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An ensemble approach to assess hydrological models' contribution to uncertainties in the analysis of climate change impact on water resources

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Abstract

Over the recent years, several research efforts investigated the impact of climate change on water resources for different regions of the world. The projection of future river flows is affected by different sources of uncertainty in the hydro-climatic modelling chain. One of the aims of the QBic^3 project (Québec-Bavarian International Collaboration on Climate Change) is to assess the contribution to uncertainty of hydrological models by using an ensemble of hydrological models presenting a diversity of structural complexity (i.e. lumped, semi distributed and distributed models). The study investigates two humid, mid-latitude catchments with natural flow conditions; one located in Southern Québec (Canada) and one in Southern Bavaria (Germany). Daily flow is simulated with four different hydrological models, forced by outputs from regional climate models driven by a given number of GCMs' members over a reference (1971–2000) and a future (2041–2070) periods. The results show that the choice of the hydrological model does strongly affect the climate change response of selected hydrological indicators, especially those related to low flows. Indicators related to high flows seem less sensitive on the choice of the hydrological model. Therefore, the computationally less demanding models (usually simple, lumped and conceptual) give a significant level of trust for high and overall mean flows.

1 Introduction

The study of climate change impact on water resources has improved our understanding of the interactions between climate and hydrological processes. Water availability will be affected at various levels by the anticipated changes in temperature, precipitation, atmospheric and oceanic circulations and other climate variables depending on the scenarios and the investigated regions. The climate change impact on evapotranspiration, runoff and water availability has been shown to be affected by the uncertainty associated to climate scenarios (Xu, 1999). The advent of regional climate models

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(RCMs) as a physically based and dynamical way of downscaling global climate model (GCM) outputs makes the combined GCM-RCM uncertainty more challenging to be assessed (Déqué et al., 2007). The uncertainty is not only due to imperfections in the models and geophysical data sets required to describe the land surface components, but also because anthropogenic greenhouse gas emissions as well as some climate change effects and feedbacks cannot be predicted in a deterministic way (Foley, 2010). Nevertheless, hydrologists have to work with these uncertain projections, taking into account the underlying assumptions on climate scenarios in their investigation on how and why runoff and hydrological responses are changing (Blöschl and Montanari, 2010).

Teutschbein and Seibert (2010) review applications of RCM output for hydrological climate change impact studies. Graham et al. (2007) and Horton et al. (2006) both used a large set of RCM projections based on different GCMs and greenhouse gas emissions scenarios provided by the PRUDENCE project (Christensen and Christensen, 2007) to quantify the uncertainties in hydrological model output when forced by climate model projections. In the analysis of the impacts on future simulated runoff, Graham et al. (2007) found that the most important source of uncertainty comes from GCM forcing while Horton et al. (2006) stress the fact that using different RCMs forced with the same global data set induces a similar variability in projected runoff as using different GCM.

The studies found in literature vary regarding the construction of the hydrological models ensembles. Prudhomme and Davies (2008) used two different versions of the same lumped model. Wilby and Harris (2006) used two hydrological model structures (CATCHMOD, a water balance model and a statistical model). Kay et al. (2009) investigated the uncertainty in the impact of climate change on flood frequency using two hydrological models: the Probability Distributed Model (PDM) and the grid-based runoff and routing model G2G. Crosbie et al. (2011) quantified the uncertainty in projections of future ground water recharge contributed by multiple GCMs, downscaling methods and hydrological models. The hydrological models were two versions of WAVES

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a physically-based model, HELP a bucket model and SIMHYD a lumped conceptual model. Dibike and Coulibaly (2005) used two conceptual runoff models (HBV and CEQUEAU) to project future runoff regimes based on one GCM scenario and two different statistical downscaling techniques. Most of these studies conclude on the fact that the uncertainty related to different hydrological model or their parameterisation is significantly less important than uncertainty from multiple GCMs.

Few studies have focused solely on the effect of the choice of hydrological model on hydrological changes or the model structural uncertainty (i.e. the uncertainty related to the internal computation of hydrological processes). For instance, Jiang et al. (2007) used six monthly water-balance models (models based on the water balance equation at the monthly time step) for one China catchment. Results show that all models have similar capabilities to reproduce historical water balance components. However, larger differences between model results occur when comparing the simulated hydrological impact of climate change.

Ludwig et al. (2009) investigated the response of three hydrological models to change in climate forcing: the distributed model PROMET, the semi-distributed model HYDROTEL and the lumped model HSAMI over one alpine catchment in Bavaria in Southern Germany. Climate data was generated by the Canadian Regional Climate Model following the IPCC SRES-A2 scenario. The hydrological model performance was evaluated looking at the following flow indicators; flood frequency, annual low flow and maximum seasonal flow. Results showed significant differences in the response of the hydrological models (e.g. estimation of the evapotranspiration or flood intensity) to changes in the climate forcing. Authors mentioned that the level of complexity of the HyMs play a considerable role when evaluating climate change impact, hence they recommend the use of hydrological model ensembles.

Gosling et al. (2011) presented a comparative analysis of projected impacts of climate change on river runoff from two types of distributed hydrological models (a global hydrological model and different catchment-scale hydrological models) applied on six catchments featuring important contrasts in spatial variability as well as in climatic

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conditions. Authors conclude that differences in changes of mean annual runoff between the two types of hydrological models can be substantial when forced by a given GCM.

Poulin et al. (2011) investigated the effects of hydrological model structure uncertainty using two models: the semi-distributed model HYDROTEL and the lumped model HSAMI over one catchment located in the province of Québec, Canada. The delta change approach was used to build two climate scenarios. Model structure uncertainty was analysed for streamflow, groundwater content and snow water equivalent. Authors suggested that the use of hydrological models with different levels of complexity should be considered as contributors to the total uncertainty related to hydrological impact assessment studies.

One of the aims of $QBic^3$ project (a description of $QBic^3$ can be found in Ludwig et al., 2012) is to assess the contribution of different structural complexity in hydrological models (i.e. lumped, semi distributed and distributed models) to the overall uncertainty in the climate change signal in the hydrology at the catchment scale. To achieve this, four hydrological models with different structure and complexity are fed with regional climate model outputs for a reference (1971–2000) and a future (2041–2070) periods. The study is conducted on two contrasted catchments located in Québec (Canada) and in Bavaria (Germany). The impact on the hydrological regime is estimated through hydrological indicators selected by water managers. In our analysis, the uncertainty from the hydrological model is compared to uncertainty originating from the internal variability of the climate system. This internal variability induced uncertainty is the lowest level of uncertainty achievable in climate change studies (Braun et al., 2012) and therefore it is used as a threshold to define the significance of the hydrological models induced uncertainty.

The article is organised as follow: Sect. 2 presents the climate data ensemble, the bias correction and downscaling methods, the structural complexity of the hydrological model ensemble and the hydro-climatic model chain. Section 3 presents the evaluation of the hydrological models over the reference period, the analysis of the impact of

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climate change on the hydrological indicators and the effect of HyM choice on the relative change in future runoff indicators. Section 4 concludes the paper.

2 Data and methods

2.1 Description of the investigated catchments

The present study looks at two contrasted catchments: the Au Saumon catchment (738 km^2) located in Southern Québec (Canada) and the Loisach catchment (640 km^2) located in Southern Bavaria (Germany). Both are head catchments of larger water systems: the Haut-Saint-François (Québec) and the Upper Isar (Southern Bavaria). The catchments' locations and topography are presented in Fig. 1. Since they are not regulated by dam operations nor significantly influenced by anthropogenic activities, flow regimes from both catchments can be considered as natural. Downstream of the investigated sub-basins, the tributary rivers join a managed river systems where complex water transfers and reservoirs affect the river flow. These anthropogenic influences to the flows are not considered in the present study but they are however covered in other activities within the QBic^3 project (Ludwig et al., 2012).

The Au Saumon catchment presents a moderately steep topography in a northern temperate region dominated by deciduous forest. Slopes range from 0.171 upstream to 0.034 at the outlet; the highest point (1100 m) in the catchment is Mont Mégantic. The annual overall mean flow at the outlet is 18 m^3 s^{-1} (ranging from 10 m^3 s^{-1} in August to 54 m^3 s^{-1} in April). High flows mostly occur in spring (driven by snowmelt) and fall (driven by rain).

The Loisach River is an important tributary of the Upper Isar River. The catchment upstream of Schlehdorf gauge (elevation 600 m) sits in the Bavarian Limestone Alps with a smaller portion in the northwest in a region composed of marshland. The dominant soils are limestone in the mountains and loam with some gravel in the plain sections. Coniferous forests with small areas of marshland, pasture and

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rocky outcrops dominate the land use. The highest point within the catchment is the Zugspitze (2962 m). The runoff regime of the Loisach is controlled by snowmelt in late spring and rain events in summer. Mean annual runoff is 22 $m^3 s^{-1}$ with a minimum in January (12 $m^3 s^{-1}$) and a maximum in June (34 $m^3 s^{-1}$).

2.2 The hydro-climatic model chain

Figure 2 illustrates the chain of models used to generate the flow simulations. This chain consists in an ensemble of climate simulations feeding an ensemble of hydrologic models (HyMs) of various structural complexities. The upper half of the diagram in Fig. 2 depicts the two climate data ensembles used in the study while the lower part represents the hydrological ensemble and the associated scaling and bias correction tools required to adjust the climate model data to the hydrological models. These tools connect the top and bottom parts. The combination of climate and hydrological models generates the hydro-climatic ensemble that is analysed to quantify the contribution to uncertainty induced by the HyMs with respect to the climate natural variability estimated from the climate models.

2.2.1 The climate simulation ensemble

Five members of the Canadian Global Climate Model (CGCM3) under the SRES A2 emission scenario are dynamically downscaled by the Canadian Regional Climate Model CRCM version 4.2.3 (de Elía and Côté, 2010) to generate the required climate data for the province of Québec, while three members of the German global model ECHAM5 under the SRES A1b emission scenario are downscaled by the KNMI's regional model RACMO2 (van Meijgaard, 2008) to supply the climate data over Bavaria. These two climate-simulation ensembles allow the exploration of the natural variability (the unforced variability) in the climate system. This natural variability can be estimated by repeating a climate change experiment using a given GCMs several times when only the intitial conditions are changed by small perturbations (Murphy et al., 2009; Braun et al., 2012). The natural variability is used to estimate the significance of the uncertainty induced by changing the hydrological models.

Driving HyMs of different structural complexity over small, heterogeneous catchments with an ensemble of climate scenarios requires further (statistical) adjustment to the forcing variables in order to suit the hydrological modelling scale (e.g. $1\,\mathrm{km}^2 \times 1\,\mathrm{km}^2$). A post-processing is applied to correct biases in RCM temperature and precipitation before downscaling the fields to the hydrological model scale. Monthly correction factors are computed based on the difference between the ensemble-mean of the 30-yr mean monthly minimum and maximum air temperature and the 30-yr monthly means of daily-observed minimum and maximum air temperature. The correction is then applied to each member of the ensemble to conserve the inter-member variance used to estimate the natural variability. Similarly, precipitation is corrected with the local intensity scaling method (LOCI) as described in Schmidli et al. (2006). The SCALMET (Marke, 2008) model output statistics (MOS) algorithm then scales all meteorological variables (humidity, wind speed, radiation and cloud cover) to the HyM grid scale using topography as the main small-scale driver. SCALMET conserves energy and mass within each RCM grid cell once downscaled on the HyM fine scale grid (Further details on SCALMET can be found in Muerth et al., 2012).

The resulting seasonal climate change signals from the climate simulations ensemble (after bias correction and downscaling) are presented in Fig. 3 for both catchments. The mean annual projected change in air temperature for the Haut Saint-François area between the reference and future period is about 3.0 °C. However, the winter months (December to February, DJF) show a stronger warming and a stronger inter-member variability. The average change in precipitation is positive for all seasons but summer (JJA). In the Upper Isar region annual warming is estimated to be 2.2 °C. Precipitation are projected to be roughly the same as in the past in autumn (SON) and winter, but to increase in spring (MAM) and decrease in summer (JJA).

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2.2.2 The hydrological model ensemble

An ensemble of four hydrological models (HyMs) displaying a range of structural complexity has been constructed. The hydrological models range from lumped and conceptual to fully distributed and physically based. Both spatial and temporal resolutions differ within the hydrological model ensemble. The model HSAMI (HSA; Bisson and Roberge, 1983; Fortin, 2000) is a conceptual and lumped model that uses a set of parameters to describe the entire catchment. The conceptual and process-based semi-distributed model HYDROTEL (HYD; Fortin et al., 2001; Turcotte et al., 2003) defines a drainage structure based on unitary catchment units and derives behavioral information for each RHHU (for relatively homogenous hydrological units). The conceptual and process-based fully-distributed model WASIM-ETH (WAS; Schulla and Jasper, 2007) and the process-based and fully distributed model PROMET (PRO; Mauser and Schädlich, 1998) are fully distributed on a grid with a mesh of 1 km. The temporal resolution for all HyMs is daily with the exception of PROMET that requires hourly forcing. PROMET simulation results are thus aggregated to daily means after the simulation is completed. Table 1 presents the characteristics of each of the HyMs.

Meteorological inputs were processed to fit each model's potential evapotranspiration formulation requirements. For the Au Saumon catchment, HSAMI and HYDROTEL use the empirical formulation developed by Hydro-Québec. For Bavaria, HSAMI still uses the Hydro-Québec formulation while the Thornthwaite formulation is used in HYDROTEL. Both formulations use daily minimum and maximum temperatures. WASIM and PROMET use the Penman-Monteith equation which requires additional meteorological inputs for relative humidity, wind speed and net radiation. The soil hydrodynamic formulation is also different within the ensemble. In HSAMI, vertical flows in the soil column are represented by two conceptual and linear reservoirs that represent the unsaturated and saturated zones, while HYDROTEL, WASIM and PROMET compute soil water fluxes and storage with parameters adjusted to different soil layers. HYDROTEL

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provides a lumped characterization of soils at the subcatchment scale and considers the soil column properties as being vertically homogenous.

The computation of snow accumulation and melting is also treated differently in each model; the snow pack evolution in PROMET respects the energy balance in the snow pack, while the other models use simpler temperature-index approaches.

In all four hydrological models, calibration (or parameters' adjustment for PROMET) has been made on the 1990–1999 period. In order to evaluate the predictive capacity of each hydrological model, a simple split sample test has been applied using the 1975–1989 period for validation. Calibration for HSAMI and HYDROTEL is automatically made using the Shuffled Complex Evolution optimization method (Duan, 2003). The objective functions to be optimized in the calibration procedure are the sum of squares error for HSAMI and the root mean squares error for HYDROTEL. These objective functions favour a good representation of high flows to the detriment of low flows. WASIM is manually calibrated by adjustment of land use specific minimal resistance parameters for evapotranspiration and four recession parameters for runoff. PROMET is not calibrated, which means that it is only possible to make an adjustment through changes of the parameters describing the physical based processes within plausible ranges. In the present study, the soil parameters were adjusted to fit the runoff characteristics. Calibration and validation processes are more widely described in Ludwig et al. (2012).

2.3 Hydrological indicators

The analysis of the impact of climate change on hydrology is evaluated on the following four hydrological indicators:

1. the overall mean flow (OMF), defined as the mean daily runoff over the entire period of the investigated time series;

2. the 2-yr return period 7-day low flow (7LF2), calculated from a 7-day moving average applied on daily runoff data. The lowest value over a year is kept as the

yearly low flow. A statistical distribution is fitted to the series of yearly low flows to compute the low flow that occurs statistically every 2 yr (DVWK, 1983);

3. the 2-yr return period high flow (HF2) is the flow that is statistically exceeded every two years or, in other terms, that has a 50 % chance of being exceeded in any given year. It is evaluated from the time series of each year's maximum daily runoff. To calculate 7LF2 and HF2, it is assumed that the time series follow the log Pearson III probability density function, from the German Association of Water (DVWK, 1979);

4. the Julian day of spring-flood half volume (JDSF) identifies the date over the hydrological year at which half of the total volume of water has been discharged at the gauging station (Bourdillon et al., 2011). This indicator targets the spring flood peak, from February to June in Québec and from March to July in Bavaria.

Both catchments show an important annual cycle in the hydrological regime. Two distinct periods representing summer and winter are therefore defined for the analysis. For the Québec watershed, the summer covers the period from June to November and the winter covers December to May while in Bavaria the summer goes from March to August and the winter from September to February.

2.4 Permutations and statistical test

At the very end of the modelling chain (Fig. 2), the present and future climatological values of the hydrological indicators are permuted across members to increase the sample of our climate change signals dataset (e.g. Bourdillon et al., 2011). This operation is based on the assumption that each member is considered as an independant realisation of climate, both in the reference and the future periods. With permutation, the future of a given member is not only compared with the present of the same member but also with the present of all other members. For instance, five GCM members used in a single branch of the modelling chain (i.e. used to drive only one RCM and one HyM)

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produce five present and five future hydrological outputs. With permutation, 25 future versus present differences are obtained for the hydrological indicators, as showed in Fig. 4. Therefore using the permutations, 25 values of relative differences are obtained with five reference and five future hydrological indicators at the Au Saumon catchment. For Schlehdorf, nine values are obtained with the three-member ECHAM5 ensemble. The median of the change values gives the climate change signal while the variability gives an estimation of the uncertainty associated to that signal.

The Wilcoxon rank sum test (Wilcoxon, 1945) is used to compare the distributions of climate change signals between two different hydrological models (Sect. 3.4). It performs a two-sided rank sum test of the null hypothesis (H_0) that two series of data are independent samples from identical continuous distributions with equal medians, against the alternative that they do not have equal medians (Wilks, 2006). In other words, the Wilcoxon test will say if two climate change signals found for a hydrological indicator (from two different HyMs) give (or not) the same information.

3 Results and discussion

The aim of the present study is to assess the contribution of hydrological model's to uncertainty in the climate change signal for water resources management. First, the performance of the hydrological models is evaluated over the reference period by validating the simulated indicators when the HyM is forced with station data against the observed flow at the gauging station. The differences from observations are used to assess the performance of the hydrological model ensemble (Sect. 3.1). Second, the impact of forcing the HyMs with the climate models is assessed through the hydro-climatic simulations using the ensemble of calibrated hydrological models forced by the ensemble of climate simulations (Sect. 3.2). Finally, the relative difference in the hydrological indicators between the reference (1971–2000) and future (2041–2070) periods is calculated to evaluate the climate change signal. A statistical test is used for all given indicators in order to compare the series of relative change of hydrological indicators obtained with the different HyMs.

3.1 Performance of the hydrological models

In order to evaluate the hydrological models when forced by observed station data, the simulated hydrological indicators are compared to the hydrological indicators computed from the gauging station data for both catchments. Fig. 5 (left) shows relative errors E_i between indicators computed from simulations and from observed flows as computed following Eq. (1):

$$E_i = \frac{I_{(\mathrm{sim})i} - I_{(\mathrm{obs})i}}{I_{(\mathrm{obs})i}} \tag{1}$$

where $(I_{\mathrm{obs}})_i$ is the value of the indicator as computed from observed flows; $(I_{\mathrm{sim}})_i$ is the indicator calculated from the simulated flows with the hydrological model i forced by stations data over the validation period. The right panels in Fig. 5 show the absolute error (in $\mathrm{m^3\,s^{-1}}$ or days for JDSF).

Errors related to the OMF over the whole period are relatively small for both catchments (less than 10 %). The HyMs underestimate the OMF for the Au Saumon catchment while they overestimate it for Schlehdorf. This highlights the fact that biases are site specific and cannot be generalised. However, in both catchments the OMF is well captured by the various HyMs. Larger relative errors affect the low flows with a wider dispersion between HyMs than for the OMF. These errors show that low flows are challenging for surface hydrological models. One of the major problems with low flow simulations is related to surface-groundwater interactions which are poorly represented by the HyMs. During low flow periods, water exchange occurs through the riverbed and the river may be fed by groundwater or may leak to feed the aquifer (Pushpalatha et al., 2011). However, the absolute error in low flow is small. For instance, for Au Saumon, HYD, PRO and WAS have a mean error of 23 % in 7LF2-SUMMER, which represents

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only $0.3\,m^3\,s^{-1}$. HSA presents a large relative error for this indicator (about 260 %) which reaches $3.4\,m^3\,s^{-1}$. Over Schlehdorf, the more complex and physically based model PRO that could be thought to better handle low flows show similar performance as the others models in 7LF2-WINTER.

For high flows, WAS and PRO have small relative errors for Au Saumon but these small relative errors can represent large amount of water as it can be seen in the right panel of Fig. 5. For Schlehdorf, the best performance in HF2-SUMMER is obtained with WAS while PRO has the largest deviation. This catchment has a complex topography that might influence the performance of PRO in both high and low flow. Mauser and Bach (2009) have reported a general decrease in PROMET quality with decreasing watershed area, which may be an indicator that the spatial resolution of $1\,km^2$ may not be sufficient for the selected model architecture when looking at small watersheds.

Figure 6 shows the observed and simulated (with the HyMs forced by meteorological station data) mean hydrographs. Au Saumon presents two high-flow events. The first one in spring (driven by snowmelt) is well simulated by HYD and PRO but underestimated by HSA and WAS. A second but smaller high-flow event occurs in summer (driven by rain) which is not captured by HSA. The Au Saumon summer low flows are overestimated by HSA and WAS. Schlehdorf is characterised by a one summer peakflow which results from both snowmelt and precipitation. The peak is overestimated by PRO and is simulated earlier by most HyMs. Schlehdorf winter low flows are overestimated by HYD.

3.2 Climate change impact on water resources

Figures 7 and 8 show the impact of climate change on hydrological indicators for both Au Saumon and Schlehdorf catchments, respectively. The change is expressed as differences of simulated hydrological indicators (ΔI_{ij}) from the reference (I_j^{ref}) to the future period (I_i^{fut}).

$$\Delta I_{ij} = \frac{I_i^{\text{fut}} - I_j^{\text{ref}}}{I_j^{\text{ref}}} \tag{2}$$

where i and j represent the member of the climate simulation from which the hydrological indicator was taken. For each HyM, the boxplots present the change values obtained by the permutations (25 values for each boxplot at Au Saumon and 9 values at Schlehdorf as seen in Fig. 4). In both figures, the relative change of each hydrological indicator (following Eq. 2) is showed along with the absolute change in $m^3 s^{-1}$. The two extreme indicators 7LF2 and HF2 are calculated for the two seasons (summer and winter). The change in JDSF is only expressed as the absolute difference between the present and future values in days.

In Fig. 7, the hydro-climatic ensemble suggest a general increase in the overall mean flow for Au Saumon. The change of the OMF median values varies between 3 % and 11 % for the different hydrological models. The extremes of the expected changes range between −6 % and 22 %. The whole hydro-climatic ensemble predicts an earlier spring flood. The median change value of the JDSF varies from −11 to −13 days, while the overall range goes from −3 to −19 days. The increase in temperature projected by the climate models (Fig. 2) simulates an earlier melt in the future simulated snow cover. The change in the low flow indicators depicts a greater uncertainty between the HyMs. For the 7LF2-SUMMER, the median change values vary from −5 % to −40 %. The reduction in the precipitation and the increase of the potential evapotranspiration (PET not shown) explain this overall decrease in 7LF2-SUMMER. For 7LF2-WINTER, HSA has a significantly larger median change value (+70 %), while the other three models show values of about +40 %. The change in the summer high flow indicator (HF2-SUMMER) ranges from −3 % to 18 %. PRO is more sensitive to the range in climate forcing and shows the largest spread in the indicator from −10 %

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to +80 %. The median change values of HF2-WINTER are around +5 % with a range from −18 % to +23 %. The overall trend shows an increase in high flows.

Schlehdorf (Fig. 8) shows a general but smaller diminution of the OMF, the median change value varies between −1 % and −6 %. The spring flood discharge happens sooner in the simulations with the median difference ranging between −4 and −6 days. Dispersion is slightly larger than for Au Saumon for all the HyMs but PRO. The median of summer low flow (7LF2-SUMMER) ranges between −5 % and −8 %. In winter the relative uncertainty about the potential changes is much larger, so the relative change of 7LF2-WINTER varies from −20 % to +20 %. The signal for this indicator seems to be very model specific. The HyMs HSA and HYD present a negative change signal (median of −15 % and −5 %, respectively) while the more complex models WAS and PRO present a positive change signal (+4 % and +12 %, respectively). The summer 2-yr return period high flow (HF2-SUMMER) has median values ranging between +1 % and −8 % and the overall relative uncertainty ranges between −18 % and +25 %. In HF2-WINTER, HSA has a negative relative difference (median of −5 %), while the other models show a median value of about +3 %. The total change in HF2-WINTER ranges between −8 % and +30 % where a general increase in high flows is expected for all HyMs but HSA. Figures 7 and 8 show that the large relative change presented by low flows are still small in absolute terms with respect to high flows.

3.3 Hydrological models contribution to uncertainty

In the present section, we explore the uncertainty induced from an ensemble of hydrological models in the impact assessment of climate change on water resources. Complex models are usually more demanding to configure over a given watershed and they also demand more computing power. Hence, it is of interest to know if they really modify the information in a climate change analysis compared to what is obtained from simpler models. If all models within the ensemble provide different signal for some indicators then an ensemble could be considered required to fully assess the impact of climate change on water resources.

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The rank-sum Wilcoxon test is used in order to compare pairs of climate change signal ensemble obtained from two distinct HyMs. For each hydrological indicator, we evaluated if two samples (one sample from each hydromodel) have been drawn from the same distribution (the null hypothesis) within the rejection level of 5 % used in this study. If the null hypothesis is not rejected, it could be an indication that the climate change signals from two HyMs provide similar information. Note that this does not verify the null hypothesis but only says that it cannot be rejected from the available information. This test was applied to the relative differences (except for JDSF where it was applied to absolute differences in days), as specified in Figs. 7 and 8.

The Wilcoxon test results are shown in Table 2 for Au Saumon and Schlehdorf where the series of climate change impact on hydrological indicators are compared for all the pairs of models. The OMF at Au Saumon, the test is not rejected when comparing the pairs HSA-HYD, and WAS-PRO. For OMF Schlehdorf, the only pairs of model that leads to rejection are WAS-HSA and WAS-HYD. The large difference in the Wilcoxon test results over the two watersheds might originate from the formulation of potential evapotranspiration (PET); PRO and WAS use the complex Penman-Monteith while HYD and HSA use temperature-based empirical approaches. However, the model pairs HSA-PRO and HYD-PRO do not reject the test for Schlehdorf. Bormann (2011) reported that different PET formulations following different approaches show significantly different sensitivities to climate change.

The change in the JDSF is similarly predicted with all HyMs over Schlehdorf. Over the Au Saumon, only WAS behaves differently to the less complex HSA and HYD. So in this case the signal is more robust because this indicator depends mostly on temperature.

The low flow shows greater differences between models. The season when low flows are most severe differs in both catchments; it happens in summer for Au Saumon and in winter for Schlehdorf. In Au Saumon, the test is rejected for all model's pairs for the 7LF2-SUMMER, but it's the conceptual model HSA which presents the largest difference with all other models (see Fig. 7). In Schlehdorf the 7LF2-WINTER test is not rejected only for the pair HSA-HYD. However, a very different behavior is shown between lumped and distributed models for low flows. The lumped and semi-distributed models predict a negative change, while the fully distributed models projected a positive change (Fig. 8). The Schlehdorf catchment is very steep and this could affect the baseflow simulation, which is better represented in the semi-distributed and fully distributed HyMs. In the less severe low flow periods (winter for Au Saumon, and summer for Schlehdorf), groundwater recharge is larger, so this leads to a more stable baseflow and smaller differences in the simulated low-flow quantities between HyMs. These differences may also be influenced by the PET formulation.

The highest flows are seen in winter for Au Saumon and in summer for Schlehdorf. The Wilcoxon test is not rejected when comparing all pairs of HyMs for the HF2 in these periods. However, a high uncertainty is present in this indicator, but it is more related to the natural variability simulated by climate models than in the choice of the hydrological model (Figs. 7 and 8). Nevertheless, the choice of the hydrological model affects the HF2-SUMMER in Au Saumon.

It is important to note that results for the rank-sum Wilcoxon test differs for the two sites and also differs from one indicator to another. Analysis over Au Saumon indicates that the hydrological models generate a significantly different signal for most indicators (except HF2-WINTER). The use of a hydrological model ensemble would thus be recommended in order to fully assess the uncertainty in the climate change signal. For Schlehdorf, only OMF and 7LF2 seem to be sensitive to the selection of a HyM. To analyse the high-flow indicator or springflood timing indicator, the recommendation to use a simple conceptual model can be made with a certain level of confidence. Another important aspect is that the analysis of the uncertainty from the HyMs cannot be transported from site to site and seems to have to be repeated for every catchment. A regional analysis would be required to see if the conclusions present a regional behaviour.

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4 Conclusions

The present study looked at the uncertainty in projecting future changes in runoff characteristics induced by the choice of hydrological models for two distinct natural flow catchments. A hydroclimatic ensemble is constructed with a combination of an ensemble of climate scenarios and an ensemble of hydrological models. The major strength of the hydro-climatic ensemble approach is that the ability of HyMs to reproduce hydrological characteristics can be compared and the uncertainty of future changes in runoff behavior can be assessed. Four hydrological models have been chosen from those used in scientific or administrative assessment of climate change impacts on river runoff in Québec and Bavaria. The complexity of these models ranges from highly calibrated, lumped to process-based and fully distributed.

The principal aim of the paper is to assess the contribution of hydrological model's uncertainty in the climate change signal for water resources management. The results of our study suggest that the added value depends on the hydrological indicator considered and on the region of interest. In the case of high flows and peak time discharge, most of the hydrological models lead to comparable results; therefore, lumped and calibrated models can be used. The evaluation of the overall mean flow is more sensitive on the type of model in the Québec watershed than in Bavaria. Therefore, an ensemble of hydrological models should be employed in order to evaluate the range of climate change impact due to the difference in the process description in different hydrological models.

The largest relative difference between hydrological models outputs is revealed for changes in low flow, where the results differ the most in our analysis. It is important to remember that the HyMs used in this study were not specifically calibrated for low flows, which is reflected in the results for the reference period. However, Mauser and Bach (2009) have pointed out that any calibration of a model on present conditions may become invalid for the evaluation of climate change impacts; such usage of HyMs can be translated to the transfer of a wet conditions calibration to the use in dry conditions.

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Therefore, one must be cautious in the evaluation of climate change impacts on low-flows conditions from a single model. This issue should be re-evaluated with models calibrated over both wet and dry conditions.

Following our result, we suggest that the uncertainty in projections added by the hydrological models should be included in climate change impact studies, especially for the analysis of mean and low flows. In the absence of an acceptance/rejection criteria (Beven, 2007), all HyMs should be considered equally probable and therefore equally contributing to the uncertainty range. The generalisation of this conclusion would require more than two sites and should include other sources of uncertainty (e.g. internal calibration of HyMs or different GCM's).

Also, a multi model combination could be used in hydrological climate change impact studies. Such an approach is based on the idea that each HyM of the ensemble provides specific information that might be combined to produce a better overall simulation (e.g. Shamseldin et al., 1997; Velázquez et al., 2010).

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Table 1. Characteristics of the hydrological model ensemble.

	HSAMI (HSA)	HYDROTEL (HYD)	WASIM-ETH (WAS)	PROMET (PRO)
Spatial reference	Lumped	Semi-distributed	Fully distributed	Fully distributed
Model type	Conceptual	Process based, Conceptual	Process based, Conceptual	Process based
PTS Meteorological Input	24 h T (min & max), P	24 h T (min & max), P	24 h T (mean), P, RH, wind, Rad	1 h T (mean), P, RH, wind, Rad
PET calculation	Empirical formula developed Hydro-Québec	Hydro-Québec or Thornthwaite	Penman-Monteith (Monteith, 1975)	Penman-Monteith
Soil hydrodynamic formulation	2 reservoirs, (unsaturated and saturated zones)	3 layers, Brooks and Corey (1966)	Multilayer, Richards' equation, (Richard, 1931) Van Genuchten (1976)	4 layers, Eagleson (1978) Brooks and Corey
Snow model	Temperature-index approach	Temperature-index approach in combination with energy-balance approach	Temperature-index approach	Energy balance of a one-layer snow pack

Note: T (temperature), P (Precipitation), RH (Relative humidity), W (wind) and R (radiation), PTS (processing time step).

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Table 2. Results of Wilcoxon tests comparing pairs of hydrological models for **(a)** Au Saumon, and **(b)** Schlehdorf. The X mark indicates a rejection of the test.

	HSA-HYD	HSA-PRO	HSA-WAS	HYD-PRO	HYD-WAS	PRO-WAS
(a) Au Saumon						
OMF		X	X	X	X	
JDSF			X		X	
7LF2-summer	X	X	X	X	X	X
7LF2-winter	X	X	X			
HF2-summer	X		X	X		X
HF2-winter						
(b) Schlehdorf						
OMF			X		X	
JDSF						
7FL2-summer						
7LF2-winter		X	X	X	X	X
HF2-summer						
HF2-winter						

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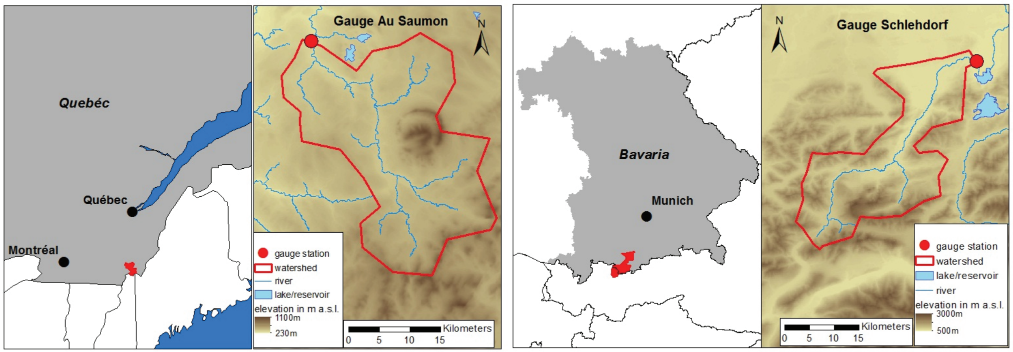

Fig. 1. Location of Au Saumon and Schlehdorf catchments.

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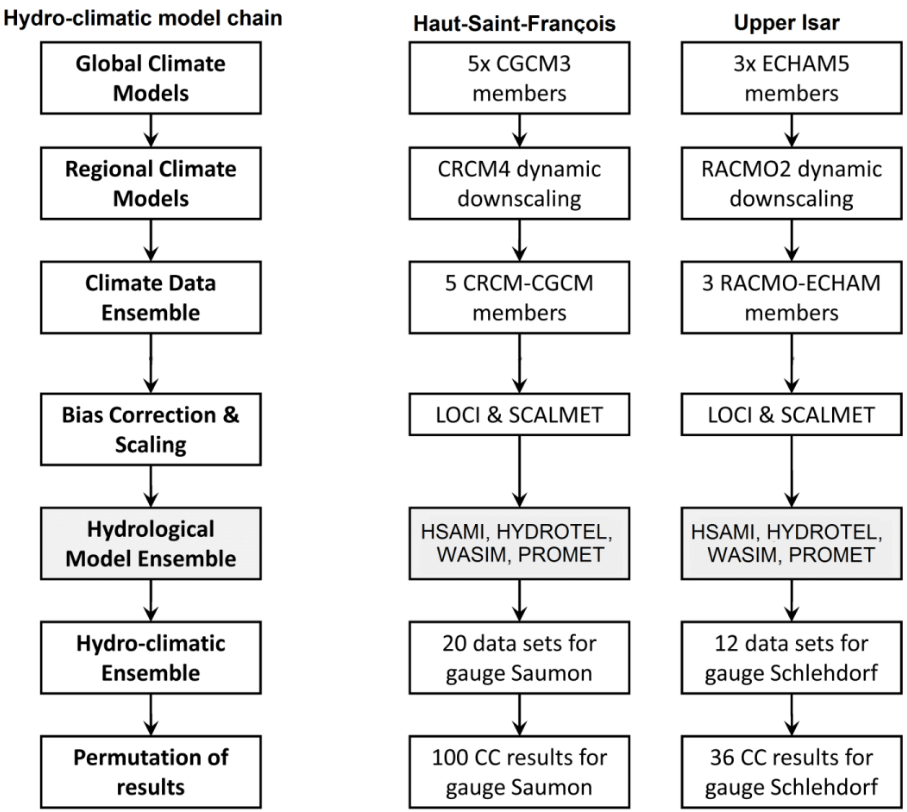

Fig. 2. The hydro-climatic model chain.

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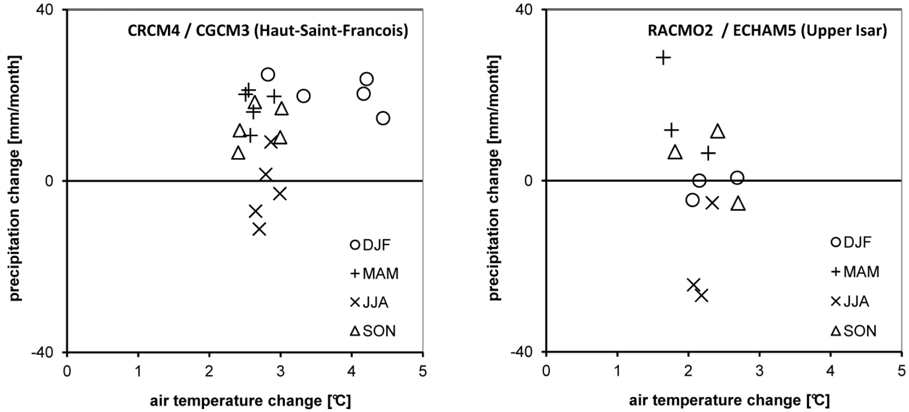

Fig. 3. Climate change signals over Haut-Saint-François (left) and Upper Isar (right) regions.

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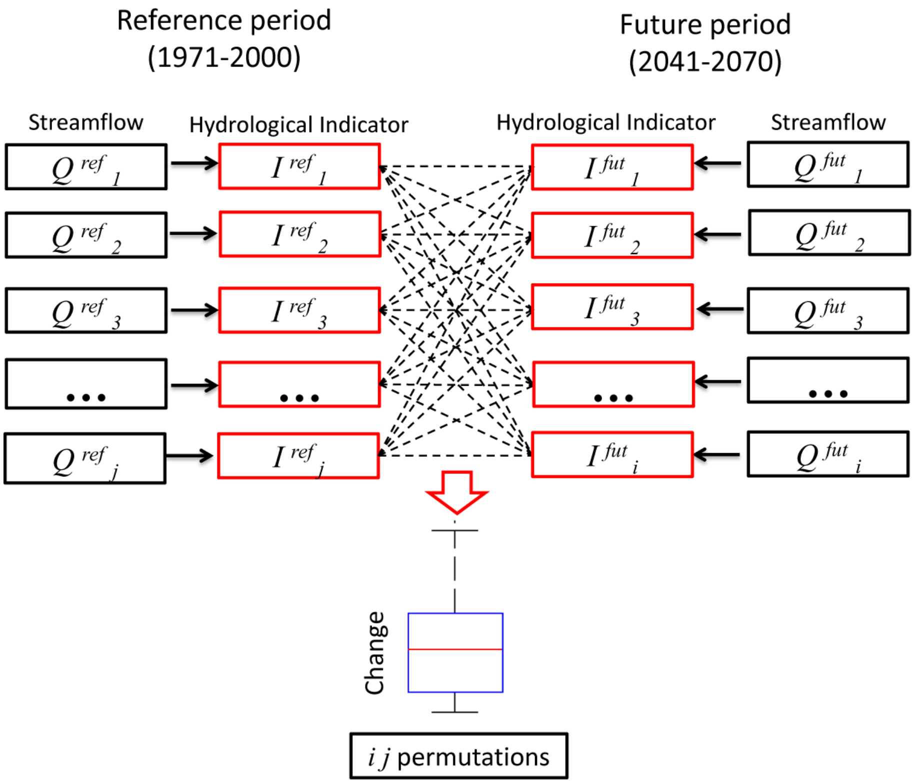

Fig. 4. Schematic representation of the permutation process.

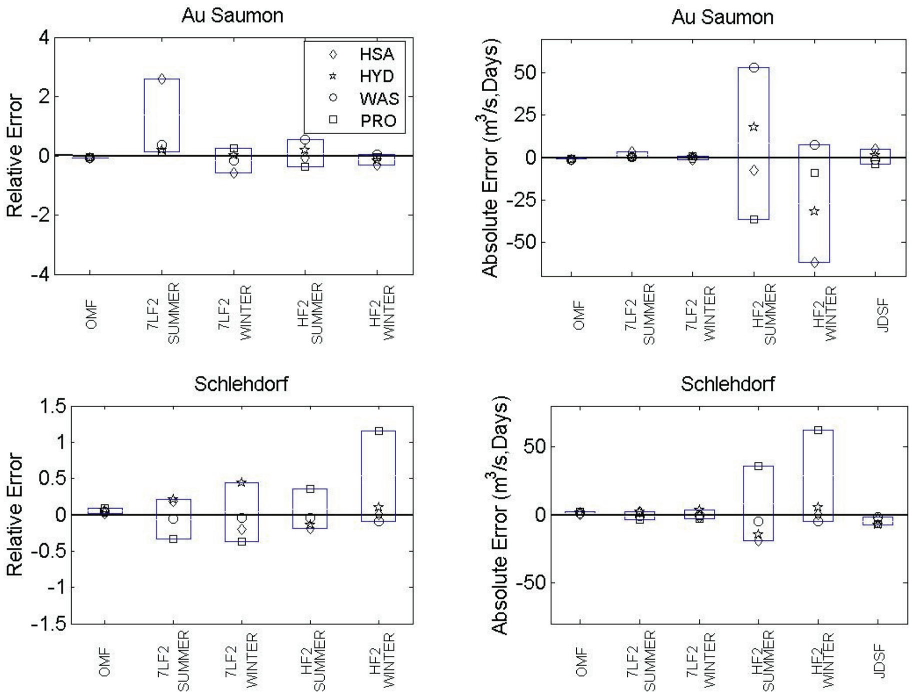

Fig. 5. Performance of the hydrological models over the reference period. The left panels show the relative error as computed with Eq. (1), while the right panels show the absolute error in $m^3 s^{-1}$.

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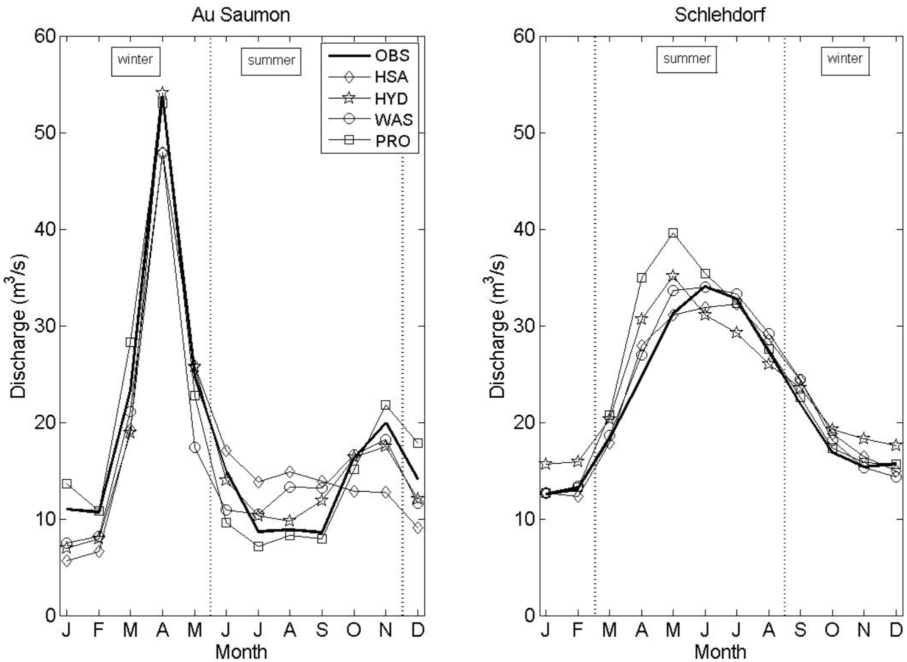

Fig. 6. Observed and simulated (forced by stations data) hydrographs for Au Saumon and Schlehdorf over the reference period.

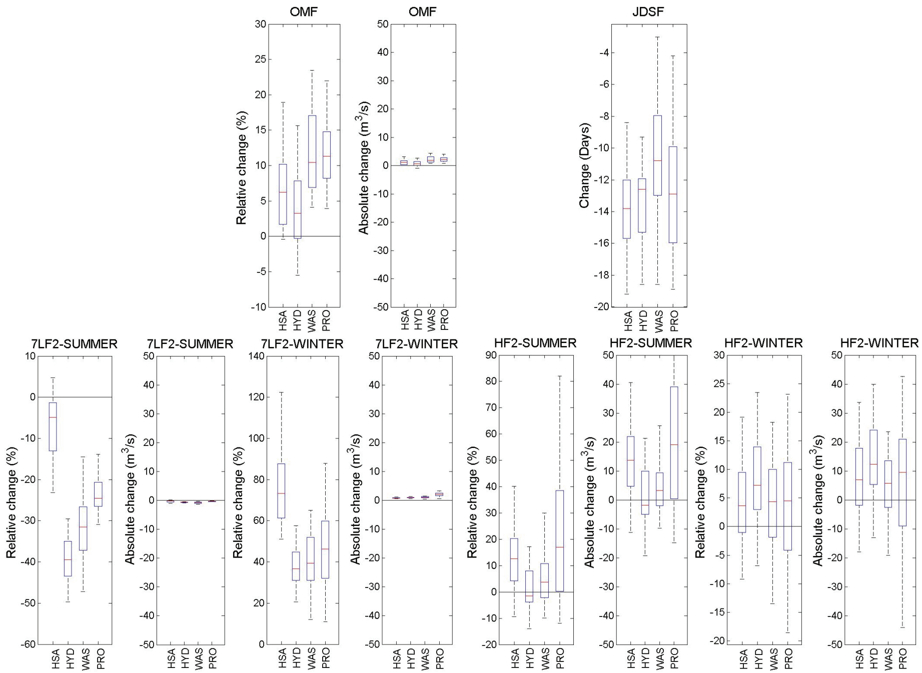

Fig. 7. Changes of hydrological indicators from reference to future period at Au Saumon (Haut St-François, Québec) of overall mean flow (OMF), the Julian day of spring-flood half volume (JDSF), the 2-yr return period 7-day low flow (7LF2) in summer and winter, and the 2-yr return period high flow (HF2) in summer and winter. For each hydrological indicator, the relative change (as calculated with Eq. 2) is presented along with the absolute change in $m^3 s^{-1}$. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the most extreme value.

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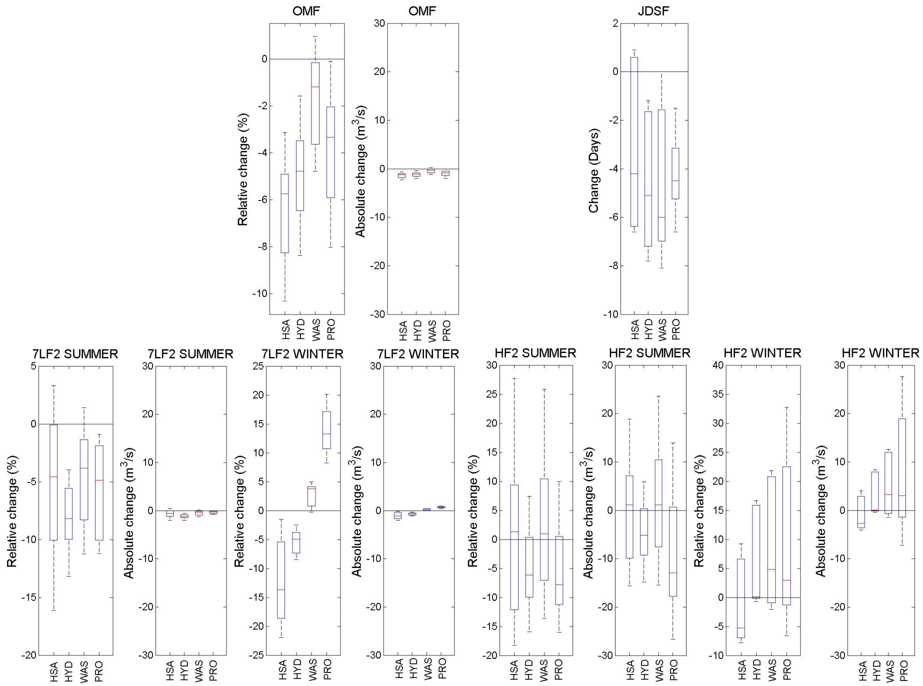

Fig. 8. Same as Fig. 7 but for Schlehdorf.

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