DE GRUYTER
OPEN

Contributions to Geophysics and Geodesy Vol. 46/2, 2016 (137–154)

The course, stratification and possibility of simulating relative air humidity in winter wheat stand

Jana KRČMÁŘOVÁ, Radovan POKORNÝ, Tomáš STŘEDA

Department of Crop Science, Breeding and Plant Medicine, Mendel University in Brno,
Zemědělská 1, 613 00 Brno, Czech Republic; e-mail: jana.krcmarova@mendelu.cz,
radovan.pokorny@mendelu.cz, tomas.streda@mendelu.cz

Abstract: The aim of this study was: (i) long-term (2010, 2011 and 2013) evaluation of the relative air humidity in the winter wheat canopy, (ii) finding of relationships between relative air humidity in canopy and computed or measured meteorological values (precipitation totals, evapotranspiration, moisture balance, specific air humidity, volume soil moisture, % of available soil water content, value of soil water potential), (iii) testing of simulation of daily relative air humidity, based on selected meteorological values and potential evapotranspiration (FAO Penman-Monteith method) and actual evapotranspiration, (iv) testing of simulation of relative air humidity hourly values in the wheat canopy, (v) evaluation of dependence between relative air humidity and leaf wetness. The measurement was performed at the experimental field station of Mendel University in Žabčice (South Moravia, the Czech Republic). Data recording for wheat canopy was conducted by means of a meteostation equipped with digital air humidity and air temperature sensors positioned in the ground, effective height of the stand and in 2 m above the ground. The main vegetation period of wheat was divided into three stages to evaluate differences in various growing phases of wheat. The data from nearby standard climatological stations and from agrometeorological station in Žabčice were used for establishment of relationships between relative air humidity in winter wheat canopy and surrounding environment by correlation and regression analysis. Relative air humidity above 90% occurred substantially longer on the ground and at the effective height of the stand in comparison with the height of 2 m. By means of regression analysis we determined that the limit of 90% was reached in the canopy when at the climatological station it was just 60 to 90% for ground level and 70 to 90% for effective height, especially during the night. Slight dependence between measured or computed meteorological variables and relative air humidity in winter wheat canopy was found ($r = 0.23 - 0.56$ for precipitation totals, $r = 0.27 - 0.57$ for % of available soil water capacity, etc.). The simulation of hourly values of relative air humidity in wheat canopy is partially possible just when using the data of relative air humidity from the relevant standard climatological station.

Key words: microclimate, canopy, relative humidity, evapotranspiration, soil moisture, phenology

doi: 10.1515/congeo-2016-0010

1. Introduction

The majority of crop models, pest or disease prediction models, agrometeorological models, drought monitoring systems etc., generally use data from standard climatological stations with monitoring at a certain height above the grassland. With regard to abiotic and biotic factors influencing stand microclimate, this method is necessarily burdened by inaccuracies. The relationships between the conditions at standard climatological stations and stand microclimate strongly depend on the nature, structure and growth phase of vegetation as well as altitudinal location of measuring sensors. The microclimate of vegetation is characterized by the appearance of diffuse solar radiation, minor fluctuations in air temperature and humidity, reduced airflow (wind, convection and turbulence), higher humidity and lower long-wave radiation during the night (*Krédl et al., 2012*). Canopy with high leaf area index (LAI) can reduce over 95% of solar radiation and this should keep the air and soil beneath the canopy cool during the day (*Bonan, 2008; Klimešová et al., 2013*). Despite many sophisticated works aimed at simulation of physiological processes in stands, a full understanding of the relationship between vegetation and microclimate is currently lacking. It is a crucial factor for the development of microclimate model across heterogeneous landscapes (*Hardwick et al., 2015*). Outputs of precise measurements of microclimate humidity can be used as input data for mathematical modelling of evapotranspiration, processes of yield-making and biomass production in relation to physiological indications of water stress and subsequently utilized to optimize irrigation systems, as a basis for predicting the occurrence of pathogens and animal pests (*Matejka et al., 2002*).

The air humidity level is not the only factor that impacts the pathogens' ability to infect various organs of plants and the consequent development of the disease. The duration of the humidity is also of key importance (*Středa et al., 2013*). *Rožnovský et al. (2002)* found that values of water vapour pressure and relative air humidity increase in comparison with the active layer of the canopy that is at the level of effective height and above. At the effective height of the stand (i.e. 0.68 × actual height with extreme values of 0.53 to 0.86; *Mölder et al., 1999*) solar radiation is transformed into other kinds of energy (*Hurtalová et al., 2003; Matejka and Huzulák, 1987*), which has a significant impact on the temperature and humidity regime. *Liu and Kang (2006)* measured the vertical distribution of vapour pressure from 1 m to 8 m above the ground surface in a winter wheat field. The values of the vapour pressure decreased with increasing height. *Han and Li (2010)* stated that air humidity was highest and saturation deficit was lowest in the middle of wheat canopy, while the maximum humidity appeared at heading and flowering stage (BBCH 51–69). In densely sown crops of wheat, *Yang et al. (2008)* found higher air humidity.

The article is aimed at clarifying the vertical stratification of air humidity in winter wheat canopy and their comparison with the data from nearest standard (reference) climatological station. The possibilities of relative air humidity simulation were tested. Consequently, the results can be used to make the prediction methods for occurrence of harmful agents more precise and thus to elaborate more accurate physiological and growth models of plants.

2. Material and methods

The microclimatic data was obtained in 2010, 2011 and 2013 at the field experimental station in Žabčice municipality (South Moravia, Czech Republic, Central Europe, GPS location: 49° 1' 18.658" N, 16° 36' 56.003" E) in the canopy of winter wheat (*Triticum aestivum* L., Sultan variety). The year 2012 was not taken into account, because of massive damage to the crop by drought. For evaluation, data of relative air humidity from the agrometeorological station (measurement of relative air humidity in 2 m height above soil surface, short-cut grass cover, sensors placed in a standard meteorological screen) located approximately 60 metres from the canopies, were used. Meteorological data (wind speed; long-term and daily average, minimum and maximum air temperature; daily and long-term precipitation totals; relative air humidity at 2 m above ground) were gained from the Czech Hydrometeorological Institute (CHMI) standard climatological station of Pohořelice, situated approximately 8 km away from the experimental plot. Further comparison (regression analysis between relative air humidity in canopy and above grass stand) also used data from standard climatological station of the CHMI in Tuřany, which is located approximately 15 km away from the experimental plot.

The experimental area Žabčice is situated in the Svratka river flood plain at the average altitude of 184 MASL. According to the agroclimatic classification (*Kurpelová et al., 1975*), the locality belongs to the warm macro area, predominantly warm area, predominantly dry sub area region with rather mild winters. The standard annual temperature during 1961–1990 was 9.2 °C, the annual precipitation standard was 483 mm.

The fifteen-minute step of data recording was carried out by the means of a meteostation equipped with relative air humidity (RH) sensors (sensor Honeywell HIH 4000) and air temperature (AT) sensors (Dallas semiconductor, DS18B20 type) placed in a solar radiation shield, rain gauge for precipitation measurement, LI-COR radiation sensors for total solar radiation measurement (measurement of sun shine duration) and anemometer W1 (Tlusťák, Praha) for wind speed measurement. The air humidity sensors were positioned at three levels (near the ground namely at a height of about 0.05 m – relative air humidity in the ground height – RHGH, at the effective height – RHEH and at 2 metres above the ground – RH2mH) in order to cover the whole vertical profile. Sensors positioned at the effective height were moved up as the crop was growing, to a height corresponding to approximately 70–85% of the actual canopy height. RH was converted on specific air humidity (SH) by the standard conversion equation.

The VIRRIB sensors (Amet, Velké Bílovice) were used for measuring the volumetric soil moisture under wheat canopy. The sensors measured hourly soil moisture at depths of 0.20 and 0.40 m (horizontally placed sensors). Available soil water content (ASWC) was assessed as an average value based on monitored volume soil moisture in depths of 0.20 − 0.40 mm and physical properties of soil (wilting point value and value of field water capacity).

With regard to the technical and time requirements of the exact establishment of leaf area index – LAI (the practice requires a simple and fast method of canopy evaluation), canopy growth and its stages were measured according to the BBCH scale (*Meier, 1997*). The vegetation period of wheat was therefore divided by the nature of the vegetation and the related effects on the microclimate into several periods: I. period BBCH 23–32 (7. 4. − 6. 5. 2010; 7. 4. − 8. 5. 2011; 1. 4. − 4. 5. 2013), II. period BBCH 33–69 (7. 5. − 6. 6. 2010; 9. 5. − 1. 6. 2011; 5. 5. − 25. 6. 2013) and III. period BBCH 70–92 (7. 6. − 11. 7. 2010; 2. 6. − 30. 6. 2011; 26. 6. − 23. 7. 2013).

For statistical processing, the data was adjusted into hourly and daily unit intervals by arithmetical average and for the purpose of this paper, the data was evaluated by the correlation and linear regression analysis. The regression equation of relations between the air humidity in the canopy in ranked altitudes was obtained as well as analysis of relative air humidity at 2 m above the ground at the climatological station.

Furthermore, values from above the ground vertical profiles were evaluated by the method of triangulation with linear interpolation and graphically displayed in the form of humidity isolines (isohumids) by Surfer ver. 8.03 (Golden Software, Inc.) software. For the purposes of evaluation of differences in relative air humidity during the light and dark parts of the day, the experiment uses data on the time of sunrise (beginning of the light part of the day) and sunset (beginning of the dark part of the day) with an accuracy of 15 min.

Relative evapotranspiration express functional dependencies among all energy and water balance equation components of the locality – net radiation, air temperature and humidity, turbulent state of atmosphere, difference of saturation water vapour pressure at the temperature of evaporating surface and water vapour pressure in the air, precipitation, change of critical soil moisture during the year, and heat flux in the soil (*Škvarenina et al., 2009*). Reference evapotranspiration of the hypothetical surface in daily steps was computed according to FAO methodology (*Allen et al., 1998*) – Eq. (1). It is based on modified Penman-Monteith equation (from the original Penman-Monteith equation and the equations of the aerodynamic and canopy resistance, the “FAO Penman-Monteith equation”):

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\,\dfrac{900}{T + 273}\,u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \tag{1}$$

where:

ET_0 – reference evapotranspiration [mm day^{-1}],

R_n – net radiation at the crop surface [MJ m^{-2} day^{-1}],

G – soil heat flux density [MJ m^{-2} day^{-1}],

T – air temperature at 2 m height [°C],

u_2 – wind speed at 2 m height [m s^{-1}],

e_s – saturation vapour pressure [kPa],

e_a – actual vapour pressure [kPa],

$e_s - e_a$ – saturation vapour pressure deficit [kPa],
Δ – slope vapour pressure curve [kPa °C^{-1}],
γ – psychrometric constant [kPa °C^{-1}].

Experiments confirmed that under optimum conditions of plant growth, the actual evapotranspiration (AE) is proximate to the potential evapotranspiration, namely to the maximum possible evapotranspiration under the given climatic conditions from sufficient soil moisture – E_0 (*Budyko and Zubenok, 1961*). The actual evapotranspiration (AE) is supposed to be proportional to the potential evapotranspiration as follows (2):

$$AE = ET_0 \times (W/W_0) \tag{2}$$

where:
ET_0 – reference evapotranspiration [mm day^{-1}],
W – soil moisture stored in the upper soil layer,
W_0 – critical value of the soil moisture above which AE equals ET_0.

Moisture balance (MB) was computed as the sum of differences of daily precipitation totals and daily potential evapotranspiration.

3. Results and discussion

There are relatively few data on the stratification of humidity in field crops. In our earlier observations we discovered that wheat and oilseed rape had higher relative air humidity of 30% on the ground, and up to 10–25% at the effective height (*Krédl et al., 2012*) which corresponds to the findings of *Hardwick et al. (2015)* who state that the air beneath canopies with high leaf area index is cooler and has higher relative humidity during the day. However, it is necessary to realize that the moisture of the vegetation depends not only on the type of the crop (*Sentelhas et al., 2005*) but also on the architecture of the stand (*Callonec et al., 2013; Tivoli et al., 2013*), the growth phase of the plant and soil water availability for plant transpiration and evaporation. By division of the growing season according to the growth stages of plants, the research defined detailed information on the relative humidity in the growth of winter wheat. The moisture conditions of the year were expressed as daily values of moisture balance (MB) and daily values of available soil water content (ASWC; average derived from hourly data) in Fig. 1. Significant difference of moisture condition in 2013 (wet year) mainly compared with 2011 (dry year) is obvious.

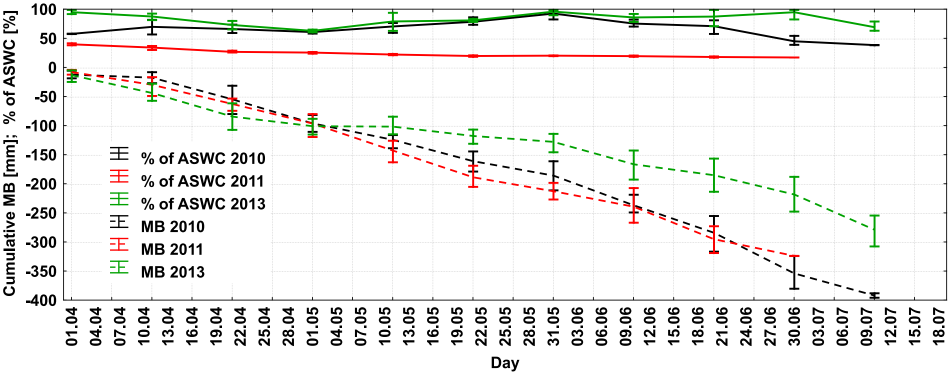

Fig. 1. The course of daily values of moisture balance (MB) and available soil water content (ASWC) on field experimental area in individual years.

Meteorological conditions of the year or more precisely vegetation season and their comparison with climatic normal values are given in Table 1. Limited stratification of relative air humidity in canopy during the I. and II. periods in 2010 (Fig. 2) was caused by higher precipitation. On the

Table 1. Comparison of meteorological conditions (air temperature and precipitation totals) with climatic normal values (1961–1990) from reference station of CHMI Pohořelice during individual periods (computed from hourly average values).

	I. period		II. period		III. period	
	AVG temp. (°C)	Precip. totals (mm)	AVG temp. (°C)	Precip. totals (mm)	AVG temp. (°C)	Precip. totals (mm)
Normal	10.4	34.5	14.9	68.1	17.9	77.3
2010	11.5	64.0	14.3	119.8	20.1	51.9
Normal	10.6	40.4	14.9	47.4	17.4	72.4
2011	11.5	36.7	16.7	45.1	18.9	64.6
Normal	9.8	39.6	15.9	115.7	18.8	53.5
2013	13.1	47.9	16.2	228.7	19.2	2.3

Notes: AVG temp. – average air temperature; Precip. totals – precipitation totals contrary, in the II. period in 2011 (air temperature above normal, precipitation normal) there was a significant humidity stratification due to canopy character and its transpiration. Higher precipitation totals in the II. period in 2013 are markedly reflected in RHGH, RHEH, MB and ASWC in the III. period with minimal precipitation. The importance of continual canopy microclimate monitoring as well as complicatedness of canopy microclimate modelling are thus demonstrated.

3.1. Stratification and development of air humidity in the canopy of winter wheat

The average air humidity in the canopy of winter wheat considering the year, growth phase, time of day and the height above the ground (height measured in centimetres – see axis Y), expressed as "average day" from fifteen minute average values from the whole period, as shown in Fig. 2. Most significant differences were seen during the light part of the day, around 3 pm CET (Central Europe Time) – time axis in fifteen minute steps – see axis X. Relatively small differences were identified at this time in the first growth phase in all years. In the second phase, the differences in humidity measured at 2 m and on the ground of the stand were from 20 to 40% in the third phase then, 20 to 35%.

The data presented in Fig. 2 show, that the largest difference of the average relative air humidity in the effective height of the stand (relative humidity at 2 m minus the relative humidity at the effective height) are achieved just before sunrise and after sunset. At ground level, the biggest differences were seen in the light part of the day. Positive differences of relative air humidity (i.e. higher relative air humidity at 2 m than at the ground or effective height) were recorded especially during the dark part of the day.

Wetting of leaves is another fairly important point for the development of many pathogens. Wetting of leaves in the vegetation is usually investigated by various sensors or modelled from relevant data of microclimate monitoring (e.g. *Bregaglio et al., 2011; Dalla Marta et al., 2007; Magarey et al., 2006*). Models based on meteorological factors such as the relative humidity, temperature, and wind speed can simulate observed dew to a satisfactory extent. This method requires less labour, but no internationally accepted standard model exists for dew observation since the conditions that

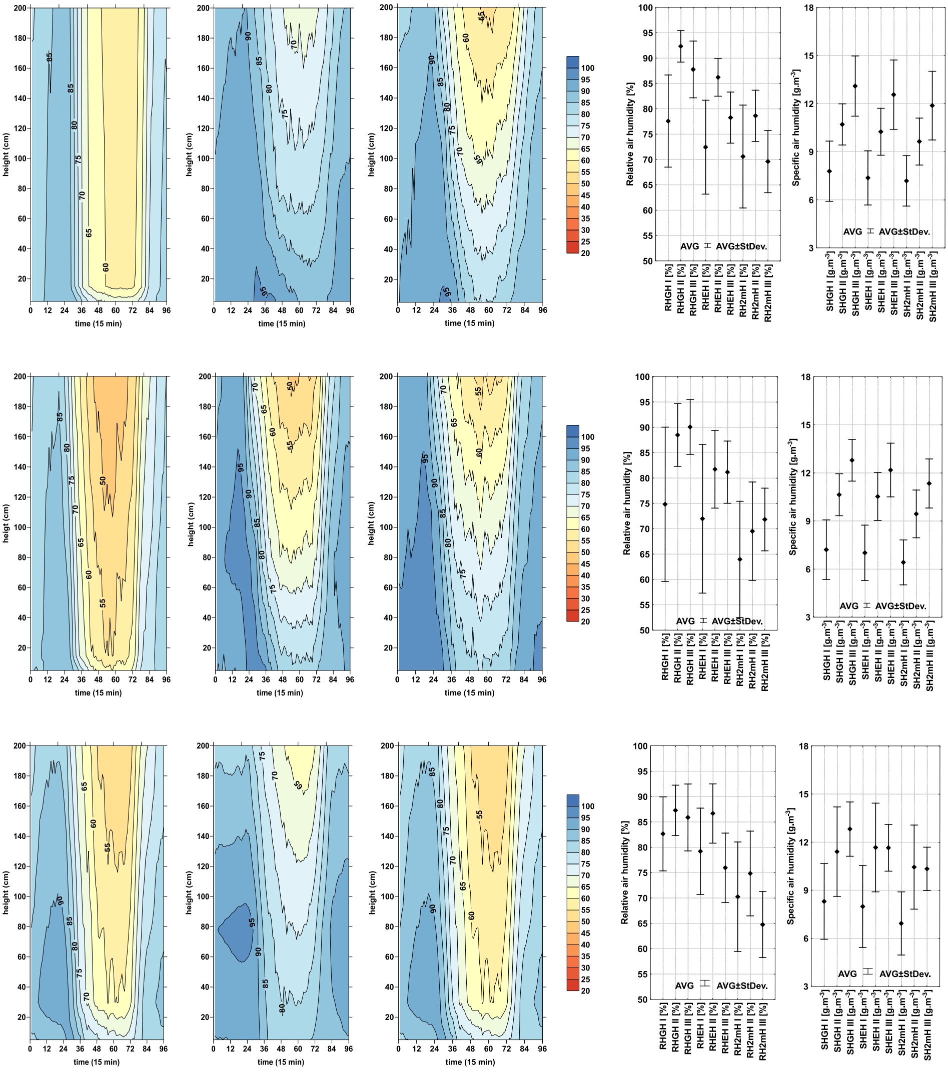

Fig. 2. Left: Stratification and development of air humidity in the canopy of winter wheat during the individual growth phases – left I. period, centre II. period, right III. period in years (downwards: 2010, 2011, 2013), expressed as "average day" from 15 minute average values from whole period. Right: box plots of average values of relative air humidity and specific air humidity in individual years, season and depths of canopy (average derived from 15 minute values).

allow the condensation of vapour are complex (*Xu et al., 2015*). With the help of high precision weighing lysimeters or using the Penman-Monteith equation some studies on dewfall have been carried out *Xiao et al. (2009)*. The marginal value of air humidity which is essential for wetting of leaves in the crop is reported as around 90% (*Sentelhas et al., 2008*), that is why this value was used for the purposes of this research. Air humidity heterogeneity in individual years, stages of vegetation, height of measurement and the time of day, expressed as percentage of hours in which the relative air humidity exceeded 90%, are shown in Table 2. In addition, this characteristic observed dependence on the year and vegetation period. Relatively small differences were observed in the period from the beginning of spring vegetation to the beginning of heading.

Table 2. Percentage of hours in which the relative air humidity exceeded 90%.

Period	Height	2010			2011			2013		
		light p.	dark p.	AVG	light p.	dark p.	AVG	light p.	dark p.	AVG
I.	Near ground	22.5	32.5	26.7	26.5	34.2	29.7	18.1	22.6	19.9
	Effective	5.3	36.8	18.5	17.9	52.2	32.3	23.3	59.7	38.5
	2 m	2 .7	21.4	10.6	3.4	26.9	13.3	8.8	28.5	17.0
II.	Near ground	71.0	79.8	74.3	53.1	55.8	54.1	42.8	55.4	47.5
	Effective	28.7	78.1	46.9	20.5	76.4	41.4	34.9	81.9	52.5
	2m	5.4	48.7	21.4	4.1	50.6	21.5	14.1	33.5	21.3
III.	Near ground	47.6	47.1	47.4	41.0	89.8	57.2	40.6	61.4	47.4
	Effective	14.7	59.5	29.9	20.2	74.7	38.3	21.0	83.2	41.4
	2 m	2.5	25.1	10.2	6.3	52.9	21.7	2.9	21.4	8.9

Notes: light p. – light part; dark p. – dark part

3.2. The capabilities of simulation of relative air humidity in the wheat canopy – application of indirect (computational) methods

Dependence of daily values of relative air humidity (computed as the arithmetical average of fifteen minute values) on the assessed variables (daily precipitation, daily potential evapotranspiration, daily value of moisture balance, daily average value of available soil water content, daily value of actual evapotranspiration) was tested with correlation analysis (Table 3).

Simulation of relative humidity for the entire period of the main wheat vegetation (BBCH 23–92) is problematic. A statistically significant relationship ($p < 0.05$) in all years was found only for daily RHEH and daily precipitation totals ($r = 0.27$ to 0.55) and for daily RH2mH and daily precipitation totals ($r = 0.36$ to 0.56).

Daily potential evapotranspiration, calculated on the basis of meteorological values from standard climatological station data, has statistically correlated with specific air humidity in wheat canopy (SHGH $r = 0.70$ to 0.88; SHEH $r = 0.67$ to 0.86; SH2mH $r = 0.63$ to 0.84).

In 2013 soil water potential and leaf wetness were also measured. Statistically significant relationships ($p < 0.05$) between relative air humidity and soil water potential $r = 0.22$ (RHGH and SWP), $r = 0.46$ (RHEH and SWP), $r = 0.39$ (RH2mH and SWP) and the relative air humidity and leaf wetness $r = 0.20$ (RHGH and LW), $r = 0.714$ (RHEH and LW), $r = 0.63$

Table 3. Relationships (expressed as correlation coefficients "r") linear correlation between average daily relative air humidity measured in the wheat canopy and chosen daily agrometeorological variables.

		1	2	3	4	5	6	7	8	9	10
2010	RHGH	0.33	0.66	−0.36		0.38	0.37	0.70			
	RHEH	0.47	0.45		0.36	0.34	0.34	0.54			
	RH2mH	0.56			0.52	0.30	0.31	0.34			
2011	RHGH	0.23	0.66	−0.59		−0.77	−0.77				
	RHEH	0.27	0.50	−0.41		−0.63	−0.63				
	RH2mH	0.36	0.30	−0.36	0.27	−0.47	−0.47				
2013	RHGH					0.32	0.36	0.28	0.21	0.22	0.20
	RHEH	0.55		0.31	0.53	0.22	0.23		0.50	0.46	0.71
	RH2mH	0.54	−0.31	0.37	0.57	0.22	0.27		0.41	0.39	0.63

Notes:

1 Daily precipitation totals measured at the climatological station Pohořelice [mm]
2 Daily potential evapotranspiration [mm]
3 Cumulative moisture balance [mm]
4 Daily moisture balance [mm]
5 Daily average soil moisture in 0.20–0.40 m in wheat stand [vol. %]
6 % of average daily value of available soil water capacity in wheat stand
7 Daily actual evapotranspiration [mm]
8 Daily average value of soil water potential in 0.20 m in wheat stand [MPa]
9 Daily average value of soil water potential in 0.10 m in wheat stand [MPa]
10 Leaf wetness in wheat stand – daily number of hours [hours]

(RH2mH and LW) were found out.

Similar results were obtained when we excluded the III. period from the evaluation (i.e. during ripening with significantly specific microclimatic conditions). Weak, but still statistically significant correlations ($p < 0.05$) were found in all three years just between RHEH and daily precipitation totals ($r = 0.33$ to 0.57) and between daily RH2mH and daily precipitation totals ($r = 0.42$ to 0.54). In addition to that, a significant correlation was identified between potential evapotranspiration and specific air humidity in wheat canopy (SHGH $r = 0.68$ to 0.87; SHEH $r = 0.68$ to 0.86; SH2mH $r = 0.62$ to 0.83) when the strongest relationship was found in 2010. SHGH, SHEH, SH2mH statistically significantly correlated with soil moisture and SWHC in 0.20–0.40 m depth. However, in 2010 this relationship was positive ($r = 0.32$ to 0.36) while in 2011 and 2013 it was a negative ($r = -0.36$ to -0.85) with the strongest correlation in 2011. The significant relationships were found between daily actual evapotranspiration and SHGH, SHEH and SH2mH ($r = 0.42$ to 0.73), nevertheless only in two years (2010 and 2013). In 2013, when soil water potential and leaf wetness were also evaluated, a strong correlation between RHEH, RH2mH and leaf wetness (0.72 and 0.60) was identified.

3.3. The capabilities of simulation of relative air humidity in the wheat canopy – application of simple linear regression method

Relationships between the measured values of relative air humidity in the winter wheat canopy (hourly values) and at 2 m above the ground on standard climatological stations were expressed by simple linear regression equations (separately for individual sites, individual year, individual stages and individual measuring height). The relationship between values measured in the wheat stand and at the climatological station was evaluated by linear regression. The tightness of the relationship was described by regression coefficient (R^2) on the example of night values – see Table 4.

Using the regression equations, presumable values of humidity in different heights of the canopy for specified reference values were calculated. It is evident from the results that the calculated values were dependent not only on the year, but mainly on the time of day. The critical value of 90% air humidity was achieved on the ground vegetation during the bright part of

Table 4. Probable values of relative air humidity (%) in the stand during the night, as calculated using regression equations based on hourly data (hourly data computed from fifteen minute data).

Period	Reference humidity	Near ground height						Effective height					
		2010		2011		2013		2010		2011		2013	
		Žab.	Tuř.	Žab.	Tuř.	Žab.	Tuř.	Žab.	Tuř.	Žab.	Tuř.	Žab.	Tuř.
I	60	80	76	68	77	80	81	77	72	67	77	80	82
	70	83	81	76	84	82	83	82	78	76	85	85	87
	80	87	86	84	**90**	85	85	86	85	85	**92**	**90**	**92**
	90	89	90	92	97	87	87	91	91	94	99	96	98
	R^2	0.52	0.55	0.65	0.42	0.18	0.11	0.68	0.62	0.69	0.45	0.60	0.53
II	60	**89**	**89**	83	87	89	88	83	84	74	86	87	84
	70	91	91	86	**89**	**89**	**89**	86	87	81	**90**	**89**	88
	80	92	93	89	92	90	90	89	**90**	87	95	93	**93**
	90	93	94	91	95	91	91	92	93	94	99	96	97
	R^2	0.07	0.07	0.31	0.30	0.02	0.04	0.56	0.45	0.73	0.42	0.36	0.50
III	60	86	87	86	**94**	**91**	**92**	83	85	71	86	88	89
	70	88	89	90	96	91	92	86	87	78	**90**	**89**	**92**
	80	**89**	**91**	**93**	98	92	92	88	**89**	85	94	92	94
	90	91	93	97	99	92	92	91	92	93	97	94	96
	R^2	0.25	0.32	0.39	0.13	0.00	0.00	0.32	0.20	0.74	0.23	0.24	0.38

Note: Žab. – Žabčice; Tuř. – Tuřany

the day already with reference values of air humidity at the climatic station of 70–80% at the effective height of the stand sometimes of 80% in all the periods of vegetation.

During the night hours, there was generally no exceeding of limit values in the corresponding model levels of air humidity during the I. period. Conversely, in the II. period, the critical value of the ground stand for values of 60–70% of humidity was usually reached at the stations, at the effective height of 70–80%, in the III. period, then 60–80% at the ground level and 70–80% at the effective height. The coefficients of determination were in many cases low.

By the means of comparison of the results of microclimatic monitoring with the results from standard climatological stations, significant deviations were found. These are significant to such extent that using data from a standard station for forecasting pathogens or pests, or growth models, have a significant impact on their explanatory power. The data taken in the vegetation show much higher air humidity than under standard conditions at 2 m above the ground of grassland. It is therefore not possible to deduce air humidity inside the stands based on data from a standard station with sufficient accuracy by linear regression for air humidity.

3.4. The capabilities of simulation of relative air humidity in the wheat canopy – application of advanced regression methods

Outlying values were deleted from the set of three year hourly data of relative air humidity at effective height (RHEH). The Grubbs' test for identication of outlying values was used. The relationship between RHEH and RH at the CHMI Tuřany climatological station (Fig. 3) is best expressed as Eq. (3):

$$\mathrm{RHEH} = 118.966/(1 + \exp(1.959 - 0.036 \times \mathrm{RH})) \qquad (3)$$

where RH – relative humidity [%].

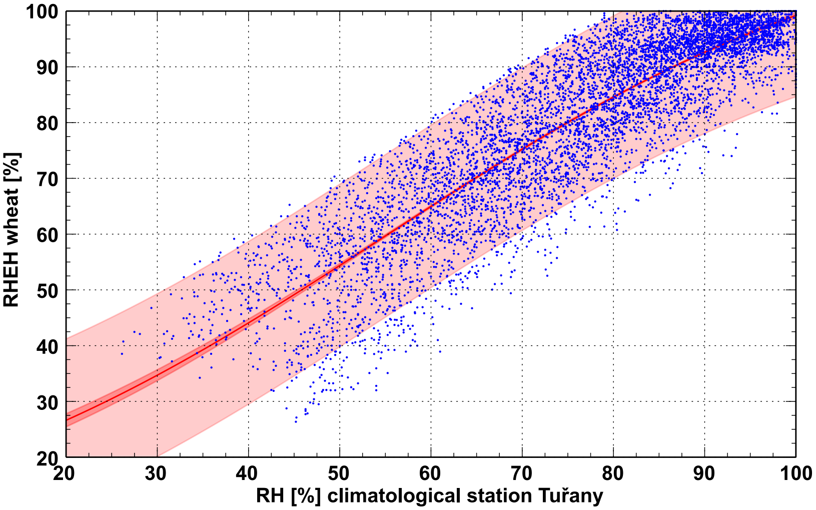

Fig. 3. The relationship between RHEH in winter wheat canopy and RH at the CHMI Tuřany climatological station – relative air humidity measured at 2 m height above surface (short-cut grass cover), sensors placed in a standard meteorological screen (0.95 confidence band; $n = 673$; $r = 0.898$; standard error SE = 7.433).

The equation was verified by using relative air humidity data from CHMI standard climatological station Pohořelice (Fig. 4). The congruence is not strong enough when standard error SE = 8.786. The simulation of RHEH in winter wheat canopy based on RH from the standard climatological station is thus doubtful.

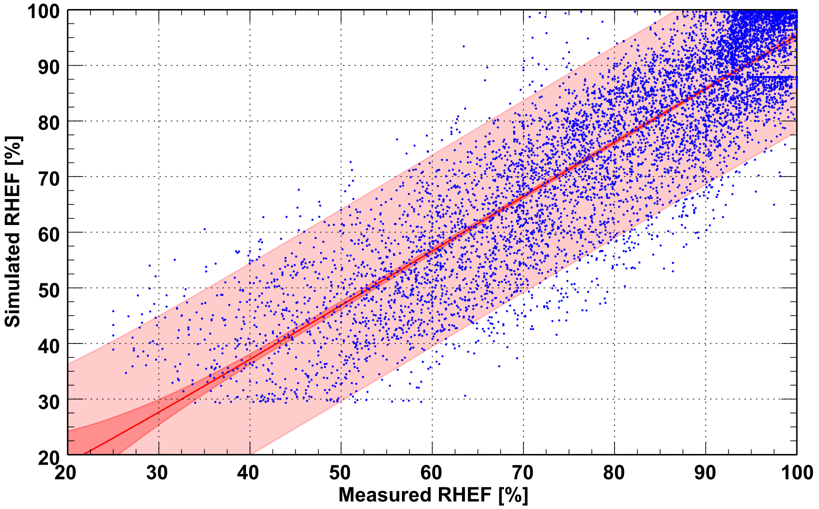

Fig. 4. The relationship between measured and simulated RHEH in winter wheat canopy with use of Eq. (4).

Significantly better congruence was not reached even when hourly data of RHEH were simulated with combined regression (modelling of RHEF based on standard climatological station data, namely RH, air temperature at 2 m, ground temperature, soil temperature, soil moisture, global radiation). However, the best congruence of simulated and measured data (n = 7105, standard error SE = 7.789) was reached with the Eq. (4):

$$\begin{aligned} \mathrm{RHEH} = 2732.75 \times \exp(-0.5 \times (((\log(\mathrm{RH}) - 15.49)/2.24)^2 + \\ + ((\log(\mathrm{PH}) - 4.14)/2.42)^2)) \end{aligned} \qquad (4)$$

where RH – relative humidity [%], PH – wheat plant height [cm].

Guo et al. (2012) achieved similar results (correlation coefficient r = 0.8975, the mean value of relative error 9.45%) with the dynamic forecast model of air humidity in a greenhouse, which was established according to dynamic balance relations of water steam quality in a sunlight greenhouse and physical process related humidity changes such as crops transpiration and soil evaporation. The study of *He and Ma (2010)* was aimed to apply the neural network to accurately model the inside humidity of a greenhouse. The environmental factors influencing the inside humidity were extracted. The predicted humidity agreed well with the measured. It was observed that the neural network model performed better than the stepwise regression model.

4. Conclusions

Wheat canopy significantly influences the microclimate of the surrounding environment. Air humidity in the vertical profile of the canopy differed significantly depending on year, developmental phase (i.e. phenology) and time of the day. The air humidity at the ground level and effective height of wheat was usually higher in the canopy. Significant vertical stratification of air humidity was recorded in the period from flowering to ripening. The prediction of air humidity in wheat canopy cannot be based on data measured in standard climatological stations as it was not proven that there is a statistically strong dependence.

The results show that wetting in the ground cover and its active height takes much longer in comparison with the height of 2 m above the ground surface directly above the crop. It is also understood that, for the purposes of precise prediction of the occurrence of pathogens or pests, it is preferable to monitor air humidity directly within the stand. It was found that when the reference values of humidity reached 60–70% at the climatological stations, the calculated values in the stand were close to 90%. In the further paper it will be necessary to confront the gained data with relative air humidity and moistening.

Acknowledgements. This article was written at Mendel University in Brno as a part of the project IGA AF MENDELU No. TP 7/2015 with the support of the Specific University Research Grant, provided by the Ministry of Education, Youth and Sports of the Czech Republic in the year of 2015. The authors would like to thank the anonymous reviewers for their helpful and constructive comments that greatly contributed to improving the final version of the paper.

References

Allen R. G., Pereira L. S., Raes D., Smith M., 1998: Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, 301 p. Roma.

Bonan G., 2008: Ecological Climatology, second ed. Cambridge University Press, Cambridge, UK.

Bregaglio S., Donatelli M., Canfalonieri R., Acutis M., Orlandini S., 2011: Multimetric evaluation of leaf wetness models for large-area application of plant disease models. Agricultural and Forest Meteorology, **151**, 1163–1172.

Budyko M. I., Zubenok L. I., 1961: The determination of evaporation from the land surface. Izvestiya Akademii Nauk, SSSR, Seriya Geograficheskaya, **6**, 6–17.

Calonnec A., Burie J. B., Langlais M., Guyader S., Saint-Jean S., Sache I., Tivoli B., 2013: Impacts of plant growth and architecture on pathogen processes and their consequences for epidemic behaviour. European Journal of Plant Pathology, **135**, 479–497.

Dalla Marta A., Magarey R. D., Martinelli L., Orlandini S., 2007: Leaf wetness duration in sunflower (*Helianthus annuus*): analysis of observations, measurements and simulations. European Journal of Agronomy, **26**, 310–316.

Guo Z., Yu H., 2012: Forecast model construction and confirmation of air humidity in sunlight greenhouse. Journal of Agricultural Mechanization Research, **3**, 94–97.

Han X., Li Y., 2010: Study on the micrometeorological characteristics and energy balance of winter wheat canopy. Meteorological and Environmental Research, **9**, 81–86.

Hardwick S. R, Toumi R., Pfeifer M., Turner E. C., Reuben N., Ewers R. M., 2015: The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. Agricultural and Forest Meteorology, **201**, 187–195.

He F., Ma CH., 2010: Modeling greenhouse air humidity by means of artificial neural network and principal component analysis. Computers and Electronics in Agriculture, **71**, 19–23.

Hurtalová T., Matejka F., Janouš D., Rožnovský J., 2003: Influence of a spruce forest stand on the flowing and air temperature and moisture vertical stratification. In: Mikroklima porostů, Brno, 26. 3. 2003, 66–79.

Klimešová J., Středová H., Středa T., 2013: Maize transpiration in response to meteorological conditions. Contributions to Geophysics and Geodesy, **43**, 3, 225–236.

Krédl Z., Středa T., Pokorný R., Kmoch M., Brotan J., 2012: Microclimate in the vertical profile of wheat, rape and maize canopies. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, **60**, 1, 79–90.

Kurpelová M., Coufal L., Culík J., 1975: Agroclimatic conditions of ČSSR (Agroklimatické podmienky ČSSR). Hydrometeorologický ústav: Bratislava, 270 p.

Liu H. J., Kang Y., 2006: Effect of sprinkler irrigation on microclimate in the winter wheat field in the North China Plain. Agricultural Water Management, **84**, 1–2, 3–19.

Magarey R. D., Russo J. M., Seem R. C., 2006: Grape canopy surface wetness: simulation versus visualization and measurement. Agricultural and Forest Meteorology, **139**, 361–372.

Matejka F., Huzulák J., 1987: Analysis of the microclimate of the stand (Analýza mikroklímy porastu). Bratislava: VEDA, 232 p.

Matejka F., Rožnovský J., Hurtalová T., Janouš D., 2002: Effect of soil drought on evapotranspiration of a young spruce forest. Journal of Forest Science, **48**, 166–172.

Meier U., 1997: BBCH-Monograph. Growth stages of plants – Entwicklungsstadien von Pflanzen – Estadios de lasplantas – Développement des Plantes. Blackwell Wissenschaftsverlag, Berlin und Wien, 622 p.

Mölder M., Grelle A., Lindroth A., Halldin S., 1999: Flux profile relationships over a boreal forest – roughness sublayer corrections. Agricultural and Forest Meteorology, **98–99**, 645–658.

Rožnovský J., Chalupníková B., Hurtalová T., Matejka F., 2002: Stratification of air temperature and air humidity in maize stand. Contributions to Geophysics and Geodesy, **32**, 3, 225–236.

Sentelhas P. C., Dalla Marta A., Orlandini S., Santos E. A., Gillespie T. J., Gleason M. L., 2008: Suitability of relative humidity as anestimator of leaf wetness duration. Agricultural and Forest Meteorology, **148**, 392–400.

Sentelhas P. C., Gillespie T. J., Batzer J. C., Gleason M. L., Monteiro J. E., Pezzopane J. R. M., Pedro M. J., 2005: Spatial variability of leaf wetness duration in different crop canopies. International Journal of Biometeorology, **49**, 363–370.

Středa T., Krédl Z., Pokorný R., Sangchote S., 2013: Effect of wetting period on infection of orchid flowers by Alternaria alternata and Curvularia eragrostidis. New Zealand Journal of Crop and Horticultural Science, **41**, 1, 1–8.

Škvarenina J., Tomlain J., Hrvoľ J., Škvareninová J., Nejedlík P., 2009: Progress in dryness and wetness parameters in altitudinal vegetation stages of West Carpathians: Time-series analysis 1951–2007. Időjárás, **113**, 47–54.

Tivoli B., Calonnec A., Richard B., Ney B., Andrivon D., 2013: Current knowledge on plant/canopy architectural traits that reduce the expression and development of epidemics. European Journal of Plant Pathology, 135, 471–478.

Xiao H., Meissner R., Seeger J., Rupp H., Borg H., 2009: Quantification of dewfall based on lysimeter studies. 13. Gumpensteiner Lysimetertagung. Irdning: Lehr- und Forschungszentrum für Landwirtschaft, Raumberg-Gumpenstein, 75–78.

Xu Y., Yan B., Tang J., 2015: The effect of climate change on variations in dew amount in a paddy ecosystem of the Sanjiang Plain, China. Advances in Meteorology, ID 793107, 9 p.

Yang W. P., Guo T. C., Liu S. B., Wang Ch. Y., Wang Y. H., Ma D. Y. 2008: Effects of row spacing in winter wheat on canopy structure and microclimate in later growth stage. Chinese Journal of Plant Ecology, **32**. 2, 485–490.