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Key Points:

- A comparison of hydrological impacts using Coupled Model Intercomparison Project version 5 (CMIP5) and Coupled Model Intercomparison Project Phase 6 (CMIP6) ensembles is performed over 3,107 catchments in North America
- The CMIP6 ensembles provide a narrower band of uncertainty for hydrological indicators in the future
- It is recommended to update hydrological impact studies performed using CMIP5 with the CMIP6 ensemble

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

J.-L. Martel,
jean-luc.martel@etsmtl.ca

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Author Contributions:

Conceptualization: F. Brissette, R. Arsenault, J. Chen
Data curation: J.-L. Martel
Formal analysis: J.-L. Martel, T. Su
Funding acquisition: R. Arsenault
Investigation: J.-L. Martel, F. Brissette, M. Troin
Methodology: J.-L. Martel, F. Brissette, R. Arsenault, J. Chen
Project Administration: R. Arsenault

CMIP5 and CMIP6 Model Projection Comparison for Hydrological Impacts Over North America

J.-L. Martel[1], F. Brissette[1], M. Troin[1,2], R. Arsenault[1], J. Chen[3,4], T. Su[3,4], and P. Lucas-Picher[5,6]

[1]Hydrology, Climate and Climate Change Laboratory, École de technologie supérieure, Université du Québec, Montreal, Quebec, Canada, [2]Hydroclimat TVT, Maison du Numérique et de l'Innovation, Toulon, France, [3]State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China, [4]Hubei Key Laboratory of Water System Science for Sponge City Construction, Wuhan University, Wuhan, China, [5]Groupe de Météorologie de Grande Échelle et Climat (GMGEC), Centre National de Recherches Météorologiques (CNRM), Centre National de la Recherche Scientifique (CNRS), Université de Toulouse, Météo-France, Toulouse, France, [6]Département des sciences de la Terre et de l'atmosphère, Université du Québec à Montréal, Montréal, Québec, Canada

Abstract A warmer climate impacts streamflows and these changes need to be quantified to assess future risk, vulnerability, and to implement efficient adaptation measures. The climate simulations from the fifth phase of the Coupled Model Intercomparison Project (CMIP5), which have been the basis of most such assessments over the past decade, are being gradually superseded by the more recent Coupled Model Intercomparison Project Phase 6 (CMIP6). Our study portrays the added value of the CMIP6 ensemble over CMIP5 in a first North America wide comparison using 3,107 catchments. Results show a reduced spread of the CMIP6 ensemble compared to the CMIP5 ensemble for temperature and precipitation projections. In terms of flow indicators, the CMIP6 driven hydrological projections result in a smaller spread of future mean and high flow values, except for mountainous areas. Overall, we assess that the CMIP6 ensemble provides a narrower band of uncertainty of future climate projections, bringing more confidence for hydrological impact studies.

Plain Language Summary Greenhouse gas emissions are causing the climate to warm significantly, which in turn impacts flows in rivers worldwide. To adapt to these changes, it is essential to quantify them and assess future risk and vulnerability. Climate models are the primary tools used to achieve this. The main data set that provides scientists with state-of-the-art climate model simulations is known as the Coupled Model Intercomparison Project (CMIP). The fifth phase of that project (CMIP5) has been used over the past decade in multiple hydrological studies to assess the impacts of climate change on streamflow. The more recent sixth phase (CMIP6) has started to generate projections, which brings the following question: is it necessary to update the hydrological impact studies performed using CMIP5 with the new CMIP6 models? To answer this question, a comparison between CMIP5 and CMIP6 using 3,107 catchments over North America was conducted. Results show that there is less spread in temperature and precipitation projections for CMIP6. This translates into a smaller spread of future mean, high and low flow values, except for mountainous areas. Overall, we assess that using the CMIP6 data set would provide a more concerted range of future climate projections, leading to more confident hydrological impact studies.

1. Introduction

The impact of climate change on streamflow and hydrological extremes is an important issue for many regions of the world due to the potentially large socio-economic repercussions (Miara et al., 2017; Piao et al., 2010). Until now, hydrological impact studies have mostly relied on climate projections from the CMIP5 (Coupled Model Intercomparison Project version 5) experiment (Konapala et al., 2020; Tabari, 2020). With the new Coupled Model Intercomparison Project Phase 6 (CMIP6)-based projections now being available (Eyring et al., 2016), the issue of revisiting hydrological projections is raised (Zhu et al., 2020), given the latest CMIP6 models and the new Shared Socioeconomic Pathways (SSP) concentration scenarios forcings (Bock et al., 2020; Gidden et al., 2019; Hirabayashi et al., 2021).

With the continuous improvements of climate models, the CMIP6 simulations could lead to more reliable climate change impacts (Fan et al., 2020), which would be useful to the vulnerability, impacts, adaptation, and climate service community (Ruane et al., 2016). The performance of the CMIP6 models with respect to the distribution of

Resources: J.-L. Martel
Software: J.-L. Martel
Supervision: J.-L. Martel, R. Arsenault
Validation: J.-L. Martel, F. Brissette, M. Troin, P. Lucas-Picher
Visualization: J.-L. Martel
Writing – original draft: J.-L. Martel, F. Brissette, M. Troin
Writing – review & editing: J.-L. Martel, F. Brissette, M. Troin, R. Arsenault, J. Chen, T. Su, P. Lucas-Picher

temperature and precipitation is increasingly being assessed at the global- and regional-scales (Masud et al., 2021; Yazdandoost et al., 2020). Generally, the CMIP6 models capture the observed global and regional patterns of precipitation and temperature (Akinsanola et al., 2020; Zamani et al., 2020; Zhu et al., 2020) in addition to the observed long-term warming until 2014 (Papalexiou et al., 2020). However, limited improvements are shown for the representation of climate trends and extremes at the global scale and for specific regions (such as Australia and Southeast Asia; Deng et al., 2021; Hamed et al., 2022) compared to the former generation of CMIP5 models (Bourdeau-Goulet & Hassanzadeh, 2021; Chen et al., 2020). The advantages of the CMIP6 models over the CMIP5 models appear somewhat more obvious for climate extremes (Fan et al., 2020; Zhu and Yang, 2020), where the extreme precipitation and temperature indices are better captured at the regional scale, especially over the tropical and subtropical band regions (Kim et al., 2020). In addition, the CMIP6 models tend to improve the representation of the seasonal climatological patterns related to the small sea surface temperatures biases, such as the East Asian summer monsoon (Chen et al., 2021; Jiang et al., 2020; Xin et al., 2020), the Indian summer monsoon (Gusain et al., 2020), the global monsoon precipitation domain (Wang et al., 2020), the intertropical convergence zone (Ortega et al., 2021), as well as the rainfall teleconnections with large-scale climate drivers (Grose et al., 2020).

Regarding climate change signal representation by the CMIP6 future projections, a stronger warming is often reported under the scenario pairs Representative Concentration Pathway (RCP) 4.5/SSP2-4.5 and RCP8.5/SSP5-8.5 at the global and regional scales (Almazroui et al., 2021; Kreienkamp et al., 2020), with an increase in frequency and intensity of hot extremes and a decrease in cold extremes. Changes in the CMIP6-projected precipitations depict an intensification of extreme precipitation events which agree with the CMIP5 projections, even though some differences appear at the regional scale (Monerie et al., 2020). There is a trend by which intense events get more intense for precipitation extremes and hot temperature over most regions (Coppola et al., 2021; Li et al., 2021) with, by extension, an intensification of hydrological droughts (Aguayo et al., 2021). The analyses of the newest CMIP6 models' projections show that the equilibrium climate sensitivity (ECS) has increased regarding the former CMIP5 models (The CMIP6 landscape, 2019; Flynn & Mauritsen, 2020); many CMIP6 models exhibit an ECS of 4.7°C or higher, upper of the CMIP5 range of 2.1–4.7°C (Zelinka et al., 2020). Although, the cause(s) of this strong ECS are currently under debate with several potential underlying explanations (Flynn & Mauritsen, 2020; Zelinka et al., 2020), it is of interest to explore how the improved CMIP6 models translate to the finer scale of catchment area, especially for hydrological impact studies.

In this study, we conduct the first continental-scale comparison of the future projected CMIP5 and CMIP6 hydrological indicators over North American catchments. The impact of each CMIP ensemble on the median and dispersion of key hydrological variables (precipitation, temperature, mean, high and low streamflow) is investigated and discussed. Our study rests on the hydroclimatic processing chain detailed in the North American Climate Change and Hydroclimatology data set (NAC^{2}H) (Arsenault, Brissette, Chen, et al., 2020). This modeling chain was adapted to a high-quality subset of 3,107 catchments from the Hydrometeorological Sandbox—École de technologie supérieure (HYSETS) (Arsenault, Brissette, Martel, et al., 2020) database.

2. Materials and Methods

The analysis is performed on 3,107 North American catchments from the HYSETS database (Arsenault, Brissette, Martel, et al., 2020). From the 14,425 catchments in HYSETS, a selection was made by applying two filters. First, selected catchments required a drainage area of at least 500 km^2 to ensure that the daily timestep was appropriate for the hydrological processes. Second, a preliminary hydrological modeling application was performed, and only catchments meeting certain criteria described hereafter were kept. The selected catchments are also unregulated (or can be considered as such due to weak regulation) and have drainage areas varying between 500 and 188,470 km^2 (Figure S1 in Supporting Information S1). HYSETS provides multiple datasets for all catchments. The two historical meteorological gridded datasets used for hydrological model calibration and bias correction are the CANOPEX (Arsenault et al., 2016) and the Livneh (Livneh et al., 2013, 2015) databases, for Canada and the USA, respectively. The CANOPEX database includes meteorological data, as well as catchment boundaries and drainage areas for Canada. The catchment-averaged meteorological datasets are provided for precipitation, minimum and maximum temperatures taken from the Natural Resources Canada (NRCan) gridded climate data product. The Livneh database contains daily meteorological data, such as precipitation, minimum and maximum temperatures, in addition to river basin characteristics for the United States. The daily meteorological data is averaged at the catchment scale using weather station observations.

Streamflow records, as well as the metadata of the hydrometric stations, are extracted from the HYSETS database, which is a combined data set from United States Geological Survey and Environment and Climate Change Canada (Arsenault, Brissette, Martel, et al., 2020).

The overall performance of the CMIP5 and CMIP6 multi-model ensemble for catchment-scale hydrological purposes is evaluated through hydrological indicators over the future (2070–2099) period. To do so, a complete hydro-climatic post-processing model chain, as done in the NAC^{2}H (Arsenault, Brissette, Chen, et al., 2020) database, is implemented and the successive steps are documented in the following.

The first step is to apply statistical post-processing for bias-correcting the forcing ensemble projections of the climate variables. This step is recommended in hydrological impact modeling studies to compensate for spatio-temporal biases of the climate models' outputs before their use in hydrological modeling. In this work, the Multivariate Bias Correction method (MBCn; Cannon, 2018) is used for producing bias-corrected precipitation and temperature while preserving consistency between variables at the hydrological model scale, using the 1971–2000 period as the reference period. The GR4J conceptual lumped hydrological model (Perrin et al., 2003) coupled with the CemaNeige (Valéry, 2010) snow model is used as the main hydrological model in this study due to its widespread use and excellent performance over the study domain, as demonstrated by multiple previous studies (Guo et al., 2020; Kunnath-Poovakka & Eldho, 2019; Tarek et al., 2020). The hydrological model is calibrated using the Kling-Gupta Efficiency (KGE; Kling et al., 2012; Kling & Gupta, 2009) objective function with 10,000 model evaluations using the SCE-UA (Shuffled Complex Evolution - University of Arizona; Duan et al., 1994) algorithm, as recommended by Arsenault et al. (2014). Only catchments with a KGE score above 0.5 with at least 2 years of streamflow observations were preserved in this work, leading to the final selection of 3,107 catchments. To avoid any bias resulting from the hydrological modeling process, GR4J with the same calibrated parameters is used for performing the hydrological simulations driven by bias-corrected climate projections of both CMIP5 and CMIP6. The annual mean streamflow (Qmean) and annual maximum streamflow (Qmax) hydrological indicators are then computed for the comparison between hydrological simulations using CMIP5 and CMIP6 ensemble projections at the catchment scale as climate forcings.

The CMIP5/CMIP6 intercomparison procedure is straightforward. First, the evaluation of the raw CMIP5 and CMIP6 ensembles outputs for mean annual total precipitation (prcptot) and mean annual temperature (tas) is done through an analysis of the projected ensemble means and standard deviations over the study North America (NA) domain. The selected 24 CMIP5 models and 22 CMIP6 models are listed in Table S1 of Supporting Information S1. Then, the effects of both CMIP ensembles on the future projections of streamflow characteristics are investigated through the analysis of three hydrological indicators over the 2070–2099 period. With this investigation, we aim to address the level of confidence in the CMIP6 climate ensemble projections for hydrological impact studies. By using one hydrological model with the same parameter set through the experiment, one bias-correction method, one realization per climate model, and the similar high-emission RCP8.5/SSP5-8.5 global warming forcings, the focus lies on the contribution of the CMIP5 and CMIP6 models (model epistemic uncertainty) to the overall uncertainty/variability within the applied hydro-climatic model chain. The inter-model mean and standard deviation (representing the inter-model spread) used to compute the differences between CMIP5 and CMIP6 for all hydroclimatological indicators are shown in the Figures S2–S6 of Supporting Information S1.

3. On the Agreement of CMIP5 and CMIP6 Climate Projections

A special focus of our study is placed on the analysis of the future period to better emphasize the uncertainty in climate model sensitivity to greenhouse-gas concentrations for both CMIP experiments. The evaluation is performed on the specific 2070–2099 time window under similar forcing conditions, that is, RCP8.5 for CMIP5 and SSP5-8.5 for CMIP6. While these two forcing scenarios are not identical, they nonetheless attempt to represent similar total energy budget conditions towards the end of the 21st century. Both forcing scenarios do not represent equal changes over time, they are parallel scenarios that converge towards similar radiative forcing near 2,100 (Bourdeau-Goulet & Hassanzadeh, 2021; Riahi et al., 2017). Thus, our study's results will undoubtedly include some of this uncertainty stemming from the underlying drivers of the CMIP project models.

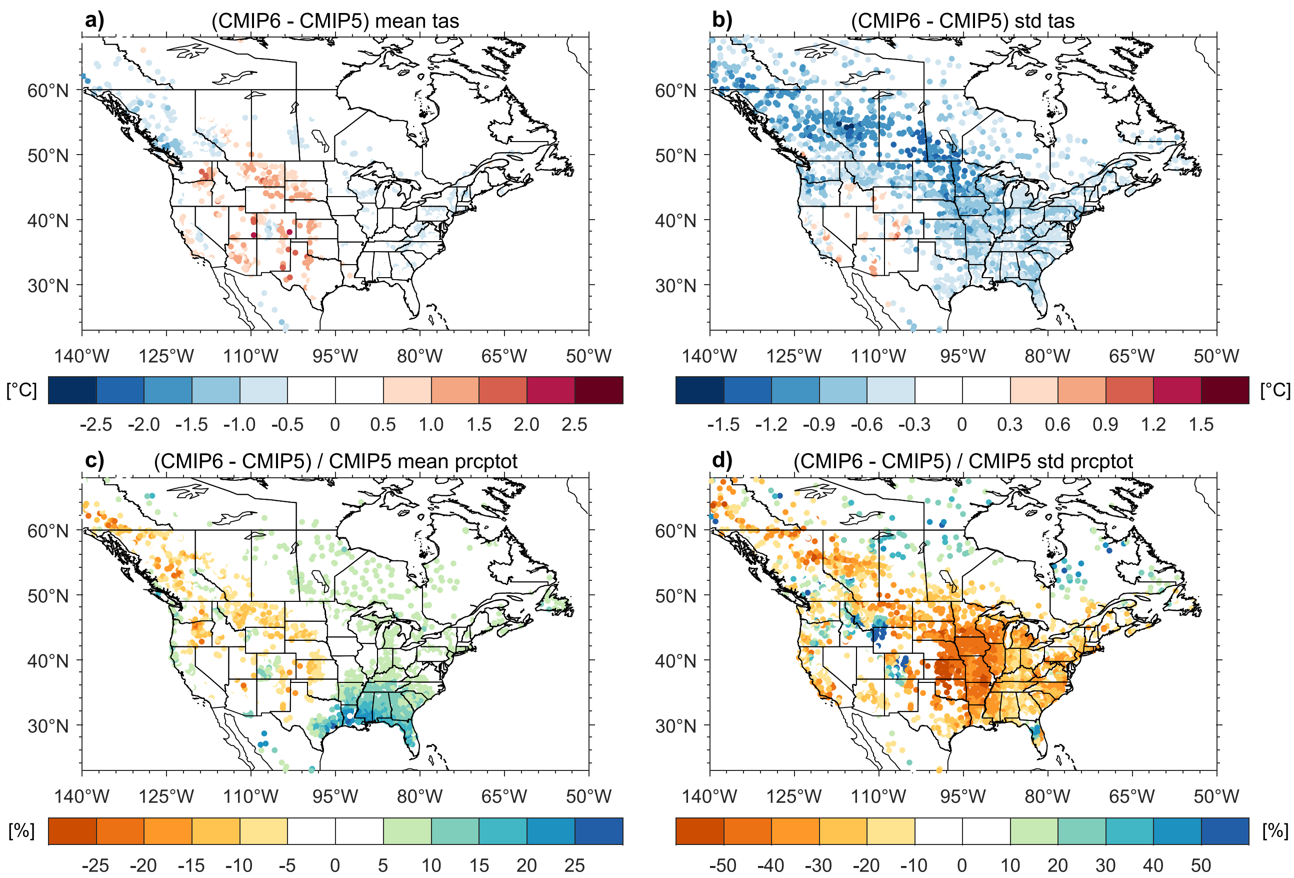

Figure 1. Differences between both raw Coupled Model Intercomparison Project Phase 6 (CMIP6) and Coupled Model Intercomparison Project version 5 (CMIP5) multimodel means (a and c) and inter-model standard deviation (b and d) over the 2070–2099 period for mean annual temperature (tas; a and b) and total precipitation (prcptot; c and d).

Considering that streamflow is an effective integrator (in space and time) of the effects of multiple meteorological variables, such as precipitation and temperature, an assessment of the raw CMIP5/CMIP6 models' outputs from these two variables is first conducted to establish relationships with the hydrological indicators and shown in Figure 1.

There is a large agreement between both CMIP5/CMIP6 ensembles in projecting future spatial patterns of mean annual temperature (Figure 1a) and total precipitation (Figure 1c) over NA. There are, however, some notable differences. Overall, the CMIP6 models project more precipitation compared to the CMIP5 models in the future, especially in the southeastern NA region, while less precipitation is anticipated over the central and western NA regions. The main explanation could be related to the higher resolution and parametrization improvements of the CMIP6 models (Grose et al., 2020; Nie et al., 2020), which lead to a higher model skill in capturing topography-induced regional patterns of temperature over high elevation areas (Li et al., 2021) such as in the Rockies, as well as regional patterns of precipitation variability (Srivastava et al., 2020).

A clear reduction of the CMIP6 inter-model spread is observed at the catchment scale for mean annual temperature (median difference of −0.56°C; Figure 1b). A reduction of the CMIP6 inter-model spread is also seen for precipitation (median difference of −20.9%; Figure 1d); however, for specific regions, such as northeastern Canada and along the spine of the Rockies, the CMIP6 inter-model spread in precipitation slightly increases. These results are consistent with some recent studies (Akinsanola et al., 2020; Cannon, 2020; Chen et al., 2020, 2021), which looked at a comparison of model skill between both CMIP6 and CMIP5 experiments.

It is noted that a more concerted range of future climate projections does not necessarily translate into higher confidence. Indeed, if all climate models show identical results, it does not mean that they perfectly represent future conditions, but that they fail at properly sampling climate model uncertainties. In the case of CMIP6, it is

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expected that its higher resolution, and the model and parametrization improvements lead to the overall reduction in the inter-model spread for both temperature and precipitation. This is supported by several studies which highlight various climatological improvements of CMIP6 over CMIP5, as previously mentioned (Chen et al., 2021; Fan et al., 2020; Grose et al., 2020; Gusain et al., 2020; Kim et al., 2020; Ortega et al., 2021; Wang et al., 2020; Xin et al., 2020; Zhu and Yang, 2020).

4. Comparison of Hydrological Impacts

The intend of our study is to contrast future projected streamflow indicators derived from both CMIP ensembles. To do so, the precipitation and temperature outputs of all climate models in both CMIP ensembles are bias-corrected and used as inputs to a calibrated hydrological model (see material and methods section). Bias correction of climate model outputs has been and continues to be a controversial topic (Ehret et al., 2012; Maraun et al., 2017), but it is widely considered as a necessary prerequisite step to obtain realistic high-resolution climate simulations for impact models (Piani et al., 2010). Hydrological model calibration and climate model bias correction are performed on a historical reference period prior to their application for a future period. The comparison of future streamflow projections driven by both CMIP ensembles is made at the catchment-scale by taking three flow indicators, representing the means of annual daily (Qmean), annual maximum daily (Qmax) and annual first percentile (QQ1) streamflow conditions. Relative differences between both CMIP-driven future projected streamflow ensembles are presented for the three indicators in Figure 2.

The patterns of differences between CMIP6- and CMIP5-driven streamflow projection ensembles is similar for the three indicators (Figures 3a, 3c and 3e). Overall, the CMIP6-driven hydrological scenarios project larger streamflow values than those driven by CMIP5 over most NA regions, except for the central and southwestern regions. The CMIP6 projected streamflow increase is particularly important over the southeastern United States.

A general reduction in the variability of the CMIP6 hydrological projections is seen at the catchment scale compared to those of CMIP5 for all three indicators (median difference of −23.9% for Qmean, −10.9% for Qmax and −0.8% for QQ1) over most NA regions (Figures 3b, 3d and 3f). This finding is generally consistent with the projections of future precipitation (Figure 1d), although the patterns are noisier for the flow indicators. Increases in variability can nonetheless be seen in mid and eastern Canada, as well as along the Rockies. The larger variability in the CMIP6 hydrological projections over these regions is probably related to the more pronounced increase in the CMIP6 temperature projections (Almazroui et al., 2021) resulting from changes in the snow albedo feedback (Ashfaq et al., 2016; Colorado-Ruiz et al., 2018). These increased changes in temperature affect components of the water balance, such as snow processes and potential evapotranspiration, which ultimately modify the hydrological response of the catchment. Regional features such as steep orography and landscape heterogeneity are strongly shaping the climate signal. The CMIP5 models with their coarser spatial grid resolution compared to the CMIP6 models cannot allow for a realistic regional climate response over large mountain ranges (Gutowski et al., 2020), explaining the lower spread of the CMIP5 ensemble observed over these areas. The differences between the CMIP5 and CMIP6 model forcings (i.e., RCP vs. SSP) could also play a role, although this is expected to be minor since the CMIP6's SSP5-8.5 is designed to provide similar forcing to the CMIP5's RCP8.5.

5. Selecting Representative Climate Models for Impact Studies

All (24) available CMIP5 models containing the required variables and the currently available (22) CMIP6 models on the Pangeo repository (in July 2021) have been included in the experiment. However, given that some climate modeling centers are overrepresented with several versions of their own model (e.g., such as the Institut Pierre Simon Laplace center through its three participating CMIP5 models), the analyses are repeated using a subsample of CMIP6 and CMIP5 models. A 10-model subsample from individual modeling centers that have contributed to both CMIP5 and CMIP6 experiments is selected, as suggested in Cannon (2020). See Table S1 in Supporting Information S1 for the list of climate models used in this work.

Figure 3 presents streamflow distributions for the three indicators expressed in specific streamflow (per unit area). Each cumulative distribution is composed of one value per climate model, and each climate model value represents the average result over the 3,107 catchments. A clear reduction of the ensemble spread for the Qmean

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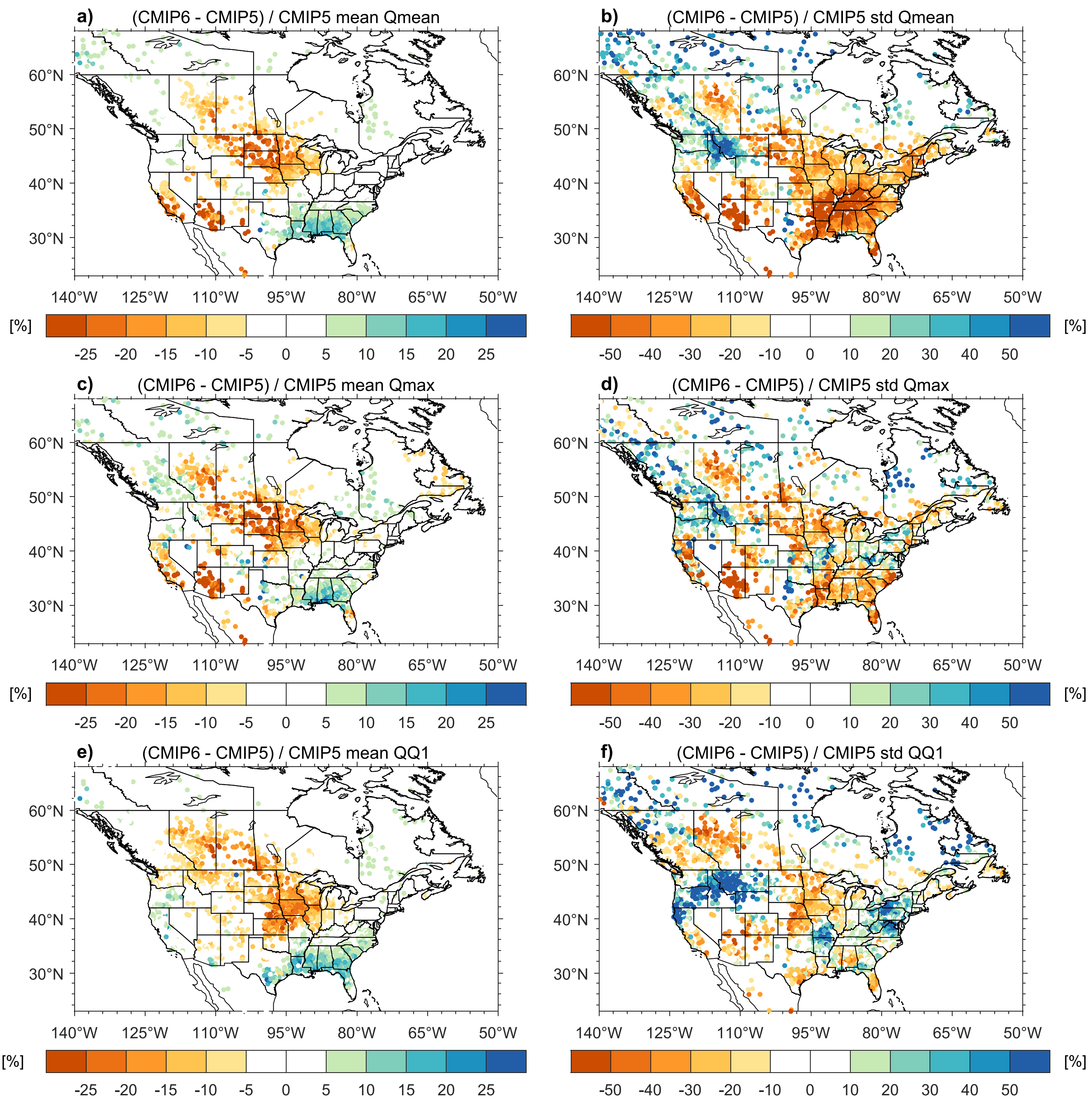

Figure 2. Difference between Coupled Model Intercomparison Project Phase 6 (CMIP6)-driven and Coupled Model Intercomparison Project version 5 (CMIP5)-driven future average (a, c and e) and standard deviation (b, d and f) of indicator values as projected by the CMIP6- and CMIP5-driven hydrological ensembles over the 2070–2099 period for Qmean (a and b), Qmax (c and d) and QQ1 (e and f). Climate forcings are post-processed using a multivariate bias correction prior to the hydrological modeling step and the flow indicators computation.

and Qmax flow indicators is observed from the CMIP5- to CMIP6-driven hydrological projections, regardless of the multimodel ensemble size. For QQ1, the distributions remain similar in all cases. For CMIP6 projections, the ensemble spread in the three indicators is not affected by the subsampling, suggesting that the subsample of CMIP6 models covers the full range of possibilities in the CMIP6 ensemble. The impact of sampling size is more obvious in the CMIP5 projections, where including more CMIP5 models can result in a different streamflow distribution, especially for the Qmean and QQ1 indicators (Figures 3a, 3b, 3e and 3f). Overall, the CMIP6-driven hydrological projections enhance the level of confidence in the projected values of the flow indicators, with a

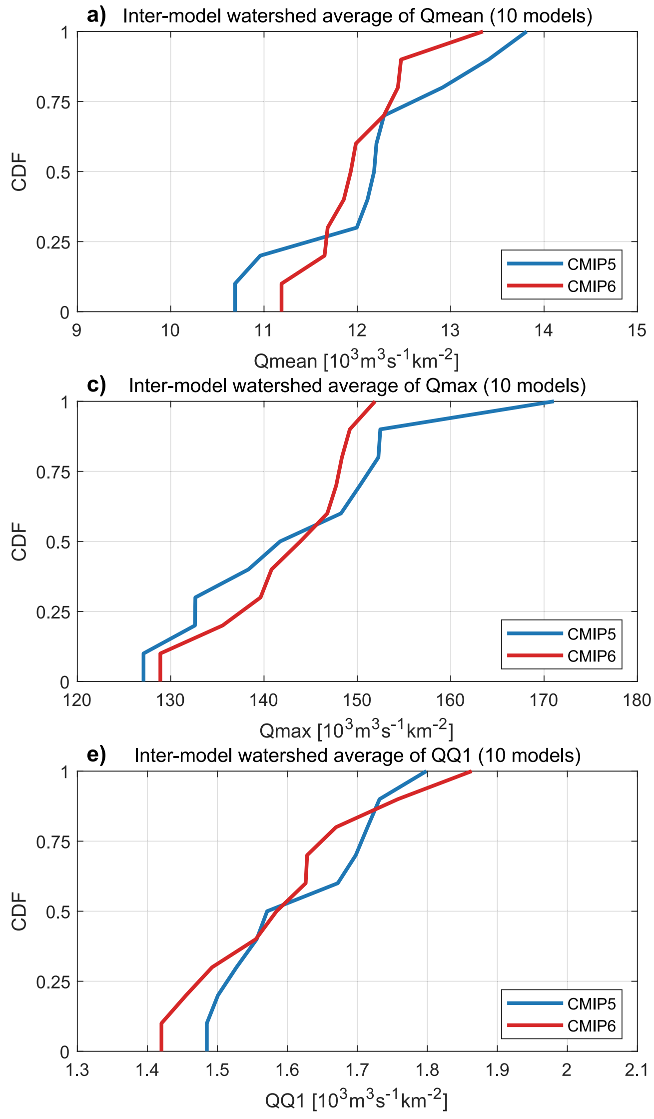

Figure 3. Coupled Model Intercomparison Project version 5 (CMIP5) (blue) and Coupled Model Intercomparison Project Phase 6 (CMIP6) (red) model distribution for Qmean (a and b), Qmax (c and d) and QQ1 (e and f) catchment average when using 10 (a, c and e) and all (b, d and f) climate models.

reduced ensemble spread, except for the QQ1 indicator. Considering that the CMIP6 models incorporate higher spatial grid resolutions, better representation of physical parameterizations and processes leading to improvements in the representation of the spread of the regional climate patterns and variability (Cannon, 2020; Gusain et al., 2020; Xin et al., 2020), it is recommended that the next hydrological impact studies rely on the CMIP6 multimodel ensemble for developing hydrological projections.

6. Limitations

The conclusions of this study could be influenced by some limitations which are discussed hereafter.

The first limitation of this study is related to the use of a simple hydrological model, the conceptual lumped hydrological model (GR4J). Despite their simplicity, lumped hydrological models show a similar level of performance at the catchment outlet compared to distributed hydrological models, which these latter allow a larger amount of physiographic and climatological data to be integrated (Martel et al., 2020; Smith et al., 2012). Furthermore, keeping only catchments with a KGE score above 0.5 ensures that the conceptual lumped hydrological model properly simulate the various hydrological processes over these catchments, providing thus more robust results.

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However, hydrological model structure error is a significant source of uncertainty in hydrological modeling (Troin et al., 2018, 2022), which probably leads to an additional source of variability in the results of this study.

This study can be limited by the poor representation of low flows. The framework used to calibrate the hydrological model does not allow for an adequate representation of low flows. Indeed, the use of the KGE objective function puts more weights on larger streamflow values, potentially leading to poorer model performance for the low flow indicator (QQ1). Hydrological models are also known to represent low flows less accurately than other aspects of the hydrograph (Nicolle et al., 2014; Pushpalatha et al., 2011). However, it is expected that this should not impact the sign of the difference in the mean and variability arising from the direct comparison between CMIP5 and CMIP6. On the other hand, the magnitude of this difference is likely to be impacted by this limitation.

Inability to properly resolve convection in climate models is another limitation of the study. Climate models of the CMIP5 and CMIP6 ensembles have limitations when it comes to reproducing precipitation, notably convective precipitation, which requires parameterization at the spatio-temporal scale of the climate model. However, by only preserving catchments with a drainage area above 500 km^2, the hydrological response time is proportionate with the daily temporal resolution of the climate model. At this spatial scale, even if convection is not properly resolved in the climate model, it is not expected to have a significant impact on the simulation of streamflow at the catchment outlet. With respect to the “prcptot” indicator, aggregating all precipitation at the annual scale reduces the impact of poorly represented convective precipitation.

The relative contribution of the anthropogenic forcing (scenario uncertainty), internal climate variability (stochastic uncertainty) and bias correction (method for reducing epistemic uncertainty) over the total uncertainty in the future climate projections and in the developing of streamflow projections at the catchment scale are out scope of this study. However, the reduction and partitioning of these uncertainty sources remains relevant for hydrological impact studies (Fatichi et al., 2016; Xu et al., 2018).

7. Conclusions

Our study aims at evaluating the improvements in using CMIP6 model simulations instead of the CMIP5 models for hydrological impact studies. We found that the CMIP6 climate simulations are more reliable on average, in particular for regions with complex topography. The higher CMIP6 model spatial grid resolutions allow capturing processes that could have been omitted in the coarser CMIP5 models. Hydrological impact studies based on the CMIP5 projections would benefit from updating to the CMIP6 ensemble to get more confident estimations of future hydrological conditions. This has important implications for policymakers and stakeholders who will have to weigh the uncertainty of climate change in their decisions. Indeed, as we progressively narrow down the probable range of the future conditions for any greenhouse-gas emission scenario, the potential climate-induced hydrological impacts, such as increased flood events, will become clearer allowing to make more informed decisions.

Data Availability Statement

The authors acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modeling, coordinated and promoted Coupled Model Intercomparison Project version 5 and Coupled Model Intercomparison Project Phase 6 (CMIP6). We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP activities and ESGF. The data that support the findings of our study are openly available from the ESGF. This page (https://pangeo-data.github.io/pangeo-cmip6-cloud/index.html) serves as a central hub for information on accessing and interacting with data from the CMIP6 in cloud storage, managed by Pangeo. This data is formatted using Zarr, a cloud-optimized storage format. Both the Hydrometeorological Sandbox over North America (HYSETS; https://osf.io/rpc3w/) and the post-processed CMIP5 and CMIP6 data (https://osf.io/45jcr/) used to produce the results and the figures of this paper can be found on OSF (open science framework).

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