

1 **C. Prudhomme (Referee)**

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

11  
12 **Main comments:**

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

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

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

31  
32 The paper would also benefit from a comprehensive comparison of all BC options  
33 (temperature or precipitation or both) considered in this paper to quantify which one is the  
34 most effective. This could be easily achieved by the following sensitivity analysis on  
35 hydrological impact using : 1) uncorrected climate; 2) BC temperature uncorrected precip; 3)  
36 uncorrected temp BC Gamma 1 precip; 4) uncorrected temp BC Gamma 2 precip; 5) BC  
37 temperature and Gamma 1 precip; 6) BC temperature and Gamma 2 precip. This could be  
38 done under control and future climate; similar control results but different future results  
39 would certainly shed light on uncertainty added by BC procedures. I believe this has never  
40 been done at this level and would improve the manuscript.

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

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

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

4

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

7 Figure and table captions standardized. New figures produced accordingly.

8

9 **Minor comments/ questions:**

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

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

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

17

18 Section 2.3. The method describing the bias correction step 2) is not clear – a schematic  
19 would be helpful. Why a 5 harmonics equation was used? What is the number of time step  
20 used? It could be 12 (one per calendar month); 12x50: one per month of the time series;  
21 12x2x50: one per 15-days of the TS?

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

25 Page 16 line 10: text added.

26

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

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

30 Page 16 lines 23-24: text added.

31

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

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

37 Page 17 lines 2-5: text revised.

38

1 P2667 last paragraph section 2.4: Are independent calibration/ evaluation periods used for the  
2 hydrological model calibration? Which periods the NSE correspond to?  
3 The NSE-values for validation period 1961-1980 and within the calibration period 1981-2000  
4 are now given and the differences are discussed.  
5 Page 19 lines 6-14: text added.  
6  
7 The last sentence of p2668 is unclear and needs to be rephrased. How many values/proportion  
8 of series were available?  
9 Page 20 lines 18-21: Text revised and proportions added.  
10 Page 20 lines 23-26: Discussion related to this.  
11  
12 It would be good to justify the point of discussion of p2679 with quantified errors  
13 Page 30 lines 17-18: Ok. Errors added.  
14  
15 **Typos:**  
16 P2663 l 1: converted from 1km?  
17 Page 15 lines 6, 8 and 9: Clarified in the text. The areal precipitation is converted to 1x1 km<sup>2</sup>  
18 grid just for calculating the average values. Now the 1x1 km<sup>2</sup> is not mentioned, that it does  
19 not cause misunderstanding.  
20  
21 Equation 2: clarify the notation 'sken' in the text  
22 Ok. Revised to 'scen'.  
23 Page 16 line 14 and page 17 line 17: abbreviation 'scen' for 'scenario' added, also 'sken' as  
24 footnote in formulas 2, 4, 6, 8, 11 and 12 were changed to 'scen'  
25  
26 P2665 l 8: remove 'also' between 'events' and 'a' and add 'also' between 'was' and 'used'  
27 Page 17 line 11: Ok.  
28  
29 P2665 l 9: remove 'partitions'  
30 Page 17 line 12: Ok.  
31  
32 P2666 l 12: remove 'also'. After hydrological model, add 'it is assumed that'  
33 Page 18 line 7: Ok.  
34  
35  
36

1 P2667 l 15-16: make sure of consistency of dates  
2 The calibration period of the hydrological model is 1981-2012, but the control period is 1961-  
3 2000. The NSE-values within the control period are relevant in this study, but the operational  
4 forecasting model has been calibrated using the last years data as well.  
5 Page 19 lines 6-14: text added.  
6  
7 P 2669: I would not qualify of 'torrential' rainfall of only 20 mm in a day. Can this be  
8 changed throughout the paper?  
9 In Finland this is torrential precipitation and thus we will keep this definition.  
10 Page 19 line 21-23: definition of torrential precipitation added.  
11 Page 21 line 1-5: Text added.  
12  
13 P2670: table 3.  
14 Page 23 line 16: Ok, table 4 corrected to table 5 due to rearrangement of tables.  
15  
16 P2672 15: -6.7 not -4.6 largest change  
17 Page 21 line 30: Revised.  
18  
19 Table 3: discuss the slightly worse errors in Loimijoki using REMO in winter after BC  
20 Pages 23-24 lines 30-4: Text added.  
21  
22 Table 5 Loimijoki results for HIRHAM inconsistent with Table 4  
23 Revised. There was a missing negative sing in table 5 (now table 4, and table 5 is now table 3)  
24 (precipitation HIRHAM-A, 1 gamma should be -0.1 in spring)  
25  
26 Figure 1: edit to capture comparison of results using corrected/ uncorrected RCM outputs  
27 Schematic presentation of figure 1 revised.  
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1 **Anonymous Referee #2**

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

9

10 **General comments:**

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

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

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

41 Page 27 lines 10-18: New text added.

42 Also new figure (Figure 15) is added.

43

44

1 **Some suggestions:**

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

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

7

8 - Concerning further analysis: It is written (p.2662, 1.6-8) that a second paper will focus on  
9 extremes, this could well be done already here. Another possibility would be to look at not  
10 only annual Q cycles but also other variables in the hydrological model (snow, ET, soil  
11 moisture, runoff components etc.). Bias correction of P and T by distribution mapping  
12 generally produces a good annual Q cycle but other other variables may be less well  
13 reproduced, this issue needs more attention.

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

17 Page 27 lines 10-18: New text added

18 New figure 15 added.

19

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

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

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

27

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

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

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

36 **Some specific comments:**

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

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

41 Page 15 lines 17-18: Text added.

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- 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.

### **Results generally:**

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'

### **Additional revisions by authors:**

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

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- 1 **Changes in Tables and figures:**
- 2 Table 4 is now table 3
- 3 Table 5 is now table 4
- 4 Table 3 is now table 5
- 5 Figure 1 is revised
- 6 Figure 4 and its caption is revised
- 7 Figure 5 and its caption is revised
- 8 Figure 6 is revised
- 9 Figure 7 is revised
- 10 Figure 9 and its caption is revised and relocated to be figure 11
- 11 Figure 10 and its caption is revised and relocated to be figure 12
- 12 Figure 11 is revised and relocated to be figure 9
- 13 Figure 12 is now figure 10
- 14 Figure 13 and its caption is revised and relocated to be figure 14
- 15 New Figure 13 (and caption) is added
- 16 New Figure 15 (and caption) is added

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

4

5 **Taru Olsson<sup>1</sup>, Juho Jakkila<sup>2</sup>, Noora Veijalainen<sup>2</sup>, Leif Backman<sup>1</sup>, Jussi Kaurola<sup>1</sup>,**  
6 **Bertel Vehviläinen<sup>2</sup>**

7 [1]{Finnish Meteorological Institute, Erik Palménin aukio 1, 00101, Helsinki, Finland}

8 [2]{Freshwater Centre, Finnish Environment Institute, Mechelininkatu 34a, P.O. Box 140, FI-  
9 00251, Helsinki, Finland}

10 Correspondence to: Taru Olsson (taru.olsson@fmi.fi)

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12

## 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;

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

3 Several approaches are available for adjusting RCM variables; these can be divided into Delta  
4 Change (DC) and Bias Correction (BC) methods. The DC approach adjusts observations with  
5 the RCM climate change signal, whereas the BC approach adjusts the daily RCM simulated  
6 variables based on the difference between observed and simulated climate in the control  
7 period. Compared to the DC method the BC approach usually better preserves the future  
8 variability in temperature and precipitation produced by the RCMs, enables representation of  
9 complex changes in climate related to changes in mesoscale weather conditions and enables  
10 transient scenarios instead of comparison between time slices (Graham et al., 2007; Lenderink  
11 et al., 2007; Beldring et al., 2008; Yang et al., 2010). Bias correction methods have been  
12 proved to improve daily mean, standard deviation (SD), and distribution of the RCM  
13 temperature and precipitation when compared to observed climate statistics (e.g. Yang et al.,  
14 2010; Teutschbein and Seibert, 2012; Räisänen and Rätty, 2013; Rätty et al., 2014).

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

25

## 26 **2 Materials and methods**

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

## 1 **2.1 Study catchments**

2 Four catchments located in different parts of Finland were selected as study catchments (Fig.  
3 2). These represent different hydrological regions in Finland. Loimijoki (Maurialankoski  
4 observation station, catchment area 2 650 km<sup>2</sup>, lake percentage 3.1) is a medium sized river  
5 with high proportion of cultivated area on clay soils. Nilakka (catchment area 2 160 km<sup>2</sup>, 18  
6 % lake percentage) and Lentua (2 050 km<sup>2</sup>, 13 %) observation stations are located at lake  
7 outlets in central Finland characterized by numerous lakes. Ounasjoki (Marraskoski  
8 observation station, 12 300 km<sup>2</sup>, 2.6 %) is a large river in Northern Finland (Fig. 2)  
9 (Korhonen and Kuusisto, 2010). All the study catchments have long water level and discharge  
10 observation series, longest from 1912 onwards (Lentua) and shortest from 1935 onwards  
11 (Loimijoki).

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

## 22 **2.2 Observations and RCM data**

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

1 Gauge precipitation observations especially for snowfall contain various systematic  
2 measurement errors (Førland et al., 1996; Taskinen, 20154), which need to be corrected  
3 before they can be used for bias correction of RCM data. The correction of precipitation  
4 measurements consisted of the exposure method for aerodynamic correction as well as  
5 wetting and evaporation corrections (Taskinen, 20154). The areal values of the meteorological  
6 observations ~~for each sub-basin~~ are calculated for each sub-basin of the hydrological model  
7 from three closest observation stations by inverse distance weighting taking into account the  
8 elevation differences. ~~and the gridded values are calculated based on these areal values.~~ The  
9 areal values were converted to ~~1x1 km grid to calculate the average values of~~ the same  
10 regular 0.25° lat x 0.25° long grid as the RCM data.

11 The observations of relative humidity at 2 m and wind speed at 10 m are used in the  
12 simulation of lake evaporation, which is an important hydrological variable for catchments in  
13 the lake area. The areal values are calculated in similar way as temperature and precipitation  
14 and the effect of fetch to the wind speed on a lake is calculated as in Resio and Vincent  
15 (1977).

16 Five climate scenarios were used from four different RCMs forced with four different GCMs  
17 as given in Table 1. Selected RCM projections are the same as used in Veijalainen et al.  
18 (2012), excluding RCA-ECHAM5, to enable comparison of results. The data was retrieved  
19 from ENSEMBLES Research team 3 database (ensemblesrt3.dmi.dk, van der Linden and  
20 Mitchell, 2009). The GCMs were run under historic (1961–2000) and with A1B scenario  
21 (2001–2100) forcing. The GCM output was then used as boundary conditions to force RCMs  
22 over a common European domain in a regular 0.25° lat x 0.25° long grid (van der Linden and  
23 Mitchell, 2009).

### 24 **2.3 Bias correction methods**

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

1 Temperature (T) is described by a Gaussian (normal) distribution with daily mean ( $\mu$ ) and  
2 standard deviation ( $\sigma$ ). 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; ( $\mu_w, \sigma_w$ ) for wet days  
5 and ( $\mu_d, \sigma_d$ ) 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 ( $\mu, \sigma$ ). (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:

$$16 \quad T_{contr}(d) = F^{-1}(F(T_{contr}(d) | \mu_{contr}, \sigma_{contr}^2) | \mu_{obs}, \sigma_{obs}^2) \quad (1)$$

$$17 \quad T_{scen}(d) = F^{-1}(F(T_{scen}(d) | \mu_{contr}, \sigma_{contr}^2) | \mu_{obs}, \sigma_{obs}^2) \quad (2)$$

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

$$19 \quad T_{contr,w/d}(d) = F^{-1}(F(T_{contr,w/d}(d) | \mu_{contr,w/d}, \sigma_{contr,w/d}^2) | \mu_{obs,w/d}, \sigma_{obs,w/d}^2) \quad (3)$$

$$20 \quad T_{scen,w/d}(d) = F^{-1}(F(T_{scen,w/d}(d) | \mu_{contr,w/d}, \sigma_{contr,w/d}^2) | \mu_{obs,w/d}, \sigma_{obs,w/d}^2) \quad (4)$$

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  $\alpha$  and scale  $\beta$ ) 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



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

$$7 \quad P_{contr}(d) = \begin{cases} 0, & \text{if } P_{contr}(d) < P_{th,contr,m} \\ P_{contr}, & \text{otherwise} \end{cases} \quad (5)$$

$$8 \quad P_{scen}(d) = \begin{cases} 0, & \text{if } P_{scen}(d) < P_{th,contr,m} \\ P_{scen}, & \text{otherwise} \end{cases} \quad (6)$$

9 (2) The remaining daily precipitation was adjusted to match the observed frequency  
 10 distribution using single gamma distribution (Eq. 7). (3) To better capture the extreme  
 11 precipitation events ~~also~~ a double gamma distribution was also used, then the observed and  
 12 RCM generated precipitation distributions were separated into two ~~partitions~~ by the 95<sup>th</sup>  
 13 percentile of CDF ( $P_{obs,95th}$ ,  $P_{contr,95th}$ ), resulting into two sets of parameters ( $\alpha_1$ ,  $\beta_1$ ) for below  
 14 the 95<sup>th</sup> percentile precipitation and ( $\alpha_2$ ,  $\beta_2$ ) above it. (4) These monthly parameters for each  
 15 grid point were then used to calculate the CDFs for observations ( $\alpha_{obs}$ ,  $\beta_{obs}$ ) and RCMs ( $\alpha_{contr}$ ,  
 16  $\beta_{contr}$ ) during the control period (Eq. 9, 10, Fig. 3). Monthly DBS parameters for the control  
 17 period and the 95<sup>th</sup> percentile threshold ( $P_{contr,95th}$ ) were used also for the scenario (scen) runs  
 18 (equations 8, 11, 12). The DBS procedure expressed in terms of single gamma CDF:

$$19 \quad P_{contr}(d) = F^{-1}(F(P_{contr}(d) | \alpha_{contr,m}, \beta_{contr,m}) | \alpha_{obs,m}, \beta_{obs,m}) \quad (7)$$

$$20 \quad P_{scen}(d) = F^{-1}(F(P_{scen}(d) | \alpha_{contr,m}, \beta_{contr,m}) | \alpha_{obs,m}, \beta_{obs,m}) \quad (8)$$

21 The DBS procedure expressed in terms of double gamma CDF:

$$22 \quad P_{contr,1}(d) = F^{-1}(F(P_{contr}(d) | \alpha_{contr1,m}, \beta_{contr1,m}) | \alpha_{obs1,m}, \beta_{obs1,m}), \quad \text{if } P_{contr}(d) < P_{contr,95th}(m)$$

$$23 \quad (9)$$

$$24 \quad P_{contr,2}(d) = F^{-1}(F(P_{contr}(d) | \alpha_{contr2,m}, \beta_{contr2,m}) | \alpha_{obs2,m}, \beta_{obs2,m}), \quad \text{if } P_{contr}(d) \geq P_{contr,95th}(m)$$

$$25 \quad (10)$$

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

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

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. 2015<sup>4</sup>). 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<sup>2</sup> (20–500 km<sup>2</sup>) (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

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

3 The WSFS was calibrated against water level, discharge and snow line water equivalent  
4 observations from 1981–2012. The Nash-Sutcliffe efficiency criterion  $R^2$  (Nash and Sutcliffe,  
5 1970) for the control period 1961–2000 in the four case study catchments was 0.78 for  
6 Loimijoki, 0.80 for Nilakka, 0.87 for Lentua, 0.87 for Ounasjoki. The  $R^2$ -values within  
7 calibration period (1981-2000) are considerably better than in validation period (1961-1980):  
8 0.84 and 0.71 for Loimijoki, 0.91 and 0.68 for Nilakka, 0.92 and 0.81 for Lentua, 0.87 and  
9 0.88 for Ounasjoki respectively for calibration and validation periods. The reasons for  
10 remarkably lower values in validation period are the possible changes in rating curves in  
11 Loimijoki and Nilakka and the change of the rain station gauges from Wild to Tretjakov type  
12 gauges. The measurement errors for different gauge types are done separately (Taskinen,  
13 2015), but the uncertainty range of wind effect on snowfalls is much larger for Wild than  
14 Tretjakov.

### 15 **3 Results**

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

#### 24 **3.1 RCM temperature and precipitation in control period**

25 The five RCMs used in this study are able to capture the annual cycle of temperature in the  
26 control period quite well, but monthly temperatures are commonly underestimated throughout  
27 the year except in winter by RCA and REMO and in autumn by HIRHAM-A (Fig. 4). The  
28 cumulative distribution functions show that all RCMs cumulate too many below 0 °C  
29 temperatures and too few above 0 °C temperatures especially in spring, although also in  
30 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 Thisextrema-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<sup>th</sup> 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 Northern 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. 449). 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  $\pm 0.1$  °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. 419). 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 4210). 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.

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

~~10 Because of the biases in RCM data the spring mean discharges are in some cases double or  
11 even triple compared to control simulation discharges, and the seasonal variation of  
12 discharges is also altered. Without effective bias correction the results of climate change  
13 impact studies could easily lead to false conclusions.~~

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

24 The differences in seasonal mean discharges between simulations with DBS adjusted RCM  
25 data and control simulation are in many cases larger than differences between observed  
26 discharges and discharges in the control simulation. Differences larger than 30 % are only  
27 found in winter and summer, when the discharges are low. But the remaining biases larger  
28 than 20 % during high flow season in Loimijoki found in REMO and RCA and larger than  
29 50 % during the low flow season in HadRM and HIRHAM-B may have significant effect on  
30 the seasonal changes and changes in extreme discharges in climate change projections. The  
31 main reason for large and in some cases even larger remaining biases in winter discharges  
32 than in uncorrected data is the sensitivity of the hydrological model on near zero



1 [temperatures. Even though the DBS method corrects the mean temperatures efficiently close](#)  
2 [to observations, the remaining biases in winter temperature extremes, which in control period](#)  
3 [are slightly above zero, cause remarkable biases in winter discharges and snow accumulation](#)  
4 [in the hydrological simulation.](#) -However, the seasonal variations in mean discharges- after [the](#)  
5 DBS adjustment are remarkably closer to [variations of results from](#) control simulation (Fig.  
6 [911](#)), highlighting the fact that the bias correction is required for RCM data- used in studies of  
7 climate change effects on hydrology.

8 In addition to biases in RCM temperature and precipitation data, also the biases in wind speed  
9 (WS) and specific humidity (SH) affect the WSFS discharge simulations for catchments with  
10 high lake percentages. Biases in WS and SH of RCMs affect the lake evaporation in the  
11 hydrological model and typically cause a 5–45 % bias in the annual lake evaporation sums. In  
12 most of the study catchments the bias is largest in the RCA scenario giving 25–35 % negative  
13 bias caused by positive bias of SH and negative bias of WS. The bias in lake evaporation can  
14 be effectively decreased to 0–13 % by the simple mean bias correction method (Fig. [4012](#)).

15 The uncorrected WS and SH of RCMs cause a 0–11 % bias in annual mean discharges, and a  
16 0–20 % bias in autumn mean discharges in the outlet of Nilakka, which has the highest lake  
17 percentage of the study catchments (18 %). In the catchments of Loimijoki and Lentua the  
18 biases in mean discharges (0–2 % and 0–4 %) and autumn discharges (0–7 % and 0–8 %) are  
19 smaller and in the most northern located catchment of Ounasjoki the bias is insignificant.

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



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

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

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

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

### 1 3.4 Future scenarios for discharges

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

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

19 In the study catchments all DBS adjusted scenarios predict on average 2–4 weeks earlier  
20 snowmelt discharge peaks in spring for the 2051–2090 period compared to the control period  
21 1961–2000. ~~(Fig. 13).~~ [Figure 14 shows the results for three scenarios producing largest](#)  
22 [variation of changes in mean discharges out of five scenarios used in this study.](#) Because the  
23 snowmelt discharge peaks occur earlier, the recession flows in summer season decrease. The  
24 summer discharges decrease 20–50 % in all scenarios except in Nilakka and Loimijoki in the  
25 HIRHAM-B-scenario, which predicts greater increase in precipitation than the other  
26 scenarios. The decrease in mean summer discharges is caused by the increase of the annual  
27 evapotranspiration by 10–40 % and lake evaporation by 10–80 %.

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

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

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

#### 20 **4 Discussion**

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

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

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

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

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

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

5 The current study shows that the effect of DBS adjustment on temperature and precipitation  
6 trends is in generally small. But with a large bias in standard deviation of the uncorrected  
7 temperature data the DBS may cause significant change in temperature trends increasing the  
8 uncertainty for the climate change projections. Also since the precipitation and temperature  
9 corrections are not interdependent, in some cases the bias in the snow accumulation remains  
10 considerably large, which leaves biases in spring discharges during the control period and  
11 certainly affects the relative changes in the future. Räisänen and Rätty (2013) and Rätty et al.  
12 (2014) concluded that since no single BC method outperforms others in all circumstances, the  
13 use of few different but well-performing correction methods would give more realistic range  
14 of uncertainty. In the hydrological studies the assessment of the performance should be based  
15 on the remaining biases in discharges during the control period to avoid unnecessary large  
16 uncertainty range and false conclusions about the impacts of climate change.

17 The DBS adjustment used in this study principally follows the method introduced by Yang et  
18 al. (2010). The method was tested using two versions of both temperature and precipitation  
19 corrections. The results show that the temperature correction in Finland works better without  
20 classification into wet and dry days. The classification is not straightforward and depends on  
21 season and area of investigation. A threshold value of observed precipitation, used to classify  
22 days to dry and wet, varies from 0 mm/day (Teutschbein and Seibert, 2012) to as high as 1  
23 mm/day (Rätty et al., 2014). In Finland RCMs produced too few days with 0 mm/day and thus  
24 a threshold value to cut off the spurious drizzle is needed. Nevertheless, a high threshold  
25 would cut too many precipitation days from both observations and RCMs and thus influence  
26 the precipitation and temperature distributions. On the other hand, when using a low  
27 threshold, e.g. 0.1 mm/day, only 20–30 % of days in autumn and winter in Finland are  
28 considered to be dry. For precipitation distribution the removal of drizzle days is important,  
29 but for temperature it is questionable whether the simulated temperature for drizzle days  
30 represents the temperature for dry days. Separation of days according to wet/dry state reduces  
31 the amount of days available for the temperature distribution on wet/dry days, which can  
32 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~~ 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

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

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

21 Previously the most commonly used method to estimate climate change impacts on hydrology  
22 was the delta change method (e.g. Andréasson et al., 2004; Steele-Dunne et al., 2008;  
23 Veijalainen et al., 2010). Often a very simple version of this method, where only the monthly  
24 mean changes of temperature and precipitation from climate model simulations were used to  
25 modify the observed temperature and precipitation records, was used (Hay et al., 2000).  
26 Compared to delta change methods the BC methods better preserve the variability in  
27 temperature and precipitation produced by the RCMs (Lenderink et al., 2007; Graham et al.,  
28 2007; Beldring et al., 2008; Yang et al., 2010). Veijalainen (2012) showed that with delta  
29 change and with QM method the changes in discharges for four catchments in Finland were  
30 similar for annual means. However, larger differences were found in flood estimates and in  
31 seasonal values. Especially during spring in Northern Finland the delta change method  
32 produced earlier snowmelt than the bias corrected RCM data. The changes in annual and

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

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

## 18 | **5 Summary and Conclusions**

19 The use of bias corrected RCM data as input to impact models is becoming a common  
20 practice. The choice of bias correction method significantly affects estimation of climate  
21 change impacts on hydrology. The DBS algorithm has been shown to perform well under  
22 changing conditions and outperform other methods in many cases (Teutschbein and Seibert,  
23 2012; Rätty et al. 2014) and was therefore selected for this study. Two different DBS methods  
24 for temperature (with and without dry/wet day separation) and two for precipitation (single  
25 and double gamma distribution) were compared. This paper focuses on mean values of  
26 temperature, precipitation and discharges simulated with hydrological model of WSFS in four  
27 catchments. The DBS adjustment significantly improves RCM data and simulated discharges  
28 compared to observations, but the magnitude of the biases of the uncorrected RCM data still  
29 influence the success of the DBS method.

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



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

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

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

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

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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



1 Table 2. Deviation between observed and RCM accumulated seasonal precipitation during  
 2 control period (1961–2000) in uncorrected and DBS adjusted (single gamma=1 gamma,  
 3 double gamma=2 gamma) precipitation in %. Values are shown for Loimijoki in Southern  
 4 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

1 Table 43. Changes in uncorrected and DBS adjusted RCM seasonal precipitation sums in %  
 2 and daily mean temperatures as °C between control (1961–2000) and scenario periods (2051–  
 3 2090). Values are shown for winter and spring in Loimijoki catchment in Southern Finland.

	Precipitation %			Temperature °C		
	UNCOR- RECTED	1 GAMMA	2 GAMMA	UNCOR- RECTED	W/D Gaussian	Gaussian
WINTER						
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 54. 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.

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

4

1 | Table 35. Deviation of simulated annual and seasonal mean discharges (MQ) between  
2 | observed, uncorrected and DBS adjusted temperature (Gaussian) and precipitation (1 or 2  
3 | gamma) as input for hydrological simulations during control period (1961–2000) in %.  
4 | Values are shown for Loimijoki in Southern Finland and Ounasjoki in Northern Finland [to](#)  
5 | [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

1

1 Table 6. Relative changes (%) in simulated annual and seasonal mean discharges (MQ) in  
 2 Loimijoki and Ounasjoki between control period (1961–2000) and future period (2051–2090)  
 3 using uncorrected and DBS adjusted temperature (Gaussian) and precipitation (1 or 2  
 4 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

1

- 1 Figure 1. Schematic presentation of application procedure used in this study for hydrological
- 2 modelling of climate change impact with bias corrected RCM data.
- 3

1 Figure 2. Map of the study catchments.

2

1 Figure 3. Procedure of the distribution based mapping. Upper panels for temperature  
2 adjustment and lower panels for precipitation (pr) adjustment. For temperature, Gaussian  
3 adjustment without wet/dry state separation (left) and with wet/dry separation (right) is  
4 shown. For precipitation, gamma adjustment with single gamma (left) and double gamma  
5 divided at 95th percentile (right) is shown. 1. Locate the cumulative probability value of RCM  
6 simulated daily temperature/precipitation. 2. Locate the observed temperature/precipitation  
7 value corresponding the same cumulative probability value as in (1). 3. This value is used as  
8 corrected value for RCM simulation.  
9

1 Figure 4. Monthly mean precipitation accumulation (left) and temperature (right) in  
2 observations and RCMs in Finland during the control period 1961–2000. Observations (black)  
3 and uncorrected RCMs (colours) in solid lines, adjusted RCMs in dashed and dotted lines.  
4 Monthly mean precipitation adjusted with single gamma (1-gamma) are presented as dashed  
5 lines, and with double gamma (2-gamma) as dotted lines (left panel). Monthly mean  
6 temperatures adjusted with wet/dry state separation (w/d ~~gGaussianeorr~~) are presented as  
7 dashed lines and without wet/dry separation (~~gGaussianeorr~~) as dotted lines (right panel). All  
8 adjusted values follow closely the observations and no big differences can be seen between  
9 the two bias correction procedures  
10

1 Figure 5. Cumulative distribution functions for daily temperature in Lentua catchment during  
2 control period (1961–2000). Observations and uncorrected RCM data in left column, daily  
3 RCM temperatures adjusted with wet/dry state separation (w/d ~~gGaussianeorrected~~) are  
4 presented in middle column and without wet/dry separation (~~gGaussianeorrected~~) in right  
5 column. Winter is shown in first row, spring in second row, summer in third row and autumn  
6 in bottom row. All the adjusted values follow closely the observed distribution and no big  
7 differences can be seen between the two bias correction procedures.  
8

1 Figure 6. Distribution of daily precipitation amounts during control period (1961–2000)  
2 spring in Nilakka catchment in observations and uncorrected RCM data (top panel), single  
3 Gamma adjusted RCM data (middle panel) and double Gamma adjusted RCM data (bottom  
4 panel). Notice the uneven precipitation division and different scaling for precipitation  
5 amounts greater than 20 mm/day.  
6

1 Figure 7. Comparison between uncorrected (black) and DBS adjusted (pink without wet/dry  
2 state separation and green with wet/dry state separation) daily temperatures during control  
3 period 1961–2000 in Lentua. Red line indicates observed abline.  
4



1 Figure 8. Comparison between uncorrected (black) and DBS adjusted daily precipitation  
2 (single gamma in green and double gamma in pink) during control period 1961–2000 in  
3 Nilakka. Red line indicates observed abline.  
4

1 | Figure [449](#). Seasonal trends in observed (red, 1961–2000) and RCM simulated daily  
2 | temperatures in Lentua basin during 1961–2090. Uncorrected RCM daily temperatures in  
3 | black, temperatures adjusted with wet/dry separation in blue and without wet/dry separation  
4 | in green.

5

1 | Figure [4210](#). Seasonal trends in observed (red, 1961–2000) and RCM simulated seasonal  
2 | precipitation accumulation in Ounasjoki catchment during 1961–2090. Uncorrected RCM  
3 | precipitation in black, precipitation adjusted with single gamma in blue and with double  
4 | gamma in green.  
5

1 | Figure [911](#). Hydrographs of simulated daily mean discharges in 1961–2000 with uncorrected  
2 | RCM outputs (dashed lines) and corrected temperatures (T ~~gGaussianerr~~) and precipitations  
3 | (P ~~single-double~~ gamma) (solid lines) compared to control simulation discharges (blue line).  
4 |

1 | Figure [1012](#). Model mean lake evaporation sums and simulated daily mean discharges of  
2 | Lake Nilakka [and Lake Lentua](#) with RCA uncorrected WS and SH (T=~~gGaussianerr~~,  
3 | P=~~24~~gamma) in red, with corrected WS and SH (T=~~gGaussianerr~~, P=~~24~~double gamma) in  
4 | green and control simulation in blue.

5

1 Figure 13. The minimum, maximum, 1<sup>st</sup> and 3<sup>rd</sup> quartile and median deviations of the  
2 simulated mean discharges with RCM data compared to control simulations (above) and  
3 climate change impacts (below) in four test sites using all five scenarios without corrections  
4 (unc), only with temperature correction (T w/d=wet/dry separation and T cor=without  
5 separation) or precipitation corrections (1-G=single gamma and 2-G=double gamma) and  
6 with both temperature and precipitation corrections.

7

1 | Figure [4314](#). Hydrographs of simulated daily mean discharges with DBS adjusted  
2 | temperatures (T ~~gaussian~~[Gaussian without separation](#)~~err~~) and precipitations (P ~~2+double~~  
3 | gamma) of RCMs in 1961–2000 (solid lines) and in 2051–2090 (dashed lines) compared to  
4 | control simulation discharges (blue line).  
5 |

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