TENDENCY ANALYSIS OF EXTREME CLIMATE INDICES WITH SPECIAL EMPHASIS ON AGRICULTURAL IMPACTS

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Abstract. Drought events in a particular region may occur in case of long-term lack of precipitation coinciding with hot weather. The main objective of our research is to detect the possible changes of intensity and frequency of the extreme events associated with precipitation and temperature. In this paper, several climate extreme indices are analyzed and compared for the Carpathian Basin (focusing on Hungary) for the second half of the 20th century based on the guidelines suggested by the joint WMO-CCl/CLIVAR Working Group on climate change detection. Daily maximum, minimum and mean temperature observations and daily precipitation amounts are used in the present statistical analysis. Because of the lack of century-long meteorological time series, the analysis has been accomplished mainly for the second half of the 20th century. However, the analysis has been extended for the entire century in case of some stations, where sufficient data was available. The statistical trend analysis includes the evaluation of 27 extreme indices, e.g., the numbers of severe cold days, winter days, frost days, cold days, warm days, summer days, hot days, extremely hot days, cold nights, warm nights, the intra-annual extreme temperature range, the heat wave duration, the growing season length, the number of wet days (using several threshold values defining extremes), the maximum number of consecutive dry days, the highest 1-day precipitation amount, the greatest 5-day rainfall total, the annual fraction due to extreme precipitation events, etc.

The results suggest that similarly to the global and continental trends, regional temperature of Central/Eastern Europe got warmer during the second half of the 20th century. Furthermore, regional intensity and frequency of extreme precipitation increased, while the total precipitation decreased in the region and the mean climate became drier.

Keywords. Climate extreme index, daily precipitation, daily temperatrure, Carpathian Basin, trend analysis

1. Introduction

National meteorological services usually monitor climate means, tendencies, and extremes only for their own region. First, IPCC SAR (1995) declared the global warming trend of the last 150 years due to anthropogenic activity, which increased the annual global mean temperature by 0.7°C. This IPCC report also concluded that changes in both the mean and the extreme climate parameters may strongly affect human and natural systems. In the mean time, several research projects published results on the analysis of climate extremes on global or continental scales (e.g., Nicholls et al., 1996; Folland et al., 2000; Easterling et al., 2000; Peterson et al., 2002). Furthermore, the Workshop on Indices and Indicators for Climate Extremes was held in Asheville, North Carolina, on June 3-6, 1997. The main objectives of this meeting were to determine the required data sets for climate extreme analysis on larger scales, and to compile the list of climate extreme indices suggested for the global analysis (Karl et al., 1999). Then, in 1998, a joint WMO-CCl/CLIVAR Working Group formed on climate change detection; one of its task groups aimed to identify the climate extreme indices and completed a climate extreme analysis on all part of the world where appropriate data was available (Frich et al., 2002). Some results of this working group also appeared in IPCC TAR (2001).

The next section of this paper presents the definition of the extreme climate indices. Section 3 summarises and compares the results of the global (Frich et al., 2002) and the European (Klein Tank and Können, 2003) extreme precipitation and temperature analyses. Similar methodology has been applied to precipitation extremes of the Carpathian Basin. Section 4 discusses the differences between continental (for Europe) and regional (for the Carpathian Basin) extreme precipitation tendencies.

Section 5 presents detailed analysis of regional extreme precipitation indices for Hungary. Section 6 discusses the continental (for Europe) and regional (for the Carpathian Basin) extreme temperature tendencies. Finally, Section 7 concludes the main findings of this paper.

2. Definition of extreme indices based on daily precipitation and temperature

In order to compile a global climate database suitable for extreme analysis, the CCl/CLIVAR task group on extreme indices contacted the national meteorological services and collected daily precipitation, maximum, minimum, and mean temperature time series for the period 1946-1999. Beside data from the national meteorological services, sources include the NOAA NCDC datasets (Peterson and Vose, 1997), the European Climate Assessment Dataset (Klein Tank et al., 2002b), and daily meteorological time series for Australia (Trewin, 1999). All these datasets have been quality controlled and adjusted for inhomogeneities. Then, in order to include a given observation station, the following general criteria have been used: (i) from the entire 1946-1999 period data must be available for at least 40 years, (ii) missing data cannot be more than 10%, (iii) missing data from each year cannot exceed 20%, (iv) in each year more than 3 months consecutive missing values are not allowed.

The CCl/CLIVAR task group decided to map station data instead of gridded database since extreme events (e.g., local floods and droughts, heat waves, local cold spells) often occur on local scale, but on the other hand, they are all important part of global climate patterns which could disappear in case of a spatial data interpolation. Therefore, maps presented in this paper use similar technique applying station-based analysis.

Results of the global and European extreme climate analysis have been published in 2002-2003 (e.g., Frich et al., 2002; Klein Tank and Können, 2003). In this section these results are summarised and compared for the global and continental scales. Table 1 lists the main extreme precipitation and temperature indices that the CCl/CLIVAR task group identified and suggested for global climate extreme analysis.

Table 1: Definition and indicator of extreme climate parameters

No.	Indicator (ECAD)	Definition of the extreme index	Unit
1	CDD	Maximum number of consecutive dry days (when $R_{day} < 1$ mm)	day
2	Rx1	Highest 1-day precipitation amount	mm
3	Rx5	The greatest 5-day rainfall total	mm
4	SDII	Simple daily intensity index (total precipitation sum / total number of days when $R_{day} \geq 1$mm)	mm/day
5	R95T	Fraction of annual total rainfall due to events above the 95th percentile of the daily precipitation in the baseperiod 1961-1990 ($\Sigma R_{day} / R_{total}$, where ΣR_{day} indicates the sum of daily precipitation exceeding $R_{95\%}$)	%
6	RR10	Number of heavy precipitation days ($R_{day} \geq 10$ mm)	day
7	RR20	Number of very heavy precipitation days (when $R_{day} \geq 20$ mm)	day
8	R75	Number of moderate wet days ($R_{day} > R_{75\%}$, where $R_{75\%}$ indicates the upper quartile of the daily precipitation in the baseperiod 1961-1990)	day
9	R95	Number of very wet days ($R_{day} > R_{95\%}$, where $R_{95\%}$ indicates the 95th percentile of the daily precipitation in the baseperiod 1961-1990)	day
10	RR5	Number of precipitation days exceeding a given threshold ($R_{day} \geq 5$ mm)	day
11	RR1	Number of precipitation days exceeding a given threshold (R_{day}	day

		$\geq$ 1 mm)	
12	RR0.1	Number of precipitation days exceeding a given threshold (R_{day} $\geq$ 0,1 mm)	day
13	ETR	Intra-annual extreme temperature range (difference between the observed maximum and minimum temperatures, T_{max}-T_{min})	°C
14	GSL	Growing season length (start: when for >5 days T > 5°C, end: when for >5 days T < 5°C)	day
15	HWDI	Heat wave duration index (for min. 5 consecutive days $T_{\max} = T_{\max}^{N} + 5°C$, where $T_{\max}^{N}$ indicates the mean T_{max} for the baseperiod 1961-90)	day
16	Tx10	Cold days (percent of time when T_{max} < 10th percentile of daily maximum temperature based on the baseperiod 1961-90)	%
17	Tx90	Warm days (percent of time when T_{max} > 90th percentile of daily maximum temperature based on the baseperiod 1961-90)	%
18	Tn10	Cold nights (percent of time when T_{min} < 10th percentile of daily minimum temperature based on the baseperiod 1961-90)	%
19	Tn90	Warm nights (percent of time when T_{min} > 90th percentile of daily min. temperature based on the baseperiod 1961-90)	%
20	FD	Number of frost days (T_{min} < 0°C)	day
21	SU	Number of summer days (T_{max} > 25°C)	day
22	Tx30GE	Number of hot days ($T_{max} \geq$ 30 °C)	day
23	Tx35GE	Number of extremely hot days ($T_{max} \geq$ 35 °C)	day
24	Tn20GT	Number of hot nights (T_{min} > 20 °C)	day
25	Tx0LT	Number of winter days (T_{max} < 0 °C)	day
26	Tn-10LT	Number of severe cold days (T_{min} < -10 °C)	day

3. Comparison of the global and the European analyses

First, one of the precipitation extreme indices are compared on global and continental scales, then, an example of the temperature indices is presented.

Figs. 1-3. present one of the extreme precipitation indices, namely, the change of the fraction of annual total rainfall due to events above the 95th percentile of daily precipitation in the baseperiod 1961-1990. Spatial distribution of global tendencies can be seen on Fig. 1, while the graph shown on Fig. 2. provides the temporal details of the global mean change of the annual fraction of extreme precipitation during the second half of the 20th century. Results of the similar analysis for Europe is presented on Fig. 3.

Changes between the two subperiods of the second half of the century (1946-1975 and 1976-1999) have been determined during the analysis presented in Frich et al. (2002). The world map of Fig. 1. indicates both the sign of change (black and grey circles for increasing and decreasing tendencies, respectively) and the magnitude of change (applying 4 different circle sizes for the percentage intervals) at each station involved in the analysis. Stations with significant changes (at 95% level of confidence) in the fraction of annual total rainfall due to events above the 95th percentile of daily precipitation in the baseperiod 1961-1990 are mapped with filled circles, while open circles indicate not significant changes. The large number of black filled circles and few grey circles on the map suggest that the annual fraction of very wet events increased between 1946 and 1999.

Based on the available time series, annual global weighted anomalies have been calculated using the baseperiod of 1961-1990. Fig. 2. presents the annual value (in percentage) of the anomaly for the entire 1950-1999 period, as well, as the fitted linear trend emphasizing the significant increasing tendency. The figure includes a small graph (in its upper left part) indicating the total number of stations used for the analysis in each year. Except the beginning and the end of the period, about 300 stations provided valuable precipitation data to determine the annual fraction of extreme precipitation.

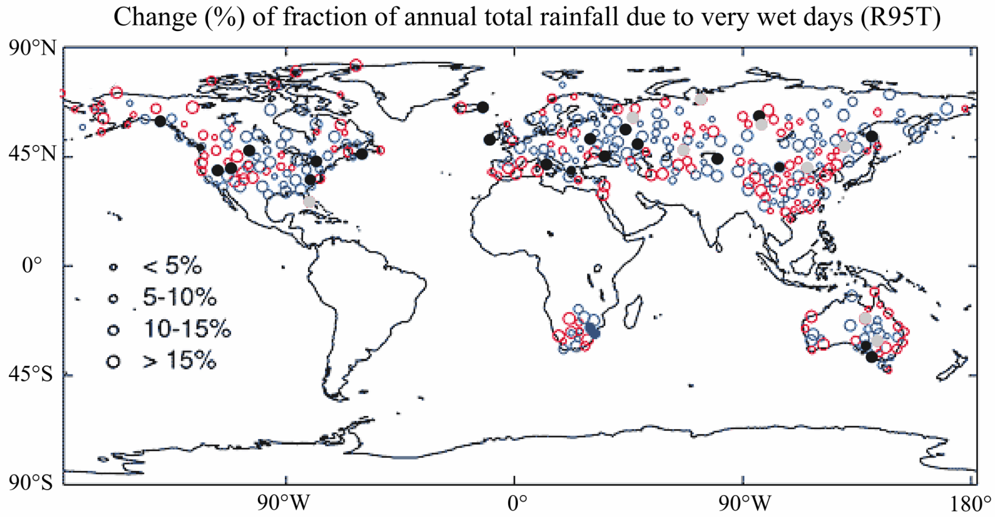


Fig. 1. Changes (%) in fraction of annual total rainfall due to events above the 95th percentile of daily precipitation in the baseperiod 1961-1990 in the second half of the 20th century. Filled circles are significant at 95% level of confidence. Grey and black indicate negative and positive changes, respectively. Circle sizes represent the magnitude of change. (Source: Frich et al., 2002)

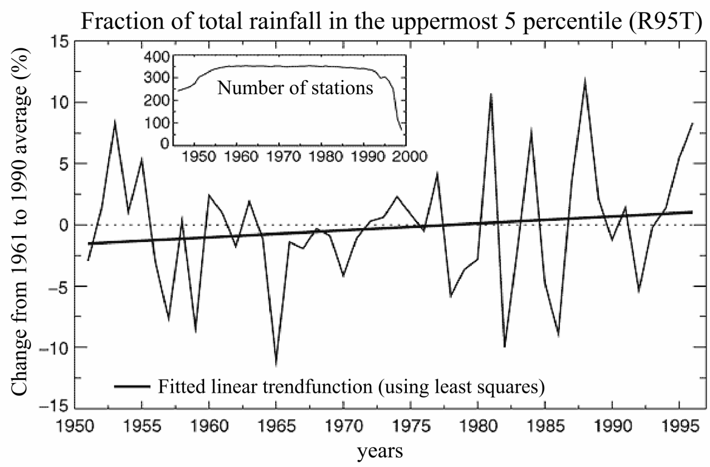


Fig. 2. Mean annual values of the fraction of annual total rainfall due to events above the 95th percentile of daily precipitation in percentage differences from the 1961-1990 weighted average values for the second half of the 20th century. The inserted graph represents the weighting factors (number of stations with valuable data) used in the linear regression analysis. The fitted linear trend is statistically significant at 95% level of confidence. (Source: Frich et al., 2002)

The European tendency analysis of the annual precipitation fraction due to very wet days is shown on Fig. 3, where the mean decadal changes of this extreme index is mapped for the stations with sufficient data for the 1946-1999 period. Open circles indicate not significant changes, while dark and grey filled circles indicate positive and negative trends, respectively. Similarly to the global analysis, significant positive tendency can be seen. According to the above results of the two large scale analyses, fraction of annual total rainfall due to events above the 95th percentile of the daily precipitation considerably increased by the end of the 20th century. Regional details of the Carpathian Basin will be presented in sections 4 and 5.

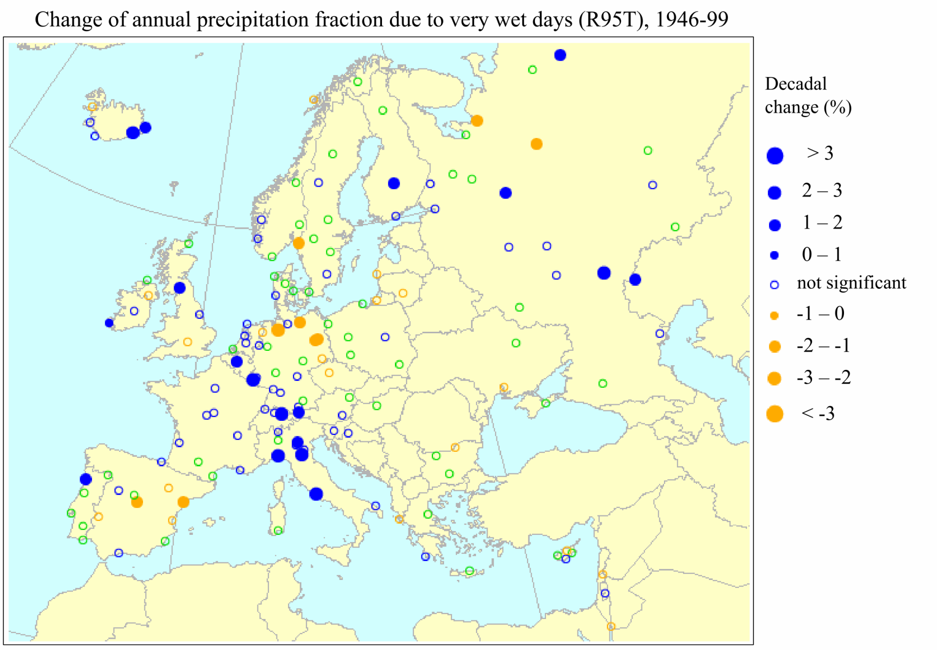


Fig. 3. Decadal trend in the fraction of annual total rainfall due to events above the 95th percentile of daily precipitation in the baseperiod 1961-1990 in Europe for the period 1946-1999. Circles are scaled according the magnitude of the trend. Open circles indicate not significant changes, while dark and grey filled circles indicate positive and negative trends, respectively.

Table 2 summarises the tendencies of all extreme precipitation indices for the global and continental scale climate analyses based on the papers of Frich et al. (2002) and Klein Tank and Können (2003), respectively. The comparison of these results is accomplished for the second half of the last century (1946-1999). Increasing, decreasing, and not significant trends are indicated with symbols „+", „–", and „0", respectively. Considerable spatial differences are emphasised using more than one type of symbol (e.g., –/+, ++/–, +/0, etc.). After identifying the main dominant trends exceptions are listed in case of each extreme climate index. In general, global and European tendencies are similar, and only a few small areas differ from the worldwide and continental dominant trends. Sometimes the Carpathian Basin belongs to these exceptions. For instance, both the SDII (simple daily intensity index) and the R95T (fraction of annual total rainfall due to events above the 95th percentile of the baseperiod) are dominantly increasing for the world, as well, as for Europe. However, for the Carpathian Basin neither the global, nor the continental scale analysis include significant trends. One of the aims of our research presented in this paper is to specify these cases on a finer spatial scale and provide more details for Hungary and the surrounding region. The next sections contain our results.

Table 2. Comparison of the tendencies of extreme climate indices based on global (Frich et al., 2002) and European (European Climate Assessment & Dataset (ECAD) project, Klein Tank and Können, 2003) extreme analysis for the period 1946-1999.

Nr.	Extreme index	World (Frich et al., 2002)	Europe (Klein Tank and Können, 2003)
1	CDD	**– / +** Negative tendency dominates except the eastern part of Asia	**0** No significant trend
2	Rx1	No analysis provided	**+ / –** Positive tendency dominates in W.and N. Europe, while negative tendency dominates in E. and S. Europe

3	Rx5	+ / – Positive tendency dominates except the eastern part of Asia	+ / – Positive tendency dominates except Central and Southern Europe
4	SDII	+ / – Positive tendency dominates except Asia	+ / **0** Positive tendency dominates in W. and N. Europe, while no significant trend can be observed at other places
5	R95T	+ / – Positive tendency dominates except Asia	+ / **0** Positive tendency dominates in N. Europe and the Alpes, while no sign. trend can be observed at other places
6	RR10	+ + / – Positive tendency dominates except the eastern part of Asia	+ / – Positive tendency dominates except Central and SE Europe
7	RR20	No analysis provided	+
8	R75	No analysis provided	+ + / – Positive tendency dominates except Central and Southern Europe
9	R95	No analysis provided	+

In case of temperature indices, Figs. 4-5. present one of the climate extreme indices, namely, the change of the number of frost days ($T_{min} < 0°C$). Spatial distribution of global tendencies can be seen on Fig. 4, while the graph shown on Fig. 5. provides the temporal details of the global mean change of the number of frost days during the second half of the 20th century.

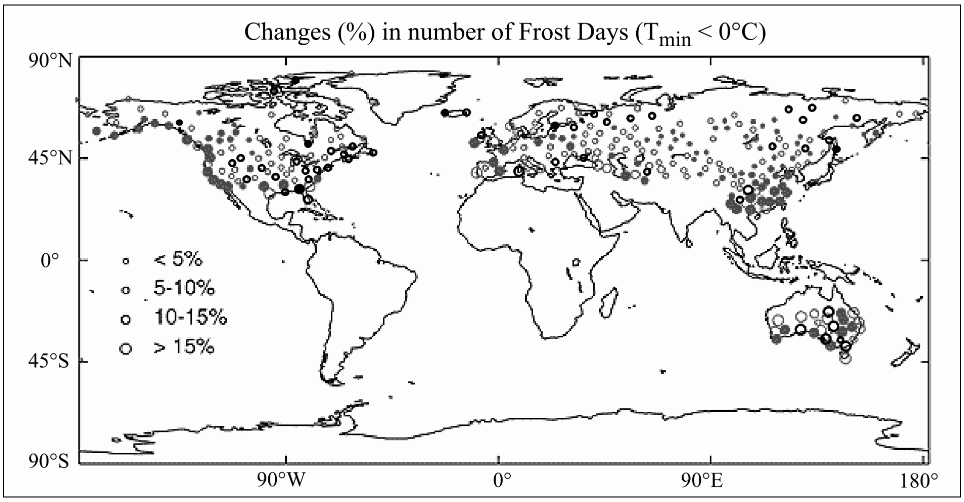


Fig. 4. Changes (%) in number of annual frost days in the second half of the 20th century. Filled circles are significant at 95% level of confidence. Grey and black indicate negative and positive changes, respectively. Circle sizes represent the magnitude of change. (Source: Frich et al., 2002)

Changes between the two subperiods of the second half of the century (1946-1975 and 1976-1999) have been determined during the analysis presented in Frich et al. (2002). The world map of Fig. 4. indicates both the sign of change (gray and black circles for decreasing and increasing tendencies, respectively) and the magnitude of change (applying 4 different circle sizes for different percentage intervals) at each station involved in the analysis. Stations with significant changes (at 95% level of confidence) in annual number of frost days are mapped with filled circles, while open circles indicate not significant changes. The large number of grey filled circles and very few black circles on the map suggest that the annual number of frost days decreased considerably between 1946 and 1999.

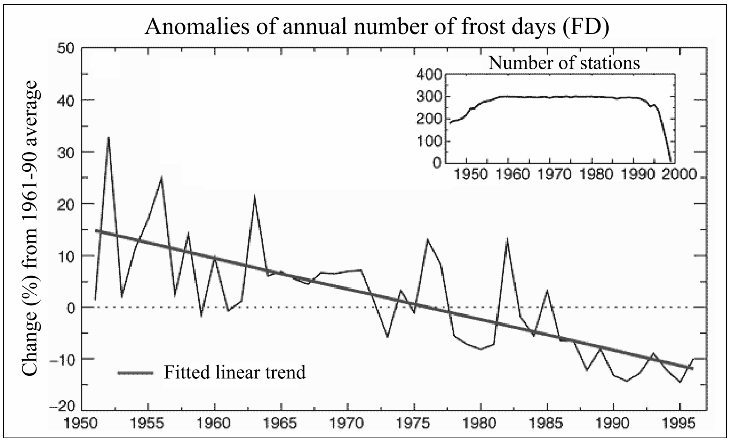


Fig. 5. Mean annual values of the number of frost days in percentage differences from the 1961-1990 weighted average values for the second half of the 20th century. The inserted graph represents the weighting factors (number of stations with valuable data) used in the linear regression analysis. The fitted linear trend is statistically significant at 95% level of confidence. (Source: Frich et al., 2002)

Based on the available time series, annual global weighted mean anomalies have been calculated using the baseperiod of 1961-1990. Fig. 5. presents the annual value (in percentage) of the anomaly for the entire 1950-1999 period, and also, the fitted linear trend emphasizing the significant decreasing tendency. The figure includes a small graph (in its upper right part) indicating the total number of stations used for the analysis in each year. Except the beginning and the end of the period, about 300 stations provided valuable temperature data to determine the annual number of frost days.

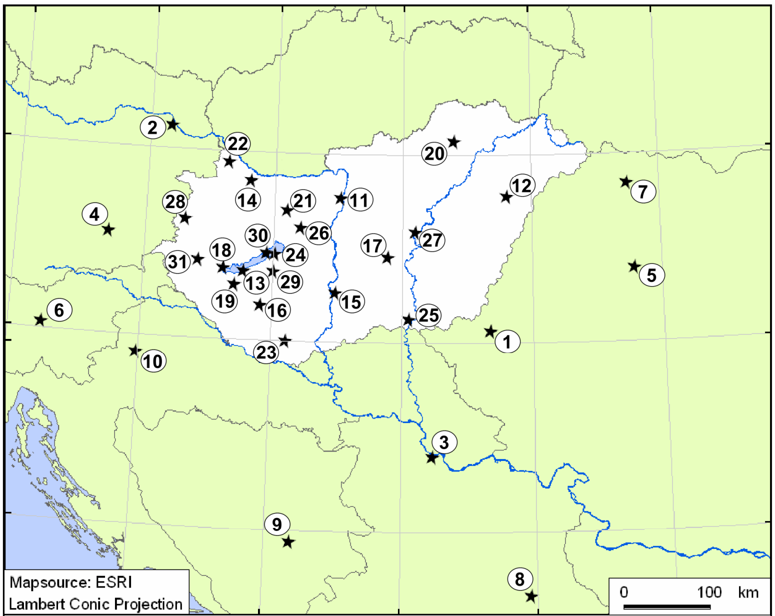
Table 3: Comparison of the tendencies of extreme climate indices based on global (Frich et al., 2002) and European (European Climate Assessment & Dataset project, Klein Tank and Können, 2003) extreme analysis for the period 1946-1999

No.	Extreme index	**World** (Frich et al., 2002)	**Europe** (Klein Tank and Können, 2003)
1	ETR	–	–
2	GSL	+	+ + / – Positive tendency dominates except Iceland
3	HWDI	+ + / – Positive tendency dominates except SE-Asia and the eastern part of North-America	+
4	Tx10	No analysis provided	+
5	Tx90	No analysis provided	+ / – Positive tendency dominates except Iceland, Italy, and the Black Sea region
6	Tn10	No analysis provided	+ +
7	Tn90	+ +	+ + / – Positive tendency dominates except Iceland, and the Black Sea region
8	FD	– –	– –
9	SU	No analysis provided	+ / – Positive tendency dominates except Eastern Europe

Table 3 summarizes the tendencies of nine extreme indices for the global and continental scale climate analysis based on the papers of Frich et al. (2002) and Klein Tank and Können (2003), respectively. The comparison of these results is accomplished for the second half of the last century (1946-1999). Four indices (Tx10, Tx90, Tn10, and SU) are analyzed only on European scale. Increasing and decreasing trends are indicated with symbols „+" and „–", respectively. Two identical or bold symbols represent large tendencies. Considerable spatial differences are emphasized using more than one type of symbol (e.g., –/+, ++/–, etc.), after identifying the main dominant trends exceptions are listed in case of each extreme climate index. In general, global and European trends are similar, and refer to a warming climate tendency. Only a few small area differ from these worldwide and continental dominant trends. For instance, in case of SU (summer days) Eastern Europe belongs to the exceptions. One of the aims of our research presented in this paper is to specify the trends on a finer spatial scale and provide more details for the Carpathian Basin and Hungary.

4. Comparison of tendecies of extreme precipitation indices for the Carpathian Basin and Europe

In order to evaluate the past and future climate tendencies of the Carpathian Basin, it is essential to compare regional tendencies of the different climate parameters to larger (i.e., continental) scale.



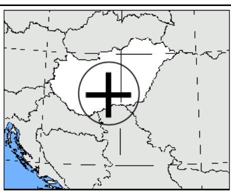
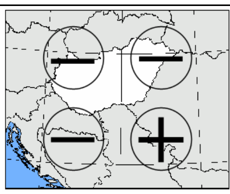
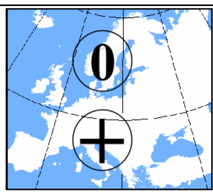
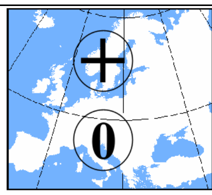
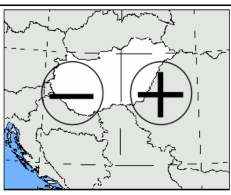
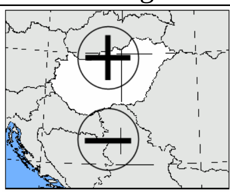
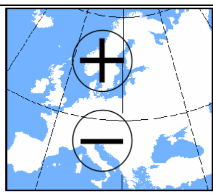
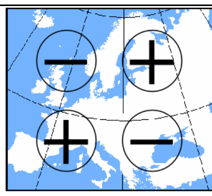
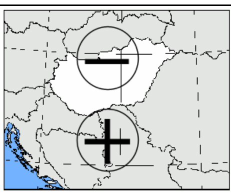
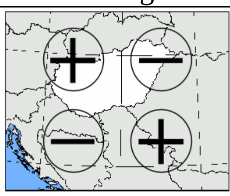
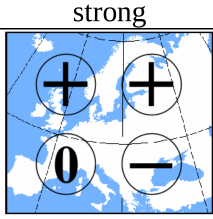
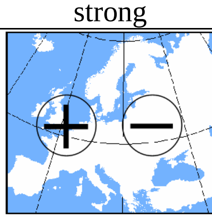
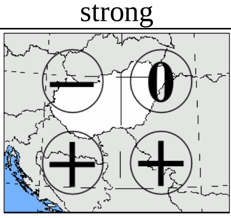
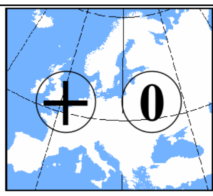
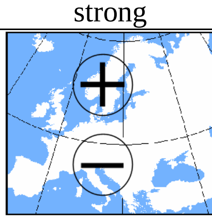
Station	N.lat.	E.long.	m	Station	N.lat.	E.long.	m
Stations in neighbouring countries				15 Kalocsa	46°31'	18°59'	92
1 Arad	46°08'	21°21'	117	16 Kaposvár	46°22'	17°50'	152
2 Vienna	48°14'	16°21'	199	17 Kecskemét	46°54'	19°46'	114
3 Beograd	44°48'	20°28'	132	18 Keszthely	46°45'	17°15'	115
4 Graz	47°05'	15°27'	366	19 Marcali	46°35'	17°25'	128
5 Cluj Napoca	46°47'	23°34'	410	20 Miskolc	48°08'	20°48'	118
6 Ljubljana	46°04'	14°31'	299	21 Mór	47°23'	18°12'	203
7 Baia Mare	47°40'	23°30'	216	22 Mosonmagyaróvár	47°53'	17°16'	121
8 Nis	43°20'	21°54'	202	23 Pécs	46°00'	18°14'	202
9 Sarajevo	52°30'	22°30'	211	24 Siófok	46°55'	18°02'	108
10 Zagreb	45°49'	15°59'	157	25 Szeged	46°15'	20°06'	82
				26 Székesfehérvár	47°12'	18°25'	111
Hungarian stations				27 Szolnok	47°10'	20°12'	90
11 Budapest	47°31'	19°02'	118	28 Szombathely	47°15'	16°38'	218
12 Debrecen	47°33'	21°37'	123	29 Tab	46°44'	18°01'	177
13 Fonyód	46°44'	17°33'	166	30 Tihany	46°55'	17°54'	150
14 Győr	47°41'	17°38'	119	31 Zalaegerszeg	46°50'	16°51'	162

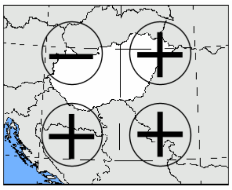
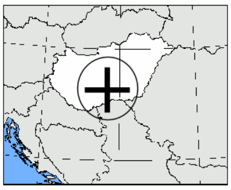
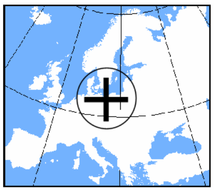
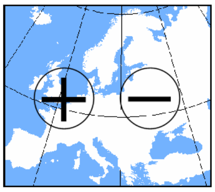
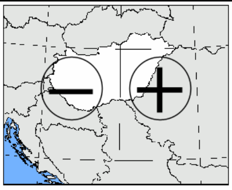
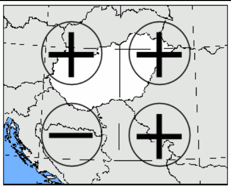
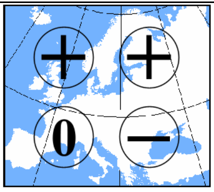
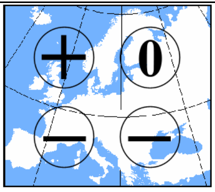
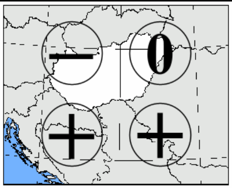
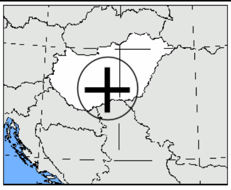
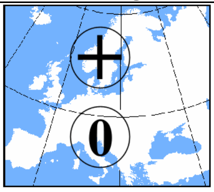
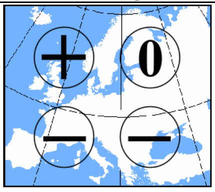
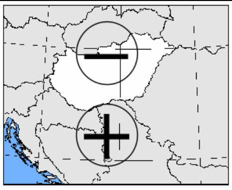
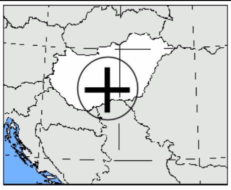
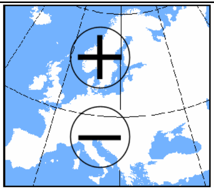
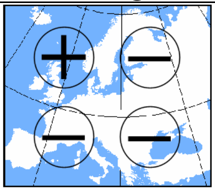
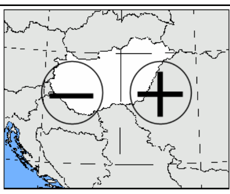
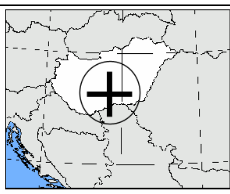
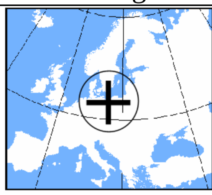
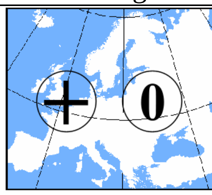
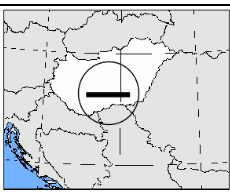
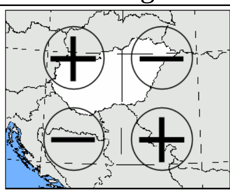
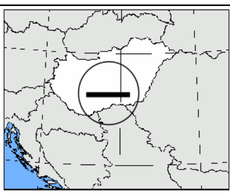
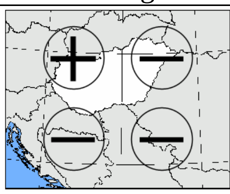
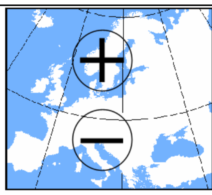
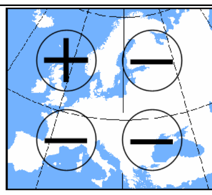
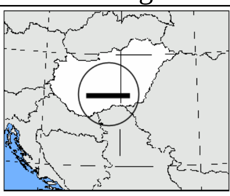
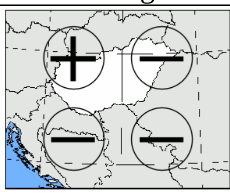
Fig. 6. Geographical locations of meteorological stations in the Carpathian Basin.

Tendency analysis of precipitation extreme indices for the last century is presented in this section for the Carpathian Basin, and compared to the results of the European analysis based on Klein Tank and Können (2003). For the evaluation of recent tendency of precipitation extremes in the Carpathian Basin 31 meteorological stations have been used (Fig. 6). Datasets for the 21 Hungarian stations were bought from the Hungarian Meteorological Service while datasets for the 10 stations in the neighbouring countries are freely available via Internet from ECAD (Klein Tank, 2003). Stations have been selected considering two main criteria, namely, (i) homogeneous spatial coverage, and (ii) minimal number of missing data.

Our datasets are compiled for 1901-2001. However, based on previous analyses (IPCC, 2001) suggesting that precipitation and temperature tendencies of the last quarter of the 20th century and the second half of the century are significantly different, and due to the limited extent of the European time series (Klein Tank et al., 2002a; Klein Tank and Können, 2003), the European-Carpathian comparison has been accomplished for 1946-2001 and for 1976-2001. Table 4 summarises the spatial structures of decadal tendency maps for the 12 extreme precipitation indices for both periods. When similar changes are detected for all stations appearing on the map, only one "+" or "–" sign indicates the tendency. While in case of more complex spatial structures two or four signs have been used to illustrate the regional tendencies. The intensity of the changes is represented by three categories (i.e., weak, medium, strong). Based on the analysis of tendency maps, only very few extreme indices can be characterised by homogeneous positive or negative trends for both periods and for both regions. However, in general, the precipitation extremes decreased slightly in the Carpathian Basin during the last 56 years, while they increased more intensely during the last 26 years. Opposite tendencies can be observed in the entire European continent, namely, increased and decreased extreme precipitation trends in the second half and in the last quarter of the century, respectively.

Table 4. Summary of tendency analyses of extreme precipitation indices for the Carpathian Basin (Barthol and Pongrácz, 2004) and Europe (based on ECAD, Klein Tank, 2003; Klein Tank and Können, 2003) for the 1946-2001 and for the 1976-2001 periods.

Nr.	Extreme index	Carpathian Basin		Europe	
		1946-2001	1976-2001	1946-1999	1976-1999
1	CDD Consecutive dry days	 medium	 strong	 weak	 weak
2	Rx1 Highest 1-day precipitation amount	 medium	 strong	 strong	 strong
3	Rx5 Greatest 5-day rainfall total	 strong	 strong	 medium	 strong
4	SDII Simple daily intensity index	 medium	 strong	 medium	 strong

5	R95T Fraction of annual total rainfall due to events above the 95th percentile	 medium	 strong	 medium	 strong
6	RR10 Heavy precipitation days	 medium	 strong	 strong	 strong
7	RR20 Very heavy precipitation days	 weak	 strong	 medium	 strong
8	R75 Moderate wet days	 medium	 medium	 strong	 strong
9	R95 Very wet days	 weak	 strong	 medium	 strong
10	RR5 Precipitation days exceeding 5 mm	 medium	 strong	No analysis available	No analysis available
11	RR1 Precipitation days exceeding 1 mm	 strong	 strong	 strong	 strong
12	RR0.1 Precipitation days exceeding 0.1 mm	 medium	 strong	No analysis available	No analysis available

In this paper two parameters of Table 4 are presented in details. European and Carpathian tendencies of annual number RR10 of heavy precipitation days (when daily precipitation is greater than 10 mm) are compared for the last quarter of the 20th century on Fig. 7. Circles represent decadal trend coefficients of the meteorological stations (using the baseperiod 1961-1990). Black and grey circles indicate increasing and decreasing tendencies, respectively, while circle size depends on the intensity of these positive or negative trends. Based on the tendency analysis of the entire European continent (upper panel of Fig. 7.), heavy precipitation days occurred more often in the last 2-3 decades in northern stations, while they became less frequent in the Mediterranean region. The Carpathian Basin is located in-between, however, our detailed regional analysis (lower panel of Fig. 7.) suggests that except a few southern stations, the annual number of heavy precipitation days (RR10) increased during the last 26 years.

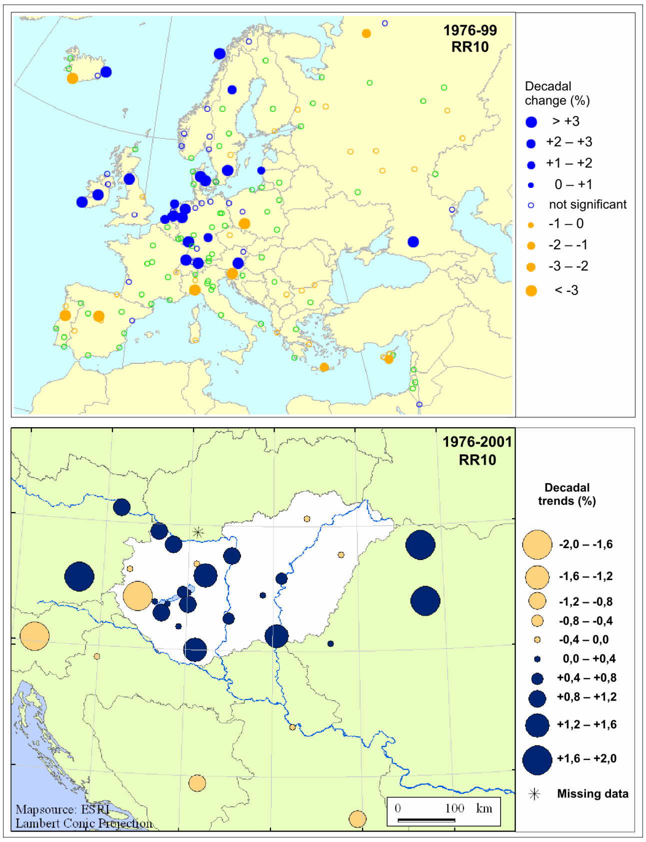


Fig. 7. Tendency of annual number of heavy precipitation days exceeding 10 mm (RR10) in Europe and in the Carpathian Basin during the last quarter of the 20th century. Trend coefficients of the Carpathian Basin greater than 0.4 in absolute value are significant at 95% level of confidence.

Indices listed in Table 1 include a few precipitation-related parameters which do not indicate extreme conditions. They belong to the index type annual number of precipitation days exceeding a given threshold, for instance, RR1 is one of them. Decadal tendency of the annual number of wet days with daily precipitation exceeding 1 mm (RR1) is analysed for the second half of the 20th century (Fig. 8.). Similarly to Fig. 7, the upper two maps compare spatial distribution of decadal trends for the European continent and the Carpathian Basin, while the lower graph shows the regional mean time series of the RR1 anomalies (using the baseperiod 1961-1990) for the Carpathian Basin only. The small graph in the upper right part illustrates the number of stations used for calculating the spatial average. For Europe, similarly to RR10, considerable zonal pattern can be recognised, namely, positive trends in the northern regions, while negative trends in the southern part. For the Carpathian Basin decadal tendency of RR1 is strongly negative in the last 56 years in most of the stations, as well, as in case of the regional mean anomaly.

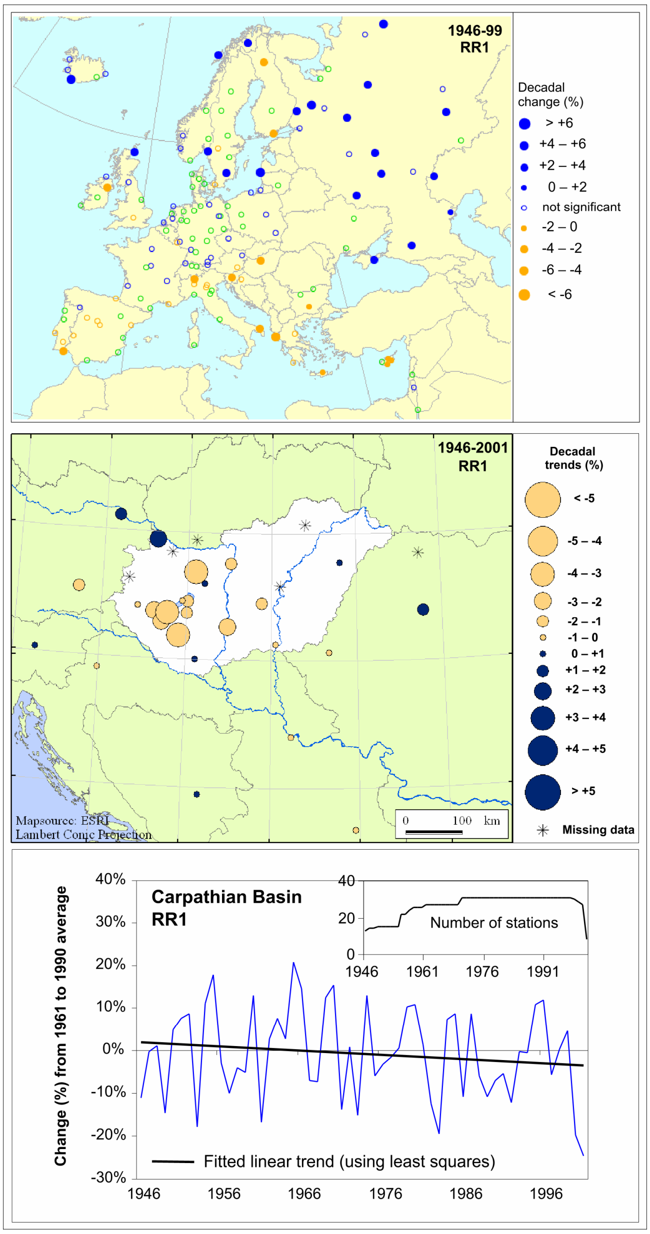


Fig. 8. Tendency of annual number of precipitation days exceeding 1 mm (RR1) in Europe and in the Carpathian Basin during the second half of the 20th century. Trend coefficients of the Carpathian Basin greater than 0.3 in absolute value are significant at 95% level of confidence.

5. Analysis of extreme precipitation indices for the Carpathian Basin

According to the IPCC TAR (2001) climate and agriculture of several regions of the world can be strongly affected by increasing occurrence of precipitation extremes in the 21st century. Based on the information of the 44 small maps presented in Table 4, most of the extreme precipitation indices increased considerably in the Carpathian Basin by the end of the 20th century. Positive trends were detected mostly in the last 26 years. The strongest increasing tendencies appear in case of extreme indices indicating very intense or large precipitation (i.e., SDII, R95T, RR20, RR75, R95). Similar results were concluded in Bartholy and Pongrácz (1998), Pongrácz and Bartholy (2000), and Bartholy et al. (2003).

In this section, spatial distribution maps of tendency of extreme precipitation indices changed the most are presented on Figs. 9-10. Decadal changes of annual number of very heavy precipitation days

(RR20) are illustrated on Fig. 9. for the last 26 years (1976-2001). The entire Carpathian Basin can be characterised by a strong positive trend. Considering only the Hungarian stations, the annual number of wet days exceeding 20 mm increased more in Transdanubia than in the Great Plains.

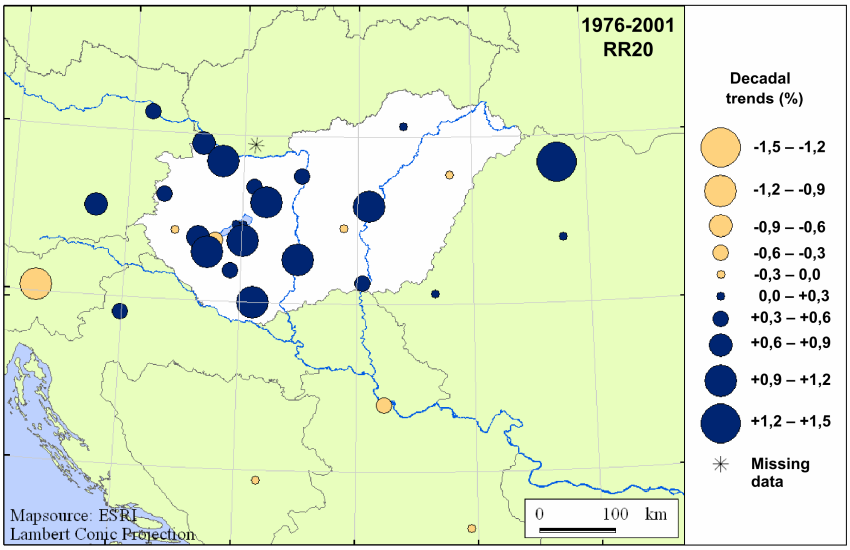


Fig. 9. Tendency of annual number of very heavy precipitation days exceeding 20 mm (RR20) in the Carpathian Basin during the last quarter of the 20th century. Trend coefficients greater than 0.3 in absolute value are significant at 95% level of confidence.

Fig. 10. compares the tendency of annual rainfall fraction due to very wet days (R95T) during the second half and the last quarter of the 20th century. Slight decreasing tendencies can be detected in the Transdanubian stations during 1946-2001, while intermediate positive trends appear in other stations of the region on the left map of the figure. Furthermore, very strong positive trends were found during the last 26 years (shown on the right map) indicating that the annual fraction of total rainfall (R_{total}) due to events above the 95th percentile (R95%) of daily precipitation in the baseperiod 1961-1990 (ΣR_{day} / R_{total} , where ΣR_{day} indicates the sum of daily precipitation exceeding R95%) increased significantly between 1976 and 2001.

Summarising the results, these analyses can be concluded that although in general precipitation occurred more rarely in the Carpathian Basin but the ratio of heavy or extreme precipitation days increased considerably by the end of the 20th century.

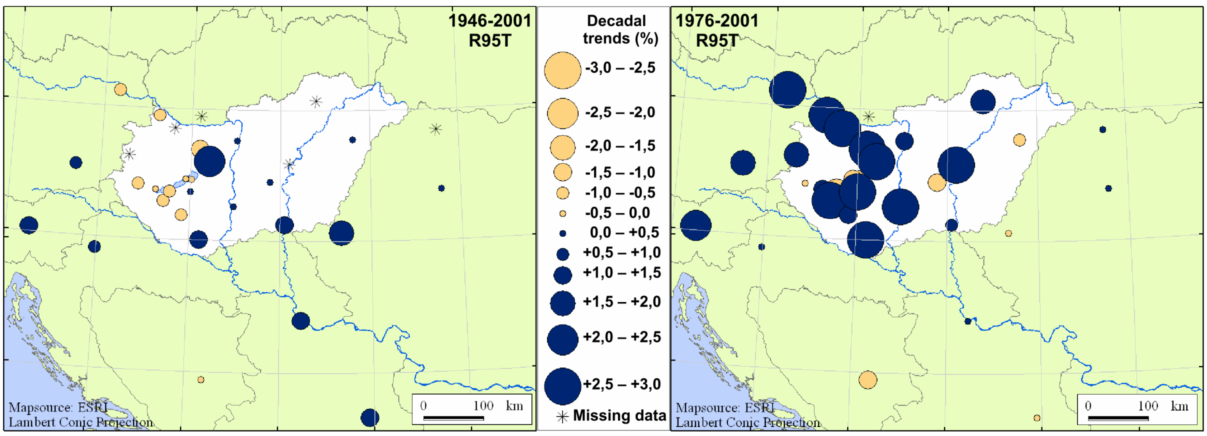
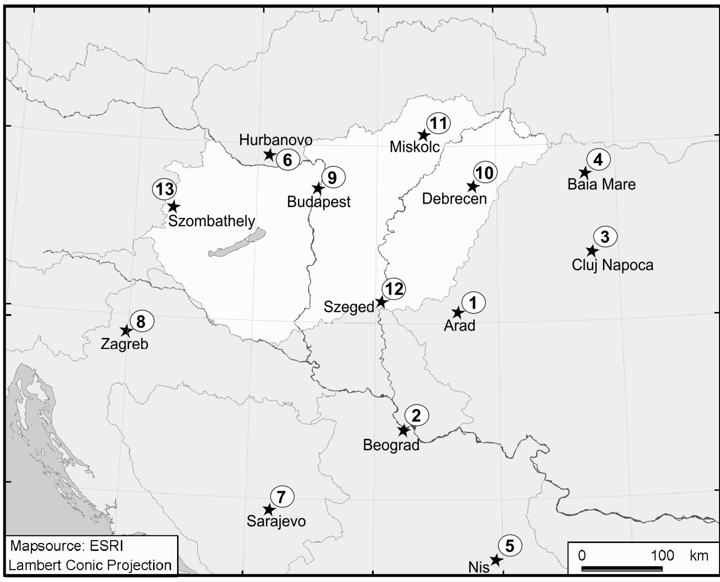


Fig. 10. Tendency of fraction of total annual rainfall due to very wet days (R95T) in the Carpathian Basin. Trend coefficients greater than 0.3 and 0.4 in absolute value are significant at 95% level of confidence on the left and right map, respectively.

6. Analysis of extreme tempearture indices for the Carpathian Basin



Station	Latitude (N)	Longitude (E)	Height above sea level (m)
1 Arad	46°08'	21°21'	117
2 Beograd	44°48'	20°28'	132
3 Cluj Napoca	46°47'	23°34'	410
4 Baia Mare	47°40'	23°30'	216
5 Nis	43°20'	21°54'	202
6 Hurbanovo	47°53'	18°12'	115
7 Sarajevo	52°30'	22°30'	211
8 Zagreb	45°49'	15°59'	157
9 Budapest	47°31'	19°02'	118
10 Debrecen	47°33'	21°37'	123
11 Miskolc	48°08'	20°48'	118
12 Szeged	46°15'	20°06'	82
13 Szombathely	47°15'	16°38'	218

Fig. 11. Geographical locations of the 13 meteorological stations used in the regional scale analysis for the Carpathian Basin. Note that Nis and Sarajevo do not belong to this region, but they were included in the analysis.

In our analysis for the Carpathian Basin, daily temperature data from 13 meteorological stations are used. Fig. 11 shows their geographical location. Minimum, maximum and mean temperature time series of the 8 stations located outside Hungary are available from the ECAD site via the Internet (Klein Tank, 2003), while data from the 5 Hungarian stations are from the Data Archive of the Hungarian Meteorological Service. Two basic constraints are taken into account during the selection of the stations: (i) covering the area of the Carpathian Basin with the best spatial homogeneity and representing the main climatic subregions, (ii) time series without the least missing values during the 1961-2001 period. The analysis presented in this paper, is focused on the Carpathian Basin, however, two of the selected stations (Nis and Sarajevo) are outside this region. We included them in order to accomplish the analysis on a larger area.

Table 5: Summary of the trend analysis of extreme temperature indices for the Carpathian Basin (Warming and cooling trends are indicated by black and light grey color of the box, respectively)

No.	Extreme index	1961-2001	1961-1975	1976-2001
1	ETR: Intra-annual extreme temperature range	–	–	+
2	HWDI: Heat wave duration index	–	–	+
3	Tx10: Cold days	–	–	+
4	Tx90: Warm days	+	–	+
5	Tn10: Cold nights	–	–	–
6	Tn90: Warm nights	+	+	+
7	FD: Number of frost days	–	–	–
8	SU: Number of summer days	+	–	+
9	Tx30GE: Number of hot days	+	–	+
10	Tx35GE: Number of extremely hot days	+	–	+
11	Tn20GT: Number of hot nights	+	–	+
12	Tx0LT: Number of winter days	–	–	+
13	Tn-10LT: Number of severe cold days	–	–	–

On the base of our previous study of time series of mean temperature and extreme temperature parameters, a strong warming tendency was detected from the middle of the 1970's (Pongrácz and Bartholy, 2000). Therefore, the entire 1961-2001 period has been separated into two subperiods, namely, 1961-1975 and 1976-2001. The tendency analysis has been accomplished for these subperiods. Table 5 summarizes the increasing (+) and decreasing (–) tendencies of the indices for the entire 41 years and for the two subperiods (15 and 26 years). Opposite sign of trend coefficients may indicate warming and cooling tendencies. For instance, negative coefficients of the number of cold days (Tx10) and positive coefficients of the number of hot days (Tx30GE) both indicate warming climate. Therefore, warming tendencies are shown in black boxes, while cooling tendencies in light grey. The trend coefficients of the index ETR (intra-annual extreme temperature range) are in white since they do not imply either warming or cooling tendency by themselves. Warming tendencies (in black) are dominant in the table. The regional climate of the Carpathian Basin tended to be warmer during the entire 41 years (except HWDI – heat wave duration index).

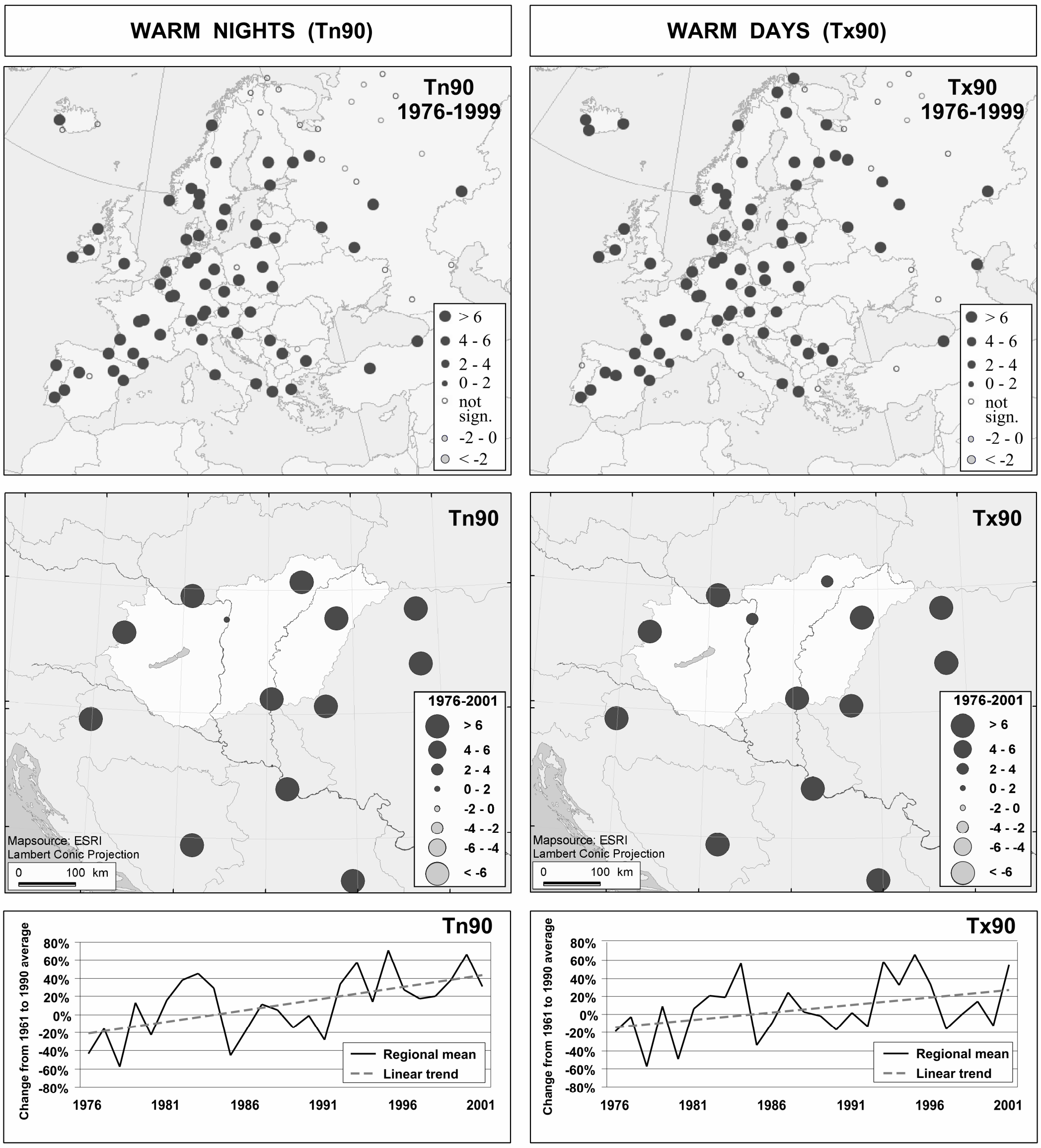


Fig. 12. Increasing tendency of warm nights (Tn90) and warm days (Tx90) in Europe and in the Carpathian Basin during the last quarter of the 20th century. Trend coefficients of the Carpathian Basin greater than 0.4 in absolute value are significant at 95% level of confidence.

In case of most of the extreme temperature indices the three periods used in our analysis cannot be characterized by the same sign of trend coefficient. Only four extreme indices (Tn10 – cold nights, Tn-10LT – number of severe cold days, FD – number of frost days, Tn90 – warm nights) indicate warming tendency in the 1961-2001, 1961-1975, 1976-2001 periods. Based on the trend coefficients of HWDI, Tx90, SU, Tx30GE, Tx35GE, Tn20LT, the cooling tendencies until the middle of the 1970's is followed by a warming climate in the last quarter of the 20th century. Opposite tendency can be detected in case of two indices (Tx10, Tx0LT) using regional scale average. However, these cooling trend coefficients of the last decades are small.

In this paper, detailed analysis is presented for the last quarter of the 20th century when the largest changes occurred. Detailed tendency analysis of the indices Tn90 (warm nights) and Tx90 (warm days) are presented in Fig. 12. Trend maps for Europe and for the Carpathian Basin are provided in the upper and the middle panels, respectively, while the lower graphs show the regional mean index anomaly from the 1961-1990 average values for the Carpathian Basin. Circles represent decadal trend coefficients of the meteorological stations (using the baseperiod 1961-1990). Black and grey circles indicate increasing and decreasing tendencies, respectively, while circle size depends on the intensity of these positive or negative trends. In case of the regional mean, the fitted linear trends are clearly increasing between 1976 and 2001 in case of both indices. Also, no decreasing tendency can be identified in either map. The positive trend coefficients are significant at 95% level of confidence.

The daily maximum temperature of summer is indicated by three extreme indices: (i) number of summer days (SU: T_{max} > 25°C), (ii) number of hot days (Tx30GE: T_{max} ≥ 30°C), and (iii) number of extremely hot days (Tx35GE: T_{max} ≥ 35°C). As it can be seen from Table 5, increasing trend coefficients of these indices are detected during the entire 1961-2001 period, and the 1976-2001 subperiod, while they are decreasing in the 1961-1975 subperiod. Fig. 13 presents the maps containing the increasing trend coefficients of extreme indices SU and Tx30GE in the Carpathian Basin in the last 26 years. Large positive trend coefficients dominate both maps, with more than 6 days per decade, in general. Tendency analysis map of the extreme index Tx35GE is not presented in this paper since the frequency of this events is quite small, however, the trend coefficients are similar to those shown in case of SU and Tx30GE.

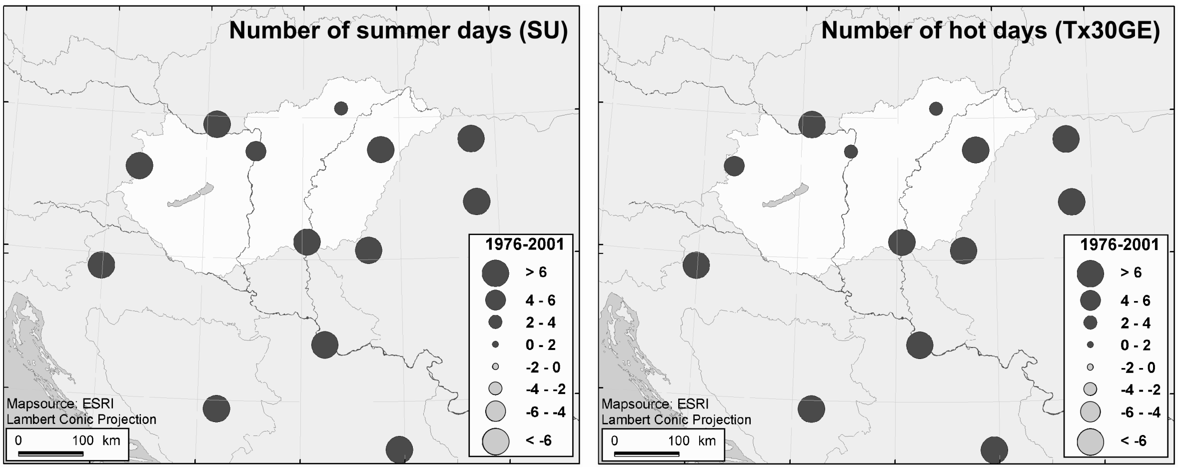


Fig. 13. Increasing tendency of the number of summer days (SU, T_{max} > 25°C) and hot days (Tx30GE, T_{max} ≥ 30°C) in the Carpathian Basin during the last quarter of the 20th century. Trend coefficients greater than 0.4 in absolute value are significant at 95% level of confidence.

Similarly to Fig. 12, map with the trend coefficients of HWDI are shown in Fig. 14. As it can be seen on the maps, only significant increasing tendency of HWDI is detected in all the stations in the last quarter of the 20th century. However, compared to the other indices, trend coefficients of more stations are not significant in Europe (left panel of the figure). The exact explanation is not known, but we can assume that the larger number of stations with insignificant tendency is related to the definition of this index. In the definition, the same 5°C threshold is used in case of oceanic and continental climates, which may not be appropriate for all climates.

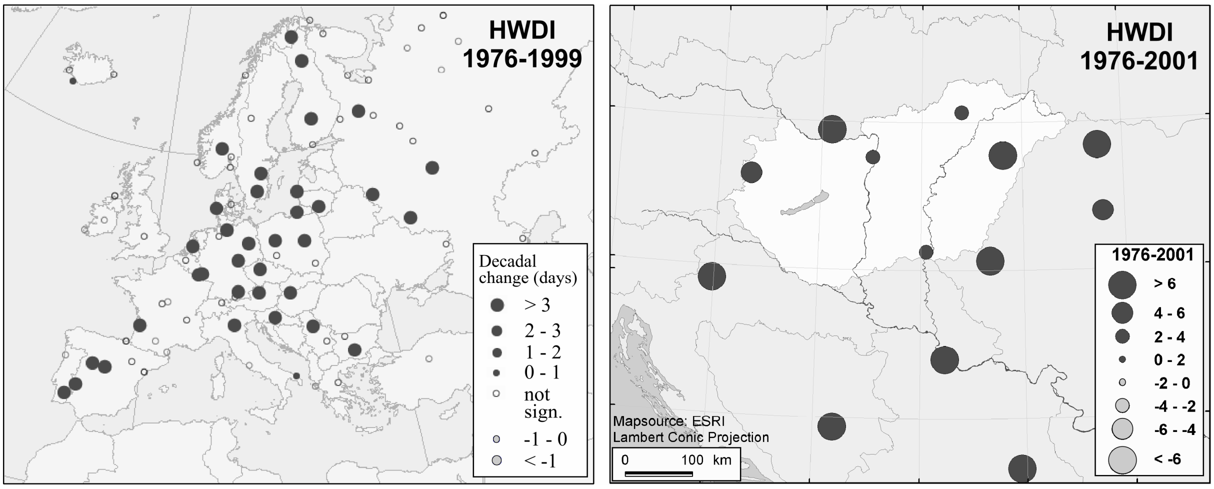


Fig. 14. Tendency of heat wave duration index (HWDI) in Europe and in the Carpathian Basin during the last quarter of the 20th century. Trend coefficients of the Carpathian Basin greater than 0.4 in absolute value are significant at 95% level of confidence.

Based on the above figures, similarly to the global and European trends (Frich et al., 2002; Klein Tank et al., 2002a), analysis of the extreme temperature indices suggests that the regional climate of the Carpathian Basin tended to be warmer in the last 41 years.

7. Conclusions

The analysis of extreme climate indices (according to the suggestions of the WMO-CCl/CLIVAR Working Group) are presented for the second half of the 20th century in this paper.

A. Based on the analysis of extreme precipitation indices, the following conclusions can be drawn.

1. Comparison of the global and European tendency resulted in:

(i) Positive trends dominate in both analyses in case of Rx5, SDII, R95T, and RR10. Opposite (i.e., negative) trends occurred in Asia and in Central/Southeastern Europe.

(ii) Most of the European continent can be characterised by increasing tendency of indices Rx1 and R75, while decreasing tendency was found only in Central and Southeastern Europe. Global analysis is not available for these indices.

(iii) In case of RR20 and R75, significant positive trend appeared in Europe (global analysis is not available for these indices).

(iv) Global decreasing (except Eastern Asia) tendency of CDD implies similar climate conditions to the consequent trends of extreme precipitation indices listed above. However, trends are not significant for the European continent.

2. Comparison of the analysis for Europe and for the Carpathian Basin:

(i) Decadal trends were evaluated separately for two periods (1946-2001 and 1976-2001). Tendencies in both the European and the Carpathian regions were more intense and spatially more homogeneous during the last 26 years than the last 56 years.

(ii) Spatial structure of the decadal tendency maps is classified into several main patterns using one, two (meridionally or horizontally), or four “+” or “–” signs. Considerable zonal patterns were often recognised in Europe, when different tendency occurred in Northern Europe and in the Mediterranean region.

3. Analysis of the extreme precipitation indices for the Carpathian Basin (according to the suggestions of the CCl/CLIVAR Working Group):

(i) Strong positive trends were detected in most of the extreme precipitation indices (e.g., SDII, R95T, RR20, R75, R95) for the last quarter of the 20th century indicating increasing precipitation extremity in the Carpathian Basin.

(ii) Significant negative trends dominate the region in case of the non-extreme parameters (i.e., RR5, RR1, and RR0.1) during the second half of the 20th century.

(iii) In general, precipitation occurred less frequently in the Carpathian Basin, however, the ratio of heavy or extreme precipitation days increased considerably by the end of the 20th century.

B. Global and European trends of the extreme temperature indices are consistent with the global warming. As an example, the decreasing tendency of the number of frost days (FD) are presented on global (300 stations) and European (140 stations) scales. Based on the analysis of the extreme temperature indices for the Carpathian Basin, the following conclusions can be drawn.

(i) Significant warming tendencies are dominant during the entire 1961-2001 period.

(ii) Most of the indices (e.g., HWDI, Tx90, SU, Tx30GE, Tx35GE, Tn20LT) the entire 41 years can be separated into a cooling period until the middle of the 1970's and then a warming period in the last quarter of the 20th century.

(iii) The largest trend coefficients (more than 6 days per decade) were detected in case of the following indices: Tn90, Tx90, SU, Tx30GE, HWDI.

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