C. Prudhomme (Referee)

The paper presents a comprehensive assessment of the impact of bias-correction techniques on the assessment of climate change on hydrology in Finland. This is an area of research currently very much debated amongst the impact community as current outputs of Global or Regional Climate Models are associated with high bias and they are not believed to be accurate enough to be used as such as input of impact models. However, very few articles have been published attempting a robust comparison of the impact of bias correction on the magnitude of resulting impacts and whether BC is necessary or not. The paper is well written and includes an informative discussion. It is worth publication after the authors have addressed the following comments.

Main comments:

In general I don't follow the fitting methods and results described in Section 3.1. and specifically: how is the double gamma distribution fitted? How does it perform compared with single gamma distribution in the middle and tail of the distribution using quantified metrics? Moreover end of section 3.1 suggests double Gamma is better for precipitation and presented in Fig 8; and in some following figures (Fig 9; Fig 13) a single gamma distribution is used, which is inconsistent. This needs clarification and requires careful proof reading. Please also specify which type of BC method (wet/dry day; Gamma 1 or 2) in all table and figure captions.

Double gamma distribution is fitted similarly as single gamma excluding the partition of monthly precipitation to two separate data series in 95th percentile of the cumulative distribution function (same CDF as used with single gamma). Some clarification is added to text. Also figures and figure and table captions revised to represent the results with double gamma. In hydrological simulations of mean discharges significant differences were not found whether single or double gamma distribution was used. However, the double gamma distribution performs better for torrential precipitation and thus now only the results of double gamma distribution are shown in the hydrograph figures as referee suggested.

New text added on Page 17 lines 12-13, Page 21 lines 1-5, Page 21 lines 10-14, Page 30 line 17-18, Page 30-31 lines 32-8.

The paper would also benefit from a comprehensive comparison of all BC options (temperature or precipitation or both) considered in this paper to quantify which one is the most effective. This could be easily achieved by the following sensitivity analysis on hydrological impact using : 1) uncorrected climate; 2) BC temperature uncorrected precip; 3) uncorrected temp BC Gamma 1 precip; 4) uncorrected temp BC Gamma 2 precip; 5) BC temperature and Gamma 1 precip; 6) BC temperature and Gamma 2 precip. This could be done under control and future climate; similar control results but different future results would certainly shed light on uncertainty added by BC procedures. I believe this has never been done at this level and would improve the manuscript.

A Figure showing the deviations of the simulated discharges using different correction methods or uncorrected data compared to control simulations and the changes in future climate is added. The changes in mean high discharge (MHQ) and mean low discharge (MNQ) are also calculated (not shown, but mentioned in the text) and the differences are much larger between uncorrected and corrected data in annual MNQ the change of

1

uncorrected data may even be to different direction than with bias corrected data. Figure 1 revised. We think that this improves the manuscript and thank for the good comment.

New figure (Figure 15) added. New text added on Pages 24-25 lines 20-17.

-Finally the paper needs to be proof read to make sure of consistency of acronyms throughout including figure and table captions and headings.

Figure and table captions standardized. New figures produced accordingly.

Minor comments/ questions:

Section 2.2: What is the spatial resolution of observed gridded temperature and precipitation time series? Page 2663 suggests 1-km grids but this would merit clarification

The areal precipitation and temperature data are first calculated for the sub-basins of the hydrological model from the three closest observation stations. Thus the resolution of the data is the same as model resolution on average 60 km^2. 1-km grid was used only for calculating the average values for RCM-grids. Now clarified in the text.

From Page 15 lines 6, 8 and 9: text revised

Section 2.3. The method describing the bias correction step 2) is not clear – a schematic would be helpful. Why a 5 harmonics equation was used? What is the number of time step used? It could be 12 (one per calendar month); 12x50: one per month of the time series; 12x2x50: one per 15-days of the TS?

Schematic figure (figure 1) is revised to better illustrate the correction procedure. 5 harmonics equation was used because we used mainly the same procedure as in Yang et al.(2010). This was found to be sufficient enough. Time steps for 15-day moving mean 15 days x 40 years.

Page 16 line 10: text added.

Section 2.3 – p2664 lines 14-17: rephrase for better flow. It is not clear either if there is a single CDF used for the whole TS or if there is one per season/ month.

Ok. We used single CDF for certain month for the whole TS.

Page 16 lines 23-24: text added.

P2664 l 24 to p2665 l2: The sentence starting 'The enable the scenario needs to be changed. I guess the assumption used is that the wet/dry bias is independent on radiative forcing but due to the rainfall parameterisation.

Ok. The assumption is based solely on stationary assumption as with all other steps in this bias correction method.

Page 17 lines 2-5: text revised.

P2667 last paragraph section 2.4: Are independent calibration/ evaluation periods used for the hydrological model calibration? Which periods the NSE correspond to?

The NSE-values for validation period 1961-1980 and within the calibration period 1981-2000 are now given and the differences are discussed.

Page 19 lines 6-14: text added.

The last sentence of p2668 is unclear and needs to be rephrased. How many values/proportion of series were available?

Page 20 lines 18-21: Text revised and proportions added.

Page 20 linees 23-26: Discussion related to this.

It would be good to justify the point of discussion of p2679 with quantified errors

Page 30 lines 17-18: Ok. Errors added.

Typos:

P2663 l 1: converted from 1km?

Page 15 lines 6, 8 and 9: Clarified in the text. The areal precipitation is converted to $1x1$ km^2 grid just for calculating the average values. Now the $1x1$ km^2 is not mentioned, that it does not cause misunderstanding.

Equation 2: clarify the notation 'sken' in the text

Ok. Revised to 'scen'.

Page 16 line 14 and page 17 line 17: abbreviation 'scen' for 'scenario' added, also 'sken' as footnote in formulas 2, 4, 6, 8, 11 and 12 were changed to 'scen'

P2665 l 8: remove 'also' between 'events' and 'a' and add 'also' between 'was' and 'used'

Page 17 line 11: Ok.

P2665 l 9: remove 'partitions'

Page 17 line 12: Ok.

P2666 l 12: remove 'also'. After hydrological model, add 'it is assumed that'

Page 18 line 7: Ok.

P2667 l 15-16: make sure of consistency of dates

The calibration period of the hydrological model is 1981-2012, but the control period is 1961-2000. The NSE-values within the control period are relevant in this study, but the operational forecasting model has been calibrated using the last years data as well.

Page 19 lines 6-14: text added.

P 2669: I would not qualify of 'torrential' rainfall of only 20 mm in a day. Can this be changed throughout the paper?

In Finland this is torrential precipitation and thus we will keep this definition.

Page 19 line 21-23: definition of torrential precipitation added.

Page 21 line 1-5: Text added.

P2670: table 3.

Page 23 line 16: Ok, table 4 corrected to table 5 due to rearrangement of tables.

P2672 l5: -6.7 not -4.6 largest change

Page 21 line 30: Revised.

Table 3: discuss the slightly worse errors in Loimijoki using REMO in winter after BC

Pages 23-24 lines 30-4: Text added.

Table 5 Loimijoki results for HIRHAM inconsistent with Table 4

Revised. There was a missing negative sing in table 5 (now table 4, and table 5 is now table 3) (precipitation HIRHAM-A, 1 gamma should be -0.1 in spring)

Figure 1: edit to capture comparison of results using corrected/ uncorrected RCM outputs

Schematic presentation of figure 1 revised.

Anonymous Referee #2

The authors apply different versions of the DBS method to bias-correct gridded daily precipitation (P) and temperature (T) data over Finland from five RCM projections. Also wind speed (WS) and relative humidity (RH) were bias-corrected, but with simple monthly adjustment factors. The bias-corrected data were used to drive the WSFS hydrological model system, and results were extracted for four catchments in different parts of the country. The results indicate that if the bias in raw RCM is large, a large bias may remain and trends may change after the application of DBS. The impact of DBS version is generally quite small.

General comments:

Today's RCM bias-correction methods certainly need further evaluation and development, and in that sense the paper is a welcome contribution. It is overall clear and well presented and technically the methods used and results obtained appear OK. My main issue with the paper is that I find the novelty and the new significant knowedge acquired rather limited. The need for bias-correction of RCM data for hydrological impact studies in Finland has been demonstrated in a similar fashion previously. Thus I do not see much added value in the comparison between uncorrected and corrected data done here. Also the future changes in P, T and discharge (Q) have been assessed previously. Then other bias-correction methods were used, but among them is the empirical quantile mapping which is likely to produce a similar result to DBS on the seasonal patterns in focus here (this is confirmed on l.24-26, p.2680).

As the DBS method is becoming rather widely used, it is indeed of interest to evaluate it and specifically reveal its limitations. The authors use different versions (1) with/without T-dependency on the wet/dry state and (2) with single or double gamma for P. These are, as I see it, method options. Which options that work best for a particular data set is of course interesting for the application itself, but of more limited general interest. But the discussions about the effects of model choices in terms of e.g. sample size for distribution fitting and distributional discontinuities are interesting. And the impact of the bias magnitude on the trends is a significant finding. Bottom line: I think the work needs to be taken a bit further to be of more general interest for the scientific community.

Thank you for the good and critical comments! We agree that similar study using quantile-quantile-mapping has been demonstrated, but the problems relating to the extrapolation of the quantiles in the both tails of the distribution may influence on the simulated extreme events. Thus the more sophisticated DBS-method is tested to justify that the method works in the mean discharges as well as quantile-quantile mapping, that it can be further used in estimations of the climate change impacts on floods and droughts. To increase the novelty and the general interest for the results we added the results of seasonal changes of MHQ and MNQ with changes in maximum snow water equivalent (SWE), maximum soil moisture deficit (SMD), evapotranspiration (ET) and runoff ® to the results. Especially the seasonal changes in MHQ and MNQ are expected to increase the interest in the results and improve the paper significantly.

Page 27 lines 10-18: New text added.

Also new figure (Figure 15) is added.

Some suggestions:

- Use the model selection analysis (condensed) as a starting point for further analysis of the performance of the selected model version.

Pages 24-25 lines 20-3: Clarification to selection of the DBS method is added to text. Also a new figure is added (Figure 13). Two new figures (Figures 13 and 15) are added to the result section and the other parts of the section are shortened.

- Concerning further analysis: It is written (p.2662, l.6-8) that a second paper will focus on extremes, this could well be done already here. Another possibility would be to look at not only annual Q cycles but also other variables in the hydrological model (snow, ET, soil moisture, runoff components etc.). Bias correction of P and T by distribution mapping generally produces a good annual Q cycle but other other variables may be less well reproduced, this issue needs more attention.

The results of the seasonal changes of mean high discharge (MHQ) and mean low discharge (MNQ) together with changes in snow water equivalent (SWE) and soil moisture (SM) are added.

Page 27 lines 10-18: New text added

New figure 15 added.

- Substantially reduce (or even omit) the results from non-corrected RCM data, highlight only any significant differences from previous results

The other referee commented to study the sensitivity of the results on non-corrected versus corrected results. A new figure (Figure 13) is added. The former chapter "*3.4. Impact of bias correction on simulated hydrology*" is now after chapter *3.2. RCM temperature and precipitation in the future* and more concise.

Pages 24-25 lines 20-3 and page 25 lines 14-22: text added

- Similarly concerning future changes, highlight only any significant differences from previous results.

The results section is more concise.. The main findings in chapter '3.4.1 *Effect of bias correction'* is included now in chapter *3.3. RCM temperature and precipitation in the future* and Page 26 line 1 to Page 27 line 18 Chapters '3.4 *Future scenarios for dischanrges'*, '3.4.2 *Impact of climate change'* are are included in '3.4 *Future scenarios for discharges*'

Page 27 lines 10-18 The results of relative changes of seasonal MHQ and MNQ and annual maxSWE, maxSMD, ET and R are discussed and Figure 15 added.

Some specific comments:

- Section 2.2: Justify why these RCM projections were chosen.

These are the same RCM projections used in Veijalainen et al. (2012), excluding RCA-ECHAM5 and HIRHAM-BCM which were chosen instead of RCA-HadCM because of some data problems.

Page 15 lines 17-18: Text added.

- Fig. 6 should appear before Fig. 7 in the text.

Page 20 line 8: Figure 6 actually appears before Fig.7 in the text. No need to change.

<u>Results generally:</u>

In the presentation of the results, sometimes one catchment is used, sometimes two. Some justification for this choice would be good (e.g. influence of lake, etc). The same goes for the selected projections. All five projections are compared until Fig. 6. From Fig. 7 and on, individual projections (or a subset) are used instead of all five. Maybe you can focus on one projection and then give a general overview using all projections. Or better justify the choice of projection, period, etc.

Only figures 11, 12 and 14 show selected projections. Selected projections are shown to preserve the clarity in figures. Shown projections cover the range between projections (minimum, maximum, mean). When illustrating the precipitation and temperature results, only one catchment is shown (figures 5-10). The selected catchment illustrates the mean results or alleviates some problem originating from the bias correction method. All figures representing hydrological results (figures 11-15), except figure 12, includes all four catchments. Tables show results for two catchments (except table 3 due to table size) to show the difference between southern and northern parts of Finland.

Page 26 lines 21-22: New text added

Text added to table captions for tables 2, 4 (old 5) and 5 (old 3).

Figures 11 (old 9), 12 (old 10) and 14 (old 13) reproduced.

- Fig. 6: How come the observations are different in each panel?

Figure 6 revised. Torrential values still have different scales in each panel to better illustrate the results.

- Conclusions: Most of this section is a summary, either rename to Summary and conclusions or include only conclusions.

Page 32 line 18: Ok, 'Conclusions' section renamed to 'Summary and conclusions'

<u>Additional revisions by authors:</u>

The results section is now more concise as suggested by referee 2. The former chapters 3.2 *'Impact of bias correction on simulated hydrology'* is now chapter 3.3. and after the chapter 3.2. *'RCM temperature and precipitation in the future'* The main findings in former chapter *3.4.1 Effect of bias correction* are now included in chapter 3.2 *'Impact of bias correction on simulated hydrology'* and the former chapters '*3.4 Future scenarios for discharges'* and '*3.4.2 Impact of climate change'* are now merged. The new figures (Figure 12 and 14) are included in chapters 3.3 and 3.4. We think these changes improves the paper significantly.

Page 13, line 12: SD revised to standard deviation (SD)

1 Page 14 lines 8, 19 and 20, page 31 line 31 northern, central and southern Finland revised to
2 Northern, Central and Southern Finland

3 Page 14, line 27: abbreviation (FMI) added after Finnish Meteorological Institute

4 Page 15, line 2: 2014 revised to 2015

5 Page 15, line 5: 2014 revised to 2015

6 Page 18, line 8: clarification: it is assumed that

7 Page 18 line 17: 2014 revised to 2015

8 Page 18 lines 24 and 26: 'catchment' changed to 'basin'

9 Page 20 line 8: 'heavy' changed to 'torrential'

10 Page 21 line 8: 'torrential' changed to 'heavy'

11 Page 21 line 18: Table 4 changed to Table 3

12 Page 21 line 32: Table 5 changed to Table 4 and Fig 11 changed to Fig 9.

13 Page 22 lines 3, 5, 14, 16, 19, 20 and 23: Table 5 changed to Table 4, Table 4 to Table 3,
14 Fig 12 to Fig 10 and Fig 11 to Fig 9.

15 Page 23 line 4: figure 9 changed to figure 11

16 Page 23 text in lines 10-13 relocated to Page 25 lines 4-7.

17 Page 23 line 16: table 4 changed to table 5

18 Page 23 text in lines 20-23 relocated to Page 24 lines 29.32

19 Page 24 lines 4 and 5: typos and "results from" changed to "variations of"

20 Page 24 lines 6 and 14: Fig. 9 changed to Fig. 11 and Fig. 10 changed to Fig. 12

21 Page 25 lines 17-32: Text shortened.

22 Page 26 line 4: figure 13 changed to figure 14

23 Page 27 lines 4 and 5: 'lower' changed to 'larger' and 'content' to 'deficit'

24 Page 30 line 13: 'Intuitively' deleted and 'would' changed to 'is expected to'

25 Page 30 line 29: 'the torrential cut-off value' changed to 'the cut-off value for heavy
26 precipitation'

27 Page 36 lines 1-7:The reference to Huttunen et al. changed to recently published paper.

28 Page 36 line 13: Jakkila et al reference revised

29 Page 36 line 16: Jylhä et al. et al. reference revised

30 Page 37 line 22: Räisänen et al. reference revised

31 Page 37 line 29: Taskinen et al. reference revised

32 Page 39 lines 4-7: Yang et al. reference revised

33

34

35

Changes in Tables and figures:

Table 4 is now table 3

Table 5 is now table 4

Table 3 is now table 5

Figure 1 is revised

Figure 4 and its caption is revised

Figure 5 and its caption is revised

Figure 6 is revised

Figure 7 is revised

Figure 9 and its caption is revised and relocated to be figure 11

Figure 10 and its caption is revised and relocated to be figure 12

Figure 11 is revised and relocated to be figure 9

Figure 12 is now figure 10

Figure 13 and its caption is reviced and relocad to be figure 14

New Figure 13 (and caption) is added

New Figure 15 (and caption) is added

Impacts of climate change on temperature, precipitation and hydrology in Finland – Studies using bias corrected Regional Climate Model data

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1 **Abstract**

2 Assessment of climate change impacts on climate and hydrology on catchment scale requires
3 reliable information about the average values and climate fluctuations of the past, present and
4 future. Regional Climate Models (RCMs) used in impact studies often produce biased time
5 series of meteorological variables. In this study bias correction of RCM temperature and
6 precipitation for Finland is carried out using different versions of distribution based scaling
7 (DBS) method. The DBS adjusted RCM data is used as input of a hydrological model to
8 simulate changes in discharges in four study catchments in different parts of Finland. The
9 annual mean discharges and seasonal variation simulated with the DBS adjusted temperature
10 and precipitation data are sufficiently close to observed discharges in the control period
11 (1961−2000) and produce more realistic projections for mean annual and seasonal changes in
12 discharges than the uncorrected RCM data. Furthermore, with most scenarios the DBS
13 method used preserves the temperature and precipitation trends of the uncorrected RCM data
14 during 1961−2100. However, if the biases in the mean or the standard deviation of the
15 uncorrected temperatures are large, significant biases after DBS adjustment may remain or
16 temperature trends may change, increasing the uncertainty of climate change projections. The
17 DBS method influences especially the projected seasonal changes in discharges and the use of
18 uncorrected data can produce unrealistic seasonal discharges and changes. The projected
19 changes in annual mean discharges are moderate or small, but seasonal distribution of
20 discharges will change significantly.

21

22 **1 Introduction**

23 Climate in Finland is boreal with temperate and sub-arctic features and four distinct seasons
24 (Castro et al., 2007; Jylhä et al., 2009a). Winters are mostly cold and snowy and summers
25 rather short, cool and rainy. Precipitation is moderate in all seasons. Hydrology in Finland is
26 characterized by seasonal variation with snow accumulation and low flow during winter,
27 snowmelt with runoff peak in spring, another low flow season in summer and increasing
28 runoffs towards autumn. Climate change is expected to significantly influence the hydrology
29 in Finland. Climate zones are expected to shift towards north during this century, and the
30 prevailing climate type would become more temperate and wet (Jylhä et al., 2009a).
31 According to Jylhä et al. (2009b) annual mean temperature is likely to increase by 3–6 °C by
32 the end of this century, compared to 1971–2000. Precipitation is expected to increase 12–22

1 % in Finland by the end of the century (Jylhä et al., 2009b), but the spatial distribution or the
2 temporal cycle of the seasonal precipitation would not change significantly.

3 Changes in temperature will inevitably affect the snow and ice accumulation and melt
4 processes as well as the extent of snow and ice cover. In southern Finland permanent snow
5 cover will become rare by the end of the century (Ruosteenoja et al., 2011). Changes in
6 temperature and precipitation and consequent changes in snow accumulation and melt will
7 affect seasonal variation of river discharges and water levels of lakes. Because the
8 temperature in winter will more frequently rise above zero degrees, winter discharges and
9 water levels will increase, while spring snowmelt discharges decrease especially in southern
10 and central Finland due to decreased snow accumulation (Vehviläinen and Huttunen, 1997;
11 Veijalainen et al., 2010). The changes in river discharge and lake water levels will cause
12 adaptation needs in water power production, flood protection and lake regulation (Veijalainen
13 2012).

14 Regional and local climate change scenarios are needed for assessments of climate change
15 impacts on hydrology and other sectors in Finland. The spatial resolution of Global Climate
16 Models (GCM) (100–300 km) is insufficient to simulate regional scale events that are needed
17 to capture different weather phenomena in a catchment scale. Projections of GCMs can be
18 dynamically downscaled with Regional Climate Models (RCMs) to scales of 25–50 km,
19 which represents the Finnish catchment scales better. Though nested models are more
20 computationally demanding, dependent on GCM forcing and need detailed surface data, they
21 are able to produce more detailed information on temporal and spatial scales than GCMs
22 (Hewitson and Crane, 1996). This information is necessary when RCM data is used as input
23 for impact models such as hydrological models.

24 Although increased horizontal resolution can improve the simulation of regional and local
25 climate features, RCMs still produce biases in the time series of climate variables
26 (Christensen et al., 2008; Rauscher et al., 2010). RCMs are found to have lower skill to
27 reproduce temperature and precipitation in colder regions (Teutschbein and Seibert, 2012) and
28 have difficulties to reproduce realistic values near coast line and lakes in Finland (Jylhä et al.
29 2009b). Hydrological simulations using the RCM data as direct input are sensitive to RCM
30 biases (Wood et al., 2004) and especially regions such as Finland, where seasonal snowpack
31 causes a time shift in runoff generation, are sensitive to temperature bias (Wood et al., 2004;

Veijalainen et al., 2012). Therefore an efficient bias correction method for both precipitation and temperature should be applied to the RCM data.

Several approaches are available for adjusting RCM variables; these can be divided into Delta Change (DC) and Bias Correction (BC) methods. The DC approach adjusts observations with the RCM climate change signal, whereas the BC approach adjusts the daily RCM simulated variables based on the difference between observed and simulated climate in the control period. Compared to the DC method the BC approach usually better preserves the future variability in temperature and precipitation produced by the RCMs, enables representation of complex changes in climate related to changes in mesoscale weather conditions and enables transient scenarios instead of comparison between time slices (Graham et al., 2007; Lenderink et al., 2007; Beldring et al., 2008; Yang et al., 2010). Bias correction methods have been proved to improve daily mean, standard deviation (SD), and distribution of the RCM temperature and precipitation when compared to observed climate statistics (e.g. Yang et al., 2010; Teutschbein and Seibert, 2012; Räisänen and Räty, 2013; Räty et al., 2014).

In this paper, bias corrected RCM data sets of precipitation and temperature covering the area of Finland are produced. Two versions of a distribution based bias correction method are evaluated for temperature and precipitation. In addition, a simple mean bias correction is applied for daily wind speed and specific humidity, which are used in simulation of lake evaporation in the hydrological model. These bias corrected values are then used as input of the hydrological model to simulate discharges and their changes due to climate change in selected catchments. The goal is to evaluate the DBS method in climate change impact studies of river discharges in Finland. This article focuses on annual and seasonal mean values, while a second part of the study in a separate paper will focus on extremes, especially heavy precipitations and floods, and their changes.

2   Materials and methods

In this study climate scenarios from RCMs are first bias corrected using observations of temperature, precipitation, wind speed and humidity and then used to produce hydrological scenarios for the study catchments (Fig. 1).

2.1 Study catchments

Four catchments located in different parts of Finland were selected as study catchments (Fig. 2). These represent different hydrological regions in Finland. Loimijoki (Maurialankoski observation station, catchment area 2 650 km^2, lake percentage 3.1) is a medium sized river with high proportion of cultivated area on clay soils. Nilakka (catchment area 2 160 km^2, 18 % lake percentage) and Lentua (2 050 km^2, 13 %) observation stations are located at lake outlets in central Finland characterized by numerous lakes. Ounasjoki (Marraskoski observation station, 12 300 km^2, 2.6 %) is a large river in Nnorthern Finland (Fig. 2) (Korhonen and Kuusisto, 2010). All the study catchments have long water level and discharge observation series, longest from 1912 onwards (Lentua) and shortest from 1935 onwards (Loimijoki).

Annual mean runoff in the study catchments varies from 280 to 370 mm. Runoff has a distinct seasonal variation with low values during winter and summer and a maximum in spring due to snowmelt. The average maximum snow water equivalent varies from 80–100 mm in the southern catchment (Loimijoki) to 180 mm in the northern Ounasjoki catchment (Perälä and Reuna, 1990). Annual soil and lake evaporation gradually decrease from southern Loimijoki (soil 400 mm, lake 540 mm) to nNorthern Ounasjoki (soil 220 mm, lake 310 mm) (Hyvärinen et al., 1995). Autumn precipitation causes a second runoff peak, which is usually smaller than the spring peak. The spring floods are more pronounced in nNorthern and cCentral Finland (Ounasjoki, Lentua, Nilakka), while in sSouthern Finland (Loimijoki) heavy rains in summer and autumn or rains with snowmelt in winter may cause major floods as well.

2.2 Observations and RCM data

Bias corrections were calculated for the entire Finland including transboundary watershed areas in Norway, Sweden and Russia. The gridded data sets needed for the bias correction were calculated using observations from approximately 190 stations with daily temperature measurements at 2 m height and 250 stations with daily precipitation measurements from the Finnish Meteorological Institute (FMI). Additional observations from 11 temperature and 16 precipitation observation stations in Norway, Sweden and Russia were provided by the Norwegian Meteorological Institute, the Swedish Meteorological and Hydrological Institute (SMHI) and the Hydrometeorological Centre of Russia. Observations from 1961–2000 were used although the observation network varies during this period.

Gauge precipitation observations especially for snowfall contain various systematic measurement errors (Førland et al., 1996; Taskinen, 2015~~4~~), which need to be corrected before they can be used for bias correction of RCM data. The correction of precipitation measurements consisted of the exposure method for aerodynamic correction as well as wetting and evaporation corrections (Taskinen, 2015~~4~~). The areal values of the meteorological observations ~~for each sub-basin~~ are calculated for each sub-basin of the hydrological model from three closest observation stations by inverse distance weighting taking into account the elevation differences~~. and the gridded values are calculated based on these areal values.~~ The areal values were converted to ~~1x1 km grid to calculate the average values of~~ the same regular 0.25º lat x 0.25º long grid as the RCM data.

The observations of relative humidity at 2 m and wind speed at 10 m are used in the simulation of lake evaporation, which is an important hydrological variable for catchments in the lake area. The areal values are calculated in similar way as temperature and precipitation and the effect of fetch to the wind speed on a lake is calculated as in Resio and Vincent (1977).

Five climate scenarios were used from four different RCMs forced with four different GCMs as given in Table 1. Selected RCM projections are the same as used in Veijalainen et al. (2012), excluding RCA-ECHAM5, to enable comparison of results. The data was retrieved from ENSEMBLES Research team 3 database (ensemblesrt3.dmi.dk, van der Linden and Mitchell, 2009). The GCMs were run under historic (1961−2000) and with A1B scenario (2001−2100) forcing. The GCM output was then used as boundary conditions to force RCMs over a common European domain in a regular 0.25º lat x 0.25º long grid (van der Linden and Mitchell, 2009).

2.3 Bias correction methods

The distribution based scaling (DBS) method described e.g. in Yang et al. (2010) and Teutschbein and Seibert (2012) was used to scale temperature and precipitation time series to better represent observed distributions. The correction procedures using Cumulative Distribution Functions (CDF) are shown in Fig. 3. In this study CDFs are constructed on a daily basis for temperature and for all days with certain month for precipitation. The method of maximum likelihood is used to estimate distribution parameters.

1   Temperature (T) is described by a Gaussian (normal) distribution with daily mean (μ) and

2   standard deviation (σ). The DBS approach for temperature included four steps: (1) To take

3   into account the dependence between precipitation and temperature, the temperature data

4   were divided into wet and dry days resulting in two sets of parameters; (μ_w, σ_w) for wet days

5   and (μ_d, σ_d) for dry days, hereafter referred to as $(\mu_{w/d}, \sigma_{w/d})$. The separation was conducted

6   after excessive drizzle days were removed (described below, equations 5 and 6). In this study

7   we also use the distribution parameters without wet/dry state separation (μ, σ). (2) To take

8   into account seasonal variations, daily mean and standard deviation were calculated using a

9   15-day moving window and (3) were further smoothed with Fourier series with five

10   harmonics on a daily basis over the control period (1961–2000) as in Yang et al. (2010). (4)

11   These smoothed daily mean and standard deviation for each grid point were then used to

12   calculate the daily *(d) CDFs* for observations $(\mu_{obs}, \sigma_{obs})$ and RCMs $(\mu_{contr}, \sigma_{contr})$ for the

13   control period (Fig. 3). DBS parameters for the control period were used also to adjust the

14   scenario (scen) runs. DBS procedure expressed in terms of Gaussian CDF without wet/dry

15   separation:

16    $$T_{contr}(d) = F^{-1}(F(T_{contr}(d) \mid \mu_{contr}, \sigma^2_{contr}) \mid \mu_{obs}, \sigma^2_{obs}) \qquad (1)$$

17    $$T_{scen}(d) = F^{-1}(F(T_{scen}(d) \mid \mu_{contr}, \sigma^2_{contr}) \mid \mu_{obs}, \sigma^2_{obs}) \qquad (2)$$

18   DBS procedure expressed in terms of Gaussian CDF with wet/dry separation:

19    $$T_{contr,w/d}(d) = F^{-1}(F(T_{contr,w/d}(d) \mid \mu_{contr,w/d}, \sigma^2_{contr,w/d}) \mid \mu_{obs,w/d}, \sigma^2_{obs,w/d}) \qquad (3)$$

20    $$T_{scen,w/d}(d) = F^{-1}(F(T_{scen,w/d}(d) \mid \mu_{contr,w/d}, \sigma^2_{contr,w/d}) \mid \mu_{obs,w/d}, \sigma^2_{obs,w/d}) \qquad (4)$$

21   For precipitation (P) single and double gamma distributions were used in four steps. In

22   contrast to Yang et al. (2010) where the DBS parameters (shape α and scale β) were estimated

23   seasonally, we estimated DBS parameters on a monthly basis. Single CDF for certain month

24   is used for the whole time slice (1961-2000). Also seasonally optimized parameters were tried

25   out, but these produced too high monthly precipitation sums for Finland (not shown) and thus

26   were not used. (1) For both distributions, excessive drizzle days in the RCM data were first

27   removed by defining a cut-off value $(P_{th,contr,m})$ that reduced the percentage of wet days in the

28   RCMs to that of the observations on a monthly (m) basis. In this study only days with

29   observed precipitation larger than 0.1 mm $(P_{th,obs,m})$ were considered wet days, and the rest

30   dry days. A monthly precipitation threshold value for each RCM control run $(P_{th,contr,m})$ was

then set to the cut-off value so that the percentage of RCM simulated and observed wet days matched (Eq. 5). Due to the stationary assumption ~~To enable the scenario run to have different wet day frequency than the control run~~ the same threshold value was used to reduce the drizzle days for future period to enable the scenario run to have different wet day frequency than the control run (Eq. 6). Precipitation amounts smaller than the threshold value were not redistributed to the remaining wet days.

$$P_{contr}(d) = \begin{cases} 0, & \text{if } P_{contr}(d) < P_{th,contr,m} \\ P_{contr,} & \text{otherwise} \end{cases} \qquad \underline{\qquad} \qquad (5)$$

$$P_{scen}(d) = \begin{cases} 0, & \text{if } P_{scen}(d) < P_{th,contr,m} \\ P_{scen,} & \text{otherwise} \end{cases} \qquad (6)$$

(2) The remaining daily precipitation was adjusted to match the observed frequency distribution using single gamma distribution (Eq. 7). (3) To better capture the extreme precipitation events ~~also~~ a double gamma distribution was also used, then the observed and RCM generated precipitation distributions were separated into two ~~partitions~~ by the 95th percentile of CDF ($P_{obs,95th}$, $P_{contr,95th}$), resulting into two sets of parameters (α_1, β_1) for below the 95th percentile precipitation and (α_2, β_2) above it. (4) These monthly parameters for each grid point were then used to calculate the CDFs for observations (α_{obs}, β_{obs}) and RCMs (α_{contr}, β_{contr}) during the control period (Eq. 9, 10, Fig. 3). Monthly DBS parameters for the control period and the 95th percentile threshold ($P_{contr,95th}$) were used also for the scenario (scen) runs (equations 8, 11, 12). The DBS procedure expressed in terms of single gamma CDF:

$$P_{contr}(d) = F^{-1}(F(P_{contr}(d) \mid \alpha_{contr,m}, \beta_{contr,m}) \mid \alpha_{obs,m}, \beta_{obs,m}) \qquad (7)$$

$$P_{scen}(d) = F^{-1}(F(P_{scen}(d) \mid \alpha_{contr,m}, \beta_{contr,m}) \mid \alpha_{obs,m}, \beta_{obs,m}) \qquad (8)$$

The DBS procedure expressed in terms of double gamma CDF:

$$P_{contr,1}(d) = F^{-1}(F(P_{contr}(d) \mid \alpha_{contr1,m}, \beta_{contr1,m}) \mid \alpha_{obs1,m}, \beta_{obs1,m}), \quad \text{if} \quad P_{contr}(d) < P_{contr,95^{th}}(m)$$

$$(9)$$

$$P_{contr,2}(d) = F^{-1}(F(P_{contr}(d) \mid \alpha_{contr2,m}, \beta_{contr2,m}) \mid \alpha_{obs2,m}, \beta_{obs2,m}), \quad \text{if} \quad P_{contr}(d) \geq P_{contr,95^{th}}(m)$$

$$(10)$$

$$P_{scen,1}(d) = F^{-1}(F(P_{scen}(d) \mid \alpha_{contr1,m}, \beta_{contr1,m}) \mid \alpha_{obs1,m}, \beta_{obs1,m}), \quad \text{if} \quad P_{scen}(d) < P_{contr,95^{th}}(m)$$

$$(11)$$

$$P_{scen,2}(d) = F^{-1}(F(P_{scen}(d) \mid \alpha_{contr2,m}, \beta_{contr2,m}) \mid \alpha_{obs2,m}, \beta_{obs2,m}), \quad \text{if} \quad P_{scen}(d) \geq P_{contr,95^{th}}(m)$$

$$(12)$$

Wind speed and specific humidity of the RCM data were corrected by adding the monthly mean differences between the observations and the RCMs. The same corrections were used ~~also~~ in the scenario periods. Since the wind speed and specific humidity affect only the calculation of lake evaporation in the hydrological model it is assumed that~~,~~ this simple bias correction works sufficiently well to achieve corresponding water level and discharge distribution as with observed input variables.

2.4 Hydrological model and modelling approaches

The hydrological model used in this paper was from the Watershed Simulation and Forecasting System (WSFS). It is a conceptual hydrological model developed and operated at Finnish Environment Institute (SYKE) (Vehviläinen et al., 2005). The WSFS is used as the national hydrological forecasting and flood warning system (Finnish Environment Institute 2011) as well as for research purposes (e.g. Veijalainen et al., 2012; Jakkila et al., 2014; Huttunen et al. 201~~5~~4). The conceptual rainfall-runoff model in the WSFS is based on the HBV (Hydrologiska Byråns Vattenbalansavdelning) model structure developed at SMHI (Bergström, 1976), but the models differ from each other e.g. in the river routing, catchment description and in some process models such as the snow model (Vehviläinen, 1992; Vehviläinen et al., 2005). HBV-type models have been used in several climate change impacts studies in different parts of the world (e.g. Steele-Dunne et al., 2008; van Pelt et al., 2009), most commonly in Scandinavia (e.g. Andréasson et al., 2004; Beldring et al., 2008)

The WSFS hydrological model consists of small sub-~~catchments~~basins, numbering over 6 000 in Finland with an average size of 60 km^2 (20–500 km^2) (Vehviläinen et al., 2005). The water balance is simulated for each sub-~~catchment~~basin, and sub-basin~~catchments~~ are connected to produce the water balance and simulate water storage and transfer in the river and lake network within the entire catchment. The sub-models in WSFS include a precipitation model calculating areal value and form for precipitation, a snow accumulation and melt model based

on the temperature-index (degree-day) approach, a rainfall-runoff model with soil moisture, sub-surface and groundwater storages, and models for lake and river routing.

The WSFS was calibrated against water level, discharge and snow line water equivalent observations from 1981–2012. The Nash-Sutcliffe efficiency criterion R^2 (Nash and Sutcliffe, 1970) for the control period 1961–2000 in the four case study catchments was 0.78 for Loimijoki, 0.80 for Nilakka, 0.87 for Lentua, 0.87 for Ounasjoki. The R^2-values within calibration period (1981-2000) are considerably better than in validation period (1961-1980): 0.84 and 0.71 for Loimijoki, 0.91 and 0.68 for Nilakka, 0.92 and 0.81 for Lentua, 0.87 and 0.88 for Ounasjoki respectively for calibration and validation periods. The reasons for remarkably lower values in validation period are the possible changes in rating curves in Loimijoki and Nilakka and the change of the rain station gauges from Wild to Tretjakov type gauges. The measurement errors for different gauge types are done separately (Taskinen, 2015), but the uncertainty range of wind effect on snowfalls is much larger for Wild than Tretjakov.

3   Results

A distinct seasonal cycle can be seen in both temperature and precipitation in Finland (Fig. 4). Annual mean temperature varies from above 5 ℃ in South Finland to below -2 ℃ in North Finland with maximum monthly mean temperatures in July (ca. 15 ℃) and minimum in January-February (ca. -12 ℃). The primary peak in seasonal precipitation accumulation occurs in summer (ca. 220 mm/season) and secondary in autumn (ca. 180 mm/season), spring being the driest season (ca. 110 mm/season). In this study we define torrential precipitation to be daily precipitation accumulation exceeding 20 mm/day which is the official threshold value used in FMI.

3.1   RCM temperature and precipitation in control period

The five RCMs used in this study are able to capture the annual cycle of temperature in the control period quite well, but monthly temperatures are commonly underestimated throughout the year except in winter by RCA and REMO and in autumn by HIRHAM-A (Fig. 4). The cumulative distribution functions show that all RCMs cumulate too many below 0 ℃ temperatures and too few above 0 ℃ temperatures especially in spring, although also in winter and autumn (Fig. 5).

1   There are prominent differences in the ability of RCMs to capture the annual cycle of
2   precipitation during the control period (Fig. 4). All models in this study heavily overestimate
3   precipitation accumulation almost throughout the year with some exceptions in summer and
4   winter. Especially HIRHAM-A and HIRHAM-B produce too much precipitation in spring
5   and autumn and are too dry in summer. The overestimation in accumulated precipitation is
6   relatively largest in spring, varying from 2.6–61 % in Nilakka to 24–81 % in Ounasjoki
7   (Table 2). All RCMs show a higher percentage of wet days than observed, which is caused by
8   too high percentage of light precipitation ($\leq$1 mm/day, Fig. 6). Occurrence of ~~heavy~~torrential
9   (>20 mm/day) precipitation events is overestimated in RCMs in every catchment and season.

10 After applying the DBS method, biases in seasonally calculated daily mean temperatures in
11 uncorrected RCM data are significantly reduced (Figs. 4 and 5), from -8.7–5.3 °C to -0.2–0.5
12 °C. Also the standard deviation of the DBS adjusted values is closer to observed values than
13 that of uncorrected RCM data (not shown). DBS scaling preserves the RCM temperature
14 variability in CDFs. The strong temperature increase around 0 °C found in the uncorrected
15 RCM data is reduced after DBS scaling but can still be found from the CDFs (Fig. 5),
16 although shifted towards observed values and higher temperatures. Daily temperatures
17 adjusted with wet/dry separation produce more frequently higher winter maxima (>5 °C) and
18 lower minima (<-30 °C) than adjustment without the separation (Fig. 7). These ~~This~~extrema ~~is~~
19 are originated from the separation of days to dry and wet ~~due to fewer days available for dry~~
20 ~~and wet state DBS after separation~~ which affects especially the CDF of dry days ~~and~~due to the
21 small amount of dry days (approx. 7–16 days/month) available ~~which affects especially the~~
22 ~~CDF of dry days~~. Otherwise there are no distinct differences between the two DBS
23 approaches (Figs. 4, 5, 7), both give distributions that are similar to the observations. Due to
24 the cases where daily winter maxima were excessively too high (e.g. >15 °C in January) in
25 DBS with wet/dry state separated data, the DBS method without separation is decided to use
26 in further analysis of hydrological simulations.

27 Both single and double gamma DBS approaches for precipitation are able to reduce biases in
28 seasonal precipitation accumulation from -22–81 % to -3.0–1.7 % (Figs. 4 and 6, Table 2) in
29 all catchments. Distribution of drizzle and torrential precipitation is shifted towards
30 observations and the amount of dry days is forced to match observed values (Fig. 6).

31 There are no considerable differences in monthly mean accumulated precipitation between
32 single and double gamma DBS. The largest differences are found in the treatment of heavy

($>95^{th}$ percentile of CDF>20mm) precipitation (Figs. 6 and 8). Considering daily mean precipitation amounts in the heavy precipitation distribution, DBS with double gamma overestimates daily mean heavy precipitation amounts in July by 0.2–6.5 % and DBS with single gamma by 12.0–21.7 % in Loimijoki and in Ounasjoki by -0.3–1.3 % and by 3.4–14.8 %, respectively, compared to observed values. Due to a longer tail in the single gamma distribution in the heavy precipitation end of the distribution, the high values are in many cases larger and more frequent with single gamma than with double gamma DBS. In some cases the single gamma DBS approach even increases torrential heavy precipitation values compared to observed values. In most cases the double gamma distribution produces torrential precipitation values closer to observed values than single gamma. Nevertheless, single gamma distribution was slightly better than double gamma e.g. in winter and spring in nNorthern Finland (RMSE 2.78–3.10 in single gamma and 3.07–3.10 in double gamma in January in Ounasjoki). Still, in most cases the double gamma distribution produces heavy precipitation values closer to observed values than single gamma.

3.2 RCM temperature and precipitation in the future

Finland is expected to experience a warmer and wetter climate towards the end of this century. Future changes in seasonal precipitation and mean temperature in Loimijoki catchment are shown in Table 43. After DBS adjustment, seasonal temperature increase varies from 1.4–5.1 °C in Loimijoki and 1.3–6.6 °C in Ounasjoki in the latter part of this century, being largest in winter. As for the control period, the DBS approach with wet/dry day separation produces higher temperature maxima for the scenario period compared to DBS approach without separation. Thus it also produces higher seasonal mean values than DBS scaling without wet/dry separation. No distinct differences between the single and double gamma DBS approaches can be found for monthly and seasonal mean precipitation sums. Again, the greatest differences can be found from torrential precipitations, which are more frequent and intense in single gamma than in double gamma DBS adjusted values. Future changes in seasonal precipitation sums vary more than temperature depending on RCM as well as season and area of investigation, and can even decrease by the end of this century. After DBS adjustment the change in seasonal precipitation sums varies between 1.7–39 % in Nilakka to -7.54.6–37.738% in Loimijoki by the end of this century, being largest in winter.

The DBS method preserves the temperature trend of the uncorrected RCM data during 1961–2100 relatively well (Table 54, Fig. 119). The projected temperature trends in uncorrected

1   RCM data vary between 0.3 and 0.5 °C/decade in the used scenarios. The difference between

2   uncorrected RCM and DBS adjusted seasonal trends are mainly less than ±0.1 °C/decade

3   (Table 54). The largest differences between temperature trends in uncorrected and DBS

4   adjusted data can be seen in the scenarios of REMO and RCA, which produce more than 0.1

5   °C/decade larger temperature rise after DBS (Fig. 119). This is probably due to a too narrow

6   temperature distribution (low standard deviation) in the control period compared to observed

7   values (not shown). In the scenario period the standard deviation decreases even further, with

8   increasing daily temperatures, causing more pronounced warming after DBS adjustment.

9   Other climate models in this study do not produce any prominent decrease in standard

10 deviation during the scenario period and thus the trends are better preserved.

11 Also trends in precipitation are preserved sufficiently well among RCMs after DBS

12 adjustment and no distinct differences between RCMs or the two DBS methods can be found.

13 In Loimijoki and Ounasjoki catchments most of the uncorrected scenarios show positive

14 precipitation trends from 1.1 to 4.2 mm/decade (Table 54). Only HIRHAM-A in Loimijoki

15 and REMO in Ounasjoki do not show significant trends. The differences between RCM and

16 adjusted seasonal trends are mainly from -0.6 to +0.3 mm/decade (Table 54). The largest

17 differences between trends of uncorrected and DBS adjusted RCM data can be seen in

18 seasonal precipitation simulated by HadRM in Ounasjoki (from -1.9 to -1.6 mm/decade) (Fig.

19 1210). The trend simulated by HIRHAM-B is largest in spring in all catchments, which

20 causes the large increase in precipitation accumulation (Table 43). Even though the trends are

21 largest in winter or spring, the summer and autumn remain the wettest seasons of the year.

22 ## 3.3   Impact of bias correction on simulated hydrology

23 The discharges simulated with uncorrected RCM values (Fig. 911) show large differences

24 compared to the observed discharges and discharges simulated with observed meteorological

25 input values in the control period (hereinafter referred to as "control simulation"). The

26 differences in simulated mean discharges in the control simulation and using RCM data with

27 and without DBS adjustment for Loimijoki and Ounasjoki test sites are shown in Table 3. In

28 the four test sites the annual mean discharges simulated with uncorrected RCM inputs were

29 16–104 % larger than annual mean discharges of the control simulation. The higher annual

30 mean discharges are mainly caused by overestimation of precipitation in RCMs.

The seasonal differences are more pronouncedly affected by temperature biases in the RCM data. The HadRM and HIRHAM-B have negative temperature biases during winter, which cause smaller winter discharges in Southern and Central Finland. The negative temperature biases in spring (HIRHAM-B) cause delay to the spring flood peak (Fig. 911). This delay causes negative biases to mean spring discharges in Northern Finland even though the snowmelt floods are larger due to greater snow accumulation caused by positive precipitation and negative temperature biases. Summer mean discharges become larger with all uncorrected RCM outputs due to positive precipitation biases and larger recession flows caused by greater and delayed spring floods.

~~Because of the biases in RCM data the spring mean discharges are in some cases double or even triple compared to control simulation discharges, and the seasonal variation of discharges is also altered. Without effective bias correction the results of climate change impact studies could easily lead to false conclusions.~~

Using single gamma or double gamma precipitation corrections and temperature corrections without wet/dry separation the biases in simulated mean discharges can be effectively reduced (Table 345). The differences in annual mean discharges decreased to less than 12 % in all test sites with DBS adjusted RCM outputs. The difference is at the same level as the difference between control simulation discharges and observed discharges (less than 13 %), which indicates that biases in annual mean discharges are partly explained by the model sensitivity on input variables and partly by the residual biases in corrected RCM outputs. ~~All four combinations of DBS temperature and precipitation correction methods used here produce similar results and none of the different DBS approaches are found to be superior with respect to mean discharges.~~

The differences in seasonal mean discharges between simulations with DBS adjusted RCM data and control simulation are in many cases larger than differences between observed discharges and discharges in the control simulation. Differences larger than 30 % are only found in winter and summer, when the discharges are low. But the remaining biases larger than 20 % during high flow season in Loimijoki found in REMO and RCA and larger than 50 % during the low flow season in HadRM and HIRHAM-B may have significant effect on the seasonal changes and changes in extreme discharges in climate change projections. The main reason for large and in some cases even larger remaining biases in winter discharges than in uncorrected data is the sensitivity of the hydrological model on near zero

temperatures. Even though the DBS method corrects the mean temperatures efficiently close to observations, the remaining biases in winter temperature extremes, which in control period are slightly above zero, cause remarkable biases in winter discharges and snow accumulation in the hydrological simulation. However, the seasonal variations in mean discharges after the DBS adjustment are remarkably closer to variations of ~~results from~~ control simulation (Fig. ~~9~~11), highlighting the fact that the bias correction is required for RCM data used in studies of climate change effects on hydrology.

In addition to biases in RCM temperature and precipitation data, also the biases in wind speed (WS) and specific humidity (SH) affect the WSFS discharge simulations for catchments with high lake percentages. Biases in WS and SH of RCMs affect the lake evaporation in the hydrological model and typically cause a 5–45 % bias in the annual lake evaporation sums. In most of the study catchments the bias is largest in the RCA scenario giving 25–35 % negative bias caused by positive bias of SH and negative bias of WS. The bias in lake evaporation can be effectively decreased to 0–13 % by the simple mean bias correction method (Fig. ~~10~~12).

The uncorrected WS and SH of RCMs cause a 0–11 % bias in annual mean discharges, and a 0–20 % bias in autumn mean discharges in the outlet of Nilakka, which has the highest lake percentage of the study catchments (18 %). In the catchments of Loimijoki and Lentua the biases in mean discharges (0–2 % and 0–4 %) and autumn discharges (0–7 % and 0–8 %) are smaller and in the most northern located catchment of Ounasjoki the bias is insignificant.

The effect of different correction methods on annual and seasonal discharges as well as on the changes in discharges by the 2051-90 period are shown in Figure 13. The deviations of the simulated discharges with RCM data compared to control simulations in four test sites using all five scenarios without corrections, only with temperature correction or precipitation corrections and with both temperature and precipitation corrections are shown in upper candlestick figure. The lower figure shows the results of the climate change impacts on mean discharges with different corrections. The results show that the effect of precipitation correction affects more the annual discharges and the temperature correction more the seasonal discharges. However, without temperature correction the annual discharges still have positive biases due to cold biases, which decrease evapotranspiration. All four combinations of DBS temperature and precipitation correction methods used in this study produce similar results and none of the different DBS approaches are found to be superior with respect to mean discharges. Thus the selection of the best methods is based on the performance of the

correction method in decreasing the extreme temperature and precipitation biases, in which the temperature correction without wet/dry separation and double gamma for precipitation work significantly better.

Because of the biases in uncorrected RCM data the mean discharge peaks caused by snowmelt (Fig. 11) are significantly larger than the control simulation discharge peaks, and the seasonal variation of discharges is also altered. Without effective bias correction the results of climate change impact studies could easily lead to false conclusions. The effect of DBS adjustment on changes in seasonal mean discharges is more pronounced than on annual discharges, because the temperature biases of uncorrected data have significant influence on seasonal discharges. The changes in mean winter and spring discharges may be double or even triple times larger than without temperature correction (Figure 13). If only temperature bias is corrected, the relative changes are close to the changes in temperature and precipitation corrected data, but the absolute changes are much larger due to wet bias in RCM data.

The temperature correction is essential especially when the high and low flows are studied. The difference between the changes in mean high discharges (MHQ) and mean low discharges (MNQ) by using uncorrected RCM data can be ten times larger or even to the other direction than with bias corrected data (not shown). This can also be seen in summer mean discharges with HIRHAM-B scenario. The uncorrected scenario shows 35 % decrease in summer discharges in Loimijoki due to large recession flow after spring flood in the control period, which caused over 300 % wet bias in mean summer discharges (Tables 5 and 6). The DBS adjusted data of HIRHAM-B show a slight increase in summer discharges because large precipitation increase compensates the increased evapotranspiration in this scenario.

The ability of the DBS method to preserve the precipitation and temperature trends (Figs. 9 and 10) in most cases leads to similar changes in simulated annual mean discharges with uncorrected and DBS adjusted RCM data (Figure 13 and Table 6). In the HadRM-scenario the DBS adjusted data produce a lower increase than the uncorrected scenario in Northern Finland, due to smaller increase in precipitation trends after DBS adjustment. In Northern Finland the differences between the results from simulations with uncorrected and DBS adjusted data are clearest in spring, when the absolute biases in mean discharges in the control period are highest. The uncorrected HIRHAM-A and HIRHAM-B produce negative bias in mean spring discharges in the control period due to delayed spring floods. Thus without bias corrections these scenarios produce too high increases in mean spring discharges.

3.4 Future scenarios for discharges

The results show that climate change will have significant impacts on seasonality of discharges in Finland due to increasing precipitation and shorter wintertime, which influence snow accumulation and increase evapotranspiration (Fig. 1314). The springtime snowmelt floods will occur earlier and the average wintertime discharges will increase because the temperature will rise more often above zero in winter increasing rainfall and causing occasional snowmelt. The summer discharges will decrease due to earlier snowmelt and increased evapotranspiration, while the changes in autumn depend on the climate scenario, location and hydrological characteristics such as lake percentage of the study catchments. The DBS method influences significantly the projected changes of the seasonal discharges and in some cases even the annual discharges of the scenarios with large temperature biases.

The changes in annual mean discharges between the control and 2051–2090 periods in all study catchments are between -15–26 % (Table 6). For the period 2051–2090 HIRHAM-B produces largest increases in annual mean discharges in all study catchments due to largest increases in annual mean precipitation. Most of the scenarios show an increase in annual discharges, but especially for Southern and Central Finland some scenarios project decrease because the longer and warmer summers cause larger increase in evapotranspiration than the projected increase in precipitation.

In the study catchments all DBS adjusted scenarios predict on average 2–4 weeks earlier snowmelt discharge peaks in spring for the 2051–2090 period compared to the control period 1961–2000. (Fig. 13). Figure 14 shows the results for three scenarios producing largest variation of changes in mean discharges out of five scenarios used in this study. Because the snowmelt discharge peaks occur earlier, the recession flows in summer season decrease. The summer discharges decrease 20–50 % in all scenarios except in Nilakka and Loimijoki in the HIRHAM-B-scenario, which predicts greater increase in precipitation than the other scenarios. The decrease in mean summer discharges is caused by the increase of the annual evapotranspiration by 10–40 % and lake evaporation by 10–80 %.

In addition to earlier spring discharge peaks and decrease in summer discharges, all scenarios predict increase in winter discharges. The increase is more pronounced in the catchments of Loimijoki and Ounasjoki (40–150 %), which have lower lake percentage than Nilakka and Lentua, in which the winter discharges increase 10–70 %, depending on the used scenario.

The results show an increase in autumn mean discharges in Northern Finland, where the autumn runoff peaks – typical in Southern Finland at present – become more frequent. In the catchments with large lake percentages in Southern and Central Finland the autumn mean discharges decrease in all scenarios due to increase in evapotranspiration and ~~lower~~ larger soil moisture deficit~~content~~ in the beginning of autumn. In the southern catchments with low lake percentages the change in mean autumn discharges depends on the scenario. Different autumn precipitation changes between the scenarios are the main reason for different changes in autumn discharges, but also the soil moisture content after summer has an influence and varies depending on temperature and precipitation changes during summer.

The relative changes in mean discharges, MHQ and MNQ together with changes in mean maximum snow water equivalent (SWE), mean maximum soil moisture deficit (SMD), mean evapotranspiration (ET) and mean runoff (R) in four test sites are shown in Figure 15. The changes in annual high flows are mostly negative, due to decreased maximum SWE and consequently decreasing spring snowmelt floods. Only in the HIRHAM-B scenario the MHQ increase or remains the same in most test sites due to large increase in precipitation. The annual low flows decrease in Southern Finland due to increased ET and maximum SMD, due to decrease in low flows in summer season. In Northern Finland the annual MNQ increase, because the annual low flows normally occur in winter in the control period.

4   Discussion

All five climate scenarios used in this study contain systematic biases and hydrological simulations with the uncorrected RCM data for the four study catchments therefore differ significantly from observations. Bias correction is necessary since RCM biases not only affect the absolute discharges, but can also influence the relative changes (Leander et al., 2008). As shown in the previous section the projected seasonal changes of the mean discharges in Finland are especially sensitive to RCM biases, because both the temperature and precipitation biases significantly influence the mean discharges.

Several studies comparing different bias correction methods have concluded that generally it is not possible to establish one single method, which would outperform others in all circumstances, but some methods outperform other methods more frequently (Teutschbein and Seibert, 2012; Räisänen and Räty, 2013). Teutschbein and Seibert (2012) validated five different bias correction methods with 11 RCMs and found DBS to perform best for

temperature and precipitation. Räisänen and Räty (2013) found combination of two quantile-quantile mapping (QM) methods to outperform each individual method when adjusting daily temperature from six RCMs. The disadvantage of the QM method is the need to extrapolate data in both ends of the QM function (e.g. Veijalainen et al., 2012; Räisänen and Räty, 2013). With DBS used in this study no extrapolation is needed because continuous distribution functions are used to adjust temperature and precipitation and DBS is thus considered to be more sophisticated method.

Although bias correction methods usually improve the RCM simulations substantially, other uncertainties still remain, especially for future simulations. Biases in RCMs, changing trends due to different correction procedures, and non-stationarity of climate conditions have been investigated e.g. by Teutschbein and Seibert (2013), Maraun (2012) and Maraun (2013). One disadvantage of bias correction is that the physical cause of precipitation and temperature bias is not taken into account. For instance a few degrees bias in temperature in winter affects the form of precipitation and snowmelt, which have significant impact on snow accumulation in hydrological models. A recent study by Räisänen et al. (2014) found that during the snow melt period in ECHAM5 model the air temperature rarely rises above zero as long as there is snow in the ground, leading to too low temperatures during the snow melt period. This study shows that even after the DBS adjustment the biases in the near zero temperatures remain. Especially with the RCA and REMO, which were driven by boundary conditions from ECHAM5, these biases influence the magnitude of winter and spring runoff and floods in the hydrological model simulations. Maraun (2013) stated that bias correction can even deteriorate future simulations and increase the future bias especially in areas where biased responses of surface albedo, soil moisture or cloud cover affected RCM simulations. According to Maraun (2013), biases are however relatively stable and bias correction on average considerably improves climate scenarios.

Another source of uncertainties with bias correction methods is the stationarity assumption of model biases, which means that the RCM biases do not change in time and the same correction algorithm is assumed to be valid also for future conditions. However, Teutschbein and Seibert (2013) found DBS to perform relatively well even in changing climate conditions. They separated the coldest and warmest years as well as driest and wettest years to evaluate the performance of six different bias correction procedures under systematically varying climate conditions. They found DBS to perform best of the studied bias correction methods

under changing conditions and questioned the use of simple bias correction methods such as delta-change and linear scaling. Without the possibility to validate future scenarios against observed values the best policy, according to Teutschbein and Seibert (2012), is to use an ensemble of RCMs with the best available bias correction method.

The current study shows that the effect of DBS adjustment on temperature and precipitation trends is in generally small. But with a large bias in standard deviation of the uncorrected temperature data the DBS may cause significant change in temperature trends increasing the uncertainty for the climate change projections. Also since the precipitation and temperature corrections are not interdependent, in some cases the bias in the snow accumulation remains considerably large, which leaves biases in spring discharges during the control period and certainly affects the relative changes in the future. Räisänen and Räty (2013) and Räty et al. (2014) concluded that since no single BC method outperforms others in all circumstances, the use of few different but well-performing correction methods would give more realistic range of uncertainty. In the hydrological studies the assessment of the performance should be based on the remaining biases in discharges during the control period to avoid unnecessary large uncertainty range and false conclusions about the impacts of climate change.

The DBS adjustment used in this study principally follows the method introduced by Yang et al. (2010). The method was tested using two versions of both temperature and precipitation corrections. The results show that the temperature correction in Finland works better without classification into wet and dry days. The classification is not straightforward and depends on season and area of investigation. A threshold value of observed precipitation, used to classify days to dry and wet, varies from 0 mm/day (Teutschbein and Seibert, 2012) to as high as 1 mm/day (Räty et al., 2014). In Finland RCMs produced too few days with 0 mm/day and thus a threshold value to cut off the spurious drizzle is needed. Nevertheless, a high threshold would cut too many precipitation days from both observations and RCMs and thus influence the precipitation and temperature distributions. On the other hand, when using a low threshold, e.g. 0.1 mm/day, only 20–30 % of days in autumn and winter in Finland are considered to be dry. For precipitation distribution the removal of drizzle days is important, but for temperature it is questionable whether the simulated temperature for drizzle days represents the temperature for dry days. Separation of days according to wet/dry state reduces the amount of days available for the temperature distribution on wet/dry days, which can cause biases in CDFs especially in the lower and upper tails of the distribution. Due to the

1 tendency of wet/dry separation to produce too low minima and too high maxima the DBS

2 approach without wet/dry separation produces better fit with observed values in most cases in

3 Finland.

4 The DBS method with wet/dry separation roughly takes into account the correlation between

5 temperature and precipitation, but precipitation is still adjusted without knowledge of

6 temperature. It would not be rational to divide precipitation events according to near surface

7 temperature since it does not determine the precipitation phase, but instead temperature at 850

8 hPa could be used. Also separation according to weather types could take stratiform and

9 torrential precipitation events better into account. The problem with these methods is the lack

10 of comprehensive observational data and thus some reanalysis or other climate models should

11 be used as observational data in the adjustment.

12 Two distributions, single and double gamma, were used for precipitation corrections.

13 ~~Intuitively t~~The double gamma distribution is expected to~~would~~ produce better fit with

14 observed precipitation, compared to single gamma, due to better performance with torrential

15 precipitations. However, depending on season and area of investigation single gamma

16 distribution fitted observed values and RCM simulations better than double gamma

17 distribution (e.g. RMSE 4.8–5.8 in single gamma and 5.4–5.6 in double gamma in Loimijoki

18 and 2.8–3.0 in single gamma and 3.1 in double gamma in Ounasjoki in January). In these

19 cases the area of investigation had not experienced many torrential precipitation events and

20 large part of the distribution consisted of drizzle days. Although double gamma usually

21 reproduces torrential precipitation events better than single gamma, the cut off value of 95 %

22 does not always produce the best results. At least for colder regions like Finland where

23 torrential precipitation events are relatively rare the cut off value could be even higher (e.g. 98

24 %) to get better gamma fit also for the torrential values. After applying the 95% cut off value,

25 the torrential 5% means roughly precipitation values higher than 10 mm/day although by

26 definition 20 mm/day is the threshold for torrential precipitation in Finland. In addition, the

27 highest 5 % of precipitation distribution does not in most cases produce real gamma function

28 and thus the gamma fit might not be valid. One problem with double gamma distribution

29 occurred near (below and above) the ~~torrential~~ cut-off value for heavy precipitation because it

30 caused discontinuity in the distribution and thus cumulated too much precipitation around this

31 point. In Finland this means an increase in near 10 mm/day precipitation amounts compared

32 to observed values. Considering accumulated monthly mean precipitation amounts below and

above the 95 % cut off value we observed that in most cases DBS with double gamma accumulated more precipitation below the 95 % cut off value and less above the 95 % cut off value than single gamma (e.g. -1.3–7.8 % below the 95 % cut off value and -26.2–0.7 % above the 95 % cut off value in March in Loimijoki, respectively). Nevertheless, the monthly total accumulated precipitation is better represented by DBS with double gamma distribution when compared to observed values. For example DBS with double gamma gives 0.3–0.8 % higher monthly mean precipitation accumulation than observations in March in Loimijoki and DBS with single gamma 0.3–1.3 %, respectively.

Precipitation varies considerably on spatial and temporal scales and thus to use either single or double gamma distribution alone is a somewhat stiff procedure. The importance of the torrential precipitations is more pronounced in the impact studies of flash floods and floods in small river catchments, which respond quickly to extreme precipitation. In the larger watersheds, the high discharges usually correlates better with 5 to 15 days extreme precipitation sums than torrential values due to the delay caused by soil moisture deficit, river transport, lake storage and wetlands inside the catchment. Thus the tendency of double gamma correction to increase the near 10 mm/day precipitations may deteriorate the DBS ability to reproduce the observed extreme discharges compared to single gamma distribution. A trade-off tool to see whether single or double gamma distribution fits better could be developed, but problems would occur when either observed or RCM simulated precipitation would not produce the same selection of gamma distribution.

Previously the most commonly used method to estimate climate change impacts on hydrology was the delta change method (e.g. Andréasson et al., 2004; Steele-Dunne et al., 2008; Veijalainen et al., 2010). Often a very simple version of this method, where only the monthly mean changes of temperature and precipitation from climate model simulations were used to modify the observed temperature and precipitation records, was used (Hay et al., 2000). Compared to delta change methods the BC methods better preserve the variability in temperature and precipitation produced by the RCMs (Lenderink et al., 2007; Graham et al., 2007; Beldring et al., 2008; Yang et al., 2010). Veijalainen (2012) showed that with delta change and with QM method the changes in discharges for four catchments in Finland were similar for annual means. However, larger differences were found in flood estimates and in seasonal values. Especially during spring in nNorthern Finland the delta change method produced earlier snowmelt than the bias corrected RCM data. The changes in annual and

seasonal discharges as well as in timing of the spring discharge peaks with DBS adjusted RCM data of this study are in good agreement with results of QM method used by Veijalainen et al. (2012). The result supports the idea to use both methods in future studies to better cover the uncertainty range caused by bias correction. On the other hand the extrapolation of the data in QM method may increase the uncertainty of the climate projections.

The uncertainties in estimation of climate change impacts on hydrology remain large, since the process of estimation is complicated and each step contains uncertainties. The results show large differences between the five climate scenarios used in this study and climate scenarios have been shown to be a major source of the uncertainties in the climate change assessments (Steele-Dunne et al., 2008; Prudhomme and Davies, 2009). The hydrological model and its sub-models also cause uncertainties in the results. Hydrological model structure and parameter uncertainties are not considered, but other studies indicate that these can be substantial, although not among the largest sources of uncertainty (Steele-Dunne et al., 2008; Prudhomme and Davies, 2009). Within the WSFS hydrological model, the snow model and evapotranspiration model are the most important sub-models influencing the results, and the evaluation of different versions of these sub-models would be required for the proper estimation of the hydrological model and overall estimation of the uncertainties.

5   Summary and Conclusions

The use of bias corrected RCM data as input to impact models is becoming a common practice. The choice of bias correction method significantly affects estimation of climate change impacts on hydrology. The DBS algorithm has been shown to perform well under changing conditions and outperform other methods in many cases (Teutschbein and Seibert, 2012; Räty et al. 2014) and was therefore selected for this study. Two different DBS methods for temperature (with and without dry/wet day separation) and two for precipitation (single and double gamma distribution) were compared. This paper focuses on mean values of temperature, precipitation and discharges simulated with hydrological model of WSFS in four catchments. The DBS adjustment significantly improves RCM data and simulated discharges compared to observations, but the magnitude of the biases of the uncorrected RCM data still influence the success of the DBS method.

Both gamma distributions used in the DBS method for precipitation provide reasonable results for Finland, where precipitation extremes are moderate in all seasons. Double gamma distribution reproduces monthly precipitation amounts and torrential values better than single

gamma distribution, but the cut-off value in 95th percentile is too low in some cases and it could be better to determine specifically for northern climate conditions. For temperature, the small fraction of dry days during some seasons affects the DBS temperature adjustment with dry/wet separation, and thus for temperature the method without dry/wet separation performs better. With most scenarios the DBS method preserves temperature and precipitation trends projected by uncorrected RCMs data sufficiently well. However, in cases when the simulated seasonal cycle of precipitation in RCM is not correct, the DBS adjustment changes the trend more than for cases with correct seasonal cycle. Also, too narrow standard deviation of uncorrected RCM data compared to observed deviation leads to increased temperature trends after DBS adjustment with two scenarios. The cold bias found in RCMs during snow melt can be reduced by DBS method, but the remaining biases are found to influence the timing of snow melt and the magnitude of winter and spring discharges in hydrological simulations.

The projected changes in annual mean discharges by 2051–2090 are moderate, but seasonal distribution of discharges will change significantly. The most notable changes are increasing winter discharges, decreased and earlier spring discharge peaks and decreasing summer discharges due to longer and warmer summer and increased evapotranspiration. The autumn discharges are projected to increase in Northern Finland and decrease in the catchments with high lake percentage in Southern Finland. The different RCMs produce a wide range of variability on magnitude of the changes. Contrary to the other scenarios used in this study, the HIRHAM-B scenario produces an increase in summer discharges due to greater precipitation increase. Also the effect of different scenarios on mean autumn discharge in the fast responding southern catchments is scenario dependent.

For relative changes in future discharges the bias correction affects mainly the seasonal results. The differences between changes in seasonal discharges with corrected and uncorrected RCM data are significant especially in the scenarios with large temperature biases. The correct seasonal changes are important when any detailed analysis of adaptation strategies for example in lake regulation rules or flood risk analysis, are considered. Especially the extremes – floods and droughts – are sensitive to both temperature and precipitation biases and without bias correction even the results of relative changes in floods can be misleading. The impact of the bias correction on precipitation extremes and on simulated extreme discharges will be examined in the next phase of this study and published in a separate paper.

Since the choice of the bias correction method influences the results and the best method cannot usually be assessed, an ensemble of bias correction methods to incorporate this uncertainty to the other sources of uncertainty such as choice of emission scenario, climate or hydrological model could be used in the future. However, the evaluation of sufficiently well performing bias correction methods is required to avoid unrealistic results in the climate change impact assessments. The remaining biases in temperature and precipitation data, independent adjustments for meteorological variables or changing temperature and precipitation trends in some climate scenarios after the DBS adjustment cause additional uncertainty in the hydrological simulations and these should be considered when the results are interpreted.

Acknowledgements

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8

1   Table 1. Regional climate model (RCM) data used in this study.

Name/Acronym	RCM	GCM	Emission scenario
HIRHAM-A	HIRHAM5	ARPEGE	A1B
HIRHAM-B	HIRHAM5	BCM	A1B
REMO	REMO	ECHAM5	A1B
RCA	RCA	ECHAM5	A1B
HadRM	HadRM3Q0	HadCM3Q0	A1B

2

Table 2. Deviation between observed and RCM accumulated seasonal precipitation during control period (1961–2000) in uncorrected and DBS adjusted (single gamma=1 gamma, double gamma=2 gamma) precipitation in %. Values are shown for Loimijoki in Southern Finland and Ounasjoki in Northern Finland to demonstrate the spatial variation.

	UNCOR-RECTED	1 GAMMA	2 GAMMA	UNCOR-RECTED	1 GAMMA	2 GAMMA
WINTER	Loimijoki			Ounasjoki		
HIRHAM-A	53,04	0,23	-0,05	45,27	-0,53	-0,55
REMO	12,22	0,52	0,19	34,55	0,04	-0,26
RCA	5,42	0,04	-0,18	5,93	-0,59	-0,57
HadRM	-0,62	-0,76	-0,46	12,37	-1,49	-0,88
HIRHAM-B	2,11	-0,69	-0,65	-3,85	-0,86	-0,53
SPRING						
HIRHAM-A	77,04	0,73	0,39	80,50	1,58	0,74
REMO	29,71	1,04	0,59	54,51	1,58	0,73
RCA	30,91	0,47	0,26	23,75	0,44	0,16
HadRM	42,41	0,22	0,15	35,76	-0,55	-0,23
HIRHAM-B	40,80	0,93	0,57	39,34	1,31	0,64
SUMMER						
HIRHAM-A	-21,75	-2,72	-1,26	16,81	-1,16	-0,46
REMO	2,90	-0,09	0,03	16,44	0,15	0,09
RCA	27,19	1,29	0,56	17,31	0,51	0,23
HadRM	1,27	-0,15	-0,03	26,88	-0,67	-0,20
HIRHAM-B	-20,53	-1,47	-0,63	-1,38	-1,47	-0,60
AUTUMN						
HIRHAM-A	24,27	-0,54	0,01	55,70	0,59	0,49

REMO	6,65	0,35	0,42	41,47	1,08	0,78
RCA	22,94	0,91	0,68	34,23	1,22	0,72
HadRM	-10,56	-0,61	-0,12	18,65	-0,53	0,06
HIRHAM-B	17,17	0,87	0,85	21,96	0,26	0,31

1

Table 43. Changes in uncorrected and DBS adjusted RCM seasonal precipitation sums in % and daily mean temperatures as °C between control (1961–2000) and scenario periods (2051–2090). Values are shown for winter and spring in Loimijoki catchment in Southern Finland.

	Precipitation %			Temperature °C		
WINTER	UNCOR-RECTED	1 GAMMA	2 GAMMA	UNCOR-RECTED	W/D Gaussian	Gaussian
HIRHAM-A	11.0	12.3	11.2	2.9	3.0	2.7
REMO	12.7	15.7	13.9	3.4	5.1	4.5
RCA	19.0	21.0	19.7	3.6	4.7	4.2
HadRM	9.3	8.9	8.6	4.4	5.0	4.5
HIRHAM-B	23.6	25.4	26.2	4.9	4.3	3.8
SPRING						
HIRHAM-A	-4.6	-4.0	-4.6	2.7	2.6	2.5
REMO	9.2	13.2	11.7	2.8	3.4	3.3
RCA	16.7	17.1	17.8	2.7	3.8	3.6
HadRM	6.7	7.3	6.1	4.5	4.3	4.1
HIRHAM-B	27.1	37.7	34.2	3.8	3.5	3.4
SUMMER						
HIRHAM-A	-6.8	-7.5	-6.7	2.1	2.4	2.4
REMO	13.7	14.0	13.6	2.3	2.9	2.7
RCA	11.4	13.9	13.3	2.0	3.3	3.2
HadRM	8.9	7.5	7.5	4.0	4.3	4.2
HIRHAM-B	17.0	16.4	15.9	1.4	1.4	1.5
AUTUMN						
HIRHAM-A	1.0	0.4	-0.5	1.4	1.4	1.4
REMO	11.2	11.8	10.4	2.8	3.9	3.6

RCA	11.7	13.4	11.9	2.8	3.8	3.5
HadRM	4.5	4.5	3.7	4.2	4.3	4.0
HIRHAM-B	6.4	7.3	7.0	3.0	2.7	2.5

1

1 Table 5̶4. Trends in seasonal precipitation sum (mm/decade) and temperature (°C/decade) in

2 uncorrected and DBS adjusted RCM simulations. Values are shown for spring in Loimijoki

3 and Ounasjoki to demonstrate the spatial variation.

	Precipitation mm/decade		Temperature °C/decade		
SPRING	Loimijoki	Ounasjoki	SPRING	Loimijoki	Ounasjoki
HIRHAM-A	-0.2	1.1	HIRHAM-A w/d g̶Gaussian	0.3	0.5
1 gamma	-̶0.1	1.3		0.3	0.5
2 gamma	-0.1	1.3	G̶gaussian	0.3	0.4
REMO	1.4	-0.1	REMO w/d g̶Gaussian	0.3	0.4
1 gamma	1.6	0.1		0.4	0.5
2 gamma	1.4	0.1	g̶Gaussian	0.4	0.5
RCA	2.3	1.5	RCA w/d g̶Gaussian	0.3	0.3
1 gamma	1.8	1.2		0.4	0.6
2 gamma	1.9	1.2	g̶Gaussian	0.4	0.5
HadRM	1.1	4.9	HadRM w/d g̶Gaussian	0.5	0.5
1 gamma	0.8	3.3		0.5	0.6
2 gamma	0.7	3.3	g̶Gaussian	0.5	0.5
HIRHAM-B	4.2	3.5	HIRHAM-B w/d g̶Gaussian	0.4	0.4
1 gamma	4.7	3.5		0.4	0.4
2 gamma	4.4	3.5	g̶Gaussian	0.4	0.4

4

Table 35. Deviation of simulated annual and seasonal mean discharges (MQ) between observed, uncorrected and DBS adjusted temperature (Gaussian) and precipitation (1 or 2 gamma) as input for hydrological simulations during control period (1961–2000) in %. Values are shown for Loimijoki in Southern Finland and Ounasjoki in Northern Finland to demonstrate the spatial variation.

	UNCOR-RECTED	1 GAMMA	2 GAMMA	UNCOR-RECTED	1 GAMMA	2 GAMMA
YEAR	Loimijoki			Ounasjoki		
HIRHAM-A	85.7	9.5	10.1	104.2	3.3	3.2
REMO	58.0	12.3	11.8	78.6	5.7	5.1
RCA	89.0	12.7	11.5	48.5	4.9	4.4
HadRM	35.3	9.4	9.8	48.9	1.9	2.8
HIRHAM-B	63.3	10.0	9.8	56.6	2.9	3.1
WINTER						
HIRHAM-A	86.7	22.9	22.1	85.7	12.5	12.6
REMO	16.4	-22.4	-21.7	73.8	-7.9	-8.3
RCA	33.5	-12.1	-12.3	67.5	3.8	3.2
HadRM	-43.3	60.3	61.8	18.8	34.2	35.5
HIRHAM-B	-46.1	79.1	79.0	19.1	46.7	46.7
SPRING						
HIRHAM-A	92.9	10.0	10.1	-20.8	-0.6	-0.8
REMO	57.0	27.6	26.8	39.0	1.2	0.9
RCA	54.6	23.8	23.4	43.9	8.7	8.5
HadRM	67.7	-9.5	-9.5	12.2	-2.5	-2.0
HIRHAM-B	64.1	-16.6	-16.5	-76.4	3.4	3.6
SUMMER						

HIRHAM-A	142.8	7.2	8.2	231.8	3.0	2.8
REMO	161.4	38.6	35.2	108.3	20.1	19.0
RCA	238.0	28.6	22.7	21.6	0.7	0.2
HadRM	140.5	4.9	3.7	97.0	-0.7	0.3
HIRHAM-B	308.2	-4.5	-5.1	220.7	-14.0	-13.8
AUTUMN						
HIRHAM-A	44.3	-2.7	-0.2	117.9	6.7	6.8
REMO	51.4	1.1	1.2	99.7	-4.1	-4.7
RCA	143.0	5.7	3.8	92.2	5.96.0	4.7
HadRM	-2.3	7.3	8.1	46.6	0.0	1.1
HIRHAM-B	57.7	11.5	11.0	32.6	10.8	11.2

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Table 6. Relative changes (%) in simulated annual and seasonal mean discharges (MQ) in Loimijoki and Ounasjoki between control period (1961–2000) and future period (2051–2090) using uncorrected and DBS adjusted temperature (Gaussian) and precipitation (1 or 2 gamma).

	UNCOR-RECTED	1 GAMMA	2 GAMMA	UNCOR-RECTED	1 GAMMA	2 GAMMA
YEAR	Loimijoki			Ounasjoki		
HIRHAM-A	-3.8	-5.9	-8.1	9.1	9.1	9.0
REMO	7.4	10.5	6.8	-0.3	-5.5	-5.3
RCA	10.1	9.8	8.5	8.6	3.4	3.4
HadRM	-6.8	-6.8	-7.6	15.3	5.0	6.1
HIRHAM-B	16.0	25.6	24.7	17.7	18.7	18.0
WINTER						
HIRHAM-A	69.8	65.2	63.1	71.1	90.3	89.8
REMO	104.2	151.5	141.1	68.6	40.9	40.6
RCA	107.6	143.2	140.0	73.8	76.4	76.6
HadRM	204.5	37.7	36.5	76.1	128.9	131.8
HIRHAM-B	148.0	50.7	51.2	44.9	74.9	68.4
SPRING						
HIRHAM-A	-25.6	-32.2	-33.3	134.3	26.0	26.0
REMO	-18.6	-21.9	-23.4	24.2	20.2	19.8
RCA	-21.9	-23.8	-23.7	-1.1	11.5	12.0
HadRM	-31.3	-29.6	-29.4	72.3	4.2	5.2
HIRHAM-B	21.2	17.5	14.7	206.3	16.5	18.1
SUMMER						
HIRHAM-A	-31.7	-31.3	-32.9	-39.1	-39.7	-39.6

REMO	-17.0	-27.7	-31.6	-43.9	-49.8	-49.2
RCA	-5.9	-34.4	-35.8	-20.3	-41.3	-41.2
HadRM	-25.4	-23.3	-25.4	-38.5	-49.7	-49.3
HIRHAM-B	-34.5	2.2	1.3	-9.1	-17.7	-17.7
AUTUMN						
HIRHAM-A	-10.6	-15.2	-19.5	28.3	21.9	21.5
REMO	13.0	18.0	11.5	18.8	19.1	19.6
RCA	12.5	12.2	8.2	26.2	27.5	26.8
HadRM	-13.0	-22.1	-23.7	37.5	23.0	24.4
HIRHAM-B	23.1	9.5	9.1	55.6	36.1	34.2

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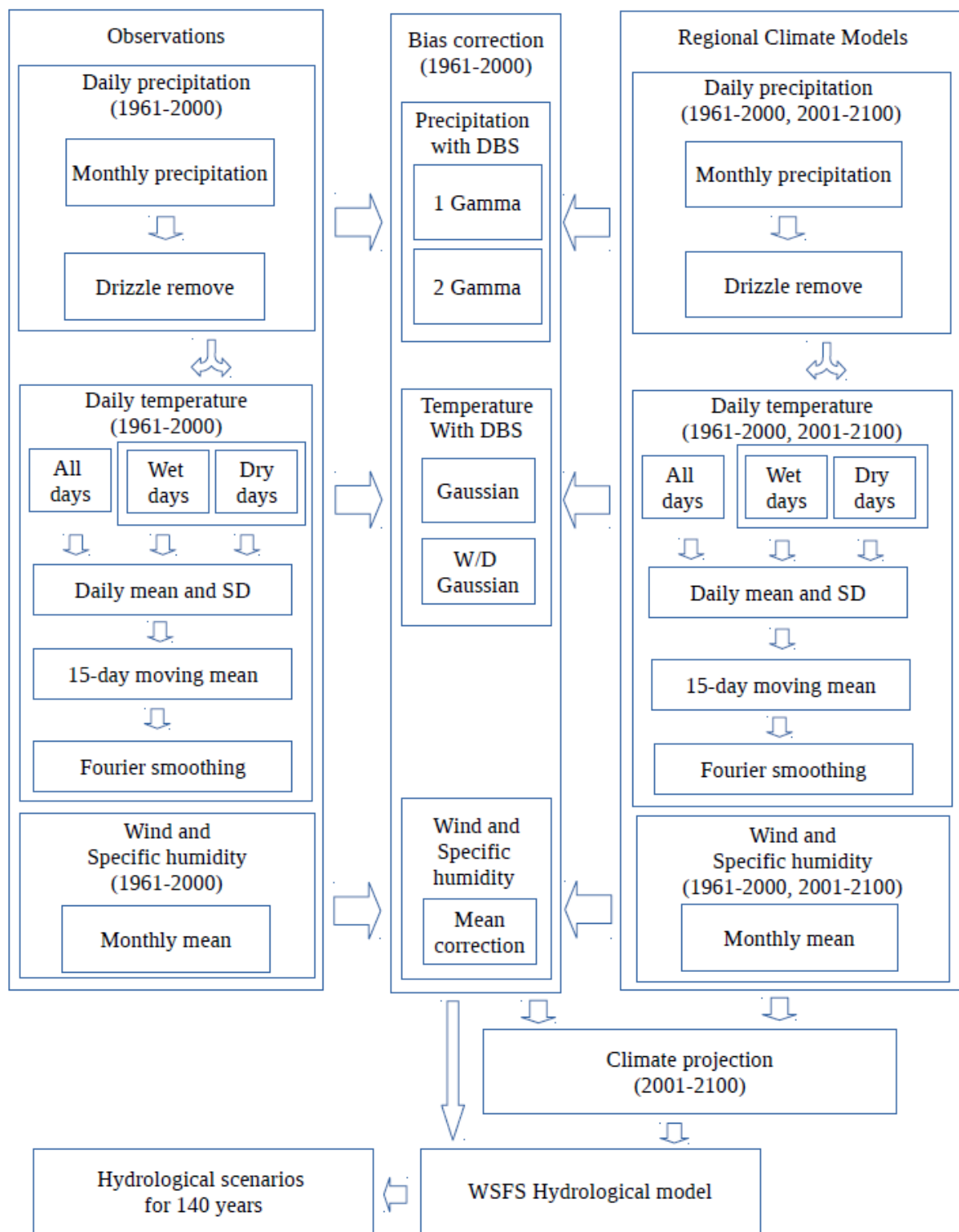
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2   Figure 1. Schematic presentation of application procedure used in this study for hydrological

3   modelling of climate change impact with bias corrected RCM data.

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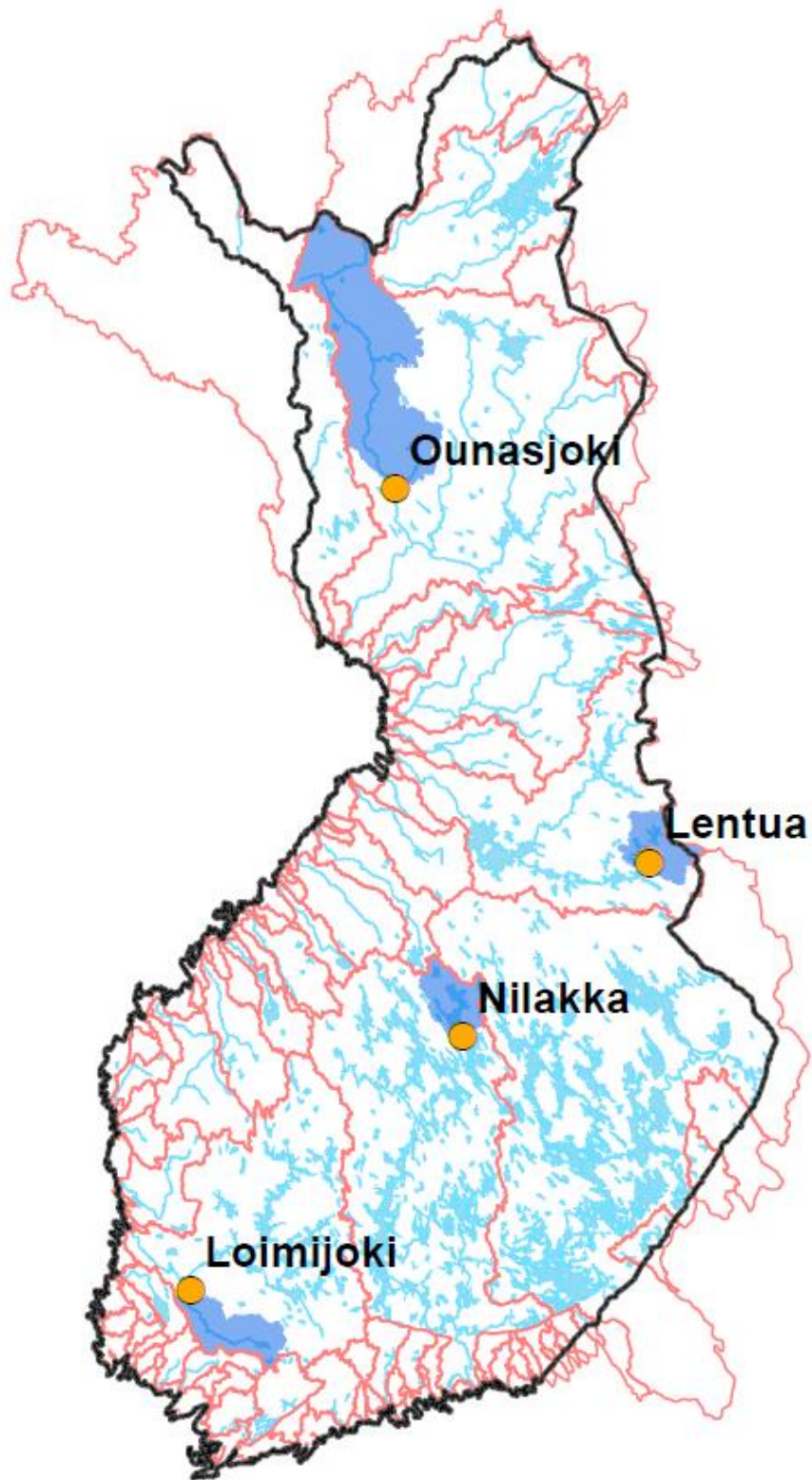
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2   Figure 2. Map of the study catchments.
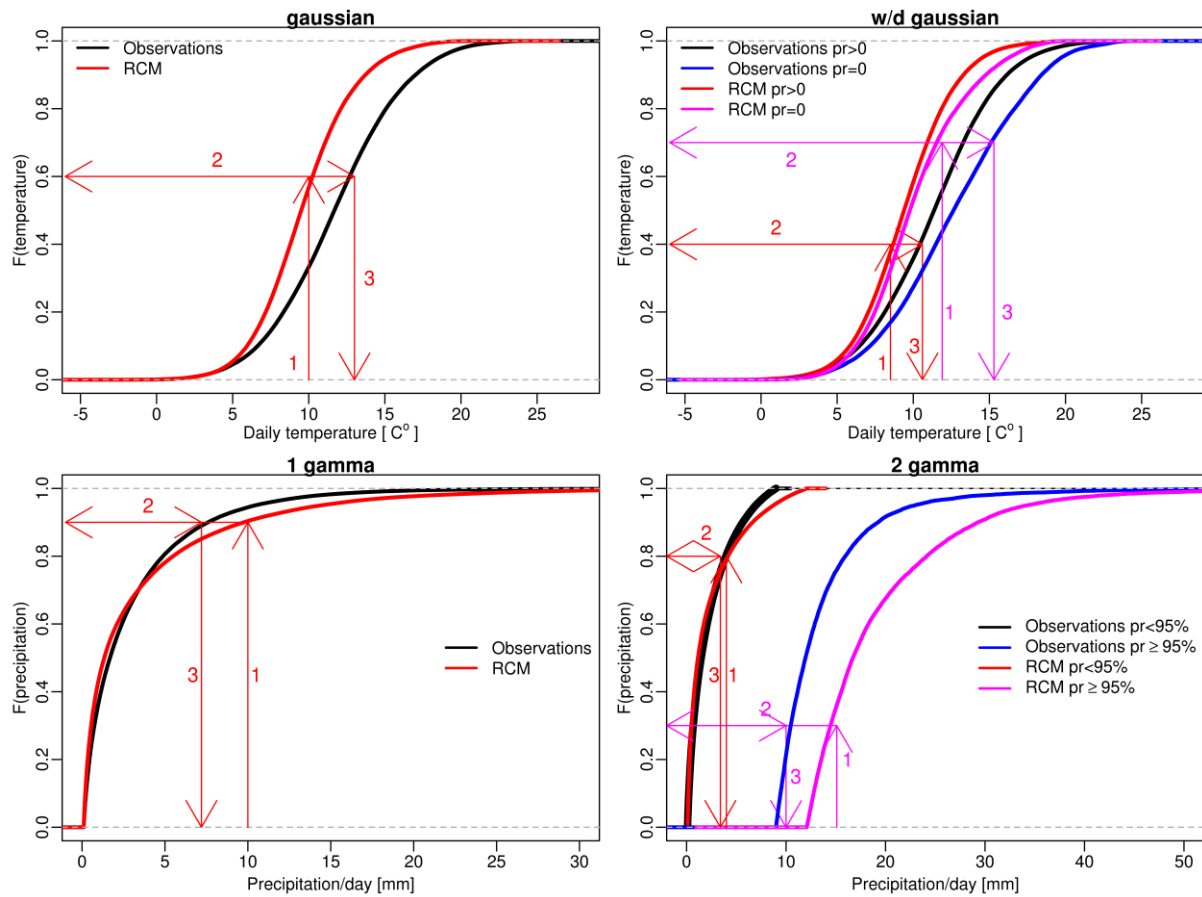
Figure 3. Procedure of the distribution based mapping. Upper panels for temperature adjustment and lower panels for precipitation (pr) adjustment. For temperature, Gaussian adjustment without wet/dry state separation (left) and with wet/dry separation (right) is shown. For precipitation, gamma adjustment with single gamma (left) and double gamma divided at 95th percentile (right) is shown. 1. Locate the cumulative probability value of RCM simulated daily temperature/precipitation. 2. Locate the observed temperature/precipitation value corresponding the same cumulative probability value as in (1). 3. This value is used as corrected value for RCM simulation.
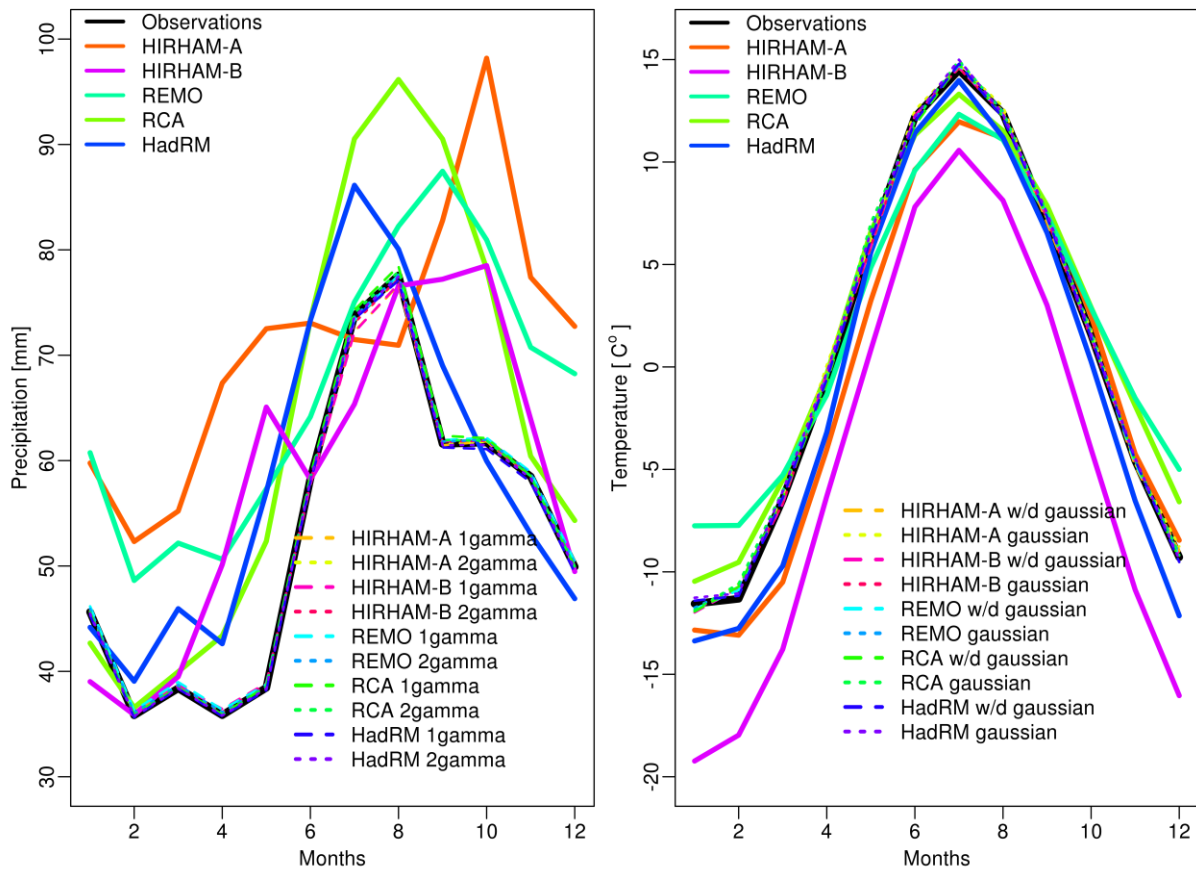
Figure 4. Monthly mean precipitation accumulation (left) and temperature (right) in observations and RCMs in Finland during the control period 1961–2000. Observations (black) and uncorrected RCMs (colours) in solid lines, adjusted RCMs in dashed and dotted lines. Monthly mean precipitation adjusted with single gamma (1-gamma) are presented as dashed lines, and with double gamma (2-gamma) as dotted lines (left panel). Monthly mean temperatures adjusted with wet/dry state separation (w/d Gaussiancorr) are presented as dashed lines and without wet/dry separation (Gaussiancorr) as dotted lines (right panel). All adjusted values follow closely the observations and no big differences can be seen between the two bias correction procedures
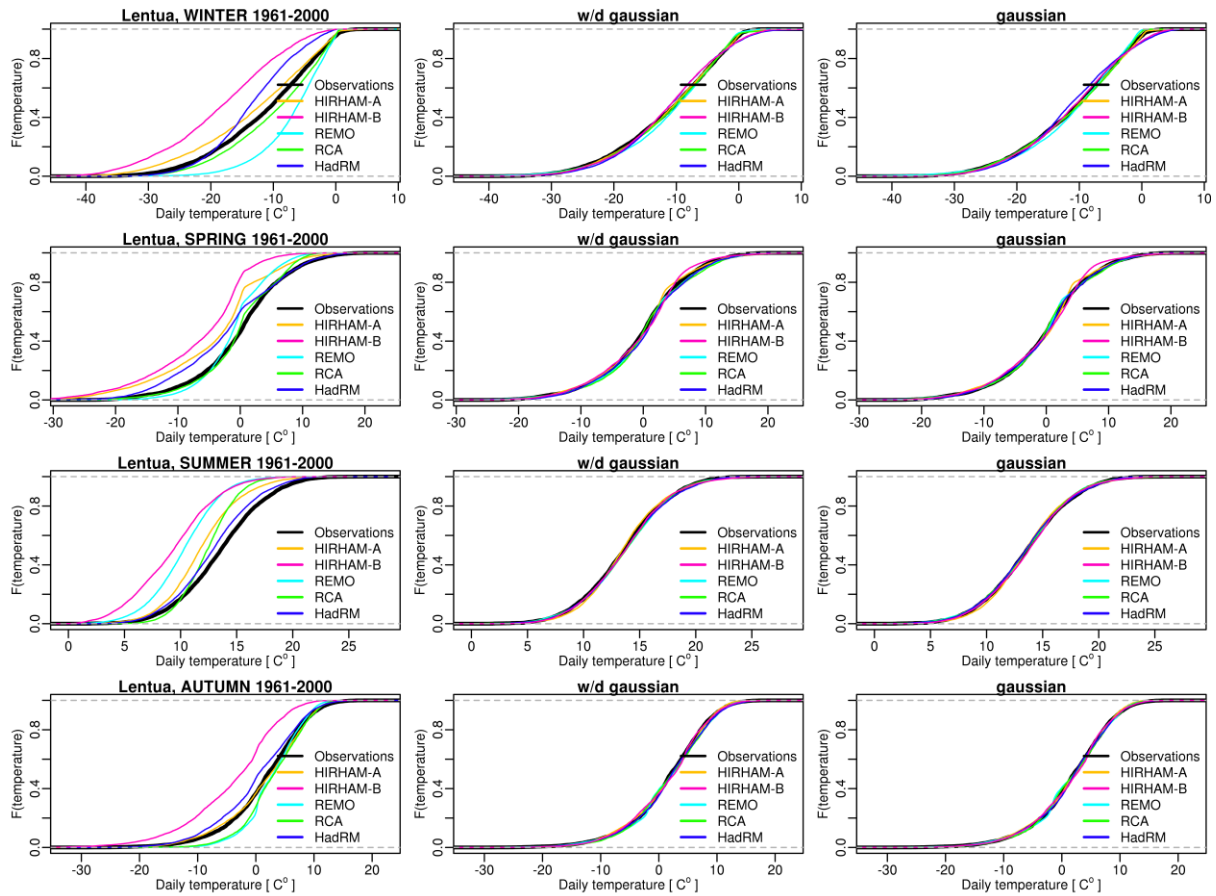
Figure 5. Cumulative distribution functions for daily temperature in Lentua catchment during control period (1961–2000). Observations and uncorrected RCM data in left column, daily RCM temperatures adjusted with wet/dry state separation (w/d gGaussiancorrected) are presented in middle column and without wet/dry separation (gGaussiancorrected) in right column. Winter is shown in first row, spring in second row, summer in third row and autumn in bottom row. All the adjusted values follow closely the observed distribution and no big differences can be seen between the two bias correction procedures.
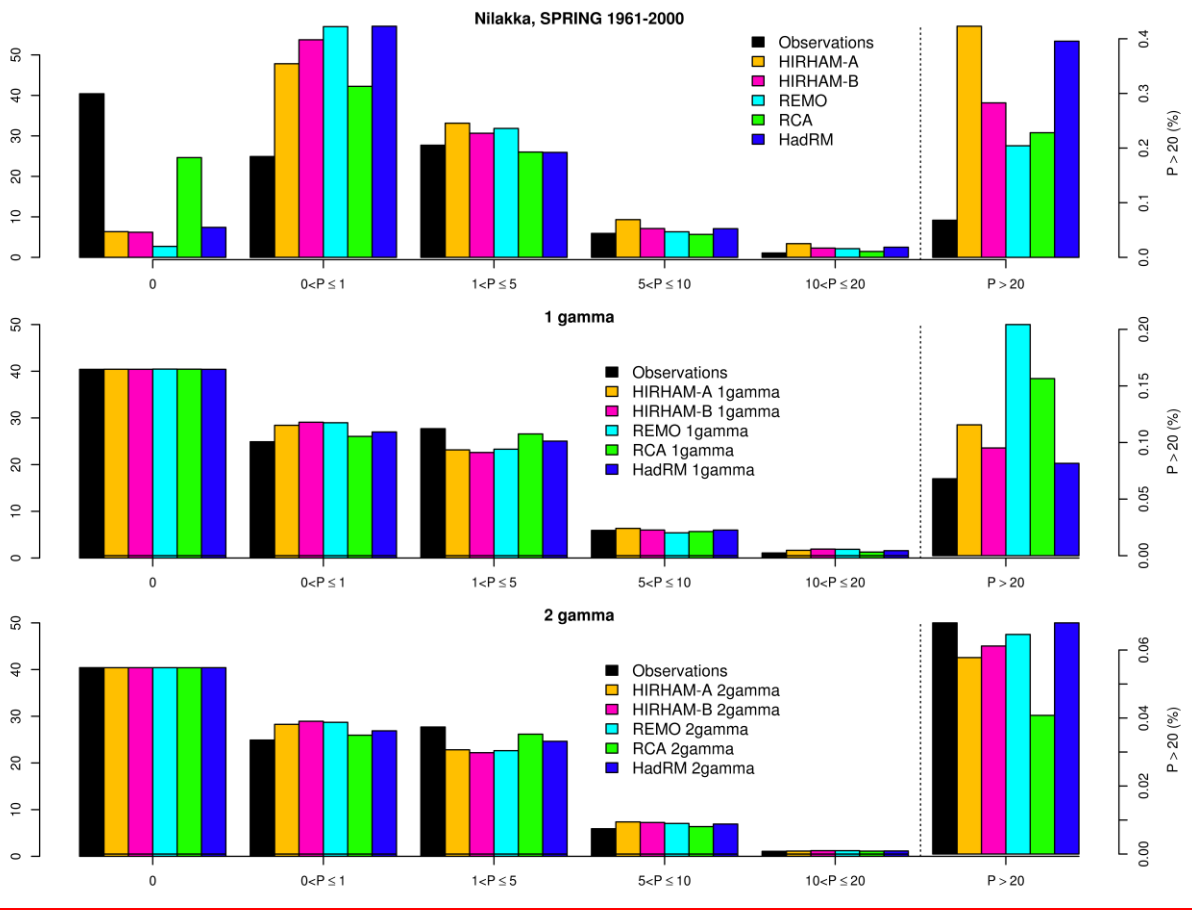
Figure 6. Distribution of daily precipitation amounts during control period (1961–2000) spring in Nilakka catchment in observations and uncorrected RCM data (top panel), single Gamma adjusted RCM data (middle panel) and double Gamma adjusted RCM data (bottom panel). Notice the uneven precipitation division and different scaling for precipitation amounts greater than 20 mm/day.
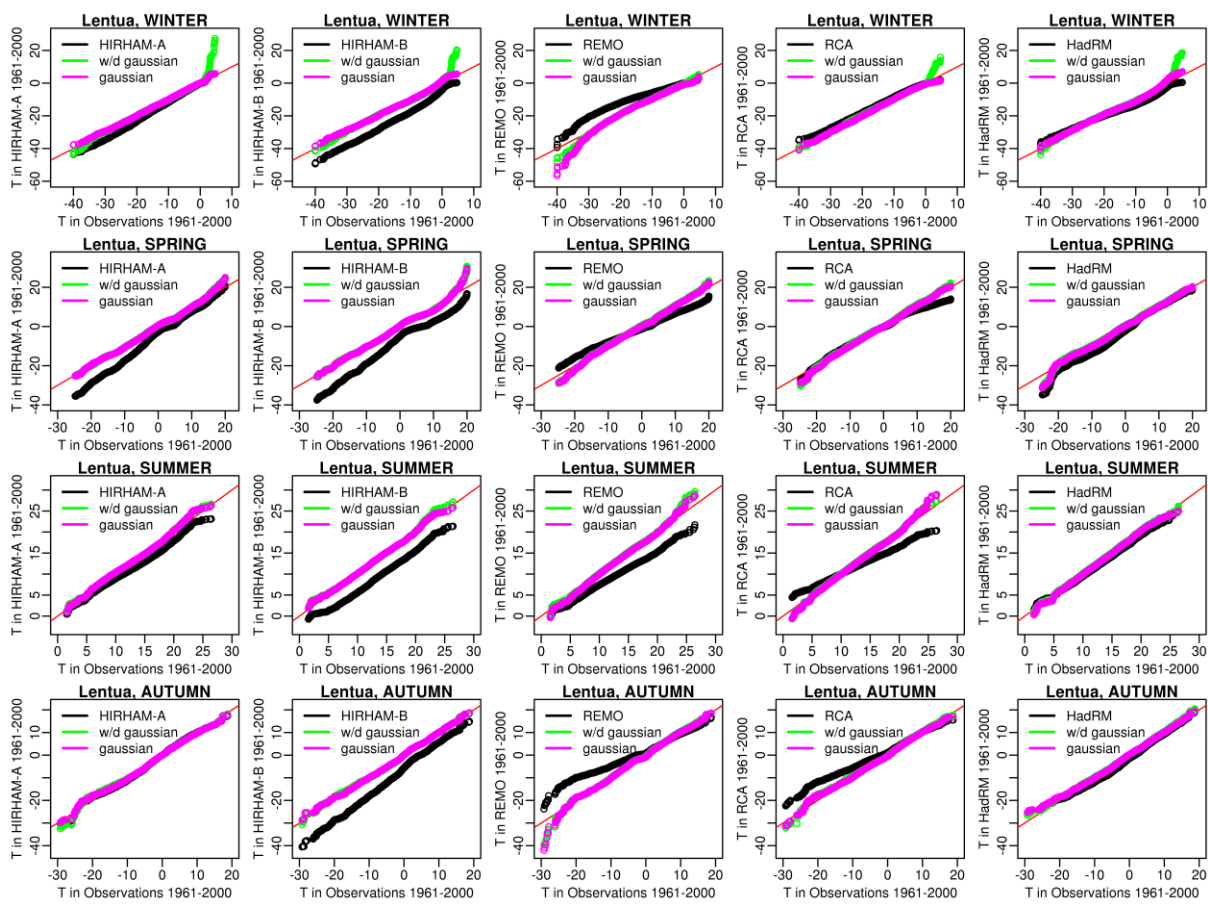
Figure 7. Comparison between uncorrected (black) and DBS adjusted (pink without wet/dry state separation and green with wet/dry state separation) daily temperatures during control period 1961–2000 in Lentua. Red line indicates observed abline.
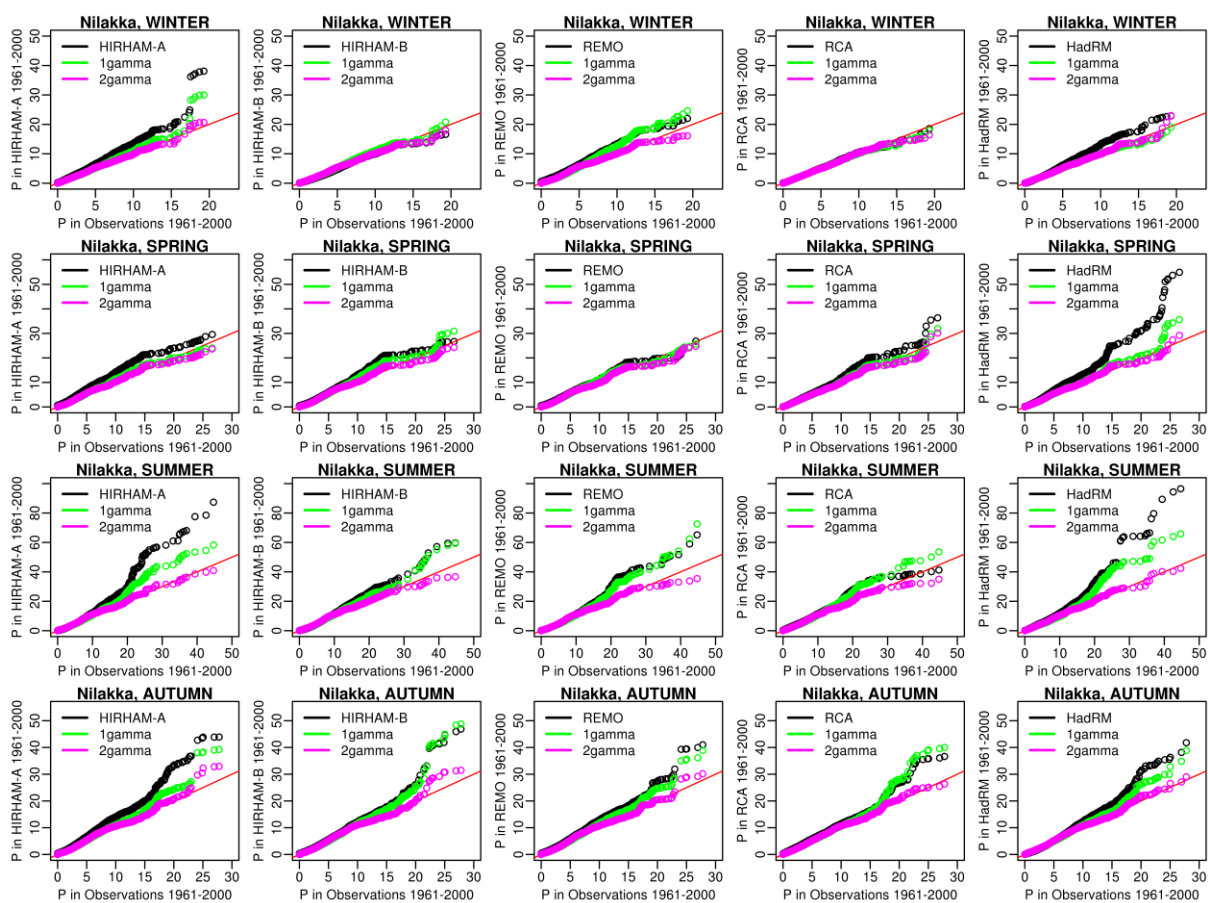
Figure 8. Comparison between uncorrected (black) and DBS adjusted daily precipitation (single gamma in green and double gamma in pink) during control period 1961–2000 in Nilakka. Red line indicates observed abline.
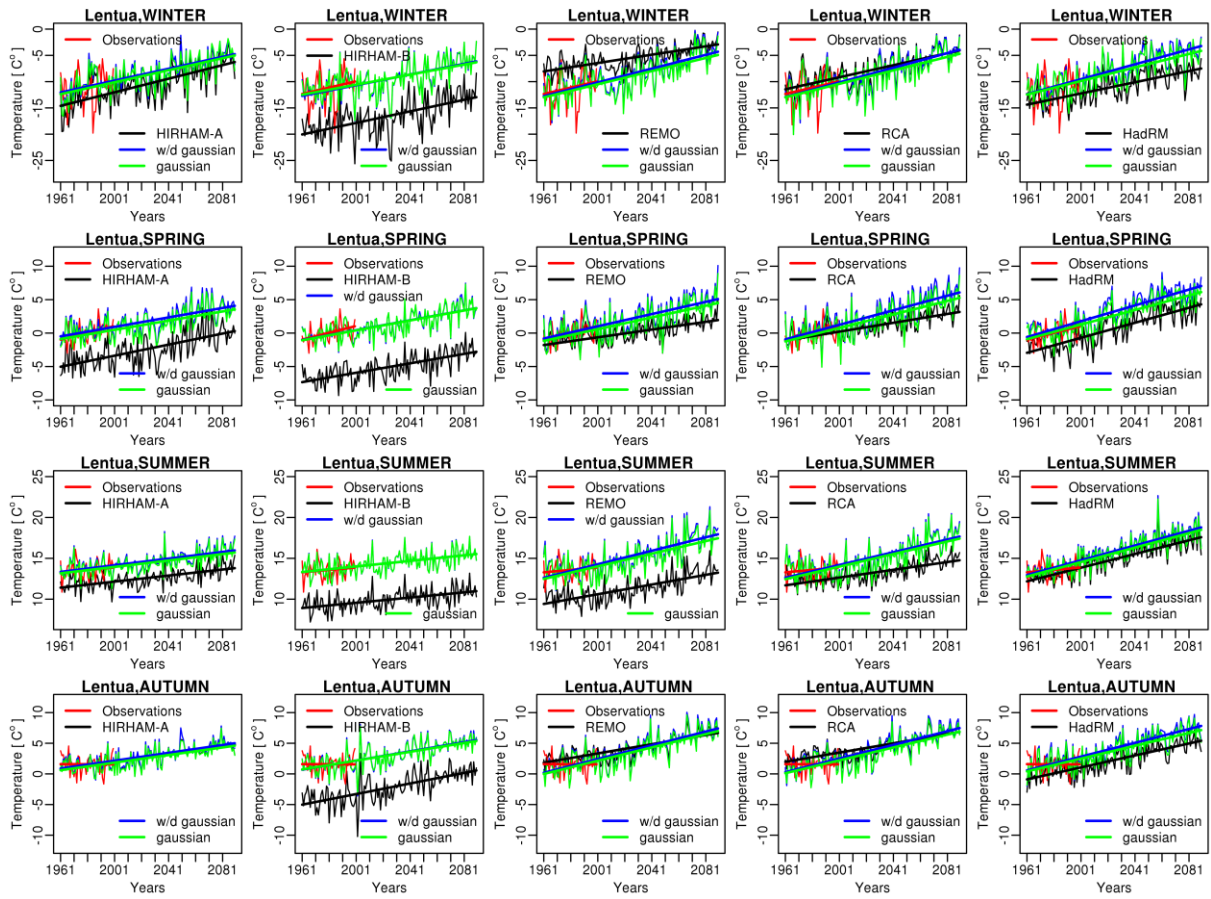
Figure ~~11~~9. Seasonal trends in observed (red, 1961–2000) and RCM simulated daily temperatures in Lentua basin during 1961–2090. Uncorrected RCM daily temperatures in black, temperatures adjusted with wet/dry separation in blue and without wet/dry separation in green.

58
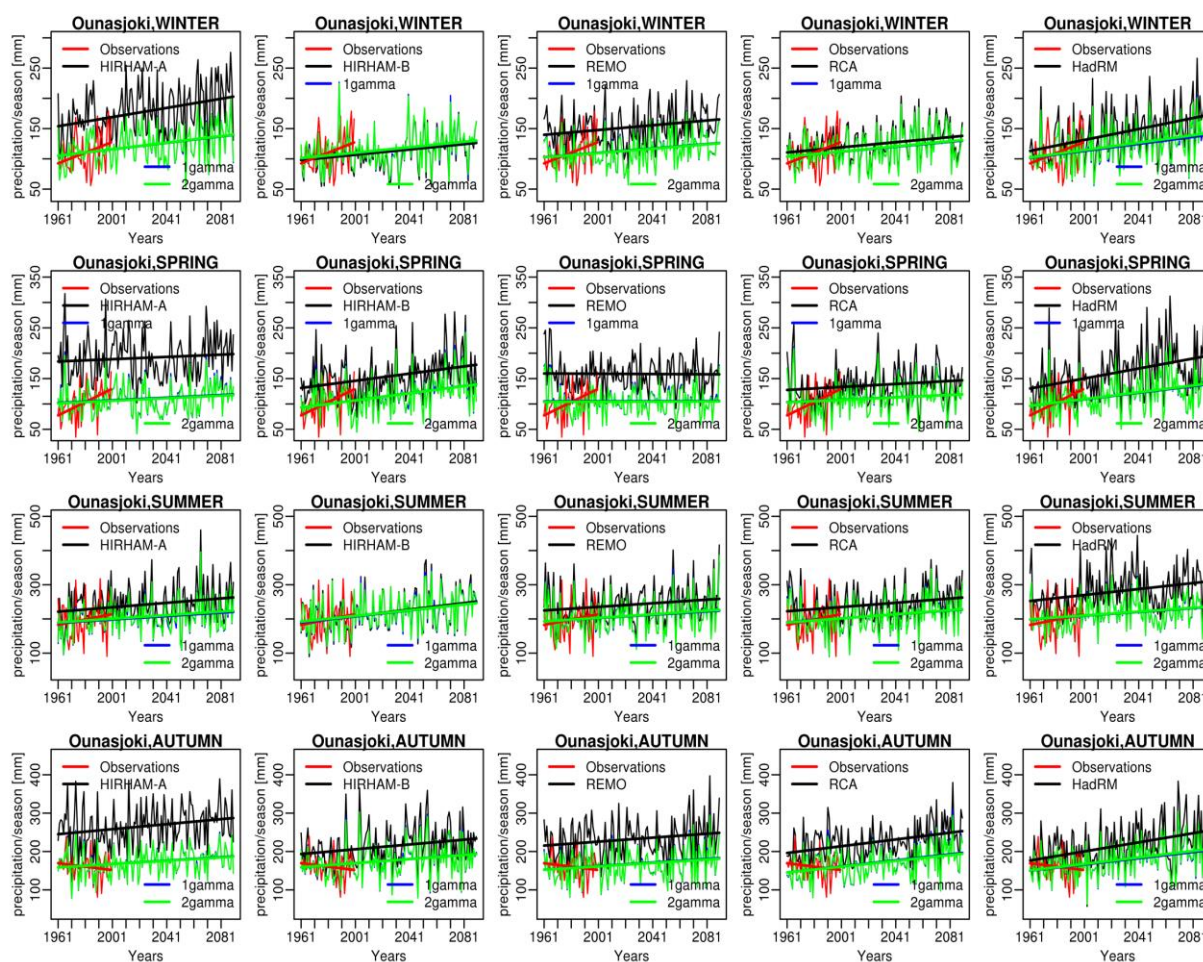
Figure ~~12~~10. Seasonal trends in observed (red, 1961–2000) and RCM simulated seasonal precipitation accumulation in Ounasjoki catchment during 1961–2090. Uncorrected RCM precipitation in black, precipitation adjusted with single gamma in blue and with double gamma in green.
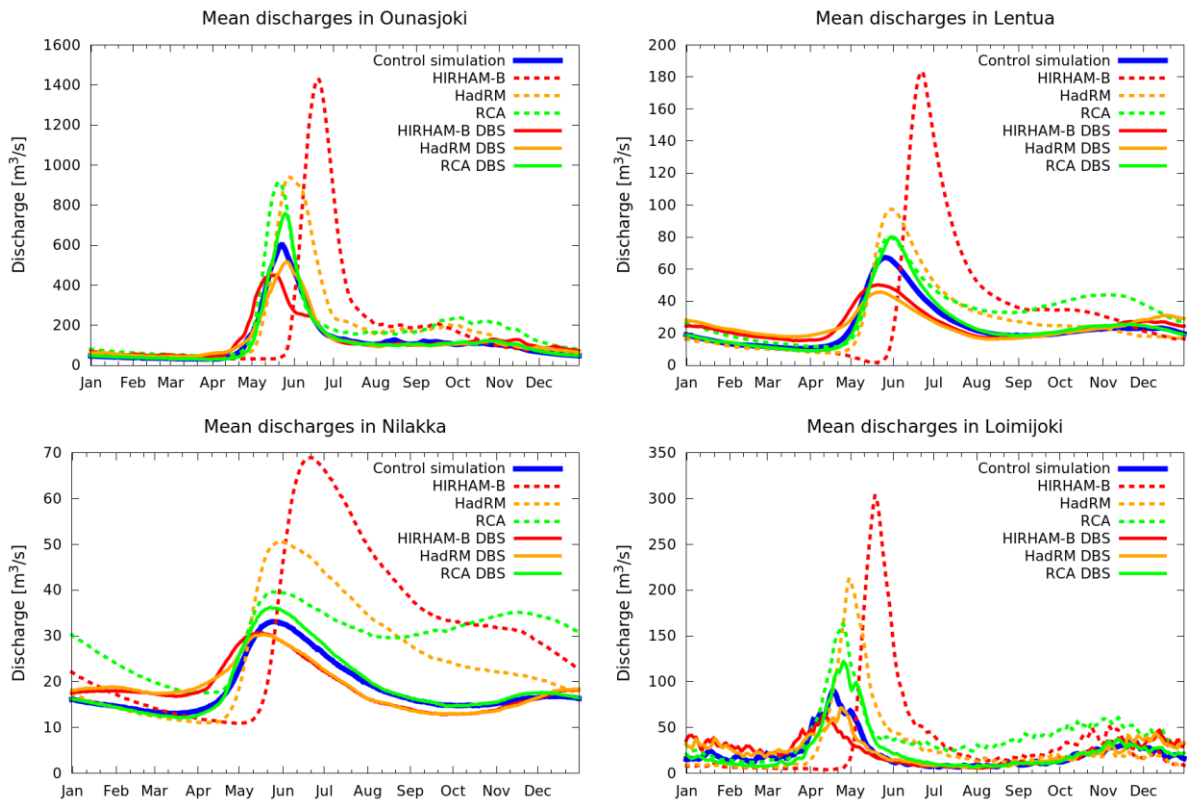
Figure 911. Hydrographs of simulated daily mean discharges in 1961–2000 with uncorrected RCM outputs (dashed lines) and corrected temperatures (T gGaussiancorr) and precipitations (P single double gamma) (solid lines) compared to control simulation discharges (blue line).
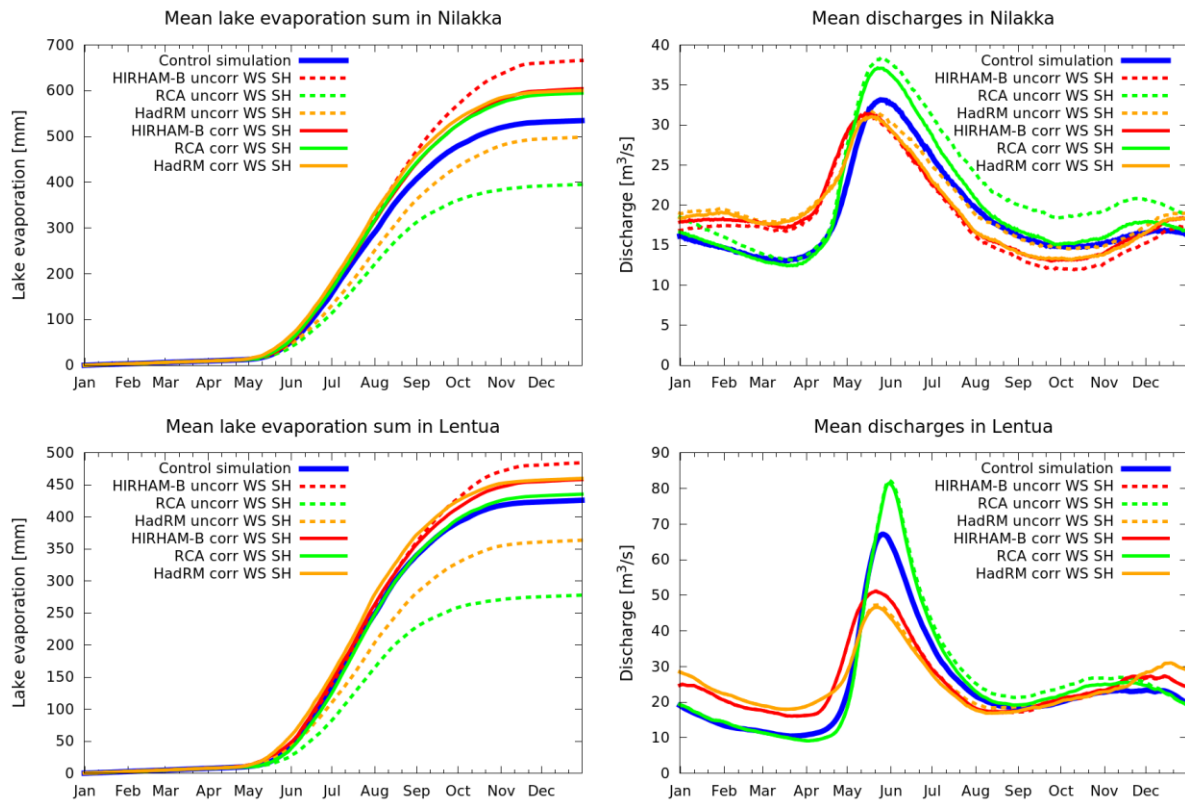
Figure 1012. Model mean lake evaporation sums and simulated daily mean discharges of Lake Nilakka and Lake Lentua with RCA uncorrected WS and SH (T=gGaussiancorr, P=21gamma) in red, with corrected WS and SH (T=gGaussiancorr, P=21double gamma) in green and control simulation in blue.
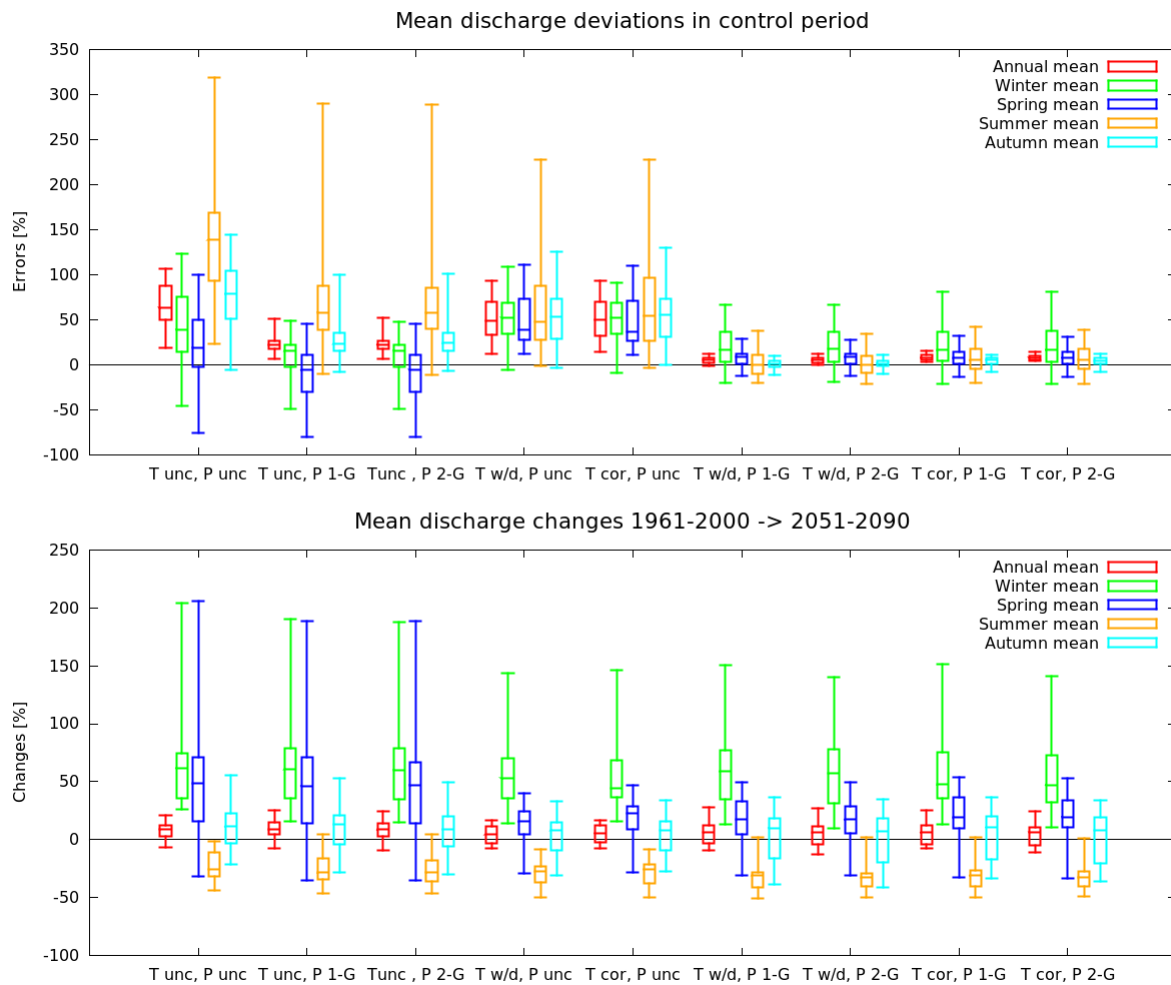
Figure 13. The minimum, maximum, 1st and 3rd quartile and median deviations of the simulated mean discharges with RCM data compared to control simulations (above) and climate change impacts (below) in four test sites using all five scenarios without corrections (unc), only with temperature correction (T w/d=wet/dry separation and T cor=without separation) or precipitation corrections (1-G=single gamma and 2-G=double gamma) and with both temperature and precipitation corrections.
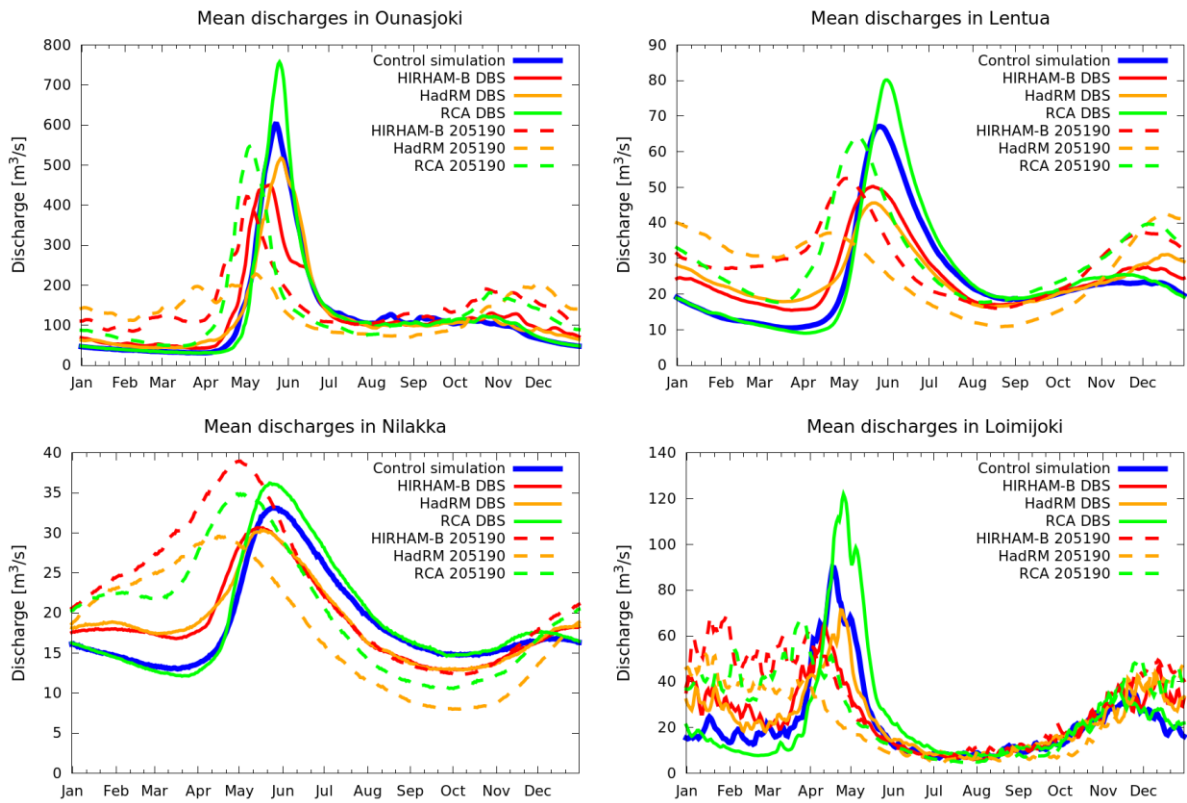
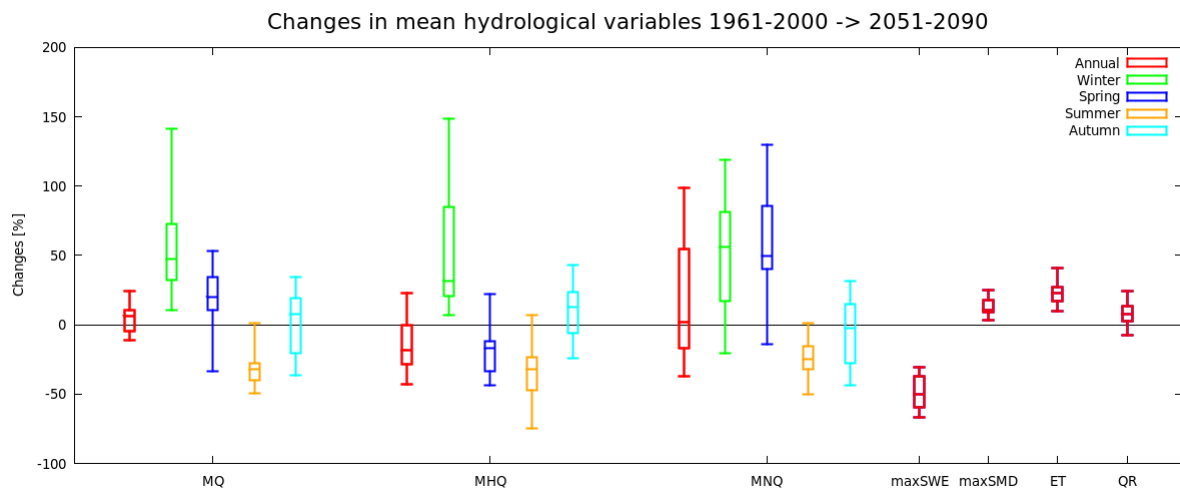Figure ~~13~~14. Hydrographs of simulated daily mean discharges with DBS adjusted temperatures (T ~~gaussian~~Gaussian without separation~~corr~~) and precipitations (P ~~21~~double gamma) of RCMs in 1961–2000 (solid lines) and in 2051–2090 (dashed lines) compared to control simulation discharges (blue line).

Figure 15. The minimum, maximum, 1st and 3rd quartile and median changes by 2051-90 period in mean discharges (MQ), mean high discharges (MHQ), mean low discharges (MNQ), mean maximum snow water equivalent (maxSWE), mean maximum soil moisture deficit (maxSMD), mean annual evapotranspiration (ET) and runoff (R) in four test catchments and five scenarios with Gaussian and double gamma adjusted RCM data.