SIMULATION OF LOCAL PLANT TEMPERATURE IN MAIZE AT KESZTHELY AS A RESULT OF GLOBAL CLIMATE MODIFICATION

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Abstract

By applying the various scenarios on global warming we examined the crop temperature in maize at Keszthely with the help of Goudriaan's micro-climate simulation model. Our scenarios contained several ideas with higher warming up beside the domestic downscaling of the IPCC 2007 report (A2 and B2). We found that the temperature in maize at cob level increased by 0.6 °C in Keszthely, compared to the 1961-1990s. The presence of the canopy slightly compensated the rise in plant temperature, even at simulations with rather high warming up. Compensation degree depended on water supply, too. The better water supply brings more intensive development of green surface of plants so provides stronger shadowing effect; this also affected the development of plant temperature.

Key-words: simulation modeling, plant temperature, maize

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Összefoglalás

A globális klímaváltozás helyi hatásának vizsgálata a kukorica növényhőmérsékletének szimulációja alapján

A globális felmelegedésre vonatkozó eltérő szcenáriók alkalmazásával vizsgáltuk a kukorica növényhőmérséklet alakulását Keszthelyen, a Goudriaan féle mikroklíma szimulációs modell felhasználásával. A jövőképeink az IPCC 2007-es jelentésének hazai leskálázása mellett (A2 és B2) néhány magasabb felmelegedésű elképzelést is tartalmaztak. Megállapítottuk, hogy Keszthelyen az elmúlt évtizedben a kukorica cső szinti hőmérséklete eddig 0.6°C-al emelkedett az 1961-90-es évekhez képest. Az állomány jelenléte a növényhőmérséklet növekedését némiképp kompenzálta, még meglehetősen erős felmelegedés szimulációnál is. A kompenzáció mértéke függött a vízellátottságtól is. Jobb vízellátás nagyobb zöldfelület képzéssel és ezzel erőteljesebb árnyékoló hatással jár együtt, mely a növényhőmérséklet alakulását is befolyásolta.

Introduction

The role of plant temperature is paramount in physiological processes since the speed of biochemical reactions is determined by the temporary value thereof. Plant temperature depends on the ambient air temperature due to the localised nature of plants. At the beginning the researchers approximated the relationship between air temperature and the different physiological processes by the temperature optimum curve

(*Larcher* 1980). It is a special feature of the function that the shape of the curve is the same at all physiological processes, only the actual temperatures change by plant species, breeds, development stage, etc. The observations pertaining to plant temperature has started much later due to the cumbersome nature of measurement of the element. In the case of plants the plant and air temperatures can only be separated in theory since these elements determine and depend on each other. Plant temperature – contrary to the body temperature of the higher living beings – is controlled by the outer air temperature in a way that the plant cools itself through evaporation so long as its surface temperature goes close to or below the air temperature (*Anda* 1993a). Stress situation (for example lack of water) could cause that plant temperature exceeds air temperature, which, however, always means damage of physiological processes (*Jackson et al.* 1981). According to the Van't Hoff's rule the intensity of the individual physiological processes from the commencement to the highest level thereof (between the basic and the optimum temperature) doubles or trebles with an increase in air temperature by 10 °C, depending on the nature of the physiological process. Production of dry matter in plants is determined by the difference between the two basic physiological processes, photosynthesis and respiration. At increasing air and plant temperature the intensity of photosynthesis rises to a certain extent – to the optimum temperature –, but the intensity of respiration rises more steeply than photosynthesis in the same temperature range, therefore the increase in production of dry matter deriving from the difference between the two physiological processes will be higher at optimum temperature and more moderate at higher outer temperature.

In Hungary there have been investigations in the Agrometeorological Research Station of Keszthely for decades in order to measure and use in practice (determining the time of irrigation) of plant temperature (*Anda* 1993b, 2002; *Anda and Ligetvári* 1991, 1993). The examinations covered many plant species, but the majority of the measurements were performed on maize (*Anda 2001a, 2001b; Anda and Decsi* 2001).

In the course of the past decades the research of special microclimate and canopy climate has shown significant developments whose outcome was that the theoretical models simulating physical processes gained ground beside the formerly prevailing empirical approaches. The model is a simplified counterpart of an existing system (e.g. a plant or canopy), which is able to emulate the behaviour of the more complex real system. The model also provides opportunity to examine one selected element of the system and not in itself but the behaviour is embedded in the real system and showed in a complex way. In this observation we chose this latter possibility, and we analysed plant temperatures on the basis of the latest scenarios of IPCC 2007 as well as the downscaled ones to Hungary (*Bartholy et al.* 2007). The model applied by us was the PC-executable version of the newer version (*Goudriaan és van Laar* 1994) of the CMSM (Crop Microclimate Simulation Model) by *Goudriaan* (1977).

Material and Methods

Input data and parameters derive from the Agrometeorological Research Station of Keszthely (46°44’N; 17°14’E; 114.2 m above sea level). Input meteorological elements were provided by the local automatic climate station equipped by Eppley pyranometer. Similarly to the meteorological inputs, we used the principle of analogy in the case of the input plant data of the given scenario. At the input plant data we searched for a year – July – that was analogous with the weather to be simulated, where the data on maize and soil moisture were the same or almost the same as the values of the year to be simulated. For this we had an about 30-year data series for medium early maturity maize.

The model inputs are site- and plant-specific values (plant height, leaf density in different layers), soil characteristics and hourly meteorological data (air temperature, global radiation, relative humidity, soil surface temperatures at 24.00 hours), which were transformed from the standard measurement level (Agrometeorological Research Station of Keszthely) to the reference level required by the model. The leaf area and its density were measured in the field on 10 sample plants weekly, using a LI-3000A type leaf area meter.

The soil moisture content in the upper 1 m was also measured in the field gravimetrically at 10 cm intervals every 10 days. The actual soil water content was expressed in terms of soil water potential. The physical properties of the Ramann type brown forest soil (heat capacity, heat conductivity, etc.) were determined at the beginning of the investigations. More details on plant and other data samples see in publication of *Anda* (2006).

The basic of the model assumption is the calculation of energy distribution in the canopy after the radiation reflection and transmission processes (*Goudriaan* and *van Laar* 1994):

$$0 = Rn - M - Q_H - \lambda E \tag{1}$$

where Rn: net radiation [W m^{-2}]

M: metabolic storage [W m^{-2}]

Q_H: sensible heat flux [W m^{-2}]

λE: latent heat flux [W m^{-2}]

The sensible heat flux (Q_{Hi}) in the i layer is:

$$Q_{H\,i} = \rho c_p \frac{T_{ci} - T_{ai}}{r_{aHi}}, \quad (2)$$

where T_{ai}: air temperature in the i layer [K]

T_{ci}: canopy temperature in the i layer [K]

r_{aHi} : aerodynamic resistance for sensible heat transfer in the i layer [s m^{-1}].

ρ and cp: air density and specific heat of the air, respectively.

The latent heat flux (λE_i) in the i layer can be calculated as follows:

$$\lambda E_i = \rho c_{p(}\{e_s(T_{ci} - e_s)\}/[\gamma(r_{awi} + r_{ci})] \quad (3)$$

where $e_s\,(T_{ci}) - e_i$: difference between saturation vapour concentration at plant temperature and actual vapour concentration [m^3 m^{-3}]

r_{awi}: aerodynamic resistance for water vapour transfer in the i layer [s m^{-1}]

r_{ci}: crop resistance in the i layer [s m^{-1}].

After calculating the sensible and latent heat, the crop temperature (T_c) in the i layer was estimated as:

$$T_{c,i} = T_{a,i} + \left(Q_{H\,i} - Q_{H\,i-1}\right) r_{H,i} / \rho c_p \quad (4)$$

where $r_{H,i}$: value characteristic of sensible heat resistance in the i layer [s m^{-1}] when i =1 (Ta_{i-1}) is the air temperature for the reference level.

For evaluating the results of the model runs we used paired t-test that was performed by the free version of STATA 5.0 (1996) program package. The process reduces the two-sample t-test to a one-sample test since there is no possibility of repetition (so of calculation of standard deviation) at the model runs. The test compares the mean value of the sample to an expected mean value. According to the null hypothesis if the mean value of the differences is 0 then the two samples are statistically the same. If the mean value of the differences is not 0 then the two samples are significantly different. The significance level was fixed at 5% in the course of the process.

Before applying the *Goudriaan* model in the present work, the validation of air temperature was carried out locally by *Anda et al.* (2001). The observed air temperature used in the validation of the model was collected in the field. To validate the model the root mean square deviation (RMSD) of a number of pairs (n) of simulated (S) and observed (O) elements was applied:

$$RMSD = \left\{ \left[\Sigma (O - S)^2 \right] / n \right\}^{0.5} \qquad (5)$$

The RMSD is one of the best overall measures of model performance (*Willmott,* 1982). More details see in publication of *Anda* (2006).

The applied scenarios

The meteorological bases (the control – first scenario) of the different scenarios – similarly to the bases of the scenarios presented in the IPCC 2007 report – were provided by the mean values of years 1961-1990 measures at Keszthely. At the control run we used the CO_2 concentration measures performed in the 1980s as well as the background concentration values of K-puszta and Hegyhátsál (*Haszpra* 2007) in order to determine the input CO_2 concentration. Finally we determined the CO_2

concentration of the basic run as 340 ppm. *Haszpra* (2007) fixed the Hungarian value for 1981 as 343 ppm.

The second scenario is to represent the changes of the close past on the basis of the data of the decade between 1997 and 2006. According to the last climate normal, in Keszthely in summer the air temperature is significantly higher by 0.6 °C than the monthly average of Julies of the 1901-2000 data series (*Kocsis* and *Anda* 2006a). Though it cannot be statistically justified, the accumulated quantity of precipitation of July has decreased by about 10-15% in Keszthely (*Kocsis* and *Anda* 2006b, *Kocsis* and *Anda* 2005). We estimated the outer CO_2 concentration to 380 ppm on the basis of the data of the background pollution.

The third scenario is to represent the impacts of the rising ambient CO_2 concentration in quantitative terms, therefore we doubled only the CO_2 gas concentration out of the input data of basic run (760 ppm), and the meteorological inputs remained the same. With this we localised the date of the expected change to 2070-2100.

In the further scenarios – beside doubling the current CO2 level (760 ppm) – we gradually rose the air temperature values compared to the basic run (1961-1990), and together with this we also modified the precipitation. The fourth scenario – on the basis of the B2 scenario of the IPCC 2007 Assessment Report – contained the summer values pertaining to Keszthely of the meteorological elements downscaled and mapped to Hungary by *Bartholy et al.* (2007) forecast to the period of 2070-2100. In this scenario the summer average temperature in Keszthely will rise by 3.8 °C, together with an about 15% decrease in precipitation. The fifth scenario used the summer data of the A2 IPCC-SRES (2000) scenario, downscaled to Hungary by the above-mentioned method, which calculates upon a stronger warming up than the former one (+4.8 °C). There is a 25% decrease in precipitation associated to this temperature rise. We note here that standard deviation is rather high at both scenarios (±15%); this implies strong uncertainty.

In the sixth scenario we increased the average air temperature by 6.0 °C, together with a 25% decrease in precipitation. This 6 °C rise is close to the value of the upper limit value (6.4 °C, annual average) in the IPCC Fourth Assessment Report (2007). This value is the result of the global level prognosis that can be higher in Hungary according to *Mika* (2007). Keeping this in view, in the last two scenarios we performed a further increase in the degree of warming up, by involving the 1.4 times product of the upper temperature rise (6.4 °C) pertaining to Hungary (9 °C). Since we knew the uncertainty of precipitation forecasts, we associated two types of precipitation supply to the 9 °C warming up; the seventh scenario assumes almost no change in precipitation (-10%), while the eighth scenario calculates upon a more significant drying (30% precipitation decrease). The comparison of these latter two scenarios later provided opportunity to quantify the impacts of the different precipitation supplies on plants. Markings of the individual scenarios are summarised in *Table 1*.

Results and Discussion

Vertical distribution of plant temperatures based on 3 measurement levels

First we illustrate the simulation results pertaining to plant temperature at three levels: at 0.38 m above the soil, at 1 m in the cob level and at 1.61 m above the leaves, by scenarios, with two solar positions (at low and high angles of entry) (*Figure 1*). For a better overview, we placed the individual scenarios on the vertical axle.

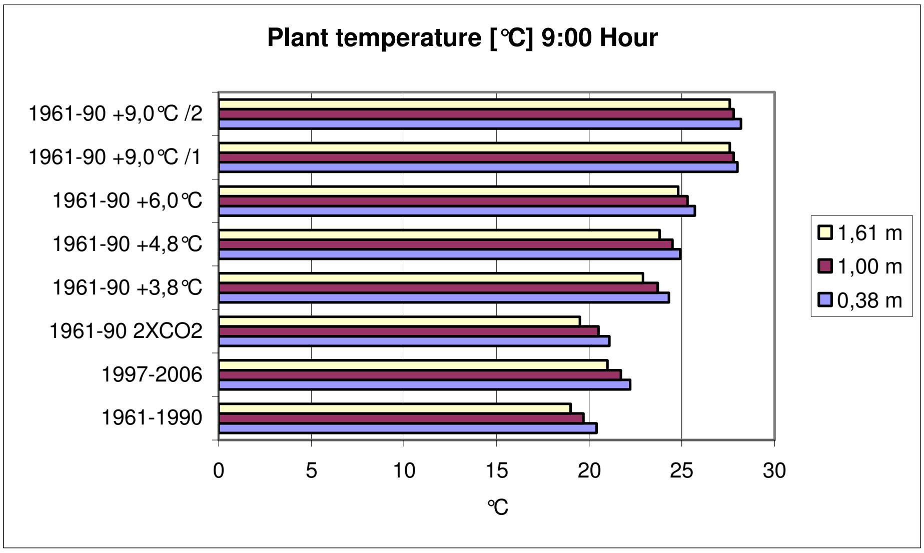

Figure 1 Development of plant temperature by scenarios at low solar position, at the 3 different plant heights simulated by the model: at 0.38 m, 1 m and 1.61 m (appearance of upper leaf levels)

The figure shows that the differences of the values of the individual levels follow the same tendencies depending on plant height in the case of the same scenario and at low angle of entry. Plant temperature is the highest at the level being closest to the soil, irrespective of the scenario; it is followed by the cob level, then temperature is the lowest at the upmost leaf levels. The tendency does not even change at high solar position, only the absolute values of plant temperature rise compared to the values measured in morning hours (*Figure 2*).

As a tendency, the values pertaining to the different levels were more expressive at lower plant temperatures (even at cooler weather simulation), irrespective of the solar position. The stronger the warming up is, the less and less differences in temperature among the individual plant height levels are. The likely reason for this is the stronger evaporation demand due to the higher air temperature whose satisfaction can only be with appropriate water supply. This phenomenon was obvious in the case of the scenarios with warming up above 6 °C, and it was characteristic of both solar positions.

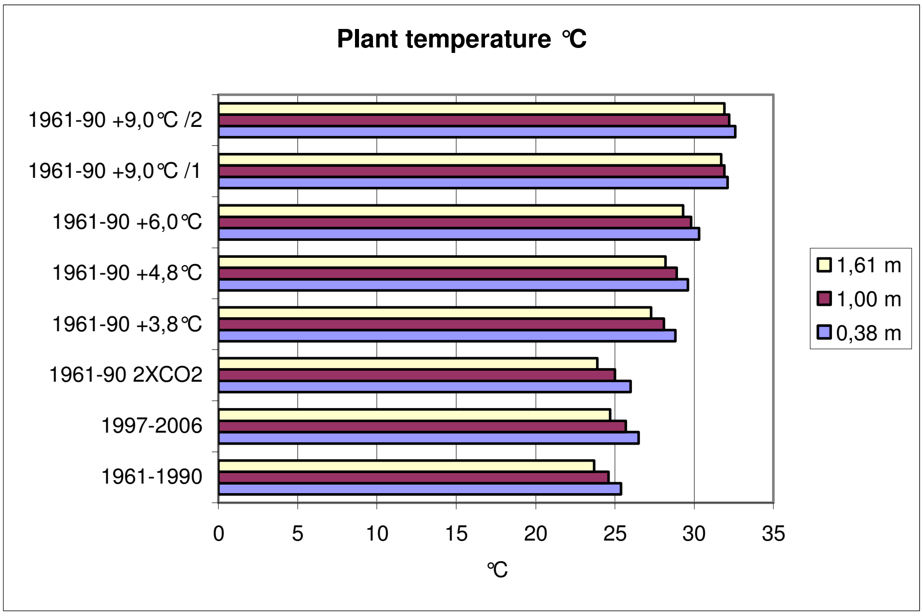

Figure 2 Development of plant temperature by scenarios at high solar position, at the 3 different plant height simulated by the model: at 0.38 m, 1 m and 1.61 m (appearance of upper leaf levels)

Development of plant temperature at cob level

Hereafter we summarise our simulation results to the cob level (1 m from the soil surface), which is the location of the most intensive physiological processes. In the course of the investigation we present the entire daily changes together with the development of plant temperature of night hours; it is a new approach.

In the case of the medium maturity hybrid we used the cob level of the maize was located at the height of 1 m from the soil surface (average of many years), and it did not significantly depend on the year itself. In drier years when the average height of the plants were smaller by 10-20 cm, the cobs were at a bit lower position, though the difference was up to 10-15 cm, similarly to the case of plant height. Based on the 30-year observation data series, the cob level of 1 m above soil surface is advantageous since this difference coincides with one of the locations of the model providing simulation results.

Plant temperature measured at cob level showed moderate rise when doubling the CO_2 concentration; it showed a significant increase of 0.2 °C (daily average) being independent from times of day (*Table 2*). It is in connection with the effect of the risen CO_2 concentration that narrows the stomata and lessens evaporation; it results in a slight increase in plant temperature due to the lack of plant cooling.

Table 1 Basic data of statistical analyses relating to the differences of the daily averages of plant temperature at cob level. Average means the daily average calculated by the model. **We highlighted those p values of the t-test in bold that represent significant difference at level of at least 5%.** At the compared scenarios we used ***bold and italic letters for the basic run***.

Scenario pairs	average [°C]	calculated p value of t-test	standard error
A=basic	21.325		
B	21.89583	**0.0059**	0.1881912
C	21.55833	**0.0000**	0.0516632
D	25.05417	**0.0000**	0.0373387
E	26.00417	**0.0000**	0.0503536
F	27.05	**0.0000**	0.0828063
G	29.425	**0.0000**	0.1290995
H	29.79167	**0.0000**	0.1270723
G=basic	29.425		
H	29.79167	**0.0000**	0.1270723
D=basic	25.05417		
E	26.00417	**0.0000**	0.0324149
F=basic	27.05		
G	29.425	**0.0000**	0.0836768
H	29.79167	**0.0000**	0.0473641

The cob level plant temperature in the past decade – similarly to the air temperature – rose significantly, by 0.6 (daily average), but this difference compared to the basic run (1961-1990) – contrary to the cob level canopy inside air temperature – was daily various by nature (*Figure 3*). From the second half of the night to a very high solar position the rise of plant temperature is significant, between 1 and 1.5 °C (hourly average). The direction of the difference between the temperatures of the two scenarios reversed – in the period with the highest solar position to a lesser extent, late afternoon to a larger extent – and its degree was stabilised between -0.2 and -0.7 °C. Finally, common handling of the values of periods with different solar positions resulted in the daily average plant temperature increase of 0.6 °C. We did not experience such a variety by times of day as we compared the other scenarios to the values of the basic run of 1960-1990. When we measured at the other scenarios, the degrees of the differences compared to the run of 1961-1990 proved as constant independently from the time of day.

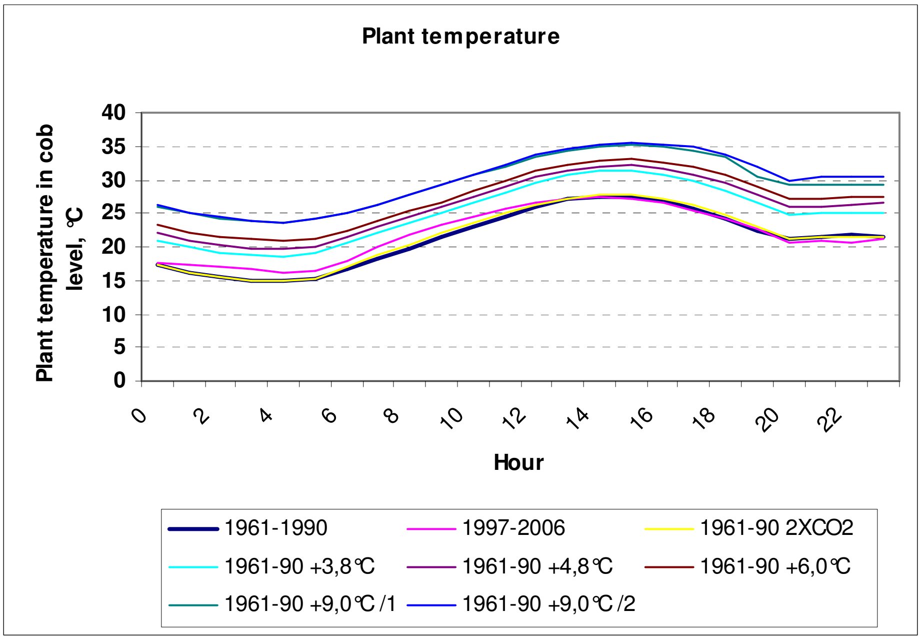

Figure 3 Development of plant temperature simulated to cob level on an average day of July

The rise in plant temperature determined for the downscaling of A2 and B2 scenarios to Hungary did not reach the value of the outer warming up simulated to the run, namely the plant temperature compensating effect of the canopy can be caught. In the case of lower simulated warming up the degree of compensation is lower, only a couple of tenth °C. A2 scenario brought the psychological breakthrough after which – with simulating a warming up of higher degree (from 6 °C up) – the plant temperature compensating effect worked but it was significantly reduced. The effect of the presence of the canopy that mitigates the increase in inside plant temperature compared to the increase in outer temperature emerged even in the case of the last two scenarios, namely depending on water supply. It was 0.9 °C at the scenario with better precipitation supply, and only about the half of it, 0.5 °C in the case of the drier treatment.

Except for the scenario pertaining to the past decade and for the one containing double CO_2 concentration, in the case of all the other runs the time of the development of the highest plant temperature changed, it changed to 3 pm from the former 2 pm. It is not a favourable tendency in itself, and mainly not because the period of the higher plant temperature became longer by one hour. During the afternoon – even under normal conditions – plant temperature frequently exceeds the temperature range favourable for the plant, so its extension increases the presence of the temperature higher than optimum; this certainly affects the production of the plant.

The values of the cob level plant temperature calculated by different scenarios compared to the values of the basic run; the two IPCC scenarios compared to each other; as well as the plant temperatures of both treatments with increased temperatures of 9 °C compared to the scenario with warming up of 6 °C – these all represented slight difference but significant at level of 5% at least. (see Table 2).

Prasad et al. (2006) earlier experienced that the negative effect of the increased plant temperature emerged mainly at the reproduction processes, which were not brought into the focus by the researcher till then. Our results may provide some new information to this topic.

Conclusions

On the basis of the simulation analysis performed to Keszthely it can be asserted that warming up increases plant temperature, but not to the same extent as the outer air temperature rises. The compensating effect of the canopy worked even in the case of serious temperature increase, but the degree thereof was also depending on water supply. The optimum plant temperature of maize is about 23-24 °C, and according to the local measurements performed around noon in Keszthely in July, the actual canopy temperature has exceeded this value several times (*Anda* 2001). The only chance of protection is to provide cooling medium and additional water supply for the plants; this supposes the re-consideration of the former irrigation practice.

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