METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **21**: 684–694 (2014)
Published online 2 July 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.1391

Spatial distribution of heavy precipitation events in Romania between 1980 and 2009

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ABSTRACT: This study focuses on the spatial distribution of heavy precipitation events that occurred in Romania over 30 years, between 1 January 1980 and 31 December 2009. It is the first such study carried out for this country, using this particular data set and methodology, whereby a Relational Database Management System was used to store data on precipitation and to filter subsets of interest out of the main dataset. Increasing trends have been found in the time series of the maximum annual precipitation amounts recorded in 24 h, and in that of the annual number of events; an increasing trend, from one decade to another, was also found in the latter dataset. Peculiarities of spatial distributions over the three decades are highlighted, such as the virtual confinement of extreme precipitation events to areas outside of the Carpathian Mountains arch in Romania and on mountain sides oriented towards the outside of it.

KEY WORDS regional analysis; climatology; extreme; rainfall; trend

Received 9 July 2012; Revised 13 January 2013; Accepted 22 January 2013

1. Introduction

As *per* the definition provided by the World Meteorological Organisation (WMO, 2011), heavy precipitation means rain or snow in amounts larger than or equal to 50 mm in 24 h. In our study, we have chosen to employ this particular definition, and further defined the amounts larger than or equal to 100 mm in 24 h as extreme precipitation.

The aim of this study is to present the spatial distribution of heavy precipitation events in Romania on the climatological interval between 1980 and 2009. It is the first such study carried out for this European country, using this particular data set and the methodology presented here; it is not a comparative study in and by itself; however, its results may assist other authors in their enterprise of studying the climate of a region close to the Mediterranean and Black Sea, with varied landscape and temperate climate. As the IPCC stated in their Fourth Assessment Report (IPCC, 2007), there is no scientific consensus over the net effects of climate change on precipitation, given different patterns around the world. As such, we will not endeavour on giving a verdict on the climate change-related significance of heavy precipitation patterns that were detected as a result of this study, but results in this paper can be added to the body of evidence regarding climate variability in this area of Europe.

The results presented here come from the analysis of a large set of data on heavy precipitation spanning 30 years, and provide insight into this climatic characteristic of the country in the last two decades of the twentieth century and the first decade of the twenty-first.

Studying the patterns of precipitation is useful both in understanding past climate and modelling future events *via* statistical means. As stated in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), the frequency of heavy precipitation events is projected to increase over most areas. Major impacts of this evolution are soil erosion, damage to crops and the disruption of settlements and societies because of flooding and loss of property. Moreover, it is a well-known fact that variations in precipitation over time impact on water balances and other hydrological processes (de Lima *et al.*, 2010). As such, studies on the spatial and temporal distribution of large amounts of precipitation, and of their extreme values over certain time intervals can be included or used in larger analyses of the evolution of climate at continental level.

Heavy precipitation has been recently analysed for other countries, for instance Spain (de Luis *et al.*, 2011), Portugal (de Lima *et al.*, 2010), Czech Republic (Kysely, 2008), Japan (Fujibe, 2008), Argentina and Chile (Minetti *et al.*, 2003), Saudi Arabia (Taher and Alshaikh, 1998). Easterling *et al.* (2000) refer to trends in the heavy precipitation events that hint towards more days with heavy precipitation totals over the twentieth century.

Karagiannidis *et al.* (2009) have analysed a set of data on heavy precipitation between 1958 and 2000 in continental Europe and the British Isles, but eliminating from this set the summer months, in order to increase the homogeneity of the data. They have defined extreme precipitation by amounts larger than 60 mm in 24 h, and found a decreasing trend of the number of such events until the 1970s, after which no increasing trend was found to the end of their interval of interest.

Studies in countries close to Romania were performed by other authors. For instance, Michalska and Kalbarczyk (2005) have studied the long-term changes in temperature and precipitation in the Szczecin Plains in Poland. They found that, between 1951 and 2000, larger amounts of precipitation in the lowlands there were recorded during the spring and autumn.

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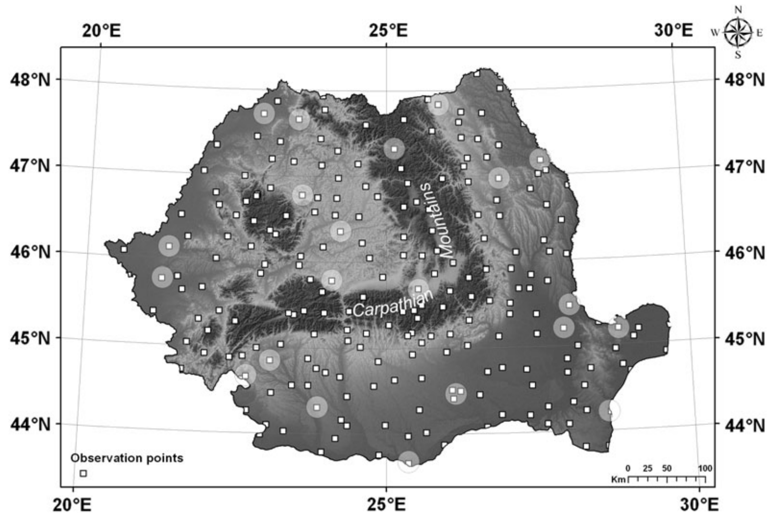

Figure 1. The observation points in Romania that have recorded P50 events between 1980 and 2009. Large urban areas are highlighted by circles.

Heavy precipitation has been decisive cause of flash floods in Romania, over the years. Extensive flooding occurred, in the last 10 years, in various parts of the country, most notably along the Danube in 2005, and along the Prut and Siret rivers and over some of their tributaries in 2008 and 2010.

The topography in Romania is varied, ranging from as low as sea level in the Danube Delta to about 2500 m in the Carpathian Mountains. Each of the landscape ranges – lowlands (below 300 m), hills (between 301 and 800 m) and mountains – accounts for about a third of the country area. Romania, by its location in Europe, is subject both to predictable, slow-changing weather caused by several active pressure systems that are often persistent in certain months (the Icelandic Low, the Azores High and the East-European High, cyclones generated in the Adriatic and Mediterranean Sea); and to severe, short-lived weather events that can only be anticipated within hours, or even minutes prior to onset, such as convective rainstorms during the summer. The peculiarities of landscape in Romania, the proximity to the Black Sea and the Mediterranean Sea, and the air circulation are key factors in explaining heavy precipitation occurring here.

The presentation of data and the methodology that were used in the analysis are presented in Section 2 of this article, followed by Section 3 that holds main results and their discussion. The paper concludes with Section 4, that summarizes main findings.

2. Data and methodology

The spatial domain involved in the analysis is the entire territory of Romania, and the temporal scale is 30 years, between 1 January 1980 and 31 December 2009. Romania is a country of varied landscape, where the lowest point is in the southeast, in the Danube Delta (0.52 m) and the highest point is located at the approximate midpoint of the Southern Carpathians, at 2544 m (National Institute of Statistics, 2012). Its location, at middle latitudes in southeastern Europe, between the Black Sea and the Mediterannean Sea, leads to the influence upon local weather of various pressure systems, for instance the Azores High, the East European High and Mediterranean cyclones.

Precipitation amounts larger than, or equal to 50 mm in 24 h ('P50', from now on in this paper) have been analysed, that were measured at 163 surface meteorological stations and 67 rain gauges in Romania ('observation points', from now on), that have carried out observations between 1980 and 2011. Extreme precipitation amounts, larger than 100 mm in 24 h will be referred to as 'P100', a subset of P50.

Table 1. The number of lowland, hill and mountain stations that were involved in analysis.

Topography	Number of stations	Percent of total (%)
Lowlands ($\leq$ 300 m)	137	59.5
Hill (301–800 m)	65	28.3
Mountain ($\geq$ 801 m)	28	12.2

For each of the 230 observation points (Figure 1) essential data were available and used in this study: (a) its unique identifier in the meteorological observational network; (b) its name; (c) its geographical co-ordinates: longitude, latitude and altitude; (d) the date of each precipitation event; (e) the amount of precipitation larger than, or equal to 50 mm in 24 h, reported at the end of a climatological observation interval that ends at 1800 UTC the day when the observation was carried out. Over the entire time interval, and the entire set of observation points, there were 2539 distinct observations on heavy precipitation, made on 874 distinct days. Table 1 shows the number of observation points by topography, or altitude range. As already mentioned in the opening of this section, the analysis presented here was made at the regional scale, onto the total number of events, that of days with events, and that of observation points. As such, no individual datasets for particular observation points are discussed.

The 163 meteorological stations have functioned continuously over the 30 years. Six of the 68 rain gauges, though, suffered interruptions as large as 5 years. This amounts to 2.6% of the total observation points. Two of these six gauges are located in the plains, and the other in hill areas, with one at the highest altitude of 880 m. However, for the purposes of this spatial analysis, it has been chosen to take into account these gauges too, since primarily there was interest in whether at least one event did, or did not, take place at each location. Temporal analysis of the precipitation over this interval requires homogenization, but for an analysis related to the appearance of an

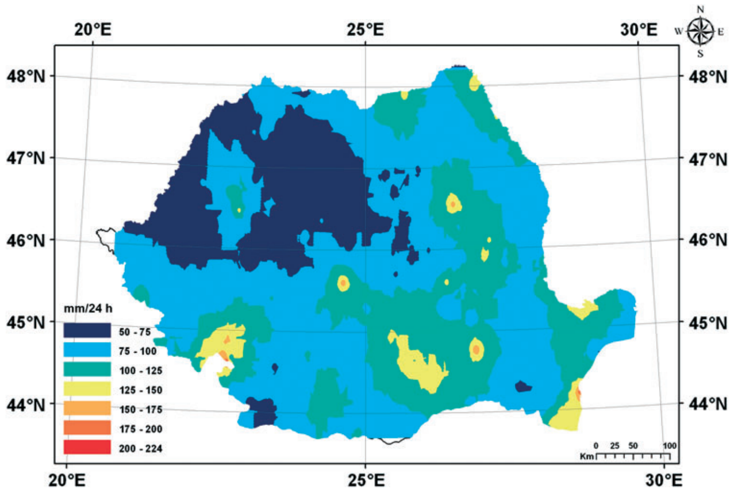

Figure 2. The maximum annual precipitation amounts in Romania between 1980 and 2009, recorded in 24 h.

event in a certain place (a true/false paradigm), these gauges were nevertheless considered as useful.

For the purposes of this study, a database was designed under the Microsoft®™ SQL Server®™ Relational Database Management System (RDBMS) that holds the entire datasaet. This RDBMS provides the capacity to easily extract and analyse subsets of data by applying filters using the Structured Query Language (SQL). The source of these data is the climatological database at the National Meteorological Administration of Romania. For graphical representation of geographically-mappable results, the capabilities of the ArcMap®™ software package were employed. For colour-scale mapping (like in Figure 2), the Geostatistical Analyst tool of ArcMap®™ was executed, applying the Inverse Distance Weighting (IDW) interpolation method in order to define domains around actual values (ESRI, 2011). With this method, interpolation was performed around each observation point by taking into account maximum 2 other points; such neighbours were sought after in four sectors of 90°, around each observation point. These particular values for parameters were selected in order to minimize the forced expansion or seeping of spatial domains marked by certain sets of values to, or into domains marked by other values. As such, graphical representations were built that reflect the reality as closely as possible, after interpolating the actual values, which is to say small domains defined by actual values of precipitation amounts.

Aside from mapping various data, statistical tests were performed over certain data series made of precipitation data corresponding to each year, for the entire set of observation points, such as the annual number of days with at least one heavy precipitation event. We have tried to complete the information about spatial spread with data on the temporal variation of precipitation over the entire country, if any was to be detectable at all. To this end, the nonparametric Mann–Kendall and Pettitt tests were chosen. Simple linear regression was also used to detect possible linear trends in some of these series.

In addition, monthly values of the North Atlantic Oscillation (NAO), provided by the National Oceanic and Atmospheric Administration (NOAA, 2012) were also used, to study the link between phases of NAO and the number of days with heavy precipitation.

Table 2. The maximum precipitation amounts in Romania as annual totals, 1961–2000, by large geographical region.

Region	Precipitation amount (mm)
Southeastern	< 700
Northeastern	850–1000
Southern	950–1100
Central and Western	1000–1300
Mountain	> 2000

As highlighted in a depiction of the climate of Romania by the National Meteorological Administration (NMAR, 2008), the almost circular disposition of the massive Carpathians, with an opening towards the west causes a concentration of stream lines associated with air masses originating over the Atlantic and in the west and north of Europe, that leads to more intense precipitation on the westward and northward mountain sides. On the other hand, air masses originating from the area of the Mediterranean Sea, in their movement towards central and Eastern Europe meet the natural obstacle of the Carpathians and their trajectories are frequently diverted by it. The southern and southwestern areas of the country are most influenced by these air masses, that in winter are a source for significant amounts of precipitation due to the increase in Mediterranean cyclonic activity (Bordei, 1983; Georgescu and Stefan, 2011). This mountain range can deflect the low-level air circulation and can alter the movement of frontal systems over Romania, so this particular geographical context is one more reason for carrying out a spatial analysis of heavy precipitation events over a larger interval. Table 2 shows the maximum precipitation amounts in Romania as annual totals, 1961–2000, grouped by large geographic regions (NMAR, 2008).

3. Results and discussion

In Figure 1, the observation points are shown on a geographical map of Romania which have recorded heavy precipitation during the reference interval. The analysis of spatial distribution of P50 and P100 events was made by proceeding from that of maximum annual amounts recorded in 24 h, over the entire interval. Figure 2, which is a colour-scaled map of these amounts, shows a clear contrast between the areas inside the Carpathian arch, in the Western Carpathians and in the mountains facing the centre of the country, and the rest of Romania. This difference marks the contrast between the strong influence over rainfall in the south and east, of Mediterranean low pressure systems and retrograde cyclones moving towards the Black Sea, and the weaker influence of low pressure systems and their associated frontal activity that brings humid and cold air from the northwestern and northern areas of Europe over to the inner regions of the Carpathian arch (Bordei, 1983).

3.1. Spatial distribution of P50 and P100 events, over the entire interval

3.1.1. Distribution of P50 events, by topography

Table 3 shows the number of both heavy and extreme precipitation events, by topography.

In the plains or lowlands, there have been 1364 P50 events, which amount to about 54% of total. Figure 3(a) shows the observations points in these areas that have recorded P50 events, and Figure 3(b) shows the observation points in the same areas that have recorded P100 events. There were 73 P100 events there, which amount to about 3% of total. Observational experience shows that, during the warm season (April to September), this area is subject to frequent rainstorms. Conversely, during the cold season (October to March), the influence of retrograde cyclones originating over the Mediterranean, that bring humidity from over the Black Sea is well known to be causing heavy precipitation episodes in the eastern half of the country (Bordei, 1983; Georgescu and Stefan, 2011). Weakening along the way, once they pass over the sea they regain strength due to them feeding off large amounts of water vapour. As such, as a result of their increased lifetime, frontal activity associated with these systems influences the east and southeast of the country. Local variability of precipitation during the winter was studied by Busuioc and von Storch (1996) and by Tomozeiu *et al.* (2005), who state that this is influenced both by a large-scale mechanism and the Carpathian Mountains.

Large amounts of precipitation recorded at higher locations are generally favoured both by instability in the warm season, and the physical blocking of humid air masses associated with frontal systems over the year. Also, experience shows that the eastward mountain sides of the Eastern Carpathians are most prone to receiving larger amounts of precipitation, mainly due to retrograde Mediterranean cyclones that get close to the Black Sea and occlusions taking place northeast of Romania. Data were available from 28 mountain stations only, so their distribution is inherently sparse. As such, it is probable that heavy precipitation events may have been in similar locations. As a consequence, statistical analyses that would be performed over this small dataset only are not able to provide telling results. Still, since there is interest in the spatial distribution of such events, and because the distribution of these 28 stations is uniform over the mountain region in Romania, this dataset is regarded with the same consideration as the rest of the data.

Table 3. The number of heavy and extreme precipitation events, grouped by topography.

Topography	(1): Total P50 events	(2): P100 events	Ratio (2)/(1), (%)
Lowlands (<=300 m)	1364	73	5.35
Hill (301–800 m)	624	21	3.36
Mountain (>=801 m)	551	28	5.08
Total events	2539	122	4.80

Figure 4 exposes an interesting peculiarity, namely the decrease of the altitude of observation points where the largest annual amount in 24 h was recorded. The polynomial regression gives the R-value of 0.56, while the corresponding Pearson correlation co-efficient is −0.38. The average altitude of the annual maximum amounts over the interval 1980–1994 is about 830 m (low mountain areas), and only about 300 m (low hill areas) over 1995–2009. A separate study is needed to look into the reasons that led to this situation, so it can only be asserted here that this could be a sign of increased convective activity in the lowlands during the summer. As an aside, it is worth mentioning that the 1990s were the warmest years in Europe in the instrumental record (IPCC, 2007). For the decade 1990–1999, the average is about 800 m. In contrast, for the decade 2000–2009, this value is about 200 m, and of about 700 m, before 1990.

3.1.2. Distribution of P100 events, by topography

Figure 5 shows the observation points that have recorded P100 events over the entire interval. Over a year, such amounts are uncommon in the lowlands, and they occur mainly in the warm season. It can be seen that these points are virtually confined to the areas outside the Carpathian arch or, on their outwards-oriented sides, and to the mountainous area of the Southern and Eastern Carpathians. In contrast, on the inside of the Carpathian arch there are only a few such observation points. Another area with P100 events is in the Western Carpathians, although even in this case there are only three observation points.

The percentage of P100 events from the total number of events is larger in the areas outside the Carpathian arch (95 events, or 3.7% of total) than inside it (27 events, or 1.1% of total).

For a measure of the scale of these extreme events, the largest amount ever recorded in Romania in 24 h is 530.6 mm, measured on 30 August 1924 at a station in the South-East (C. A. Rosetti, no longer active). All of the P100 events between 1980 and 2009 are smaller than half this value, since the largest amount in our dataset is 224 mm, measured on 12 July 1999 at a station in the extreme South-West (Drobeta-Turnu Severin).

3.1.3. Distribution of P50 events, by topography and season

This analysis was made by combining in 'total seasons' the data available for individual cold and warm seasons each year in the interval. As such, cold and warm 'seasons' resulted from combining data from individual seasons have been looked at, and this discussion refers strictly to this dataset.

The number of events during the warm season (2085) was five times larger than that during the cold season (454).

During the warm season, most of the observation points have recorded heavy precipitation events. This is explained as a proof for thermodynamic instability, which as a rule for Romania from May until early September, is a cause for violent storms and rainfall, wherever local conditions favour it. The largest amounts were outside the Carpathian arch, and the smallest inside it. This information is one more signal of, or proof for, the different patterns of precipitation, that were previously cited (NMAR, 2008) as a particular climatic feature of each of these regions.

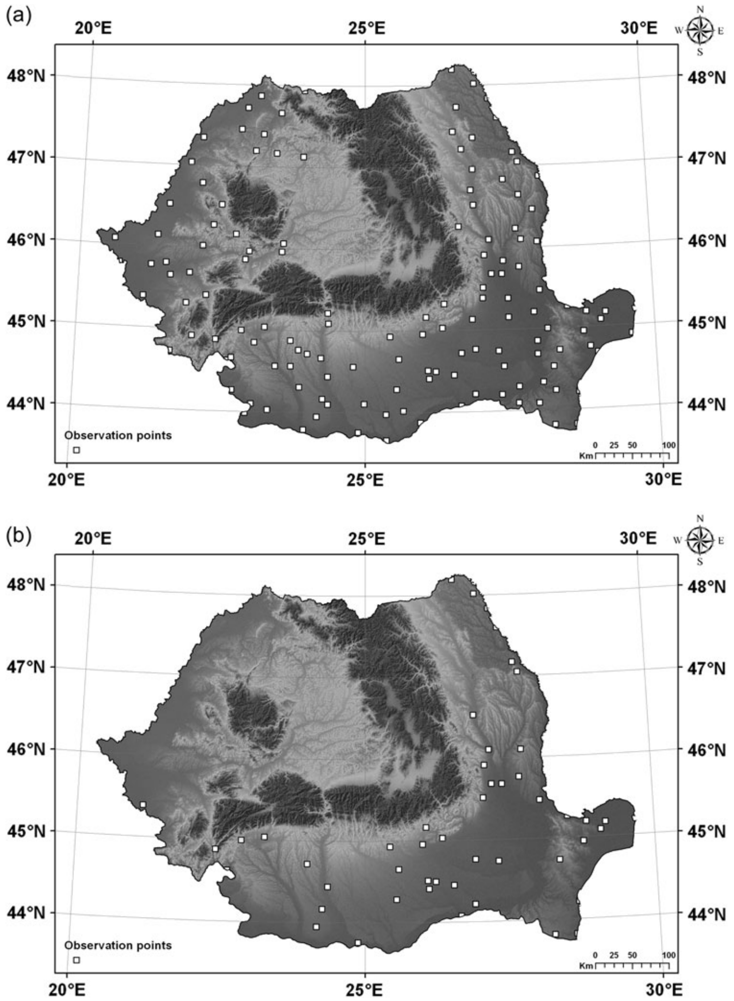

Figure 3. The observation points in Romania, in the plains (lowlands) area that have reported P50 (a) and P100 (b) events.

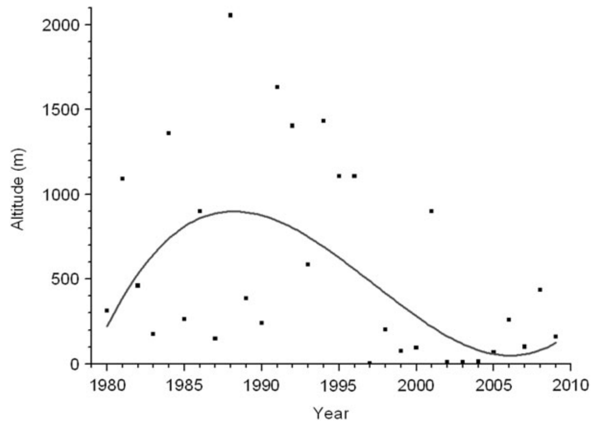

Figure 4. The trend of the altitude of observation points that have reported the maximum annual precipitation amount, recorded in 24 h; polynomial regression.

Figure 6 exposes the incidence of heavy precipitation in the lowland areas (Figure 6(a)) and in other regions (Figure 6(b)). Concerning the lowlands, during the cold season the number of observation points in the plains of western and northeastern Romania was smaller than in the warm season. One particular group of stations where events occurred during the warm season only is visible in the western half of the country (Figure 6(a), middle left), stations that are located in the region that separates the Western from the Southern Carpathians, along the large corridor where the River Mures flows through.

As to the hill and mountain areas, one notices the scarcity of observation points in the central areas of the country during the cold season (Figure 6(b), up centre), an opposite situation to that in the warm season, and also the fact that roughly the same observation points in the Southern Carpathians have experienced heavy precipitation in both seasons (Figure 6(b), down centre). This can be explained by convective activity during the warm season, when frontal passages can also bring persistent precipitation that may amount to large daily amounts, which in turn qualify as heavy precipitation. In contrast, a difference is clear between seasons for the Eastern Carpathians, where such events are scarce during the cold season, and also confined to the lower areas of their sides.

3.2. Distribution of maximum amounts of P50, over each of the three decades

The spatial distribution of maximum annual precipitation amounts, recorded in 24 h, was analysed over each of the three decades in the period of interest: 1 January 1980 to 31 December 1989; 1 January 1990 to 31 December 1999 and 1 January 2000 to 31 December 2009. Figure 7(a)–(c) shows the

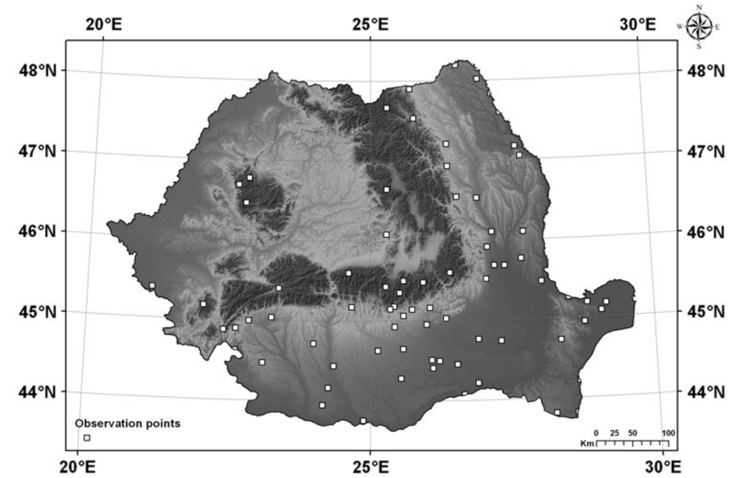

Figure 5. The observation points in Romania that have reported P100 events.

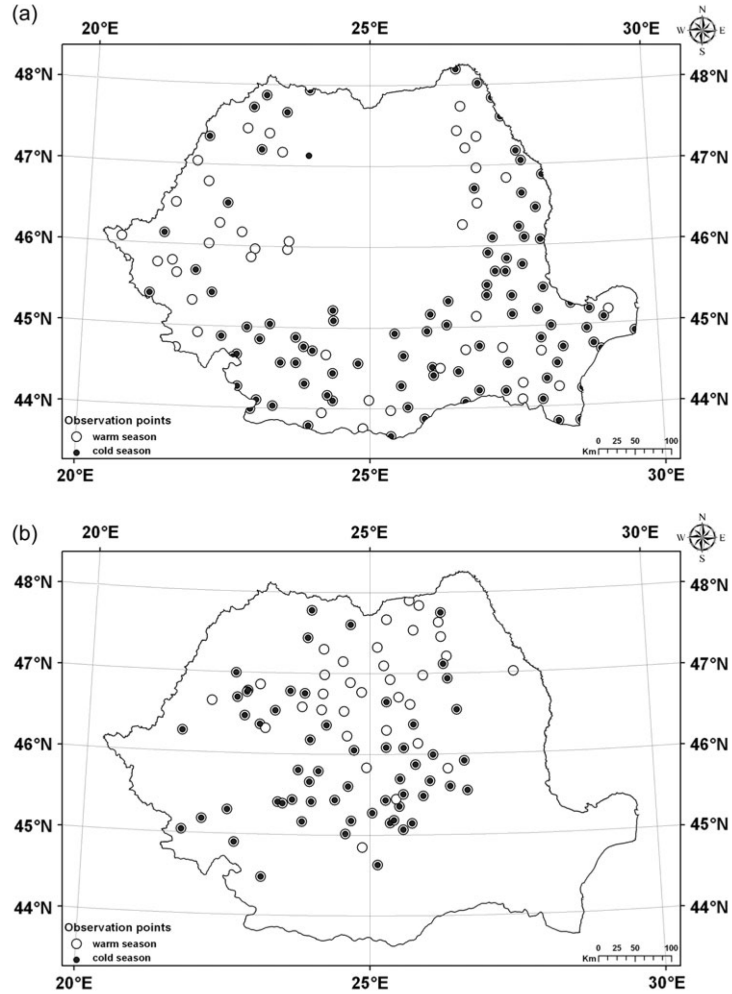

Figure 6. The distribution of heavy precipitation events in Romania, during the 'total' warm and cold seasons in the lowlands (a) and in the hill and mountain areas (b). Combined data, from individual seasons each year.

approximate extent of these amounts recorded in each of these decades. Looking at these figures, where the same colour scale has been used in all legends, one can see how the decadal maximum amounts have generally been on the increase in the areas outside the Carpathian arch, and that the domains that they occupy were gradually spreading. In contrast, outside of the arch no significant change from a decade to another is noticeable. In the southeast, an area around Bucharest (the capital city) can be easily spotted where amounts over 100 mm 24 h^{-1} have been recorded in the last decade only.

This is seen as a sign of the effect that this range has on precipitation caused by approaching low pressure systems

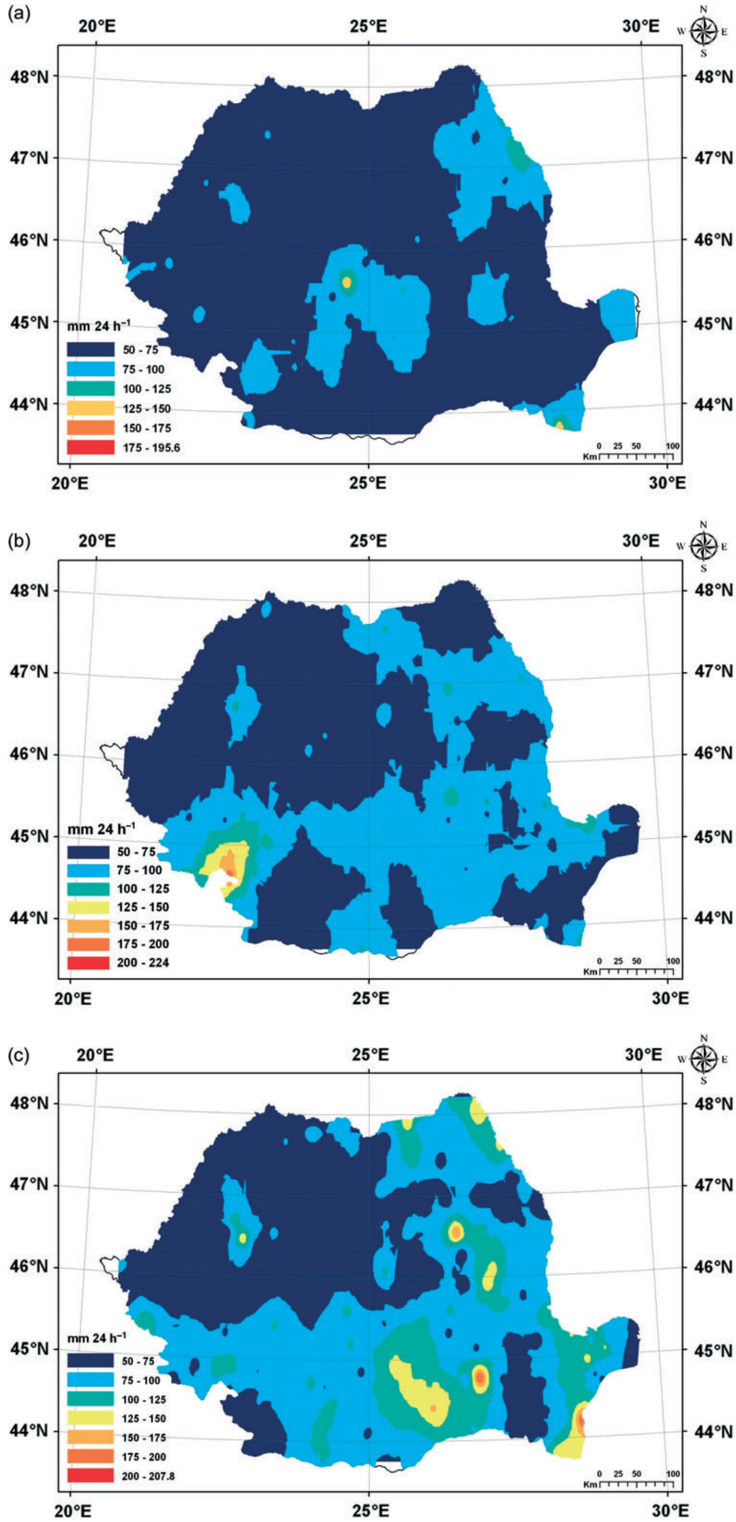

Figure 7. (a) The distribution of maximum precipitation amounts in Romania, 1980–1989. (b) The distribution of maximum precipitation amounts in Romania, 1990–1999. (c) The distribution of maximum precipitation amounts in Romania, 2000–2009.

originating in the Mediterranean area, systems that evolve towards occlusion over the Black Sea.

A maximum is visible in the southwest of Romania, in the 1990–1999 decade. This was the outstanding event mentioned in Section 3.1.2., on 12 July 1999. This event was caused by intense instability during the day, fed by warm and humid air advection from the Mediterranean area. Since this analysis was driven by the magnitude of P50 events, this particular one was not left out of the data set. Even if one decides to leave out this event, a visible increase in maximum amounts over this decade can be seen in the southern and eastern areas.

Table 4 shows the evolution of the number of P50 and P100 events in the three decades. One can see how the last decade was the richest in such events. Also, an increase is visible in the

Table 4. The number of heavy and extreme precipitation events, grouped by decade and topography.

	Number of events each decade, since 1 January 1980					
	1 January 1980 to 31 December 1989		1 January 1990 to 31 December 1999		1 January 2000 to 31 December 2009	
Topography	P50	P100	P50	P100	P50	P100
Lowlands (<= 300 m)	266	9	456	14	642	50
Hill (301–800 m)	152	4	141	3	331	14
Mountain (>= 801 m)	118	5	157	9	274	14

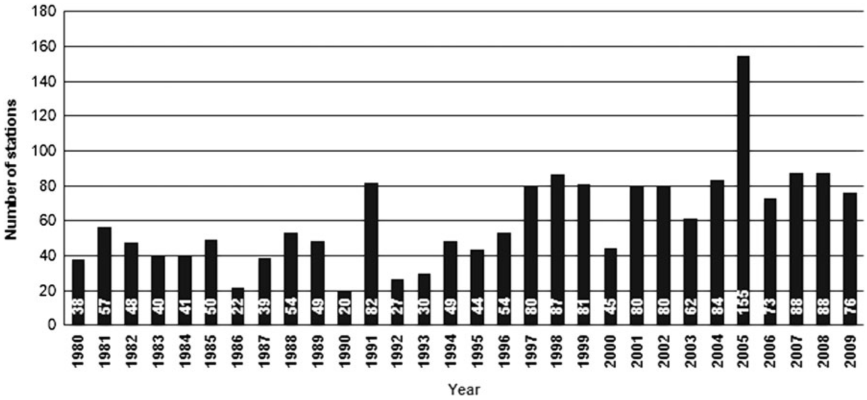

Figure 8. The annual number of observation points (‘stations’) in Romania that have recorded P50 events between 1980 and 2009.

number of events from a decade to another, with the exception of the hill areas between 1990 and 1999, when this number was lower than in the previous 10 years.

3.3. Trends exposed by various data series, between 1980 and 2009

The majority of heavy precipitation events (275) occurred in 2005, which was an exceptional year for Romania in terms of precipitation. After 2005, the number of observation points remained somewhat stable, around 80 each year. In Figure 8, the annual number of observation points reporting heavy precipitation is represented on a histogram. One can see how, from around 1995, the number of observations was getting larger, in comparison with previous years. These assessments were confronted statistically.

Polynomial regression was carried out over three series of data: the annual number of P50 events (Figure 9); the annual number of days with at least one P50 (Figure 10); and the annual maximum amount recorded in 24 h (Figure 11). The corresponding R^2 values are provided in Table 5. Despite the dispersion of values, an increase over the years can be seen in all these series.

The nonparametric Pettitt statistical test (Pettitt, 1979) was performed over three time series: the number of days each year, when at least one heavy precipitation event was recorded (‘SD’); the number of such events each year (‘SE’); and the number of observation points (‘SP’) each year. This test is useful in detecting a change point of decrease or increase in the average value for a time series, and it can also detect a change in the slope of a linear trend over a time interval (Busuioc and von Storch, 1996). Table 6 shows the results of this test. In the case of SD, a change point was identified, corresponding to year 1995. For SE, two change points were detected: one towards decrease, in 1985, and the other towards increase, in 1996. The change in the trend, either in 1995 or 1996, is visible for the three series, quite understandably in the case of SE and SP, but the value for SD enforces the signal of a change point.

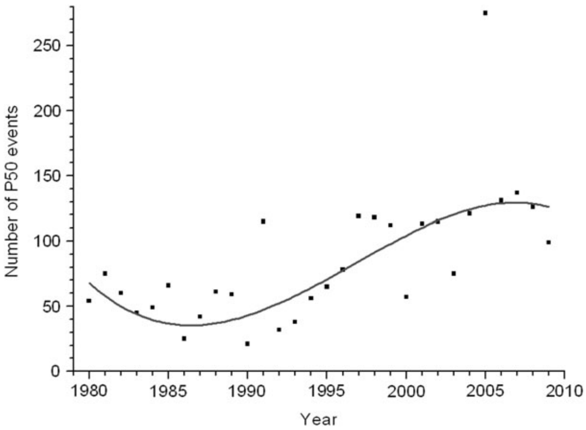

Figure 9. The trend of the annual number of P50 events; polynomial regression.

The nonparametric Mann–Kendall test (Mann, 1945; Kendall, 1975) can be stated generally as a test for whether values in a set tend to increase or decrease with time. This test is commonly used to assess the significance of monotonic trends in hydro-meteorological time series (Yue and Pilon, 2004). It was applied to the same three series as the Pettitt test, and the results are presented in Table 7. Since the normalized test statistic Z is positive and larger than 1.97 in all cases and the corresponding probabilities $f(z)$ are very low, as Busuioc *et al.* (2007) have shown, this is taken as the signal of an increasing trend which is statistically significant at the 5% significance level. The results can be therefore be interpreted

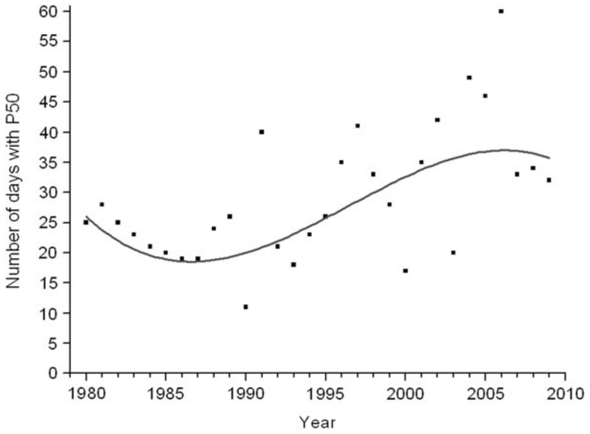

Figure 10. The trend of the annual number of days with at least one P50 event; polynomial regression.

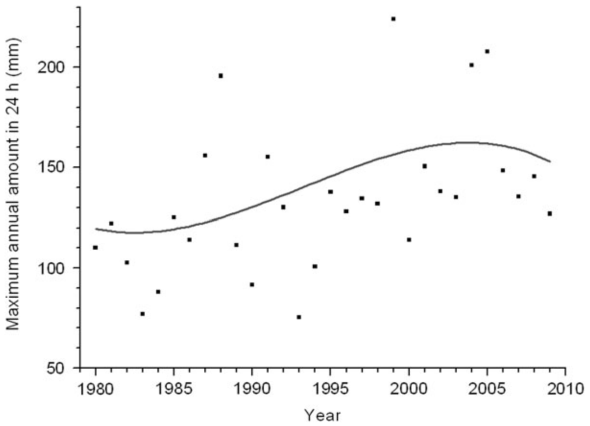

Figure 11. The trend of the annual maximum amount of precipitation, recorded in 24 h; polynomial regression.

Table 5. R^2 values for polynomial regressions in Figures 9, 10, 11.

Regression modelfor the P50 events	R^2
Annual number of days (Figure 9)	0.436
Annual number of events (Figure 10)	0.514
Maximum annual amounts in 24 h (Figure 11)	0.267

as the presence of an increasing trend in all the series subject to this test.

Trends in precipitation have been detected and investigated for several countries in Europe, for instance the United Kingdom (Osborn and Hulme, 2002), Portugal (de Lima *et al.*, 2010), while others note the difficulty spotting clear trends, such as for the Czech Republic (Kysely, 2008) and Switzerland (Schmidli and Frei, 2005). Others have used statistical models in order to analyse scenarios for greenhouse-gas-induced increases in heavy precipitation that reflect the observations (Groisman *et al.*, 1999). Busuioc *et al.* (2010), analysing some extreme precipitation indices calculated on the seasonal scale at 104 Romanian stations over 1961–2007, have found significant linear trends only for certain areas and seasons, while no significant trends were found for the others: namely, a significant increase in heavy precipitation (daily amounts exceeding the long-term 90th percentile) over the western, northern and southeastern parts of Romania. For the maximum precipitation amount recorded in 24 h, no significant trends over large areas were found, for any season, except for a few stations having a decreasing trend during the winter and an increasing trend during the autumn. The behaviour of extreme precipitation has been analysed in the present study too, although for a shorter interval (30 years as opposed to 47 in Busuioc *et al.*) and by using a different method, namely as a spatial index considering all stations together not for each station separately. This method is a novelty in the given context, since it allows one to overcome the difficulty related to the statistical analysis of single-station time series, which are sets that may contain null-values. A larger and finely-distributed set of real observation points, that leaves no room for excessive extrapolation, has been used.

Table 6. Results of the Pettitt test.

Data set	Statistical parameter	Value
Annual number of dayswith at least one event (SD)	Minimum	11
	Maximum	60
	Change point index	16
Annual number of events (SE)	Minimum	21
	Maximum	275
	Change point index	
		6 (towards decrease)
		17 (towards increase)
Annual numberof observation points (SP)	Minimum	20
	Maximum	155
	Change point index	17

Table 7. Results of the Mann–Kendall test.

Data set	Statistical parameter	Value
Annual number of days with at least one event (SD)	S	146
	$VAR(S)$	3132.67
	Z	2.59
	$f(z)$	0.014
Annual number of events (SE)	S	217
	$VAR(S)$	3139.67
	Z	3.82
	$f(z)$	0.0002
Annual number of observation points (SP)	S	203
	$VAR(S)$	3132.33
	Z	3.61
	$f(z)$	0.0006

3.4. Annual distribution of days with P50 events *versus* the average value of North Atlantic Oscillation (NAO)

Studies of this teleconnection pattern in regard to weather in the Northern Hemisphere have been performed by many authors (Hurrell and van Loon, 1997; Bojariu and Giorgi, 2005; Bartholy *et al.*, 2009; among others). Given that during the negative phase of NAO, precipitation in the southern parts of Europe is influenced by cyclonic activity in the Mediterranean, the evolution of the number of annual days with P50 *versus* the annual average value of NAO (Figure 12) has been considered. It is considered that averaging, over each year, the monthly values of NAO, is able to provide minimal information as to the prevalence of one of its two phases, either in time or intensity. Therefore, the averages over each year could be linked with the overall number of days with heavy precipitation the same year.

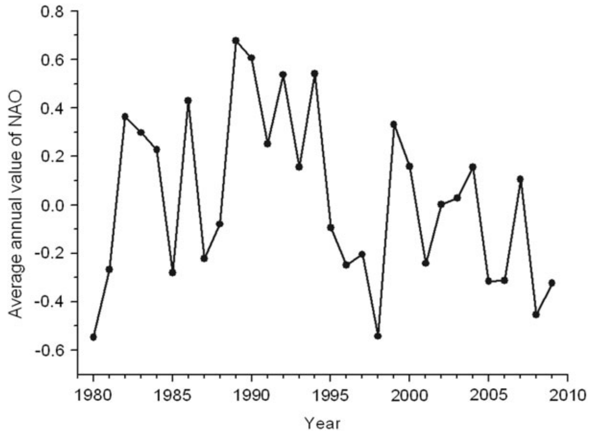

Figure 12. The annual average values of NAO between 1980 and 2009.

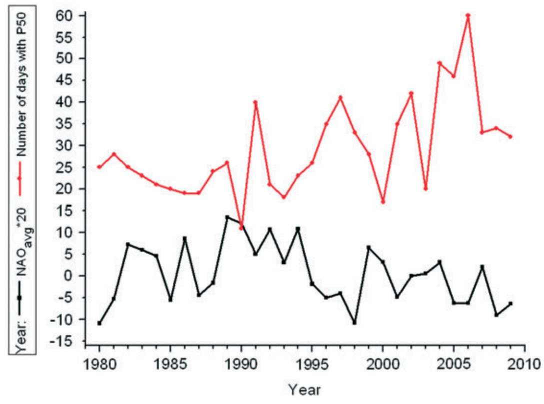

Figure 14. The annual number of days with at least one P50 event and the annual averages of NAO.

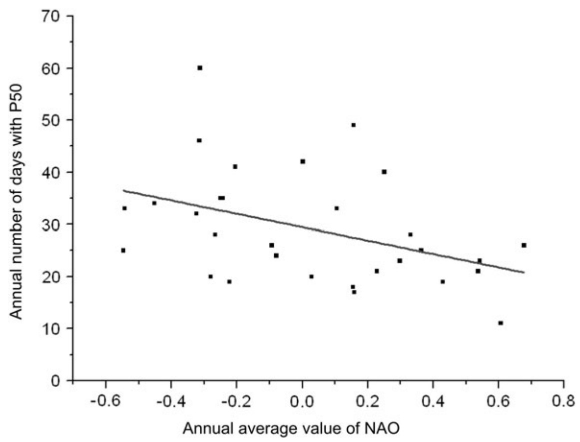

Figure 13. The trend of the annual number of days with at least one P50 event, by the annual average values of NAO.

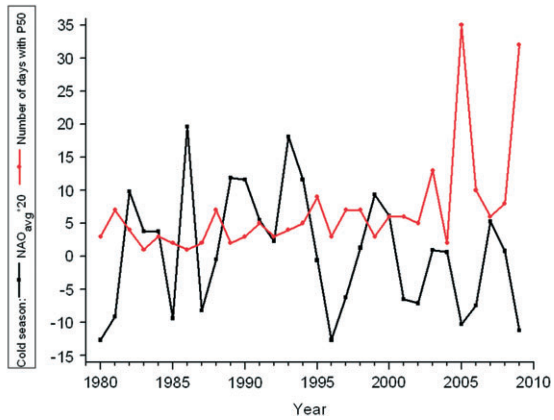

Figure 15. The number of days with at least one P50 event and the averages of NAO, both over the cold season (October to March) of each year.

The linear regression presented in Figure 13 shows the decreasing trend of the annual number of days with P50, as the annual average of NAO increases. As expected for these latitudes, during the negative phase of NAO, precipitation is stimulated more intensely than during the positive phase. It should be recognized, though, that local effects induced by the high obstacle of the Carpathians may also be a factor that favours the persistence of conditions leading to heavy precipitation in this particular area of Europe. Figure 14 shows the evolution of the annual number of days with P50 *versus* the annual average value of NAO, and the corresponding Pearson correlation co-efficient is −0.41. Figure 15 shows the number of days *versus* the average value of NAO during the cold season only (October to March), when the same co-efficient is −0.39.

4. Conclusions

A series of techniques, from database and SQL queries design to geostatistical tools and statistical tests was employed, in order to obtain an image of the distribution of heavy precipitation events in Romania, over three decades until 2009. Due to the nature of this study, visual analysis after mapping the data proved to be essential in assessing the spatial distribution of certain subsets of events, such as the extreme ones (P100). These maps deliver rich visual information that cannot be shown clearly by other means.

Different patterns were found for these events, in the regions inside and outside the Carpathian Mountain arch: those inside it were least exposed to heavy precipitation, both in the number of events and maximum annual amounts, while those outside it have recorded the most events and the largest annual amounts recorded in 24 h. In the low areas outside the Carpathian arch, the maximum daily annual amounts have increased from decade to decade.

The ratio of P100 events from the total number of events is close to 5%. Over the three separate decades in the interval of interest, an increase in the number of P50 and P100 events is noticeable over all landscape ranges. Also, in the last decade the respective numbers are very close to the sum of similar events in the previous two decades.

An increasing trend was found in the time series of the annual number of days and events, and in the time series of the annual maximum amount recorded in 24 h. The Mann–Kendall test confirms this trend, and the Pettitt test shows that the year 1995 or 1996 marked a change in both series, towards an increase of values. Such trends have been found by other authors for countries close to Romania, and this study may add to the body of evidence towards the influence of recent climate variability on precipitation at middle latitudes.

A correspondence between the phases of NAO and the number of days with heavy precipitation in Romania was found over the recent 30 year interval: that there were more such days in a year when the annual average value of NAO was negative.

Acknowledgements

We thank the Department of Database Design and Management at the National Meteorological Administration of Romania for providing the precipitation data set used in this paper. Mr Stefanescu was supported by the POSDRU/88/1.5/S/56668 Project at the University of Bucharest. Results of this study are part of the inter-institutional CLIMHYDEX (Changes in Climate Extremes and Associated Impact in Hydrological Events in Romania) project.

Appendix A

Data extraction from the events database was performed using SQL queries of the SELECT type, and various subsets have been subsequently separated from the bulk of data. SELECT queries allow for the retrieval of information from a table in a database, when the required information has to be conform to single or multiple criteria. These queries have the general syntax (Microsoft Corporation, 2012):

SELECT *select_list* [INTO *new_table*] FROM *table_source* [WHERE *search_condition*]
[GROUP BY *group_by_expression*] [HAVING *search_condition*]
[ORDER BY *order_expression* [ASC|DESC]]

Depending on the subset that we wanted to pull out, in the *select_list* we entered either lists of identifiers for various sets of stations, or their number, or their altitude and so on. In the *search_condition* we entered filters for data, e.g. *precamount>=100*, or *stationposalt_metres BETWEEN 301 AND 800*. Using such queries, we were able to essentially obtain primary statistical results related to the location and time of occurrence.

The actual images are provided in standalone files. All of the images provided here are also available in 600 dpi. Those showing the map of Romania were created in ArcMap®™ 10. The histograms were created in Microsoft®™ Excel®™ 2007, and the graphs in Origin®™ 8.

References

Bartholy J, Pongracz R, Gelybo GY. 2009. Climate signals of the North Atlantic Oscillation detected in the Carpathian basin. *Appl. Ecol. Env. Res.* **7**(3): 229–240.

Bojariu R, Giorgi F. 2005. The North Atlantic Oscillation signal in a regional climate simulation for the European region. *Tellus* **57A**: 641–653.

Bordei EI. 1983. *Rolul Lantului Alpino Carpatic in Evolutia Ciclonilor Mediteraneeni (The Role of Alps-Carpathians Range in the Evolution of Mediterranean Cyclones)*. Romanian Academy: Bucharest.

Busuioc A, Caian M, Cheval S, Bojariu R, Boroneant C, Baciu M, Dumitrescu A. 2010. *Variabilitatea si Schimbarea Climei in Romania*. Editura Pro Universitaria: Bucuresti; 226pp. ISBN: 978-973-129-549-7.

Busuioc A, Dumitrescu A, Soare E, Orzan A. 2007. Summer anomalies in 2007 in the context of extremely hot and dry summers in Romania. *Romanian J. Meteorol.* **9**(1–2): 1–16.

Busuioc A, von Storch H. 1996. Changes in the winter precipitation in Romania and its relation to the large scale circulation. *Tellus* **48A**: 538–552.

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. 2000. Climate extremes: observations, modeling, and impacts. *Science* **289**: 2068–2074, DOI: 10.1126/science.289.5487.2068.

Environmental System Research Institute (ESRI) 2011. ArcGIS desktop 10 documentation. http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html (accessed 8 November 2011).

Fujibe F. 2008. Long-term changes in precipitation in Japan. *J. Disaster Res.* **3**(1): 51–60.

Georgescu F, Stefan S. 2011. Dynamic of the troposphere in cases of weather extreme events. EGU General Assembly 2011, Vienna, Austria, Geophysical Research Abstracts, Vol. 13, EGU2011-2700.

Groisman PY, Karl TR, Easterling DR, Knight RW, Jamason PF, Hennessy KJ, Suppiah R, Page CM, Wibig J, Fortuniak K, Razuvaev VN, Douglas A, Førland E, Zhai PM. 1999. Changes in the probability of heavy precipitation: important indicators of climate change. *Clim. Change* **42**(1): 243–283 (41).

Hurrell JW, van Loon H. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Change* **36**: 301–326.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Fourth Assessment Report: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC: Geneva, Switzerland.

Karagiannidis A, Karacostas T, Maheras P, Makrogiannis T. 2009. Trends and seasonality of extreme precipitation characteristics related to mid-latitude cyclones in Europe. *Adv. Geosci.* **20**: 39–43.

Kendall MG. 1975. *Rank Correlation Methods*. Griffin: London.

Kysely J. 2008. Trends in heavy precipitation in the Czech Republic over 1961–2005. *Int. J. Climatol.* **29**(12): 1745–1758, DOI: 10.1002/joc.1784.

de Lima MIP, Carvalho SCP, de Lima JLMP. 2010. Investigating annual and monthly trends in precipitation structure: an overview across Portugal. *Nat. Hazards Earth Syst. Sci.* **10**: 2429–2440, DOI: 10.5194/nhess-10-2429-2010.

de Luis M, Gonzalez-Hidalgo JC, Brunetti M, Longares LA. 2011. Precipitation concentration changes in Spain 1946–2005. *Nat. Hazards Earth Syst. Sci.* **11**: 1259–1265, DOI: 10.5194/nhess-11-1259-2011.

Mann HB. 1945. Nonparametric tests against trend. *Econometrica* **13**: 245–259.

Michalska B, Kalbarczyk E. 2005. Longterm changes in air temperature and precipitation in Szczecilska Lowland. *Electron. J. Pol. Agric. Univ.* **8**(1). http://www.ejpau.media.pl/volume8/issue1/art-17.html (accessed May 2013).

Microsoft Corporation. 2012. http://msdn.microsoft.com/en-us/library/aa259187%28SQL.80%29.aspx (accessed 8 March 2012).

Minetti JL, Vargas WM, Poblete AG, Acuna LR, Casagrande G. 2003. Non-linear trends and low frequency oscillation in annual precipitation over Argentina and Chile, 1931–1999. *Atmosfera* **16**: 119–135.

National Institute of Statistics. 2012. Statistical Yearbook 2010: geography, meteorology and environment. http://www.insse.ro/cms/files/Anuar%20statistic/01/01%20Geografie_ro.pdf (accessed 12 May 2012).

National Meteorological Administration of Romania. 2008. *Climate of Romania*. Romanian Academy: Bucharest.

National Oceanic and Atmospheric Administration (NOAA). 2012. *Standardized Northern Hemisphere Teleconnection Indices (1981–2010 Clim)*. National Weather Service, Climate Prediction Centerftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh (accessed 22 January 2012).

Osborn TJ, Hulme M. 2002. Evidence for trends in heavy rainfall events over the UK. *Philos. Trans. R. Soc. Lond. A* **2002**(360): 1313–1325, DOI: 10.1098/rsta.2002.1002.

Pettitt AN. 1979. A non-parametric approach to the change-point problem. *Appl. Statist.* **28**: 126–135.

Schmidli J, Frei C. 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th Century. *Int. J. Climatol.* **25**: 753–771, DOI: 10.1002/joc.1179.

Taher S, Alshaikh A. 1998. Spatial analysis of rainfall in Southwest of Saudi Arabia using GIS. *Nord. Hydrol.* **29**(2): 91–104.

Tomozeiu R, Stefan S, Busuioc A. 2005. Winter precipitation variability and large-scale circulation patterns in Romania. *Theor. Appl. Climatol.* **81**: 193–201, DOI: 10.1007/s00704-004-0082-3.

World Meteorological Organization. 2011. Severe weather information centre. http://severe.worldweather.wmo.int/rain (accessed 22 November 2011).

Yue S, Pilon P. 2004. A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection. *Hydrol. Sci. J.* **49**(1): 21–38.

