Difference in Canopy and Air Temperature as an Indicator of Grassland Water Stress

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Abstract: In 2003–2005 in conditions of the moderately warm region of the Třeboň Basin (Czech Republic) the difference between canopy temperature (T_c) and air temperature at 2 m (T_a) was tested as an indicator of grassland water stress. To evaluate water stress ten-minute averages of temperature difference $T_c - T_a$ were chosen recorded on days without rainfall with intensive solar radiation from 11.00 to 14.00 CET. Water stress in the zone of the major portion of root biomass (0–0.2 m) in the peak growing season (minimum presence of dead plant residues) documented by a sudden increase in temperature difference, its value 5–12°C and unfavourable canopy temperatures due to overheating (> 30°C) was indicated after high values of suction pressure approaching the wilting point (1300 kPa) were reached. High variability of temperature difference in the conditions of sufficient supply of water to plants was explained by the amount of dead plant residues in canopy, value of vapour pressure deficit (VPD), actual evapotranspiration rate (ETA) and soil moisture content. At the beginning of the growing season (presence of dead plant residues and voids) we proved moderately strong negative linear correlations of $T_c - T_a$ with VPD and $T_c - T_a$ with ETA rate and moderately strong positive linear correlations of ETA rate with VPD. In the period of intensive growth (the coverage of dead plant residues and voids lower than 10%) moderately strong linear correlations of $T_c - T_a$ with VPD and multiple linear correlations of $T_c - T_a$ with VPD and soil moisture content at a depth of 0.10–0.40 m were demonstrated.

Keywords: water stress indicator; air temperature; canopy temperature; soil moisture; grassland; vapour pressure deficit; actual evapotranspiration

Water stress of plants is the state when plants reduce the utilisation of radiation energy to transpiration as a consequence of the lower storage of soil water that limits hydraulic conductivity for water transport from soil to atmosphere. Due to the diminished leaf potential the plants close stomata, and so they cannot cool their surface efficiently, subsequently reducing their photosynthetic production. The incident solar energy is consumed mainly for the warming of air and canopy while the canopy is mostly cooled through the radiation of heat energy. A by-effect of this state is a decrease in the canopy capacity to balance air temperature differences between day and night (PROCHÁZKA *et al.* 2001).

Water stress may be determined by the measurement of soil water potential, but it is a generally costly and complicated method of determining the water regime of soils. This method is hardly applicable in deep-rooted plants and stony soils. By an easy measurement of surface temperature with infrared sensors it is possible to use this important indicator for determination of plant water stress and/or of the rate of actual evapotranspiration

because a difference between the temperature of air and that of canopy (temperature difference) is a generally accepted indicator of water availability to plants (e.g. Jackson *et al.* 1977, 1981; Keener & Kircher 1983; Paw U 1984, and Olufayo *et al.* 1994). In the period of water stress temperature difference is influenced not only by the increasing surface resistance to water vapour transmission due to the closure of stomata but also by other factors limiting the use of this proposed indicator. Its values are influenced e.g. by the canopy structure through the occurrence of non-transpiring dead plant residues and voids at the beginning of spring. Vapour pressure deficit is another important evaluation criterion contributing to the definition of water stress on the basis of the difference between canopy (T_c) and air temperature (T_a) in the conditions of humid climate (Keener & Kircher 1983); this deficit and radiation balance are very variable in such conditions. The negative linear relation of T_c-T_a to vapour pressure deficit (VPD) under unlimited availability of soil water to plants (so called baseline) was included in the computation of the crop water stress index (Idso *et al.* 1981; Jackson *et al.* 1981) which indicates to what extent the crop suffers from water stress. E.g. phenophase and crop shading are other factors influencing the temperature difference (Idso 1982). An important factor of the correct evaluation of water regime by means of temperature difference is a suitable selection of daytime and weather when the informative capacity of indicators is highest. Days with fine sunny weather (e.g. Idso *et al.* 1981, Oliva *et al.* 1994, Zavadil & Doležal 2005) seem ideal at about midday or shortly after midday (Jackson *et al.* 1977, 1981). Zavadil and Doležal (2005) stated that temperature difference was also influenced by free liquid water on the plant surface.

The objective of the paper is to define suitability of the use of temperature difference for the indication of grassland water stress in conditions of the humid climate of the Czech Republic.

METHODS, DESCRIPTION OF EXPERIMENTAL LOCALITY

The method of grassland water stress analysis is based on the testing of suitability of the difference between T_c and T_a at a height of 2 m on the basis of comparison with soil characteristics (soil moisture content, % by volume, soil water potential, bar). To test water stress we chose the values of temperature difference T_c-T_a measured at 10-minute intervals from 11:00 to 14:00, on days without rainfall with global radiation intensity higher than 700 W/m². Under these conditions T_c-T_a indicates the water regime of the site more exactly than in cloudy or even rainy weather (a decrease in temperature difference and vapour pressure deficit) and a precondition for the validity of Bowen ratio method (maximisation of temperature gradient or air humidity) suitable for the computation of actual evapotranspiration (ETA) may be satisfied. To evaluate T_c-T_a variability in the period without water stress we determined simple linear regressions of T_c-T_a on ETA rate and VPD, the difference between maximum pressure of water vapour at a given air temperature and actual pressure of water vapour in hPa and multiple linear regressions of temperature difference simultaneously on VPD and soil moisture content. The ETA rate was determined by the method of energy balance and Bowen ratio that was derived from the theory of turbulent diffusion. The results document the growing seasons 2003 to 2005.

Site description

An experimental plot is entered in the land register of Klečaty municipality in the former district Tábor, Czech Republic; geomorphologically it is situated in the Třeboň Basin, at an altitude of 423 m above sea level, in a moderately warm climatic region. Precipitation and temperature means (1.1.1961–31.12.1990) at Borkovice Station (of Czech Hydrometeorological Institute) are 596 mm and 7.2°C, in the growing season (IV–IX) 388 mm and 13.3°C. In pedological terms, the soil type is pseudogleyic Luvisol (Evaluation Soil Ecological Unit 7 43 00) and the soil texture is sandy loam. The plot was drained, and the groundwater table is not mostly available to plants in the growing season. The grassland is not fertilised, its constant height of ca. 10 cm is maintained, and *Alopecurus pratensis* is a dominant species.

Method of actual evapotranspiration determination on the basis of energy balance and Bowen ratio

Actual evapotranspiration was determined on the basis of energy balance and Bowen ratio. ETA

is calculated from the energy balance equation and Bowen ratio determination (Monteith 1973):

Energy balance equation:

$$Rn = G + LE + H + P \tag{1}$$

where:
Rn – radiation balance (W/m^2)
G – heat flux into soil (W/m^2)
LE – heat flux consumed for evaporation (W/m^2) (L – latent heat of water evaporation, E – density of water vapour flux from evaporating surface to atmosphere, i.e. ETA intensity (kg/m^2/s))
H – turbulent heat flux (W/m^2)
P – energy value of photosynthetic production (W/m^2), usually neglected for its low value

We adjust Eq. (1) for the calculation of *LE* with omission of *P* to:

$$LE = Rn - G - H \tag{2}$$

Rn and *G* are relatively easy to be measured but it is difficult to determine *H*, it can be calculated from so called Bowen ratio β. β is based on the turbulent diffusion theory and if some assumptions are satisfied, it can be calculated from the vertical temperature gradient and water vapour concentration. The basic assumption is the equality of transport coefficients for vertical turbulent transport of heat and water vapours under the condition of neutral atmosphere stratification and sufficiently extensive canopy.

Bowen ratio β is defined as the quotient of *H* and *LE* from equations for vertical turbulent transport of heat (Monteith 1973) and transport of water vapours (Novák 1995). After modifications of those equations and after introduction of the concept of psychrometric constant γ (kPa/°C) we get the equation:

$$\beta = \gamma \frac{(T_2 - T_1)}{(T_2 - T_1)} \tag{3}$$

where:
$T_2 - T_1$ – difference in air temperature at two heights above the canopy (°C)
$e_2 - e_1$ – difference in humidities at those two heights above the canopy (kPa)

By easy modification of Eq. (2) and by introduction of β we calculate ETA:

$$ETA = \frac{Rn - G}{L\,(1 + \beta)} \qquad (mm/s) \tag{4}$$

Heat flux into soil G (W/m^2) was determined indirectly from the vertical gradient of temperature in soil and its heat conductivity on the basis of the simple relationship:

$$G = \frac{\alpha\,(T_2 - T_1)}{(z_2 - z_1)} \tag{5}$$

where:
α – heat conductivity of soil: 1.0 (W/m/K) (Baver *et al.* 1972)
T_1, T_2 – soil temperature (°C) at the depth of 0.1 and 0.2 m
z_1, z_2 – soil depth of 0.1 m and 0.2 m

Instrumentation

ETA values were computed from the data of an automated meteorological station placed on the grassland maintained at a constant height (ca. 0.10 m). Sensors registered measured values each minute and a datalogger stored their ten-minute means.

The measuring system for the acquisition of ETA data consists of a MiniCube VV/VX datalogger (EMS Brno, CR) registering data: from 2 sensors measuring temperature and relative air humidity at two heights (0.5 and 2.0 m, sensors with the same error were chosen, so called sensor pairing), from a pyranometer for the measurement of global solar radiation, from a balancemeter, from two sensors registering the soil temperature at two depths (0.1 and 0.2 m), and from an anemometer measuring the wind speed (at 2 m).

As the station was equipped with the balance-meter in October 2003, before its installation *Rn* was determined on the basis of estimation of grassland albedo from literature to amount to 20% (Novák 1995) and calculation of long-wave radiation of the Earth (Allen *et al.* 1998). Since the growing season 2004 *Rn* values were measured with a balancemeter (Schenk Company, model 8110, annual stability 3%).

Methods for determination of canopy and air temperature, air humidity, soil moisture content and soil water potential

Canopy and air temperature, air humidity. Both air and canopy temperature together with next common meteorological variables were measured with a small meteorological station uEMSet 99 manufactured by Environmental Measuring

Systems, Brno, CZ. Air temperature/humidity sensor EMS 32A inside the radiation shield was installed at 2 m level above the ground. Infrared thermocouple OS36-2-80 made by Omega Engineering, Inc, U.S.A. was located 0.85 m above the ground and pointed downwards. Field of view of this sensor is defined as a circle with diameter/sensor distance ratio equal 1:2. With respect to the above-mentioned level the canopy area the average temperature of which is measured is represented by a circle with ca. 40 cm in diameter. The sensor output is linear (2% error) within the temperature range between 10 and 49°C. The emissivity of grass cover was estimated to 0.95 and set in datalogger configuration.

Soil moisture content (by volume). Soil moisture content (by volume) was measured by Time Domain Reflectometry (Water Content Reflectometer, Campbell Scientific, USA, model CS 616, length 30 cm, to the nearest 2.5%). Water content in the environment is derived from the speed of propagation of electromagnetic waves in the space with variable dielectric constant given practically only by the water content in soil. Sensors were placed at a depth of 0.13–0.43 m (soil moisture 1, the sensor was placed at 13 cm below the surface to hide also the sensor body), 0.3–0.6 m (soil moisture 2) and 0.6–0.9 m (soil moisture 3).

Soil water potential. Soil water potential describes energy requirements of plants for depletion of a unit of water from the soil at different soil moisture contents within available water capacity and is expressed by suction pressure. Suction pressure (SP) was measured with gypsum blocks (model GB 2, Delmhorst, USA, range 10–1500 kPa) at a depth of 0.1; 0.2; 0.3; 0.4; 0.5 and 0.6 m (SP 1, SP 2, SP 3, SP 4, SP 5, SP 6). The used equation of conversion of SP values from the resistance between the block electrodes in the form of a polynomial of 4th degree was determined by regression from tabular values given by the manufacturer (Kučera, personal communication).

The data on soil water characteristics were stored in the interval of 10 min by the MiniCube VF datalogger (EMS Brno, CR) installed at the meteorological station.

Statistical methods

Mini 32 software (version 3.65.22.29 of EMS Brno Company, CR) was used for determination of simple linear relationships; to evaluate multiple linear regressions Statgraphics software, version 7.1, was used.

RESULTS AND DISCUSSION

Periods evaluating temperature difference as a potential indicator of water stress comprised different growing seasons from the season with extremely below-normal rainfall and extraordinarily above-normal temperatures (2003) through that with normal rainfall and temperatures (2004) to the season with extremely above-normal rainfall and normal temperatures (2005).

At the beginning of the growing season the growth activity is influenced by the temperature of air and/or soil. The amount of available water is not usually limiting for canopy development in this period (after winter). The grassland of the given site starts growing actively after the average air temperature does not drop below 10°C, minimum daily temperature below 0°C and minimum soil temperature at 0.1 m below 5°C. Before these conditions are established, the growth rate is minimum and the grassland has a low index of active leaf area (LAI), i.e. in the canopy there are voids (ca. 10%) and a lot of non-transpiring dry parts (10–30%) coming from the preceding off-season and being overheated. As a consequence of these phenomena, and due to low VPD (about 5–7 hPa) and lower solar radiation that limit the transpiration process, $T_c–T_a$ reached the values up to 10–14°C. So the high temperature differences $T_c–T_a$ did not indicate the limited transpiration and minimum cooling of canopy as a result of water stress. The energy of radiation balance was mostly used for air warming. In the course of time (i.e. 2nd half of April–1st half of May) with a decreasing proportion of dead plant residues VPD and transpiration rate increased, the canopy was cooled more intensively and temperature difference also decreased. In this period (early April to mid-May) the values of $T_c–T_a$ were very variable and ranged between 0 and 14°C in relation to weather conditions (VPD) and proportion of dead plant residues (> 10%) even though the soil contained enough water for evaporation (Figure 1, the maximum value of T_c reached by about 3 h earlier than the maximum of T_a was caused by the relation of air temperature to canopy temperature, also Zavadil & Doležal 2005). Linear regression indicated a negative linear correlation of selected values of $T_c–T_a$ with VPD – Figure 2, for the chosen year
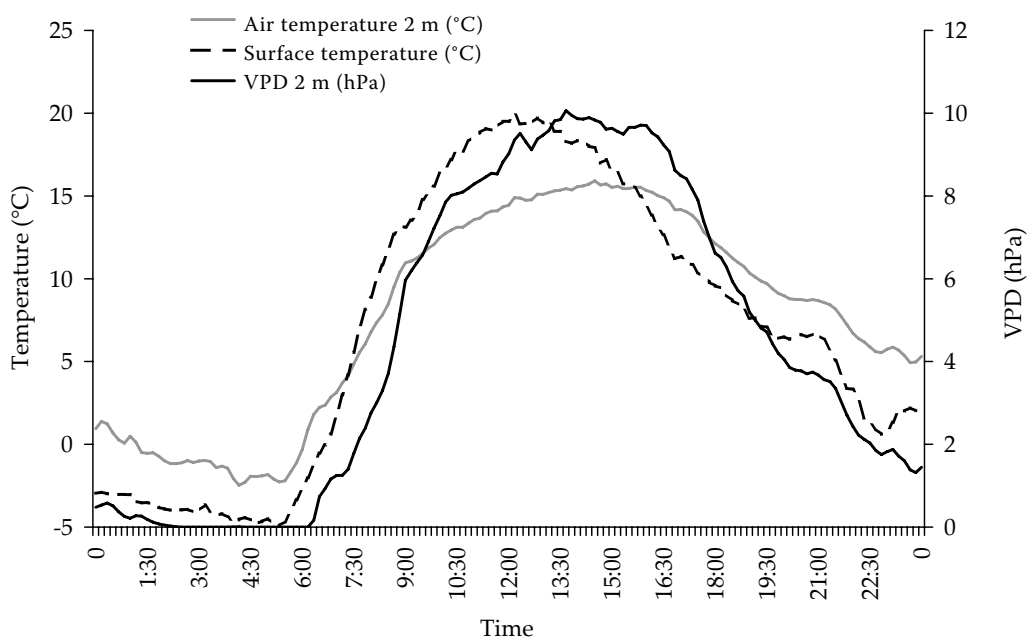
Figure 1. Vapour pressure deficit (hPa), air and canopy temperature (°C), period of the presence of dead plant residues (sufficient amount of water in the soil), Klečaty 15.4.2004

2005, similarly reported by ERHLER (1973) and IDSO *et al.* (1981) – and a positive linear correlation between ETA rate and VPD (Figure 3). A negative linear correlation of $T_c - T_a$ with ETA rate (Figure 4) was also calculated. The determined correlations for the period 2003–2005 are all statistically significant on a 0.01 significance level and are expressed as moderately strong by means of linear equations in Table 1.

The values of absolute members and slopes of the given equations are influenced not only by the relation of $T_c - T_a$ to VPD and ETA rate but also by the change in the proportion of dead plant residues. The large temperature difference is con-

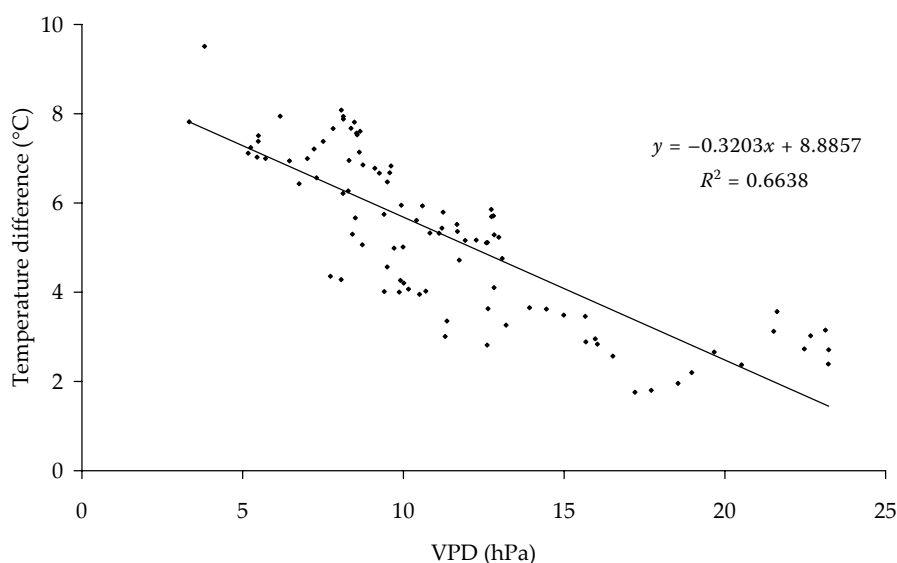$$y = -0.3203x + 8.8857$$
$$R^2 = 0.6638$$

Figure 2. Correlation of temperature difference (°C) with vapour pressure deficit (hPa) in a rainless period around midday (11:00–14:00), at global radiation intensity > 700 W/m², Klečaty, 1.4.–6.5.2005

Table 1. Correlations expressed by the parameters of linear lines including the expression of coefficient of determination (R^2), Klečaty, beginning of the growing season (presence of dead plant residues)

Variable y	Variable x	Period	Absolute member	Slope of line	R^2
T_c-T_a	VPD	26.3.–9.5.2003	11.662	−0.386	54.7
T_c-T_a	VPD	1.4.–8.5.2004	11.149	−0.664	51.1
T_c-T_a	VPD	1.4.–6.5.2005	8.886	−0.320	66.4
T_c-T_a	ETA rate	26.3.–9.5.2003	13.349	−17.840	38.4
T_c-T_a	ETA rate	1.4.–8.5.2004	12.485	−21.649	65.6
T_c-T_a	ETA rate	1.4.–6.5.2005	10.134	−14.203	70.3
ETA rate	VPD	26.3.–9.5.2003	0.209	0.013	48.9
ETA rate	VPD	1.4.–8.5.2004	0.154	0.021	37.4
ETA rate	VPD	1.4.–6.5.2005	0.147	0.017	56.0

nected with the beginning of the growing season when the proportion of dead plant residues is high while VPD and ETA rate are relatively low. The low value of T_c-T_a reflects higher VPD, ETA rate and decreasing proportion of dead plant residues later on. Hence the proportion of dead plant residues increases the parameters of the above-mentioned equations.

With the onset of canopy intensive growth (May, June), with a decreasing proportion of dead plant residues and canopy voids (up to 10%) and if a relatively sufficient amount of water for canopy cooling through transpiration was available (we chose the periods when the values of suction pres-

sure were lower than those of the reduced availability point RAP, i.e. to 100–200 kPa), T_c-T_a was lower than in the preceding period, nevertheless it was still quite variable (mostly in the range of 0–6°C, Figures 5 and 6). By determining the same relationships as in the period of dead plant residues presence, i.e. the correlation of T_c-T_a with ETA rate and VPD, and of the correlation of ETA rate with VPD (Figures 7–9), the correlations with lower coefficients of determination than in the period of dead plant residues presence were computed. It is so because the proportion of dead plant residues is relatively stable (up to 10%) and does not influence the variations in T_c-T_a like in

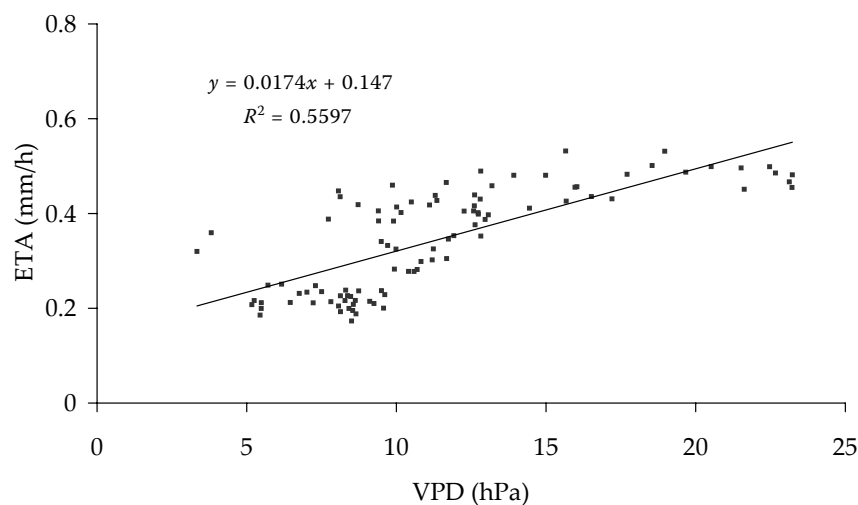$$y = 0.0174x + 0.147$$
$$R^2 = 0.5597$$

Figure 3. Correlation of actual evapotranspiration rate with vapour pressure deficit in a rainless period around midday (11:00–14:00), at global radiation intensity > 700 W/m^2, Klečaty, 1.4.–6.5.2005
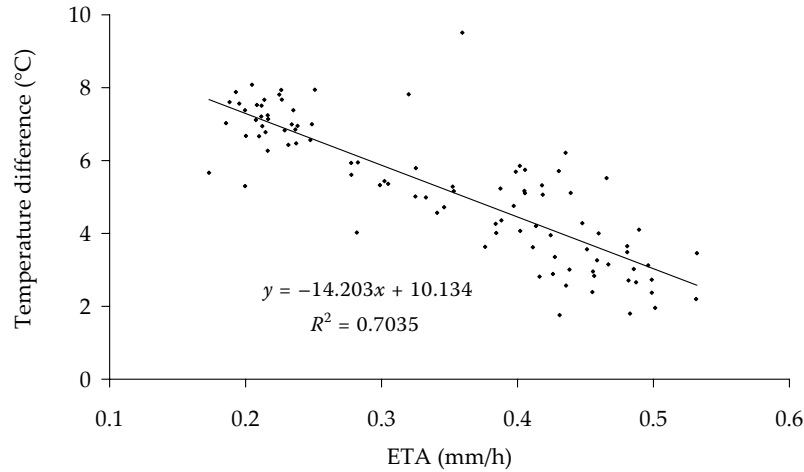
Figure 4. Correlation of temperature difference (°C) with actual evapotranspiration rate (mm/h) in a rainless period around midday (11:00–14:00), at global radiation intensity > 700 W/m^2, Klečaty, 1.4.–6.5.2005

the preceding period. This is the reason why the absolute members and slopes in regression linear equations are lower than in the preceding period (except the absolute members of equations of the correlation of ETA rate with VPD that express a higher rate of ETA in this period compared to the preceding one). Due to the presence of dead plant residues and canopy voids the computed negative linear correlation of $T_c - T_a$ with VPD is not identical with the baseline as reported by Jackson *et al.* (1977, 1981) and Idso *et al.* (1981), i.e. with the relation of $T_c - T_a$ to VPD in the canopy with 100% coverage and not limited by the content of soil water, when $T_c - T_a$ is lower than or equal 0°C. The
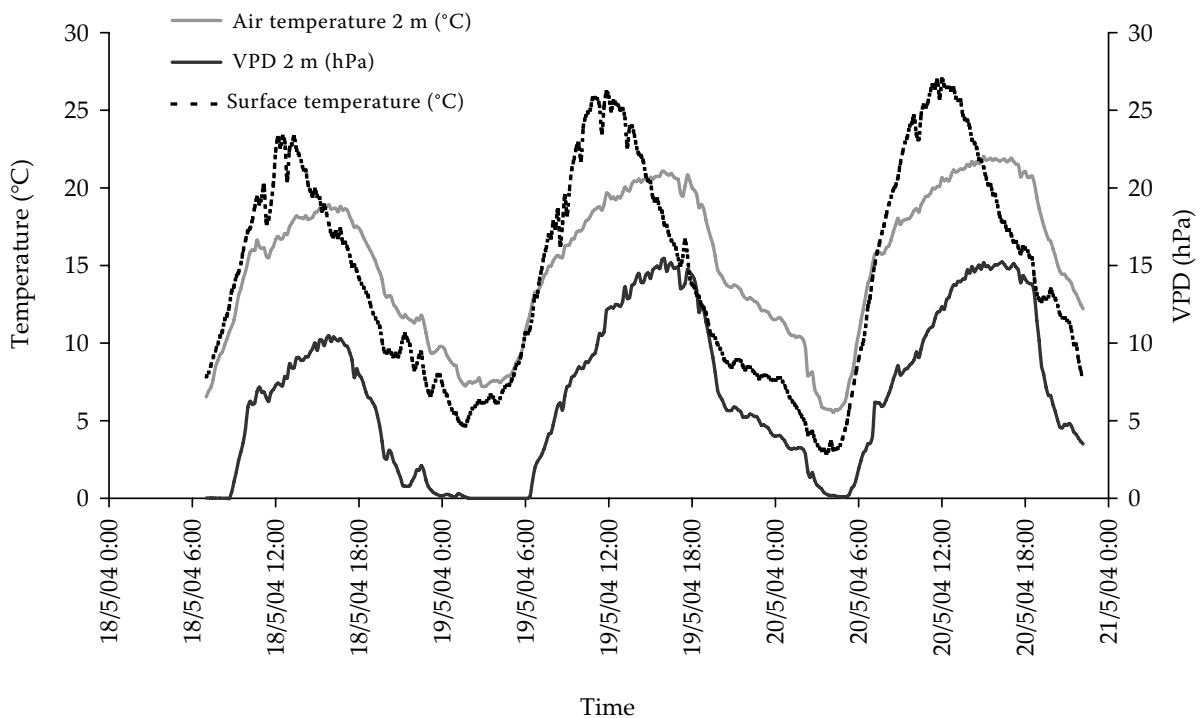

Figure 5. Vapour pressure deficit (hPa), air and canopy temperature (°C), increased surface temperature (sufficient amount of water in the soil), Klečaty 18.–20.5.2004

Table 2. Correlations expressed by the parameters of linear lines including the expression of coefficient of determination (R^2), Klečaty, period of intensive growth

Variable y	Variable x	Period	Absolute member	Slope of line	R^2
T_c-T_a	VPD	10.5.–2.6.2003	5.876	−0.361	**70.2**
T_c-T_a	VPD	14.5.–9.7.2004	8.274	−0.341	**29.7**
T_c-T_a	VPD	12.5.–12.6.2005	6.416	−0.225	**64.5**
T_c-T_a	ETA rate	14.5.–2.6.2003	6.727	−8.579	18.0
T_c-T_a	ETA rate	14.5.–9.7.2004	7.912	−9.213	9.8
T_c-T_a	ETA rate	12.5.–12.6.2005	7.913	−10.298	**31.5**
ETA rate	VPD	14.5.–2.6.2003	0.407	0.012	**32.2**
ETA rate	VPD	14.5.–9.7.2004	0.355	0.004	4.3
ETA rate	VPD	12.5.–12.6.2005	0.304	0.010	**42.1**

relatively high value of T_c-T_a is also caused by the measurement of T_a at 2 m above the ground, which is lower than at a height of 1.5 m (Jackson *et al.* 1977, 1981; Idso 1982). Last but not least, the relation of T_c-T_a to VPD is influenced by the crop species – its aerodynamic resistance r_a (e.g. Idso 1982).

In Table 2 all computed relationships are documented as statistically significant on a 0.01 signifi-

cance level (the relationships in bold are defined as moderately strong).

The introduction of two independent variables into the model of multiple linear regression – soil moisture 1 and VPD – contributed to the more exact explanation of T_c-T_a variability (2003 and 2005). The year 2004 was not evaluated because the sensor for the measuring of soil moisture 1 had
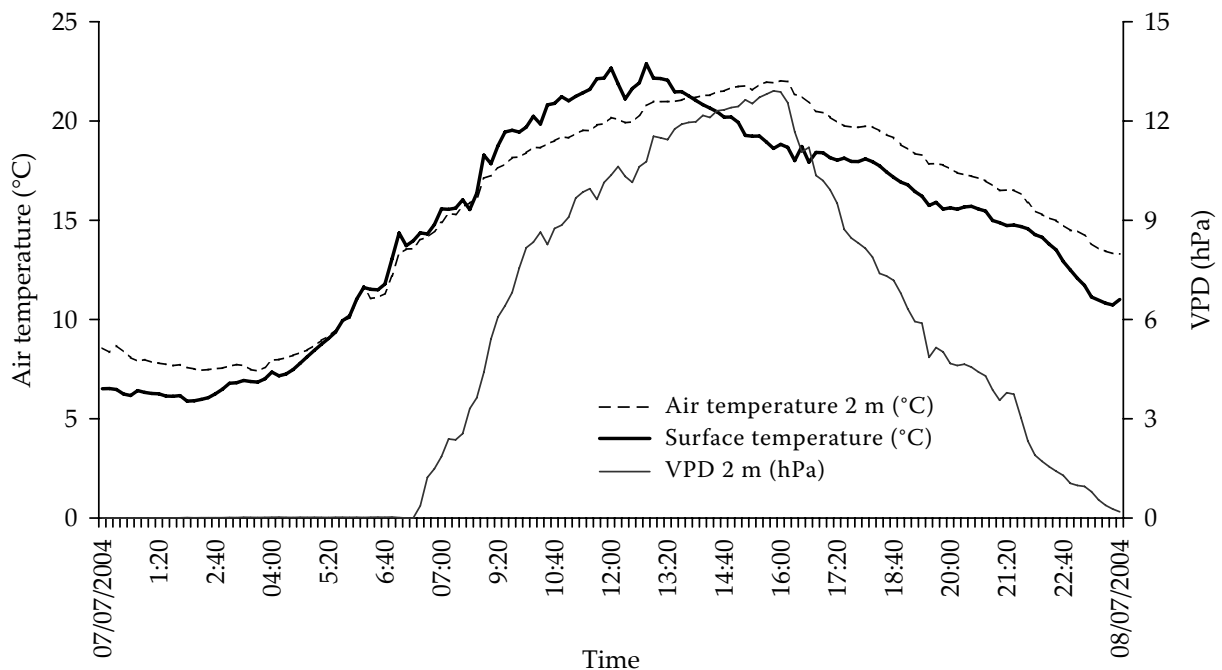

Figure 6. Vapour pressure deficit (hPa), air and canopy temperature (°C), balanced air and surface temperature (sufficient amount of water in the soil), Klečaty 7.7.2004
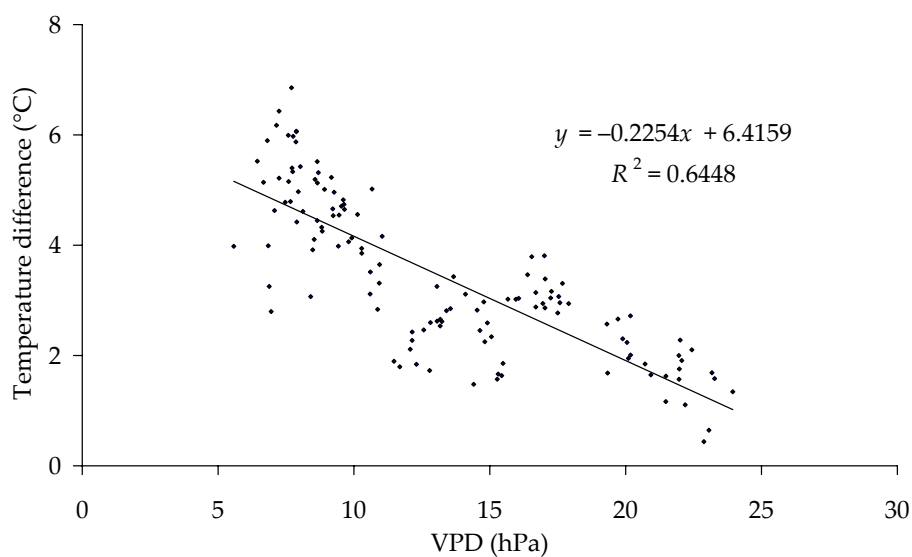
Figure 7. Correlation of temperature difference (°C) with vapour pressure deficit (hPa) in a rainless period around midday (11:00–14:00), at global radiation intensity > 700 W/m², Klečaty, 6.5.–16.6.2005

to be repaired. All correlations were significant on a 0.01 significance level (Table 3).

Similarly, Park *et al.* (2005) reported statistically significant correlations of the deviation of canopy temperature from air temperature and soil water storage.

Although the coefficients of determination of the given linear relationships are highly variable, the exist-

Table 3. Correlations expressed by the parameters of the plane including the expression of coefficient of determination (R^2), Klečaty, period of intensive growth

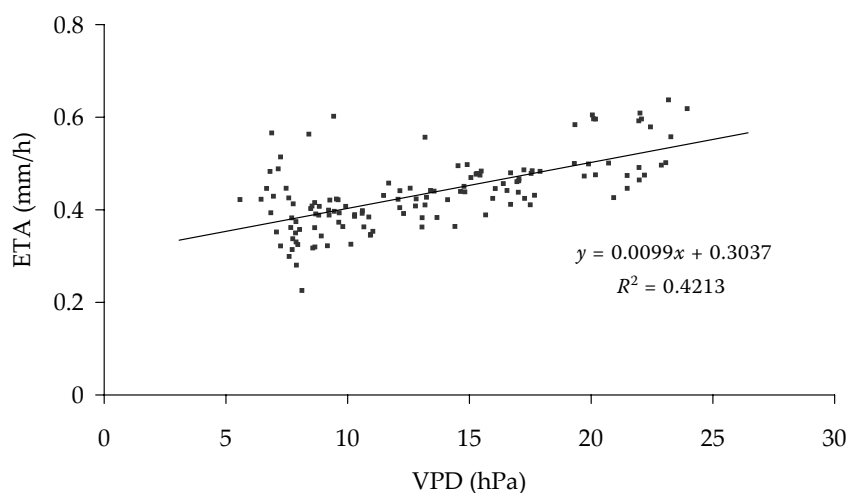| Dependent variable	Independent variable	Period	Absolute member	Partial regression coefficients	R^2
$T_c - T_a$	moisture 1, VPD	14.5.–2.6.2003	18.16	−56.13; −0.30	77.33
$T_c - T_a$	moisture 1, VPD	12.5.–12.6.2005	10.51	−15.88; −0.19	72.68

Figure 8. Correlation of actual evapotranspiration rate with vapour pressure deficit in a rainless period around midday (11:00–14:00), at global radiation intensity > 700 W/m², Klečaty, 6.5.–16.6.2005
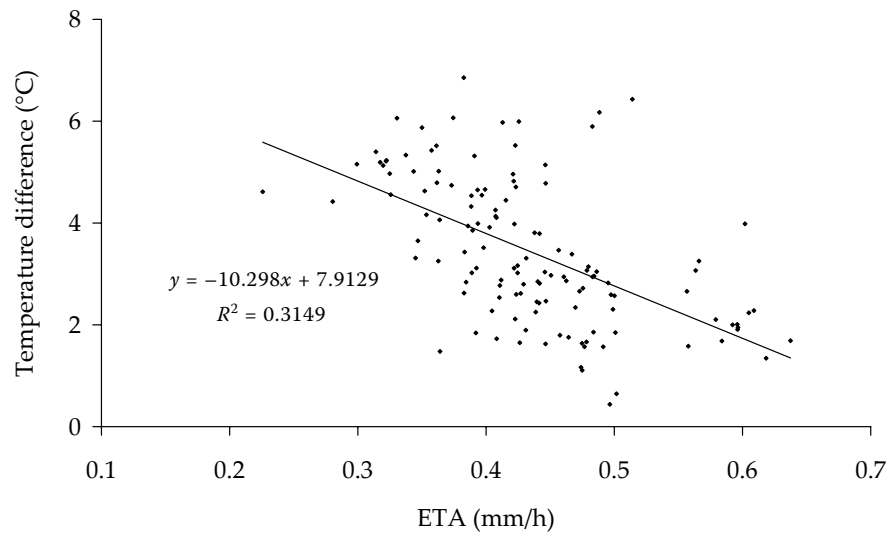
Figure 9. Correlation of temperature difference (°C) with actual evapotranspiration rate (mm/h) in a rainless period around midday (11:00–14:00), at global radiation intensity > 700 W/m², Klečaty, 6.5.–16.6.2005

ence of the above-mentioned correlations is obvious. Our results are also confirmed by the conclusions of KEENER and KIRCHER (1983), who recommended in humid conditions for the reason of high variability of saturation deficit and radiation balance to include also saturation deficit and/or radiation balance in the evaluation of water stress besides the difference between canopy and air temperature.

In the peak growing season (June–August) the grassland was frequently (except in 2005) affected
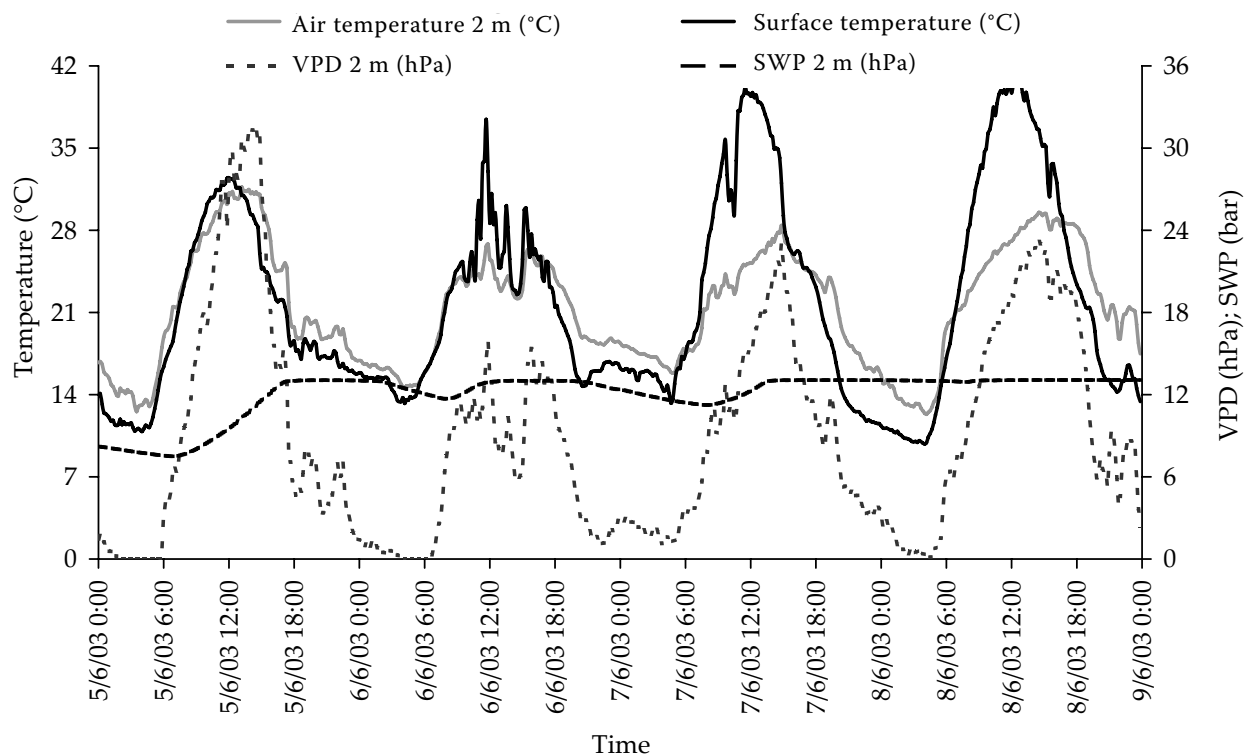

Figure 10. Vapour pressure deficit (hPa), air and canopy temperature (°C), soil water potential at 0.2 m (bar), onset of water stress, Klečaty 5.–8.6.2003

by water stress, mainly in 2003. Plants saved soil water by increasing the surface resistance and reducing the transpiration rate, and for this reason on a sunny day their maximum temperature markedly exceeded an optimum temperature (i.e. 22–27°C, Figure 10). T_c-T_a suddenly increased (Figure 10, similarly like in 2004) as soon as the maximum value of suction pressure of the gypsum block was reached (1300 kPa) in the soil profile 0–0.2 m, where the major portion of root biomass is placed, and in the course of water stress it reached the value up to 12°C when the maximum daily canopy temperature mostly exceeded 30°C. Obviously, a steep increase in T_c-T_a and at the same time an increase in canopy temperature markedly above the physiological optimum mostly occur in the zone where the major portion of root biomass is placed (80–90%) after a suction pressure close to the wilting point has been reached (i.e. suction pressure 1500 kPa, pF 4.18). As the increase in T_c-T_a was proved after the substantial dehydration of the soil layer 0.0–0.2 m, it was necessary to draw water for transpiration and canopy cooling from deeper layers of the soil profile (> 0.2 m) before the steep increase in T_c-T_a. After T_c-T_a increased, there was not a sufficient amount of water in the whole soil profile for canopy cooling.

In the period of water stress no regression correlations of T_c-T_a with the factors of the surrounding environment were determined.

CONCLUSION

The interrelationships of ETA rate, VPD and T_c-T_a in the period when transpiration rate is not limited by soil water content indicate that ETA rate influences T_c-T_a through VPD and that the midday rate of evapotranspiration can be estimated by means of VPD. During the peak growing season (June–August) temperature difference between canopy and air can be used to determine grassland water stress on days without precipitation, with intensive global radiation and at midday. The onset of water stress in the zone of the major portion of root biomass characterised by the proximity of wilting point was indicated very exactly by the sudden increase in T_c-T_a simultaneously when the canopy temperature exceeded the physiological optimum. The determined high variability of T_c-T_a in the period without water stress was quite exactly explained by variable VPD, ETA rate, soil moisture content and proportion of dead plant residues. The quantification of water stress by means of T_c-T_a can be applied in practice to determine the harvest of grassland aboveground biomass or to regulate the cattle load of pasture under water stress.

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