

Dear Dr. Schymanski,

We hereby submit the revised version of our m/s entitled “Global evaluation of runoff from ten state-of-the-art hydrological models”. Our responses to each of your and the reviewer’s comments are presented in green font below. The main changes in this revision are:

- 1) improved the colormap of Table 5 by maximizing the tone, hue, and saturation differences between the performance classes, to improve the readability;
- 2) produced Budyko plots based on all grid cells, instead of only grid cells at latitudes $<50^\circ$;
- 3) computed normalization values for the runoff signatures based on the observations rather than the Global Streamflow Characteristics Dataset (GSCD), to reduce the complexity of the analysis; and
- 4) introduced some textual improvements and clarifications.

We want to sincerely thank you for handling the m/s and trust that this revision is suitable for publication.

Sincerely,
Hylke Beck (on behalf of all co-authors)

Comments to the Author:

Dear authors,

I agree with the reviewers that the manuscript has improved substantially, but I think that some of the remaining points are not just minor, as they could potentially change some of the conclusions.

In Report #1, the reviewer doubts that the conclusion about the potential of multi-parameterization ensembles is backed by the analysis and asks for additional analysis to support the statements. The report further highlights a potential flaw in the evaluation of SWBM runoff results and the potential sensitivity of the conclusions to uncertainty in the daily climate data. If it is not feasible to remove these ambiguities, they should at least be clearly discussed. In Report #2, the reviewer echoes my original concern about the normalization of the performance metrics using the GSCD data. In contrast to your assessment that a different choice of normalization would probably not have affected the results, the reviewer suggests that the normalization may affect the conclusions. I think this is too important to be left to speculations either way and I would like to ask you to provide evidence (in the manuscript) that the normalization does indeed not affect the results and conclusions. As pointed out by the reviewer, Table A5 is still very difficult to comprehend. I am not sure if a heat map or bar chart would help, but perhaps a reduction of the table to convey the main points needed to support the conclusions would be helpful, while the full table could be given in the SI. I also concur with the reviewer that the rationale for limiting the Budyko plots to the lower latitudes (<50 degr.) is not clear. Why not include all data? You should at least show the same plots including all data in the SI and briefly discuss any striking differences.

We have improved the colormap and increased the font weight of Table 5, which makes the table easier interpret. We have considered presenting the results in bar plots, but feel this would not not necessarily be an improvement due to the large number of bar plots it would require. We are not in favor of making the results less accessible by moving them to the Supplementary information.

We now normalize the runoff signature values using the observations rather than the GSCD data, as requested, which resulted in very minor changes in the scores in Table 5 and no changes to the conclusions.

We have improved the Budyko plots by using all data, instead of only data for latitudes <50°.

In addition to the reviewer comments, I still have a few comments of my own:

EC1 - The paper contains a number of value statements that are not clearly backed by the analysis, and some could even be misleading. In several occasions, you use the word "reliable", which implies some degree of trust and robustness. When referring to models, I would propose to replace "reliable models" by "accurate model simulations", as your assessments are drawn

from correspondence between particular observations and model simulations, which strongly depend on the calibration procedure and data. When referring to conclusions, I really see no evidence to suggest that your conclusions are more reliable and generalizable than those presented in other papers, so I would remove this statement and instead be more specific about the additional insights gained.

We have replaced “reliable” by “accurate” throughout the m/s, as suggested. In addition, we have removed the statement that our results are more reliable and generalizable than previous studies from the Introduction.

EC2 - I also think that the value of calibration is over-stated and not discussed in a balanced way. As I alluded to before, calibration does not necessarily account for, nor compensate for inadequate understanding or missing information. All it evidently does is to reduce mismatch between model simulations and (calibration) data. Therefore, I would propose to replace the sentence on P17L12, "Calibration is a prerequisite for both conceptual and physically-based hydrological models to provide reliable runoff estimates, to account for (i) the impossibility of measuring all required model parameters at the model application scale, (ii) lack of process understanding..." by something like:

"Calibration is necessary whenever model parameters cannot be estimated *a priori* and is also used in both conceptual and physically-based hydrological models to reduce simulation-observation mismatch, commonly assumed to be caused by (i) lack of process understanding..."

Your result that calibration against one signature does not improve the model-observation mismatch in another signature does not fill me with confidence that the calibration makes the model any more "reliable", but you are of course free to express your own opinion, as long as you mark it as such.

Thank you for the comment. In an effort to soften the sentence we have replaced “prerequisite” with “important” and added “more” before “accurate” (“reliable” in the previous revision). We certainly agree that calibration does not fully compensate for inadequate understanding or missing information, but in our opinion it does help to some degree (hence our use of “more accurate”). We want to thank you for proposing a sentence, this is really appreciated. However, we have two issues with the sentence. First, it does not refer to runoff which is the topic of this paper. Second, it implies that for some models their runoff-related parameters can be estimated *a priori* and therefore do not need calibration. Such models do not exist, because (i) there is simply no way to obtain accurate information on important subsurface hydrologic characteristics that control runoff generation processes at the model application scale (see, e.g., Beven, 1989; Blöschl and Sivapalan, 1995), and (ii) all hydrological models (even high-resolution physically-based models) represent gross simplifications of reality and therefore even if you would be able to estimate all parameters *a priori* they would still not behave realistically. Perhaps for other hydrologic variables which are not the topic of this paper (e.g., lake outflow) it might be possible to estimate the relevant parameters *a priori*, but for runoff this is simply not possible.

Beven, K. J.: Changing ideas in hydrology — the case of physically-based models, *Journal of Hydrology*, 105, 157–172, 1989.

Blöschl, G. and Sivapalan, M.: Scale issues in hydrological modelling: A review, *Hydrological Processes*, 9, 251–290, 1995.

EC3 - In any case, the reader is entitled to know what the calibration actually entailed, i.e. how much overlap between calibration and validation data there was for the different models and what process parameters were actually calibrated, be it conceptual or physically-based.

We certainly agree, and therefore outline the calibration exercises performed for each model on page 16 line 29 to page 16 line 17. For more details we refer to the corresponding publications.

EC4 - This is crucial for the missing discussion of the reliability of the models or multi-model ensembles in assessing climate change impacts, which was also requested by Reviewer #2 in Report #1. For example, if one calibrates parameters relating to vegetation water use, one should expect that the calibration will become inadequate as vegetation properties change, e.g. due to change in rainfall or atmospheric CO₂ concentrations. Please add a balanced discussion about the utility of this approach for climate change analysis or remove reference to climate change analysis and specify more clearly what the intended use of the models and multi-model ensembles is. I doubt that the intended use is to "mimic reality", where "reality" is expressed by a set of observations. One could use a purely statistical model for this, or, to be provocative, a set of polynomials of an arbitrary level of complexity.

It is true that the calibrated parameters becomes less representative when the model is subjected to new conditions, which we now explicitly mention in the m/s ("for climate projections one should bear in mind that calibrated parameters become less valid when the model is subjected to climatic conditions it has never seen before (Knutti, 2008)"). We have also added to the Introduction that the objective of the earthH2Observe project is "to develop a global reanalysis of water resources that supports efficient water management and decision making", to avoid any confusion about the intended use of the models.

I am sorry to ask for additional work at this stage, but given the potential impact of the concerns expressed in this round of review, I cannot accept the paper for publication in HESS in its current form. I hope that this last revision will result in a valuable paper.

We understand and appreciate your time and constructive help to further improve the m/s.

REFEREE #1

OVERALL RATING:

I do appreciate the effort of Beck et al to further improve their manuscript, with respect to both textual clarifications as well as additional analysis in the re-arranged Budyko space. Nevertheless I do have several specific comments and suggestions as listed below:

We want thank Dr. Gudmundsson for his insightful comments.

SPECIFIC COMMENTS (SC):

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** SC1:

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I am still not convinced of the authors strategy to normalise their performance metrics using the GSCD data. While I do understand the argument that this data set does only serve normalization purposes and may provide more consistent global estimates of the standard deviations, I do still believe that utilizing this data set makes the analysis more complicated without a significant benefit. Nevertheless, I must also admit that the choice of the data set used for normalization (either GSCD or station data) will most likely impact the overall conclusions drawn by the authors.

We now use the standard deviation of the observed values to normalize the signatures, resulting in very minor changes in the scores in Table 5 and no changes to the overall conclusions. We have modified the text in the Methods section accordingly.

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** SC2:

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Overall the overwhelming information content makes Table 5 very difficult to read. I had to spend several minutes staring at the numbers before I could get any meaningful information from it. Unfortunately the colours for “fair”, “moderate” and “good” are almost indistinguishable on my screen, which does render this information almost meaningless. Consequently I would like to encourage the authors to replace this table with one or two figures (e.g. bar charts, heat maps) and to present the detailed quantitative information in the supplement.

Thank you for the comment. We now use a colorscale that maximizes the difference in tone, hue, and saturation between the different performance intervals (produced using ColorBrewer, see <http://colorbrewer2.org>), to improve the readability of the table. We are now confident that the table is easy to interpret.

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** SC3:

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If I got it correctly: Table 5 presents global means whereas Table S1 shows global medians. This is inconsistent and should be adjusted accordingly.

We would indeed have preferred to use means for the NSE values for consistency. However, the use of means would render Table S1 meaningless because the values would be completely dominated by some catchments with extremely low NSE values. We therefore decided not to use means, although we appreciate the suggestion.

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** SC4:

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I do really appreciate the authors effort to present “budyko-plots” for a wider range of options. I am, however, not convinced by their choice to mask out regions >50deg N/S. While I can follow the argument that most of Rn will feed into the sensible heat flux, I do not understand why this would be an argument to exclude this from the analysis. To me this reads like an attempt to hide/mask out unwanted information. Note also that much of the Original work if Budyko was based on Rn AND included also information from high latitudes.

We have redone the plots to include all grid cells and changed the text accordingly. Thank you for the suggestion.

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** SC5:

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In some sections there is still a tendency of value statements and a fair degree of “NSE-bashing” which I think is not necessary. I fully support the authors choice not to focus on NSE I think that a more neutral wording would be valuable for the scientific discourse

We have removed “widely” from the sentence “the NSE has been widely criticized for being overly sensitive to the magnitude and timing of peak flows” to soften our critique.

REFeree #2

The authors have to a large extent responded to the comments of the reviewers and the editor. After reading the authors` response as well as the revised version of the manuscript, a few important suggestions remain that I would like to be addressed in the final publication.

We would like to thank the reviewer for their comments and suggestions.

I think that my concern regarding the conclusion about the potential of multi-parameterization ensembles (no. 2 of my review) not being backed by the analysis was not clarified.

“2) The study of Beck et al. (2016) also indicates that performance of the HBV-SIMREG model results that are not derived as the ensemble mean of 10 runs with 10 different parameter sets but just 1 (derived from the most similar donor catchment) perform only slightly worse than the

ensemble mean and better than the other models (Tables 6 and 7 of Beck et al.). Therefore, the conclusion that the fact that HBV-SIMREG with 10 runs performs better than the ensemble mean of all models tentatively suggests that a multi-parameterization ensemble for a single, sufficiently flexible model could replace multi-model ensemble studies (p. 20), is not backed by the analysis in the manuscript. I suggest including the HBV-SIMREG variant with 1 run/parameter set only, and consider the result when formulating such a conclusion. In addition, it should be taken into account (and explained very clearly in the manuscript) that HBV-SIMREG only computes runoff in 0.5° grid cells and not river discharge, as grid to grid lateral routing including the impact of lakes and wetlands as well as water abstraction are not simulated by this model.”

The HBV-SIMREG output that is not the ensemble mean of 10 runs with 10 different parameter sets (evaluated in the manuscript) but, like in the case of all other evaluated models just the output derived from using one (calibrated) parameter set does need to be included in a study that concludes (P21L8ff, also P23) that “a multi-parameterization ensemble for a single, sufficiently flexible mode provides performance comparable to a multi-model ensemble”. Please either add the performance indicators of such a values HBV-SIMREG variant either to Table 5, the supplement or just provide selected values in the text. In addition, the conclusions may need to be extended by a consideration regarding the benefit of multi-model ensembles (with different model structures) for e.g. climate change impact studies.

We would like to clarify that our study does not *conclude* that “a multi-parameterization ensemble for a single, sufficiently flexible model provides performance comparable to a multi-model ensemble”. Instead, our results *“tentatively suggest* that a multi-parameterization ensemble for a single, sufficiently flexible model provides performance comparable to a multi-model ensemble”. The words “tentatively” and “suggests” highlight the uncertain nature of this finding. In addition, immediately after this statement we further emphasize the inconclusive nature of this finding with the words “If this is confirmed, ...”.

Moreover, Table 7 of Beck et al. (2016) shows that HBV with spatially-uniform parameters performs, on average, worse than two models but better than seven models, meaning that while HBV with spatially-uniform parameters performs indeed fairly well among the models, it certainly did not perform outside the range of the other models. Thus, the fact that HBV-SIMREG outperforms the other models is therefore mainly attributable to the calibration and regionalization efforts, and our conclusions and insights would not change by including HBV with spatially-uniform parameters in the current analysis. We explicitly mention this in the m/s: *“In their study, Beck et al. (2016) show that HBV using spatially-uniform parameters performs within the range of the other models, confirming that the relatively good performance of HBV-SIMREG stems from the regionalization exercise.”*

Furthermore, the current study is about evaluating the earthH2Observe collection of models, and HBV with spatially-uniform parameters is not part of this collection.

We agree that a multi-parameterization model may not perform as well when it is subjected to climate projections, which is one of the reasons why we push for additional research on this topic.

B

Looking at Dutra (2015), I noticed that it is not clear in the manuscript, what output variable of the models have actually been evaluated by comparing their value to the streamflow at the outlet of small catchments. On P4L10, the variable is only described as “simulated daily (non-routed) runoff (mm/d).” I think that for a proper comparison to observed streamflow, the “simulated runoff” should be the amount of water that is simulated to enter the stream each day, i.e. is the storage of water in the groundwater and the surface water bodies (if they exist in the models) taken into account. Could you please clarify this the text.

However, Dutra (2015), section 4.8, writes about SWBM as used in Tier1, i.e. for the study described in the manuscript, that SWBM runoff results should not be evaluated at the daily time scale because the model in the Tier1 version does not include the impact of groundwater storage on streamflow:

“The OS13 model version incorporates a delayed formation of streamflow to account for the (sub-surface) transport of runoff water to the stream-gauge site, whereby the runoff water is stored in a groundwater storage before it is transformed into streamflow. Even if this mechanism is crucial to estimate daily streamflow dynamics we excluded it from the model because (i) this reduces the computational effort considerably through the removal of a parameter and because delayed streamflow is not calculated and (ii) it does not impact soil moisture and ET. All results related to runoff in this study are only valid on the monthly time scale where runoff and streamflow are rather similar.”

However, in the ms, daily SWBM runoff seems to have been used.

Thank you for the comment. For all models we used simulated specific runoff depths rather than routed discharge volumes, because the latter was available for only a subset of models. These runoff amounts include both surface and subsurface runoff and these thus include groundwater contributions. We now explicitly mention in the text that “for each model the sum of the subsurface and surface runoff components was calculated” (page 4 line 22), to avoid any confusion. We agree that it would be better to compare simulated discharge to discharge observations but note that the simulated runoff is similar to the simulated discharge since we focus catchments with an area comparable to the model's grid.

We want to note that Rene Orth, the developer of SWBM, is co-author of this study, and thus supports the daily evaluation performed in this study. We are also aware that SWBM does not include a baseflow component and therefore performs worse for baseflow-related metrics, which we explicitly mention in the text (page 14 line 24).

C

Section 3.3. Caveats

I suggest adding one further caveat which is according to my experience very important: That the results of the model evaluation may strongly depend on the applied climate data set, in particular because the evaluation considers small time periods (days) and areas (0.5° grid cells) for which e.g. the uncertainty of precipitation data is very high.

We appreciate the suggestion and have added the forcing data as an additional caveat (“the forcing data quality has an important influence on the evaluation results that should not be overlooked”, page 9 lines 15-16).

Minor

P10: Replace reference Döll and Flörke (2005) by

Döll, P., Fiedler, K. (2008): Global-scale modeling of groundwater recharge. Hydrol. Earth Syst. Sci., 12, 863-885.

Changed, thanks for the suggestion.

P17L7: Replace: “assess the impacts of climate change” by “assess the impacts of past climate change”

Changed as suggested.

Global evaluation of runoff from ten state-of-the-art hydrological models

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Abstract. Observed streamflow data from 966 medium sized catchments (~~1000 to 5000~~ 1000–5000 km²) around the globe were used to comprehensively evaluate the daily runoff estimates (1979–2012) of six global hydrological models (GHMs) and four land surface models (LSMs) produced as part of Tier-1 of the earth2Observe project. The models were all driven by the WATCH Forcing Data ERA-Interim (WFDEI) meteorological dataset, but used different datasets for non-meteorologic

5 inputs and were run at various spatial and temporal resolutions, although all data were re-sampled to a common 0.5° spatial and daily temporal resolution. For the evaluation, we used a broad range of performance metrics related to important aspects of the hydrograph. We found pronounced inter-model performance differences, underscoring the importance of hydrological model uncertainty in addition to climate input uncertainty, for example in studies assessing the hydrological impacts of climate change. The uncalibrated GHMs were found to perform, on average, better than the uncalibrated LSMs in snow-dominated

10 regions, while the ensemble mean was found to perform only slightly worse than the best (calibrated) model. The inclusion of less ~~reliable~~ accurate models did not appreciably degrade the ensemble performance. Overall, we argue that more effort should be devoted on calibrating and regionalizing the parameters of macro-scale models. We further found that, despite adjustments using gauge observations, the WFDEI precipitation data still contain substantial biases that propagate into the simulated runoff. The early bias in the spring snowmelt peak exhibited by most models is probably primarily due to the widespread precipitation

15 underestimation at high northern latitudes.

1 Introduction

Hydrological models are indispensable tools for many purposes, including but not limited to, (i) flood and drought forecasting, (ii) water resources assessments, (iii) assessing the hydrological impacts of human activities, and (iv) increasing our understanding of the hydrological cycle. It is more than 50 years since the first attempts at hydrological modeling (Lins-

ley and Crawford, 1960; Rockwood, 1964; Sugawara, 1967; Freeze and Harlan, 1969). Since then, a plethora of conceptual, physically-based, and stochastic hydrological models has been developed, each with its own assumptions and characteristics (for non-exhaustive overviews, see Singh, 1995; Singh and Frevert, 2002; Rosbjerg and Madsen, 2006; Trambauer et al., 2013; Sooda and Smakhtin, 2015; Bierkens et al., 2015; Kauffeldt et al., 2016). Because all hydrological models are inevitably imperfect representations of reality, they produce highly uncertain estimates even if we would have access to perfect meteorological data (Beven, 1989).

The quantification of these uncertainties using independent data sources is of critical importance to advance model development, reject deficient model structures and parameterizations, quantify model credibility, and ultimately bring some order in the plethora of models (Klemeš, 1986; Wagener, 2003; Döll et al., 2015; Clark et al., 2015). There have been several collaborative research efforts focusing on the intercomparison and verification of hydrological models. The earliest were coordinated by the World Meteorological Organization (WMO, 1975, 1986, 1992). Other noteworthy initiatives include the Model Parameter Estimation Experiment (MOPEX; Duan et al., 2006), the Global Soil Wetness Project (GSWP; Dirmeyer, 2011), the Water Model Intercomparison Project (WaterMIP; Haddeland et al., 2011), and the Global Energy and Water Exchanges (GEWEX) LandFlux project (McCabe et al., 2016). These initiatives have led to numerous multi-model evaluation studies focusing on such hydrological variables as runoff (e.g., Gudmundsson et al., 2012a; Zhou et al., 2012), evaporation (e.g., Schlosser and Gao, 2010; Jiménez et al., 2011; Miralles et al., 2015), soil moisture (e.g., Guo et al., 2007; Xia et al., 2014), snow cover (e.g., Slater et al., 2001), and total water storage (Güntner, 2008), among others.

One of the most useful variables for hydrological model evaluation is runoff, since it reflects the integrated response of a host of hydrological processes occurring in a catchment (Fekete et al., 2012) and because observations are readily available for many catchments across the globe (Hannah et al., 2011). Table 1 lists, to our knowledge, all macro-scale (i.e., continental to global scale) studies evaluating the runoff estimates of multiple models that have been published so far. Out of these 20 studies, two focused on the conterminous USA, five focused on Europe, while thirteen had a global scope. However, many of these studies used observations from a relatively small number (< 100) of large catchments ($\gg 10000 \text{ km}^2$). The use of a small number of basins limits confidence in the results and precludes a spatially detailed assessment, while the large size of the catchments makes it more difficult to distinguish between deficiencies in the forcing, the (sub-)surface component, or the river routing component of the modeling chain. Moreover, a large number of the studies only evaluated monthly mean runoff, precluding the analysis of the shape of individual flow events, or used the Nash and Sutcliffe (1970) efficiency (NSE), which has been criticized in several previous studies for being overly sensitive to the timing and magnitude of peak flows (Schaeffli and Gupta, 2007; Jain and Sudheer, 2008). Furthermore, many studies considered only a few hydrological models (≤ 5) or performance metrics (≤ 2), limiting the insights that can be gained.

As part of Tier-1 of the earth2Observe project⁺, ten state-of-the-art hydrological models were run globally at a daily time step for the period 1979–2012 using the same forcing dataset, [in an effort to develop a global reanalysis of water resources that supports efficient water management and decision making \(Schellekens et al., 2016\)](#). Six of the models are global hydrological models (GHMs) while four of the models are land surface models (LSMs). GHMs have traditionally been designed to simulate (sub-)surface water fluxes and storages, while LSMs have traditionally been designed to simulate the soil-vegetation-

Table 1. Overview of, to the best of our knowledge, all macro-scale (continental to global) studies evaluating the runoff estimates of multiple models, sorted by region and then publication date. The present study has been added for the sake of completeness.

Study	Region	Number of models	Number of catchments (size range)	Evaluation time scale(s)
Lohmann et al. (2004)	Cont. USA	4	1145 (23 to 10 000 km ²)	Daily, monthly, annual, long term
Xia et al. (2012)	Cont. USA	4	969 (23 to 1 353 280 km ²)	Daily, weekly, monthly, annual, long term
Prudhomme et al. (2011)	Europe	3	579 (< 1000 km ²)	Daily
Gudmundsson et al. (2012a)	Europe	9	426 (< 4000 km ²)	Daily, annual, long term
Gudmundsson et al. (2012b)	Europe	9	426 (< 4000 km ²)	Annual, long term
Greuell et al. (2015)	Europe	5	46 (9948 to 658 340 km ²)	Daily, monthly, annual, long term
Gudmundsson and Seneviratne (2015)	Europe	10	426 (< 4000 km ²)	Monthly, annual, long term
Milly et al. (2005)	Global	12	165 (> 50 000 km ²)	Long term
Decharme and Douville (2006)	Global	6	80 (100 000 to 4 758 000 km ²)	Daily, monthly
Decharme and Douville (2007)	Global	6	80 (100 000 to 4 758 000 km ²)	Monthly
Decharme (2007)	Global	2	80 (100 000 to 4 758 000 km ²)	Monthly
Materia et al. (2010)	Global	13	30 (82 000 to 4 677 000 km ²)	Monthly
Zaitchik et al. (2010)	Global	4	66 (19 000 to 4 600 000 km ²)	Daily, annual
Haddeland et al. (2011)	Global	11	8 (650 000 to 4 600 000 km ²)	Monthly
Zhou et al. (2012)	Global	14	150 (not specified; ≥ 10 000 km ²)	Annual
Van Dijk et al. (2013b)	Global	5	6192 (10 to 10 000 km ²)	Monthly
Beck et al. (2015)	Global	4	4079 (10 to 10 000 km ²)	Daily, long term
Yang et al. (2015)	Global	7	16 (135 757 to 3 475 000 km ²)	Monthly, annual
Zhang et al. (2016)	Global	4	644 (≥ 2000 km ²)	Monthly, annual
Beck et al. (2016)	Global	10	1113 (10 to 10 000 km ²)	Daily, 5-day, monthly, long term
This study	Global	10	966 (1000 to 5000 km ²)	Daily, 5-day, monthly, annual, long term

atmosphere interactions within climate models (Haddeland et al., 2011; Bierkens, 2015). GHMs generally represent hydrological processes in a more conceptual way, solve only the water balance, commonly operate at daily time steps, and typically have a small number of soil layers (≤ 3 in the current study) and a single snow layer. Conversely, LSMs generally represent hydrological processes in a more physically-based way, solve both the water and energy balances, typically operate at (sub-)hourly time steps, and tend to have many soil and snow layers (4–11 and 1–12, respectively, in the current study; for more details on the models, see Table 4.1 of [Schellekens et al., 2016](#)). The present study aims to comprehensively evaluate the runoff estimates of these ten models across the globe in an effort to answer the following pertinent research questions:

1. How well do the different models simulate runoff?
2. How well do the models perform in terms of long-term runoff trends?
3. How do the results of the GHMs differ, if at all, from those of the LSMs?
4. Are calibration and regionalization important or even essential?
5. What is the impact of the forcing data on the simulated runoff?

6. How valuable are multi-model ensembles for improving runoff estimates?

7. Do all models show the early bias in runoff timing in snow-dominated catchments previously documented (e.g., Zaitchik et al., 2010) and what is the cause?

We use daily streamflow observations during 1979–2012 from a large, highly diverse, quality-controlled set of medium sized catchments. ~~This leads to more reliable and generalizable conclusions, and,~~ which allows us to ~~explicitly~~ compare the performance among different regions and climate types (Andréassian et al., 2007; Stahl et al., 2011; Gupta et al., 2014). Moreover, we use a broad range of performance metrics, including runoff signatures (measures that quantify the hydrograph shape such as runoff coefficient and baseflow index; Olden and Poff, 2003; Monk et al., 2007) that can be related to specific hydrological processes (Yilmaz et al., 2008).

2 Data

2.1 Forcing

The models were all driven by the daily 0.5° WATCH Forcing Data ERA-Interim (WFDEI) meteorological dataset (1979–2012; Weedon et al., 2014) with the precipitation (P) data adjusted using the monthly 0.5° gauge-based Climate Research Unit (CRU) TS3.1 dataset (Harris et al., 2013). Although the models all used the same P data, they used potential evaporation (PET) derived using diverse formulations, ranging from the temperature-based Hamon equation (PCR-GLOBWB) to various radiation-based approaches (WaterGAP3, SWBM, and HBV-SIMREG), the Penman-Monteith combination equation (HTESSEL, JULES, LISFLOOD, SURFEX, and W3RA), and a surface-energy balance approach (ORCHIDEE). The models also used different datasets for non-meteorologic inputs. For more details, see [Schellekens et al. \(2016\)](#).

2.2 Simulated runoff

Table 2 lists the ten state-of-the-art macro-scale hydrological models of which we evaluated the simulated daily unrouted runoff depths (~~non-routed~~) ~~runoff~~ (mm d^{-1}). The data used in this study have been named Tier-1 and represent an initial run by all participating modeling groups ([Schellekens et al., 2016](#)). All data were acquired through the earth2Observe Water Cycle Integrator (WCI; <http://wci.earth2observe.eu>), and for each model the sum of the subsurface and surface runoff components was calculated. Six of the models are GHMs (LISFLOOD, PCR-GLOBWB, SWBM, W3RA, WaterGAP3, and HBV-SIMREG) and four are LSMs (HTESSEL, JULES, ORCHIDEE, and SURFEX). The GHMs were all run at daily time steps and the LSMs at hourly and 15-minute time steps. The models were run at a 0.5° spatial resolution, with the exception of LISFLOOD and WaterGAP3, which were run at 0.1° and 0.08°, respectively. For the analysis, however, all model output was resampled to a common 0.5° spatial and daily temporal resolution. Four of the models were subjected to varying degrees of calibration to improve their parameters (LISFLOOD, SWBM, WaterGAP3, and HBV-SIMREG; see Section 4.4 for specifics). More details concerning the models can be found in Table ~~4.1 of~~ [Schellekens et al. \(2016\)](#).

Table 2. Overview of the hydrological models considered in this study. For definitions of the model name acronyms, see [Schellekens et al. \(2016\)](#). Definitions of model-class acronyms: GHM, global hydrological model; and LSM, land surface model.

Model name	Data provider(s)	Reference(s)	Model class
HTESSEL	European Centre for Medium-Range Weather Forecasts (ECMWF)	Balsamo et al. (2009, 2011)	LSM
JULES	Natural Environment Research Council (NERC)	Best et al. (2011)	LSM
LISFLOOD	Joint Research Centre (JRC)	Burek et al. (2013)	GHM
ORCHIDEE	Centre National de la Recherche Scientifique (CNRS)	Krinner et al. (2005)	LSM
PCR-GLOBWB	University of Utrecht	Van Beek and Bierkens (2009)	GHM
SURFEX	Météo France	Decharme et al. (2011, 2013)	LSM
SWBM	Eidgenössische Technische Hochschule (ETH) Zürich	Orth and Seneviratne (2015)	GHM
W3RA	Australian National University (ANU) and Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Van Dijk (2010)	GHM
WaterGAP3	University of Kassel	Verzano (2009)	GHM
HBV-SIMREG	JRC	Beck et al. (2016)	GHM

2.3 Observed streamflow

Daily and monthly observed streamflow data were used in this study to evaluate the runoff estimates of the models. The observed streamflow and catchment boundary data used in this study originate from the same three sources as Beck et al. (2013, 2015, 2016), namely (i) the Global Runoff Data Centre (GRDC; <http://www.bafg.de/GRDC/>), (ii) the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES)-II database (Falcone et al., 2010), and (iii) an Australian streamflow data compilation by Peel et al. (2000). The following seven criteria were used to select suitable catchments for our analysis:

1. The streamflow record length was required to be ≥ 5 years (not necessarily consecutive) during 1979–2012 (the temporal span of the simulated runoff data).
2. The catchment area had to be $< 5000 \text{ km}^2$, to minimize the effects of channel routing delays and to reduce the likelihood of significant anthropogenic water use. We could not use larger catchments and evaluate routed streamflow estimates since three of the models did not not simulate river routing (JULES, SWBM, and HBV-SIMREG).
3. The catchment area had to be $> 1000 \text{ km}^2$, to prevent catchments unrepresentative of the 0.5° grid cells (2182 km^2 at 45°N/S) from confounding the results.
4. To reduce human influences, catchments were required to have $< 2 \%$ classified as urban (using the “artificial areas” class of the GlobCover version 2.3 map; 300-m resolution; Bontemps et al., 2011) and subject to irrigation (using version 5 of the Global Map of Irrigation Areas—GMIA; 5-min resolution; Siebert et al., 2005).
5. We used the Global Reservoir and Dam (GRanD) database (v1.1; Lehner et al., 2011) to exclude catchments influenced by major reservoirs (defined by total reservoir capacity $> 10 \%$ of the observed mean annual streamflow).

6. Catchments with forest gain or loss $> 20\%$ of the catchment area (the threshold at which changes in runoff can generally be detected; Bosch and Hewlett, 1982) were excluded using version 1.1 of the Landsat-based forest change dataset (30-m resolution; Hansen et al., 2013).

7. To further reduce the number of disinformative catchments, all streamflow records were visually screened for artifacts and anthropogenic influences (caused by, for example, diversions and impoundments). Furthermore, USA catchments flagged as “non-reference” in the GAGES-II database were discarded, and GRDC catchments for which the catchment boundaries could not be reliably determined were discarded (Lehner, 2012).

In total 966 catchments (median size 1970 km²; median record length 19 y during 1979–2012) were found to be suitable for the analysis, of which 641 catchments have daily streamflow data and 325 catchments (mainly located in Russia) have only monthly streamflow data. The locations of the selected catchments will be shown in the Results section. All observed streamflow data were converted to runoff in mm d⁻¹ using the provided catchment areas.

3 Methodology

3.1 Model evaluation

The simulated runoff of the models were evaluated in five ways. First, for each catchment, we calculated the differences D (–) between simulated and observed values of several runoff signatures. Table 3 lists the six runoff signatures selected including their computation from the period with simultaneous simulated and observed runoff. The baseflow index (BFI), square-root transformed 1st percentile exceedance flow (Q1), and square-root transformed 99th percentile exceedance flow (Q99) require daily (rather than monthly) flow data. To compute the flow timing (T50) from monthly data, we first computed daily time series from monthly time series using linear interpolation. The square-root transformed runoff coefficient (RC), square-root transformed mean annual flow (MAR), Q1, and Q99 values were square-root transformed to give more weight to small values. D was computed according to:

$$D_q = \frac{Y_{q\text{sim}} - Y_{q\text{obs}}}{\sigma_q}, \quad (1)$$

where Y represent the values of the runoff signatures (–), the q subscript denotes the runoff signature, and the ‘sim’ and ‘obs’ subscripts refer to simulated and observed, respectively. The σ values (–) are constants that represent the spatial variability in the runoff signatures across the landscape and are used to normalize the D values (i.e., to make the D values of the different signatures intercomparable; [see Table 3](#)). The σ values were computed by taking the standard deviation of ~~global-scale signature maps from the Global Streamflow Characteristics Dataset (GSCD) v1.9 (Beck et al., 2015; ; see Table 3) taking into account the entire ice-free land surface excluding deserts (defined by an aridity index > 5), with the exception of the T50 σ , which considers only the snow-dominated ice-free land surface~~[the observed values](#). Next, the mean D value over all catchments was computed (expressed by \overline{D}). D and \overline{D} values closer to zero correspond to better model performance (see Table 4). It should be

Table 3. The long-term runoff behavioral signatures considered for evaluating the model performance. The signatures were computed, for each catchment, from the entire record of simultaneous observed and simulated runoff. The σ values represent the spatial variability in the runoff signatures across the landscape.

Runoff signature	Units	Description	Evaluated flow aspect	Standard deviation (σ)
RC	—	Square-root transformed runoff coefficient, ratio of long-term runoff to P	Water balance	0.33
MAR	$\sqrt{\text{mm yr}^{-1}}$	Square-root transformed long-term mean annual runoff	Water balance	11.21
T50	d	The day of the water year marking the timing of the center of mass of flow (Stewart et al., 2005). A water year is defined as the 12-month period from October to September in the Northern Hemisphere and April to March in the Southern Hemisphere	Seasonal flow distribution	34.36
BFI	—	Base flow index, the ratio of long-term baseflow to total runoff. The baseflow portion of the total runoff was computed following the procedure of Gustard et al. (1992), which takes the minima at five-day non-overlapping intervals and subsequently connects the valleys in this series of minima to generate baseflow	Partitioning between quickflow and baseflow, flow peakiness	0.18
Q1	$\sqrt{\text{mm d}^{-1}}$	Square-root transformed 1st percentile exceedance flow	Peak-flow magnitude	1.27
Q99	$\sqrt{\text{mm d}^{-1}}$	Square-root transformed 99th percentile exceedance flow	Low-flow magnitude	0.21

noted that, although \bar{D} provides a valuable estimate of the overall performance, a good \bar{D} value may reflect an overestimation in one region that is compensated by an underestimation in another region.

Second, to evaluate the temporal variability of the simulated runoff time series, we computed Pearson linear correlation coefficients (r) between daily, log-transformed daily, 5-day, monthly, monthly climatic, and annual time series of simulated and observed runoff (termed r_{dly} , $r_{\text{dly log}}$, $r_{5\text{ day}}$, r_{mon} , $r_{\text{mon clim}}$, and r_{yr} , respectively). The r_{dly} , $r_{\text{dly log}}$, and $r_{5\text{ day}}$ values were only computed for catchments with daily observations. If monthly data were not supplied by the data providers, monthly values were computed by simple averaging of the daily data only if > 25 non-missing values were available. Annual values were computed by simple averaging of the monthly data (either supplied or computed) only if > 10 non-missing values were available. We subsequently computed for each model and metric the mean r value over all catchments, expressed by \bar{r} . The r and \bar{r} values range from -1 to 1 , with higher values corresponding to better model performance (see Table 4).

Third, to summarize the overall performance of each model, we computed for each catchment a summary performance statistic (termed OS) incorporating the previously mentioned metrics, and computed the mean value over all catchments ($\overline{\text{OS}}$). The OS consists of two parts, of which the first (OS_{sig}) considers the performance in terms of runoff signatures and is defined as:

$$\text{OS}_{\text{sig}} = 1 - \text{mean} \left[|D_{\text{RC}}|, |D_{\text{MAR}}|, |D_{\text{T50}}|, |D_{\text{BFI}}|, |D_{\text{Q1}}|, |D_{\text{Q99}}| \right]. \quad (2)$$

The second part (OS_{var}) evaluates the performance in terms of temporal variability, and is defined as:

$$\text{OS}_{\text{var}} = \text{mean} \left[r_{\text{dly}}, r_{\text{dly log}}, r_{5\text{ day}}, r_{\text{mon}}, r_{\text{mon clim}}, r_{\text{yr}} \right]. \quad (3)$$

Table 4. Qualitative descriptions of intervals of the performance metrics to aid in interpreting the results.

	$ D $	r, ρ	OS
Excellent	$[0, 0.2)$	$[0.8, 1]$	$[0.8, 1]$
Good	$[0.2, 0.4)$	$[0.6, 0.8)$	$[0.6, 0.8)$
Moderate	$[0.4, 0.6)$	$[0.4, 0.6)$	$[0.4, 0.6)$
Fair	$[0.6, 0.8)$	$[0.2, 0.4)$	$[0.2, 0.4)$
Poor	$[0.8, +\infty]$	$[-1, 0.2)$	$[-\infty, 0.2)$

The summary score is subsequently computed following:

$$OS = \frac{OS_{\text{sig}} + OS_{\text{var}}}{2}. \quad (4)$$

The BFI, Q1, and Q99 components of Equation 2 and the r_{dly} and $r_{\text{dly log}}$ components of Equation 3 were omitted if daily observations were unavailable for a particular catchment. Higher OS values correspond to better model performance; the maximum attainable value is 1 (see Table 4).

- 5 Fourth, to evaluate the ability of each model to simulate the variability among the catchments in the six previously mentioned runoff signatures, Spearman rank correlation coefficients (ρ) were computed between simulated and observed values of the runoff signatures. Spearman rank correlation coefficients rather than Pearson linear correlation coefficients were used to minimize the influence of outliers. The ρ values range from -1 to 1 , with higher values corresponding to better model performance (see Table 4).
- 10 Fifth, we computed trends in simulated and observed mean annual runoff time series (termed MAR trend) using the simple non-parametric approach of Sen (1968). We subsequently calculated the ρ between simulated and observed MAR trends ($\rho_{\text{MAR trend}}$), reflecting the agreement in spatial trend patterns.

- Sixth and last, we produced density plots of grid cell values of aridity index (AI; ratio of long-term ~~PET~~available energy to P) versus runoff coefficient (RC; ratio of long-term simulated runoff to P), revealing how the models behave in terms of RC under different climatic conditions. ~~PET data was available~~To estimate the available energy we used PET for four models (ORCHIDEE, PCR-GLOBWB, W3RA, and WaterGAP3) ~~while net radiation data were used to approximate PET and net radiation~~ for three models (HTESSEL, JULES, and SURFEX). For the remaining models ~~PET or net radiation estimates~~estimates of the available energy were not available.

- For the evaluation, we used for each catchment the simulated runoff time series of the 0.5° grid cell with its center located within the catchment. However, if multiple grid cell centers were located within the catchment, we calculated the mean simulated runoff time series, and if no grid cell center was located within the catchment, we used the simulated runoff time series of the grid cell with its center located closest to the catchment centroid.

3.2 Multi-model ensembles

- Ensemble modeling—using the outputs from multiple models or from different realizations of the same model—typically improves predictive accuracy and is widely used in atmospheric, climate, and hydrological sciences (Wandishin et al., 2001;

Tebaldi and Knutti, 2007; Breuer et al., 2009; Viney et al., 2009). We tested two ways of combining the runoff estimates of the individual models into ensembles. First, for each 0.5° grid cell and day with non-missing values for all models, the mean simulated runoff of the ten models was calculated (i.e., equal weights were assigned to the models). The resulting runoff estimates will be referred to hereafter as “MEAN-All”. Second, we computed the mean based on only the four models that performed best in terms of \overline{OS} , to examine the effect of excluding less ~~reliable~~-accurate models. These runoff estimates will be referred to hereafter as “MEAN-Best4”.

3.3 Caveats

There are a number of caveats that should be kept in mind when interpreting the results. First, some of the models (notably the LSMs) were not traditionally developed to estimate daily runoff for such small catchments. Some of the GHMs, on the other hand, have runoff estimation in small catchments among their primary aims (e.g., LISFLOOD, WaterGAP3, W3RA, and HBV-SIMREG), and four GHMs were even explicitly calibrated against observations (LISFLOOD, SWBM, WaterGAP3, and HBV-SIMREG; see Section 4.4 for specifics). Second, a model performing poorly in one respect may well perform better for other hydrological variables, climates, catchments, or performance metrics. Third, a poor model performance could simply be the result of suboptimal parameter values. Fourth, some studies have found that less ~~reliable~~-accurate models may still lead to a better ensemble mean (Ajami et al., 2006; Viney et al., 2009), although this did not appear to be the case here (see Section 4.6). ~~Fifth and finally~~, we stress that while some models may perform well, they are inherently unsuitable for specific types of impact assessments. For example, SWBM and HBV-SIMREG do not account for physical differences among land-cover types and hence cannot be used for studies assessing the hydrological impacts of changes in land cover. Sixth and finally, the forcing data quality has an important influence on the evaluation results that should not be overlooked.

4 Results and discussion

In this section we will answer the questions posed in the introduction.

4.1 How well do the different models simulate runoff?

~~Tables ?? and ??~~ Table 5 show, for the uncalibrated models, the calibrated models, and the ensembles, (i) the mean difference between simulated and observed values of the (normalized) runoff signatures (\overline{D}), (ii) the mean temporal correlation between simulated and observed runoff time series (\overline{r}), and (iii) the mean overall performance in terms of runoff signatures and temporal correlation coefficients (\overline{OS}). HTESSEL obtained negative D values for the square-root transformed runoff coefficient (RC) and the square-root transformed mean annual runoff (MAR), indicating it underestimates runoff. JULES performed moderately in terms of temporal correlation, as indicated by the low r values. Conversely, LISFLOOD performed good overall, particularly in terms of temporal correlation, although it tends to overestimate RC and MAR. ORCHIDEE appears to strongly underestimate runoff and performed fairly in terms of temporal correlation, whereas PCR-GLOBWB shows moderate to good scores for most metrics. Apart from a much too early bias in the flow timing (T50), SURFEX demonstrated moderate to good perfor-

mance overall. Similar to SURFEX, W3RA exhibits a very early bias in T50, but generally obtained moderate to good scores. WaterGAP3 and particularly HBV-SIMREG outperformed the other models in most cases. JULES, ORCHIDEE, SURFEX, WaterGAP3, and especially SWBM displayed negative D values for the baseflow index (BFI) and the square-root transformed 99th flow percentile (Q99), and a positive D value for the square-root transformed 1st flow percentile (Q1; [Tables ?? and ??Table 5](#)), suggesting they consistently overestimate quickflow. Conversely, LISFLOOD and particularly PCR-GLOBWB exhibited positive D values for BFI and Q99, and a negative D value for Q1, indicating they tend to underestimate quickflow.

For the six uncalibrated models, (i) the mean difference between simulated and observed values of the (normalized) runoff signatures (\bar{D}), (ii) the mean temporal correlation between simulated and observed runoff time series (\bar{r}), (iii) the mean overall performance in terms of runoff signatures and temporal correlation (\overline{OS}), and (iv) the spatial correlation between simulated and observed values of the runoff signatures (ρ). Color legend: poor, fair, moderate, good, excellent (see Table 4 for the corresponding metric intervals). See Figure 1 for the locations of the catchments. Metric HTESSEL JULES ORCHIDEE PCR-GLOBWB SURFEX W3RA \bar{D}_{RC} ($n=966$) -0.41 -0.16 -0.52 -0.02 -0.26 -0.21 \bar{D}_{MAR} ($n=966$) -0.30 -0.10 -0.38 -0.00 -0.19 -0.13 \bar{D}_{T50} ($n=966$) -0.36 -0.52 -0.07 -0.27 -0.86 -0.68 \bar{D}_{BFI} ($n=632$) -0.06 -1.11 -1.22 -1.35 -1.37 -0.31 \bar{D}_{Q1} ($n=641$) -0.07 -0.26 -0.20 -0.29 -0.37 -0.08 \bar{D}_{Q99} ($n=641$) -0.22 -0.73 -0.92 -0.27 -0.89 -0.08 \bar{r}_{dly} ($n=641$) -0.33 -0.23 -0.21 -0.34 -0.31 -0.44 \bar{r}_{dlylog} ($n=641$) -0.50 -0.41 -0.33 -0.50 -0.51 -0.56 \bar{r}_{5day} ($n=641$) -0.45 -0.36 -0.33 -0.44 -0.41 -0.52 \bar{r}_{mon} ($n=966$) -0.53 -0.44 -0.40 -0.58 -0.43 -0.57 $\bar{r}_{monclim}$ ($n=966$) -0.66 -0.50 -0.49 -0.73 -0.47 -0.64 \bar{r}_{yr} ($n=966$) -0.58 -0.61 -0.51 -0.58 -0.57 -0.63 All ($n=966$) -0.43 -0.39 -0.26 -0.41 -0.32 -0.46 A: tropical ($n=57$) -0.41 -0.46 -0.28 -0.03 -0.41 -0.39 B: arid ($n=38$) -0.52 -0.50 -0.38 -0.07 -0.46 -0.50 C: temperate ($n=203$) -0.46 -0.54 -0.35 -0.37 -0.51 -0.51 D: cold ($n=633$) -0.43 -0.34 -0.23 -0.47 -0.25 -0.45 E: polar ($n=35$) -0.32 -0.25 -0.20 -0.53 -0.23 -0.33 ρ_{RC} ($n=966$) -0.67 -0.64 -0.30 -0.56 -0.65 -0.60 ρ_{MAR} ($n=966$) -0.80 -0.78 -0.61 -0.73 -0.79 -0.77 ρ_{T50} ($n=966$) -0.76 -0.82 -0.66 -0.63 -0.78 -0.85 ρ_{BFI} ($n=632$) -0.38 -0.28 -0.46 -0.10 -0.01 -0.35 ρ_{Q1} ($n=641$) -0.77 -0.74 -0.54 -0.53 -0.64 -0.67 ρ_{Q99} ($n=641$) -0.70 -0.69 -0.51 -0.43 -0.59 -0.68 $\rho_{MARtrend}$ ($n=966$) -0.37 -0.38 -0.37 -0.36 -0.32 -0.38

For the four calibrated models and the ensembles, (i) the mean difference between simulated and observed values of the (normalized) runoff signatures (\bar{D}), (ii) the mean temporal correlation between simulated and observed runoff time series (\bar{r}), (iii) the mean overall performance in terms of runoff signatures and temporal correlation (\overline{OS}), and (iv) the spatial correlation between simulated and observed values of the runoff signatures (ρ). Color legend: poor, fair, moderate, good, excellent (see Table 4 for the corresponding metric intervals). See Figure 1 for the locations of the catchments. Metric LISFLOOD SWBM WaterGAP3 HBV-SIMREG MEAN-All MEAN-Best4 \bar{D}_{RC} ($n=966$) -0.08 -0.14 -0.09 -0.06 -0.14 -0.04 \bar{D}_{MAR} ($n=966$) -0.08 -0.07 -0.08 -0.03 -0.09 -0.02 \bar{D}_{T50} ($n=966$) -0.13 -0.32 -0.34 -0.03 -0.31 -0.24 \bar{D}_{BFI} ($n=619$) -0.56 -2.80 -0.91 -0.10 -0.16 -0.20 \bar{D}_{Q1} ($n=641$) -0.03 -0.76 -0.37 -0.12 -0.01 -0.00 \bar{D}_{Q99} ($n=641$) -0.35 -1.40 -0.17 -0.03 -0.15 -0.33 \bar{r}_{dly} ($n=641$) -0.59 -0.32 -0.33 -0.56 -0.44 -0.54 \bar{r}_{dlylog} ($n=641$) -0.70 -0.34 -0.56 -0.71 -0.64 -0.71 \bar{r}_{5day} ($n=641$) -0.64 -0.48 -0.52 -0.65 -0.59 -0.65 \bar{r}_{mon} ($n=966$) -0.71 -0.63 -0.65 -0.74 -0.69 -0.72 $\bar{r}_{monclim}$ ($n=966$) -0.84 -0.75 -0.76 -0.86 -0.80 -0.84 \bar{r}_{yr} ($n=966$) -0.62 -0.60 -0.59 -0.62 -0.64 -0.63 All ($n=966$) -0.55 -0.34 -0.52 -0.62 -0.57 -0.60 A: tropical ($n=57$) -0.43 -0.29 -0.40 -0.47 -0.48

$\overline{D_{BF1}} (n = 613)$	$-0.06-0.041.11-0.841.22-0.921.35$	$1.021.37-1.030.31$	$0.230.56$	$0.422.80-2.120.91-0.690.10-0.080.16-0.120.20$	0.15								
$\overline{D_{Q1}} (n = 641)$	$-0.07-0.060.26$	$0.220.20$	$0.170.29-0.240.37$	$0.310.08-0.070.03-0.020.76$	$0.630.37$	$0.310.12$	$0.190.01$	$0.010.00$	0.00				
$\overline{D_{Q99}} (n = 641)$	$-0.22-0.170.73-0.550.92-0.700.27$	$0.210.89-0.670.08$	$0.060.35$	$0.271.40-1.060.17-0.130.03-0.020.15$	$0.110.33$	0.25							
(ii) Mean temporal correlation between simulated and observed runoff time series													
$\overline{\tau_{\text{dly}}} (n = 641)$	-0.33	$0.330.23$	$0.230.21$	$0.210.34$	$0.340.31$	$0.310.44$	$0.440.59$	$0.590.32$	$0.320.33$	$0.330.56$	$0.560.44$	$0.440.54$	0.54
$\overline{\tau_{\text{dly log}}} (n = 641)$	-0.50	$0.500.41$	$0.410.33$	$0.330.50$	$0.500.51$	$0.510.56$	$0.560.70$	$0.700.34$	$0.340.56$	$0.560.71$	$0.710.64$	$0.640.71$	0.71
$\overline{\tau_{5\text{ day}}} (n = 641)$	-0.45	$0.450.36$	$0.360.33$	$0.330.44$	$0.440.41$	$0.410.52$	$0.520.64$	$0.640.48$	$0.480.52$	$0.520.65$	$0.650.59$	$0.590.65$	0.65
$\overline{\tau_{\text{mon}}} (n = 966)$	-0.53	$0.530.44$	$0.440.40$	$0.400.58$	$0.580.43$	$0.430.57$	$0.570.71$	$0.710.63$	$0.630.65$	$0.650.74$	$0.740.69$	$0.690.72$	0.72
$\overline{\tau_{\text{mon clim}}} (n = 966)$	-0.66	$0.660.50$	$0.500.49$	$0.490.73$	$0.730.47$	$0.470.64$	$0.640.84$	$0.840.75$	$0.750.76$	$0.760.86$	$0.860.80$	$0.800.84$	0.84
$\overline{\tau_{\text{yr}}} (n = 966)$	-0.58	$0.580.61$	$0.610.51$	$0.510.58$	$0.580.57$	$0.570.63$	$0.630.62$	$0.620.60$	$0.600.59$	$0.590.62$	$0.620.64$	$0.640.63$	0.63
(iii) Mean overall performance in terms of runoff signatures and temporal correlation													
All ($n = 966$)	-0.43	$0.430.39$	$0.390.26$	$0.260.41$	$0.410.32$	$0.320.46$	$0.460.55$	$0.550.34$	$0.340.52$	$0.520.62$	$0.620.57$	$0.570.60$	0.60
A: tropical ($n = 57$)	-0.41	$0.410.46$	$0.460.28$	$0.280.03$	$0.030.41$	$0.410.39$	$0.390.43$	$0.430.29$	$0.290.40$	$0.400.47$	$0.470.48$	$0.480.47$	0.47
B: arid ($n = 38$)	-0.52	$0.520.50$	$0.500.38$	$0.380.07$	$0.070.46$	$0.460.50$	$0.500.32$	$0.320.44$	$0.440.42$	$0.420.55$	$0.550.50$	$0.500.44$	0.44
C: temperate ($n = 203$)	-0.46	$0.460.54$	$0.540.35$	$0.350.37$	$0.370.51$	$0.510.51$	$0.510.52$	$0.520.31$	$0.310.48$	$0.480.61$	$0.610.59$	$0.590.58$	0.58
D: cold ($n = 633$)	-0.43	$0.430.34$	$0.340.23$	$0.230.47$	$0.470.25$	$0.250.45$	$0.450.58$	$0.580.35$	$0.350.55$	$0.550.65$	$0.650.59$	$0.590.63$	0.63
E: polar ($n = 35$)	-0.32	$0.320.25$	$0.250.20$	$0.200.53$	$0.530.23$	$0.230.33$	$0.330.60$	$0.600.25$	$0.250.44$	$0.440.60$	$0.600.51$	$0.510.57$	0.57
(iv) Spatial correlation between simulated and observed values of the runoff signatures													
$\rho_{RC} (n = 966)$	-0.67	$0.670.64$	$0.640.30$	$0.300.56$	$0.560.65$	$0.650.60$	$0.600.57$	$0.570.54$	$0.540.82$	$0.820.70$	$0.700.72$	$0.720.79$	0.79

~~-0.47~~**B: arid ($n=38$)** ~~0.32~~ ~~0.44~~ ~~0.42~~ ~~0.55~~ ~~0.50~~ ~~0.44~~**C: temperate ($n=203$)** ~~0.52~~ ~~0.31~~ ~~0.48~~ ~~0.61~~ ~~0.59~~
~~-0.58~~**D: cold ($n=633$)** ~~0.58~~ ~~0.35~~ ~~0.55~~ ~~0.65~~ ~~0.59~~ ~~0.63~~**E: polar ($n=35$)** ~~0.60~~ ~~0.25~~ ~~0.44~~ ~~0.60~~ ~~0.51~~
~~-0.57~~ ρ_{RC} ($n=966$) ~~0.57~~ ~~0.54~~ ~~0.82~~ ~~0.70~~ ~~0.72~~ ~~0.79~~ ρ_{MAR} ($n=966$) ~~0.71~~ ~~0.74~~ ~~0.87~~ ~~0.81~~ ~~0.81~~ ~~0.83~~ ρ_{T50}
~~($n=966$)~~ ~~0.87~~ ~~0.88~~ ~~0.88~~ ~~0.91~~ ~~0.91~~ ~~0.90~~ ρ_{BFI} ($n=619$) ~~0.28~~ ~~0.37~~ ~~0.03~~ ~~0.71~~ ~~0.55~~ ~~0.54~~ ρ_{QI} ($n=641$)
5 ~~-0.65~~ ~~0.73~~ ~~0.80~~ ~~0.76~~ ~~0.76~~ ~~0.78~~ ρ_{Q99} ($n=641$) ~~0.58~~ ~~0.09~~ ~~0.71~~ ~~0.76~~ ~~0.75~~ ~~0.74~~ $\rho_{MARtrend}$ ($n=966$) ~~0.42~~
~~-0.39~~ ~~0.35~~ ~~0.37~~ ~~0.40~~ ~~0.39~~

Tables ?? and ?? also present Table 5 also presents, for the ten models and the ensembles, the spatial correlation between simulated and observed values of the runoff signatures (ρ). HTESSEL, JULES, W3RA, WaterGAP3, and HBV-SIMREG performed good overall, while the remaining models performed moderately overall. PCR-GLOBWB, SURFEX, and WaterGAP3 performed poorly in terms of BFI, while SWBM obtained a poor score for Q99. WaterGAP3 performed good to excellent for all signatures except BFI, likely due to the empirical estimation of groundwater recharge and thus baseflow as a function of landscape characteristics (Döll and Fiedler, 2008). HBV-SIMREG attained good to excellent ρ values for all signatures. The models generally performed best for T50 and worst for BFI among the signatures.

Tables ?? and ?? also show Table 5 also shows, for the ten models and the ensembles, \overline{OS} scores for the major Köppen-Geiger climate types. We used the newly produced Köppen-Geiger climate map from Beck et al. (2016) which is based on the high-quality WorldClim climatic dataset (Hijmans et al., 2005) supplemented with regional climatic datasets for the USA (Daly et al., 1994) and New Zealand (Tait et al., 2006). All four LSMs (HTESSEL, JULES, ORCHIDEE, and SURFEX) generally demonstrated fair performance in cold and polar climates. Conversely, PCR-GLOBWB demonstrated poor performance in tropical and arid climates, likely due to the overestimation of baseflow. SWBM performed moderately only in arid catchments, probably at least partly due to the lack of baseflow under these conditions (Pilgrim et al., 1988; Beck et al., 2013). Similarly, Orth et al. (2015) found that SWBM performs well during dry periods for eight small Swiss catchments (60 to 39260–392 km²). Only LISFLOOD WaterGAP3 and HBV-SIMREG exhibited at least moderate performance for all climates.

Figure 1 presents, for the ten models and the ensembles, maps of simulated minus observed MAR for the catchments, revealing the data underlying the \overline{MAR} and ρ values listed in Tables ?? and ?? Table 5. Maps of all other runoff signatures are presented in Supplementary material Figures S1.2–8. HTESSEL and ORCHIDEE strongly underestimate runoff for most of the catchments, while LISFLOOD appears to strongly overestimate runoff for most of the globe with the exception of snow-dominated regions. All models showed negative MAR biases in snow-dominated regions such as Alaska, the Rocky Mountains, and southern Russia, while they consistently showed positive MAR biases for the Great Plains (USA) and southern Australia. Figure 2 shows, for the ten models and the ensembles, maps of the correlation between simulated and observed monthly flows (r_{mon}) for the catchments, showing the data underlying the $\overline{r_{mon}}$ values presented in Tables ?? and ?? Table 5. Maps of all other temporal variability metrics are presented in Supplementary material Figures S1.9–14. In general, the GHMs obtained good r_{mon} values for most catchments, while the LSMs obtained moderate r_{mon} values for most catchments. All LSMs showed poor to fair r_{mon} values for snow-dominated catchments.

Although the NSE has been widely criticized for being overly sensitive to the magnitude and timing of peak flows (e.g., Schaeffli and Gupta, 2007; Jain and Sudheer, 2008; Criss and Winston, 2008; Gupta et al., 2009), we did calculate NSE scores

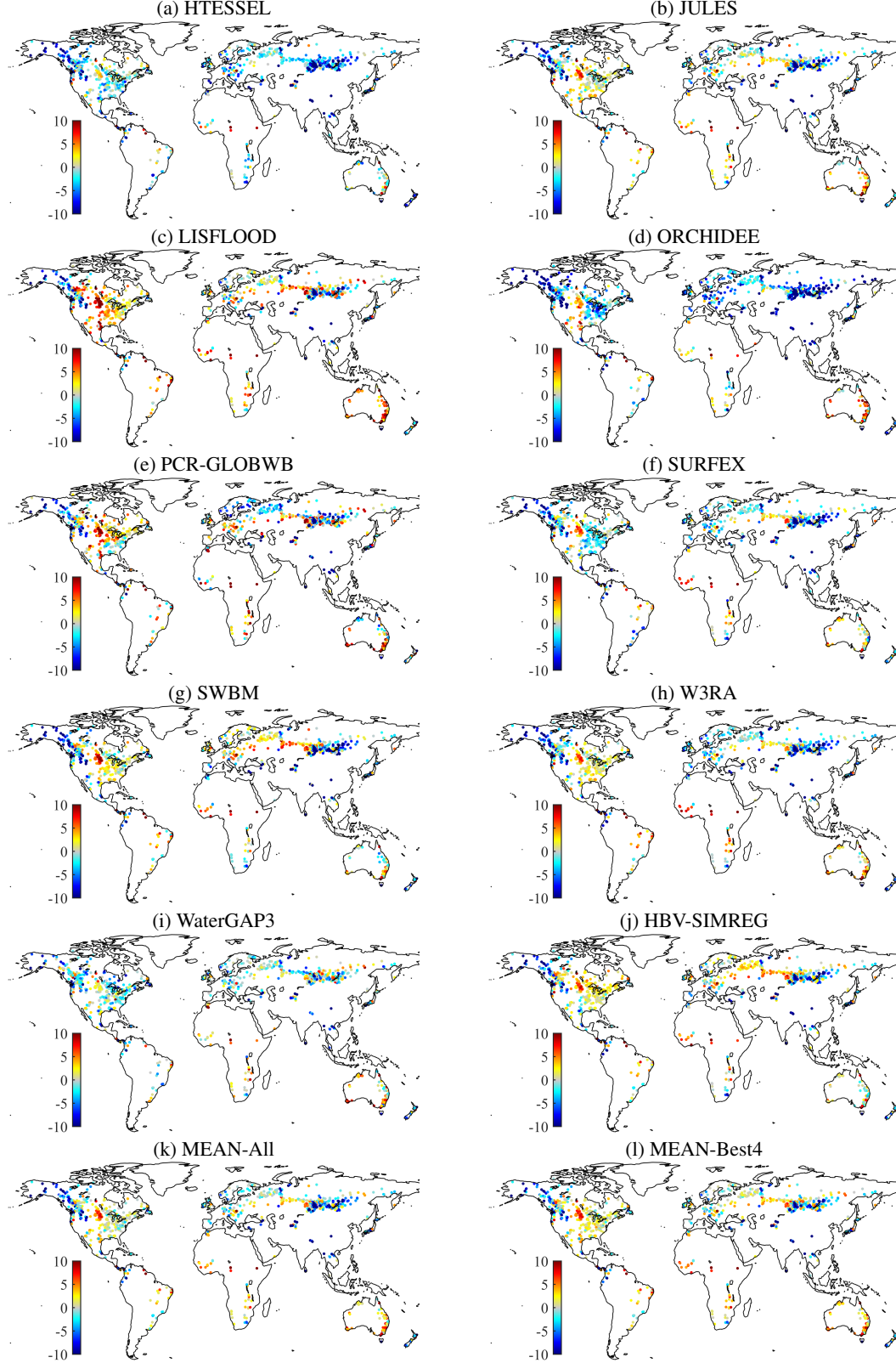


Figure 1. Simulated minus observed square-root transformed mean annual runoff (MAR; units $\sqrt{\text{mm yr}^{-1}}$) for the catchments. Each data point represents a catchment centroid ($n = 966$). Red (blue) indicates an overestimated (underestimated) MAR relative to the observations.

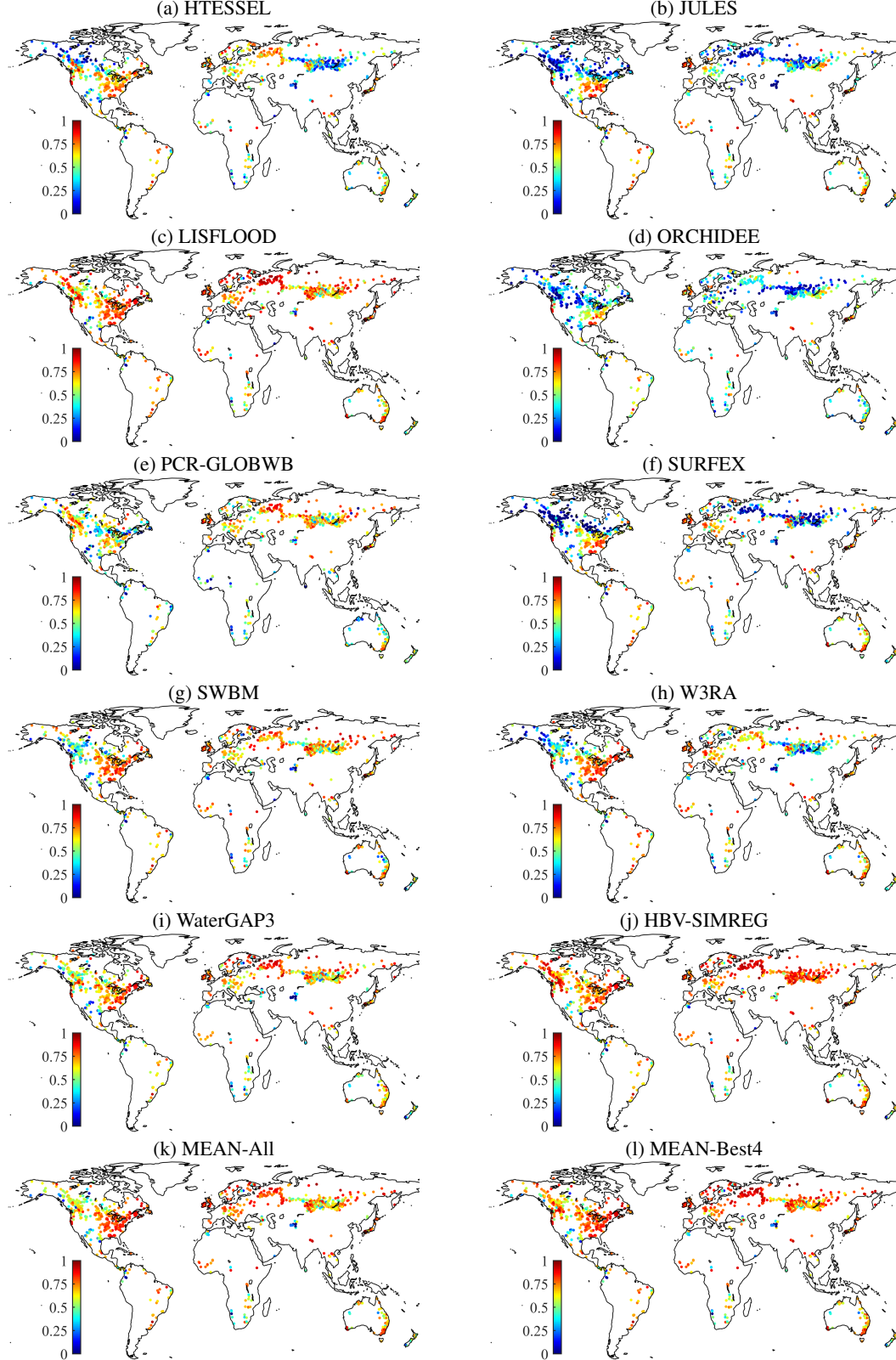


Figure 2. Correlation coefficients calculated between simulated and observed monthly runoff (r_{mon} ; unitless) for the catchments. Each data point represents a catchment centroid ($n = 966$).

to allow the present results to be put in the context of previous macro-scale studies (see Supplementary material Table S1). For most models negative median NSE scores were obtained, similar to Zhang et al. (2016), who evaluated the monthly and annual runoff estimates from 14 (uncalibrated) macro-scale models in 644 large Australian catchments ($> 2000 \text{ km}^2$). Our scores are, however, slightly lower than those obtained by Lohmann et al. (2004) and Xia et al. (2012), who evaluated the daily runoff estimates from four (uncalibrated) macro-scale models in about a thousand small-to-medium sized USA catchments ($< 10000 \text{ km}^2$), but this is probably attributable to the high quality of the USA forcing data (?). They are also somewhat lower than those obtained by Decharme and Douville (2007), who evaluated two (uncalibrated) macro-scale models in 80 large catchments ($> 100000 \text{ km}^2$) around the globe, but this can be explained by their much larger catchment sizes.

Figure 3 shows, for the seven models with data on energy availability, density plots of grid cell values of aridity index (AI; ratio of long-term energy availability to P) versus runoff coefficient (RC; ratio of long-term mean runoff to P), revealing how the models respond in terms of RC to different climatic conditions. ~~Grid-cells $> 50^\circ\text{N/S}$ were excluded from this analysis, as the majority of the net radiation is converted to sensible heat in cold climates (Kleidon et al., 2014).~~ Also shown are the energy-limit line for which actual evaporation equals the available energy, the water-limit line for which runoff equals P , and the Budyko (1974) curve, the most well-known among several similar empirical relationships describing the competition between runoff and actual evaporation (Ol'dekop, 1911; Pike, 1964; Zhang et al., 2001; Porporato et al., 2004). ~~We note that given~~ Given its empirical nature, the Budyko curve should only be used ~~as for~~ as for visual reference, and not to judge the performance of the different models. Besides the striking differences in behavior among the models, it can be seen that ~~ORCHIDEE~~ HTESSEL, JULES, PCR-GLOBWB, W3RA, and WaterGAP3 do not adhere to the water and/or energy limits (~~Figure 3e~~ Figures 3a, 3b, 3d, 3f, and 3g, respectively). For WaterGAP3, this may be due to the use of calibration factors, which have the potential to generate runoff that can go beyond the physical limits in an effort to compensate for errors in the P , PET, or ~~runoff~~ streamflow data. For ~~ORCHIDEE,~~ the other models this could be indicative of issues with the runoff and/or evaporation routines. The larger spread found for the models for which we used net radiation to estimate the available energy (HTESSEL, JULES, and SURFEX; Figures 3a, 3b, and 3e, respectively) is because the majority of the net radiation is converted to sensible heat rather than latent heat in cold climates (Kleidon et al., 2014).

It is generally difficult to gain insight into why a particular model performs as it does due to the large number of interacting model components, equations, and parameters. Nevertheless, the underestimation of runoff by HTESSEL probably reflects the excessive evaporation by HTESSEL previously reported by Haddeland et al. (2011). PCR-GLOBWB most likely suffers from suboptimal baseflow-related parameter values, since its structure is similar to that of LISFLOOD which performs markedly better. SWBM clearly suffers from the absence of a baseflow routine outside (semi-)arid regions. Although W3RA and HBV-SIMREG use an identical snow routine, W3RA performs considerably worse in snow-dominated regions, probably because HBV-SIMREG uses a snowfall gauge undercatch correction factor. The unsatisfactory performance demonstrated by the LSMs in snow-dominated regions could be related to deficiencies in the snow routines or the energy balance estimates (see Section 4.3). WaterGAP3 and particularly HBV-SIMREG performed quite well overall, likely because of their comprehensive calibration (see Section 4.4). In any case, the pronounced inter-model performance spread found here suggests that model choice should be regarded as a critical step in any hydrological modeling study. Moreover, it underscores the importance of

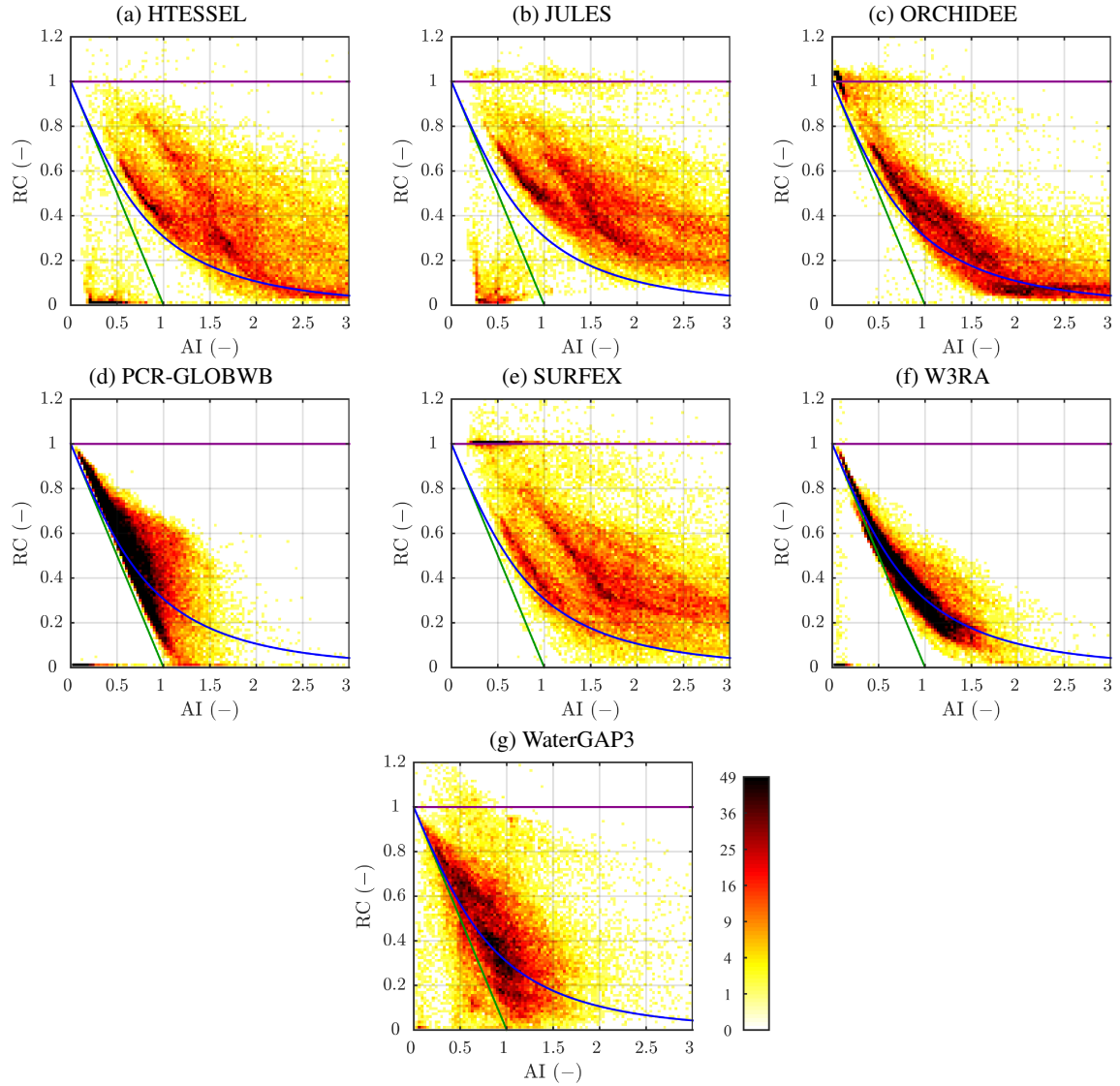


Figure 3. For the seven models with data on the available energy, density plots of grid cell values of aridity index (AI) versus runoff coefficient (RC). Grid cells $> 50^{\circ}\text{N/S}$ were excluded from the analysis. The green line represents the energy limit for which actual evaporation equals PET, the purple line represents the water limit for which runoff equals P , whereas the blue line represents the Budyko (1974) curve.

hydrological model uncertainty in addition to climate input uncertainty, as also emphasized in several other recent macro-scale studies (Haddeland et al., 2011; Schewe et al., 2013; Prudhomme et al., 2014; Mendoza et al., 2015b; Giuntoli et al., 2015a). Currently, the large majority of studies assessing the hydrological impacts of climate change completely neglect hydrological model uncertainty (Teutschbein and Seibert, 2010).

5 4.2 How well do the models perform in terms of long-term runoff trends?

The models displayed very similar MAR trends (Supplementary material Figure S1.8), meaning they respond similarly to climate variability, given that none of the models account for land-use or land cover changes, urbanization, reservoir construction, or increasing atmospheric CO₂. However, the models obtained rather low spatial (Spearman) correlation coefficients ($\rho_{\text{MAR trend}}$) ranging from 0.32 (SURFEX) to 0.42 (LISFLOOD; ~~Tables ?? and ??~~ [Table 5](#)), indicating that the simulated MAR trends correspond fairly to moderately well to the observed ones. These values are lower than the (Pearson) correlation coefficients ranging from 0.52 to 0.63 obtained by Stahl et al. (2012), who evaluated MAR trends from seven models using observations from 293 small European catchments (100–1000 km²), presumably due to the better quality of the European meteorological forcing and observed streamflow data. Milly et al. (2005) evaluated MAR trends from a 12-model ensemble using observations from 165 large catchments (> 50 000 km²) around the globe, obtaining a (Pearson) correlation coefficient of 0.34 which is similar to ours. These low correlations, which were somewhat unexpected given the relative ease with which MAR can be estimated (e.g., Westerberg and McMillan, 2015; Beck et al., 2015), may be indicative of changes in non-climatic drivers of hydrological change or drift errors in the forcing or observed streamflow data. We expect the inter-model variability in trends to be higher and the agreement with observations to be even lower for seasonal and monthly averages as well as runoff signatures sensitive to the shape of individual flow events (cf. Bastola et al., 2011; Gosling et al., 2011). Overall, these results suggest that studies ~~assessing using global-scale datasets to assess~~ the impacts of ~~past~~ climate change on runoff in small-to-medium sized catchments should be interpreted with considerable caution.

4.3 How do the results of the GHMs differ, if at all, from those of the LSMs?

Similar to Haddeland et al. (2011), the LSMs were found to produce less runoff overall (~~Tables ?? and ??, and~~ [Table 5](#) and Figure 1), perhaps due to their use of physically-based Richards-Darcy type equations which neglect preferential flows. We further found that the GHMs perform, on average, worse than the LSMs in rain-dominated regions: the GHMs (excluding the comprehensively calibrated models—WaterGAP3 and HBV-SIMREG; see Section 4.4) obtained mean $\overline{\text{OS}}$ scores of 0.28, 0.33, and 0.43 for tropical, arid, and temperate climates, respectively, while the same values for the LSMs are 0.39, 0.47, and 0.47, respectively (~~Tables ?? and ??~~ [Table 5](#)). However, the lower performance of the GHMs is primarily attributable to PCR-GLOBWB and SWBM. As mentioned before, PCR-GLOBWB probably suffers from a suboptimal baseflow-related parameterization, while SWBM suffers from the absence of a baseflow routine.

The GHMs do appear to perform consistently better than the LSMs in snow-dominated regions: the GHMs (again excluding WaterGAP3 and HBV-SIMREG) obtained mean $\overline{\text{OS}}$ scores of 0.46 and 0.32 for cold and polar climates, respectively, while the same values for the LSMs are 0.31 and 0.25, respectively (~~Tables ?? and ??~~ [Table 5](#)). The performance of the LSMs

appears to be mainly due to a very early bias in flow timing, a very low baseflow contribution, and a misrepresentation of the seasonal cycle (Supplementary material Figures S1.4, S1.5, and S1.13, respectively). Our results are in agreement with Giuntoli et al. (2015b), who found five GHMs to outperform, on average, four LSMs using observations from 252 temperate and cold catchments (64 to 1 350 000 km²) located in the central USA, and with Zhang et al. (2016), who found that two LSMs performed considerably worse than two GHMs in cold and polar regions using observations from 644 catchments (> 2000 km², upper limit not reported) around the globe. The poorer performance obtained by the LSMs is probably indicative of differences between the snow routines used by GHMs and LSMs. The GHMs use relatively simple conceptual temperature-index snow routines driven by air temperature which can be estimated with relative ease, whereas the LSMs use more complex physically-based energy balance snow routines driven by estimates of energy balance components which are subject to considerable uncertainty, particularly in regions with complex topography (Ferguson, 1999). Although several previous studies have found that the two types of snow routines yield comparable performance (e.g., WMO, 1986; Franz et al., 2008; Zeinivand and De Smedt, 2009; Debele et al., 2010), these studies used a very small number of relatively well-instrumented catchments (six, two, one, and three, respectively) which may have led to less-generalizable conclusions. Overall, it appears that the energy balance estimates and snow routines used by the LSMs require re-evaluation (cf. Zhang et al., 2016).

4.4 Are calibration and regionalization important or even essential?

Calibration is ~~a-prerequisite-important~~ for both conceptual and physically-based hydrological models to provide ~~reliable-more~~ accurate runoff estimates, to account for (i) the impossibility of measuring all required model parameters at the model application scale, (ii) lack of process understanding, (iii) possibly overly simplistic process representations, (iv) the spatio-temporal discretization of highly heterogeneous rainfall-runoff processes, and (v) errors in the forcing data (Beven, 1989; Blöschl and Sivapalan, 1995; Duan et al., 2001, 2006; McDonnell et al., 2007; Nasonova et al., 2009; Rosero et al., 2011; Minville et al., 2014). Yet, despite the development of numerous calibration techniques over the last 50 years (Dawdy and O'Donnell, 1965; Duan et al., 2004) and the current widespread availability of streamflow observations (Hannah et al., 2011), macro-scale models generally tend to be uncalibrated (Sooda and Smakhtin, 2015; Bierkens, 2015; Kauffeldt et al., 2016). This is perhaps mainly due to (i) the substantial amount of work involved with calibration (e.g., Bock et al., 2015), (ii) the risk of obtaining unrealistic parameters due to equifinality and data issues (Andréassian et al., 2012), and (iii) the lack of a commonly accepted regionalization technique (Beck et al., 2016). In addition, the modeler may feel that since their model is physically based, it does not require calibration (Beven, 1989). LSMs in particular are rarely calibrated against runoff, likely because: (i) runoff estimation is generally not among the primary aims of LSMs; (ii) for water transport in the soil, LSMs typically use Richards-Darcy type equations which are computationally expensive and require a fine vertical and temporal soil discretization; and (iii) LSMs often do not account for river routing, confounding the calibration of large catchments. Instead, the parameters in macro-scale models are usually based on “expert opinion” and thus founded on the bold assumption that the modeler sufficiently understands the hydrological processes, feedbacks, and parameter interactions taking place within the model for any location on Earth.

Nevertheless, out of the ten models considered in this study, four use parameters derived by calibration (LISFLOOD, SWBM, WaterGAP3, and HBV-SIMREG—all GHMs). LISFLOOD was calibrated against observed streamflow for 24 large catchments

(84 230 to 4 680 000 km²) across the globe using the WFDEI forcing and an aggregate objective function incorporating bias, NSE, and log-transformed NSE computed from daily [runoff](#) [streamflow](#) data. The calibration might have influenced the present evaluation; although we used much smaller catchments (1000 to 5000 km²), 47 % of our catchments are located within the calibration catchments. SWBM uses a spatially-uniform parameter set based on calibration using the E-OBS forcing (Haylock et al., 2008) against European data on such key hydrologic variables as soil moisture, total water storage, evaporation, and runoff (Orth and Seneviratne, 2015). For the calibration against runoff, they used observations from 436 small European catchments (mostly < 1000 km²), and considered daily and monthly correlations as well as bias. The calibrated parameter set was subsequently applied globally. Besides the addition of a baseflow routine, SWBM would probably benefit from regionalized parameters that vary according to landscape characteristics. WaterGAP3 has been calibrated using the WFDEI forcing in terms of bias for the interstation regions (the catchment of a station excluding the catchments of nested upstream stations) of 2071 stations (catchment size ranging from 2830 to 966 321 km²) around the globe, some of which have also been used in the current evaluation. The calibrated parameters were subsequently regionalized to ungauged regions using multiple linear regression based on six predictors (Döll et al., 2003). The model does indeed perform very well for MAR and thus RC, but this did not necessarily translate into good performance for BFI (Table [??5](#), and Figures 1 and 2). HBV-SIMREG also uses regionalized parameter fields, produced by transferring calibrated parameters from 674 small-to-medium sized “donor” catchments (10 to 10 000 km²) across the globe to “receptor” grid cells with similar climatic and physiographic characteristics (Beck et al., 2016). In their study, Beck et al. (2016) show that HBV using spatially-uniform parameters performs within the range of the other models, confirming that the relatively good performance of HBV-SIMREG stems from the regionalization exercise. In addition, although Beck et al. (2016) did not use the WFDEI forcing for the calibration, they calibrated against several of the performance metrics also used here and used 179 of our catchments as parameter donors, further explaining the relatively good performance obtained by HBV-SIMREG (Table [??5](#), and Figures 1 and 2).

Overall, it appears that the calibration exercises for WaterGAP3, HBV-SIMREG, and possibly LISFLOOD have resulted in markedly improved performance. However, WaterGAP3 performed poorly in terms of ρ_{BFI} (Table [??5](#)), meaning the calibration of MAR did not translate into better BFI performance. These results underscore the benefits of calibrated parameters over *a priori* parameters (cf. Duan et al., 2006; Hunger and Döll, 2008; Nasonova et al., 2009; Rosero et al., 2011; Greuell et al., 2015; Zhang et al., 2016) and highlight the importance of using an objective function for the calibration that incorporates a broad range of metrics related to various important aspects of the hydrograph (cf. Gupta et al., 2008; Vis et al., 2015; Shafii and Tolson, 2015). These results also emphasize the usefulness of regionalization techniques (Parajka et al., 2013), which typically enhance performance over the entire model domain and are thus of particular value for macro-scale modeling, given that the majority of the land surface is ungauged or poorly gauged (Sivapalan, 2003; Hannah et al., 2011). However, although there are numerous studies performing regionalization at a regional scale (see reviews by He et al., 2011; Hrachowitz et al., 2013; Razavi and Coulibaly, 2013; Parajka et al., 2013), only few studies have attempted regionalization at a macro scale (see review by Beck et al., 2016). We argue that more effort should be devoted to regionalizing the parameters of macro-scale models (cf. Bierkens, 2015; Döll et al., 2015).

It should be noted, however, that the potential performance improvement gained by calibration and regionalization will depend on the structure and flexibility of the model in question. Many current models have rigid structures and/or insufficient free parameters and thus cannot be calibrated successfully (Mendoza et al., 2015a). Moreover, for climate projections one should bear in mind that calibrated parameters become less valid when the model is subjected to climatic conditions it has never seen before (Knutti, 2008).

4.5 What is the impact of the forcing data on the ~~results~~ simulated runoff?

There are not only strong inter-model differences in the performance patterns but also clear inter-model similarities. Specifically, suggesting that the forcing data quality imparts a strong limit on the performance. This is most notable for the MAR metric: all models showed negative biases in MAR in snow-dominated regions such as Alaska, the Rocky Mountains, and southern Russia, while they consistently showed positive biases in MAR for the Great Plains (USA) and southern Australia (Figure 1). The high spatial correlation in the performance patterns suggests that these consistent performance patterns may be due to biases in the WFDEI P data, rather than biases in the streamflow observations which are unlikely to be spatially correlated.

It is conceivable that biases are present in the WFDEI P data, because: (i) the monthly CRU dataset, which has been used to correct the WFDEI dataset, is based on only a subset of the available gauges and does not explicitly account for orographic effects; (ii) in sparsely gauged regions the correction using CRU is more likely to deteriorate rather than improve the P estimates; and (iii) the Adam and Lettenmaier (2003) gauge undercatch correction factors are based on interpolation of a very sparse sample of gauges and thus subject to considerable uncertainty. For the conterminous USA we quantified the biases in the WFDEI P data using the high-quality Parameter-elevation Relationships on Independent Slopes Model (PRISM) climatic dataset (Daly et al., 1994), which is based on considerably more gauges than CRU and includes sophisticated corrections for orography. Figure 4a shows the bias in mean annual P from WFDEI relative to that from PRISM, suggesting that the WFDEI P data are indeed subject to large biases. Figure 4b shows the bias in MAR from the MEAN-All ensemble relative to MAR from the observations, revealing a comparable bias pattern, thus confirming that the biases in the WFDEI P propagate in the simulated runoff. The correlation coefficient between the MAR and P bias values is 0.58, indicating a moderately strong relationship. These P biases appear to translate into even more pronounced runoff biases in (semi-)arid regions (notably the northern Great Plains; Figures 4b and 4c) due to the highly non-linear response behavior in these environments (Lidén and Harlin, 2000; Fekete et al., 2004; Van Dijk et al., 2013a). We were unable to quantify the P biases globally since no other independent, global-scale P dataset exists (the WorldClim and CHPClim datasets are likely to exhibit similar biases as the CRU TS3.1 dataset, given that they are based on similar sets of gauges). However, we expect the P biases to be at least similar, if not more severe, outside the well-instrumented conterminous USA (cf. Fekete et al., 2004; Hijmans et al., 2005; Biemans et al., 2009; Zhou et al., 2012; Kauffeldt et al., 2013; Greuell et al., 2015). It should be noted that biases in PET are probably of secondary importance as compared with biases in P (Donohue et al., 2010; Sperna Weiland et al., 2011; Seiller and Anctil, 2015).

The global-scale quantification and reduction of these P biases should be a priority for future research. Satellite-derived P offers unique opportunities in this regard (e.g., Funk et al., 2015) that extend beyond the tropics with the recent launch of the

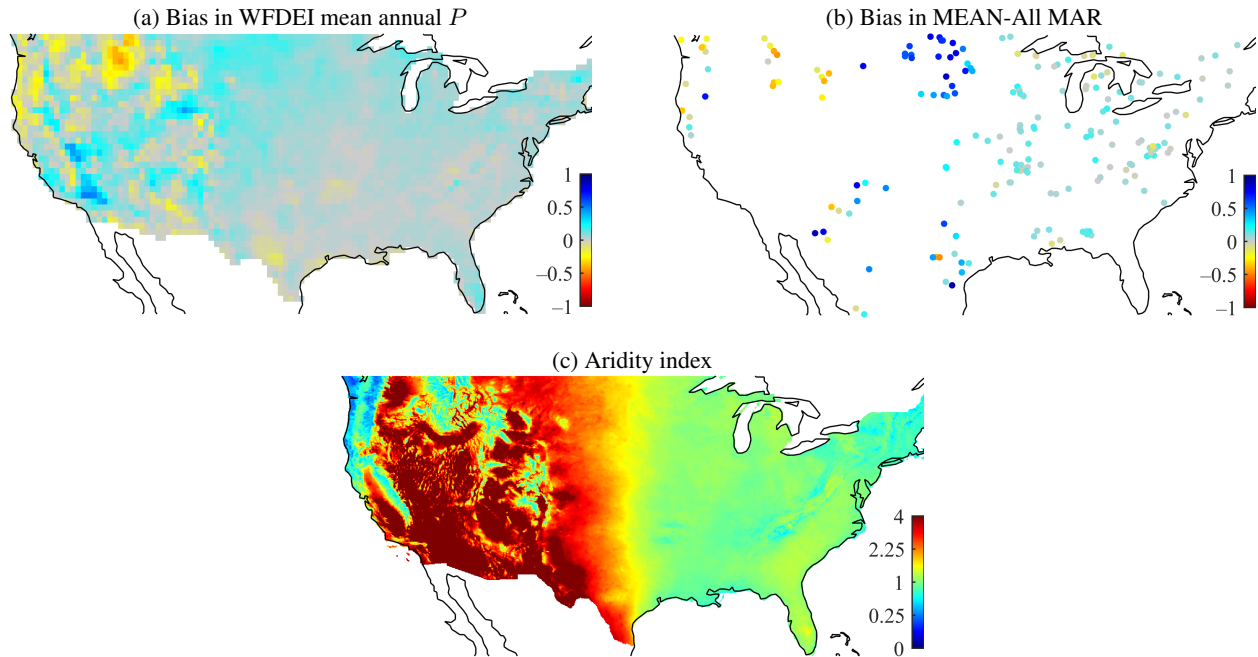


Figure 4. For the conterminous US, (a) the bias in mean annual P from WFDEI relative to PRISM, (b) the bias in MAR from the MEAN-All ensemble relative to the observations, and (c) the aridity index, the ratio of mean annual PET (computed from PRISM air temperature using Hargreaves et al., 1985) to P (PRISM; note the non-linear color scale). Each data point in panel (b) represents a catchment centroid. The bias in (a) and (b) was computed following $B = (X - R)/(X + R)$, where B is the bias, X the uncertain value, and R the reference value. B values range from -1 to 1 . A 100 % overestimation results in $B = 1/3$, whereas a 50 % underestimation results in $B = -1/3$.

Global Precipitation Measurement (GPM) mission (Smith et al., 2007). Another little-explored way of reducing P uncertainty is by “doing hydrology backwards”; that is, to use information on other hydrological variables—for example, satellite-derived surface soil moisture (e.g., Brocca et al., 2014), streamflow observations (e.g., Adam et al., 2006; Beck et al., 2017), and snow-depth observations (e.g., Cherry et al., 2005)—to reconstruct P through hydrological modeling. Arguably the most important

5 obstacles to combining multiple data sources are the inconsistent temporal coverage and scale of different data sources and the general lack of error/uncertainty estimates.

Although the models all used the same P data, they used different formulations to compute PET which has likely contributed to differences in simulated runoff among the models in energy-limited regions (Weiß and Menzel, 2008; Kingston et al., 2009; Haddeland et al., 2011; Weedon et al., 2011; Sperna Weiland et al., 2011). However, PET data were available for only four

10 models, which is insufficient to examine whether the PET formulation has had a discernible influence on the simulated runoff, given the numerous other differences in structure and parameterization among the models.

4.6 How valuable are multi-model ensembles?

The multi-model ensemble MEAN-All incorporated all ten models, while MEAN-Best4 incorporated only LISFLOOD, W3RA, WaterGAP3, and HBV-SIMREG (i.e., the four models that performed best in terms of \overline{OS} ; ~~Tables ?? and ??~~ [Table 5](#)). MEAN-All and MEAN-Best4 were found to perform better than all individual models (with the exception of HBV-SIMREG, which has been comprehensively calibrated; ~~Tables ?? and ??~~ [Table 5](#), and Figures 1 and 2). These results highlight the benefits of multi-model ensembles, in line with several previous studies (Ajami et al., 2006; Duan et al., 2007; Viney et al., 2009; Matera et al., 2010; Velázquez et al., 2010; Gudmundsson et al., 2012a; Xia et al., 2012; Yang et al., 2015). The similar \overline{OS} scores obtained by MEAN-All and MEAN-Best4 (0.57 and 0.60, respectively; [Table ??5](#)) suggests that the inclusion of less ~~reliable-accurate~~ models has only limited adverse effects. It may be worthwhile for future studies to examine the benefits of more sophisticated multi-model combination techniques involving bias correction or model weighting (e.g., Ajami et al., 2006; Duan et al., 2007; Bohn et al., 2010). These weights can subsequently be transferred from gauged to ungauged areas using regionalization techniques typically used for hydrological model parameters (Blöschl et al., 2013).

HBV-SIMREG differs from the other models because it represents a so-called “multi-parameterization ensemble”, which means the model was run multiple (ten) times globally using different (regionalized) parameter sets representing different catchment response behaviors (Beck et al., 2016). HBV-SIMREG obtained slightly better performance than both MEAN-All and MEAN-Best4 overall ([Table ??5](#)), tentatively suggesting that a multi-parameterization ensemble for a single, sufficiently flexible model provides performance comparable to a multi-model ensemble (cf. Oudin et al., 2006; Yang et al., 2011; Coxon et al., 2014). If this is confirmed, it would negate the need to set up, run, and maintain multiple models, and incentivize the development of a single community hydrological model (cf. Weiler and Beven, 2015) as well as modeling systems allowing selection of alternative model structures (cf. Bierkens, 2015), such as the Framework for Understanding Structural Errors (FUSE; Clark et al., 2008), Noah Multi-Parameterization (Noah-MP; Niu et al., 2011), and SUPERFLEX (Fenicia et al., 2011).

4.7 Do all models show the early bias in runoff timing in snow-dominated catchments previously documented and what is the cause?

With the exception of ORCHIDEE and HBV-SIMREG, all models showed early T50 biases in snow-dominated regions (Supplementary material Figure S1.3), indicating that the models produce the spring snowmelt peak early, as has also been reported in several previous studies using different models and forcing data (Lohmann et al., 2004; Slater et al., 2007; Decharme and Douville, 2007; Balsamo et al., 2009; Zaitchik et al., 2010; Beck et al., 2015). The early runoff timing is probably primarily due to P underestimation which leads to insufficient snow accumulation that subsequently melts too quickly (Hancock et al., 2014). The fact that HBV-SIMREG performs well in this regard is probably attributable to the snowfall gauge undercatch correction factor of the model. Indeed, Figure 5 tentatively shows that catchments in which the models strongly underestimate runoff (i.e., negative D_{RC}) generally tend to exhibit an early bias in T50 (i.e., negative D_{T50}) and vice versa. The absence or misrepresentation of certain processes that delay snowmelt runoff in the models may have exacerbated the early runoff timing

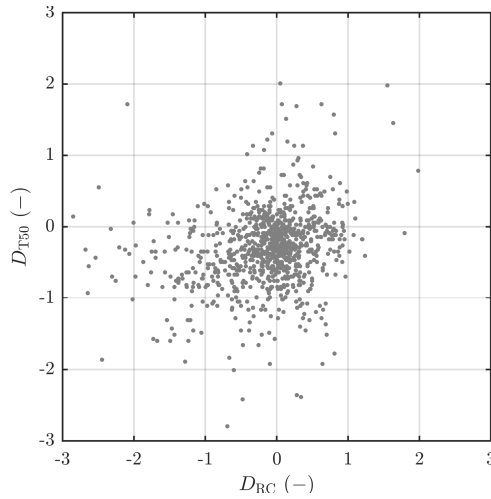


Figure 5. Scatterplot of the difference between simulated (MEAN-All) and observed transformed RC (D_{RC}) versus the difference between simulated (MEAN-All) and observed T50 (D_{T50}) for the catchments ($n = 966$).

problem. Examples of such processes include the isothermal phase change of the snowpack, retainment of meltwater in the snowpack in pore spaces, infiltration of meltwater into the soil, meltwater refreezing during cold days and nights, and icejams in rivers. On the whole, more research is needed to ascertain the exact reasons of the early runoff timing.

5 Conclusions

- 5 The runoff estimates from ten state-of-the-art macro-scale hydrological models, all forced with the WFDEI dataset, were evaluated using observations from 966 medium sized catchments around the globe. With reference to the questions posed in the introduction, the following was found:
 1. The performance differed markedly among models, underscoring the importance of hydrological model uncertainty in addition to climate input uncertainty, and suggesting that model choice should be regarded as a critical step in any hydrological modeling study.
 2. The models displayed similar MAR trends, although they were in poor agreement with observed trends. Model-based runoff trends in small-to-medium sized catchments should thus be interpreted with considerable caution.
 3. Considering only the uncalibrated models, the GHMs performed similarly to the LSMs in rainfall-dominated regions but consistently better than the LSMs in snow-dominated regions, perhaps due to the use of more data-demanding snow routines or the misrepresentation of frozen-soil and snowmelt processes by the LSMs.
 4. The models that have been calibrated obtained higher scores for the performance metrics incorporated in the respective objective functions used for calibration.

5. The WFDEI P forcing data still appear to contain substantial biases, despite adjustments using gauge observations. These P biases translate into biases in the simulated runoff which are amplified in (semi-)arid regions. In snow-dominated regions there appears to be a consistent underestimation in P and thus simulated runoff.
6. The multi-model ensembles obtained only slightly worse performance than the best (calibrated) model, and the inclusion of less ~~reliable~~-accurate models did not severely degrade the performance. A multi-parameterization ensemble for a single, sufficiently flexible model is easier to realize but we speculate may yield the same performance benefits as a multi-model ensemble.
7. Most models were indeed found to generate the spring snowmelt peak early, probably due to the previously mentioned P underestimation and the absence or misrepresentation of certain processes that delay snowmelt runoff in the models.
- 10 *Author contributions.* H.B. designed and performed the model evaluation and wrote most of the manuscript. A.v.D., A.d.R., E.D., G.F., R.O., and J.S. helped with the interpretation of the results and contributed to writing of the manuscript. H.B., A.v.D., A.d.R., E.D., G.F., and R.O. assisted in running the hydrological models and making available the model output.

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