



Projected changes in Rhine River flood seasonality under global warming

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Abstract. Climatic change alters the frequency and intensity of natural hazards. In order to assess potential future changes in flood seasonality in the Rhine River Basin, we analyse changes in streamflow, snowmelt, precipitation, and evapotranspiration at 1.5, 2.0 and 3.0 °C global warming levels. The mesoscale Hydrological Model (mHM) forced with an ensemble of climate projection scenarios (five general circulation models under three representative concentration pathways) is used to simulate the present and future climate conditions of both, pluvial and nival hydrological regimes.

Our results indicate that the interplay between changes in snowmelt- and rainfall-driven runoff is crucial to understand changes in streamflow maxima in the Rhine River. Climate projections suggest that future changes in flood characteristics in the entire Rhine River are controlled by both, more intense precipitation events and diminishing snow packs. The nature of this interplay defines the type of change in runoff peaks. On the sub-basin level (the Moselle River), more intense rainfall during winter is mostly counterbalanced by reduced snowmelt contribution to the streamflow. In the High Rhine (gauge at Basel), the strongest increases in streamflow maxima show up during winter, when strong increases in liquid precipitation intensity encounter almost unchanged snowmelt-driven runoff. The analysis of snowmelt events suggests that at no point in time during the snowmelt season, a warming climate results in an increase in the risk of snowmelt-driven flooding. We do not find indications of a transient merging of pluvial and nival floods due to climate warming.

1 Introduction

The current climate crisis entails changes in the frequency and intensity of natural hazards. Among other things, rising temperatures reinforce heat waves (Meehl and Tebaldi, 2004; Della-Marta et al., 2007; Fischer and Schär, 2010) and dry spells (Blenkinsop and Fowler, 2007; Samaniego et al., 2018b; Grillakis, 2019) and more intense precipitation increases the risk posed by floods and land slides (Dankers and Feyen, 2008; Rojas et al., 2012; Alfieri et al., 2015; Crozier, 2010; Huggel et al., 2012). Fundamental changes are expected in snow-dominated regions; alpine climatic changes go along with declining seasonal snow packs (Steger et al., 2013; Beniston et al., 2018; Hanzer et al., 2018), thawing permafrost (Serreze et al., 2000; Schuur et al., 2015; Elberling et al., 2013; Beniston et al., 2018) and retreating glaciers (Zemp et al., 2006; Huss, 2011; Radić



and Hock, 2014; Hanzer et al., 2018). Those cryospheric changes, in turn, impact water availability in and outside mountain areas (Barnett et al., 2005; Stewart, 2009; Junghans et al., 2011; Viviroli et al., 2011). The European Alps, for example, are the source region of numerous large rivers that form the basis of the economic and cultural development in various cities and communities (Beniston, 2012).

5 Recent studies suggest that rapid climatic changes have already altered flood characteristics in river systems across Europe. For example, Blöschl et al. (2019) indicate that during 1950–2010, increasing rainfall and soil moisture led to higher river flood discharges in northwestern Europe, while decreasing rainfall together with higher evapotranspiration rates decreased flood discharge in southern parts of the continent. Detected trends in flood magnitudes seem to align with trends in the spatial extent of the floods (Kemter et al., 2020). A further distinction of floods depending on return period and catchment area enables
10 a detailed investigation of processes generating floods (Bertola et al., 2020). Most important mechanisms driving flooding in Europe are extreme precipitation, snowmelt and soil moisture excess (Berghuijs et al., 2019).

In large and diverse river basins, such as the the Rhine River Basin, all relevant mechanisms generating riverine floods can be detected. The southern part of the basin is influenced by snowmelt from the Alps and therefore commonly classified as nival (Belz et al., 2007; Speich et al., 2015). The runoff of a nival hydrological regime is primarily controlled by the accumulation
15 and melt of a seasonal snow cover. Hence, runoff is low during winter and high during summer. The main tributaries of the Rhine River are rainfall-dominated. Runoff is high during winter and low during summer. Flooding in the rainfall-dominated tributaries usually occurs in winter and is driven by large-scale advective precipitation (Pfister et al., 2004; Bronstert et al., 2007).

Investigating changes in runoff seasonality and flood-generating mechanisms is important to assess challenges in future
20 water resources management. Previous investigations conducted in Switzerland (e.g., Horton et al., 2006; Addor et al., 2014; Brunner et al., 2019), Austria (e.g., Kormann et al., 2015, 2016; Hanzer et al., 2018), Norway (e.g., Vormoor et al., 2015, 2016) or the United States (e.g. Brunner et al., 2020a, b) point at changes in snowmelt- and rainfall-generated runoff. For the Rhine River, studies have indicated that changes in both nival and pluvial flow alter hydrological regimes and their high/low flow characteristics (e.g., Middelkoop et al., 2001; Belz et al., 2007; Hurkmans et al., 2010; Huang et al., 2013; Alfieri et al.,
25 2015; Stahl et al., 2016; Thober et al., 2018; Marx et al., 2018; Huang et al., 2018). Projections of discharge attained using hydrological models proved key in the attempt to assess the impact of climatic changes.

The aim of the present study is to investigate future changes in rainfall- and snowmelt-induced flooding in the Rhine River. We use the mesoscale Hydrologic Model (mHM; Samaniego et al., 2010; Kumar et al., 2013) forced with an ensemble of climate projection scenarios (five general circulation models under three representative concentration pathways) to assess
30 projected changes in streamflow, snowmelt, rainfall and evapotranspiration characteristics under 1.5, 2.0, and 3.0 °C global warming. Special focus is on the hypothesis of a transient merging of nival and pluvial flow regimes by climate change, which suggests that in a warmer world, earlier snowmelt-induced floods originating from the Alps might superimpose with more intense rainfall-induced runoff from pluvial-type tributaries, creating a new flood type with potentially disastrous consequences (Fig. 1).

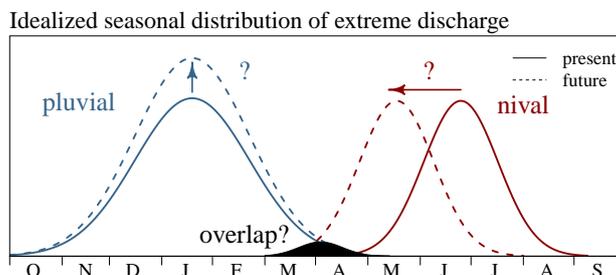


Figure 1. Idealised seasonal distribution of nival and pluvial flood frequencies and potential overlap due to climate change.

2 Data and Methods

The mesoscale hydrologic model (mHM) v.5.10 (Samaniego et al., 2010; Kumar et al., 2013; Samaniego et al., 2018a) is used to detect and assess projected changes in Rhine River floods under future climate conditions (Fig. 2 and 3). mHM is a spatially distributed hydrologic model based on grid cells. Key feature of mHM is the Multiscale Parameter Regionalization (MPR) technique, which allows to account for subgrid variability (Samaniego et al., 2010, 2017). During MPR, high resolution physiographic land surface descriptors are translated into model parameters. A detailed description of the two phases of MPR, i.e., regionalization and upscaling, is given in Samaniego et al. (2010). In the framework of this study, the high resolution physiographical datasets describing the main features of the terrain, e.g., digital elevation model, aspect, slope, soil texture, geological formation type, land cover and leaf area index (LAI), are in 500 m resolution. More information on underlying data sources is presented in Rakovec et al. (2016).

Meteorological forcing data of the model consists of daily average, maximum and minimum temperature and precipitation. Observational data sets are based on the E-OBS v12 gridded data sets (Haylock et al., 2008). Climate model data originates from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013a, b; Warszawski et al., 2014). Within ISI-MIP, data from five Global Climate Models (GCMs), i.e., GFDL-ESM2M, HadGEM2-ES, IPSL-CMSA-LR, MIROC-ESM-CHEM, NorESM1-M, were bias corrected and down-scaled to a $0.5^\circ \times 0.5^\circ$ grid. The statistical bias correction is trend-preserving and "adjusts the monthly mean and daily variability of simulated climate data to observations." (Hempel et al., 2013b). GCM data cover the period 1950–2099 and include three representative concentration pathways (RCPs) 2.6, 6.0 and 8.5. In the framework of the project "EDgE - End-to-end Demonstrator for improved decision making in the water sector in Europe" by order of the Copernicus Climate Service (edge.climate.copernicus.eu; Samaniego et al., 2019), meteorological data sets were interpolated to a 5 km grid using external drift kriging (e.g., Thober et al., 2018; Marx et al., 2018; Samaniego et al., 2018b; Wanders et al., 2019).

mHM forced with E-OBS meteorological data is calibrated against observed streamflow at the three gauges Lobith, Basel and Cochem during 1951–1975 using the Dynamically Dimensioned Search algorithm (DDS; Tolson and Shoemaker, 2007) and the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970). In the framework of this multi-basin calibration, we attain one parameter set, which we apply to the entire basin. In order to evaluate the model performance in all important sub-regions

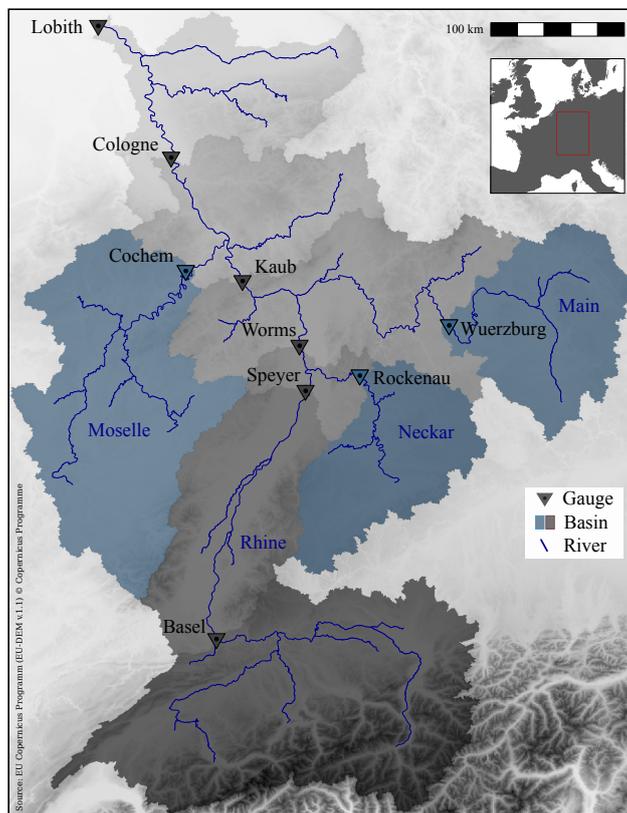


Figure 2. Topographic map of the Rhine River Basin until gauge Lobith with locations of all gauges and sub-basins investigated.

of the entire Rhine River, the mHM performance is evaluated at additional six independent gauges (Fig. 2) and during an independent evaluation period (1976–2000) using the NSE and the Kling-Gupta-Efficiency (KGE; Gupta et al., 2009) (Table 1). Analyses evaluating streamflow simulations for the historic time frame 1951–2000 are given in the Appendix (Fig. A1, B1 and C1). Similar to investigations presented in the supplementary material of Thober et al. (2018), we assess streamflow maxima and the 90 % streamflow quantile of the hydrological year. In addition, we evaluate the timing of annual streamflow maxima and 90 % streamflow quantiles on a monthly basis. All discharge time series are obtained from the Global Runoff Data Centre (GRDC).

The multiscale Routing Model (mRM; Thober et al., 2019) is used for routing river runoff using the adaptive time step scheme (aTS). The kinematic wave equation (Lighthill and Whitham, 1955), a simplification of the Saint-Venant equation (de Saint-Venant, 1871), is solved using a finite difference scheme. The kinematic wave equation only needs little information on the river topography and assess the advection and the attenuation of flood waves. The time step selected within aTS only depends on the spatial resolution and is independent of the temporal resolution of the meteorological forcing. In our model set-up, water is routed through the river network at a temporal resolution of 30 min. The high-resolution river network bases on a 500 x 500 m digital elevation map and is upscaled to operate on a 5 km routing resolution. Within the upscaling process,



Table 1. River gauges investigated: Location (WGS 84), GRDC identification number, catchment area, Nash-Sutcliffe efficiency (NSE) and Kling-Gupta efficiency (KGE) between observed and modelled runoff (NSE / KGE). The model has been calibrated against observation from the three gauges (Lobith, Basel and Cochem) with the NSE objective function during 1951–1975.

Name	GRDC-ID	Lat.	Lon.	Area (km ²)	1951-1975	1976-2000	1951-2000
Lobith	6435060	51.840	6.110	$1.61 \cdot 10^5$	0.91 / 0.93	0.90 / 0.89	0.91 / 0.91
Cologne	6335060	50.937	6.963	$1.44 \cdot 10^5$	0.92 / 0.96	0.92 / 0.94	0.92 / 0.95
Cochem	6336050	50.143	7.168	$2.71 \cdot 10^4$	0.84 / 0.75	0.87 / 0.77	0.85 / 0.77
Kaub	6335100	50.085	7.765	$1.03 \cdot 10^5$	0.90 / 0.90	0.92 / 0.92	0.91 / 0.91
Wuerzburg	6335500	49.796	9.926	$1.40 \cdot 10^4$	0.73 / 0.81	0.79 / 0.84	0.76 / 0.83
Worms	6335180	49.641	8.376	$6.89 \cdot 10^4$	0.85 / 0.87	0.88 / 0.90	0.87 / 0.88
Rockenau	6335600	49.438	9.005	$1.27 \cdot 10^4$	0.75 / 0.74	0.74 / 0.71	0.74 / 0.73
Speyer	6335170	49.324	8.449	$5.31 \cdot 10^4$	0.82 / 0.88	0.86 / 0.90	0.84 / 0.89
Basel	6935051	47.559	7.617	$3.59 \cdot 10^4$	0.71 / 0.83	0.75 / 0.85	0.73 / 0.84

the flow direction in the lower resolution (routing resolution) is equal to the flow direction in the underlying high-resolution grid cell with the highest flow accumulation (Samaniego et al., 2010). The stream celerity is determined as a function of terrain slope (Thober et al., 2019).

All dominant hydrological processes are modelled at 5 km spatial resolution. We estimate reference crop evapotranspiration following the Hargreaves-Samani equation, an empirical approach using minimum climatological data (Hargreaves and Samani, 1985; Samani, 2000). The empirical coefficient of the equation is determined during calibration. The usage of this simple approach enables a consistent set-up across historical and future model space. The actual evapotranspiration is estimated based on the fraction of roots in the soil horizons and a stress factor for reducing potential values calculated based on the actual soil moisture. The stress factor is determined using the Feddes equation (Feddes et al., 1976). If the soil moisture is below the permanent wilting point, evapotranspiration is reduced to zero. In case the soil moisture is above field capacity, the evapotranspiration equals the fraction of roots. If the soil moisture is in between the permanent wilting point and field capacity, evapotranspiration is reduced by the fraction of roots times the stress factor. Our model set-up distinguishes six soil layers up to a total depth of 2 m. Organic matter is possible until 0.3 m. In total, more than 2000 soil types with different clay content, sand content and bulk density are defined. Land surface with impervious cover are treated as free-water surfaces and actual evapotranspiration is estimated with an additional evaporation coefficient. More details of the soil parameterization in mHM can be found in Livneh et al. (2015).

The canopy interception is modelled with a maximum interception approach. The maximum interception capacity is estimated based on the given LAI values. Water can leave the interception storage as throughfall, which is estimated as a function of the current and maximum canopy water content and the incoming precipitation. Evaporation from the canopy storage depends on the current and maximum canopy water content and the potential values of evapotranspiration. We simulated snow



using an empirical degree-day approach, whereas degree-day-factors differ depending on the dominant land use class. In order to account for snowmelt following the energy input from liquid rainfall, degree-day factors are increased depending on the amount of liquid precipitation. Degree-day factors only can increase to a certain threshold value. Surface runoff from impermeous areas is calculated based on a linear reservoir exceedance approach. Interflow from the unsaturated zone is determined
5 using a nonlinear reservoir with saturation excess. Groundwater is assumed as a linear reservoir.

The changes in mHM-based flood seasonality are further differentiated and scrutinised for three different warming levels: 1.5, 2.0 and 3.0 °C. Within each future model run, the 30-year time windows when the warming levels (compared to the historic time window 1971–2000) are reached, are determined. 14 GCM/RCP realisations reach 1.5 °C, 13 reach 2.0 °C, and 8 reach 3.0 °C global warming. A detailed description of the determination of warming levels is given in the supplementary material
10 of Thober et al. (2018). The period 1971–2000 is assumed to be warmer by 0.46 °C compared to pre-industrial levels already.

In order to assess the changes in flood characteristics, we determine the timing and magnitude of annual and monthly maxima of streamflow, precipitation (total and liquid), snowmelt and actual evapotranspiration for the hydrological year starting on the 1st of October (Tab. 2). In case of precipitation, we investigate maxima of 5-day sums (P_{max5}). Previous investigations indicate that precipitation accumulating a couple of days before the event is most relevant for flooding (Froidevaux et al., 2015). For
15 snowmelt and evapotranspiration, we extend this time window to 14 days and assess the magnitude and timing of 14-day sums (S_{max14} and ET_{max14}). We assume that in order to have substantial impact on streamflow, meteorological conditions favouring snowmelt or evapotranspiration need to prevail longer than only a few days. According to our experience, a 14-day window width provides a good estimate to assess potential impacts on streamflow.

In the framework of the analysis, we focus on the three gauges: Basel, Cochem and Cologne (Fig. 3). Selected gauges
20 and sub-basins enable a detailed insight into changes in pluvial and nival processes and changes in the main channel of the Rhine River. Gauge Basel is located at the transition from High to Upper Rhine. The basin upstream gauge Basel encompasses large areas of high alpine character. Snowmelt during spring and early summer is an important runoff/flood-generating process (Wetter et al., 2011; Stahl et al., 2016). Runoff at gauge Cochem (Moselle River) is characterised by a pluvial flow regime with high runoff during winter and low runoff during summer (Fig. 4). Flooding typically occurs in winter and early spring due
25 to large-scale advective precipitation (Pfister et al., 2004; Bronstert et al., 2007). The gauge Cologne is located in the Lower Rhine region after the confluences of the main tributaries Moselle, Neckar and Main (Fig. 2).

In the case of annual maxima, we display the timing and magnitude as boxplots and histograms. The length of the boxplot whiskers is 1.5 times the interquartile range (IQR). However, if no data point exceeds this distance, the whiskers only reach until the minimum/maximum value. The notches extent to $\pm 1.58 \cdot \frac{IQR}{\sqrt{n}}$ with n being the length of the data vector (McGill et al.,
30 1978; R Core Team, 2019). The notches roughly represent 95% confidence intervals for the difference in two medians. For visualisation purposes, we do not display whiskers and outliers of boxplots displaying monthly maxima values. Histograms always depict the probability density and have a total area of one. In order to estimate the importance of snowmelt with regard to runoff peaks, we calculate the ratio between snowmelt the preceding 14 days and snowmelt the preceding 14 day plus precipitation the preceding 5 days (melt fraction). We also determine the average annual cycle of this ratio. In addition

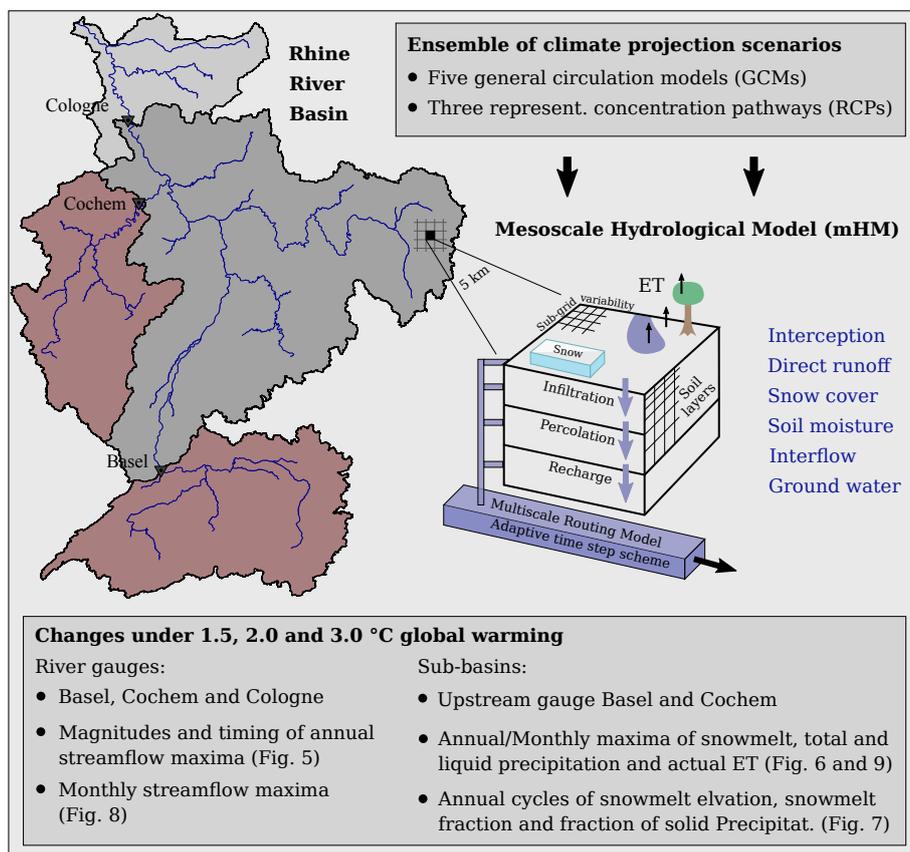


Figure 3. Scheme of the analytical set-up depicting gauges and sub-basins investigated in detail.

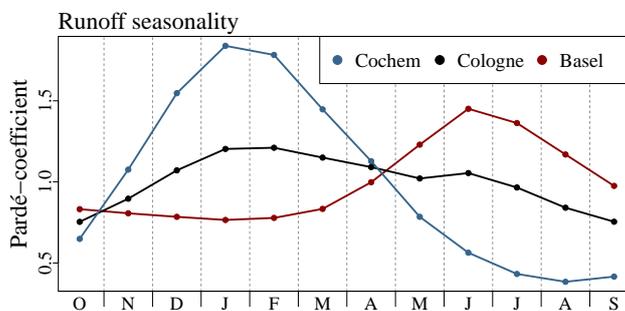


Figure 4. Pardé-coefficients (ratio of average monthly discharge and the mean annual discharge) (Pardé, 1933; Spreafico and Weingartner, 2005) for gauges Cochem, Basel and Cologne calculated based on measured discharge from the time frame 1917 to 2016.

to the average annual cycles of the melt fraction, we calculate the average elevation of the snowmelt and the fraction solid precipitation compared to the total precipitation.



Table 2. Names/Abbreviations and descriptions of variables investigated on sub-basin level.

Variable	Description
P_{max5}	Maximum 5-day precipitation (total or liquid)
S_{max14}	Maximum 14-day snowmelt
ET_{max14}	Maximum 14-day actual evapotranspiration
Melt fraction	Contribution of snowmelt to streamflow estimated as the ration between snowmelt the preceding 14-day and snowmelt the preceding 14 days plus precipitation the preceding 5 days
Melt elevation	Average elevation of snowmelt for a given day
Precip. solid	Solid fraction of precipitation (snowfall)

3 Results

The magnitudes of annual streamflow maxima at gauge Basel increase with rising temperatures (Fig. 5 a). However, this increase is not linear with the magnitude of the warming. The most prominent increase shows up between the historic time frame and the 1.5 °C warming level. Among the different warming levels we distinguish marginal differences. In general, annual runoff maxima are recorded throughout the year (Fig. 5 b). In the historical period, runoff peaks cluster during spring and early summer (snowmelt season). In a warming climate, this cluster is more and more dispersed and annual maxima are increasingly recorded during winter, in particular for the 3 °C warming level. At gauge Cochem, no clear signals of change are detected, neither for the magnitudes nor the timing of annual streamflow maxima (Fig. 5 b and e). At gauge Cologne, streamflow maxima tend to be stronger at the selected warming levels compared to the historic time frame. Again, differences among warming levels are only marginal.

For both gauges Basel and Cochem, the estimated contribution of snowmelt to annual streamflow maxima strongly decreases with rising temperatures (Fig. 6 a and b). At gauge Cochem, the number of streamflow maxima having an estimated runoff contribution of snowmelt of more the 20% is reduced by 45% between the historic time frame and the 3 °C warming level. Magnitudes of S_{max14} diminish (Fig. 6 c and d). The median of S_{max14} for gauge Basel is around 40 mm in the historic time frame. At a 3 °C warming, it is almost halved. In the Rhine Basin upstream gauge Basel, S_{max14} do not only get weaker, they also tend to be recorded earlier in the hydrological year (Fig. 6 e). In both sub-basin, liquid and solid P_{max5} increase with rising temperatures (Fig. 6 g, h, i, and j). At gauge Basel (Cochem), the median of liquid P_{max5} increases from 25.7 mm (17.4 mm) in the historic time frame to 31.3 mm (19.8 mm) at a 3 °C rise in temperature. Also magnitudes of ET_{max14} increase with rising temperatures (Fig. 6 k and l). At a 3 °C warming, the median of ET_{max14} magnitudes increases by 10% (7%) for the sub-basin upstream gauge Basel (Cochem) compared to the historic simulations.

Decreases in solid precipitation are most prominent in winter (Fig. 7 a and b). Our results indicate that at a 3 °C warming, on average, the fraction of solid precipitation will be reduced to less than 40% in the sub-basin upstream gauge Basel in winter. The estimated fraction of snowmelt contributing to streamflow strongly decreases in the Moselle catchment during the cold

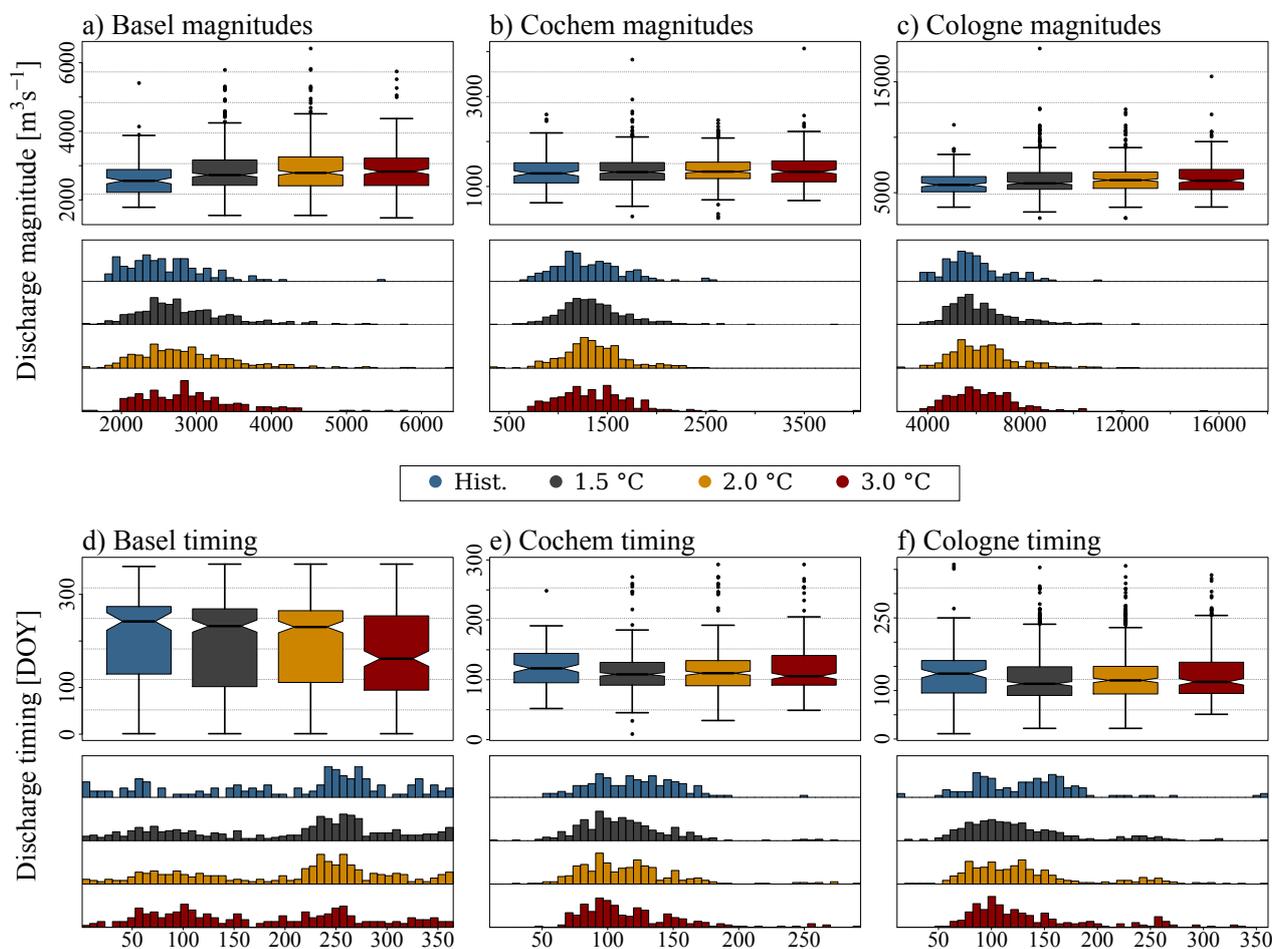


Figure 5. Magnitudes and timing (hydrological year starting 1. October) of annual streamflow maxima simulated for gauges Basel, Cochem and Cologne under selected warming levels and displayed as boxplots and histograms. Histograms depict probability density and have a total area of one.

season (Fig. 7 d). At gauge Basel, strongest decreases in the melt fractions show up end of spring and in summer (Fig. 7 c). The average melt elevation is moving upward the elevation range throughout the year (Fig. 7 e).

At gauge Basel, monthly streamflow maxima generally increase during winter and decrease in late summer (Fig. 8 a). Streamflow maxima in May and June seem to increase in magnitude at the more moderate warming levels (up to a warming of 2°C) and decrease as warming progresses. A similar pattern of initial increases in monthly maxima and a subsequent stabilisation or even a decrease at higher warming levels shows up in December and January at gauge Cochem (Fig. 8 b) and in all winter months at gauge Cologne (Fig. 8 c). In general, patterns of change in monthly streamflow maxima at gauge Cologne seem to reflect an overlap of features visible at gauges Basel and Cochem.

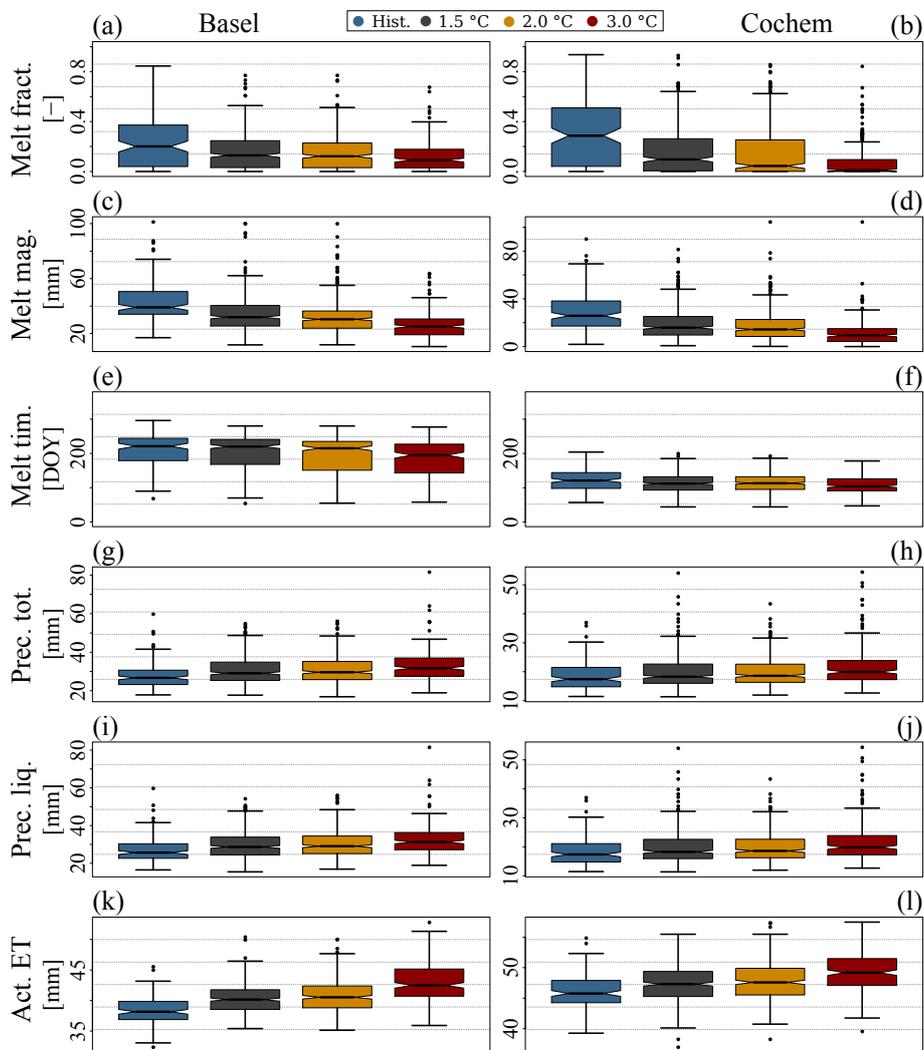


Figure 6. Estimated contribution of snowmelt to the annual runoff maxima (melt fraction; a and b), magnitudes (c and d) and timing (e and f) of annual snowmelt maxima (14-day sums), magnitudes of annual total (g and h) and liquid (i and j) precipitation maxima (5-day sums) and magnitudes of annual maxima of actual evapotranspiration (14-day sums; k and l) for sub-basins upstream of gauges Basel (left column) and Cochem (right column) under selected warming levels.

Magnitudes of snowmelt peaks remain fairly stable for gauge Basel during winter (Fig. 9 a). Strong decreases in S_{max14} show up in spring and are most pronounced from May to July. In the Moselle catchment upstream gauge Cochem, S_{max14} strongly decrease throughout the cold season (Fig. 9 b). P_{max5} tend to increase in intensity throughout the year (Fig. 9 c, d, e and f). In the Moselle catchment, no big differences between changes in liquid and total P_{max5} is detected. In the Rhine Basin

5 upstream gauge Basel, rising temperatures seem to evoke changes from solid to liquid precipitation, which enhances the overall increase in rainfall intensity, particularly in the cold season (Fig. 9 c and e). Evapotranspiration only plays a marginal role in

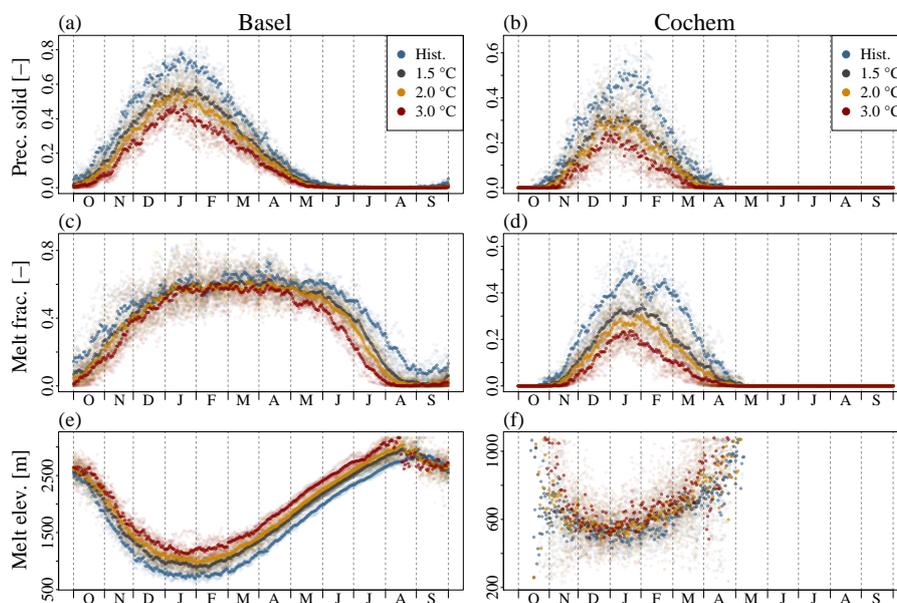


Figure 7. Mean annual cycles of the fraction of solid precipitation (a and b), estimated contribution of snowmelt to streamflow (melt fraction; c and d) and average elevation of snowmelt for sub-basins upstream gauges Basel and Cochem under selected warming levels.

the Rhine Basin during winter (Fig. 9 g and h). We detect highest values of ET_{max14} reaching up to 50 mm in the sub-basin upstream gauge Cochem during summer. Values of ET_{max14} increase with rising temperatures.

4 Discussions

Rising temperatures diminish seasonal snow covers (see also Bavay et al., 2009; Rousselot et al., 2012; Schmucki et al., 2015; Beniston et al., 2018). As a result, the importance of snowmelt as a flood-generating process decreases (Fig. 6 a, b, c and d). In the Rhine Basin upstream gauge Basel, S_{max14} decrease for all months of spring and summer (Fig. 8 a). At no point in time during the snowmelt season, a warming climate results in an increase in risk of snowmelt-driven flooding. Our results indicate that the temporal shift forward of the annual snowmelt maxima (Fig. 6 e) is not due to an increase in snowmelt magnitudes earlier in the year. It rather seems that events early in the snowmelt season, even if weakened by rising temperatures, more often are the strongest of the year already, as snow packs are increasingly depleted within the course of the snowmelt season. We can not confirm the hypothesis that an earlier snowmelt due to rising temperatures shifts the risk of snowmelt-driven flooding forward in time. Despite the temporal shift forward of annual snowmelt maxima, flood hazard seems to decrease, as the temporal shift concurs with a strong decrease in snowmelt magnitudes (Fig. 6 c). Our findings go along with results from Musselman et al. (2017), who suggest that a “shallower snowpack melts earlier, and at lower rates, than deeper, later-lying snow-cover”. However, the disappearance of snow packs and glaciers is likely to favour low-flow conditions along the Rhine

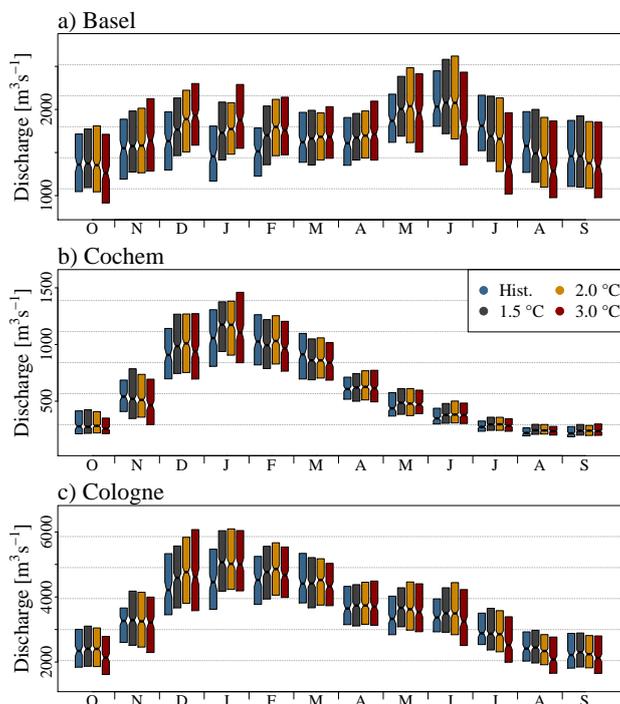


Figure 8. Magnitudes of monthly streamflow maxima simulated for gauges a) Basel, b) Cochem and c) Cologne under selected warming levels. Whiskers and outliers of the boxplots are not displayed.

River (Junghans et al., 2011; Stahl et al., 2016). Another factor having the potential to initiate or reinforce low-flow situation are increasing values of evapotranspiration, particularly during summer (Fig. 9 g and h).

Our results indicate that at in the sub-basin upstream gauge Basel during winter, the lack of snowmelt from lower elevations, at least partly, is compensated by snowmelt from areas located at higher elevations (Fig. 7 e and Fig. 9 a). This compensation effect seems to be increasingly insufficient as the snowmelt season progresses and the snowline moves upward. We suggest that in winter, the almost unchanged potential of snowmelt-induced runoff encounters more intense rainfall events (Fig. 9 c), in turn, resulting in a strong increase in streamflow maxima (Fig. 8 a). Our results confirm previous studies suggesting that rising temperatures lead to more intense precipitation events (e.g., Lehmann et al., 2015; Alfieri et al., 2015; King and Karoly, 2017; Bürger et al., 2019; Rottler et al., 2020) and a shift from solid to liquid rainfall (e.g., Allamano et al., 2009; Addor et al., 2014; Davenport et al., 2020). In catchments having mixed hydrological regimes with rainfall and snowmelt, rising temperatures seem to lead to a shift from snowmelt to rainfall as most important flood generating process (Vormoor et al., 2015, 2016). Reconstructing the largest floods in the High Rhine since 1268, Wetter et al. (2011) indicate that about half of all large events occurred during summer due heavy precipitation combined with high baseflow from snow- and ice-melt. Our results indicate that with rising temperatures, most flood events will occur in winter.

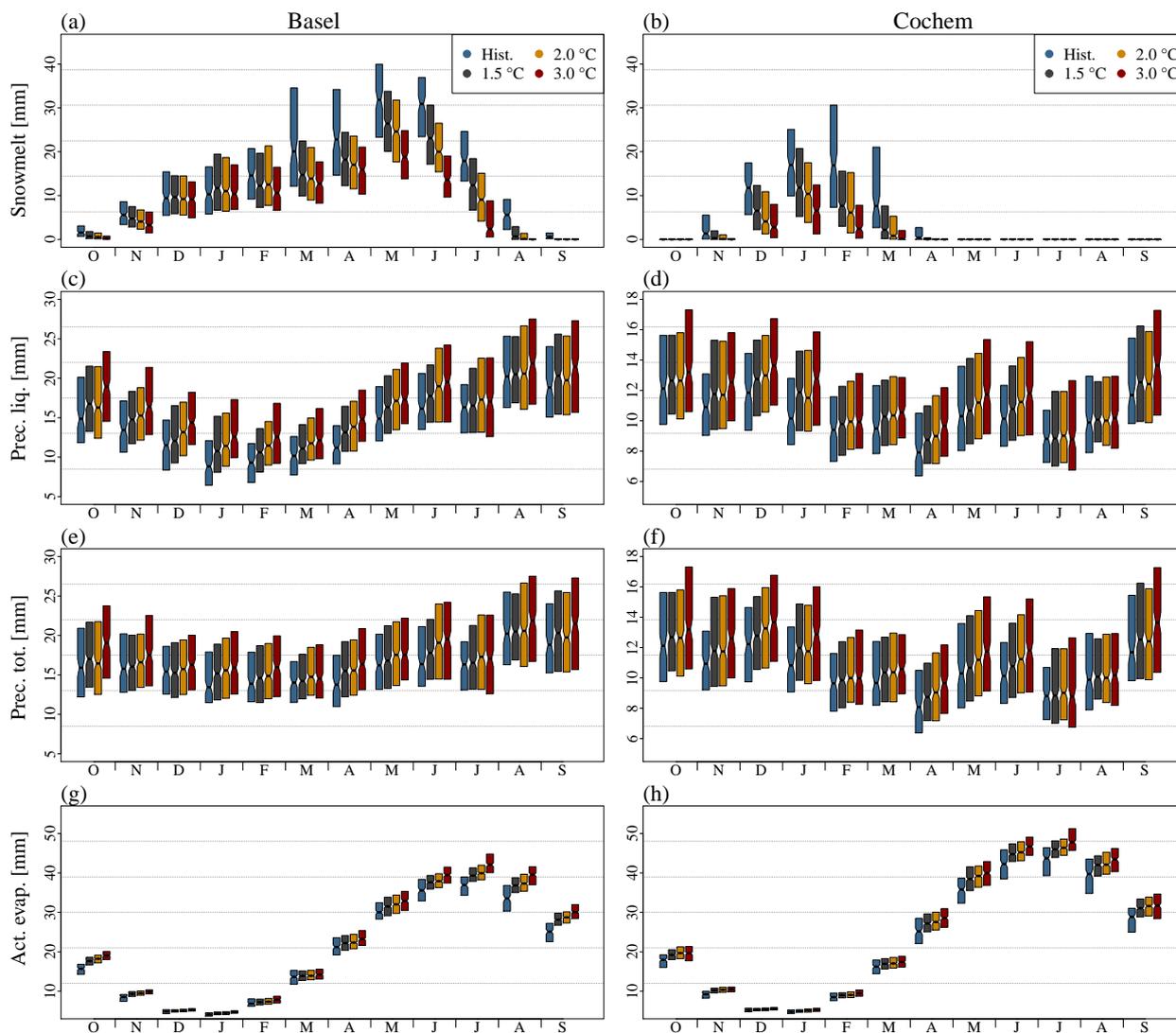


Figure 9. Magnitudes of monthly snowmelt maxima (14-day sums; a and b), liquid and total precipitation (5-day sums; c, d, e and f) and actual evapotranspiration (14-day sums; g and h) for sub-basins upstream of gauges Basel and Cochem under selected warming levels. Whiskers and outliers of the boxplots are not displayed.

In March and April, the increase in rainfall intensity in the Rhine Basin upstream gauge Basel compares to increases in winter, the magnitudes of streamflow maxima, however, hardly change (Fig. 8 a). We suggest that the increasing potential of rainfall-induced flooding is counterbalanced by decreasing snowmelt (Fig. 9 a and c). Furthermore, our results hint at a transient increase in flood magnitudes during May and June (Fig. 8 a). It seems that during those two months, snowmelt is still strong enough to support an increase in discharge peaks due to more intense rainfall at moderate warming levels (1.5 °C



and 2.0 °C). With further rising temperatures, however, the magnitudes of streamflow maxima reduce along with declining snowmelt (Fig. 8 a).

For gauge Cochem and the associated sub-basin of the Moselle River, we detect a similar interaction between snowmelt and rainfall: an increasing flood potential due to more intense rainfall encounters declining snow packs. Again, decreases in snowmelt magnitudes seem to counterbalance increased precipitation intensity resulting in comparatively small and transient increases in streamflow maxima (Fig. 8 b and Fig. 9 b and d). As highest mountains in the sub-basin only reach up to around 1300 m a.s.l., snowmelt compensation effects, i.e., snowmelt from higher elevations, at least partly, replaces the lack of snowmelt from lower elevation, only plays a marginal role. Analysing changes in frequencies of rain-on-snow (RoS) events with flood-generating potential for large parts of Europe for the historic time frame 1950–2011, Freudiger et al. (2014) hint at similar processes changing flood hazard. Their analyses suggest an increase in flood hazard from RoS events in medium-elevation mountain ranges in the Rhine River Basin in winter due to increased rainfall and a decrease in RoS events in spring due to decreases in snow cover. Although important Rhine tributaries, such as the Moselle River, often are characterised as pluvial-type rivers, the importance of snowmelt as runoff component must not be underestimated. Simulating the Rhine River for the time frame 1901–2006, Stahl et al. (2016) conclude that at gauge Cochem, 26 % of the annual streamflow originate from snowmelt. During winter, this fraction increases up to almost 40 %.

In Cologne, which is located at the main stream after the confluence of all major tributaries, signals emerging from the different sub-basin superimpose. Accordingly, we detect increases in runoff peaks during winter (Fig. 8 c). Detected increases seem to level off as temperature continue to rise beyond the 2 °C warming level. We do not find indications supporting the hypothesis describing the creation of a new flood type in the Rhine River Basin due to a transient merging of nival and pluvial flood types.

5 Conclusions

We investigate changes in flood seasonality in the Rhine River Basin under 1.5, 2.0 and 3.0 °C warming using the spatially distributed hydrologic model mHM. In order to improve our understanding of changes in rainfall- and snowmelt-driven runoff, we carried out a detailed inspection of the Rhine River Basin upstream gauge Basel and the Moselle River Basin upstream gauge Cochem. We detect significant changes in both rainfall- and snowmelt-driven runoff peaks. Rising temperatures deplete seasonal snowpacks. As a consequence, the importance of snowmelt as flood-generating process diminishes. At no time during the year, a warming climate results in an increase in the risk of snowmelt-driven flooding. Furthermore, solid precipitation (snowfall) strongly decreases during winter. The shift from solid to liquid precipitation further enhances the overall increase in rainfall intensity.

Our results indicate, that in order to understand changes in annual and monthly streamflow maxima, the examination of the interplay between changes in snowmelt- and rainfall-driven runoff is crucial. We suggest that future changes in flood characteristics in the Rhine River Basin are controlled by more intense precipitation events on the one hand, and reduced snowmelt on the other hand. The nature of their interplay defines the type of change in runoff peaks. In the case of the Moselle



River, more intense rainfall during winter, at least partly, is counterbalanced by reduced snowmelt contribution to the runoff peaks. In the Rhine Basin upstream gauge Basel, strong increases in liquid precipitation intensity encounter almost unchanged snowmelt-driven runoff during winter. Hence, streamflow maxima increase strongly. We can not find indications of a transient merging of pluvial and nival flood types.

5 The understanding of future changes in flood characteristics along the Rhine River and its tributaries is of great importance for water resources and flood management. Within this study, some progress has been made in assessing the importance of rainfall and snowmelt as flood-generating processes under different warming levels. However, only further studies pursuing the improvement of meteorological input data and hydrological modelling can ensure a comprehensive understanding of future flood characteristics in the Rhine River. Next steps could be the implementation and validation of a physically-based snow routine and a glacier module in mHM in order to substantiate our current results regarding the relevance of snowmelt magnitude and timing for the generation of Rhine floods. A streamflow component model enabling the tracing of river flow originating processes (e.g., Stahl et al., 2016) might ameliorate the understanding of snowmelt and rainfall as flood-generating processes at different Rhine gauges. Furthermore, the representation of lakes and reservoirs and their management might improve streamflow simulations, particularly during low-flow conditions.

15 *Code and data availability.* Source code of the hydrologic model mHM v.5.10 can be accessed at <https://git.ufz.de/mhm/mhm> (last access: 8 October 2020). R-scripts used to analyse simulation results are available at https://github.com/ERottler/mhm_rhine (last access: 9 November 2020). Discharge data can be requested from the Global Runoff Data Centre, 56068, Koblenz, Germany (GRDC). Further data sets used can be made available upon request.

20 *Author contributions.* ER conducted the analysis and wrote the manuscript. AB, GB and OR provided support and guidance in the process of model set up, data analysis and preparation of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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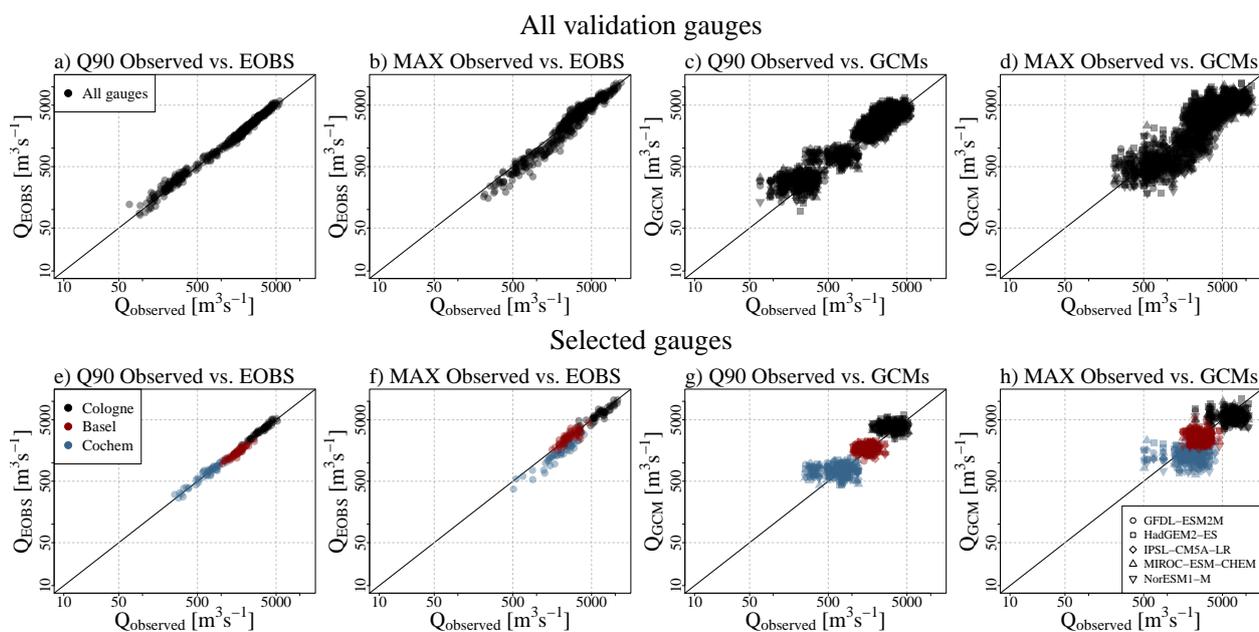


Figure A1. Scatter plot of observed and simulated annual streamflow maxima (MAX) and the 90 % streamflow quantile (Q90) of the hydrological year starting 1 October for all validation gauges (a-d; Fig. 2) and for selected gauges (e-h). Panels a, b, e and f depict observed discharge and simulated discharge using E-OBS-based meteorological forcing. Panels c, d, g and h depict observed discharge and simulated discharge using climate model data from the ISI-MIP project. Time frame investigated: 1951-2000.

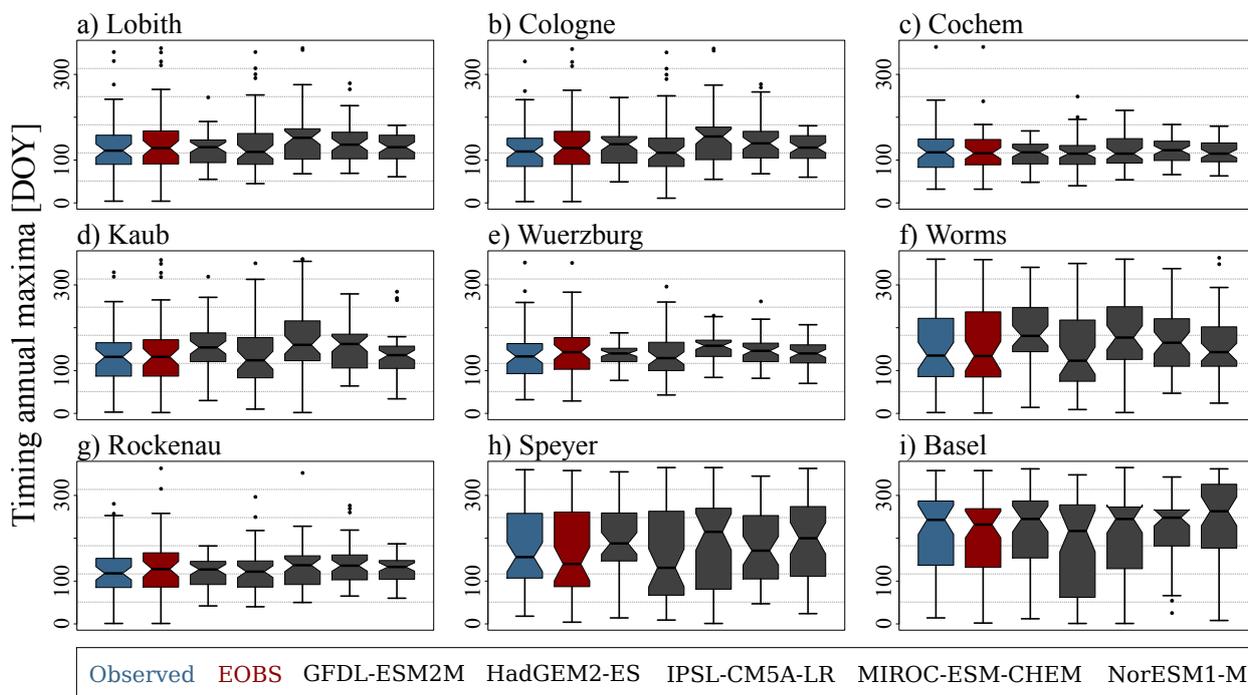


Figure B1. Timing of annual streamflow maxima observed and simulated using E-OBS-based meteorological forcing and climate model data from the ISI-MIP project for all validation gauges (Fig. 2). Time frame investigated: 1951-2000.

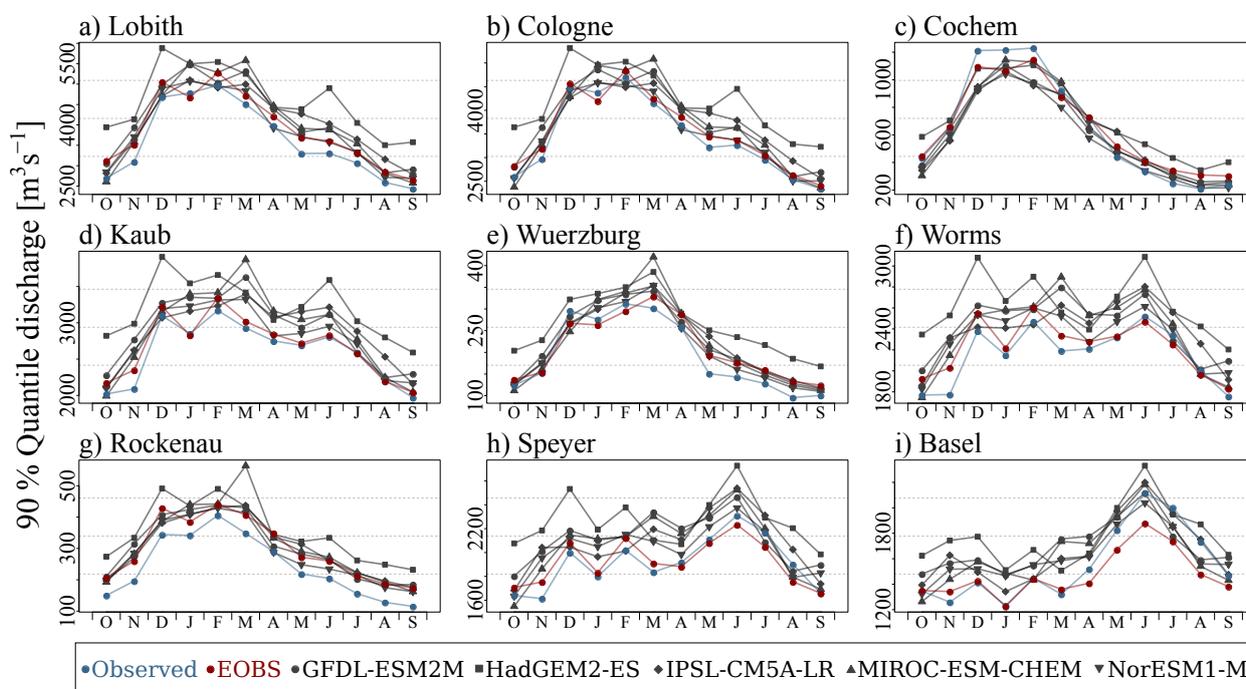


Figure C1. Streamflow quantiles (90 %) for every month of the year based on daily resolution observations and simulations using E-OBS-based meteorological forcing and climate model data from the ISI-MIP project for all validation gauges (Fig. 2). Time frame investigated: 1951-2000.