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PROJECTED CHANGES IN FLOOD-GENERATING PRECIPITATION EXTREMES OVER THE CZECH REPUBLIC IN HIGH-RESOLUTION REGIONAL CLIMATE MODELS

JAN KYSELÝ[1,2], LADISLAV GAÁL[1,2,3], ROMANA BERANOVÁ[1]

[1]Institute of Atmospheric Physics AS CR, Prague, Czech Republic, email: kysely@ufa.cas.cz
[2]Global Change Research Centre, Brno, Czech Republic.
[3]Slovak University of Technology, Bratislava, Slovakia.

Climate change scenarios of high quantiles of 5-day precipitation amounts (proxies for flood-generating events) over the Czech Republic are evaluated in an ensemble of high-resolution Regional Climate Model (RCM) simulations from the ENSEMBLES project. The region-of-influence method of the regional frequency analysis is applied as a pooling scheme. This means that for any single gridbox, a homogeneous region (set of gridboxes) is identified and data from that region are used when fitting the Generalized Extreme Value distribution.

The climate change scenarios for the late 21st century (2070–2099) show widespread increases in high quantiles of 5-day precipitation amounts in winter, consistent with projected changes in mean winter precipitation. In summer, increases in precipitation extremes occur despite an overall drying (prevailing declines in mean summer precipitation), which may have important hydrological implications. The results for summer suggest a possible substantial change in characteristics of warm-season precipitation over Central Europe, with more severe dry as well as wet extremes. The spatial pattern of projected changes in summer precipitation extremes, with larger increases in the western part of the area and smaller changes towards east, may also point to a declining role of Mediterranean cyclones in producing precipitation extremes in Central Europe in a future climate. However, uncertainties of the climate change scenarios remain large, which is partly due to biases in reproducing precipitation characteristics in climate models, partly due to large differences among the RCMs, and partly due to factors that are poorly or not at all represented in the examined ensemble. The latter are related also to uncertainties in future emission scenarios and socio-economic development in general.

KEY WORDS: Precipitation Extremes, Regional Frequency Analysis, Climate Change, Regional Climate Models, the Czech Republic.

Jan Kyselý, Ladislav Gaál, Romana Beranová: PREDPOKLADANÉ ZMENY V ZRÁŽKOVÝCH EXTRÉMOCH NEBEZPEČNÝCH PRE TVORBU POVODNÍ NA ÚZEMÍ ČESKEJ REPUBLIKY V REGIONÁLNYCH KLIMATICKÝCH MODELOCH S VYSOKÝM PRIESTOROVÝM ROZLÍŠENÍM. J. Hydrol. Hydromech., *59*, 2011, 4; 44 lit., 6 obr., 1 tab.

Práca analyzuje scenáre klimatickej zmeny pre vysoké kvantily 5-denných úhrnov zrážok (ktoré predstavujú možné riziko z pohľadu tvorby povodňových udalostí) na území Českej republiky, a to na základe širšej množiny simulácií z regionálnych klimatických modelov (RCM) s vysokým priestorovým rozlíšením, dostupných z projektu ENSEMBLES. Kvantily zrážkových extrémov sa odhadujú na základe metódy vplyvného regiónu, ktorá je jedným z variantov regionálnej frekvenčnej analýzy. To znamená, že pre každý gridový bod sa identifikuje jedinečný homogénny región (t.j. množina ďalších gridových bodov) a zrážkové údaje dostupné zo všetkých gridových bodov v rámci daného regiónu sa zužitkujú v procese odhadovania kvantilov využitím zovšeobecneného extremálneho rozdelenia.

Scenáre klimatickej zmeny pre obdobie posledných troch dekád 21. storočia (2070–2099) naznačujú rozsiahly nárast vysokých kvantilov 5-denných úhrnov zrážok počas zimy, čo je v súlade s predpokladanými zmenami v priemerných úhrnoch zrážok za zimu. V lete sa tiež očakáva zvýšenie extrémnych úhrnov zrážok, čo môže v súvislosti s predpokladaným všeobecným úbytkom zrážok v tomto období (t.j. napriek prevažujúcemu poklesu priemerných úhrnov zrážok v lete) viesť k vážnym hydrologickým následkom. Výsledky pre leto naznačujú zásadnú zmenu v režime úhrnov zrážok v strednej Európe v teplom období roka, spojenú s častejším výskytom nepriaznivých suchých aj vlhkých extrémov. Priestorové rozdelenie predpokladaných zmien v extrémnych úhrnoch zrážok za leto – s vyšším nárastom v západných častiach skúmanej oblasti a postupne menej výrazným nárastom smerom na východ – zrejme poukazuje na slabnúcu úlohu stredomorských cyklón pri tvorbe zrážkových extrémov v strednej Európe v nastávajúcich klimatických podmienkach. Treba však podotknúť, že neurčitosť scenárov klimatickej zmeny je stále veľká, a to jednak v dôsledku nepresností v reprodukcii charakteristík úhrnov zrážok v klimatických modeloch, ďalej kvôli významným rozdielom medzi jednotlivými RCM, a nakoniec aj v dôsledku klimatických faktorov, ktoré sú slabo reprezentované, prípadne nie sú vôbec zahrnuté v analyzovanej množine výstupov klimatických modelov. Spomínané klimatické faktory takisto závisia od emisných scenárov skleníkových plynov, resp. od socio-ekonomického vývoja ľudstva vo všeobecnosti.

KĽÚČOVÉ SLOVÁ: zrážkové extrémy, regionálna frekvenčná analýza, klimatická zmena, regionálne klimatické modely, Česká republika.

1. Introduction

Central Europe is a region that has recently been affected by several severe floods, associated with loss of lives and enormous damage to infrastructure and buildings. In late June and early July 2009, a series of flash floods affected several isolated areas of Central Europe, mainly in the Czech Republic and Austria; the most devastating was the flood in the Nový Jičín district on June 24, leaving 10 people dead (see *Kyselý* et al., 2011a for more detail on the event, including estimates of its recurrence probability). In May–June 2010, widespread floods from large-scale heavy precipitation devastated parts of Slovakia, eastern Czech Republic, and southern Poland (*Pecho* et al., 2010), and in August 2010, a more local flooding but with similarly severe consequences impacted northern parts of the Czech Republic close to the borders with Germany and Poland. Although neither of these events matches economic losses associated with the 'millenium flood' in Central Europe in 2002 (*Ulbrich* et al., 2003), an increased frequency of floodings with large material losses in recent years raises questions on recurrence probabilities of such events, particularly in the context of climate change.

Since warmer atmosphere has enhanced water-holding capacity, climate change is expected to increase severity of precipitation extremes (*Trenberth* et al., 2003). Climate change effects on the hydrologic cycle would have important implications, among other, for water resources management (flood estimation and prevention), design of hydraulic structures (e.g. dams, culverts, spillways) as well as agriculture (soil loss and vegetation damage). From the point of view of practical applications, it is important to refine projections of how extreme rainfall distributions and design values may change within the planning horizon for system design (~20–100 years; *Ekström* et al., 2005). Most climate models are in a relatively good agreement concerning increases in the frequency and intensity of heavy precipitation events under enhanced greenhouse gas concentrations over many land areas of middle and high latitudes, which are projected in both Global Climate Models (GCMs; *Kharin* and *Zwiers*, 2005; *Barnett* et al., 2006; *Tebaldi* et al., 2006; *Kendon* et al., 2010) and Regional Climate Models (RCMs) over Europe (*Frei* et al., 2006; *Buonomo* et al., 2007; *Beniston* et al., 2007; *Fowler* et al., 2007; *Boberg* et al., 2009; *Nikulin* et al., 2011; *Hanel* and *Buishand*, 2011), the latter enabling a construction of GCM-consistent climate change scenarios with more regional detail and better representation of processes leading to heavy precipitation. However, the changes simulated by RCMs in Central Europe (e.g. *Kyselý* and *Beranová*, 2009) are less conclusive in this area than, for example, in the Mediterranean region and northern Europe (*Pal* et al., 2004; *Frei* et al., 2006).

Although floodings in Central Europe may result from both short-term heavy precipitation from convective storms and extended periods of widespread precipitation from large-scale cloud belts associated with persistent low pressure systems (in winter and early spring, another cause of flooding may also be rapid snow melt or 'rain-on-snow' events as classified by *Merz* and *Blöschl*, 2003), the most devastating floods that affect large areas are usually associated with multi-day precipitation events (e.g. *Dubicki* et al., 2005; *Mayes* et al., 2006). That is why heavy 5-day precipitation amounts are frequently considered measures of the occurrence of floods in climate model studies (e.g. *Christensen* and *Christensen*, 2003; *Pal* et al., 2004; *Gao* et al., 2006; *Boroneant* et al., 2006; *Hanel* and *Buishand*, 2011), and they are examined as approximation to flood-generating precipitation extremes also in the present analysis.

The study evaluates climate-change scenarios of 5-day precipitation extremes over the Czech Republic in high-resolution RCM simulations from the EU-FP6 ENSEMBLES project, for two time slices corresponding to the 'near future' (2020–

–2049) and the late 21st century (2070–2099). In order to get more robust spatial patterns of high precipitation quantiles, regional frequency analysis (the region-of-influence method, briefly introduced in Section 2.3) is adopted for the estimation of extreme value distributions. The results are also compared with those for 1-day precipitation extremes evaluated by *Kyselý* et al. (2011b).

2. Data and methods

2.1 Regional climate models

Regional climate models (RCMs) are the most frequently used tools for simulating climate change scenarios at subcontinental and regional levels (IPCC, 2007). This is because the coarse grid scale of GCMs has severe limitations with respect to the simulation of mesoscale processes and the representation of orography and land-sea distribution. RCMs are driven by outputs from a GCM with a coarser resolution, and allow for regional details and local peculiarities to be captured, although they are not capable of correcting biases in large-scale forcing fields inferred from the driving GCM.

RCMs have undergone a rapid development in recent years and have been increasingly used to examine climate variations at scales that are not resolved by global models. A relatively large number of European meteorological offices and research institutions operate RCMs and perform control climate simulations (based on present climate conditions) and climate change experiments; these activities were supported within several large European projects over the past decade, including PRUDENCE (http://prudence.dmi.dk, 2000–2005), ENSEMBLES (http://ensembles-eu.metoffice.com, 2004–2009) and CECILIA (http://www.cecilia-eu.org, 2006–2009). Although surface air temperature and precipitation amounts have been the variables most frequently examined in outputs of climate models, increasing attention has been paid to their extreme values (*Fowler* and *Ekström*, 2009; *Pongracz* et al., 2009; *Ballester* et al., 2010; *Lenderink*, 2010).

2.2 Variables and RCMs under study

We examine seasonal maxima of 5-day precipitation amounts, separately in winter (DJF) and summer (JJA), in 12 RCM simulations with the resolution of 0.22° (25 km). This ensemble includes 7 RCMs (HadRM3, CLM, RCA, HIRHAM, RACMO, RegCM, and REMO) driven by 4 GCMs (ECHAM5, HadCM3 – 3 ensemble members with low, normal and high sensitivity, BCM, and Arpege). All RCM data come from the ENSEMBLES project database (http://ensemblesrt3.dmi.dk). The scenarios are evaluated for the 'near future' (2020–2049) and the late 21st century (2070–2099) with respect to the control period 1961–1990. All scenarios are taken as time slices from transient runs under the SRES A1B emission scenario (IPCC, 2007).

The area under study, including its orography, is shown in Fig. 1.

2.3 Methodology of regional extreme value analysis

The region-of-influence method (e.g. *Burn*, 1990; *Gaál* and *Kyselý*, 2009) is applied as a pooling scheme when estimatinq high quantiles. In contrast to a regional frequency analysis based on fixed regions (cf. *Kyselý* and *Picek*, 2007 for the Czech Republic; *Gaál* et al., 2009 for Slovakia), the regions are defined in a flexible way. Each gridbox has its own region, a unique set of similar gridboxes from which information is taken when fitting an extreme value distribution in a given gridbox. Weights are assigned to data from individual gridboxes in a region according to a dissimilarity measure based on distance from the target gridbox (i.e. the gridbox for which the estimation is made), and all (weighted) regional data are employed when estimating model parameters and high quantiles. The regions are formed so that the 'homogeneity' condition (cf. *Hosking* and *Wallis*, 1997) is met, i.e. one may assume that the distributions of extremes in a region are identical apart from a gridbox-specific scaling factor. The target size of the regions satisfies the 5*T*-rule (*Jakob* et al., 1999) for long return period T = 200 years, and the regional homogeneity is tested by a built-in test of *Lu* and *Stedinger* (1992). More details on the method and settings are given in *Kyselý* et al. (2011b).

The Generalized Extreme Value (GEV) distribution and the method of L-moments are applied to estimate the high quantiles of 5-day precipitation amounts; we focus on 20-yr to 100-yr return levels. Uncertainty of the estimates (the 90% and 80% confidence intervals) is obtained from parametric bootstrap (cf. *Hosking* and *Wallis*, 1997).

The region-of-influence method leads to spatial patterns of projected changes in extremes that are smoothed compared to those estimated at the gridbox scale, i.e. by means of the extreme value analy-

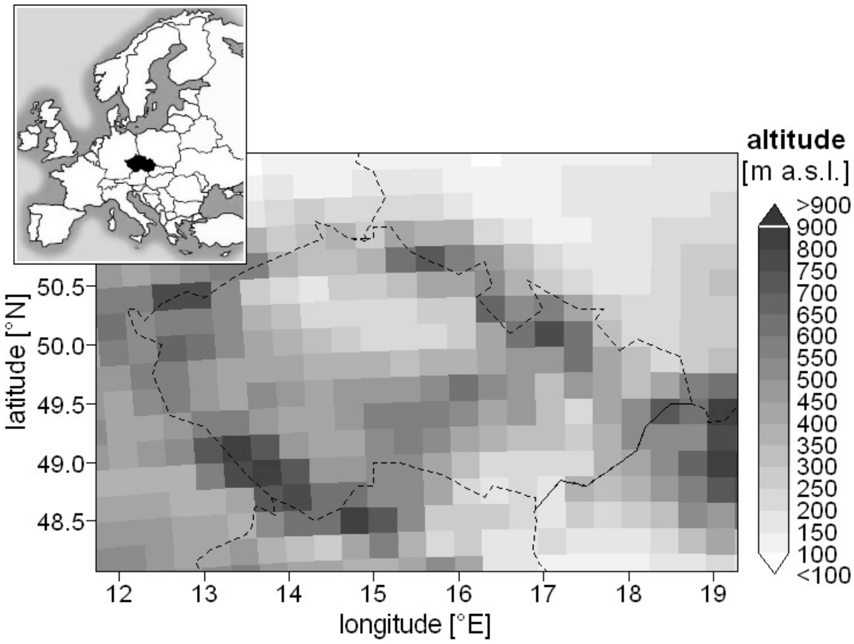

Fig. 1. Area under study.

sis for each gridbox separately (*Kyselý* et al., 2011b), and it is particularly advantageous in areas with complex orography in which fixed homogeneous regions may be difficult to delineate, which is also the case of Central Europe.

3. Results

3.1 Winter (DJF)

Widespread significant increases in the 20-yr return precipitation are projected over the examined area for the late 21st century (2070–2099) in most RCMs (Fig. 2). In two RCMs only, RCA driven by BCM and HIRHAM driven by Arpege, the changes are little pronounced and increases and decreases are approximately balanced. On the other hand, in 5 RCMs the projected increases make at least 20% if averaged over the area (Tab. 1). The magnitude of the projected increase in characteristics of 5-day winter precipitation depends little on the quantile of the distribution, and it is close to 18% for the 20-yr to 100-yr return levels as well as for mean seasonal precipitation (Tab. 1).

Projected changes in the 20-yr to 100-yr return levels of 5-day winter precipitation are much less pronounced for the near future time slice (2020–2049); the spatial patterns are substantially influenced by random variability, and larger areas with significant positive changes appear in 4 RCMs only (not shown). The average increase is close to 4% for the 20-yr to 100-yr return values, which is approximately half of that of mean precipitation (Tab. 1).

3.2 Summer (JJA)

Projected changes in the 20-yr return precipitation for the late 21st century are spatially less uniform and less often significant in summer, but increases prevail in most RCMs (Fig. 3). If averaged over the area, declines in the 20-yr, 50-yr and 100-yr precipitation are found for 1 RCM only (Tab. 1). This is particularly interesting compared to the projected change in mean summer precipitation, which shows declines in 9 out of the 12 RCMs (Tab. 1). The magnitude of the simulated changes has a clear tendency to rise with the quantile of the distribution, as demonstrated for the 20-yr to 100-yr return levels in Tab. 1, and also for lower quantiles in Fig. 4. The changes are mostly negative up to the 95% quantile, and positive for the uppermost tail of the distribution only.

Projected changes in 20-yr to 100-yr return precipitation are smaller for the near future time slice (2020–2049), but increases prevail already in this time interval (bottom row of Tab. 1), and in contrast to the late 21st century, they are larger in summer than winter.

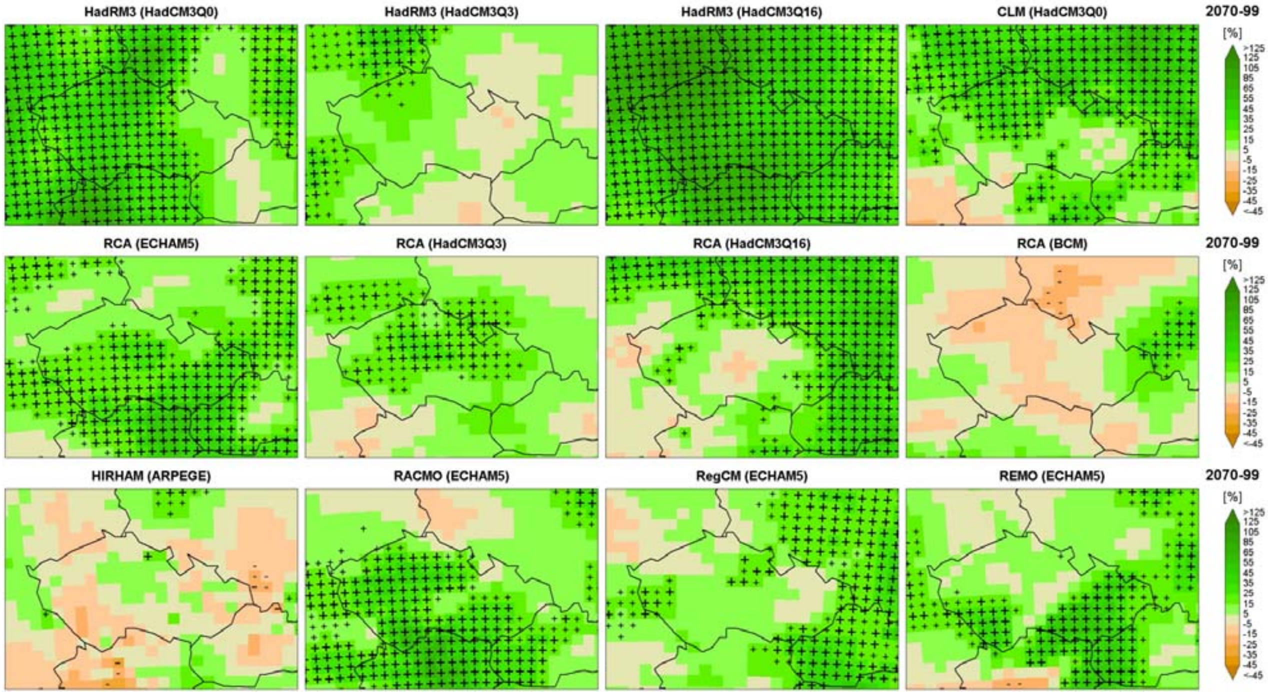

Fig. 2. Relative changes (in %) in 20-yr return values of 5-day precipitation between the late 21st century (2070–2099) and the control climate (1961–1990) in 12 RCM simulations in winter (DJF). Larger (smaller) +/– indicates gridboxes in which the estimated 90% (80%) confidence intervals of the 20-yr return values do not overlap.

T a b l e 1. Mean relative changes (in %) in seasonal precipitation amounts and high quantiles (20-yr, 50-yr, and 100-yr return values, r.v.) of 5-day precipitation for the late 21st century (2070–2099), averaged over gridboxes in the area 11.8–19.0°E, 48.0–51.5°N. Average over the 12 RCMs is shown in the last two rows for two time slices.

	Winter (DJF)				Summer (JJA)			
RCM (driving GCM)	Seasonal	20yr r.v.	50yr r.v.	100yr r.v.	Seasonal	20yr r.v.	50yr r.v.	100yr r.v.
HadRM3 (HadCM3Q0)	32.5	30.4	29.4	28.8	–25.3	0.4	0.9	0.8
HadRM3 (HadCM3Q3)	2.8	8.6	11.3	13.6	–22.6	0.9	13.9	25.7
HadRM3 (HadCM3Q16)	21.9	54.3	56.9	58.8	–29.0	3.4	5.2	6.1
CLM (HadCM3Q0)	18.9	20.0	18.0	16.5	–14.9	29.1	40.3	49.9
RCA (BCM)	20.1	0.6	–3.2	–5.6	5.2	14.0	18.4	21.9
RCA (ECHAM5)	25.7	20.5	21.4	22.0	–6.2	12.4	12.7	12.9
RCA (HadCM3Q3)	14.4	12.3	12.3	12.7	5.2	22.4	27.2	31.2
RCA3 (HadCM3Q16)	17.0	14.4	15.5	16.6	2.3	40.2	51.8	61.5
HIRHAM (Arpege)	4.5	–1.1	–1.4	–1.4	–19.3	–11.4	–14.1	–16.1
RACMO (ECHAM5)	25.5	22.4	22.6	22.9	–6.8	12.3	12.2	12.1
RegCM (ECHAM5)	16.6	12.5	12.6	12.8	–3.9	9.1	7.8	6.6
REMO (ECHAM5)	18.1	16.9	18.3	19.5	–13.3	12.4	15.7	18.5
Average (2070–2099)	18.2	17.7	17.8	18.1	–10.7	12.1	16.0	19.3
Average (2020–2049)	8.8	4.6	4.0	3.7	0.6	7.4	8.9	10.4

3.3 Climate change scenarios taken as average over 11 RCMs

Mean changes in characteristics of the distribution of 5-day precipitation amounts over 11 RCM simulations that use the same grid (leaving out RegCM) are plotted in Fig. 4 and compared with changes in mean seasonal precipitation (summer). The climate change signal is small for the near future (2020–2049), except for a tendency to slight increases in extremes (20-yr to 100-yr return values) over most of the area. For the late 21st century, the patterns look quite different for mean seasonal precipitation and 'lower' quantiles (up to the 95%), for which more or less uniform declines are projected. For the 99% quantile and the extremes, increases clearly prevail (note that in some areas they are found in at least 10 out of the 11 RCMs; marked

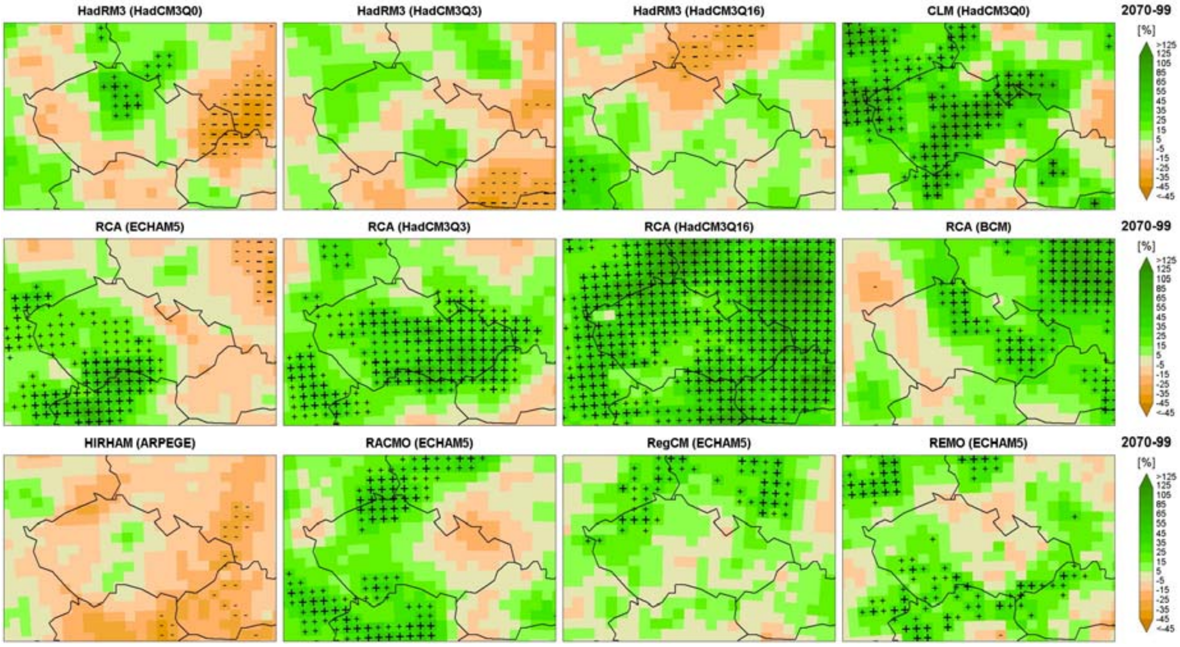

Fig. 3. Same as in Fig. 2 except for summer (JJA).

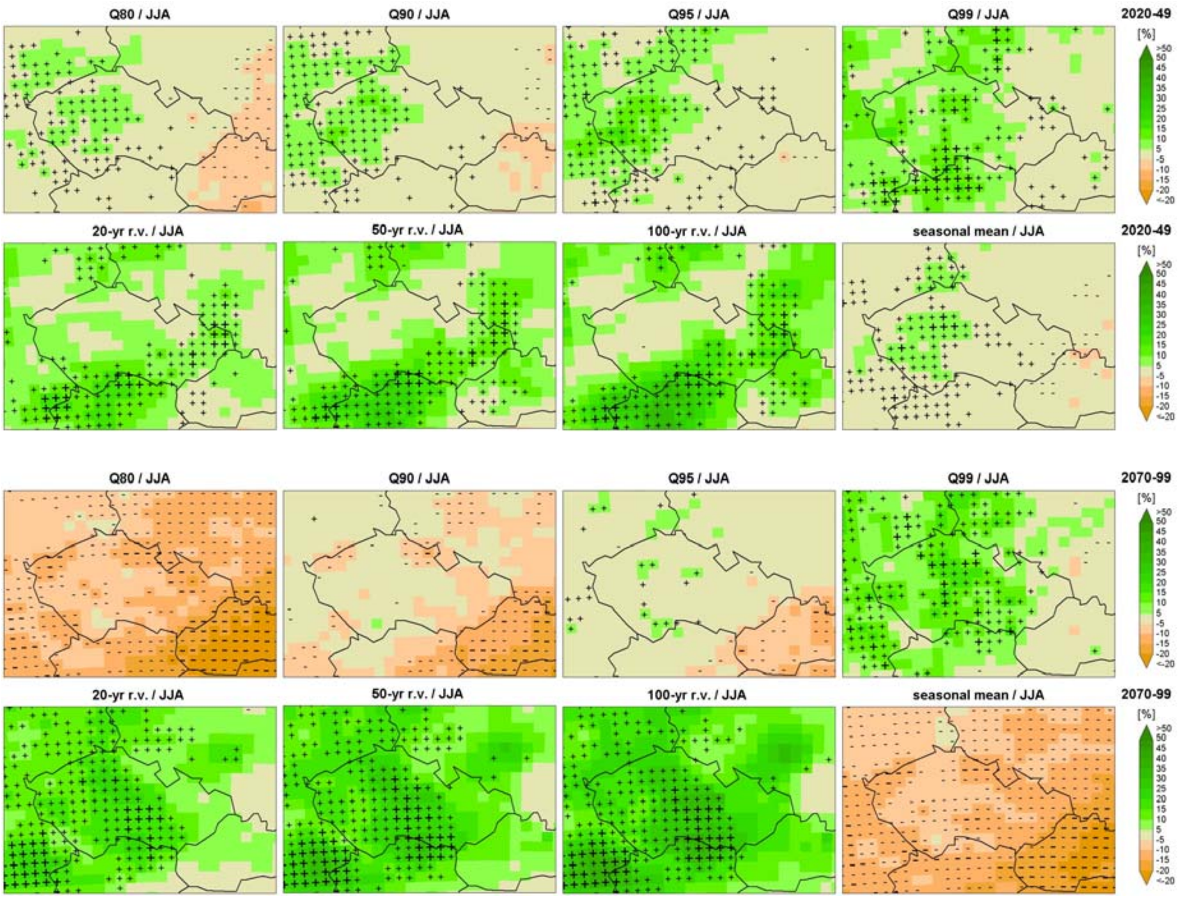

Fig. 4. Mean relative changes in the 80%, 90%, 95% and 99% quantiles (top panels) and the 20-, 50- and 100-yr return values of 5-day precipitation (bottom panels) together with changes in seasonal precipitation totals (bottom right panels) in summer (JJA), averaged over 11 RCMs with the same grid, in 2020–2049 (top) and 2070–2099 (bottom). Larger (smaller) +/– indicates gridboxes in which at least 10 (8) RCMs agree on a given sign of change.

with larger signs + in Fig. 4). They are much more pronounced and the agreement among RCMs is much better in the western than eastern parts of the Czech Republic, which may also have synoptic-climatological interpretation (see Discussion).

Similar patterns do not show any interesting features in winter; the projected increases are more or less uniform over the area (widespread increases for the late 21st century) and very similar for all parts of the distribution (not shown).

4. Discussion and conclusions

4.1 Different patterns of winter and summer changes in flood-generating precipitation extremes

Future scenarios of high quantiles of 5-day precipitation amounts, examined in an ensemble of 12 regional climate model (RCM) simulations over the Czech Republic, show little pronounced increases in winter for the near future time horizon (2020––2049) but widespread significant increases for the late 21st century (2070–2099). The changes affect all parts of the distribution of precipitation amounts in a similar fashion, i.e. the relative increases are very similar for mean winter precipitation and extremes.

In summer, on the other hand, increases in flood-generating precipitation extremes are projected in most RCMs in spite of an overall drying and prevailing declines in mean summer precipitation as well as in all parts of the distribution up to the 95% quantile. Differences among the RCMs are larger in summer, and also the spatial patterns are more affected by sampling variability.

The different patterns of projected changes in winter and summer suggest that while increases in precipitation extremes in winter are related primarily to enhanced water-holding capacity of the (warmer) atmosphere, the patterns of the change are more complex in summer when changes in atmospheric dynamics and land-atmosphere coupling seem to play important roles in modifying precipitation characteristics, including extremes, over Central Europe.

4.2 Decreased role of Mediterranean cyclones in summer floods in Central Europe?

Widespread heavy precipitation events in Central Europe in summer are often related to low pressure systems of a Mediterranean origin, residing over the area (often with a centre located eastward) for several days and associated with upper-air inflow of warm moist air. Since their role in producing heavy precipitation increases towards east, the spatial patterns of projected changes presented for the 20-yr to 100-yr return levels (as well as the 99% quantile) in Fig. 4 suggest that the role of the Mediterranean cyclones in producing heavy precipitation over Central Europe may decrease in a future climate, while the Atlantic influences (more important in the western part of the area) may become more important.

This finding seems to be consistent with declines in cyclonic activity over the Mediterranean, projected in some climate change studies (*Bengtsson* et al., 2006; *Pinto* et al., 2007). However, most studies dealing with changes in cyclonic activity/storm tracks focus on winter, and increases have been reported over Mediterranean in some models in summer (*Löptien* et al., 2008), so the pattern of a possible future change may be complicated. This is even more so if one considers changes in the number of cyclones and their intensity, which are sometimes found to be of opposite direction in climate change projections (*Musculus* and *Jacob*, 2005). *Lionello* et al. (2008) also reported an increase in the number of Mediterranean cyclones in summer but a significant reduction of storm track intensity over the Mediterranean region during late summer and autumn. The results are obviously dependent on the climate model and large uncertainties in the future projections remain.

4.3 Towards more severe dry and wet extremes in summer

The projected changes in precipitation extremes in summer tend to be of the opposite sign than changes in mean seasonal totals; increases in the 20-yr to 100-yr return precipitation are coupled with declines in mean seasonal precipitation in 8 out of the 12 RCMs, and in all RCMs, there is a clear tendency to larger (more positive) changes in extremes than seasonal mean in summer (Tab. 1). This indicates an important change in the distribution function of daily precipitation in summer, which is also presented in Fig. 5: while the amount of precipitation falling as low (up to the 75% quantile of the distribution of daily amounts, as defined in the control climate) and moderate (from the 75% quantile up to the 95% quantile) declines in most RCM simulations in the late 21st century scenario, the fractions corresponding to heavy precipitation (95% to 99% quantile) change only little, and extreme precipitation (above the 99% quantile) increases in all RCMs except for HIRHAM.

A combination of enhanced precipitation extremes and reduced water infiltration capabilities of a dry soil may increase peak river discharges and flood-related risks, and consequently, poses demands on more elaborated flood warning systems (*Hlavčová* et al., 2004, 2005).

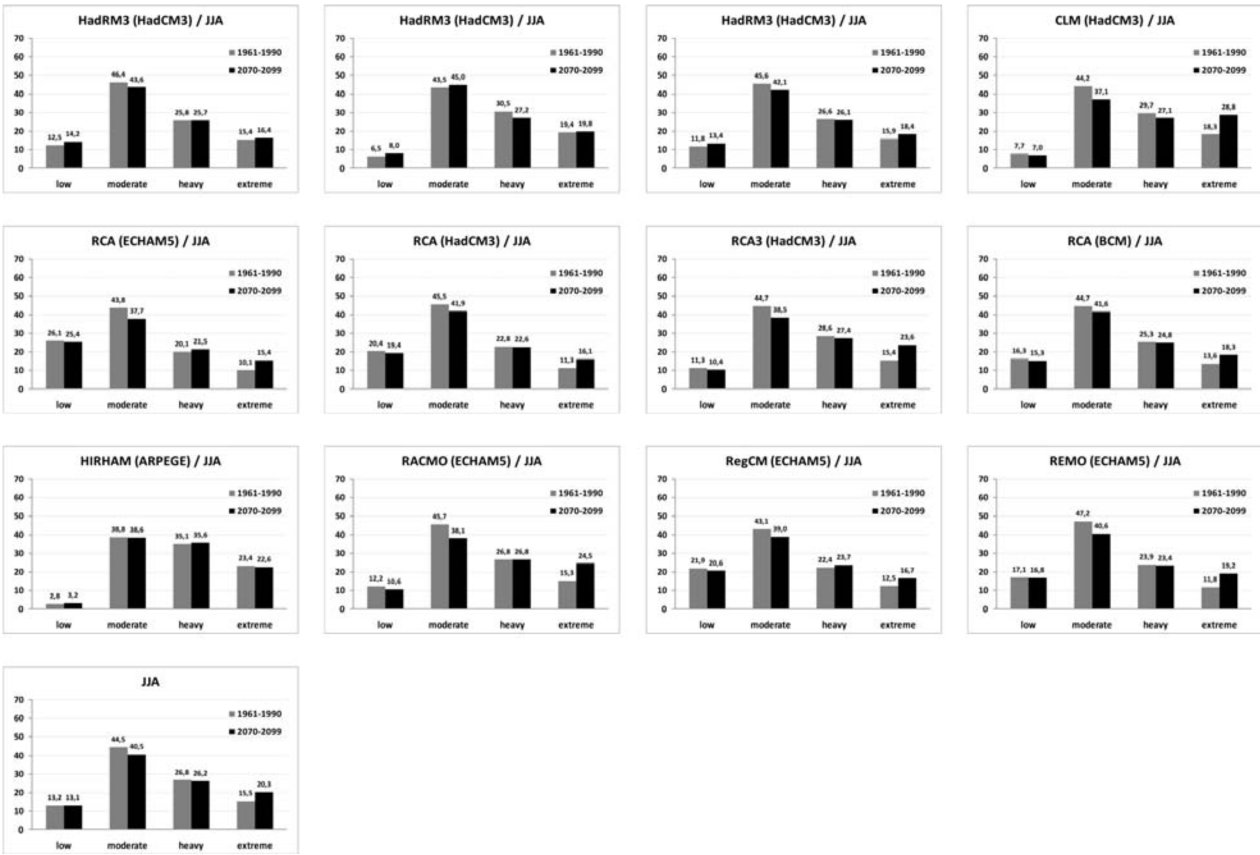

Fig. 5. Projected changes in the percentage of precipitation falling on days with low (up to the 75% quantile of the distribution of daily amounts defined in the control climate), moderate (75% to 95% quantile), heavy (95% to 99% quantile) and extreme precipitation (above the 99% quantile) for the late 21st century in summer. Data are averaged over gridboxes in the area 11.8–19.0°E, 48.0–51.5°N.

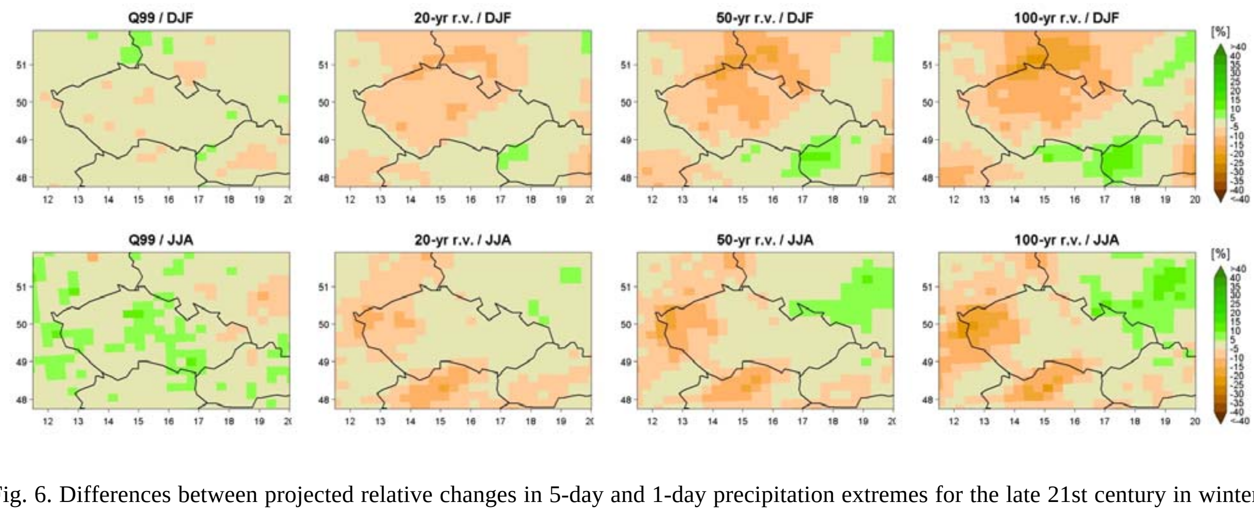

Fig. 6. Differences between projected relative changes in 5-day and 1-day precipitation extremes for the late 21st century in winter (top) and summer (bottom), averaged over 11 RCMs with the same grid.

4.4 Comparison with projected changes in daily precipitation extremes

Differences between the projected changes in characteristics of 5-day precipitation amounts and those of daily amounts are shown in Fig. 6 (for the late 21st century time slice). Increases are slightly smaller for 5-day precipitation extremes than short-term daily extremes over most of the area, particularly the western part. However, the tendency to enhanced heavy precipitation events in the climate change scenario is similar for one-day and multi-day amounts in both seasons. This may suggest that the change in precipitation concerns both short-term events (predominantly of convective origin in summer) and multi-day precipitation (associated with persistent synoptic disturbances).

Since the database of climate model outputs contains precipitation data on the sub-daily scale (daily maxima of hourly amounts) as well, it may be interesting to look at a wider range of time scales in follow-up studies on precipitation extremes in RCMs, although some studies reported large deviations from reality of simulated hourly precipitation extremes in RCMs which may question projected changes in these extremes (*Hanel* and *Buishand*, 2010).

4.5 Inter-model variability and related uncertainties

Presented results for the scenarios of possible changes in flood-generating precipitation extremes over the Czech Republic in the ensemble of 12 RCMs highlight large inter-model variability and associated uncertainty. The inter-model spread is similar in winter and summer: projected changes, averaged over the examined area, range from –1% to +54% (–6% to +59%) for the 20-yr (100-yr) return values in winter, and from –11% to +40% (–16% to +60%) for the 20-yr (100-yr) return values in summer.

However, the inter-model spread represents only a part of the true uncertainty. One has to keep in mind that all RCM simulations in the ensemble were run under a single radiative forcing corresponding to the SRES A1B scenario, which represents only one possible ‘path’ of development of greenhouse gas emissions in the 21st century (*IPCC*, 2007). Another source of uncertainty stems from the fact that most RCMs are driven by 2 GCMs only, HadCM3 (6 RCMs) and ECHAM5 (4 RCMs), so the RCM-GCM matrix is quite incomplete and asymmetric. It should be noted that the two remaining RCM simulations, driven by BCM and Arpege, yield relatively minor changes in precipitation extremes in both winter and summer (Tab. 1; in winter, they are the only RCMs which project declines in the 50-yr and 100-yr return precipitation), hence the ensemble-average change may look very different if more RCM simulations driven by other GCMs than HadCM3 and ECHAM5 are available. Last but not least, biases in reproducing precipitation characteristics in climate models, related also to deficiencies of the parameterizations used to represent convective processes, contribute to the uncertainties of the climate change scenarios.

Future studies should also concentrate on the identification of physical mechanisms responsible for the projected changes in precipitation characteristics, such as changes in circulation patterns, cyclonic activity and storm tracks, etc. The examined ensemble suggests that the uncertainty of future changes in precipitation characteristics over Central Europe remains large, particularly in comparison to changes projected in northern and western Europe (prevailing increases in precipitation) and the Mediterranean (drying).

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