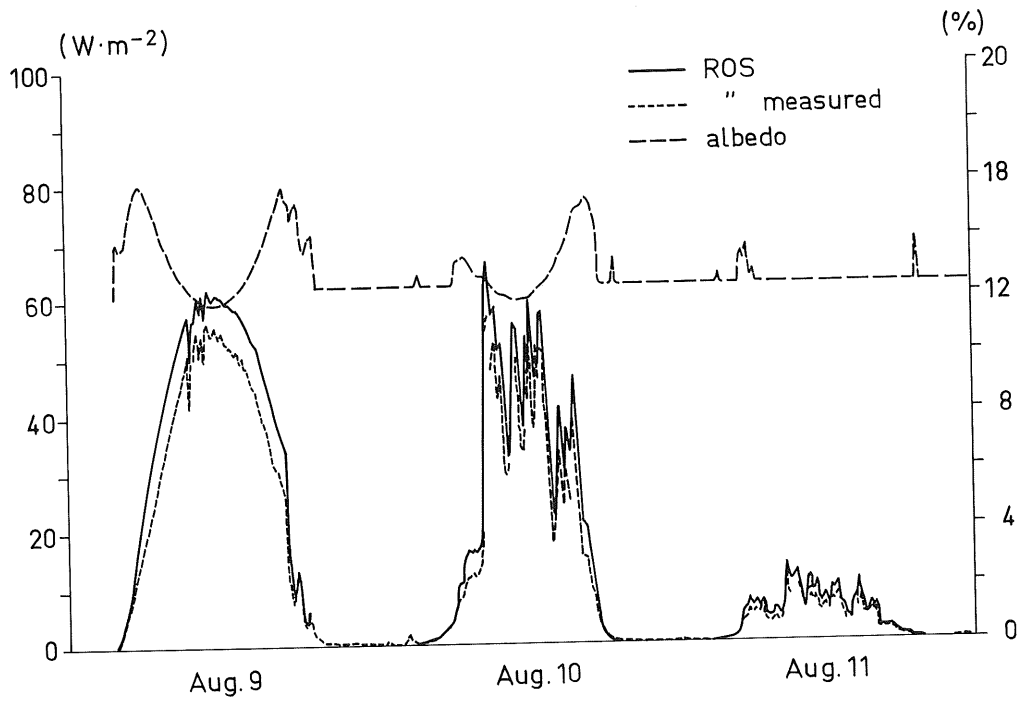
Figure 2. Measured and simulated reflected short wave radiation and albedo.

In Fig 2 the simulated reflected outgoing short wave radiation (ROS) is plotted together with the measured values. The agreement is very good on the overcast day. On the clear day, ROS is slightly overestimated. The measured albedo is about 7.7 % at 12.00 a.m., whereas the simulated value is 9 %. Perhaps the diurnal course of the albedo shows an even stronger depression around noon than the simulated (Fig 2).

According to the simulation, the heat storage in the soil is about twice as large as in the trunks. In Fig 3 the measured and cumulated total storages are compared. The agreement is remarkable except during the early evening, when a much larger release of heat was measured than could possibly be explained by simulation. The course of the simulated soil temperatures in the first six layers is given in Fig 4.

One of the most important outputs of the model is given in Fig 5, the simulated and measured latent heat loss above the canopy. The agreement is reasonable, except on the overcast day (770811). The measured flux is three times larger than the simulated flux, and in fact is as large as half the flux on the clear day. The big discrepancy between models is due to the stomatal behaviour. In the simulation, stomatal conductance is directly linked to the rate of net CO_2 assimilation so that on an overcast day the stomata are much more closed than on a clear day. On this point Scots pine is clearly different from maize! When the stomatal aperture

of Scots pine is connected to the vapour pressure deficit of the air, as was suggested during the workshop, the situation might be just the opposite, resulting in a daily transpiration which is much less dependent on incoming radiation. This example dramatically illustrates the importance of an adequate description of stomatal behaviour.
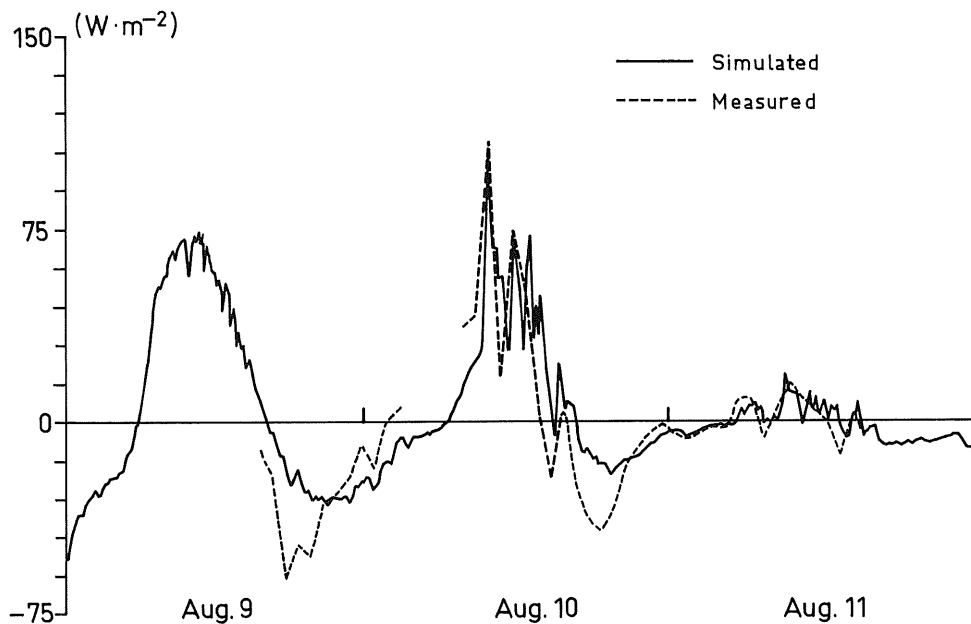

Figure 3. Measured and simulated heat storage flux in soil and trunks together (measured flux also includes storage in air).

The simulated net radiation below the canopy is only about 50-70 % of the measured fluxes. In reality more radiation will penetrate than simulated, because of the clustered leaf area distribution. This deviation does not affect the total energy balance, as the reflected radiation was simulated correctly, but it is very important for the energy balance of the soil surface.

During the simulated period the windspeeds were always so large that the stability corrections remained negligible. Dew was only formed during the last night, when the measured relative humidity rose slightly above 100 %. Because of the released heat of condensation, the sensible heat flow became postive on this occasion (30 W m^{-2}). In the other nights the negative long wave radiation was not able to cool the needles sufficiently strongly and cause their temperature to drop below dewpoint. Apparently the needles remained close enough to the air temperature because of the small value of the boundary layer resistance r_b, which is again related to the small needle width.
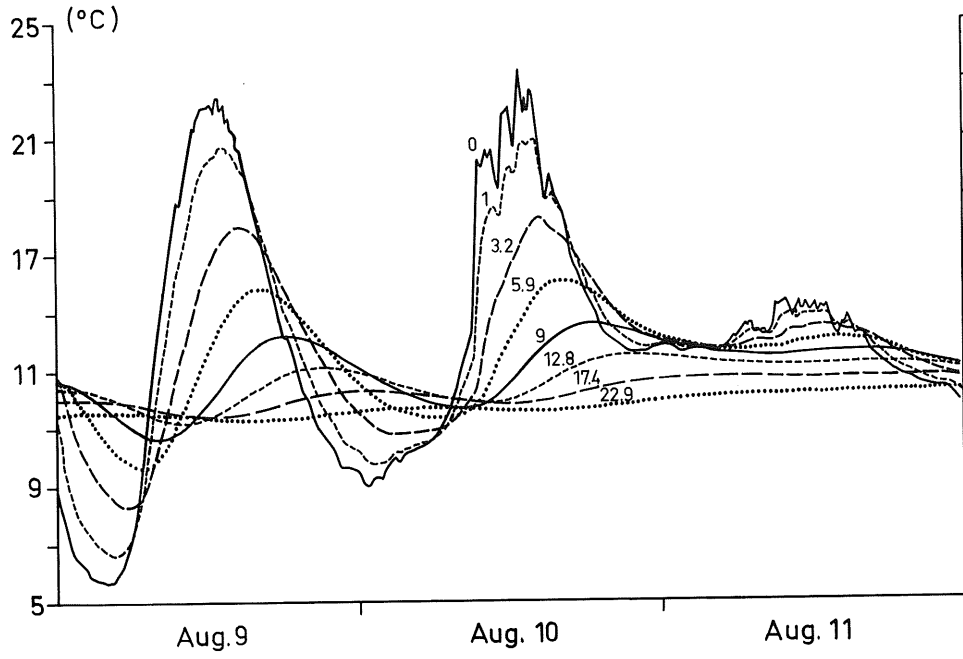
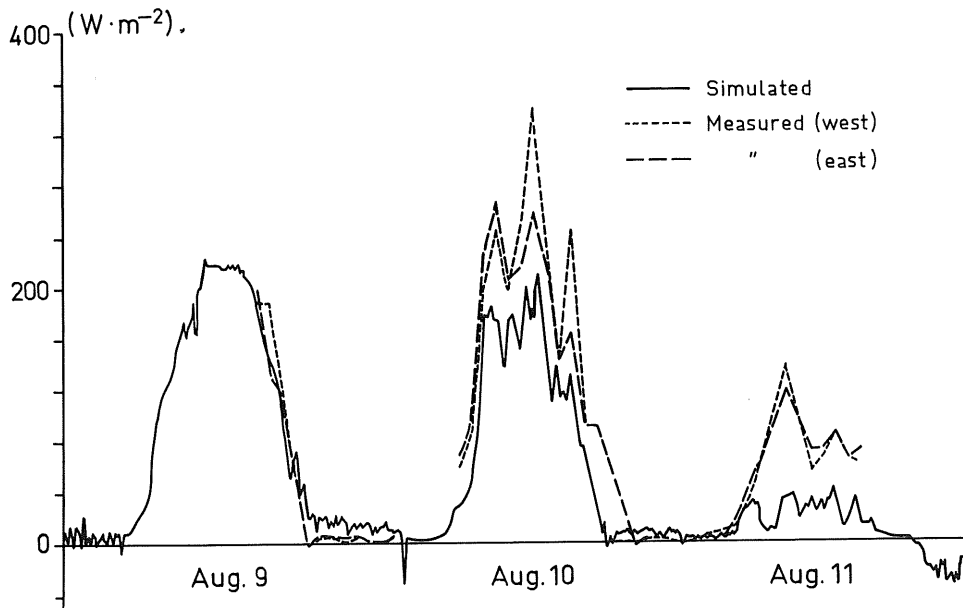Figure 4. Simulated temperatures at surface and different soil depths (cm).

Figure 5. Simulated and measured latent heat flux above the canopy.

The simulated CO_2 balance of the stand (excluding undergrowth and soil) is positive and amounts to 100 kg CO_2, or almost 70 kg D.M. fixed per day, as an average over the three days.

DISCUSSION

As the simulation results show, the gradients of the air temperature and humidity are usually very small. Therefore, neglection of the aerial profiles will hardly influence the simulated energy and mass fluxes, except during calm nights when an inversion may develop. Such an inversion is only formed above the canopy and not inside, so that it seems well justified to simplify the model and employ only one layer of air inside the canopy. Then also the calculations of stability corrections inside the canopy can be abandoned. This result partly justifies the one layer concept of the CANOPY model (Halldin *et al.*, 1979). For radiation extinction a compartmentalization in three layers remains necessary in view of the non-linarity of the photosynthetic and stomatal response to irradiation.

For the trunks it may be desirable to divide the trunk cylinder into two concentric compartments instead of just one. The heating of the trunk surface by solar radiation is asymmetric, but there is no need to take this into account since all heat exchange properties are linear or almost linear.

A more fundamental change in the model might be to treat the undergrowth as a vegetation layer in its own right, and not as just as part of the soil surface.

Summarizing I would say that the performance of the model is satisfactory, that simplification of some structural aspects is possible, and that the lack of data on stomatal behaviour is the weakest point of any model of this kind.

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