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Contributions to Geophysics and Geodesy Vol. 47/2, 2017 (133–148)

Detection of future changes in seasonality in extreme short-term rainfall in selected stations of Slovakia

Marianna VASILAKI[1], Silvia KOHNOVÁ[2], Martin HANEL[3],
Ján SZOLGAY[2], Kamila HLAVČOVÁ[2], Athanasios LOUKAS[1],
Peter RONČÁK[2]

[1] Laboratory of Hydrology and Aquatic Systems Analysis, Department of Civil Engineering,
University of Thessally,
PedionAreos, 38334 Volos, Greece

[2] Dept. of Land and Water Resources Management, Slovak University of Technology,
Radlinského 11, 810 05 Bratislava, Slovak Republic;
e-mail: silvia.kohnova@stuba.sk, jan.szolgay@stuba.sk, kamila.hlavcova@stuba.sk,
peter.roncak@stuba.sk

[3] Czech University of Life Sciences Prague, Faculty of Environmental Science,
Kamýcká 129, 165 00 Prague 6 – Suchdol, Czech Republic

Abstract: This paper analyses the projected changes in short-term rainfall events during the warm season (April–October) in an ensemble of 30 regional climate model (RCM) simulations. The seasonality analysis was done for the Hurbanovo, Bratislava, Oravska Lesna, and Myjava stations in Slovakia. The characteristics of maximum rainfall events were analysed for two scenario periods, one past and one future (1960–2000 and 2070–2100) and compared to the characteristics of the actual observed events. The main findings from the analysis show that short-term events of 60 minutes appear to have stronger seasonality than daily events that show a rather high variability. The seasonality concentration index calculated for the 60 min events averages to 0.77, while that of daily events averaged to 0.65. The differences between the dates of the occurrence of past and future events are not significant in the lowland areas, while in the mountainous areas the future events have been found to occur earlier than past ones.

Key words: seasonality analysis, short-term rainfall, RCM projections

1. Introduction

Expected changes in precipitation are supposed to be one of the most critical factors determining the overall impact of climate change. For most

doi: 10.1515/congeo-2017-0009

parts of Europe, wet winters and drier summers over Central and Southern Europe are expected. Growing evidence shows that in some regions of the world, rainfall has increasingly become characterized by high-intensity events (*Groisman et al., 2012; Higgins and Kousky, 2013; Trenberth et al., 2003; Trenberth, 2011; Dourte et al., 2012* and *Keggenhoff et al., 2014*). This trend subsequently lead to longer dry spells and a higher risk of floods.

Extreme precipitation events could intensify more in the future due to increases in the atmospheric water vapor content as a result of global warming. To obtain estimates of possible future changes in precipitation, climate models are widely used. Projections of future climate change also suggest increasingly intense rainfall in some locations. Thus, information on future precipitation events is very useful in many applications and potential changes in the characteristics of precipitation events, such as the magnitude and seasonality of precipitation are of significant societal concern, especially after evidence of the increasing intensity of daily rainfall due to climate change (*Alexander et al., 2006; Trenberth, 2011, Cápayová et al., 2017*).

The seasonality of hydrological characteristics belongs among the main elements controlling natural ecosystems. When a firm seasonal pattern of high flow occurrences is detected for a given region, then it can be expected with a high level of probability that water and water-dependent ecosystems are reasonably sensitive to such patterns and that changes in the seasonality of floods could adversely affect their well-being. There are many examples that point out that the high significance of seasonal extremes is closely related to water resources management, engineering design and climate change studies (e.g. *Krasovskaia and Gottschalk, 2002; Krasovskaia et al., 2003; Bower et al., 2004; García and Mechoso, 2005*). In Slovakia and Central Europe, *Lapin et al. (2001)* analyzed seasonal changes in monthly precipitation for future time horizons on the basis of downscaled outputs from GCM scenarios. *Gaál (2005)* analyzed the maximum k-day precipitation totals in Slovakia and applied seasonality indices of mean monthly and extreme precipitation of Slovakia. The seasonality of seasonal and annual flood and precipitation maxima in the Alpine–Carpathian region has been analysed in many studies. For example, *Merz et al. (1999)* and *Merz and Blöschl (2003)* used flood seasonality as an indicator to describe different flood types based on the timing of floods. *Parajka et al. (2009)* applied a seasonality index to identify the main climatic and physiographic drivers behind flood-generating processes. In Slovakia, a seasonality analysis was mainly been applied in studies examining the regionalization of floods for example, *Kriegerová and Kohnová (2005)* dealt with seasonality of maximum annual and seasonal (summer and winter) discharges for the allocation of flood risk regions. *Jeneiová et al. (2016)* studied the variability of seasonal floods in the Upper Danube River basin. The above considerations show that appropriate attention must be given to an analysis of the seasonal occurrence of rainfall events.

The paper is organized as follows; First, a theoretical description of the climate models applied is provided, followed by the methodology which describes the methods used to estimate short-term rainfall seasonality and its changes in future horizons. The study area and data sets used are described and followed by the results of the seasonality analysis follows in their respective sections. The paper concludes with a discussion and summary.

2. Methodology

Over recent decades a lot of statistical methods have emerged for capturing flood seasonality. In this study, Burn's vector methodology (*Burn, 1997*) for the estimation of seasonality was applied. It is a method frequently used for estimating the seasonal occurrence of extreme events and was originally modified for detecting flood seasonality changes. This method describes the variability of the date on which the maximum annual precipitation occurs in such a way that the direction of the vector corresponds to the expected date of occurrence within a year, while the vector length describes the variability around the expected date of occurrence (*De Michele and Rosso, 2002*).

The mean date of occurrence (D) represents an average position of particular event occurrences, which are plotted in polar coordinates on a unit circle. Burn's vector is calculated by first, determining the orientation (direction) of the unit vector of the date the maximum annual value has occurred for each year. The position of the event occurrence on a unit circle is defined by the angle:

$$\theta_i = D_i \frac{2\pi}{365}, \tag{1}$$

where:

θ_i – "orientation" of that date in the year on which the maximum annual rainfall has occurred (rad),
n – ordinal number of the year in a time series (from 1 to n),
i – total number of years in the time series,
D_i – ordinal number of the date in year i on which the maximum annual rainfall has occurred (0–365).

The abscissa $\bar{x}$ and ordinate $\bar{y}$ of the Burn's vector are calculated as follows (*Burn, 1997*):

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \cos\theta_i\,, \tag{2}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} \sin\theta_i\,, \tag{3}$$

from which the orientation of Burn's vector $\bar{\theta}$ can be derived:

$$\bar{\theta} = \tan^{-1}\frac{\bar{y}}{\bar{x}}\,, \tag{4}$$

and the seasonal concentration index r is:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2}\,, \tag{5}$$

The orientation $\bar{\theta}$ of Burn's vector can have a value from 0 (which corresponds to the expected occurrence of an annual extreme on 1 January) to 2π (which corresponds to the expected occurrence of an annual extreme on 31 December). Burn's vector orientation can be used to calculate a given date. Burn's vector seasonality concentration index can have a value between 0 and 1, where it is equal to 1 if an extreme event has occurred every year on the same date, while it move towards zero if extreme occurrences are uniformly distributed during the year. However, in case extreme occurrences are approximately uniformly distributed during the year then, due to the small vector intensity, its orientation can change significantly as a result of small changes in the input data.

In order to investigate the seasonality of the extreme precipitation events, the seasonality index ($\bar{\theta}$ and r) was separately estimated for each station and rainfall duration.

2.1. Regional Climate Models (RCMs)

For downscaling Global Climate Models (GCMs) Regional Climate Models (RCMs) are now a widely accepted tool. The basic strategy is to use ta global model to simulate the response of the global circulation to large-scale forcing and the RCM to account for sub-GCM grid scale forcing (e.g., complex topographical features and inhomogeneous land cover) in a physically-based way and to enhance the simulation of atmospheric circulations and climatic variables using fine spatial scales.

The regional climate modelling technique consists of using initial conditions, time-dependent lateral meteorological conditions, and surface boundary conditions to drive high-resolution RCMs. The driving data is derived from GCMs (or analyses of observations) and can include greenhouse gases and aerosol forcing. A variation of this technique is to also force the large-scale components of the RCM solution throughout the entire domain (e.g., *Kida et al., 1991; Cocke and LaRow, 2000; von Storch et al., 2000*).

Using RCM we can get localized, high-resolution information that is consistent with large-scale climate simulated by the GCMs (*Rummukainen, 2010*). As GCMs operate on a relatively coarse horizontal resolution, they do not resolve all regional details in surface heterogeneity. Therefore the dynamic downscaling of GCM simulations is of particular importance in regions with a complex topography and large contrasts in their surface features (e.g., land/water contrasts). Precipitation and near-surface wind speeds are particularly sensitive to horizontal resolutions due to their strong interactions with topography and surface physiography. Furthermore, key atmospheric processes, particularly those controlling the development of high-impact weather events, often interact across a range of spatial scales from the convective through mesoscale to synoptic scales. The ability to capture this range of interactions and thereby provide useful information on extreme weather events improves with increasing the model resolution. Hence the increased resolution of RCMs offers the potential for an improved simulation of the location, frequency and intensity of extreme events, such as localized precipitation and wind maxima.

The nested regional modelling technique essentially originated from numerical weather predictions and the use of RCMs for climate application was pioneered by *Dickinson et al. (1989)* and *Giorgi (1990)*. RCMs are now used in a wide range of climate applications. They can provide high resolution (up to 10 to 20 km or less) and multi-decadal simulations and are capable of describing climate feedback mechanisms acting on a regional scale. A number of limited area modelling systems that are widely used have been adapted for climate application. More recently, RCMs have begun to couple atmospheric models with other climate process models, such as hydrology, ocean, sea-ice, chemistry/aerosol and land-biosphere models. Information about the RCMs used in the present study is provided in the data section.

3. Study area

Slovakia is located in a mild climate zone with precipitation influenced by the Atlantic Ocean that impacts predominantly in the western part of the country; the continental influence is typical for the southeastern part. The Mediterranean climate mainly influences the southern part of central Slovakia with higher precipitation totals in the autumn.

The Sixth National Communication of the Slovak Republic on Climate Change (2013) for the period of 1880–2012 showed a significant increase in the mean annual air temperature of 1.8 °C and an insignificant decrease in the annual areal precipitation totals by about 1.3% was recorded. While the increase in air temperature was nearly the same in the whole territory, a significant decrease in the annual precipitation totals was mainly observed in southern Slovakia (up to 10%) and a small increase in the precipitation totals was only observed at the northern border of Slovakia (about 3%). The developments in temperature and precipitation were accompanied by a decrease in relative air humidity and an increase in potential evapotranspiration by about 5% in southern of Slovakia. The period of 1880–2012 was significant not only for the rapid increase in air temperature (by about 2 °C) but also for the great variability in precipitation totals (164% of normal in 2010, 74% of normal in 2003), which caused several episodes of serious drought on the one hand and local or regional floods on the other. The changes in the winter precipitation totals and the increase in the winter air temperature caused unstable snow conditions in Slovakia; but an increase of snow cover days and depths was recorded only in the higher mountains.

3.1. Data

The observed data of the hourly rainfall values from the warm season (April –October) were provided by the Slovak Hydrometeorological Institute for the Myjava, Oravska Lesna, Bratislava and Hurbanovo climatological stations. The locations of the stations are presented in Fig. 1 than were selected due to the availability of the climate scenarios and also to cover the southern, northern and western parts of Slovakia, which have the longest actual observation periods of short-term rainfalls. The annual maxima rainfall for various durations from 60 min up to one day were determined from the hourly rainfall time series. For Hurbanovo, the observation period was from 1961 to 1994, while for the other stations it was from 1995 to 2009.

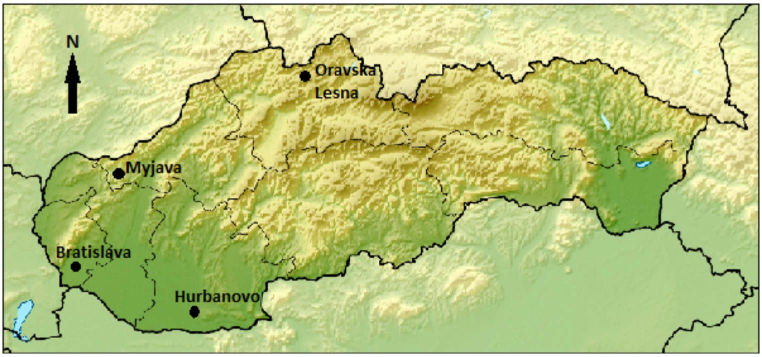

Fig. 1. Location of stations analysed in Slovakia.

The RCM simulation data were derived for selected study areas, see Table 1. The RCM simulations used consist of time series of annual maximum short-term precipitation events for two scenario periods, in the past (1960–2000) and the future (2070–2100) and the month of occurrence of each year's maxima. The time scale of the simulations is hourly, while until now only results for simulations evaluated on a daily time scale had been used in Slovakia. The ensemble of 30 simulations examined is described in more detail in Table 1. The RCMs are forced by scenarios SRES A1B, RCP2.6, RCP 4.5 and RCP 8.5. The HadRM and RACMO2 simulations were conducted within an ensemble project (*van der Linden and Mitchell, 2009*), while the RCA4 and RACMO22E simulations were evaluated within the

EURO-CORDEX project (*Jacob et al., 2014*). To select the most appropriate scenarios for the stations selected, we contacted the climatologist prof. M. Lapin and Dr. M. Gera from the Department of Astronomy, Physics of the Earth and Meteorology, Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovakia. The final models suggested are the highlighted ones in Table 1.

Table 1. Overview of the RCM simulations applied.

RCM	Driven by GCM	Project	Forcing	Temp Res	Spat Res
HadRM3.0 (*Collins et al., 2011*) – Met Office Hadley Centre (MOHC), UK					
HadRM3Q0_HadCM3	HadCM3Q0	ENSEMBLES	SRES A1B	1h	25 km
HadRM3Q3_HadCM3	HadCM3Q3	ENSEMBLES	SRES A1B	1h	25 km
HadRM3Q16_HadCM3	HadCM3Q16	ENSEMBLES	SRES A1B	1h	25 km
RCA4.0 (*Kupiainen et al., 2011; Samuelsson et al., 2011*) – Swedish Meteorological and Hydrological Institute (SMHI)					
RCA4_CanESM2	CCCma-CanESM2	EUR-44 CORDEX	RCP4.5, RCP8.5	20min	50 km
RCA4_CNRM-CM5	CNRM-CM5	EUR-44 CORDEX	RCP4.5, RCP8.6	20min	50 km
RCA4_EC-EARTH	ICHEC-EC-EARTH	EUR-44 CORDEX	RCP2.6, RCP4.5, RCP8.5	20min	50 km
RCA4_CM5A-MR	IPSL-CM5A-MR	EUR-44 CORDEX	RCP4.5, RCP8.5	18min	50 km
RCA4_MIROC5	MIROC5	EUR-44 CORDEX	RCP4.5, RCP8.5	20min	50 km
RCA4_HadGEM2-ES	MOHC-HadGEM2-ES	EUR-44 CORDEX	RCP4.5, RCP8.5	20min	50 km
RCA4_ESM-LR	MPI-ESM-LR	EUR-44 CORDEX	RCP4.5, RCP8.5	20min	50 km
RCA4_NorESM1-M	NCC-NorESM1-M	EUR-44 CORDEX	RCP4.5, RCP8.5	20min	50 km
RCA4_ESM2M	NOAA-GFDL-ESM2M	EUR-44 CORDEX	RCP4.5, RCP8.5	20min	50 km
RACMO2.1 (*van Meijgaard et al., 2008*) – Royal Netherlands Meteorological Institute (KNMI)					
RACMO2_ECHAM5	ECHAM5-r3	ENSEMBLES	SRES A1B	1h	25 km
RACMO2_MIROC	MIROC3.2	ENSEMBLES	SRES A1B	1h	25 km
RACMO22E (*van Meijgaard et al., 2012*) – Royal Netherlands Meteorological Institute (KNMI)					
RACMO22E	ICHEC-EC-EARTH	EUR-11 CORDEX	RCP4.5, RCP8.5	1h	12 km

4. Results

The results obtained for all the scenarios applied show that the expected maxima of the short-term annual rainfall of various durations predominantly occurs during the months of July and September. The occurrence of both the past and future simulated extreme rainfall events at the Hurbanovo station appears to be spread from middle of June until September, while the observed events mostly occurred in middle of July (Fig. 2). Similar behavior can be observed at the Bratislava station, which is located close to a lowland area (Fig. 2). On the other hand, extreme rainfall events at the Oravska Lesna and Myjava stations, which are located in mountainous areas, occur earlier. In these stations only a few events occur in August and none in September, while the majority of the events are reported in June (Fig. 3).

In the next step only selected RCM simulations for estimations of seasonality were used in order to get better insight into their possible changes in the future. Each set of simulations was represented with different sym-

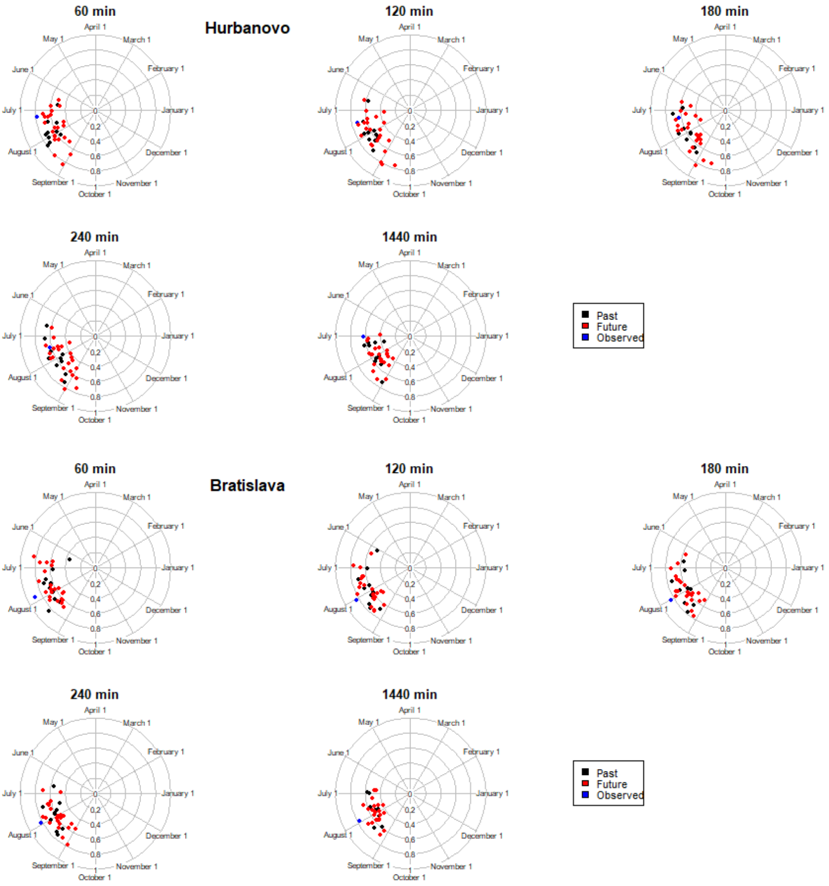

Fig. 2. Seasonality of simulated past, future and actual observed values of extreme annual rainfall of certain duration at the Hurbanovo and Bratislava stations.

bols, which made it possible to detect shifts between the past and future projections (Figs. 4-6).

The results regarding the Bratislava station showed that the date of occurrence between the past and future events has not changed, except for a slight tendency for the future events to occur in earlier months.

At the Hurbanovo (Fig. 4) and Myjava stations, the results of the simulations present the same tendency for the future events to occur earlier, while the results from the last simulation present a shift towards the au-

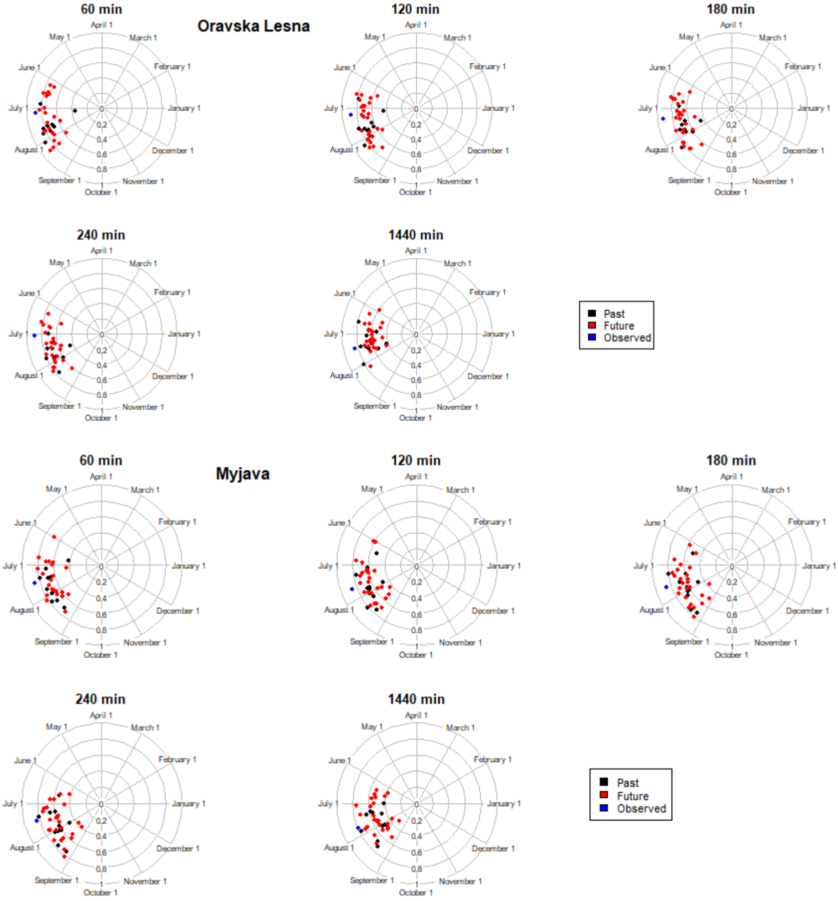

Fig. 3. Seasonality of simulated past, future and actual observed values of extreme annual rainfall of certain duration at the Oravska Lesna and Myjava stations.

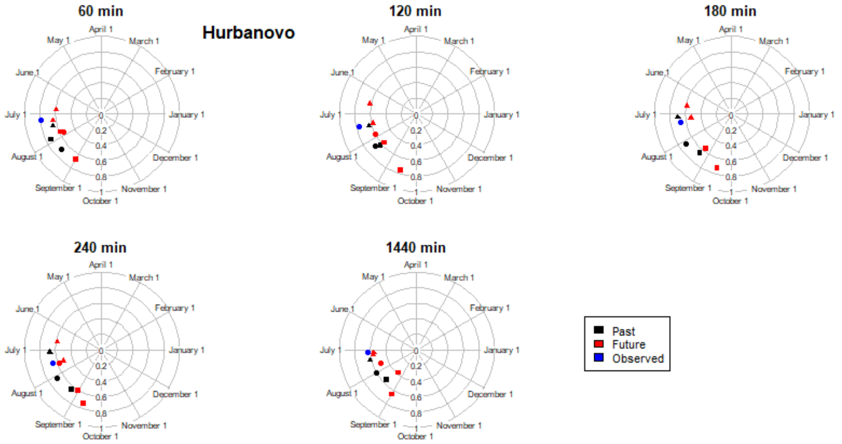

Fig. 4. Seasonality of simulated past, future and real observed values of extreme annual rainfall of certain duration at Hurbanovo station (selected simulations only).

tumn months. Hurbanovo is the station with the highest variability in the occurrence of events, where the seasonality concentration index calculated using Burn's method equals to 0.6.

At the Oravska Lesna station past and future events occur almost on the

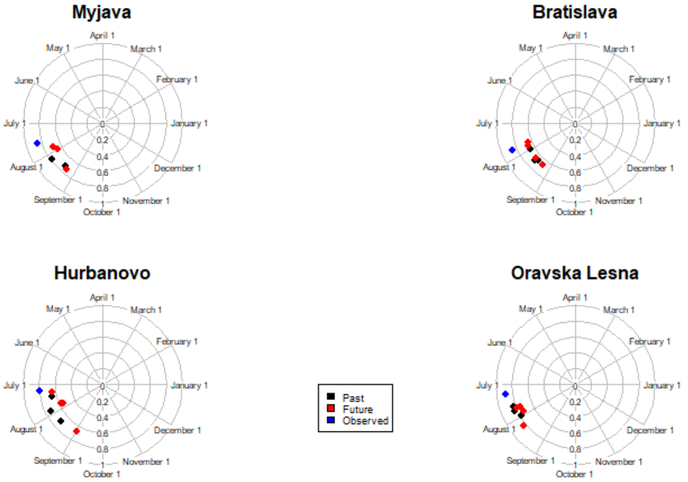

Fig. 5. Seasonality of simulated past, future and actual observed values of extreme annual rainfall of 60 min (selected simulations only) at all the stations analysed.

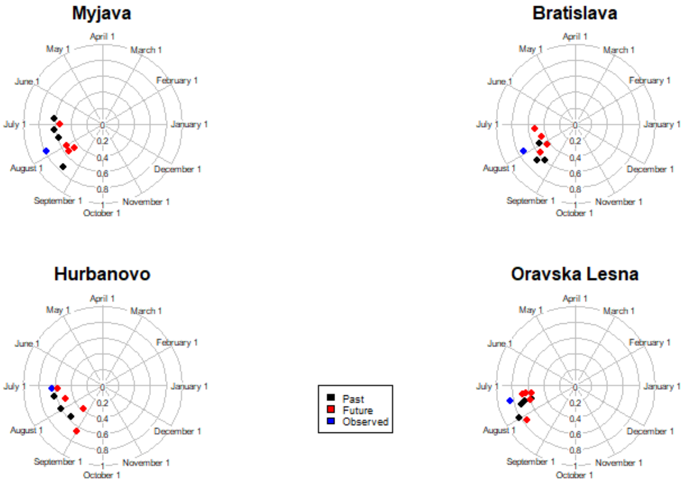

Fig. 6. Seasonality of simulated past, future and actual observed values of extreme daily rainfall events (selected simulations only) at all the stations analysed.

same dates in July and during the first days of August. At the Oravska Lesna station the events have a very strong seasonality, with a seasonality concentration index equal to 0.8. At all the stations the future events present weaker seasonality patterns than the past events.

Finally, the changes in seasonality of short and long duration events (60 min and 1 day) were compared to detect possible differences in the occurrence of maximum rainfall events regarding their duration (Figs. 5,6).

From Figs. 5 and 6 we can see that short duration events of 60 minutes appear to have stronger seasonality than the daily events which show a rather high degree of variability. The seasonality concentration index calculated for the 60 min events averages to 0.77, while the daily events average to 0.65. The differences between the date of the occurrence of past and future events are not significant.

5. Discussion and summary

Projected changes in the seasonality of short term annual maxima rainfall events were assessed at four stations in Slovakia: the Myjava, Bratislava, Hurbanovo and Oravska Lesna stations. The seasonality indices were analyzed for two scenario periods, one past and one future (1960–2000 and 2070–2100) and compared to the actual observed data.

According to the changes in the mean characteristics of 60 min rainfall events, we identified 3 groups of RCM simulations. The largest part of the RCM simulations (11 out of 23) was identified as simulations with relatively unchanged rainfall intensities and depths. A considerable part of the RCM simulations (8 out of 23) show increases in the depths and intensities of 60-min events. Finally, four RCM simulations project decreased rainfall intensities and depths. The increases were in general more pronounced in the RCM simulations forced by RCP8.5 compared to the SRES A1B and RCP4.5 scenarios. On the other hand, all the RCM simulations project significant increases, even up to 10 times higher, in daily rainfall intensities and depths. From these results we could deduct that these RCM simulations significantly overestimate daily precipitation events. For a comparison, *Jacob et al. (2014)* found statistically significant increases in total precipitation in large parts of Central Europe for the late 21st century from an ensemble of RCM simulations evaluated on a daily time scale (from the EUROCORDEX and ENSEMBLES projects). The aforementioned changes in detection were only possible for the Hurbanovo station; as for the other stations, the time series length of the observed events was inadequate.

We have to be aware of several uncertainties related to RCM results such as those related to human activities, such as emissions of greenhouse gases, and the climate system's response to increased greenhouse gas forcing, which includes climate sensitivity and feedbacks. But there are also uncertainties that include initial and boundary conditions inherited from the driving global model, methods of parameterizations and grid resolutions, intermodel variability, and issues surrounding the validation or verification of models. Any numerical model is limited by the knowledge the scientist has about the actual systems, and the computing resources available to run it. As a result, uncertainty is unavoidable in regional climate scenarios and indeed in any geographical discipline which utilizes numerical modelling. Therefore, the projected changes in precipitation on short temporal scales from the current RCMs have to be interpreted cautiously.

The main findings can be summarized as follows: short duration events of 60 minutes appear to have stronger seasonality than the daily events which show a rather high degree of variability. The seasonality concentration index calculated for the 60 min events averages to 0.77, while that of the daily events averages to 0.65. The differences between the dates of the occurrence of past and future events are not significant.

At the Hurbanovo station, the average 60 min event depths and intensities for most of the RCM simulations are projected either to increase or remain constant. On the other hand, the daily event depths and intensities are projected to increase significantly; in some cases they were found to be ten times larger.

The dates of occurrence of past and future events at the Bratislava station is almost the same, except a slight tendency for future events to occur earlier than the past. At the Myjava and Oravska Lesna stations the future extreme rainfall events were found to occur earlier. At all the stations the future events present a weaker seasonality than the past events.

Acknowledgements. This study was supported by the Slovak Research and Development Agency under Contract No. 15-0497 and the Slovak Grant Agency under VEGA Project Nos. 1/0891/17 and 1/0710/15.

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