Regional climate model and model output statistics method uncertainties and the effect of temperature and precipitation on future river discharges in Scandinavia

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ABSTRACT

We analyze the importance of regional climate models (GCM-RCMs) and model output statistics (MOS) methods as uncertainty sources for future changes of various hydrological variables in Scandinavia. The Hydrological Predictions for the Environment (HYPE) model, driven with daily mean temperature and precipitation, is used to simulate changes in river discharges and other hydrological components from the present-day climate (1980–2009) to mid-21st century conditions (2041–2070).

The results show that GCM-RCM differences explain most of the spread in the simulated changes in the annual mean cycle of river discharge. At seasonal level, MOS-method uncertainties are most important during the winter and spring, which is likely explained by the sensitivity of snow processes to the representation of daily variability in the MOS methods. To gain physical insights into the physical processes, the relative importance of changes to temperature or precipitation on changes in surface hydrology are also assessed. In most regions of Scandinavia, changes to temperature explain most of the changes in river discharge volumes and spring peaks. Precipitation changes only have a secondary role in modulating these changes. Again, these results are mostly explained by changes in snow processes in winter and increases in evapotranspiration in summer.

Key words | analysis of variance (ANOVA), bias correction, HYPE, regional climate models, uncertainty

INTRODUCTION

Recent climate change studies have given strong evidence that daily weather variability will change along with average climate conditions. Due to these changes, the global hydrological cycle is expected to intensify (Held & Soden 2006). At high latitudes, as well as around alpine regions at lower latitudes, changes in river flows are driven by changes in snow melt/accumulation (López-Moreno & García-Ruíz 2004; Stewart 2009) and evapotranspiration (Nohara et al. 2006), which depend on combined changes in temperature and precipitation. In Scandinavia, changes in snow melt affect river flows in winter and spring (Beldring et al. 2008; Arheimer & Lindström 2015), while changes in evapotranspiration dominate in summer (Olsson et al. 2015). The implications of changes in river flows for socio-economic sectors such as hydro-power production, water resource management and the environment including inflows to the Baltic Sea need a proper assessment.

However, due to uncertainties in future greenhouse gas emissions, inherent limitations in hydrological and climate model formulations and resolutions as well as differences between the statistical tools used to bias-correct climate model simulations (Chen et al. 2011a, 2011b; Hagemann et al. 2011; Dobler et al. 2012; Bosshard et al. 2013; Donnelly et al. 2013), uncertainties in the hydrological climate change impact modeling chain are substantial. Part of the uncertainty is also related to the internal variability of the climate system, which can be as important as the other major sources of uncertainty (Hawkins & Sutton 2011; Lafaysse et al. 2014). Thus, the assessment of potential uncertainties is an integral part of communication for adaptation.
and mitigation studies. Without them, decision-making might be misled causing potential economic losses.

Model output statistics (MOS) is a technique commonly used when correcting biases in global (GCM) and regional (RCM) climate model simulations before using them as input for hydrological models (Fowler et al. 2007; Graham et al. 2007; Maraun et al. 2010; Teutschbein et al. 2011). MOS consists of several types of methods of differing complexity, including the commonly used quantile mapping methods. The ability of many MOS methods in adjusting climate projections has been documented extensively in the literature (Piani et al. 2010; Chen et al. 2013), and studies have shown that most of the MOS methods perform relatively well in reproducing the identified observed hydrological conditions (Chen et al. 2013). However, several methods should be used in parallel in climate change impact studies, since the identification of a single universally well performing method is practically impossible (Räisänen & Räty 2013; Räty et al. 2014).

As the main drivers of changes in surface hydrology are changes in precipitation and temperature, it is of interest both from the hydrological model development and downscaling perspectives, how a hydrological model responds to changes in these quantities. In a recent study by Bosshard et al. (2014), the separate effects of temperature and precipitation changes on river discharge in the Rhine River catchment were examined. The study showed that in snow-dominated areas, temperature effects tend to have a larger impact on the annual cycle whereas in other areas precipitation effects are also important. Similar conclusions have also been obtained in earlier studies (Barnett et al. 2005 and references therein). The study made by Bosshard et al. (2014), however, covered a relatively small area in central Europe and used a spectral delta change method, which does not take changes in daily variability directly into account. Some processes, such as snow melting and accumulation, may be sensitive even for small changes in daily (co-)variability in areas where temperatures are in the present-day climate close to the melting point (Barnett et al. 2005).

The relative importance of GCM-RCMs and MOS methods as uncertainty sources in hydrological simulations have been studied previously both at global (Hagemann et al. 2011; Chen et al. 2011a) and regional scales (Chen et al. 2011b; Teutschbein et al. 2011; Dobler et al. 2012), but less attention has been given to the spatial sensitivity of these two uncertainty components as well as to their contributions at different parts of the discharge distribution. This study aims to evaluate these aspects in the Scandinavian region. In particular, we aim to:

1. evaluate how uncertainties in the forcing data are reflected in hydrological simulations, i.e., how climate model and MOS method differences contribute to the overall spread in the future climate change signal;
2. assess separate temperature and precipitation effects on the simulated changes in river discharges and how their contributions depend on a particular GCM-RCM and MOS-method combination.

Analysis of variance (ANOVA) methods are used in a similar manner as depicted in Dobler et al. (2012), Bosshard et al. (2013), and Räty et al. (2014). Similarly, the analysis of separate temperature and precipitation effects on simulated changes in river discharges is based on ANOVA methods (Bosshard et al. 2014). In contrast to the previous study, the daily variability is taken into account in the assessment of these effects, and the effects are evaluated not just for one GCM-RCM but a whole set of GCM-RCMs and MOS methods, thus providing more insight into the generality of the results.

The paper is organized as follows. Immediately below, the hydrological model setup and the input data are described, while the following section introduces the MOS methods and the ANOVA frameworks used in the study. The next section presents the results, particularly the different sources of uncertainty and the effects of temperature and precipitation on different components of the water balance. Also the main aspects of simulated changes in river discharges as well as in daily temperature and precipitation are illustrated. Finally, conclusions are drawn.

**MODEL SETUP**

**Input data**

The ERA-Interim re-analysis (Dee et al. 2011) is used as the baseline data. To reduce differences between the re-analysis and the observed precipitation climatology, monthly precipitation means have been adjusted to the monthly means from
the Global Precipitation Climatology Centre (GPCC) gridded data set (Schneider et al. 2011). These adjusted ERA-interim data (hereafter referred to as ERA-I-adj) are used as the reference data in the bias-correction. For future projections of climate, six GCM-RCMs (Table 1) were selected from the ENSEMBLES database (van der Linden & Mitchell 2009). To maximize independence between the GCM-RCM formulations, all the selected models have a different GCM and RCM component. The model simulations have been driven with SRES A1B emission scenario forcing and their spatial resolution is 0.25° (~25 km) in both latitude and longitude. Both ERA-I-adj and the RCM simulations were interpolated to the corresponding sub-basins using the nearest-neighbor interpolation method. One should note that the selected GCM-RCMs might not be optimal in terms of their performance in the present-day climate, but act as a useful test for MOS method ability to adjust GCM-RCM biases.

**Hydrological model**

Hydrological simulations were made using the Hydrological Predictions for the Environment (HYPE) model. HYPE is a semi-conceptual, high-resolution model designed for multi-catchment simulations. Details of the model formulation can be found in Lindström et al. (2010) and from the documentation in the HYPE open-source community web page (hypecode.smhi.se). The model domain has been extracted from the larger European scale setup (E-HYPE 2.1, Donnelly et al. 2009) and covers most of the Scandinavian region (Figure 1). All land-use and topographical information have been extracted from freely available sources (Donnelly et al. 2016). One of the main advantages of HYPE is its computational efficiency, which allows the construction of the relatively large ensemble of hydrological simulations used in this study. However, the simplified description of physical processes such as snow melting/accumulation might be unrealistic in non-stationary conditions (Merz et al. 2011), which limits the usability of HYPE in such cases.

The modeling experiments are kept as simple as possible, i.e., only daily mean temperature and daily precipitation are used as input variables. The study concentrates on analyzing simulated changes in the seasonality of river discharges in the mid-21st century (2041–2070) as compared to current conditions (1980–2009), but also changes to total runoff and evapotranspiration are discussed.

Previous studies with the E-HYPE v2.1 have shown that in Scandinavia the model tends to underestimate river discharges (Donnelly et al. 2016). This is at least partly related to the underestimation of precipitation in the baseline data even after the adjustment with GPCC, as the data set has not been corrected for undercatch for snow falling as precipitation or the under-representation of stations at higher latitudes. To take the underestimation of discharge values in the present-day climate into account, a regional correction of precipitation and an adjustment of evapotranspiration parameters (soil type and land-use dependent) was made to the original model. These parameters were optimized to the Nash–Sutcliffe efficiency coefficient (NSE) and the relative volume error (RE) for 213 stations around the Scandinavian region in the years 1991–2000 and then validated over the whole baseline period (1980–2009).

### METHODS

**MOS methods**

Three MOS methods were selected for studying the contribution that differences in MOS methods make to the overall spread in the hydrological climate impact simulations. The simple delta-change scaling (DC) is included as a reference method. The method simply adjusts

<table>
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<tr>
<th>Institution</th>
<th>GCM</th>
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<tr>
<td>CNRM</td>
<td>ARPEGE</td>
<td>ALADIN</td>
<td>CNRM-RM5.1</td>
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<td>ETHZ</td>
<td>HadCM-Q0</td>
<td>CLM</td>
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<td>Met Office</td>
<td>HadCM-Q16</td>
<td>HadRM-Q16</td>
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<td>MPI</td>
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<td>SMHI</td>
<td>BCM</td>
<td>RCA3</td>
<td>SMHI-RCA-B</td>
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The first column shows the institution, second column the GCM part and third the RCM part of each model simulation. The last column shows the abbreviation used for each GCM-RCM combination.
ERA-I-adj monthly means of daily mean temperature and daily precipitation according to the monthly means of GCM-RCM simulated changes. To make the delta change scaling more robust, a two (three) month window centered on the month under consideration was used in the calculation of monthly change factors for daily mean temperature (precipitation). To cover the daily variability in the adjustment step, a non-parametric version of quantile mapping was applied both as a delta change (DQ) and bias correction (BQ) method. These methods were chosen as they can be used for both daily mean temperature and precipitation in a very similar manner. In its delta change form, quantile mapping converts the observed temperature and precipitation values \( o_i \) into projected values \( p_i \) in the future period as

\[
p_i = F_s^{-1}(F_o(o_i)),
\]

where \( F_c \) and \( F_s^{-1} \) denote the empirical cumulative distribution in the control period and its inverse in the future period, respectively. Formulation for the bias correction form is obtained by simply switching \( F_s^{-1} \) to the observed distribution \( F_o^{-1} \) and \( o_i \) to the future period simulation \( s_i \) in Equation (1).

Detailed descriptions of the application of this method can be found from Räisänen & Räty (2013) and Räty et al. (2014). A common limitation to all these methods is that they take neither inter-variable relationships nor spatial correlation structures directly into account (Vrac & Friederichs 2013).

**ANOVA framework**

To estimate the contributions of MOS-method and GCM-RCM differences to the overall spread in the HYPE simulations, a fixed-effect ANOVA was used. The overall variance \( V_{TOT} \) is decomposed according to:

\[
V_{TOT} = V_{MOD} + V_{MET} + V_{INT},
\]

where \( V_{MOD} \) is the fraction of variance due to GCM-RCM differences, \( V_{MET} \) the fraction due to the MOS-method differences and \( V_{INT} \) denotes the so-called interaction term. It should be kept in mind when interpreting the results that this type of ANOVA model does not separate the effect of the internal climate variability which is mainly reflected in the GCM-RCM and to a lesser extent in the other two components.

To study the separate effects that changes to temperature and precipitation have to changes in river discharges, the analysis follows the approach described in Bosshard et al. (2014). Assuming that as a first approximation non-linear effects are negligible, the relative contributions of temperature and precipitation changes are derived using four sets of HYPE simulations: one for present-day conditions, one including both temperature and precipitation changes, one for precipitation changes, and one for temperature changes only. From these simulations, using a simple ANOVA analysis one can assess the magnitudes of temperature and precipitation effects to the simulated changes together with the interaction term. The separation of temperature and precipitation effects is done individually for each GCM-RCM simulation and the two delta change methods, which allows us to compare how the relative importance of these two effects vary from one GCM-RCM and MOS-method combination to another. Due to methodological constraints (see Bosshard et al. 2014 for more details), only the two delta-change methods are included in the assessment of temperature and precipitation effects on the changes in the annual cycle of simulated surface hydrology.

**RESULTS**

**Baseline period**

We briefly demonstrate the performance of the HYPE model in the present-day climatic conditions. Validation against the observed discharges showed that the median daily NSE was close to 0.5 and ranged between 0.87 and 13.51. Locations with poor performance could often be related to strong regulation of the river for hydro power. Also the limited resolution of the baseline forcing and the limited capability of river routing network data sets to delineate small catchment areas (Donnelly et al. 2012) hamper the use of the model in catchments with size <5,000 km². The median annual mean relative volume error for river discharge was small (-1%) after the simple calibration and ranged between ±20% for 74% of the stations.

Further issues related to the model formulation were also identified: first, the snow melting scheme used in this model version was found to be sensitive to changes in the
parameter values, which causes uncertainties to the simulated snow accumulation and melting; second, the potential evapotranspiration is calculated using a relatively simple temperature-based scheme, which may not be sufficient in regions where wind or other processes strongly affect evapotranspiration. These limitations, together with the fact that the model parameters and structure are uncertain for future climatic conditions, need to be kept in mind when assessing the model results, even though HYPE is able to simulate seasonal aspects as well as inter-annual variability realistically in the present-day climate (Donnelly et al. 2016). Qualitatively, the accuracy of such a model is somewhere between a land surface scheme and an individual catchment model.

Temperature and precipitation changes

Before assessing uncertainties in the simulated changes of the annual cycle of river discharge, the projected changes in daily mean temperature and precipitation are briefly illustrated. Figure 2 shows the projected GCM-RCM and MOS method mean changes in temperature and precipitation for the winter and the summer seasons together with the standard deviation over the 18 model–method combinations, respectively. Temperature shows the expected warming pattern with the increasing warming towards the northern parts of the domain in winter. The projected mean warming varies from 1 °C in the southern parts of the model domain to around 4 °C in northern Lapland. The spread between the different temperature projections is largest in the northern parts of the domain and around the southern Finland and Karelian region. For precipitation, the mean of the GCM-RCM and MOS method combinations shows increasing precipitation in winter. Increases are projected to be largest around the Atlantic coastal regions (>1.0 mm/d), where the spread between the projections is of the same order as the mean simulated change. Decreases in precipitation are seen mainly in southern Sweden.

During the summer months, the average projected increases for temperature are smaller than in winter. Also the spread between the model–method combinations follows the spatial pattern of the mean changes and varies less between different areas than in the winter. Compared to the winter season, disagreement between the projections is smaller during the summer around Norwegian coastal areas, but slightly larger around Finland and the southern parts of Sweden.

Changes in river discharges

Domain mean changes in daily discharges from 1980–2009 to 2041–2070 are shown in Table 2. The results show that several of the GCM-RCM and MOS-method combinations project decreases in the annual mean discharge. These values are somewhat lower than the results obtained in recent literature (Donnelly et al. 2013; van Vliet et al. 2015). However, there are large regional variations. In Norway, discharges seem to mainly increase, while in southern Sweden and Denmark discharges are projected to decrease (not shown). Variations between the GCM-RCMs are also substantial (as also seen by van Vliet et al. (2015)). Some models project increases also at annual level, which underlines the uncertainty related to the choice of the GCM-RCM component.

The changes in the seasonal characteristics of river discharge from 1980–2009 to 2041–2070 are shown in Figure 1. During the summer, the mean river discharge seems to decrease nearly everywhere, especially in the Scandinavian mountains and in the northern parts of the model domain. During the winter months, discharges are projected to increase by over 40% in most parts of the domain reflecting the shift of the snowmelt from spring season to winter with the exception of southern Sweden and Denmark where the discharges seem to decrease instead due to projected decreases in precipitation and increases in evapotranspiration. Thus, even if mean annual precipitation is expected to increase in almost all of Scandinavia, the future discharge is projected to increase only in some parts of the region. Although the annual multi-model-mean changes of daily discharge are uncertain, seasonal and spatial variations are relatively well in line with previous results (e.g., Donnelly et al. 2013).

GCM-RCM and MOS-method uncertainties

The left panel of Figure 3 shows the ANOVA decomposition for individual percentiles of domain-mean daily discharge
distribution changes for the period 2041–2070. It is seen that the GCM-RCM effect (which includes the internal variability) is larger than the other two components for most percentiles and usually exceeds 40% of the total variance. However, for low and high flows (i.e., the tails of the distribution), the contribution of the MOS-method differences increases, which is important information when using these methods for assessing changes to extremes such as floods and droughts. This
is likely caused by the differing treatment of extremes in the MOS methods, which varies from constant scaling to adjustment to an empirical frequency distribution. For high flows the interaction term is also relatively large. These results resemble those obtained in Räisänen & Räty (2014) and Räty et al. (2015), who showed that most of the uncertainty in daily mean temperature and precipitation projections comes from the GCM-RCM differences, rather than differences between the MOS methods.

When compared to the right panel of Figure 3, which shows a similar decomposition for the changes in the annual mean cycle (seasonality) of daily discharge, it is seen that the contribution of the GCM-RCM differences is always more than 40% of the total variance. The contribution of MOS-method differences is largest during the late winter and spring, which coincides with the spring flood peak caused by snow melt. A more detailed inspection revealed that DC strongly reduces the snow amount in winter, which leads to the absence of the spring flood peak in many locations. Both quantile mapping methods, on the other hand, lead to smaller decreases in the snow pack and retain larger spring flooding, particularly in the northern parts of the domain. This suggests that the magnitude and timing of this peak is sensitive to the covariance between both precipitation and temperature, which is not directly taken into account by these methods (Barnett et al. 2005; Olsson et al. 2015).

Maps showing the decomposition of the overall variance in the simulated discharge changes in GCM-RCM, MOS method and interaction components (Figures 4 and 5)
support the previous results. During the winter (Figure 4), GCM-RCM differences generally explain over 50% of the overall variance, although small-scale variations are noticeable. Furthermore, the MOS fraction of the overall variance tends to be largest in the northern parts of the model domain and around the Scandinavian mountains, probably due to the sensitivity of snow melting/accumulation in HYPE to the inclusion of daily variability in the MOS step (see also Figure S1 in the supplementary material for snow cover length projections, available with the online version of this paper). The better inter-model agreement at least in temperature changes (Figure 2) might also play a role in these regions. Maps for the total runoff are relatively similar to discharge, although MOS-method differences tend to explain a larger part of the overall variance.

Similar decompositions are also shown for daily mean temperature and precipitation. For temperature, the model component dominates over the other two components, as in Räisänen & Räty (2013). The same also holds for precipitation, although the interaction component is slightly larger. To cover the most important water balance components, results are also shown for evapotranspiration. In winter the spatial pattern resembles those for the total runoff and river discharge, with somewhat lower (higher) contribution from the model (method) differences, indicating greater dependence on the selected method. Yet, it has to be kept in mind that evapotranspiration values are small during the winter also in the future climate, which might add to the interaction term.

The results are slightly different for the summer season (Figure 5), when climate model differences generally explain a larger part of the overall uncertainty in river discharge and total runoff. Note the absence of the relatively larger values for the MOS-method component in the northern parts of the domain seen during the winter. This further indicates that it is snow melting and accumulation which are affected by the choice of the MOS method. Also for evapotranspiration, the RCM component is noticeably larger in summer.

Temperature and precipitation effects

Previous results lead to the question, to what extent are future changes in river discharge and other hydrological aspects regulated by changes in either precipitation or temperature? Figure 6 illustrates how temperature and precipitation changes modify separately the annual cycle of river discharge for the years 2041–2070 in comparison to the baseline period. Comparing the simulations that include either temperature or precipitation changes only, it is seen that changes in temperature have a positive effect
Figure 4 | Maps for the GCM-RCM (left), MOS method (middle), and interaction (right) components of the overall variance between the six GCM-RCMs and three MOS methods for changes in total runoff (R), temperature (T), precipitation (P), and evapotranspiration (E) averaged over December-January-February in years 2041–2070.
Figure 5 | Similar maps as in Figure 4, but for June–July–August.
on river discharges in winter and early spring whereas in other seasons the temperature effect tends to be negative. On average, the temperature effect is much stronger than the precipitation effect and explains most of the changes in discharge seasonality. In particular, decreases in river discharges during the spring and summer seem to be mostly temperature regulated. Based on the previous results, this is probably due to the smaller snow reservoir in winter and earlier timing of snow melt in spring in a large part of the model domain. Also the sensitivity of evapotranspiration to temperature changes might explain the larger temperature dependence in summer. Evapotranspiration is mostly energy-, rather than moisture-limited in Scandinavia, although moisture dependence becomes more important towards the southern parts of the domain.

Furthermore, Figure 6 shows that differences in temperature and precipitation effects are relatively small between the two MOS methods most of the time. The biggest exception is seen in the late winter and spring, when
the difference in the temperature effect between the MOS methods is most noticeable. This suggests that the methods alternate the seasonality differently. Differences between the two methods are also noticeable later in the summer and autumn for some GCM-RCMs, which is probably caused by differences in the evapotranspiration response. This illustrates that changes in the annual cycle of river discharge (and other hydrological components) are, to a large extent, defined by changes in temperature with the exception being regions without a reliable snow cover for which precipitation changes are more dominant.

Differences between the curves showing the sum of the separate temperature and precipitation change simulations and simulations including changes for both variables illustrate how non-linear processes contribute to the simulated changes in the annual cycle of river discharge. The importance of non-linear processes varies from one GCM-RCM to another, but is generally largest during the time of the spring maximum in river discharge values. A possible explanation for this is that some threshold processes related to snow melting become important when temperature and/or precipitation changes grow large enough. This is indicated by the fact that the difference between the sum of the separate temperature and precipitation effect simulations (long-short dashed lines in Figure 6) and the full non-linear simulation (solid lines in Figure 6) is largest for those GCM-RCM combinations that also have the largest non-linear response in the simulated discharge changes.

Some examples of spatial ANOVA patterns are given in Figure 7, which shows maps for the precipitation and temperature effects on changes in the seasonal mean discharge for the winter and summer seasons from years 1980–2009 to 2041–2070. The effect of precipitation changes is mostly smaller than the effect of temperature changes. There is, however, a general tendency for the effect of precipitation changes to be larger in the southern parts of the domain and in the coastal areas of Norway during the winter as these regions have less snow and in the case of the Norwegian coast also have a strong precipitation change signal. Differences in spatial patterns are small between the two delta change methods and GCM-RCM differences tend to dominate (Figure S2 in the supplementary material, available with the online version of this paper). However, the effect of precipitation changes is slightly larger for DQ, which shows that the inclusion of daily variability in the scaling step modifies the relative importance of temperature and precipitation effects to changes in the annual cycle of river discharge.

Maps for the summer season show noticeable differences in comparison to the winter months. The temperature effect is systematically larger in the southern parts of the domain, where precipitation is projected to decrease. As in winter, DQ shows a greater contribution from precipitation changes than DC, probably due to differences in the evapotranspiration response. These results suggest that the simple delta change scaling likely overestimates the effect of temperature on changes in river discharges through other hydrological processes, which illustrates the importance of the selection of proper statistical tools for downscaling climate model data in hydrological climate change impact studies.

CONCLUSIONS

The proper communication of uncertainties in the response of surface hydrology to future climate changes is of primary importance for stakeholders in several socio-economic sectors, such as hydro power production and water management. In this study, the relative importance of uncertainties arising from GCM-RCM and MOS-method differences when simulating changes in future discharges in Scandinavia are studied using the hydrological model HYPE. To gain more insights into the processes which might explain these uncertainties, effects of temperature and precipitation changes on simulated changes in the annual cycle of river discharge were analyzed to assess their relative importance to the simulated hydrological changes and to also reveal how their relative contributions vary between the GCM-RCM and MOS-method combinations. The main results are two-fold:

1. Most of the spread in the changes of the annual cycle of river discharges is explained by GCM-RCM differences caused by the internal variability and model-specific response to external forcing. This result is in line with previous studies, which have shown that GCM-RCM differences generally explain a major part of the spread in daily mean temperature and precipitation projections (Räisänen & Räty 2013, Räty et al. 2014) as well as in simulated future
river discharges (Chen et al. 2011a, 2011b). However, the importance of method differences increases towards the tails of the distribution of daily discharge values (Dobler et al. 2012). Also, the magnitude and location of the spring flood peak is sensitive to the selected MOS method. It was found that this behavior is related to the snow accumulation and melting processes in northern parts of the domain in winter and that this depends on whether daily variability is taken into account in the bias correction step or not. Overall, the results imply that the regional-scale spatial variations in the relative contributions of GCM-RCM and MOS-method effects are non-negligible and should be covered when assessing uncertainties in future hydrological changes.

2. The effect of temperature changes is generally larger than the precipitation effect and explains a major part of the changes in the intra-annual variations of river discharges. A similar finding for Alpine tributaries was made by Bosshard et al. (2014). The smaller snow reservoir and earlier timing of snow melt season in winter and in spring together with the increased evapotranspiration in summer probably explain the relatively large
importance of temperature changes. The results also show that non-linear processes are important especially in the spring, which has implications on the bias correction step; due to the threshold effects the use of bias correction methods (including the studied ones), which assume stationary biases, can lead to biased results in the future climate. Also, differences in temperature and precipitation effects were generally larger between different GCM-RCMs than between the two delta change methods. This illustrates that the response of HYPE is more sensitive to the selected GCM-RM and that the inclusion of daily variability to the MOS-adjustment step has a secondary (albeit important) role in modulating the projected changes in the annual cycle of river discharges.

We stress that the results are specific for the selected GCM-RCMs and hydrological model. Furthermore, the overall set of different methods should have optimally been larger, although the selected ones should cover a relatively broad range of uncertainties related to the MOS methods, since a large part of the uncertainty arises from differences between the delta change and bias correction approaches (Räty et al., 2014). Emission scenario uncertainties, which are likely to become increasingly important in relation to other sources of uncertainty at longer time scales, should also be assessed.

Due to the structural limitations of HYPE and uncertainties in the model parameters, care should be taken in the interpretation of the results. The parametric uncertainty, for example, might be in some cases important but is not expected to be the dominant source here (Dobler et al., 2012). To get a better idea of the overall uncertainty in the future changes of surface hydrology, several hydrological models should be used in parallel, as hydrological model differences in simulated future changes can be one of the largest sources of uncertainty at some locations (e.g., Hagemann et al., 2011).

An obvious extension to the present study is to compare the results between single-variable and multi-variable bias correction methods (Vrac & Friederichs, 2015), which take co-variability into account. The comparison of joint and univariate bias correction methods in the hydrological modeling step will be targeted in future research.

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