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RUNOFF SENSITIVITY TO CLIMATE WARMING: A PROCESS STUDY WITH A COUPLED CLIMATE-RUNOFF MODEL

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1. INTRODUCTION

The consequences of extreme runoff and extreme water levels are within the most important natural hazards induced by weather. The question about the impact of global climate change on the runoff regime, especially on the frequency of floods, is of utmost importance.

In winter-time, two possible climate effects could influence the runoff statistics of large Central European rivers: the shift from snowfall to rain as a consequence of higher temperatures and the increase of heavy precipitation events due to an intensification of the hydrological cycle (e.g. Frei et al 2000, IPCC 2001, Trenberth 1999). The combined effect on the runoff statistics is examined in this study for the river Rhine. To this end, sensitivity experiments with a model chain including a regional climate model and a distributed runoff model are presented. The experiments are based on an idealized surrogate climate change scenario (Schär et al 1996). It should be stressed that this study does not provide a full climate change scenario but merely an analysis of relevant nonlinearities and sensitivities. In addition to these sensitivities, climate change would also imply changes in synoptic climatology that are not considered in this study.

2. THE MODEL CHAIN AND EXPERIMENT SETUP

The model suite consists of the regional climate model CHRM and the distributed runoff model WaSiM. The regional climate model CHRM is based on the mesoscale weather prediction model HRM of the German Weather Service (DWD) and has been adapted for climate simulations (Vidale et al). The CHRM is being used in a nested mode with horizontal grid spacings of 56 km and 14 km (hereafter called CHRM56 and CHRM14). The distributed runoff model WaSiM is operated at a horizontal grid spacing of 1 km for the whole Rhine basin down to Cologne, covering about 145’000 km^2. WaSiM is a distributed, gridbased runoff model using physically based algorithms like the Richard’s equation. The entire model suite covers scales of more than two orders of magnitude.

The coupling of the models is purely one-way, i.e. from the large to the small scale. It is provided by the downscaling of the climate model fields (precipitation, temperature, radiation, humidity, and wind) to the resolution of the distributed runoff model. Downscaling of precipitation fields is done according to Widmann & Bretherton (2000) using a high resolution precipitation climatology and the downscaling of temperature fields is done using the vertical temperature gradient provided by the climate model and the fine-scale topography.

The boundary conditions for the regional climate model are taken from the original ECMWF reanalysis and from a modified version representing the surrogate scenario, both at a horizontal resolution of approximately 120 km (T106). The scenario of a warmer climate (hererafter called WARM, the control simulation is called CTRL) consists of driving fields with a uniformly increased temperature of 2 Kelvin and therefore an increased atmospheric humidity of about 15%. Such a temperature shift can be formulated consistently with the governing equations (Schär et al 1996), and the methodology has earlier been applied by Frei et al (1998). The simulations cover the five winter seasons 1989/90 till 1993/ 94, each from November until January.

The model chain is described in detail in Kleinn et al. (2003) in this volume.

3. VALIDATION OF THE MODEL CHAIN

A detailed validation of the model precipitation is done using the precipitation climatology of Frei and Schär (1998), that uses approximately 6’000 daily precipitation measurements.

The model chain is capable of reproducing the interannual variability of precipitation as well as its finescale distribution. Deviations to the observations can be found in the altitudinal distribution of precipitation and in the precipitation distribution along mountains.

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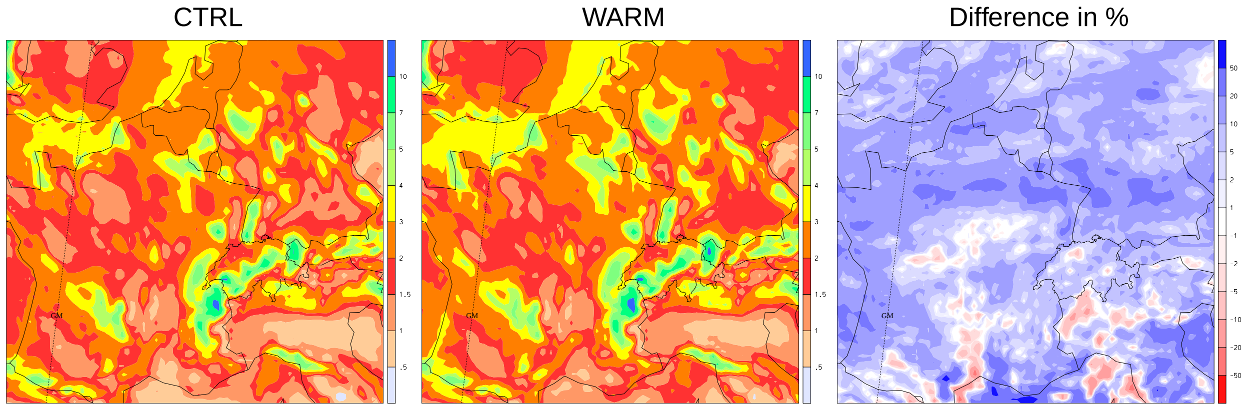

Figure 1: Mean daily precipitation in mm, CTRL, WARM, and difference in %. Mean change in the Rhine Basin: +11%.

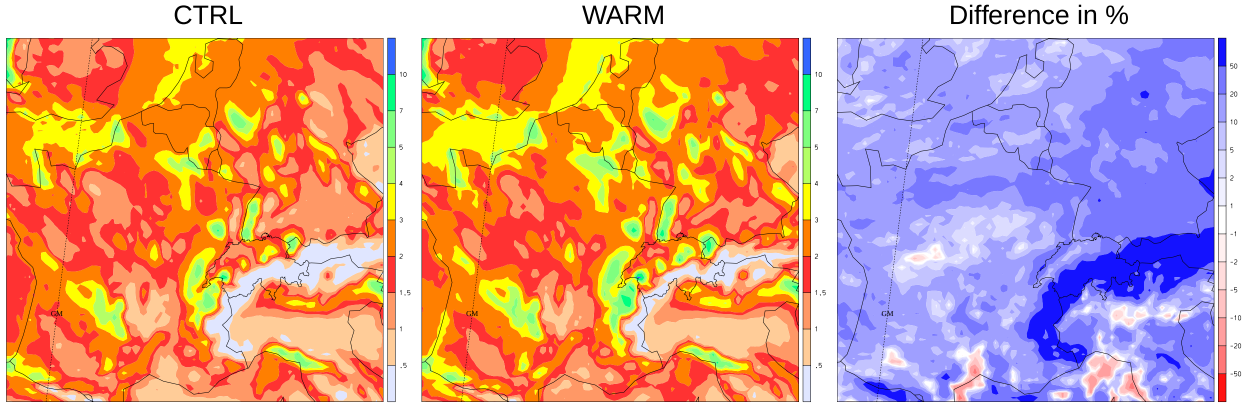

Figure 2: Mean daily liquid precipitation in mm, CTRL, WARM, and difference in %. Mean change in the Rhine Basin: +26%.

The runoff simulations correspond well with observations for foreland subbasins and for the whole Rhine basin. The yearly cycle in monthly discharge as well as the statistics of daily runoff values show good correspondence between simulation and observation. The runoff simulations of the alpine subbasins still show some deficiencies.

A more detailed description of the validation can be found in Kleinn et al. (2003) in this volume.

4. PRECIPITATION IN A WARMER CLIMATE

The precipitation pattern in WARM is very similar to the precipitation pattern of CTRL (Figure 1). WARM shows an increase in winter time precipitation of more than 10% in most parts of Europe (Figure 1). A slight decrease in winter time precipitation can be observed in central and southern France, south of the Alps, and in the Swiss middle land. The increase in daily precipitation for the whole Rhine basin and for the main tributaries is shown in Table 1. The increase in precipitation is smallest in the alpine Aare basin (7 %).

With an increase in temperature, precipitation is more likely to reach the surface as rainfall compared to snowfall. For an analysis of the changes in the wintertime hydrologic cycle, it is important to consider the changes in liquid precipitation separately. WARM shows an increase in liquid precipitation by more than 20% in most parts of Europe (Figure 2). In the Alps, the increase in liquid precipitation even exceeds 50%. The changes in liquid precipitation for the whole Rhine basin and for the main tributaries is shown in Table 1.

The increase in precipitation is mainly due to an intensification of precipitation events. The frequency of rain days within the Rhine basin changes very little while the frequency of days with more than 20 mm precipitation increases by about

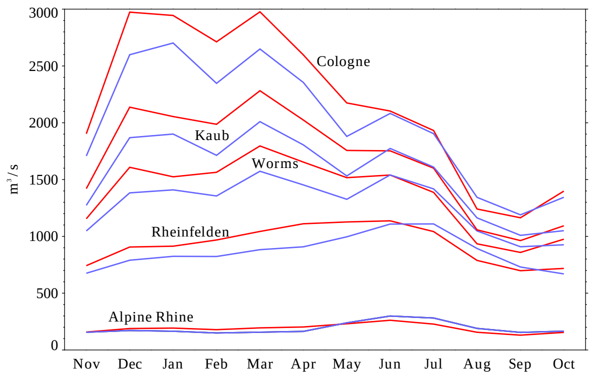

Figure 4: Mean monthly discharge from CTRL (blue) and WARM (red) simulations driven by CHRM56.

25% (Figure 3). The stronger increase in the frequency of intense precipitation events agrees with the considerations of a stronger hydrologic cycle by Trenberth (1999) and to theoretical considerations about increased intensity of precipitation events by Fowler and Hennessy (1995). RCM simulations Frei et al. (1998) with the same surrogate climate change scenario by Schär et al. (1996) and GCM simulations of 2xCO_2 scenarios analyzed by Hennessy et al. (1997) found similar results of increased frequency of strong precipitation events.

5. RUNOFF IN A WARMER CLIMATE

The runoff regime of the Rhine river changes in the simulations of a warmer climate (Figure 4). All along the Rhine basin, the monthly mean discharge decreases in late summer and early fall and increases in winter. The shift from summerly to winterly and spring discharge in the Alpine catchments can be explained, on the one hand, by less snowfall, more rainfall, and more frequent melt events in winter leading to higher runoff in winter and, on the other hand, by lower runoff in summer due to less snow melt and due to less precipitation.

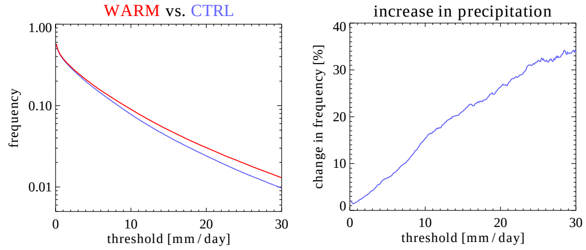

Figure 3: Change in precipitation intensity in a warmer climate in the Rhine basin, WARM (red) vs. CTRL (blue), difference in %.

Basin	Difference of WARM and CTRL					
	Precip.		Liquid Precip.		Runoff	
	mm	%	mm	%	mm	%
Aare	0.25	7	0.73	40	-0.06	-3
Neckar	0.37	17	0.53	28	0.35	27
Main	0.25	10	0.46	21	0.14	13
Mosel	0.34	14	0.46	21	0.33	18
Rhine to Cologne	0.30	11	0.55	26	0.14	10

Table 1: Changes in total precipitation, liquid precipitation and runoff, WARM vs. CTRL in mm/day and %.

The relative change in discharge is similar all over the Rhine basin. Summerly discharge is reduced by about 5% while winterly discharge increases by 10% - 15%. Whereas the increase of winterly discharge leads to a shift in the yearly runoff regime in the Alpine catchments, it leads to an increase of the yearly cycle downstream.

The changes in total amount of winterly discharge are smallest in the alpine Aare basin and biggest in the Neckar (Table 1). For the whole Rhine basin down to Cologne, the increase in winterly discharge amounts to about 10%. These results match the increase in total precipitation in the different subbasins, which is also smallest in the Aare and largest in the Neckar (Table 1).

The changes in summertime runoff are smaller than those in winter time. Furthermore, it has to be kept in mind, that it is uncertain, whether the method used for WARM is a suitable scenario for summer time. We therefore concentrate on winter time runoff in the following considerations.

The changes in the winterly runoff frequencies (Figure 5) in the foreland subbasins show little sensitivity to the model driving the runoff simulation. The changes in runoff frequencies are similar for the runoff simulations driven by CHRM56 and for those driven by CHRM14, even though the absolute values of the runoff frequencies are different.

In the alpine Aare basin, the frequency of small runoff events decreases while the frequency of

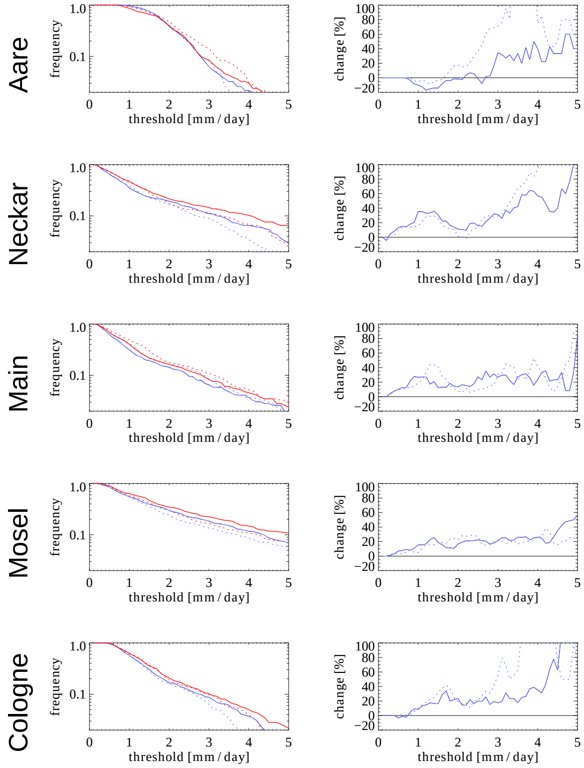

Figure 5: Change in runoff intensity in a warmer climate in the Neckar and Main basins, WARM (dotted) vs. CTRL (dashed), difference in %.

strong runoff events increases. In the foreland basins, the frequency of runoff events increases for all of the runoff events. The frequency of strong runoff events though increases more than the frequency of small runoff events. For the foreland basins and for the whole Rhine basin, the frequency of runoff events with more than about 1 mm/day increases by about 20%.

6. CONCLUSION

To asses the influence of a warmer climate to the regional hydrology, coupled climate-runoff simulations were performed. The model chain is capable of reproducing the interannual variability of precipitation as well as its finescale distribution and the runoff.

The sensitivity experiments of a warmer climate with the CHRM show an increase in precipitation and an increase in the number of strong precipitation events. Due to warmer conditions, a shift from snowfall to rain occurs. These signals in precipitation significantly influence the runoff statistics resulting in higher winter discharge, a longer duration and/or a larger number of high winter runoff events.

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