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An overview of drought events in the Carpathian Region in 1961–2010

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Abstract. The Carpathians and their rich biosphere are considered to be highly vulnerable to climate change. Drought is one of the major climate-related damaging natural phenomena and in Europe it has been occurring with increasing frequency, intensity, and duration in the last decades. Due to climate change, land cover changes, and intensive land use, the Carpathian Region is one of the areas at highest drought risk in Europe. In order to analyze the drought events over the last 50 yr in the area, we used a 1961–2010 daily gridded temperature and precipitation dataset. From this, monthly $0.1° \times 0.1°$ grids of four drought indicators (Standardized Precipitation-Evapotranspiration Index (SPEI), Standardized Precipitation Index (SPI), Reconnaissance Drought Indicator (RDI), and Palfai Aridity/Drought Index (PADI)) have been calculated. SPI, SPEI, and RDI have been computed at different time scales (3, 6, and 12 months), whilst PADI has been computed on an annual basis. The dataset used in this paper has been constructed in the framework of the CARPATCLIM project, run by a consortium of institutions from 9 countries (Austria, Croatia, Czech Republic, Hungary, Poland, Romania, Serbia, Slovakia, and Ukraine) with scientific support by the Joint Research Centre (JRC) of the European Commission. Temperature and precipitation station data have been collected, quality-checked, completed, homogenized, and interpolated on the $0.1° \times 0.1°$ grid, and drought indicators have been consequently calculated on the grid itself. Monthly and annual series of the cited indicators are presented, together with high-resolution maps and statistical analysis of their correlation. A list of drought events between 1961 and 2010, based on the agreement of the indicators, is presented. We also discuss three case studies: drought in 1990, 2000, and 2003. The drought indicators have been compared both on spatial and temporal scales: it resulted that SPI, SPEI, and RDI are highly comparable, especially over a 12-month accumulation period. SPEI, which includes PET (Potential Evapo-Transpiration) as RDI does, proved to perform best if drought is caused by heat waves, whilst SPI performed best if drought is mainly driven by a rainfall deficit, because SPEI and RDI can be extreme in dry periods. According to PADI, the Carpathian Region has a sufficient natural water supply on average, with some spots that fall into the "mild dry" class, and this is also confirmed by the FAO-UNEP aridity index and the Köppen-Geiger climate classification.

1 Introduction

The Carpathian Mountains are one of the longest (approximately 1500 km) and most important mountain chains in Europe: they extend over seven countries ranging from the Czech Republic to Serbia, encompassing Slovakia, Poland, Hungary, Ukraine, and Romania. The Carpathians represent a link between North-European taiga and Mediterranean landscapes and they often are a natural barrier for air masses thus, for instance in winter, climate is oceanic to the West from the Carpathians, snowy on the mountain ridge, cold and continental to the East, and Mediterranean to the South-East (Romania). Because of the special orography of the Carpathians, the basin effects are manifold and they cause many different site-specific phenomena, such as a stable boundary layer in winter, rain shadows, or temperature inversions. The Carpathians are extraordinarily rich in flora and endemic plants, as they include the widest primeval forests across all Europe. Moreover, the Carpathians have one of the most valuable biodiversity in Europe, in fact many different bird species and the largest communities of carnivores and predators such as bears and wolves live there.

The Carpathian Region has always been sensitive to hydrological extremes. Examples are the frequent droughts that affected the Great Hungarian Plain, Romania and Serbia from 1983 to 1995. Recent changes in human activities as the development of mass tourism or unsustainable rates of soil exploitation lead to land degradation, a decrease in agricultural production, and an increase in waste and pollution (UNEP, 2007). Deforestation, global warming, and soil erosion processes have been causing floods, droughts, and landslides with a higher frequency in the last 15 yr, especially in the South-Eastern area (e.g. the long drought period in Romania between 2000 and 2003, see e.g. Kozak et al., 2011a).

In the last years a few projects have been developed in order to preserve the unique landscapes, local cultural heritages, and biodiversity of the whole region. Examples are the Carpathian EcoRegion Initiative (Webster et al., 2001), the Carpathian Convention (Kozak et al., 2011a), CarpathCC (Szalai, 2012), and CARPIVIA (http://www.carpivia.eu). Regional studies (Bartholy et al., 2004; Lakatos et al., 2011, for Hungary) and climate change projections by means of scenarios and circulation models (Krüzsely et al., 2011) are quite frequent in the scientific literature related to the Carpathians, as well as small scale or local analyses about floods and/or droughts (Paltineanu et al., 2007; Parajka et al., 2010). On these topics, see also two projects promoted by the European Union: CLAVIER EU Project (http://www.clavier-eu.org) and CECILIA EU Project (http://www.cecilia-eu.org). Until 2010, the Carpathian Region lacked a high-quality climate dataset. To fill this gap and with the financial support of the European Parliament, the European Commission launched and financed the CARPATCLIM Project in late 2010. A consortium of hydro-meteorological institutions from nine countries (Austria, Croatia, Czech Republic, Hungary, Poland, Romania, Serbia, Slovakia, and Ukraine), together with the European Commission's Joint Research Center (JRC, Institute for Environment and Sustainability) set out for the creation of a digital climate atlas of the Carpathian Region (Szalai and Vogt, 2011). This atlas (that will be completed in 2013) is based on a 1961–2010 daily gridded database of 14 meteorological variables: the spatial resolution of the grids is $0.1° \times 0.1°$, the area under examination is 17–27° E (Longitude) and 44–50° N (Latitude), excluding the territories under the political administration of Bosnia-Herzegovina.

After the introduction, the second section of this paper is dedicated to the construction of the dataset: data collection, quality check procedures, homogenization methods, harmonization techniques, and interpolation models are described. Mean temperature (T_{M}) and precipitation (RR) grids have been used as input for calculating a set of four drought indicators: Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI), Reconnaissance Drought Indicator (RDI), Palfai Aridity/Drought Index (PADI), and two climate indicators, Köppen-Geiger climate classification (KG), and FAO-UNEP aridity index. Section 3 provides details on basic features, pros, and cons of these indicators. By means of the listed indicators, computed on different time scales, we performed a detailed study of the drought events of the last 5 decades: a table with the list of relevant drought occurrences and a 1961–2010 monthly drought series for each indicator are presented in Sect. 4. Three case studies (drought in 1990, 2000, and 2003) are then discussed in detail (Sect. 5). A close examination on aridity and shifts in climate classes in the Carpathian Region is presented in Sect. 6. Finally, a summary of the results together with a short overview on some expected outcomes of the CARPATCLIM Project conclude the paper.

2 Data

In most trans-national projects, the main problem is related to different data-sharing policies at country level: local authorities, national or regional meteorological services, independent data providers, etc., usually manage the climate data following different strategies. The philosophy of the CARPATCLIM project lies on the fact that the national members of the consortium retain the property of their data that remain under the custody of the respective owners: no large common database has been created, but the data have been collected and homogenized following shared quality assurance and interpolation methods. Each country, except Austria, collected its own dataset and exchanged data within a belt of 50 Km from the borders with their neighboring countries to enable the cross-border harmonization. For each variable, each member homogenized the records, interpolated them on a national grid, and then the single national products have been merged into harmonized daily grids for the entire Carpathian Region. All the countries used the same homogenization and interpolation methods, in order to avoid producing artificial spatial inhomogeneities. Eventually, daily grids of fourteen variables for the period 1961–2010 have been computed: minimum (T_{N}), mean (T_{M}), and maximum temperature (T_{X}), precipitation (RR), wind speed, wind gust, snow depth, snow water equivalent, relative humidity, air pressure, water vapor pressure, sunshine duration, global solar radiation, and cloud cover. We focus on the creation of T_{M} and RR grids, because they have been the inputs for calculating the drought indicators.

Project members collected data from various sources such as national meteorological datasets, hand-written annals, and long-term records obtained from regional providers; the

Table 1. Number of mean temperature (T_M) and precipitation (RR) station records used to compute the grids.

PROVIDER	T_M	RR
Czech Rep.	6	23
Croatia	7	26
Hungary	37	176
Poland	9	35
Romania	93	158
Serbia	41	94
Slovakia	26	85
Ukraine	39	130
TOTAL	258	727

station network for RR data (727, see Table 1) is much denser than for T_M data (258). Daily T_M values have been computed as the sum of daily measured T_N and T_X divided by two. In Fig. 1 we show the geographical distribution of the stations.

After the border data exchange, all the 1961–2010 daily records have been quality-checked, completed, and homogenized by means of the Multiple Analysis of Series for Homogenization (MASH, Szentimrey, 1999) software, implemented by the Hungarian Meteorological Service (OMSZ). The original MASH was developed for the homogenization of monthly data series based on hypothesis testing. Later versions have been adapted for the homogenization of daily data series also (Szentimrey, 2008). Depending on the distribution of the examined variable, MASH can be based on an additive or a multiplicative model. In the last version, the following subjects were elaborated for monthly and daily series: series comparison, break-point (change-point) and outlier detection, correction of series, missing data completion, automatic usage of metadata, and a verification procedure to evaluate the homogenization results. The most significant improvements carried out by the current version (MASHv3.03) are connected with the automation of the procedures.

MASH has been chosen because it was recognized as one of the best performing homogenization methods with long-term temperature and precipitation monthly series (Venema et al., 2012). Here we list the basic steps run by MASHv3.03 in the frame of CARPATCLIM: from daily values it calculated monthly series and subsequently estimated monthly inhomogeneities. On the basis of monthly inhomogeneities, it performed a smooth estimation for daily inhomogeneities, then it automatically corrected the daily series, quality checked the homogenized daily data, completed the missing daily values, recalculated monthly series from homogenized daily series, and finally tested the monthly series for homogeneity. All the records shown in Fig. 1 have been completed and homogenized.

After a further border data exchange to ensure the harmonization of the dataset, the station data have been interpolated onto the $0.1° \times 0.1°$ regular grid (see the black rectangle in Fig. 1). Each country member interpolated T_M and RR series onto national daily grids by means of the Meteorological Interpolation based on Surface Homogenized data basis software (MISH, Szentimrey and Bihari, 2007). The daily national grids have been merged and harmonized into grids for the whole Carpathian Region (17–27° E; 44–50° N) from 1 January 1961 to 31 December 2010. The MISH was developed at OMSZ too: it is a spatial interpolation method with a strong mathematical background that leads to an efficient use of all the valuable meteorological and auxiliary information (Szentimrey et al., 2011). As for MASH, additive (T_M) or multiplicative (RR) interpolation scheme was chosen. In the additive case a regression-Kriging based procedure is performed, while in the multiplicative case everything has been led back to the additive case by a logarithmic transformation. The climate statistical parameters that determine the optimal interpolation parameters by minimizing the expected error are modeled with the help of auxiliary variables. The biggest difference between MISH and the common geo-statistical interpolation methods lies in the application of the meteorological data series for modeling: in geo-statistics (e.g. Cressie, 1991), the sample for modeling is usually based on a single realization in time of the predictor, whilst MISH takes into account the whole data series, i.e. a sample in time and space as well. The auxiliary variables applied in the realization of gridded climatologies for the CARPATCLIM project are: spatial distance, elevation, and the so called AURELHLY (Benichou and Le Breton, 1987) principal components. After the automatic modeling procedure, the gridding interpolation was automatically performed by MISHv1.03.

3 Drought indicators

Though no universal definition exists, the word drought usually refers to a temporal, albeit prolonged shortfall in precipitation as compared to the climatological normal for a defined period of time. Drought is a slowly developing phenomenon with widespread impacts over extended regions and we usually distinguish between meteorological, agricultural, hydrological, and socio-economic drought, depending on the impacts of the rainfall deficit. Due to this complexity, many indicators have been proposed to evaluate the occurrence, duration, and intensity of a drought (e.g. EEA, 2008). We selected four meteorological drought indicators (SPI, SPEI, RDI, and PADI) based on their wide use or regional relevance. The first three are statistical indicators that can be used to detect droughts on a long-term interval, whilst PADI may be used on annual basis as the deviation from the normal value. We based our study on four indicators to provide the user with a more objective determination of drought phenomena in the Carpathian region in the period 1961–2010.

SPI, first introduced by McKee et al. (1993), is a statistical indicator that compares the precipitation during a period

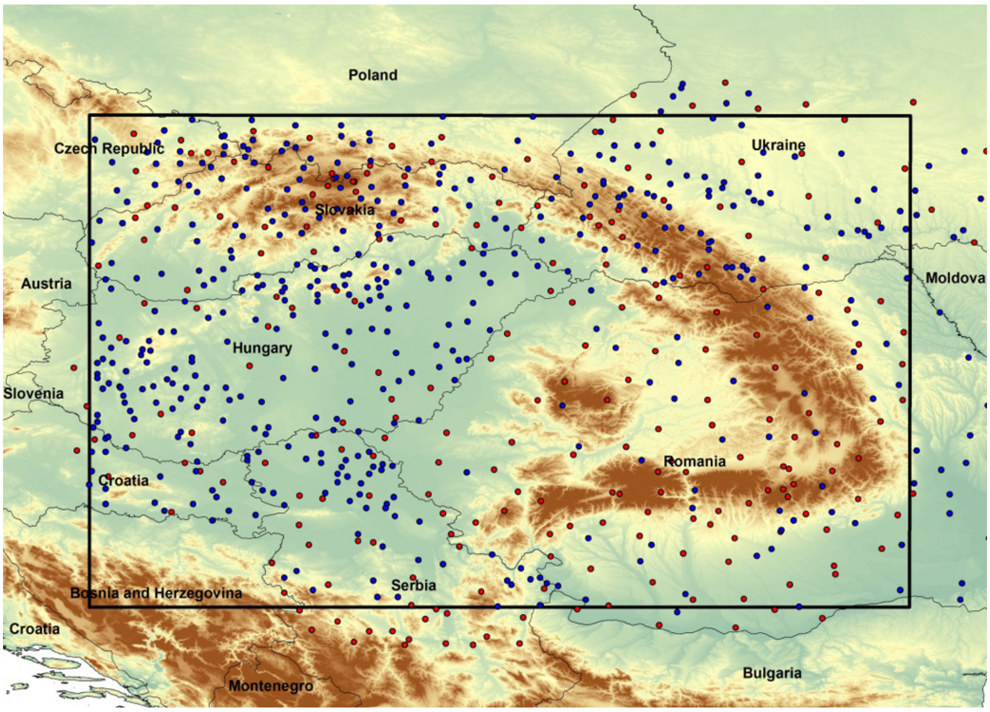

Figure 1. Stations with both RR and T_M data (red dots) and station with RR data only (blue dots). The black rectangle encloses the Carpathian Area (44–50° N, 17–27° E). Bosnia-Herzegovina must not be considered.

Table 2. Classification used for SPI, SPEI, and RDI (left), and for PADI (right). This table also represents the legend for Fig. 3–6.

SPI-SPEI-RDI	Class	PADI	Class
≥ 2.0	Extreme Wet	< 4	Normal
$1.5 \leq \; < 2.0$	Very Wet	$4 \leq \; < 6$	Sub-Humid
$1.0 \leq \; < 1.5$	Wet	$6 \leq \; < 8$	Mild Dry
$-1.0 < \; < 1.0$	Normal	$8 \leq \; < 10$	Dry
$-1.5 < \; \leq -1.0$	Dry	$10 \leq \; < 15$	Very Dry
$-2.0 < \; \leq -1.5$	Very Dry	$15 \leq \; < 30$	Heavy Dry
≤ -2.0	Extreme Dry	> 30	Extreme Dry

of n months versus the long term rainfall distribution at the same location and for the same period of time; it may also be used to determine the drought onset and duration. In this paper, we deal with SPI-3, SPI-6, and SPI-12 (3, 6, and 12 months of rainfall accumulation as input variables); SPI has been calculated on the basis of a Gamma distribution, chosen for it best fits precipitation sums (Thom, 1966). Because the Gamma function is not defined in $x = 0$ (no rainfall), the cumulative probability distribution must be transformed into a standardized distribution with mean 0 and standard deviation 1. Practically, SPI values are the number of deviations left (dry), or right (wet) from 0 (see Table 2 for the classification); the magnitude of the departure from the mean gives us a probabilistic measure of a wet or dry event: following Guttman (1999), a drought occurs anytime the SPI is continuously negative and reaches -1 or less; the drought ends when SPI becomes positive, though some consequences of drought may be left over for months. SPI needs only RR data, it is multi-scalar in time and space, it is good for comparing indices between different locations, and the frequencies of extreme events are comparable. Since the fitting of the data to the theoretical distribution is an approximation, the choice of the distribution itself can introduce a bias. Depending on the fit between empirical and theoretical distribution, dry regions can be misrepresented.

SPEI was introduced by Vicente-Serrano et al. (2010): its theoretical background is very similar to SPI, but instead of the accumulated rainfall, it is based on the accumulated difference between rainfall and potential evapo-transpiration (PET). As for the calculation of SPI, a Gamma distribution can be used (namely, a shifted version), but a log-logistic distribution or a Paerson-III similarly perform. We chose the shifted Gamma distribution as to compare SPI and SPEI in the best way. We computed SPEI-3, SPEI-6, and SPEI-12. SPEI uses the same classification as SPI (see Table 2). The use of SPEI has two main advantages: it has a better connection to soil water balance than SPI and it considers also temperature (used to compute PET), which is very important in a climate change environment. We used an improved version of the Thornthwaite's model (original: see Thornthwaite, 1948; improved: see Willmott et al., 1985; van der Schrier et al., 2011) that needs only T_M and Latitude as

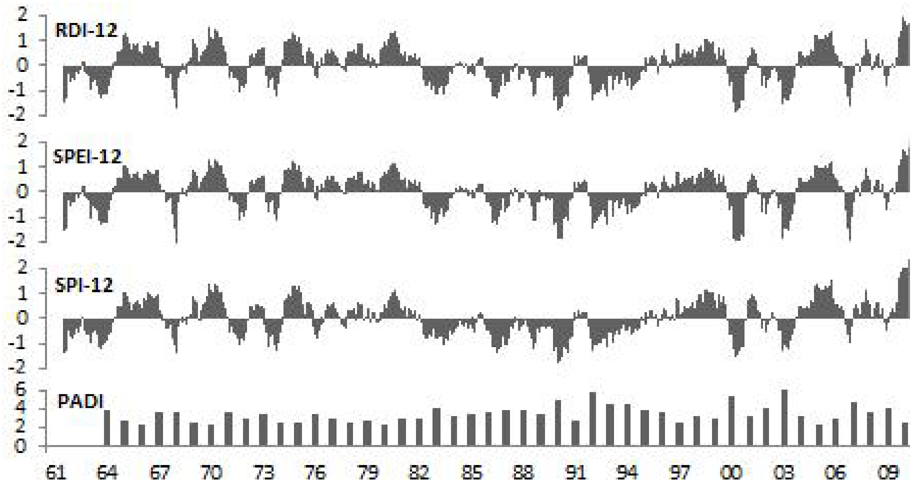

Figure 2. Monthly 1961-2010 drought series of RDI-12, SPEI-12, RDI-12, and annual 1964–2010 series of PADI.

inputs, and it is proven to perform close to the more enhanced Penman-Monteith's model (Allen et al., 2006) if applied to drought indicators (van der Schrier et al., 2011). Due to the fact that RR values can be much higher than PET, precipitation is the basic driver of SPEI, however SPEI may overestimate droughts especially during prolonged heat waves or in very dry areas if large differences between actual and potential evapo-transpiration hold. Be aware of the fact that the subtraction of RR and PET may not precisely follow a Gamma distribution.

RDI (Tsakiris and Vangelis, 2005) is based on the cumulative ratio of precipitation and PET: it is simple, universal and as SPEI, and it includes PET. Because it is based on a ratio, it may be extreme in very arid or wet periods. RDI is a monthly indicator and we computed it as RDI-3, RDI-6, and RDI-12; unlike SPI and SPEI we chose a log-normal distribution for RDI, as suggested by Tsakiris and Vangelis (2005); RDI follows the same classification used for SPI and SPEI (Table 2). When it is computed as RDI-12 for December, it can be compared to FAO-UNEP aridity Index (UNEP, 1992).

The Palfai Aridity Index (*PAI*) was proposed by Palfai (1990) for drought monitoring in Hungary and it has been applied mostly in Eastern European countries. It has been reviewed and modified in the *PADI* in order to be applied to other regions (Kozak et al., 2011b). PADI is an annual indicator (°C mm^{-1}) based on monthly T_M and RR, annual means and cumulates, and precipitation sum of the previous 3 yr (see Table 2 for the classes); it is based on three correction factors related to temperature, precipitation, and groundwater availability. PADI is not a standardized indicator, so the classes are not objective (Kozak et al., 2011b). It is not suitable for assessing the occurrence of droughts in real time, and we did not differentiate between plains and mountains in the correction factor related to groundwater availability because it is an approximation not calibrated on real data.

The cited indicators have been used to reconstruct 1961–2010 drought series for the Carpathian Region (Sect. 4) and also to analyze three drought events (Sect. 5). Details about the equations used to compute the drought indicators can be found in the cited literature and in Spinoni et al. (2013).

4 Drought events in 1961–2010

For each grid point, we computed annual values of PADI from 1964 to 2010 (PADI needs monthly precipitation data of the previous 3 yr, so we could compute it from 1964 only), and monthly SPI, SPEI, and RDI at 3, 6, and 12-month timescales from 1961 to 2010. It clearly emerges that SPI, SPEI, and RDI, if computed at the same time scale, are highly correlated. We compared the indicators over each grid point and then we averaged the correlation coefficient (r) over the whole grid. For 3-month indicators, r is highest for SPEI-SPI (0.95), followed by RDI-SPEI (0.91), and SPI-RDI (0.82); for 6-month indicators r is highest for RDI-SPEI (0.97), followed by SPEI-SPI (0.95), and SPI-RDI (0.91); for 12-month indicators, r is highest for RDI-SPEI (0.99), followed by SPI-RDI (0.96), and SPEI-SPI (0.94).

In order to calculate drought series for the Carpathian Region, we averaged, for each month or year, the values of the considered indicator over the entire gridded area. In the future, we will construct drought series for climatic sub-regions of the Carpathians, dealing in particular with the differences amongst the plain regions West and East to the Carpathian chain, and also versus the mountain area itself. In Fig. 2 we show the 1961–2010 series for SPI-12 (top), SPEI-12 (center), and RDI-12 (bottom), followed by the annual series of PADI from 1964 to 2010. All the monthly indicators agree: the worst droughts occurred in 1990, 2000, and 2003; less intense or prolonged droughts took place in 1964, 1970, 1973/74, 1983, 1987, 1992, and 2007. Over the whole period the mean value of PADI is 3.51, the highest positive

Table 3. Most relevant drought events from 1961 to 2010 in the Carpathians.

Drought		Duration			Intensity			Peak			PADI
N	Period	3-m	6-m	12-m	3-m	6-m	12-m	3-m	6-m	12-m	Anom
1	Winter 61/62	4	5	5	3	4	3	Oct-61	Jan-62	Dec-61	–
2	Winter 63/64	8	8	10	2	2	6	Jan-64	Nov-63	Feb-64	0.28
3	First half 68	4	3	6	2	2	6	Jun-68	Jun-68	Jun-68	0.16
4	Early 72	4	5	6	3	2	3	Mar-72	Mar-72	Mar-72	−0.50
5	Spring 74	4	5	5	3	4	1	Apr-74	Apr-74	Apr-74	−0.85
6	Winter 86/87	4	5	11	3	4	4	Nov-86	Feb-87	Feb-87	0.41
7	Early 89	3	3	5	2	1	2	Mar-89	Mar-89	Mar-89	−0.05
8	1990	9	12	13	3	7	11	Feb-90	Mar-90	Aug-90	1.57
9	Late 92	3	9	14	2	2	4	Sep-92	Aug-92	Aug-92	2.44
10	2000	9	10	10	6	8	8	Dec-00	Oct-00	Dec-00	2.00
11	Spring 02	6	6	–	4	3	–	Feb-02	May-02	–	0.54
12	Late 03	5	9	10	4	5	7	Jun-03	Aug-03	Jan-04	2.50
13	Early 07	4	8	5	3	3	3	Dec-06	Feb-07	Jun-07	1.36

anomalous years are 1990 (5.07), 1992 (5.94), 2000 (5.51), and 2003 (6.00).

Following McKee et al. (1993) and Guttman (1999), a "drought" takes place when the indicator is "constantly negative and more negative than −1 for at least 1 month before it turns back to positive values". On the basis of this definition, from 1961 to 2010, RDI-3 detects 19 events, SPEI-3 17 events, and SPI-3 15 events; RDI-6 detects 14 events, SPEI-6 13 events, and SPI-6 12 events; RDI-12 detects 12 events, SPEI-12 11 events, and SPI-12 9 events only. In Table 3 we list the "drought events" that have been detected by at least two indicators out of SPI, SPEI, and RDI. The numbers shown in Table 3 are based on a "3-month accumulation drought series" that has been calculated as the average between SPI-3, RDI-3, and SPEI-3 series over the whole grid (*3-m* in Table 3). We did the same for 6-month and 12-month indicators (*6-m* and *12-m* in Table 3). For each event, *Duration* stands for the number of months from the first month where the indicator becomes lower than −1 to the last month with a negative value before the indicator turns back positive. *Intensity* stands for the number of months in which the drought indicator is lower than −1. *Peak* refers to the month with the lowest value in the "drought period". PADI's annual anomaly is positive when the year is "drier" than the normal value of 1961–2010, negative when it is "wetter". Table 3 provides a complete overview on the droughts in the Carpathian Region over the last 5 decades: at a first look, the drought frequency is increasing, in fact in the 00s four events have been detected, whilst 3 events have occurred in the 60s, and 2 in the 70s, 80s, and 90s. A previous study, carried by Snizell et al. (1998), reported as well a statistically significant increase in drought frequency in Hungary, especially in the late 80s and in the 90s. However, the increase is just based on a simple observation of the fact that the number of droughts is slightly increasing in the last decades as compared to earlier decades. An analysis based on statistical significance of such an increase has not been carried out because it would have been based on the arbitrariness of defining a "drought" event. Out of the 13 events listed, 3 of them can be considered exceptional: the drought in 1990 (the longest one), the drought in 2000 (the most intense), and the drought in the second half of 2003, which followed the heat wave of summer 2003. It seems that in the last 15–20 yr the droughts have also been longer and more intense than in the past and this is probably due to the temperature rise in the Carpathians because of climate change. A deeper analysis on the temporal evolution of drought frequency, intensity, and duration in the Carpathian area will be performed in the future.

5 Case studies: the droughts of 1990, 2000, and 2003

The drought of 1990 (see Vermes and Mihalyfy, 1995) was a long and particularly intense one, especially in February, March, and autumn. If we look at Table 4 we notice that, from a meteorological point of view, it started between January (RDI-3) and February (SPEI-3, SPI-3) and ended in October. For 6-month indicators it started in February, peaked in March, and softened progressively till it ended in spring 1991. Also 12-month indicators see a long drought that started in June, lasted approximately one year, and ended up in spring 1991. The temporal correlation between indicators is evident and the indicators suggest that the drought in 1990 was most intense in February and March, and stroke also in autumn on a hydrological perspective. It was the longest one in 1961–2010, especially in the western side of the Carpathians. We also present the maps of SPI-3, SPEI-3, and RDI-3 for the peak month February 1990 (Fig. 3): for this particular month we notice that SPI-3 and SPEI-3 show very similar spatial patterns, and RDI-3 differs from the other drought indicators as it detects a more intense drought in all the regions

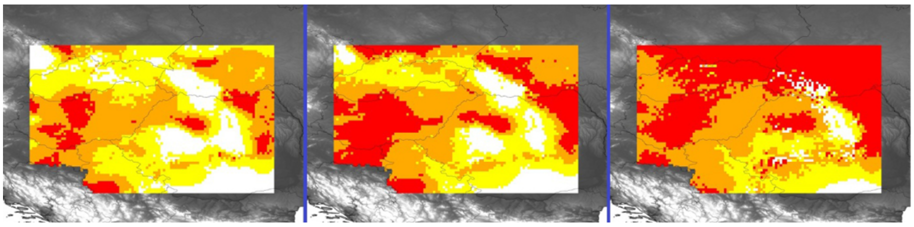

Figure 3. Left to right: drought maps of SPI-3, SPEI-3, and RDI-3 related to February 1990. See Table 2 for colour-scale.

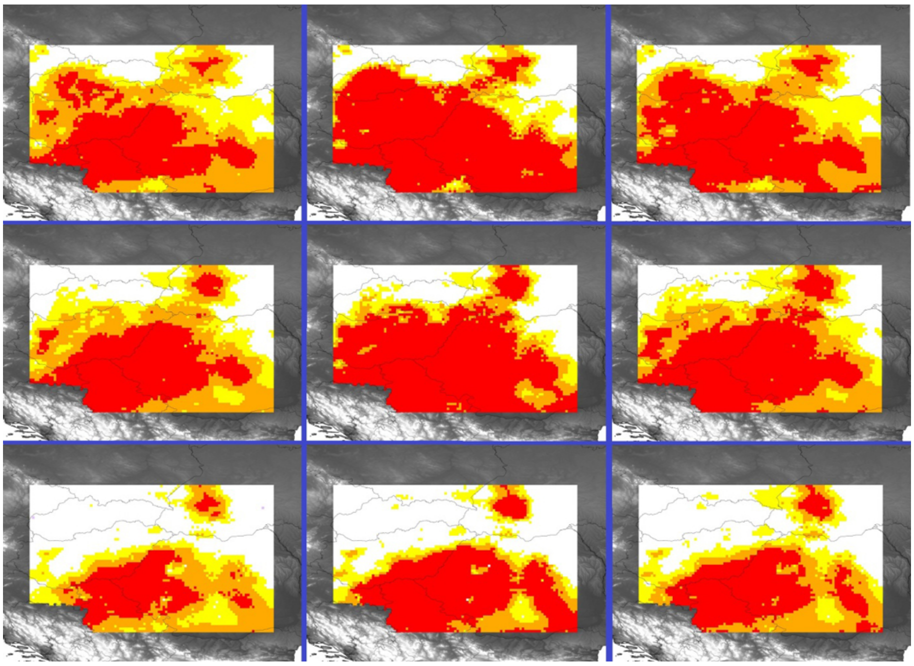

Figure 4. Spatio-temporal evolution of drought from October 2000 (top images), to November 2000 (center) and December 2000 (bottom). From left column to right, SPI-6, SPEI-6, and RDI-6. See Table 2 for colour-scale.

North, North-East and East to the Carpathian Chain. This is due to the highly positive T_M anomalies in winter 1989/90 (up to 3.2 °C compared to the long-term T_M in winters from 1961 to 1990), so RDI is extreme due to low values of PET in the ratio between RR and PET.

The drought of 2000 hit the whole Pannonian Basin, an area located within the natural borders of the Alps, the Carpathian Mountains, the Dinarides, and the Balkan Mountains (Szalai et al., 2000). It was particularly heavy in Romania, where it caused more than 500 million dollars of economic damage (EM-DAT, the International Disasters Database, see http://www.emdat.be). All 3-month and 6-month indicators agree on the fact that the drought started in June 2000, peaked in the last months of 2000, and ended between February 2001 (SPI-3, SPEI-3) and May 2001 (RDI-6). The 12-month indicators detect the drought with a five to six months delay (see Table 5), so the drought-involved period is shifted onwards in time. This case study remarks that it is important to deal with drought indicators with different accumulation periods in order to account for the various features of a drought event. The main driver was the rainfall deficit, but also the temperatures in the second half of 2000 were higher than the normal values and forced the drought to be intense: in this case the drought shows very similar spatial features if evaluated with any of the three indicators, though in Central Hungary, Serbia and Romania the values of SPEI-6 are the lowest (i.e. more intense drought), especially in October and November. The spatial correlation between drought indicators is very high, as we see in Fig. 4, where the evolution of RDI-6, SPEI-6, and SPI-6 from October to December 2000 is presented. In the "peak months" the regions most involved were Hungary, Romania and Serbia, whilst the regions North to the Carpathian Mountains do not seem to be involved by this drought event.

The drought that followed the European spring and summer positive temperature anomalies *of 2003* is probably the most known of the last 15 yr: it caused huge damages in agricultural production, especially in Central and Eastern Europe

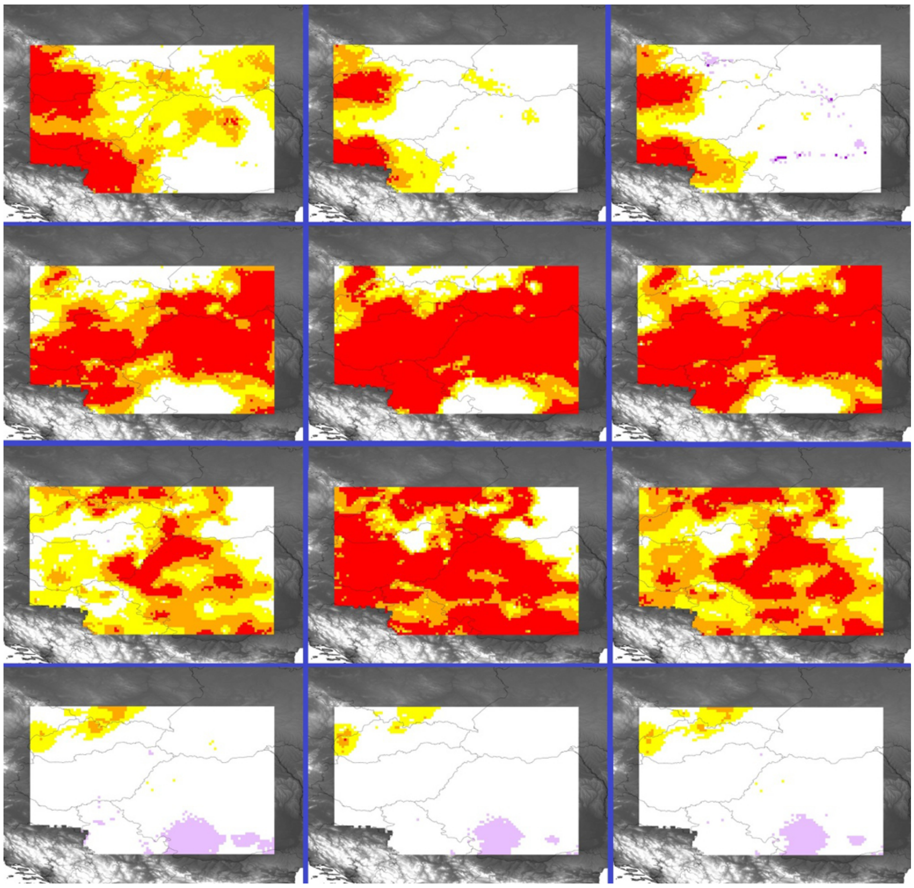

Figure 5. Left to right: SPI-3, SPEI-3, and RDI-3. Top to bottom: April 2003, June 2003, August 2003, October 2003. See Table 2 for colour-scale.

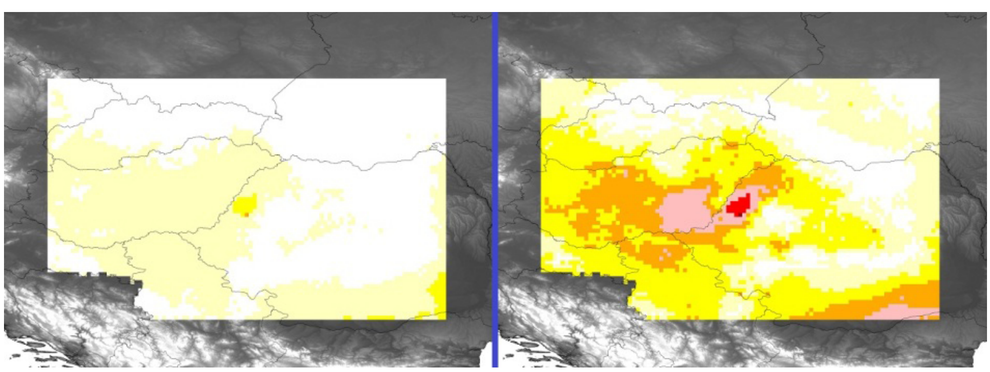

Figure 6. Palfai Aridity and Drought Index: mean value in 1964–2010 (left), 2003 (right). See Table 2 for colour-scale.

(Rebetez et al., 2006). The 2003 drought was caused by a severe lack of summer precipitation and extremely high temperatures (up to 4 °C above 1961–1990 mean values in Central Europe) as the heat wave lasted from April (or May) to September. Compared to the other drought phenomena described above, it was very intense but "limited" to 4–6 months as it was mainly concentrated between May and September 2003: in fact, all the indicators reached values lower than −1.50 in these months only. SPI detects it one month in advance than RDI and SPEI, but if analyzed with SPI only, the drought event is not found to be as intense as SPEI and RDI suggest, in particular from June to September (see SPEI and RDI for 3 and 6 months in Table 6). In October, T_M and RR turned back to almost normal values, so the drought conditions disappeared faster than the in the first two case studies described in this paper. Moreover, because the

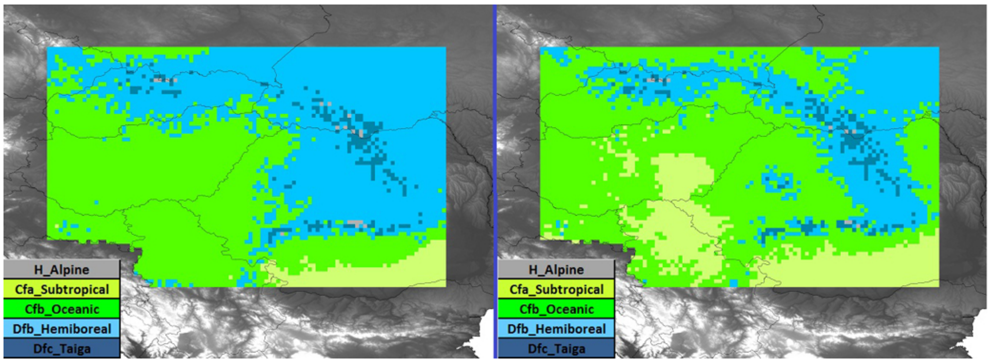

Figure 7. Köppen-Geiger climate maps of the Carpathians for 1961–1990 (left) and 1981–2010 (right).

Table 4. The drought of 1990 for SPI, SPEI, and RDI. The bold boundaries enclose the drought event.

M	Y	SPI3	SPEI3	RDI3	SPI6	SPEI6	RDI6	SPI12	SPEI12	RDI12
12	89	-0.92	-0.77	-0.70	-0.68	-0.46	-0.61	-0.41	-0.32	-0.47
1	90	-1.40	-1.17	-0.19	-0.63	-0.55	-0.54	-0.35	-0.26	-0.37
2	90	-1.40	-1.62	-2.00	-1.27	-1.36	-1.31	-0.26	-0.23	-0.34
3	90	-1.12	-1.82	-1.74	-1.52	-1.96	-2.00	-0.34	-0.34	-0.45
4	90	-0.29	-0.86	-1.06	-1.10	-1.42	-1.58	-0.44	-0.28	-0.42
5	90	-0.65	-0.86	-0.86	-1.30	-1.82	-1.65	-0.80	-0.75	-0.82
6	90	-0.52	-0.22	-0.36	-1.10	-1.19	-1.28	-1.31	-1.32	-1.35
7	90	-1.06	-0.71	-0.91	-1.02	-1.07	-1.11	-1.17	-1.20	-1.20
8	90	-1.27	-0.97	-1.19	-1.31	-1.20	-1.33	-1.78	-2.09	-1.82
9	90	-0.95	-0.54	-0.83	-1.01	-0.56	-0.83	-1.73	-1.96	-1.71
10	90	-0.49	-0.27	-0.43	-1.08	-0.74	-0.97	-1.64	-1.94	-1.65
11	90	-0.01	0.10	0.05	-0.96	-0.70	-0.88	-1.57	-1.86	-1.64
12	90	0.20	0.12	-0.07	-0.60	-0.35	-0.50	-1.15	-1.07	-1.23
1	91	-0.34	-0.44	-0.67	-0.69	-0.46	-0.56	-1.18	-1.10	-1.20
2	91	-0.46	-0.35	0.31	-0.30	-0.09	-0.02	-1.22	-1.02	-1.14
3	91	-1.22	-1.16	-1.08	-0.67	-0.78	-0.95	-1.22	-0.95	-1.07
4	91	-0.73	-0.59	-0.62	-0.79	-0.78	-0.77	-1.41	-1.14	-1.21
5	91	0.30	0.58	0.63	-0.07	0.23	0.44	-0.84	-0.34	-0.46
6	91	0.33	0.64	0.64	-0.37	0.00	-0.05	-0.73	-0.28	-0.41
7	91	0.92	0.92	0.96	0.44	0.52	0.51	-0.12	0.12	0.05
8	91	0.54	0.45	0.45	0.54	0.58	0.58	0.26	0.42	0.41

Table 5. The drought of 2000 for SPI, SPEI, and RDI. The bold boundaries enclose the drought event.

M	Y	SPI3	SPEI3	RDI3	SPI6	SPEI6	RDI6	SPI12	SPEI12	RDI12
5	00	-0.32	-0.56	-0.60	0.06	-0.08	-0.32	0.59	0.28	0.20
6	00	-1.55	-1.97	-1.76	-1.09	-1.37	-1.33	-0.06	-0.21	-0.33
7	00	-1.18	-1.30	-1.23	-0.83	-1.11	-0.98	-0.21	-0.26	-0.33
8	00	-1.37	-1.60	-1.49	-1.19	-1.56	-1.37	-0.63	-0.77	-0.82
9	00	-0.55	-0.42	-0.54	-1.34	-1.71	-1.49	-0.61	-0.60	-0.67
10	00	-1.53	-1.74	-1.80	-1.73	-2.38	-1.91	-0.97	-1.25	-1.12
11	00	-1.03	-1.20	-1.21	-1.68	-2.32	-1.94	-1.22	-1.89	-1.51
12	00	-1.49	-2.37	-2.25	-1.18	-1.63	-1.40	-1.54	-2.43	-1.91
1	01	0.46	-0.85	-1.50	-1.50	-2.15	-1.82	-1.47	-2.32	-1.77
2	01	-0.06	-0.17	-0.47	-0.94	-1.18	-1.24	-1.48	-2.37	-1.79
3	01	0.80	0.53	-0.38	-0.38	-0.87	-1.40	-1.30	-2.27	-1.69
4	01	0.98	0.73	0.40	0.43	0.11	-0.50	-1.11	-1.74	-1.38
5	01	0.50	0.30	0.22	0.28	0.13	-0.98	-1.12	-1.79	-1.39
6	01	0.40	0.48	0.45	0.77	0.65	0.63	-0.24	-0.27	-0.39
7	01	0.60	0.55	0.55	0.94	0.74	0.74	-0.06	-0.21	-0.34
8	01	0.68	0.52	0.55	0.74	0.49	0.51	0.13	-0.03	-0.16
9	01	1.18	0.87	0.94	1.05	0.85	0.91	0.71	0.44	0.36

anomalous temperature and rainfall regimes lasted approximately 6 months and were forerun and followed by quasi-normal conditions, the 12-month indicators never peaked to values lower than −2.0. As we see in Fig. 5, all the 3-month indicators agree: in the Carpathians, the first clear drought signals appeared in April, the drought peaked twice (June and August), and it vanished almost completely in October. Drought shifted from West to East and the geographical patterns are very similar in all the indicators, nevertheless for SPEI the drought was a bit more intense and widespread in August. As for the drought of 2000, the Carpathians acted as a natural barrier for the drought: the regions North and East to the mountain barrier experienced a less intense drought than the regions West and South to it. In the Carpathians, elevation plays a leading role; in fact it is also worth noticing that, according to RDI-3, while drought was starting in the westernmost areas of the Carpathian region, in April 2003, the mountaintops of the Carpathian Chain experienced wet conditions.

The whole 2003 was extremely dry in Europe, including our study area, which is shown in Fig. 6: the differences amongst the mean value of PADI in 1964–2010 (left)

Table 6. The drought that followed the summer heat wave of 2003 as seen by for SPI, SPEI, and RDI. The bold boundaries enclose the drought event.

M	Y	SPI3	SPEI3	RDI3	SPI6	SPEI6	RDI6	SPI12	SPEI12	RDI12
3	03	-0.42	-0.12	0.37	-0.13	0.06	0.33	0.05	0.02	-0.09
4	03	-1.39	-0.69	-0.49	-0.90	-0.59	-0.13	-0.01	-0.01	-0.10
5	03	-1.50	-1.69	-1.57	-1.05	-0.97	-0.98	-0.10	-0.20	-0.27
6	03	-1.77	-2.58	-2.05	-1.72	-2.21	-1.90	-0.47	-0.65	-0.69
7	03	-0.94	-1.94	-1.31	-1.47	-2.09	-1.68	-0.46	-0.51	-0.59
8	03	-1.33	-2.25	-1.63	-1.79	-2.84	-2.10	-1.03	-1.24	-1.22
9	03	-0.49	-0.65	-0.64	-1.42	-2.27	-1.73	-1.29	-1.89	-1.54
10	03	0.08	0.15	0.10	-0.58	-1.01	-0.86	-1.08	-1.50	-1.29
11	03	0.54	0.66	0.68	-0.59	-0.84	-0.79	-1.12	-1.47	-1.31
12	03	0.39	0.54	0.73	-0.18	-0.18	-0.26	-1.17	-1.45	-1.40
1	04	-0.46	-0.57	-0.79	-0.29	-0.23	-0.29	-1.20	-1.54	-1.36
2	04	0.40	0.44	0.58	0.65	0.78	0.95	-0.94	-1.17	-1.12
3	04	0.77	0.72	0.22	0.75	0.82	0.92	-0.69	-0.88	-0.93
4	04	0.50	0.42	0.23	0.00	-0.09	-0.32	-0.50	-0.85	-0.88
5	04	-0.03	0.12	0.07	0.16	0.30	0.31	-0.39	-0.45	-0.53
6	04	-0.21	-0.01	-0.11	0.23	0.33	0.30	0.01	0.08	0.01

and PADI in 2003 (right) are remarkable. According to the long-term mean PADI, the Carpathians are in "normal conditions", except of Hungary and South-Eastern corner (Romania), where "sub-humid" conditions can be found (see Table 2 for the complete classification). In 2003, the "sub-humid" areas turned to be mild-dry, the South-Eastern corner was "dry", and the areas along the country border between Hungary and Romania were very or heavy dry, confirming that 2003 was anomalous in the Carpathians.

6 Shifts in climatic regions

Following the Köppen-Geiger's (KG) climate classification (Köppen, 1936; Geiger, 1961), the Carpathian Mountains are a climatic barrier between oceanic (South and West) and continental (North and East) climate. In Fig. 7 we show the KG maps related to 1961–1990 and 1981–2010, computed using monthly and average T_{M} and RR values over the two 30-yr periods. Out of the 31 KG climate classes, only 5 are present in the Carpathian Region: alpine (*H*: alpine or *ET*: tundra) on the mountain peaks, two oceanic subclasses (*Cfa*: humid subtropical and *Cfb*: mild oceanic), and two continental subclasses (*Dfb*: continental hemi-boreal and *Dfc*: taiga). No desert, steppe or dry Mediterranean classes can be found. However, the subtropical (*Cfa*) is very similar to a semi-arid class. From 1961–1990 to 1981–2010 the alpine climate slightly decreased (0.32 to 0.17 %), subtropical strongly increased (4.94 to 16.86 %), oceanic increased (46.25 to 55.20 %), whilst hemi-boreal strongly decreased (45.33 to 24.63 %), and taiga is constant (3.12 to 3.14 %). In Fig. 7 we notice a steep increase of the mild oceanic climate in the last decades, which confines the continental to the Carpathian chain and part of Ukraine only; on the other hand, the warmest areas with oceanic climate became semi-arid subtropical regions, as in the Csongrad and Vojovdina regions near the intersection between Hungarian, Romanian and Serbian country borders.

The FAO-UNEP aridity index (UNEP, 1992) is probably the most widespread indicator which quantifies the aridity of an area according to climate factors: it is calculated as the ratio between annual precipitation and evapotranspiration (ET). We used PET instead of ET, because of simplicity and because we are interested in climate features only, not in biological or agronomic factors. If the ratio is higher than 0.75, there is no desertification risk, if it is lower than 0.03 the area is desert-like. In between, we call it "hyper-arid" if the index is ≥ 0.03 but < 0.05, "arid" if ≥ 0.05 but < 0.2, "semi-arid" if ≥ 0.2 but < 0.5, "dry or sub-humid" if ≥ 0.5 but > 0.65, "mild dry/humid" if the ratio lies between 0.65 and 0.75. In the Carpathian region, no area falls in a "dry/arid/desert" category in 1961–1990, neither in 1981–2010. Only a small increase in the "mild dry/humid" class can be seen: from 2.34 % in 1961–1990 to 4.39 % in 1981–2010, mainly due to 2 dry years, 2000 and 2003. Regions that turned into "mild dry/humid" class are located in the south-eastern Romanian corner of the Carpathian region. Going eastwards, the Eastern Romania is facing a desertification threat, especially in the Danube Delta and on the Black Sea coast, two areas out of the Carpathian Region (Spinoni et al., 2012). Similar results can be found using other aridity indices, as Crowther's (Bove et al., 2005), De Martonne's (De Martonne, 1926), and Bagnouls-Gaussen's (Kosmas et al., 1999): the Carpathians are not under an increased desertification risk due to natural factors. However, in spite of the seemingly favourable mean conditions, episodic droughts can cause very serious damage.

7 Summary and conclusions

A 1961–2010 daily gridded dataset of T_{M} and RR, collected by the CARPATCLIM consortium, has been used as the basis for computing four drought indicators (RDI, SPEI, SPI, and PADI) and two climate indicators (KG and FAO-UNEP) over the Carpathian Region.

In this paper we dealt with drought events in the last 5 decades in the Carpathian Region: the most intense droughts took place in 1990, 2000, and 2003, followed by other 10 notable events. On the other hand, 2005 and 2010 were the wettest years. We discussed in detail the three most important drought events: all the indicators agreed on the temporal structure and geographical patterns of the droughts. SPI, SPEI, and RDI proved to be highly correlated if computed at the same accumulation scale (3, 6 or 12 months). PADI confirmed the a-normality of 1990, 2000, and 2003 yr. We do not recommend using PADI as a standalone indicator, because it is not able to capture the monthly evolution of a drought. In general, the drought frequency is slightly increasing: in fact, during in the last decade (2001–2010), 4 drought events occurred out of the 13 detected between 1961 and 2010. Anyway, this rise is not confirmed by significance tests, but we think that the increasing tendency is an important indication based on the fact that in the recent decades more drought events took place than in the earlier decades.

The Carpathian Mountains are an orographic border between mild oceanic (South and West) and continental (North and East) climates. In the last 20 yr, a shift from oceanic to continental climate can be seen, especially in the Romanian part of the Carpathians and on the country borders between Serbia and Hungary. Using the KG climate classification, no desert, steppe or arid areas are present in the area under examination; furthermore, using the FAO-UNEP aridity's index, it is clear that the Carpathians cannot be considered an arid area.

In the future, we plan comparing the results obtained by means of the CARPATCLIM dataset with an independent dataset collected by JRC (Spinoni et al., 2013). The results obtained in this paper and the future comparisons will be part of the European Drought Observatory, a web-portal developed by the DESERT Action of the Climate Risk Management Unit of Institute for Environment and sustainability of JRC (http://edo.jrc.ec.europa.eu/).

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