TRENDS OF EVAPOTRANSPIRATION IN SLOVAKIA, INCLUDING SCENARIOS UP TO 2100

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Mean air temperature increased in Slovakia by about 2.0 °C in 1981-2015 (both in Warm and Cold Half Years (CHY and WHY)), since 1951 it was 1.5 °C and 2.0 °C resp., since 1900 it was 1.5 °C and 2.0 °C and since 1881 it was 1.9 °C and 1.9 °C (all linear trends calculated from areal Slovakia temperature means). On the other hand relative air humidity decreased in the southern Slovak lowlands by about 5 % in WHY since 1901 as well as since 1951. Annual and WHY precipitation totals had only insignificant linear trends both since 1901 and 1951. Potential (E_o) and actual (E) evapotranspiration monthly sums have been calculated by the modified Budyko-Tomlain complex method for about 30 stations in Slovakia since 1951 (using other climatic data). Sums of E_o show significant increasing trend at annual and WHY values mainly in the lowlands. E sums trend is more complicated because of dependence on precipitation totals. Since 2011 new versions of General Circulation Models (GCMs) and Regional Circulation Models (RCMs) outputs have been used for regional climate change scenarios design in Slovakia as daily time series until 2100. This enabled to calculate quite reliable series of daily and monthy saturation deficit time series at all stations. These data were applied for E_o calculation by simplified Zubenok method. Calculated trends of E_o scenarios are significantly increasing what results in decrease of soil moisture and serious drought risk increase because of precipitation scenarios show no change or some decrease at WHY totals. In specific hydrologic and agroclimatic tasks also daily E_o sums are needed. In the paper a simple method of monthly to daily E_o sums recalculation is presented (using daily saturation deficit means).

***Keywords:** climate change scenarios, trend of climatic time series, daily data of potential evapotranspiration*

INTRODUCTION

Potential evapotranspiration $\boldsymbol{E_o}$ depends mainly on air temperature and air humidity changes, if no significant changes in radiation balance, wind speed and surface quality is considered.

Slovak Hydrometeorological Institute offers high quality data on air temperature (3 stations) and precipitation totals (203 stations) for the 1881-2014 time period and relative humidity data since 1901 from Hurbanovo Observatory and all data from about 30 stations since 1951. A sample of these data is presented in Fig. 1. It can be seen a significant increase of mean annual air temperature by about 2 °C and no significant trend in annual precipitation totals in the whole period, but more intense temperature increase and variance of precipitation totals in the period 1980-2014.

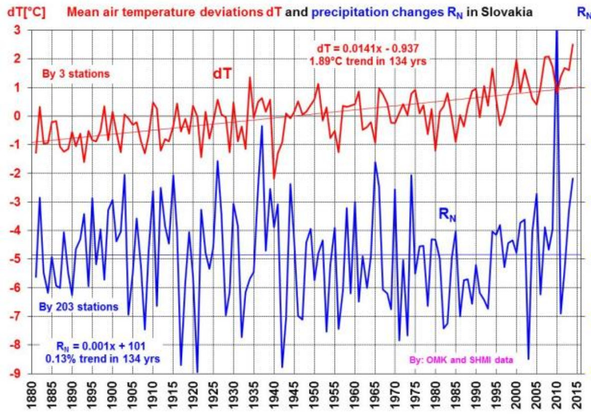

Figure 1: Deviation of annual air temperature means (***dT***) from the 1961-1990 average and annual precipitation totals ($\boldsymbol{R_N}$) in % of 1961-1990 average in Slovakia (by the SHMI data elaborated in OMK).

Such development of principal meteorological data impacted also evapotranspiration and water balance in the country. Fig. 2 shows rapid decrease of annual and Growing period relative humidity (***RH***) by about 6 % at Hurbanovo (SW Slovakia, 115 m a.s.l.). ***RH*** decrease was very probable also in other lowland localities in Slovakia. In the mountainous part of other Slovakia, ***RH*** decrease in the mountains was lower but still significant, mainly since 1951. This influenced increase of potential evapotranspiration E_o (recalculated values in Fig. 3).

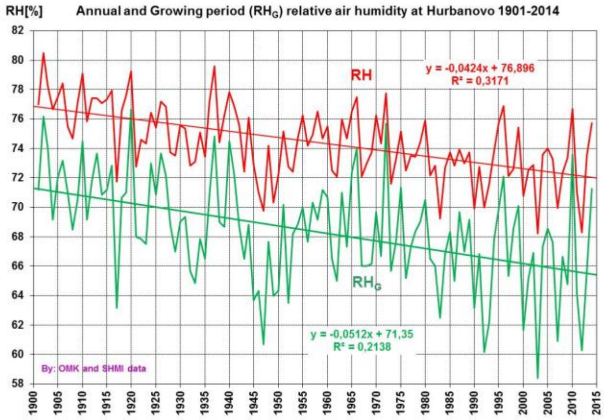

Figure 2: Trends of Annual and Growing season (Apr.-Sept.) relative humidity (***RH***) means at Hurbanovo in 1901-2014 (by the SHMI data elaborated in OMK).

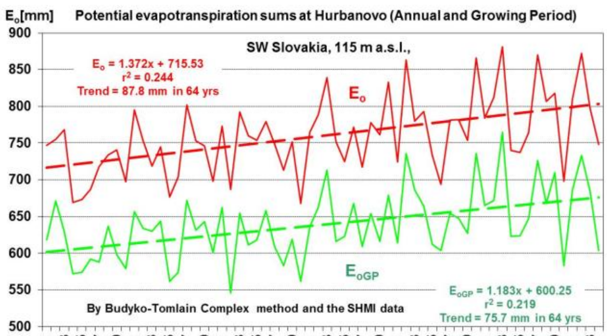

Figure 3: Trends of Annual and Growing Period (Apr.-Sept.) potential evapotranspiration ($\boldsymbol{E_o}$) sums at Hurbanovo in 1951-2014 (by the SHMI data elaborated in OMK).

MATERIALS, METHODS AND RESULTS

All calculations have been done in the Meteorology and Climatology Division (OMK) at the Comenius University using tested daily and monthly SHMI data from selected 10 stations (Table 1). Another souce of data were modified outputs of GCMs and RCMs (Global and Regional General Circulation Models) CGCM3.1, ECHAM5, KNMI and MPI, SRES emission scenarios A2, B1 and A1B (Lapin et al., 2012). Only a sample from wider elaboration is presented here.

These models belong to the newest category of so called coupled atmosphere-ocean models with more than 10 atmospheric levels and more than 20 oceanic depths of model equations and variables integration in the network of grid points. The model CGCM3.1 has 9 grid points in the Slovak territory and its neighborhood, the model ECHAM5 has 12 such grid points (about 200x200 km resolution) and with corresponding smoothing of topography. The regional GCMs (shortly RCMs), KNMI and MPI represent a more detail integration of the atmospheric and oceanic dynamic equations with grid points resolution about 25x25 km, while the boundary conditions are taken from the ECHAM5 GCM. The KNMI and MPI RCMs have 19x10 grid points (190) in Slovakia and its neighborhood with a detailed topography and appropriate expression of all topographic elements larger than 25 km. All the GCMs and RCMs offer outputs of several variables with daily frequency for the period from 1951 to 2100. Based on these outputs and measured meteorological data (1961-1990) the daily scenarios for about 30 climatic and about 50 other precipitation stations in Slovakia have been designed. Scenarios for the following variables have been prepared predominantly: the daily means, maxima and minima of air temperature, daily means of relative air humidity all measured at 2 m elevation above the ground, daily precipitation totals measured at 1 m elevation above the ground, daily means of wind speed measure at 10 m elevation above the ground and daily sums of global radiation. These scenarios and user manuals can be easily used to prepare studies on impacts and vulnerability to climate change.

Table 1: List of 10 meteorological stations in Slovakia with calculated potential evapotranspiration E_o[mm] by Budyko-Tomlain method from measured data in 1951-1990 and Zubenok method by RCMs (KNMI, MPI) in the Growing seasons (Apr.-Sept.) 1951-1990, 2051-2100 (2075 time frame)

Station	Alt.	Budyko	KNMI	KNMI	MPI	MPI
	m	51-90	51-90	2075	51-90	2075
Boľkovce	214	594.3	602.2	693.4	607.4	672.4
Hurbanovo	115	622.6	654.7	742.3	660.5	726.0
Košice	230	557.2	612.6	702.8	616.6	676.1
L. Hrádok	640	468.4	533.9	604.8	537.8	583.6
Milhostov	100	-	584.2	672.6	587.3	646.5
Or. Lesná	780	404.3	451.6	510.9	455.9	491.9
Piešťany	165	575.3	617.4	697.7	622.5	679.4
Poprad	695	469.1	525.7	595.9	529.6	577.1
Sliač	313	534.0	558.8	638.0	563.0	616.0
Telgart	901	432.6	473.2	544.5	477.6	525.6

The potential evapotranspiration (E_o) is a complex meteorological, hydrologic and climatic variable depending on temperature (radiation balance), wind speed (turbulence conditions), saturation deficit and active Earth surface properties (including vegetation type) at well saturated upper soil layer and unchanged meteorological conditions. Preparation of climate change scenarios for such a complex element is a complicated task. We decided to apply quite simple Zubenok (1976) formula, where only saturation deficit is necessary. The semiempiric Zubenok formula was calculated separately for each month during the year and for specific geobotanic areas (like desert, semidesert, steppe, forest-steppe, deciduous forest, conifer forest and tundra). We applied the forest-steppe region for Hurbanovo. The calculated E_o values are presented in Figs. 3 - 5, 7 -10 and Tab. 1 according to measured values and as the KNMI and MPI scenarios (SRES A1B emission scenario) as an example. More detail is E_o calculation by the Budyko - Tomlain method (Tomlain, 1980), where simple formula based on monthly data is applied.

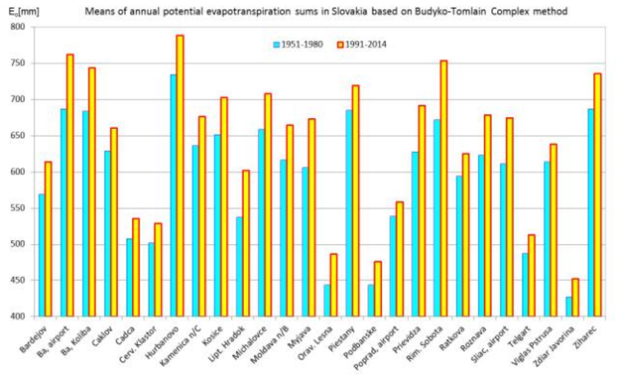

Figure 4: Annual sums of potential evapotranspiration (E_o) at 26 stations in Slovakia in 1951-1980 and 1991-2014 (by the Budyko-Tomlain Complex method, SHMI data used, elaborated in OMK).

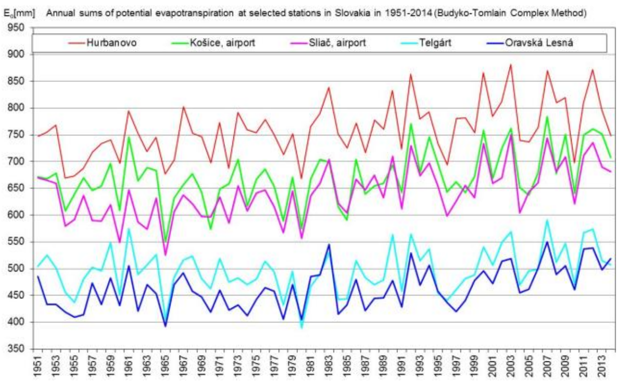

Figure 5: Annual sums of potential evapotranspiration (E_o) at 5 stations in Slovakia in 1951-2014 (by the Budyko-Tomlain Complex method, SHMI data used, elaborated in OMK).

Monthly potential evapotranspiration sums (E_o) are denoted by the equation of water vapor diffusion in the atmosphere:

$$E_o = \rho \, D \, (s^* - s_2),$$

where ρ is the air density, D - integral diffusion coefficient, s^* - saturated specific humidity at the temperature of evaporating surface and s_2 - specific humidity in meteorological shelter. The actual evapotranspiration sum (E) is supposed to be proportional to the potential evapotranspiration sum (E_o) as follows (simplified scheme, just a sample for Hurbanovo is here):

$$E = E_o \frac{\overline{W}}{W_o},$$

the storage $\overline{W}$ is specified as the moisture stored in the upper soil layer of one m depth, W_o is critical value above which the E equals E_o. The average soil moisture $\overline{W} = (W_1 + W_2)/2$ is determined from the water balance equation by the method of step-by-step approximation (W_1 is the moisture stored in the soil at the beginning of the month and W_2 at the end). The W_o usually represents a layer of 100 to 200 mm water with seasonal and regional variations (in Fig. 6 is a sample of calculations).

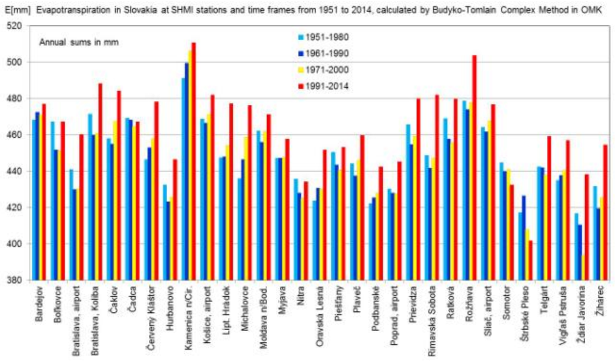

Figure 6: Annual sums of evapotranspiration (***E***) at 31 stations in Slovakia in different time frames from 1951 to 2014 (calculated by the Budyko-Tomlain Complex method, SHMI data used, elaborated in OMK).

POTENTIAL EVAPOTRANSPIRATION SCENARIOS

As mentioned above four different GCMs and RCMs have been applied at climate change scenarios design. Just two of them are presented in this paper, the KNMI and MPI modified model outputs for 10 stations in Slovakia (Table 1). The Zubenok method of monthly potential evapotranspiration (E_o) calculation is based on saturation deficit (*Δ*) monthly averages. Because of exponential dependence of saturated water vapor pressure (***e****) on air temperature (***T***) the saturation deficit depends on ***T*** also exponentially, so arithmetic averages of ***T***, ***e*** and ***e**** are not suitable for monthly Δ values calculations. That is why monthly *Δ* values were calculated from daily data ($\Delta = e^* - e$). The E_o resuts are presented in the Figs. 7-10.

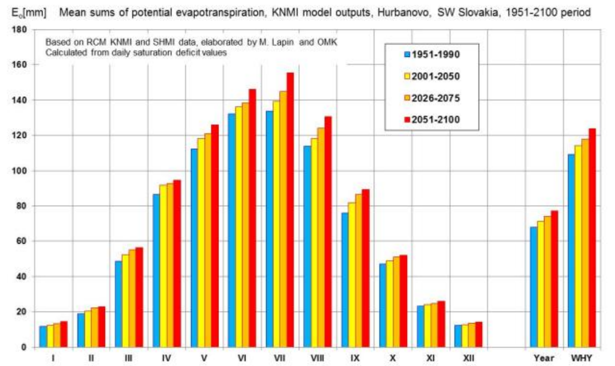

Figure 7: Mean monthly sums of potential evapotranspiration (E_o) at Hurbanovo (115 m a.s.l.) in different time frames from 1951 to 2100 as scenarios calculated from the KNMI, A1B model output (used SHMI data, elaborated in OMK).

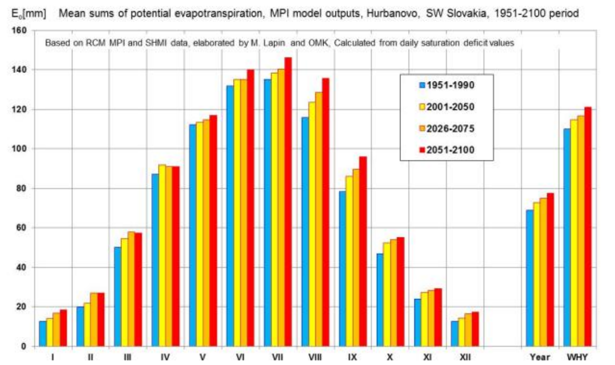

Figure 8: Mean monthly sums of potential evapotranspiration (E_o) at Hurbanovo (SW Slovakia) in different time frames from 1951 to 2100 as scenarios calculated from the MPI, A1B model output (used SHMI data, elaborated in OMK).

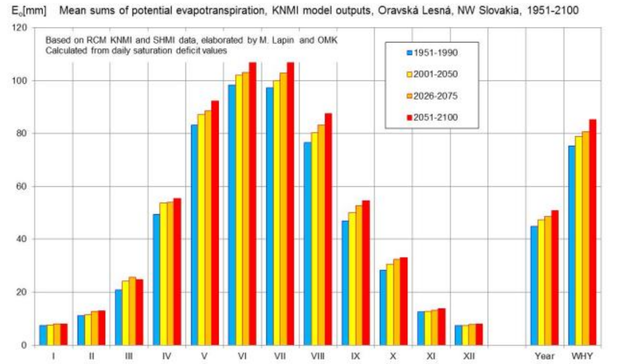

Figure 9: Mean monthly sums of potential evapotranspiration (E_o) at Oravská Lesná (780 m a.s.l.) in different time frames from 1951 to 2100 as scenarios calculated from the KNMI, A1B model output (used SHMI data, elaborated in OMK).

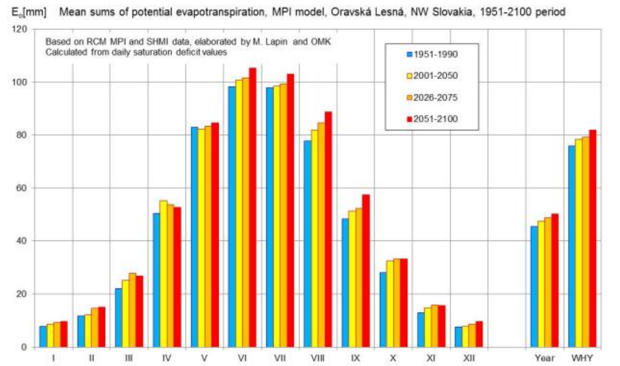

Figure 10: Mean monthly sums of potential evapotranspiration (E_o) at Oravská Lesná (N Slovakia) in different time frames from 1951 to 2100 as scenarios calculated from the MPI, A1B model output (used SHMI data, elaborated in OMK).

Detail results of E_o calculation by Zubenok method (1976) is presented for only two stations as an example. It can be seen that inspite of the same IPCC SRES A1B emission scenario and the same global GCM (ECHAM5) output as basic boundary input for both RCMs (KNMI and MPI), the results are slightly different. This is caused only by slightly different physics of both RCMs because of the same topography with resolution 25x25 km. General increase of potential evapotranspiration E_o is caused only by rising air temperature at nearly unchanged mean relative humidity at both stations. This resulted in increase of saturation deficit $\Delta = e^* - e$ as can be seen in Table 2.

Table 2: Change of saturation deficit *Δ*[hPa] at 10 stations in Slovakia by RCMs KNMI and MPI in the Growing seasons (Apr.-Sept.) between time frames 1951-1990 and 2051-2100

Station	Alt.	KNMI	KNMI	MPI	MPI
	m	1951-990	2051-100	1951-990	2051-100
Boľkovce	214	5.2	7.3	5.3	6.8
Hurbanovo	115	6.3	8.5	6.5	8.1
Košice	230	5.4	7.5	5.5	6.8
L. Hrádok	640	4.2	5.6	4.2	5.1
Milhostov	100	4.9	6.8	4.9	6.2
Or. Lesná	780	2.8	3.9	2.9	3.5
Piešťany	165	5.5	7.4	5.6	6.9
Poprad	695	4.0	5.4	4.0	5.0
Sliač	313	4.8	6.6	4.9	6.1
Telgart	901	3.1	4.4	3.2	4.0

Modelled *Δ* averages by RCMs KNMI and MPI are in the 1951-1990 period practically the same as calculated from measured data of air temperature and air humidity. Deviations between stations in the same altitude are caused by different surface conditions (soil moisture, vegetation, turbulent fluxes…).

RECALCULATION TO DAILY POTENTIAL EVAPOTRANSPIRATION SUMS

In some cases the daily sums of potential evapotranspiration (E_{od}) are needed. Such data can be obtained using sophisticated physical methods based on calculation of vertical turbulent fluxes of heat, momentum and water vapor, or also from heat balance equation. Slightly more convenient is Penmann formula. We present here very simple method based on monthly E_o data and Zubenok formula $E_{od} = k\Delta_d$, where k is coefficient calculated individually for each month in the E_o series. The E_{od} and Δ_d are daily values of E_o and saturation deficit.

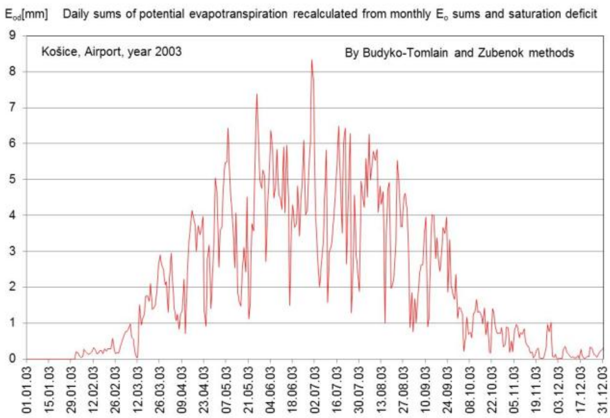

Figure 11: Daily sums of potential evapotranspiration (E_{od}) at Košice, Airport station, SE Slovakia in 2003 (monthly Eo sums by the Budyko-Tomlain Complex method, daily sums recalculated by modified Zubenok method, SHMI data used, elaborated in OMK).

The method of monthly E_o sums recalculation is based on the supposition that the coefficient k in the equation $E_{od} = k\Delta_d$ is the same for each day in the given month and calculated from formula $k = E_o(n.\Delta_M)^{-1}$, where Δ_M is monthly average of saturation deficit Δ and n is number of days in the given month. Generally the k coefficient is a complex value dependent on mean solar radiation and mean turbulence conditions during the given day. Simplification to equal k value for each day of given month probably brings some errors which are reduced by correction of monthy sum of all E_{od} to E_o calculated by Budyko-Tomlain method. For example, in case of year 2003 the monthly values of E_o, Δ_M and a k coefficient for Košice are in Table 3.

Table 3: Monthly E_o sums in mm, mean monthly saturation deficit in hPa and k coefficients in the warm half-year (Growing season) 2003 (Košice, Airport, 230 m a.s.l., SE Slovakia)

	Apr.	May	June	July	Aug.	Sept.
E_o	76	123	142	123	130	75
Δ_M	5.6	8.1	10.2	9.2	10.8	5.2
k	0.452	0.490	0.464	0.431	0.388	0.481

It can be seen from the Table 3 that the coefficient k is quite conservative in the months of Growing period, but it can have some deviations for different stations because of different turbulence conditions. In other years and the Košice station the k coefficient varies from 0.38 to 0.63 for months March to October and it is lower for winter months November to February. Maximum daily values of E_{od} are about 9 mm per day at Košice, Airport and can be slightly higher at other lowland stations in Slovakia. This simple method of E_{od} calculation is determined by accuracy of daily Δ_d assessment. It is clear that exponential dependence of momentary Δ values on air temperature is a problem. The best way how to improve Δd values assessment is to calculate it from hourly Δ values.

CONCLUSION

In the paper a summary of wider research on water balance components is presented. Main source of areal water balance is precipitation, more accurately areal averages of precipitation totals calculated by agreed method. The SHMI uses a method of double weighted averages from 203 stations in Slovakia measuring since 1901, most of them also since 1881 (Fig. 1). The next very important parameter is areal evaporation, or evapotranspiration, what is calculated from potential evapotranspiration (E_o) and precipitation (R). That is why great attention is paid to correct assessment of both these climatic and also hydrologic elements. The method presented in this paper in brief shows that there are applicable data for complex hydrologic assessment of complete hydrologic balance in the past as well in the future as alternative scenarios.

The future development of hydrologic and water balance in Slovakia is considered as probably negative because of significant increase of E_o and no change of R (small decrease of R in summer, mainly in southern lowlands and small increase in the remaining part of the year, mainly in the mountains). More about these problems are under research in the projects APVV mentioned below. Reasearchers as Hlavčová et al. (2008), Fendeková et al. (2012), Pekárová et al. (2005) and Šiška et al. (2009), Gaál et al. (2014), Damborská et al. (2015) showed that there are several important tasks for the next research.

Acknowledgement

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