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Progress in dryness and wetness parameters in altitudinal vegetation stages of West Carpathians: Time-series analysis 1951–2007

Jaroslav Škvarenina[1], **Ján Tomlain**[2], **Ján Hrvoľ**[2], **Jana Škvareninová**[1], and **Pavol Nejedlík**[3]

[1]*Technical University Zvolen,*
T. G. Masaryka 24, 960 53 Zvolen, Slovak Republic
E-mails: jarosk@vsld.tuzvo.sk , janask@vsld.tuzvo.sk

[2]*Comenius University Bratislava,*
Mlynská dolina, 842 48 Bratislava, Slovak Republic
E-mails: tomlain@fmph.uniba.sk, hrvol@fmph.uniba.sk

[3]*Slovak Hydrometeorological Institute Bratislava,*
Jeséniova 17, 833 15 Bratislava, Koliba Slovak Republic
E-mail: pavol.nejedlik@shmu.sk

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Abstract—This article analyzes trends in the occurrence of dry and wet periods in altitudinal vegetation stages in the West Carpathian region of Slovakia for the period 1951–2007. The relative evapotranspiration, drought index, and radiation drought index were applied on meteorological data from eight meteorological stations representing the predominant vegetation stages in the investigated region. These indices were used to characterize humidity conditions. The radiation drought index ranges from 1.31 for the area heavily prone to drought (southern part), to 0.41 for the mountainous areas (northern part), where the sum of precipitation exceeds potential evapotranspiration. The relative evapotranspiration shows values as high as 97% in northern mountainous regions to the low value of 58% in the Danubian Lowland**.** A significant increase in the severity of drought was identified by means of the radiation drought index for the period 1951–2007 only in the Danubian Lowland (stage 1, oak vegetation). A significant trend in the case of humidity was determined in the mountains and in the northern part of East Slovakia.

Key-words: drought, drought index, radiation drought index, actual evapotranspiration, potential evapotranspiration, precipitation, relative evapotranspiration, vegetation stage

1. Introduction

In principle, drought is defined as the state of water deficit concerning soil, plants, and atmosphere (*Krečmer,* 1980). In agriculture and forestry, it is understood as an important meteorological factor, distressing all ecosystems. Drought features strongly vary from region to region. The primary cause of drought under the conditions prevalent in the investigated territory is a deficit at precipitation over a certain period of the growing season. Other climatic factors, such as high temperature, strong wind, and low relative humidity, can significantly aggravate its severity (*Hayes et al.*, 1999; *Heim*, 2002).

Altitude and topography are strong climate-differentiating factors. Consequently, under conditions of considerably broken topography in the West Carpathians, drought plays an extra-important role. The primary importance of climate from the point of view of the natural vegetation has already been pointed out by *Zlatník* (1976). The author defines the vegetation stages as basic units characterizing altitudinal climate conditions (vertical differentiation) through vegetation (biocenoses). The bio-geocenoses resulted from variability in altitude, exposure, and topography can be classified as belonging to 9 vegetation stages. The Slovak territory has been divided by *Zlatník* (1976) into altitudinal vegetation stages named after the significant tree or bush indicator species dominating the area. These stages are characterized by their dominant climax tree species as follows: stage 1, oak (*Quercus*) vegetation, stage 2, beech-oak (*Fagus-Quercus*) vegetation, stage 3, oak-beech (*Quercus-Fagus*) vegetation, stage 4, beech (*Fagus*) vegetation, stage 5, fir-beech (*Abies-Fagus*) vegetation, stage 6, spruce-fir-beech (*Picea-Abies-Fagus*) vegetation, stage 7, spruce (*Picea*) vegetation, stage 8, mountain pine (*Mughetum*) vegetation, stage 9, alpine vegetation (non-forest high mountain pastures).

The vegetation stages of lower elevations, i.e., oak vegetation (stage 1), oak vegetation with admixture of beech (stage 2), and beech vegetation with admixture of oak (stage 3) are rather arid during the vegetation period (from March to September). The precipitation deficit reaches 100–300 mm during the vegetation season. The beech vegetation (stage 4) is characterized by an equitable climatic water balance. The climate humidity increases in higher vegetation stages (beech vegetation with fir (stage 5) and fir with beech and spruce (stage 6)). Humidity belongs to the fundamental properties of mountain forests. The water balance reaches the highest values in the 8th vegetation stage of mountain dwarf pine and the 9th alpine stage, where the amount of precipitation considerably exceeds the evaporation requirements of the atmosphere. Within the annual balance, the surplus of precipitation water is approximately 1000 mm (*Škvarenina et al.,* 2004). Experiments confirmed that under optimum conditions of plant growth, the actual evapotranspiration (E) is proximate to the potential one (to the maximum possible evapotranspiration under the given climatic conditions from sufficient soil moisture – E_o). That is why the ratio E/E_o (relative evapotranspiration) and the drought index (E_o/P, where P is the total precipitation) enable the quantification of the deficit of water in the soil root zone for optimum plant growth (*Budyko* and *Zubenok*, 1961). The radiation drought index (B/LP), where B is net radiation and L is the latent heat of vaporization, expresses the energy of net radiation in amounts of heat needed to evaporate the annual precipitation total. The indices were proposed to characterize general environmental conditions and processes on the Earth's surface. It approximates the ability of precipitation to provide the water required by native vegetation for an undisturbed evapotranspiration process and is often used in ecological studies (*Tomlain*, 1996; *Tomlain*, 2004).

In this paper, for the first time, we present the relative evapotranspiration, radiation drought index, and drought index results for the altitudinal vegetation stages in Slovakia, covering the period 1951–2007.

2. Method

Relative evapotranspiration and drought indices 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 vapor pressure at the temperature of evaporating surface and water vapor pressure in the air, precipitation, change of critical soil moisture during the year, and heat flux in the soil). The model resulted from common solution of the energy and water balance equations was performed at eight selected climatic stations in the investigated territory. The following data were taken as inputs into the model: air temperature and humidity, cloudiness, precipitation, and number of days with snow cover. The potential evapotranspiration was computed by the equation of water vapor diffusion in the atmosphere according to *Budyko* and *Zubenok* (*Budyko*, 1980), and the actual evapotranspiration was supposed to be proportional to the potential evapotranspiration:

$$E = E_o\, W / W_o, \tag{1}$$

where the water storage W is specified as a moisture content stored in the upper soil layer of 1 m depth and W_o as a critical value above which E equals to E_o. W_o usually amounts to a layer of 100–200 mm of water with seasonal and regional variations. The average soil moisture, $W = (W_1 + W_2)/2$, is determined from the water balance equation by the method of step-by-step approximation (W_1 is the moisture stored in the soil layer at the beginning of the month, and W_2 is the same at its end). As the number of meteorological stations for which the potential evapotranspiration has been calculated was limited, we decided to use the method of representative climatic stations, where the station represents the climate-hydric conditions of a particular vegetation stage. The climatic stations were classified into the appropriate vegetation stages (stages 1–8). For stage 9 there were no data based on the map of vegetation stages (*Raušer* and *Zlatník*, 1966) and typological maps of the forest type groups (scale 1:200,000).

3. Results and discussion

Table 1 presents the average annual values of seven parameters affecting the humidity conditions at selected stations in 1951–2007 as well as their classification into vegetation stages. The distribution of stations in the territory is shown in *Fig. 1*. The territory of the West Carpathians is divided into the area of Pannonia (Pannonian Lowland) and the foothills to the north, influenced by Mediterranean climate, and the area of the inner Carpathians, influenced by sub-ocean mountainous climate and by the climate of both Northern and Baltic Seas. The line dividing these areas has been determined by *Zlatník* (1959) by the so-called main climatic line, where the Carpathian bow separates two European climatic areas. The area to the north of this line is quite wetter and colder than the southern one, which is drier and warmer. The northern part is favorable for the growth of spruce, unlike the southern part, where spruce grows only in the highest vegetation zone.

The E/E_o is a suitable measure of the water sufficiency for vegetation. It approaches its lowest values of about 60% in the lowest areas. Towards the higher vegetation stages, the E/E_o increases reaching more than 90% in stage 4 beech vegetation. However, in the mountain sites this measure partly loses its accuracy. By the 5th vegetation stage its resolution approaches only about 1–5%. Finally, the B/LP has appeared as the most suitable complex index for describing the humidity and drought phenomenon in the region. It keeps higher stability than E_o/P, while accounting both for energy and precipitation elements.

Table 1. Average annual values of net radiation (B) in kWh m^{-2}, precipitation (P) in mm, radiation drought index (B/LP), drought index (E_o/P), potential (E_o) and actual evapotranspiration (E) in mm, and relative evapotranspiration (E/E_o) in percentages at selected locations of Slovakia for the period 1951–2007 (L is the latent heat of vaporization)

Station	H(m)	B	P	B/LP	E_o/P	E_o	E	E/E_o	Vegetation stage
Hurbanovo	115	488	537	1.31	1.40	751	433	58	1, oak
Myjava	375	461	672	0.99	0.94	630	449	71	2, beech-oak
Kamenica and Cirochou	178	467	722	0.93	0.89	645	500	78	3, oak-beech
Plaveč	488	410	694	0.85	0.75	523	450	86	4, beech
Červený Kláštor	474	410	763	0.77	0.67	509	458	90	5, fir-beech
Oravská Lesná	780	392	1116	0.51	0.41	458	433	95	6, spruce-fir-beech
Ždiar-Javorina	1020	356	1258	0.41	0.34	426	414	97	7, spruce
Štrbské Pleso	1360	357	997	0.52	0.44	437	408	93	7, spruce, 8, mountain pine

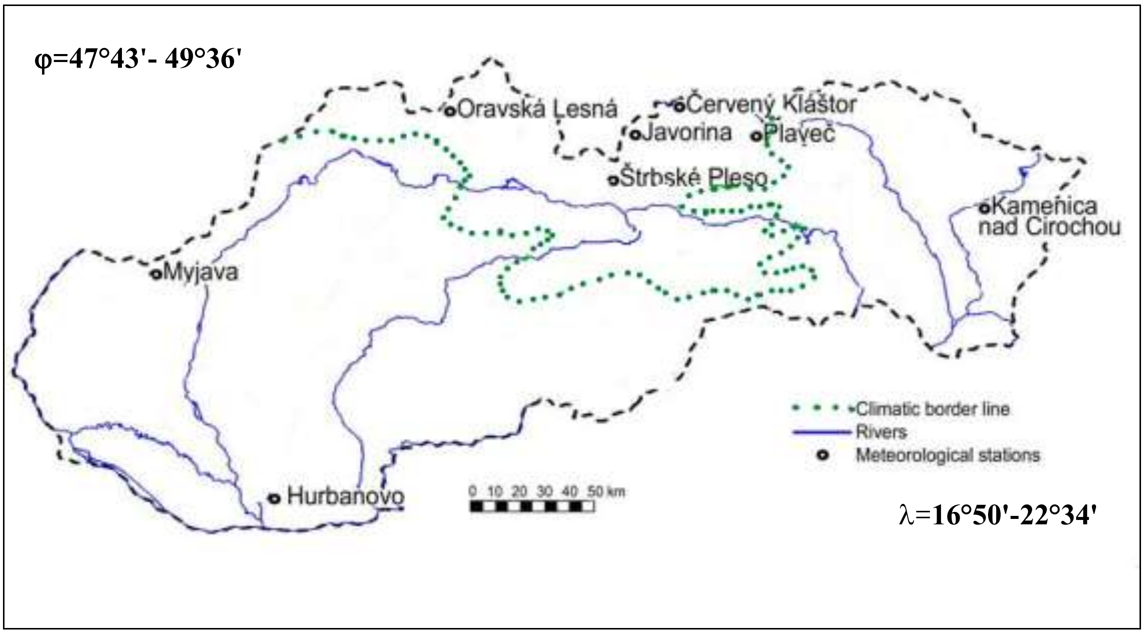

Fig. 1. The borders of Slovakia (dashed line) representing the West Carpathians with particular meteorological stations that represent conditions in the vegetations stages. The map displays the climatic border line (dotted line) and rivers (solid lines).

The E_o/P describes the relationship between the energy and precipitation inputs within particular vegetation stages. Beyond any expectations, the E_o/P index proved to be very sensitive to altitudinal changes and it was able to detect differences in bioclimatological conditions also in the comparatively small territory of the investigated region. As presented by Budyko (1980), the values of $E_o/P > 1$ indicate the territory of dry (arid) climate (steppe, forest-steppe). Values of $0.3 < E_o/P < 1$ specify forest bioms and values of $E_o/P < 0.3$ reveal the climate ecosystems of tundra or mountain forest of a temperate zone as well. The presented distribution of E_o/P values also corresponds to climate conditions in Slovakia. Warm forest-steppe formations dominated by oak, provides E_o/P values about 1. This represents the 1st vegetation stage (in the sense of Zlatnik classification) or a part of the 2nd vegetation stage dominated by beech-oak formations. Vegetation stages up to the E_o/P value of 0.3 represent the predominant area of Slovak forest; the values of index E_o/P decrease relatively proportionaly when related to both increasing altitude and precipitation amounts. The vegetation stages with $E_o/P < 0.3$ are of mountainous (boreal) climate, characterized by low temperatures and high precipitation amounts, with norway spruce and dwarf pine being the predominant tree species growing here.

The radiation drought index reaches the value about 1.3 in our driest region Hurbanovo. In mountainous areas which are rich in precipitation (Štrbské Pleso, Ždiar-Javorina) it moves about a mean value of 0.5. *Fig. 2* presents the regression dependence between the average annual values of the radiation drought index and the terrain altitude. Annual values of this index in the period 1951–2007 varied from 0.90 (1965, P = 827 mm) to 2.08 (2003, P = 333 mm) at

Hurbanovo, from 0.64 (1974, P = 1010 mm) to 1.68 (1961, P = 400 mm) at Kamenica nad Cirochou, from 0.76 (1987, P = 825 mm) to 1.55 (2003, P = 445 mm) at Myjava, from 0.53 (1980, P = 908 mm) to 1.15 (1971, P = 548 mm) at Červený Kláštor, from 0.62 (1985, P = 930 mm) to 1.31 (1961, P = 477 mm) at Plaveč, from 0.36 (1974, P = 1463 mm) to 0.72 (1959, P = 860 mm) at Oravská Lesná, from 0.25 (1980, P = 1630 mm) to 0.61 (1971, P = 908 mm) at Ždiar-Javorina, and from 0.35 (2004, P = 1299 mm) to 0.79 (1986, P = 690 mm) at Štrbské Pleso.

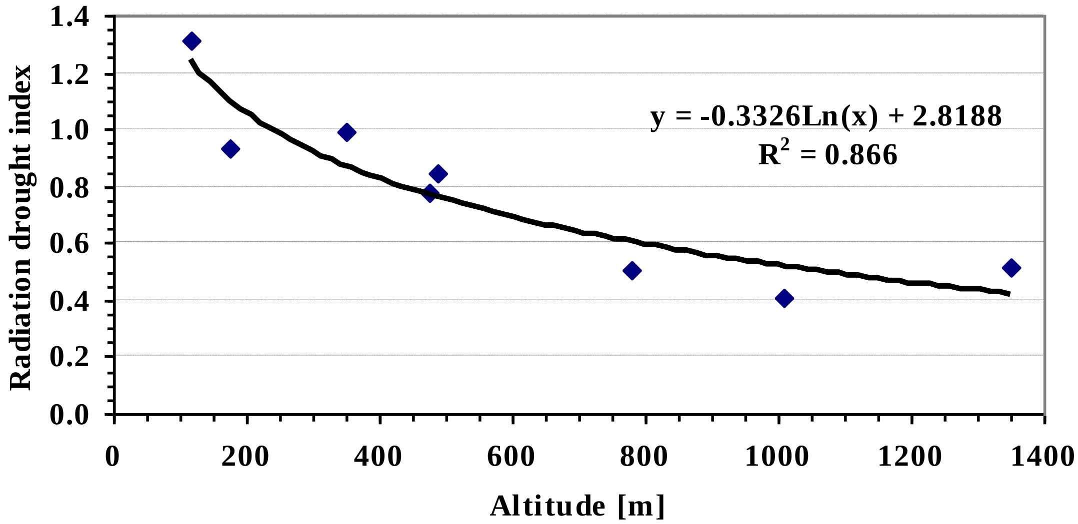

Fig 2. Logarithmic regression dependence of the radiation drought index annual values on the altitude (m a.s.l.) on the territory of Slovakia for the period 1951–2007.

The results presented in *Fig. 3* point out the overwhelming trend to aridity at the station in Hurbanovo, situated in the southern part of Slovakia. In Hurbanovo, as well as at other stations, linear and polynomial trends practically mingled one with another, so that only the linear trend is shown. This station represents the regions of most intensive agricultural production in Slovakia. Frequent occurrence of drought as well as its rising frequency negatively influences the production of the main crops in this region as well as in other regions of Central Europe (*Hlavinka et al.*, 2008; *Dubrovský et al.*, 2008). Further more, a statistically significant tendency to more intensive dry episodes in the region were stated by recent studies (*Brazdil et al.*, 2008). The next two stations with elevations below 500 m a.s.l. show practically no time trend in B/LP with relatively good water supplies as E_o/P drops below 1. B/LP starts to show the trend to lower values from the elevation around 500 m a.s.l. The stations situated to the north of the climatic line (Štrbské Pleso, Ždiar-Javorina, and Červený Kláštor) show an overwhelming trend to humidity during 1951–2007. Similar results are also presented by *Škvarenina et al.* (2008).

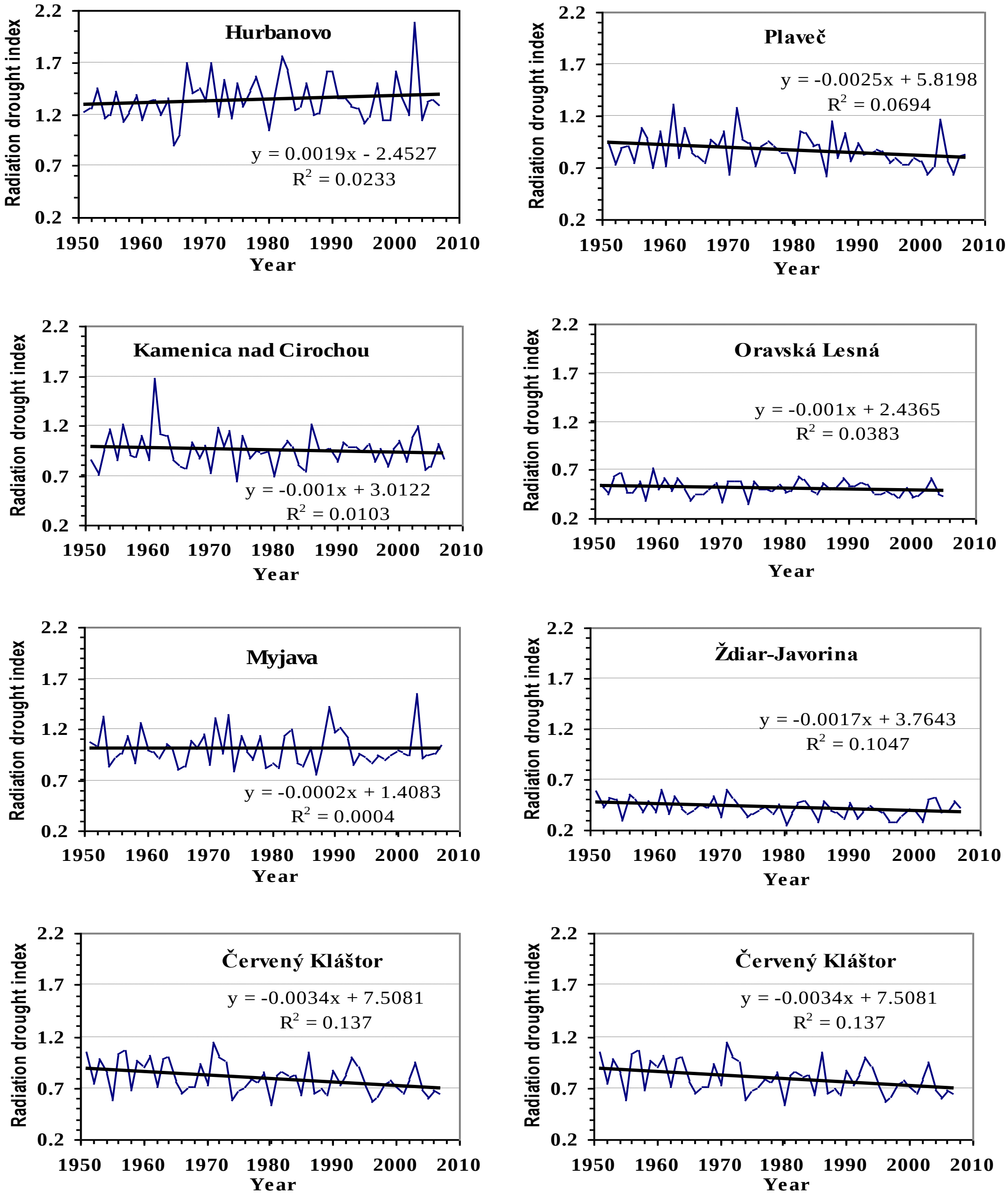

Fig. 3. Long-term course of the radiation drought index annual values at stations Hurbanovo, Kamenica nad Cirochou, Myjava, Červený Kláštor, Plaveč, Oravská Lesná, Ždiar-Javorina, and Štrbské Pleso for the period 1951–2007 with the linear trend.

4. Conclusions

– The calculations show that the radiation drought index is a suitable bio-climatic parameter. Its averages vary in a wide range from 1.31 in our driest region to 0.41 in mountain locations, but it is sensitive enough to indicate and reflect the diverse ecological conditions of the West

Carpathians from xerotherm oak plant communities to mountainous plant communities of spruce and dwarf pine.

– Maximum values of the radiation drought index for the processed period did not occur in the east and west parts of Slovakia in the same year.

– A significant increase in the severity of drought was identified from 1951 to 2007 only in the Danubian Lowland (stage 1, oak vegetation).

– In the mountains and in the northern part of East Slovakia, a significant trend of humidity increase was determined.

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