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The use of multi-source cryospheric datasets to improve the simulation of future icemelt contribution to streamflow in large glaciarized basins

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Abstract. The glacierized mountains are impacted by dramatic changes in the context of global warming with large implications for hydrology. However, the projection of icemelt contribution to streamflow remains a complicated task and is subject of large uncertainties, especially when the calibration-validation process was performed with little or no cryospheric data. In this study, we present the integration of a glacier module in the distributed conceptual hydrological model J2000, taking into consideration the evolution of glacier surface in the simulations. A calibration and a validation was done using a large panel of hydro-cryospheric datasets, including glacier mass balance observations and simulations, snow reanalyses, snow-cover by satellites and stream gauges. The calibration-validation was performed by applying J2000-Rhône-glaciers to the entire Rhône basin in the historical period (1976-2022) using the SAFRAN climate reanalysis at 8 km horizontal resolution. The set of parameters identified in the past and meteorological data from 5 "GCM-RCM" chains of climate projections under RCP 8.5 scenario were used to simulate the hydrological response of the Rhône basin under climate change projections (1976-2095). The results show that snowmelt, icemelt and streamflow are satisfactorily simulated by J2000-Rhône-glaciers in the Rhône basin. The projections show a decrease of annual streamflow expected by the end of the 21st century due to a decrease of precipitation and glacier shrinkage in highly glaciated subbasins. The results of the simulations also show an increase of streamflow in winter but a dramatic decrease in summer mainly due to a change in snow seasonality. The icemelt will become extremely low in Isère, Drac and Durance subbasins, while in the Arve, upper Rhône, and along the Rhône River, the future evolution of icemelt contribution to summer streamflow is very uncertain. Despite these uncertainties, our results suggest that the remaining glaciers will still be crucial to sustain the summer streamflow at the end of the century. However, the peak water may be passed by 2040s in the Arve subbasin, and 2050s in the upper Rhône, and the change in snow seasonality will still threaten the availability of water resources in most of the

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Rhône subbasins. The use of multi-source cryospheric datasets allowed to gain confidence in the projections of icemelt contribution to streamflow in a large basin in the Alps.

1. Introduction

Mountainous regions are particularly impacted by global warming, mainly due to the snow albedo feedback (Kotlarski et al., 2023), enhancing the melting of the cryosphere (Yang et al., 2021). This warming has large impacts on the water cycle due to multiple factors such as changes from snowfall to rainfall and timing of snow cover melt (Le Roux et al., 2023; Monteiro and Morin, 2023), increase of evapotranspiration (Moraga et al., 2021) and thickening of the active layer depth consecutive to the degradation of permafrost (Peng et al., 2023) or glacier retreat (Zekollari et al., 2019). Until now, rivers from mountainous regions exhibit low flow in winter when snow accumulates, and high flow in spring (and summer) when snow (and ice) are melting. While the glacierized high elevated basins still benefited from icemelt water to sustain the summer streamflow in the last decades, icemelt contribution is starting to decrease in many regions because the peak water has been passed in most glacierized catchments (Huss and Hock, 2018).

In the European Alps, climate change has a particularly strong impact (Dumont et al., 2025; Sauquet et al., 2026) and the simulations project a large decrease of summer precipitation in the future (Kotlarski et al., 2023), with a stream level that may become extremely low in summer (Bonaldo et al., 2023). In glacierized catchments, icemelt can greatly sustain the streamflow during dry summers (Van Tiel et al., 2026) so the future projections of icemelt contribution to streamflow is extremely valuable. The use of glacier retreat routines in hydrological models have been developed in the last 15 years (Horton et al., 2022). This method was used to assess the future change of icemelt in very large catchments in Europe (Hanus et al., 2024; Huss and Hock, 2018), in a smaller highly-glacierized catchment in France (Laurent et al., 2020) or in all the glacierized watersheds in Switzerland (Freudiger et al., 2021). A recent research program (Explore 2), aiming to project the future evolution of hydrological regimes in the French catchments (Sauquet et al., 2026), used only one model considering glaciers (Mordor SD) among 9 hydrological models. This may be due to the difficulty to simulate properly cryospheric and hydrological processes simultaneously without glacier retreat routines and without a multi-variable calibration process that need multiple datasets (Van Tiel et al., 2020). The multimodel approach such as in Sauquet et al. (2026), that has been proved to give satisfactory results (Kushwaha et al., 2021) are in the need of new hydrological models including these aspects.

The J2000 hydrological model, developed by Krause (2002), was used in the Explore 2 research program (Sauquet et al., 2026), but originally did not take into account glacier retreat. J2000 has been recently improved, incorporating the evolution of glacier surfaces and tested in a small subbasin of the Rhône basin (Bolibar Navarro, 2020). The goal of this study is to use

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this new J2000 dynamic glacier component in the Rhône basin (hereafter referred to as J2000-Rhône-glaciers) to analyze the future icemelt contribution to streamflow in the Rhône subbasins. The Rhône River, fed with Swiss and French glaciers, is one of the major rivers flowing from the European Alps, with a drainage area of 96 000 km². The Rhône basin has an average elevation of 800 m a.s.l. and glaciers cover about 3% of the drainage area. In this basin, the local population is highly dependent on the hydrological regimes of the rivers and a decrease in summer streamflow may have significant socio-economical impacts. Winter electricity production relies on high spring-summer streamflow that recharge the reservoirs (Anghileri et al., 2018; Schaefli et al., 2019), agriculture needs are higher in summer season (Beniston, 2012), and the water used in the major downstream cities of Lyon, Grenoble or Marseille are highly dependent on river water levels. The summer low flows may also be a threat for the river ecosystems (Rolls et al., 2012), emphasized by the recent very dry summers of 2003 and 2022. Therefore, the future contribution of glaciers to the hydrology in the Rhône River basin is a key concern. The large size of the Rhône River basin gives the opportunity to assess the glacier contributions in a large variety of subbasins, from small well-glaciated upper basins to the large downstream pluvial basins.

The impact of climate change on the Rhône River streamflow has been studied for many years. Etchevers et al. (2002), found that a doubling of CO_2 may cause an increase in streamflow mainly in winter due to an increase of liquid precipitation in the northern lowlands, and a decrease in summer in the mountainous part of the catchment due to a reduced snowpack. More recent scenarios of climate change also show an increase of winter streamflow and a decrease in summer (Forzieri et al., 2014; Hanus et al., 2024). The consideration of the glacier dynamics in the simulations within the Rhône basin, showed that part of the decrease in summer streamflow is associated to a reduction of glacier surface (Hanus et al., 2024; Huss, 2011; Huss and Hock, 2018; Wiersma et al., 2022). However, the contribution of icemelt was computed using observed streamflow (Huss and Hock, 2018), the contribution of snowmelt and icemelt were not investigated independently (Hanus et al., 2024; Laurent et al., 2020) and an hydrological model with a glacier retreat routine were never applied to all the Rhône subbasins.

The main objectives of the study are (i) to calibrate and evaluate the J2000 simulations in the historical period using mult-source datasets of snow, glacier surface mass balance, and streamflow in the 5 glaciarized main subbasins (sized from 500 to 5700km²) that encompass all glaciated surface of the Rhône basin, (ii) to evaluate the streamflow simulations of J2000-Rhône-glaciers for 48 hydrometric stations fed by glaciers, and (iii) to assess the glacier and snow melt contribution to streamflow throughout the 21st century in various subbasins of the Rhône River basin using future projections of glacier surfaces and climate variables.

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2. Data and methods

2.1 Glacier module in J2000 hydrological model

J2000 is a distributed hydrological model, developed by Krause (2002), that uses precipitation, temperature, and reference evapotranspiration to calculate the water balance over hydrological response units (HRU). The main components of J2000 are shown on Fig. 1. The HRUs are delineated based on the subbasins, the geology, the soil type, the land cover, the elevation, and the slopes. For each HRU, precipitation is first separated between snowfall and rainfall using temperature thresholds (*snow_trs* and *snow_trans*). The interception of rainfall and snowfall by the canopy is then calculated using the Leaf Area index. The accumulated snow on the ground melts when the cold content of the snowpack, calculated based on air temperature and a cold-content factor (*ccf_factor*), becomes positive. The melting is computed via a degree day approach using a snowmelt factor (*t_factor*). Snowmelt and net rainfall reaching the ground are then directed to the soil module that calculates surface flow and infiltration based on a maximum infiltration rate and an imperviousness factor of the soil. Infiltration water goes to a Middle Pore Storage (MPS) up to the maximum storage set for different soil depth and texture, where it can evaporate. The infiltration that is not going to MPS is directed to the Large Pore Storage (LPS) and becomes interflow (subsurface), surface flow or percolation depending on the slope and a calibrated factor. The percolation water is directed to the groundwater component. The amount of water that can be held in the ground is a function of the maximum storage capacity. Base flow is calculated using a retention coefficient and a calibration parameter to calibrate. The surface flow, interflow, and base flow calculated at a given HRU are then transferred to the downstream HRU located downhill or alternatively, to the riverine network embodied in the model by “reaches”. In the reach the integrated flow is calculated using a cinematic wave approach depending on the flow velocity calculated with the Manning-Strickler equation, the flow length and a routing coefficient (TA) to calibrate. This flow is then directed to the next downhill reach.

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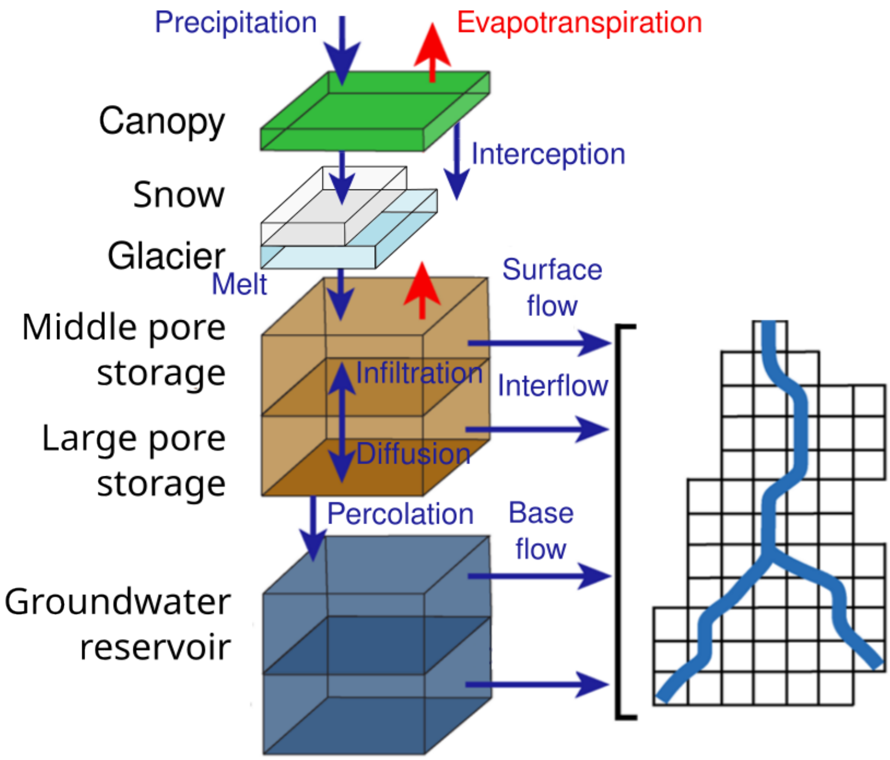

Figure 1. Main components of J2000

A glacier module was previously integrated in J2000 for the Himalaya (Nepal et al., 2014) and improved by Bolibar Navarro (2020). In Nepal et al. (2014), snow and glacier melt were applied to the entire surface of the HRU considered as glacier, while Bolibar Navarro (2020) takes into account the evolution of the glacier surface through time in each HRU. This fraction of glaciated area per HRU, is provided as an input to J2000 at a daily time-step. For each glaciated HRU, ice melts at a speed defined by an icemelt factor (*ddfIce*), as soon as all the snow has melted. The melted ice and the fraction of melted snow and rainfall corresponding to the glaciated fraction of the HRU, are then transferred to the soil module component according to the routing coefficients *ksnow*, *kice* and *krain*.

2.2 Calibration of J2000-Rhône-glaciers

We applied the glacier module developed and tested in a small French alpine catchment by Bolibar Navarro, (2020) to the entire Rhône basin. The Rhône River basin covers 96000 km², with an elevation ranging from 4 m a.s.l. at the outlet to 4806 m a.s.l. at Mont-Blanc (Fig. 2a). The Rhône basin mainly includes forested and agricultural areas, with some areas of rock/bare-soil and grassland in particular in mountain regions (Table 1). The urban areas cover less than 2% of the basin and the glacial HRU represents 3% of the total surface. The basin includes very heterogeneous areas with the Saône river basin

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in the North (Northern black contour in Fig. 2a), which consists of plains and low elevation mountains up to 1700 m a.s.l.r., high mountainous regions with or without glaciers, and the lower Rhône in the South-West drained by the lower Rhône river surrounded by hills. The J2000 versions used in this study represent the natural streamflow and do not consider water usage, dams, reservoirs or transfer of water between subbasins.

Table 1: Characteristics of subbasins used for calibration (colours in Fig. 2a) and other subbasins along the Rhone River (black contours in Fig. 2a). The percentages of land cover are calculated from the total surface area of the hydrological response units (HRU) covered by each land cover (European Environment Agency, 2019). An HRU is considered as glacierized whenever it intersects with the glacier outlines the map of glacierized areas from the 2015 glacier inventory (Paul et al., 2020).

	Rhône at Porte du Scex [CH002009]	Arve at Sallanches [V0032010]	Isère at Grenoble [W1410010]	Drac at Fontaine [W2832020]	Durance at Espinasses [X0500010]	La Saône at Couzon [U4710010]	Rhône at Pougny [V100010]	Rhône at Ternay [V3130020]	Rhône at Valence [V4010010]	Rhône at Beaucaire [V7200010]
Area (km²)	5220	514	5720	3550	3580	29274	10320	50560	66450	96134
Mean? Elevation Basin (m)	2112	2015	1684	1601	2028	373	1525	668	793	792
Elevation station (m)	393	543	217	209	762	169	393	155	149	4
Urban (%)	1,2	1.9	1.7	0.3	0	1.4	3.2	2.6	2.3	1,8
Forest (%)	29,8	35,5	38,2	35,6	37.5	29.6	33	33.9	34.1	39
Agriculture (%)	5,9	2,8	8,6	14,3	4.3	68.9	17.8	53.2	48.5	43
Grassland (%)	14,2	9,6	23,2	15,4	16,9	0.1	9.5	2.2	4.6	7,4
Rock or bare soil (%)	15,8	10,2	18	24,1	37,2	0	10.1	2.1	4.6	4,9
Glacier	33,1	40,1	10,3	10,3	3,9	0	18.6	3.9	4.4	3,2

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(%)										
Lakes (%)	0	0	0	0	0	0.1	7.8	2%	1.5	0.9

A version of J2000 was already used in the Rhône basin (Branger et al., 2018; Morel et al., 2023; Morin et al., 2023; Sauquet et al., 2026), referred to as J2000-Rhône-classic, were glaciers were coarsely imitated by accumulated snow in high elevation during an initialization period (spinup). The hydrological parameters used in J2000-Rhône-classic were previously calibrated using a trial and error approach and using only streamflow in the objective function (Branger et al., 2016; Morel et al., 2023). In J2000-Rhône-glaciers, the factors used in the snow and ice modules are adjusted manually with a stepwise approach to match the glaciological and snow observations. The parameters that drive the accumulation of snow *precip_mult and precip_mult_low* were first adjusted. Then values of *t-factor*, that was set for the entire basin in J2000-Rhône classic, were adjusted for each subbasin to improve the timing of the snow-cover. The cold content factor was then adjusted to improve the timing of snowmelt. Once all the snow factors were adjusted, the icemelt factor was adjusted. This multi-data calibration approach was done to improve the representation of snow and glacier melt processes in the simulation and to reduce the problem of equifinality (Van Tiel et al., 2020). The value of using glacier data to improve the simulation of hydrological processes has been previously tested (Konz and Seibert, 2010; Mimeau et al., 2019; Van Tiel et al., 2020). The calibration of parameters used to simulate the glacier mass balance and snow processes was done for each of these subbasins (coloured in Fig. 2a):

- The Upper Rhône at Porte du Scex (5200 km2, ranging from 393 m - 4636 m a.s.l.), highly glaciated (33%), and including the Rhône glacier (the River Source)
- The Arve at Sallanches, ranging 543 m - 4806m a.s.l , the smallest (500 km^2), but also the most glaciated (40%)
- Isère at Grenoble (ranging 217 m - 3855 m a.s.l., 10% glacier cover), the largest (5700 km^2) and well covered by grasslands (23%)
- The Drac at Fontaine (3550 km^2, ranging 209 m - 4087 m a.s.l., 10% glacier cover) , more agricultural (14%)
- The Durance at Espinasses (3580 km^2, 762 m - 4102 m a.s.l., 4% glacier cover).

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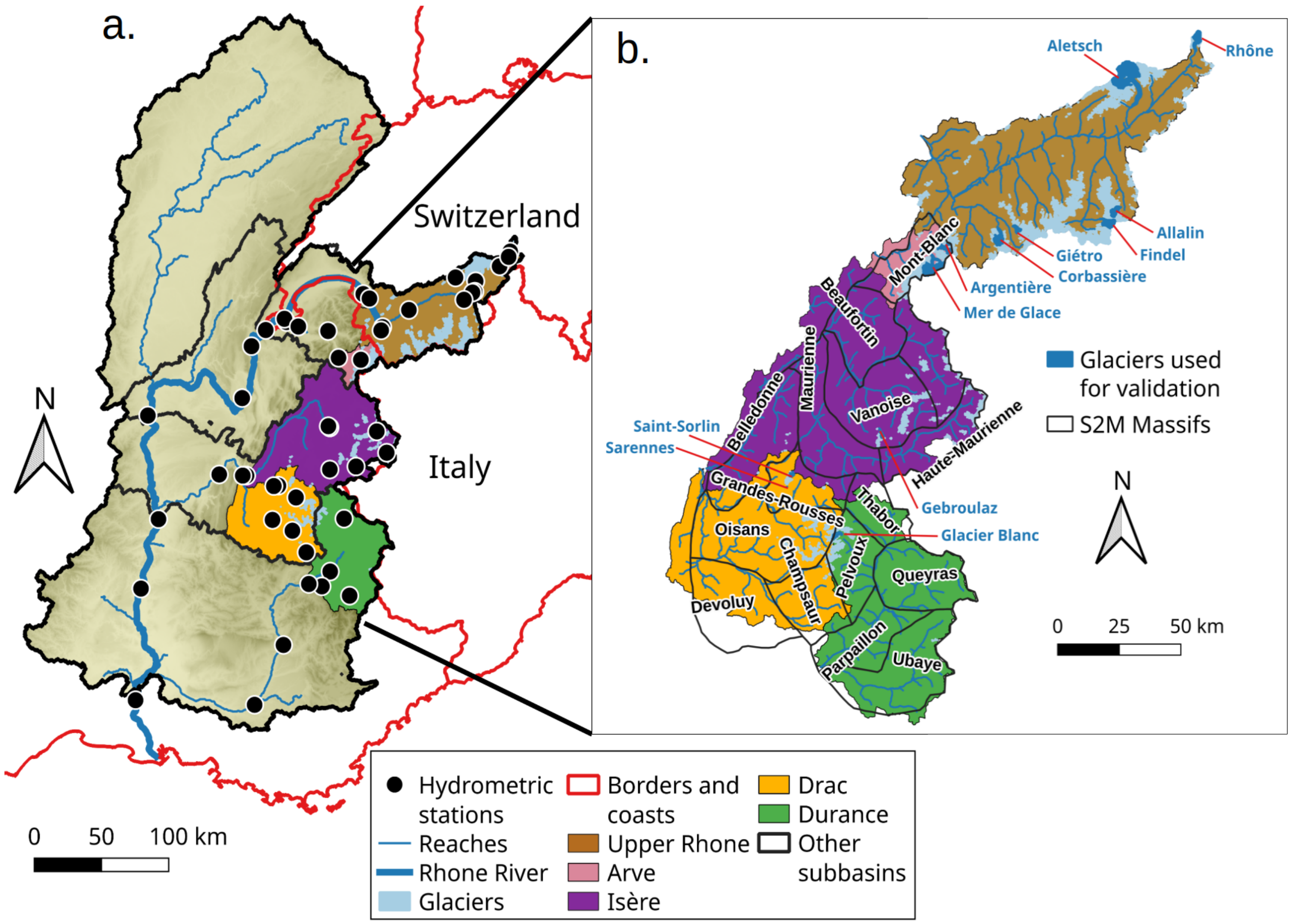

Figure 2: a. The Rhone river basin considered in this study, with subbasins used for calibration (colors) and hydrometric stations (black dots). b. Zoom on the studied glacierized subbasins (colored) featuring the massifs with available snow data from S2M reanalysis (black contours) and glaciers used for validation (dark blue)

2.2.1 Input data for the calibration of J2000-Rhône-glaciers

The J2000 model needs input of daily temperature, precipitation and reference evapotranspiration. For the purpose of the calibration we used the gridded reanalyses SAFRAN (Le Moigne et al., 2020) with a spatial resolution of 8x8km (Fig. S1) available in the period 1958-2022. The SAFRAN grid point closest to each HRU centroid was used as climate forcing for the HRU. SAFRAN also covers the upper Rhône in Switzerland but this data was built from an extrapolation of the closest point with similar elevation located in France (Le Moigne et al., 2020). This extrapolation constitutes an approximation that will be discussed in the part 4.2.1.

The evolution of glacier fraction for each HRU was estimated using observed glacier area inventories available for the 1970s, 2003, and 2015. For the 1970s, the surface area of glaciers located in Switzerland were defined in 1973 (Müller et al., 1977) while the French glaciers were delineated for the period 1967-1971 (Gardent et al., 2014). For 2003, the glaciated

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surface area was taken for the entire Rhône basin from the Randolph Glacier Inventory (Pfeffer et al., 2014). For 2015, the Alpine Glacier inventory was used (Paul et al., 2020). The glacier fraction was then calculated per HRU for each of these three dates (1970, 2003, and 2015) and the fraction of each HRU was then estimated per year in the period 1970-2015 using a linear interpolation between the three dates. To estimate the glacier fraction in the period 2015-2022, the linear regression between 2003 and 2015 was kept constant. We therefore obtained glacier surface for the period 1970-2022.

	Short name	Unit	J2000-Rhône-classic	J2000-Rhône-glaciers	Dataset used for calibration
Temperature threshold of rain/snow transition	*snow_trs*	°C	2	2	literature
Range around the temperature threshold of transition	*snow_trans*	°C	3	3	literature
Snowmelt factor	*t_factor*	mm/°C/days	1.84	2.5-4	literature and MOD10A2 (upper Rhône)
Cold content factorEnergy deficit of Snow	*ccf_factor*	-	0.0012	0.005	S2M and OSHD
Snow factor (>2800m)	*precip_mult*	-		1.5-2.5	OGGM
Snow factor (<2800m, Upper Rhône)	*precip_mult_low*	-		0.5	OSHD
icemelt factor	*ddfIce*	mm/°C/days		2.7-5	OGGM
Routing coefficient for ice	*kice*	-		10	literature
Routing coefficient for snow	*ksnow*	-		5	literature
Routing coefficient for rain	*krain*	-		5	literature
Threshold for icemelt	*Tbase*	°C		0	literature

Table 2: Calibrated parameters of snow and ice modules in J2000-Rhône-classic and J2000-Rhône-glaciers

2.2.2 Calibration of snow accumulation

The correct representation of winter snow accumulation is very important to accurately simulate the hydrological components in high mountain catchments. The accumulation on the glaciers is especially important because it determines the end of snow cover on ice and the onset of icemelt. Snowfall is known to be underestimated by most meteorological products in high elevation (be they derived from radar and/or in-situ rain-gauge observations, reanalysis, forecasts from numerical weather prediction systems or hybrids thereof ; e.g. Vernay et al., 2025 and Leroux et al., 2021). In addition, the snow

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accumulation underestimation is larger on glaciers because they receive a large amount of additional snow due to topography (local precipitation enhancement) and avalanches that redistribute snow on the glacier's accumulation areas (Vionnet et al., 2022). Therefore, we apply a factor enhancing snowfall (Snow factor) to HRUs with an average elevation higher than 2800 meters, which is approximately the average lowest elevation of glaciers in the Rhône catchment. To adjust this snow factor, the average snowfall on glaciers computed by J2000 in each subbasin (coloured in Fig. 2), was compared to the average snowfall from the Open Global Glacier Model (OGGM, Maussion et al., 2019) in the corresponding subbasin. OGGM calculates accumulation (snowfall) and ablation (snowmelt and icemelt) using a degree day method for all glaciers. The final value retained for the snow factor, that minimizes the difference between J2000 and OGGM snowfall, is 1.5 for the upper Rhône, 1.8 in the Arve catchment, 2.3 for the Isère and Durance subbasins, and 2.5 for the Drac subbasin.

The snowfall had also to be diminished in the upper Rhône, because the annual amount of snowfall was greatly overestimated, due to the extrapolation of the closest French SAFRAN grid point located in an area with a large amount of precipitation (the Mont-Blanc massif), while the upper Rhône is known for relatively low precipitation (MeteoSwiss, 2025). The snowfall was reduced in HRUs lower than 2800 meters (*precip_mult_low*) to reduce the average snowmelt simulated by J2000 in the period 2002-2022 at a level close to the longterm average observed snowmelt. This observed snowmelt was from the gridded data of snowpack water equivalent and snow melt runoff, with a spatial resolution of 1x1 km and daily temporal resolution (Mott, 2023). This data was produced with the Operational Snow-Hydrological model for Switzerland (OSHD), a conceptual temperature index based model. The snowpack water equivalent from all the grid points inside the upper Rhône subbasin were averaged. To calculate snowmelt, we then subtracted the snowpack water equivalent of a given day from the snowpack water equivalent of the previous day. The lowest long-term average difference between simulated and observed snowmelt was found with a value of *precip_mult_low* close to 0.5.

2.2.3 Calibration of Snowmelt

In J2000-Rhône-classic the snowmelt factor t_factor was estimated at 1.8mm/°C/days for the entire Rhône basin, which is low for snow degree day factors in this area (Réveillet et al., 2017). This factor was set low to create an over-accumulation of snow in high elevation that can melt every summer in an unlimited way, imitating glaciers. With J2000-Rhône-glaciers this parameter was increased to allow the snow to melt before the end of the summer season at least in non-glaciated areas. We used the values found in Gouttevin et al. (2017): 2.5 mm/°C/days in the Durance, Drac, and Isère subbasins and 3.5 mm/°C/days in the Arve subbasin. We also verified that these values create a snow cover in line with the 8-days maximum snow cover data from MOD10A2 (Moderate Resolution Imaging Spectroradiometer, Collection 6 ; Riggs et al., 2017). In this weekly product, a pixel (500 meters resolution) is considered as snow covered when snow is detected at least one day during the 8-days period. The number of grid cells covered by snow is then used to calculate a fraction of snow for each

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basin in an 8-days time step. For the upper Rhône basin, we visually compared seasonal J2000 simulations and MOD10A2 over the period 2002-2022 and found a t_factor value of 4 mm/°C/days.

The cold content factor of snow (*ccf_factor*) was also readjusted using the comparison of snowmelt simulated by J2000-Rhône-glaciers with OSHD in the upper Rhône and S2M reanalysis in the French subbasins. S2M reanalyses are a combined meteorological and snow reanalysis daily product covering the French mountains (Vernay et al., 2022) used here in the period 2002-2022. The meteorological part relies on the SAFRAN reanalysis system (Durand et al., 2009) and the snow is estimated using the Surfex/ISBA-Crocus snowpack model (Vionnet et al., 2019). This reanalysis is available for each French Alpine massif (Fig. 2b) and for different elevation bands of 300 meters. For each subbasin, we calculated a weighted average of the quantity of snowfall and snow water equivalent, depending on the surface occupied by each elevation band, in the massifs intersecting with each subbasin (Fig. 2b). After calibration the *ccf_factor* was set to 0.005.

2.2.4 Calibration of Icemelt

The ice melting factor (*ddfIce*) was then adjusted to match the average annual mass balance from J2000 with the average annual mass balance from OGGM. We found values of 2.7 in the Isère and Drac subbasins, 2.9 in the Durance, 3.7 in the Arve subbasin and 5 in the upper Rhône. The slightly higher melt factor for ice than snow is consistent with the literature (Réveillet et al., 2017).

2.4 Validation of J2000-Rhône-glaciers

2.4.3 Glacier surface mass balance

For validation purpose, the simulated mass balance from J2000 in the accumulation period (October to May) and the whole year was compared to the surface mass balance from 6 glaciers of the GLACIOCLIM observatory in the French part (Wagnon et al., 2011) and 6 glaciers from GLAMOS (Glacier Monitoring Switzerland) dataset in the Swiss part (Kurtzböck and Huss, 2021). The locations of the glaciers are depicted in Fig. 2b. The winter mass balance is a good proxy of winter snowfall on glaciers (melt process remaining low). For the French part, Argentière and Mer de Glace glaciers are located in the Arve basin, Gebroulaz is in the Isère basin; Saint Sorlin is also in the Isère basin but because of its closeness to the glaciers of the Drac basin it was analysed with the Sarennes glacier in the Drac basin; Glacier Blanc is located in the Durance basin. For the upper Rhône catchment, the 6 glaciers analyzed are : the Rhône, Aletsch, Findel, Allalin, Corbassiere, and Giétro glaciers.

2.4.4 Streamflow

The 48 hydrometric stations used in this study for validation are the stations located in the Rhône basins, with a glacier contribution in the historical periods and no missing data in the period 2004-2015 for the French part (SC Vigicrues -

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HydroPortail, 2025) and 2003-2012 for the Swiss part (Höge et al., 2025). These periods were chosen because they correspond to the largest numbers of complete hydrometric records. These hydrometric stations are referenced in Table S1 and their locations can be seen on Fig. 2a. J2000-Rhône-glaciers used in this study simulates the behavior of natural streams, while most rivers are in reality heavily influenced by dams and diversions. It is therefore challenging to calibrate the model with streamflow observations. Nineteen stations can be considered as nearly natural and are included as reference stations in the reference observatory of basins for international hydrological climate change detection (ROBIN, Turner et al., 2025) and in the Global Runoff Data Center (GRDC, 2026) datasets (Table S1). These stations can be studied with more confidence when comparing observed and simulated natural streamflow.

2.5 Future climate and glaciated data

The set of J2000 parameters estimated during calibration (Table 2) was used to simulate the evolution of snowfall, rainfall, snowmelt, icemelt, reference evapotranspiration, and streamflow in the entire Rhône basin using SAFRAN reanalysis in the period 1970-2022 and 5 “GCM-RCM” chains of climate simulations (Table S2) in the period 1970-2095. The years 1970-1975 were used as the initialization period and are not used in the analysis. For the climate simulations period (1976-2095), we used daily temperature, precipitation and reference evapotranspiration from five Global-Regional climate models couples (GCM-RCM) forced with the Representative Carbon Pathway 8.5 (RCP8.5) retrieved from EURO-CORDEX (Vautard et al., 2021) with a resolution of 12km (Fig. S1) . RCP 8.5 corresponds to a very high baseline emission scenario widely used in previous works. These five couples have been previously bias-corrected against the closest SAFRAN grid point using the Adamont method (Verfaillie et al., 2017) and used in the Explore2 French research program (Sauquet et al., 2026).

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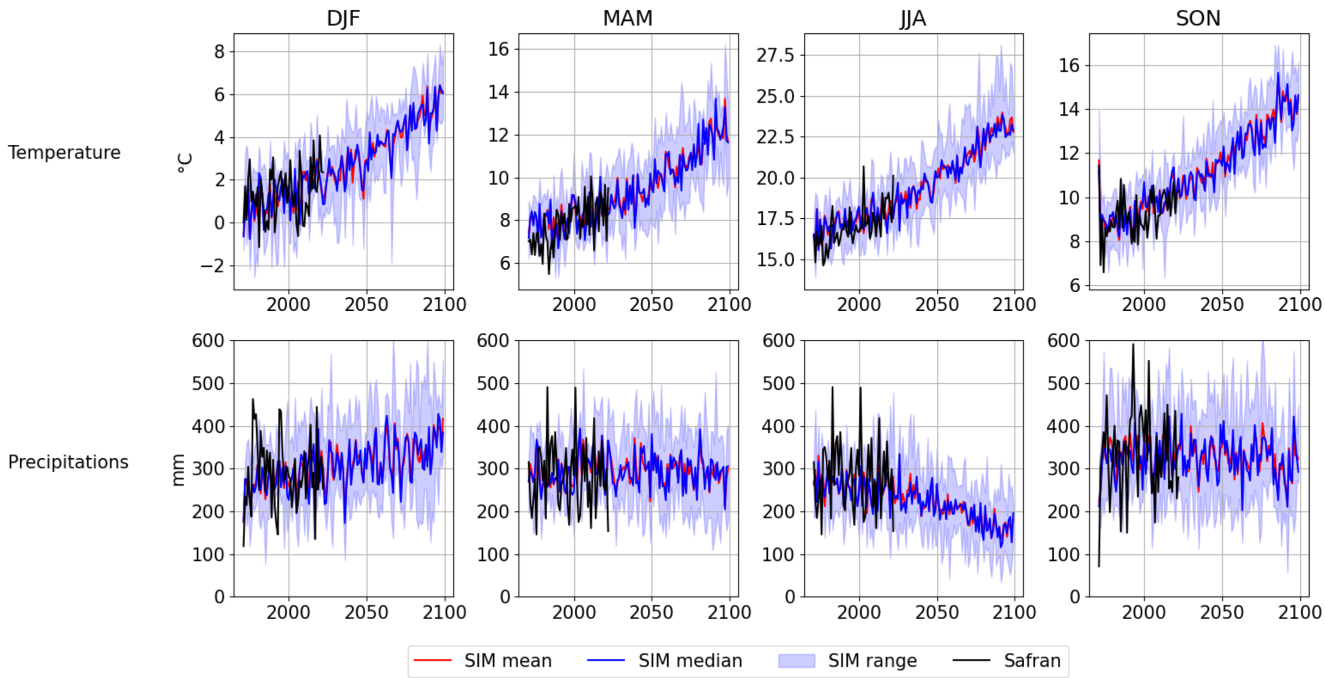

Figure 3: Evolution of seasonal (DJF= Winter, MAM = Spring, JJA= Summer, SON=Fall) temperature and precipitation simulated (SIM) from the 5 GCM-RCM model couples (with average in red, median in blue line and range as the blue shades) and from SAFRAN (black), averaged for all HRUs in the Rhône basin.

In the historical period, precipitation and temperature from the 5 projections are close to the SAFRAN reanalysis (Fig. 3), with the average and the interannual variability well reproduced by the projections in all seasons. In these RCP8.5 simulations, the temperature is expected to increase by 5°C in all seasons by the end of the 21st century. The evolution of precipitation shows a decrease in summer, a slight increase in winter and no change in fall and spring (Fig. 3).

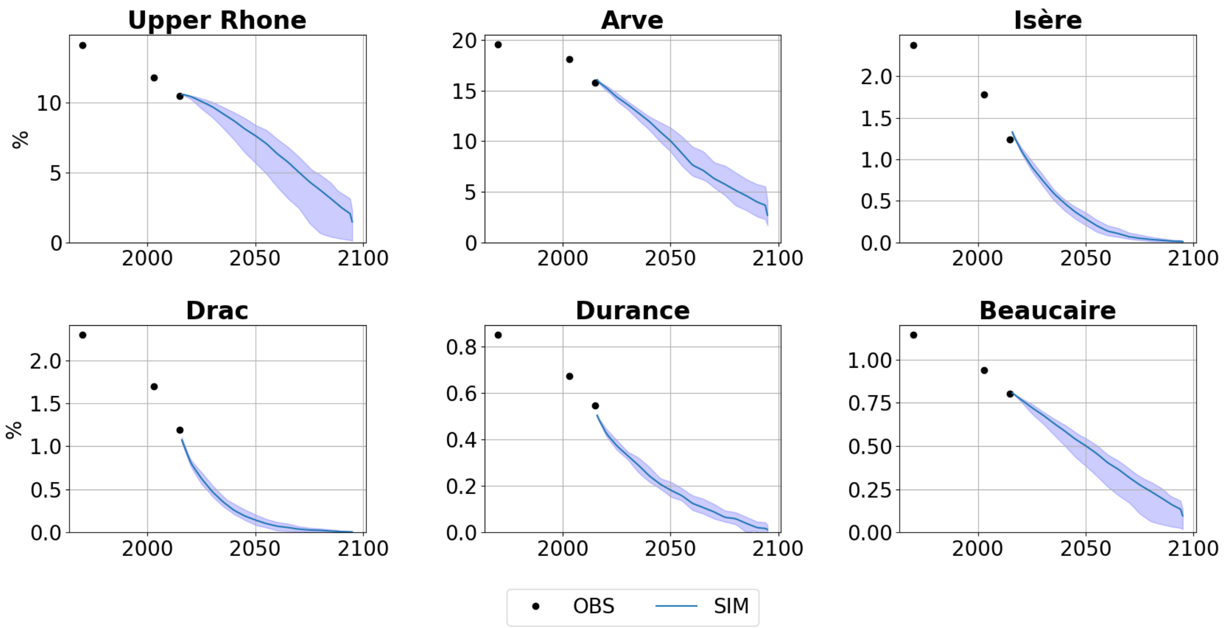

Figure 4: Observed (OBS, black dots in 1970, 2003, and 2015) and simulated glacier fraction (SIM, blue lines between 2015-2095), using 5 climate simulations under RCP 8.5 scenario (spread with shaded area) within the 5 studied glacierized subbasins and the entire basin at Beaucaire (Table 1)

The glaciated areas for the current period without observations and the future (2016-2095) were taken from the glacier evolution model ALPGM (Bolibar et al., 2022) for the French part and from the GloGEMflow coupled ice flow and surface mass balance model for the Swiss part (Zekollari et al., 2019). Both datasets were built using the temperature and precipitation from the EURO-CORDEX dataset. The glacier surface areas from the 5 simulations were selected and used to calculate the fraction of glaciers in each HRU with a 5 years time step. The fraction of each HRU was then estimated per year in the period 2015-2095 using a linear interpolation between each 5 year period. The observed and simulated glacier fractions in the 5 main glacierized subbasins and the entire Rhône catchment at Beaucaire are shown on Fig. 4. For the hydrological projections, the glacier surface was merged between the observed glacier fraction in the period 1970-2015 and the projected glacier fraction in the period 2016-2095.

2.6 Statistical analysis

The change in trends of the variables simulated by J2000-Rhône-glaciers were statistically tested with the non parametric Mann-Kendall statistical test (Mann, 1945) and the eventual shift was tested using the Pettitt's test for change point detection (Pettitt, 1979). The results of all tests were considered as significant when reaching the 95% confidence level. The coefficient of variation between projections of simulated streamflow, icemelt, and contribution of icemelt to streamflow over 1976-2005 and 2066-2095 were also calculated. The coefficient of variation was calculated as the ratio of the standard

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deviation to the mean of the given variable. A high value indicates that the spread between models is large compared to the average of all 5 models.

3. Results

3.1 Evaluation of J2000-Rhône-glaciers

3.1.1 Snow processes

In these sections, different cryo-hydrological processes simulated by J2000 are evaluated against observations. Fig.5 shows the yearly and seasonal snowmelt as well as the seasonal snow cover from J2000-Rhône-glaciers and J2000-Rhône-classic compared to the observed snowmelt from S2M/OSHD and the observed snowcover from MOD10A2. The figure shows that in comparison to snow cover from satellites, the snow cover from J2000-Rhône-glaciers is in better agreement compared to J2000-Rhône-classic. Note that MOD10A2 data were used for calibration of J2000-Rhone-glaciers only over the Upper Rhone, where a better agreement with these data is henceforth expected. The snowmelt is slightly higher in J2000-Rhône-glaciers compared to J2000-Rhône-classic in the French subbasins, likely because of a higher *t_factor*. In the upper-Rhône the value of snowmelt is lower and closer to the observations, because the amount of snowfall, and hence the corresponding snowmelt, has been divided by 2 under 2800m elevation by the parameter *precip_mult_low*. A similar feature observed in all subbasins is an underestimation of snowmelt in summer and an overestimation in winter, likely due to the meteorological observations having very large grids that tends to overestimate temperature in high elevation. Therefore snow tends to melt too quickly in winter and does not remain in the spring.

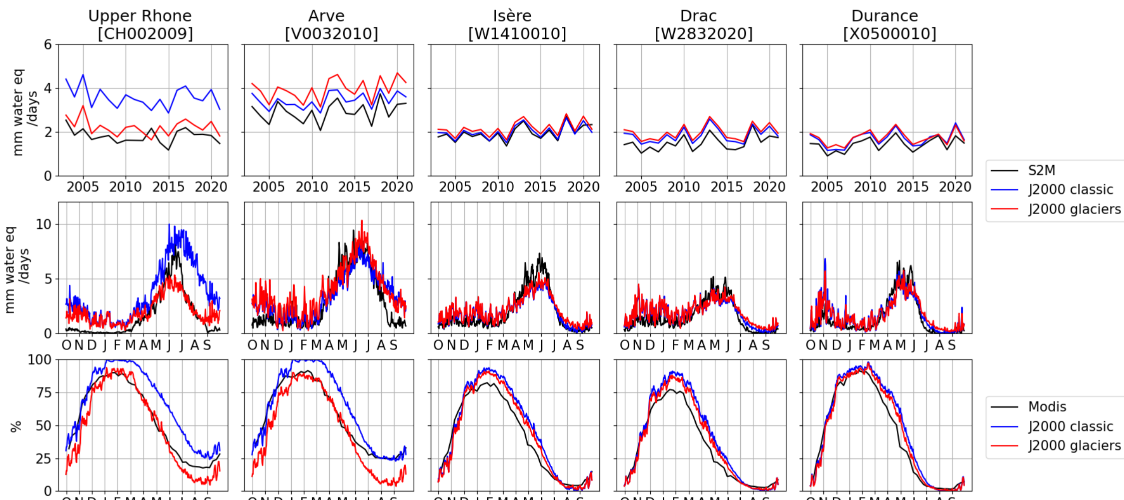

Figure 5: Yearly (first row) and interannual daily (second row) average of snowmelt from S2M/OSHD and J2000, and snow cover (third row) from MOD10A2 and J2000 for the period 2002-2022

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3.1.2 Glacier surface mass balance

The annual snowfall simulated by J2000-Rhone-glacier and by OGGM is shown for all subbasins (Fig. 6). The good visual match between both products is merely a confirmation of the consistency of the calibration of precip-mult against OGGM data. The R^2 coefficient between J2000 and OGGM is relatively good with the exception of the Isère and Durance subbasins. The annual mass balance simulated by J2000 was also compared to the mass balance simulated by OGGM. The results also show lower R^2 coefficient in Isère subbasin.

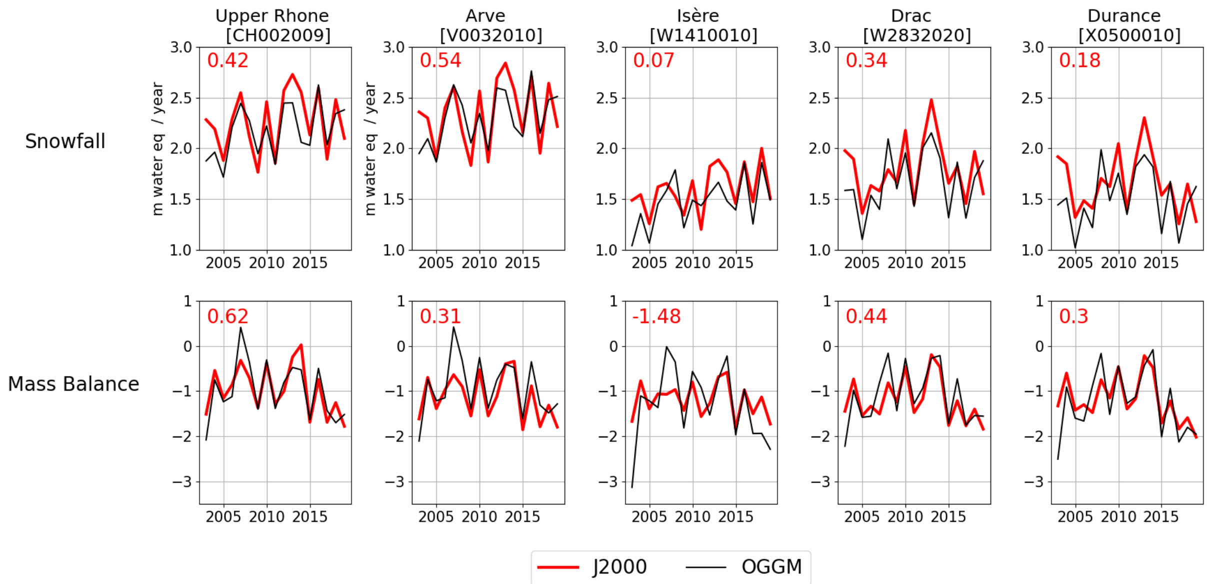

Figure 6: annual snowfall (upper panels) and annual surface mass balance (lower panels) averaged for all glacier surface of each subbasin with J2000 glaciers (red lines) and OGGM (black lines). The number show the R^2 coefficient between the two annual products.

For validation purposes, our results from J2000 at each subbasins were also compared to glacier measurements (Fig. 7). The winter mass balance computed by J2000 remains a little bit low compared to observations on glaciers in all subbasins. This result can be associated with the snowmelt that seems overestimated in J2000 in winter (Fig. 5). The results averaged for the entire year seem closer between J2000 and the observations with the exception of Saint Sorlin and Sarennes where J2000 simulates a higher mass-balance. However, observations from these two glaciers seem to be lower compared to all other glaciers in the Rhone River basin, so these specific glaciers may not be representative of all the glaciers located in the Drac subbasin. These glaciers are far from the glaciers from the Oisans massif while the glacier Blanc may be more representative of this massif.

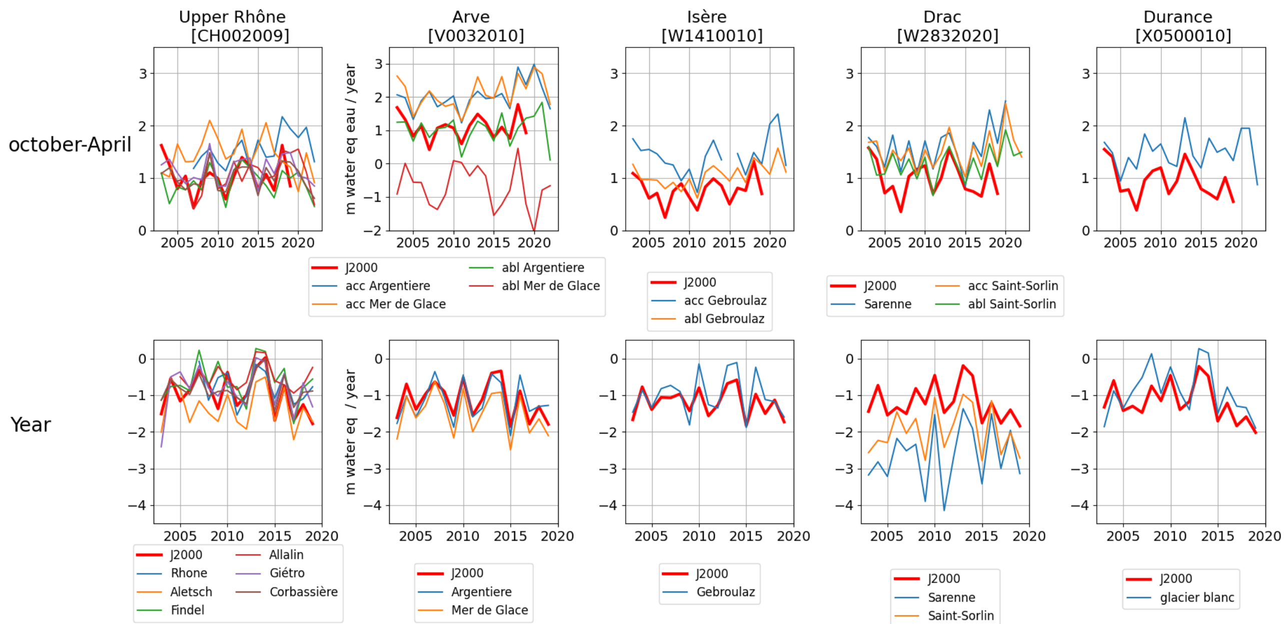

Figure 7: winter surface mass balance (upper panels) and annual surface mass balance (lower panels) from different glaciers, averaged for each subbasin with J2000 (red lines). acc = accumulation zone, abl =ablation zone, otherwise = entire glacier

3.1.3 Streamflow

To validate the ability of the new calibrated J2000-Rhône-glaciers model to simulate streamflow, the simulated streamflow is compared to the stream gauges observations for the period 2005-2014 for the French subbasins, and 2002-2013 in the upper Rhône. The Kling-Gupta efficiency (KGE) for J2000-Rhône-glaciers is satisfactory (KGE > 0.5) in most tested French basins (Fig. 8a) and is improved in 21 subbasins compared to J2000 Rhône-classic (Fig. 8b). The KGE is greatly degraded for some gauging stations such as Arve at Chamonix and Arc at Bramans. However, these results need to be taken with caution, as in these two basins part of the runoff is transferred to another subbasin. This transfer is not considered in J2000-Rhône. Therefore, the measured streamflow is lower than the natural streamflow and the simulations are more likely to be overestimated. For the stations located in the upper Rhône, only 2 subbasins out of 13 show an improved KGE, also likely because in many of the rivers, summer melt water is kept in reservoirs (dams) while water abstractions are not represented in J2000. Some stations are still degraded while they are considered as nearly natural (Fig. 8b). However, none of the stations with a KGE lower than 0 (Fig. 8a) are part of the ROBIN or GRDC network. Along the Rhône river, the glacier module slightly worsens the streamflow but the KGE remains higher than 0.75 in the lower Rhône (Fig. 8a).

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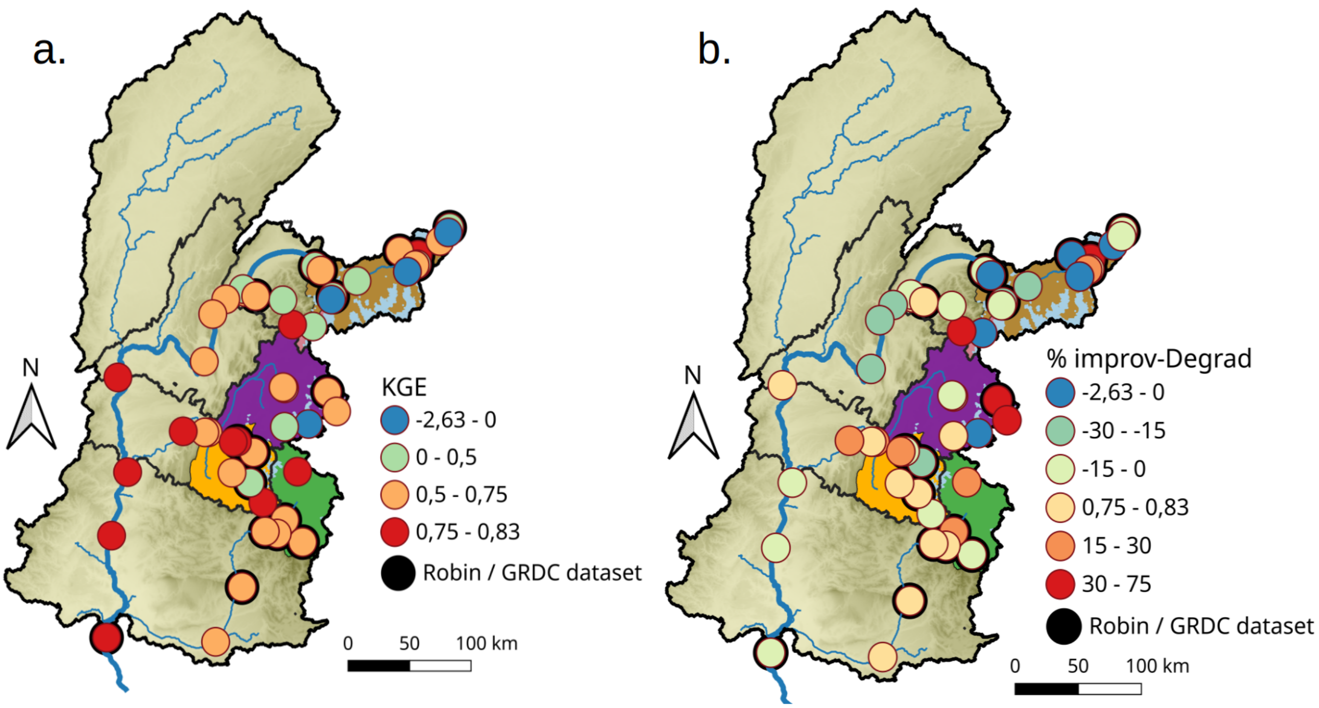

Figure 8: a) Kling-Gupta efficiency (KGE) between observations and J2000-Rhône-glaciers, and b) change of KGE between J2000-Rhône-classic and J2000-Rhône-glaciers with respect to the maximum possible improvement of KGE (1 minus J2000-Rhône-classic KGE), in the period 2006-2014 for the French subbasins and 2004-2012 for the Swiss subbasins

At the scale of the four main French sub-basins (Arve, Isère, Drac, and Durance), J2000-Rhône-glaciers shows a better KGE and a reduced negative bias (Table 3), partly associated with a higher snowmelt compared to J2000-Rhône-classic (Fig. 5). Visually, the improvement appears mostly at the beginning of the melt period where streamflow was largely underestimated in J2000-Rhône-classic (Fig. 9), but the underestimation remains. This underestimation may be associated with the overestimation of snowmelt in winter, associated with an overestimation of temperature, with therefore not enough snow to be melted at the beginning of the spring season (Fig. 5). Later in the season, when ice is melting, the streamflow is increased and becomes closer to the observations. In the upper Rhône, the spring streamflow appears later in J2000-Rhône-glaciers compared to J2000-Rhône-classic, likely because the snowfall was reduced in low elevation to match the snow observations, so the snowmelt has a better timing in the J2000-Rhône-glaciers (Fig. 5). The timing of streamflow in J2000-Rhône-glaciers is worse compared to J2000-Rhône-classic, but the spring underestimation is also shown in the other subbasins and was explained above. It is likely that in the Upper Rhône the timing of streamflow was better in J2000-Rhône-classic for the wrong reasons. In summer the overestimation persists in J2000-Rhône-glaciers and may be associated with anthropic influence, as the observed streamflow shown in Fig. 8 is lower in summer, and higher in winter compared to the natural streamflow (Meile et al., 2011).

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Table 3: Efficiency criterias for J2000-Rhône-classic and J2000-Rhône-glaciers in the periods 2004-2015 from French subbasins, and 2003-2012 for the Rhône at porte du Scex

	Upper Rhône at porte de Scex **[CH002009]**	Arve at Arthaz **[V0222010]**	Isère at Grenoble **[W1410010]**	Drac at Fontaine **[W2832020]**	Durance at Espinasses **[X0500010]**	Rhône at Beaucaire **[V7200010]**
Pbias (J2000-Rhône-classic)	12	-9	-24	-19	-29	3
Pbias (J2000-Rhône-glaciers)	13	5	-15	-9	-23	5
KGE (J2000-Rhône-classic)	0.44	0.67	0.66	0.62	0.47	0.83
KGE (J2000-Rhône-glaciers)	0.40	0.71	0.73	0.65	0.52	0.82

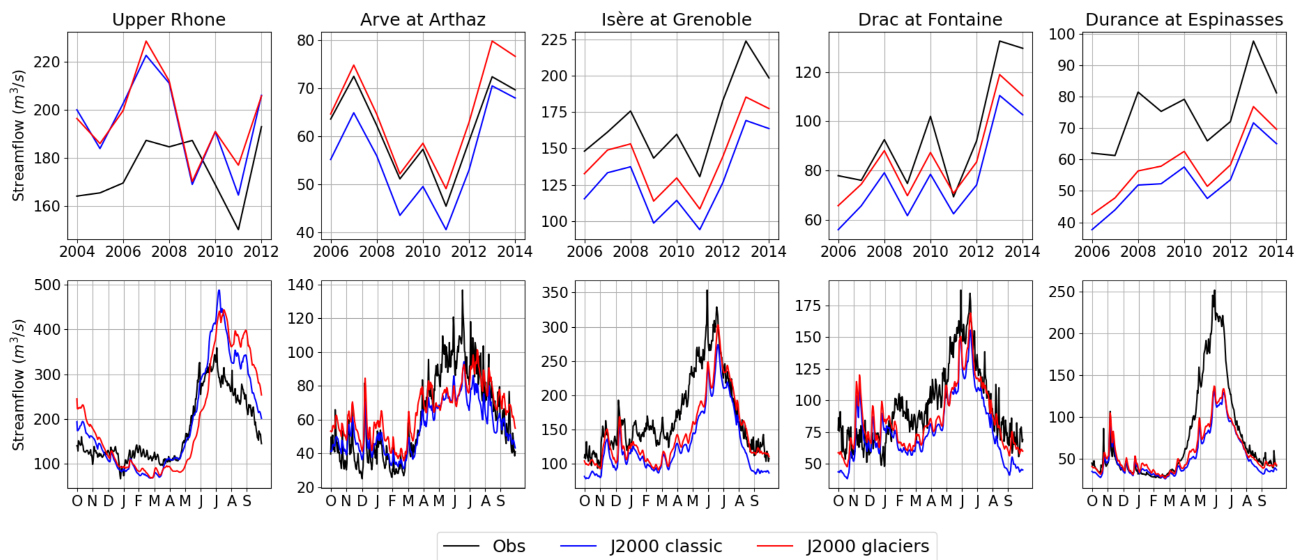

Figure 9: annual (first row) and seasonal (second row) streamflow for the observations, the simulations with J2000-Rhône-classic (blue) and simulations with J2000-Rhône-glaciers (red) in 2006-2014 for the French basins and 2004-2012 for the Upper Rhône at Porte du Scex

Even though the timing is improved and the streamflow is higher, there is still an underestimation of annual streamflow in the Isère, Drac, and Durance subbasins (Fig. 9). The underestimation remains very large in the Durance basin probably due to an underestimation of precipitation in SAFRAN as suggested in Magand (2014). These results of the seasonal streamflow on a short period are representative of the period 1976-2022 (Fig. S2).

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3.2 Icemelt contribution under past-present climate

Over the period 1976-2022 the yearly contribution of icemelt to streamflow generally increased (Fig. 10) and was significant in the highly glaciated subbasins of the upper Rhône, in all the Durance subbasin and along the Rhône down from the upper Rhône outlet. Some stations show a significant decrease of the icemelt contribution, suggesting that the peak water was passed. These stations are located mostly in the southern part of the Drac subbasin. In August, the month with the highest icemelt contribution, the contribution is also increasing in most areas but this trend is not significant along the Rhône River. The change of icemelt contribution remains significantly positive in most highly glaciated subbasins and in the Durance subbasin and significantly negative in the south part of the Drac subbasin.

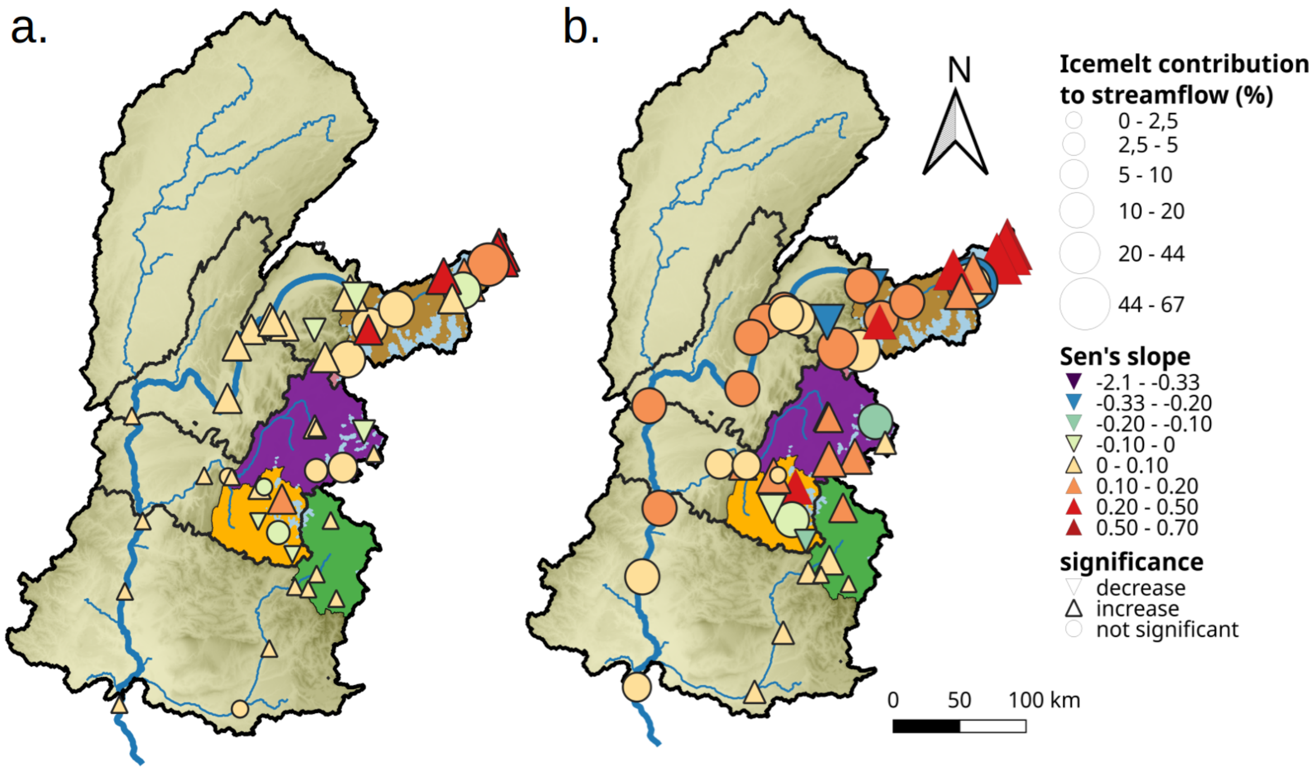

Figure 10: Contribution of icemelt to streamflow (size) in 1976-2022, sen's slope of the change (colours) and 95% level of significance (triangles) for the entire year (a) and August (b)

Figure 11, showing the evolution of yearly and summer-fall month icemelt contribution from 1976 to 2022 in the main subbasins, confirms the results of an overall increase, but not always significant. The icemelt contribution increased significantly only yearly in the Arve subbasin, yearly and in September in the upper Rhône, in July and September for the Isère and from July to September in the Drac and Durance (Fig. 11). The significant increase of icemelt contribution is transferred to the lower Rhône (Fig. S3). Interestingly, the test for change point detection shows a shift in icemelt

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contribution in 2003 that is significant in the upper Rhône and the Drac subbasins. This shift in 2003 is consistent with an acceleration of glacier retreat (Fig. 4).

Fig. 11 also shows a large seasonal and interannual variation of icemelt contribution. The maximal monthly icemelt contribution is reached in August or September with values as high as 21 % in the upper Rhône, 18 % in the Arve, 9 % in the Drac, 8 % in the Isère and 4 % in the Durance. In some years the icemelt contribution in August was as high as 40 % in the upper Rhône and the Arve subbasins, as in 2022, a year of very low snowpack and hydrological drought (Gascoin et al., 2024). The maximum value for the upper Rhône was reached in August 1976 (42 %), a very dry year, while in Isère and Drac a maximum of 22 % was reached in August 2003, another extremely dry and warm summer. Along the Rhône (Fig. S3) the average August icemelt contribution reaches 18% down from the confluence upper-Rhône-Arve (Rhône at Pougny), 13 % between the Saône and south of the Isère confluence (Rhône at Ternay and Rhône at Valence), and still 10 % close to the Mediterranean sea (Rhône at Beaucaire). The contribution in August 2022 overtook August 2003 all along the Rhône and reached respectively 26 and 23 % at the outlet (Fig. 11).

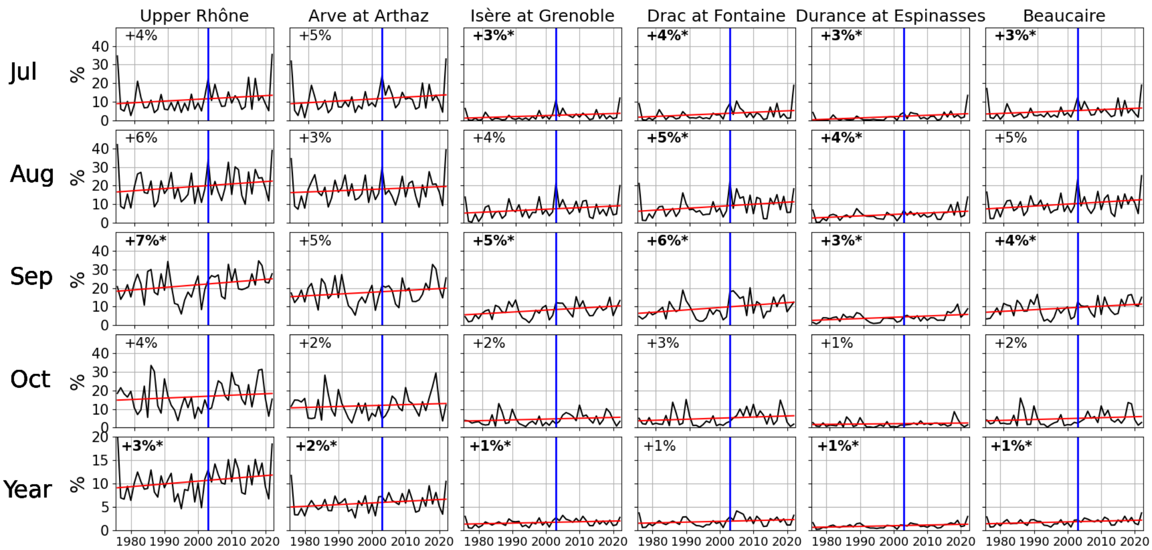

Figure 11: yearly Contribution (black) and linear regression (red) of icemelt to total streamflow in summer months and the entire year in the period 1976-2022. The vertical blue line is the year 2003. The numbers represent the evolution of the linear regression from the first to the last year that is significant when bolded with a star.

3.3 Projections of streamflow and icemelt contributions

Over the historical period (1976-2005), streamflow simulated by J2000-Rhône-glaciers using the climate runs satisfactorily represent the streamflow simulated using the SAFRAN reanalysis dataset (Fig. S4). Simulated icemelt using the climate runs is also satisfactory in the historical period (Fig. S4). These results give confidence in using the climate projections, with the

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same GCM-RCM combinations as for the past runs, to assess the future evolution of the hydrology in the Rhône basin. Our results show that the annual streamflow is projected to decrease in all studied subbasins by the end of the 21st (Fig. 12). The decreasing trend reaches 5 % in the upper Rhône on average with the 5 climate models but with a standard deviation higher than the average trend (±14 %) due to a high spread between models (Table S3). The decrease of streamflow is larger in the other subbasins, reaching 18 % (± 21 %) in the Drac, 19 % (± 15 %) in the Arve , 20% (± 19 %) in the Isère and 24% (± 18 %) in the Durance. The results of the change point detection test show a shift earlier in the south and later in the north of the Rhône River basin: 2042 in the Durance (± 13 yrs) and Drac (± 12 yrs), 2043 (± 11 yrs) in the Isère, 2048 in the Arve (± 8 yrs) and 2051 in the upper Rhône (± 11 yrs). The average decrease of streamflow is transferred downstream from the confluence with the Arve river (Rhône at Pougny) but disappeared from the confluence with the Saône River (Fig. S5) likely associated with an increase of annual precipitation expected in the Saône river basin (Sauquet et al., 2026).

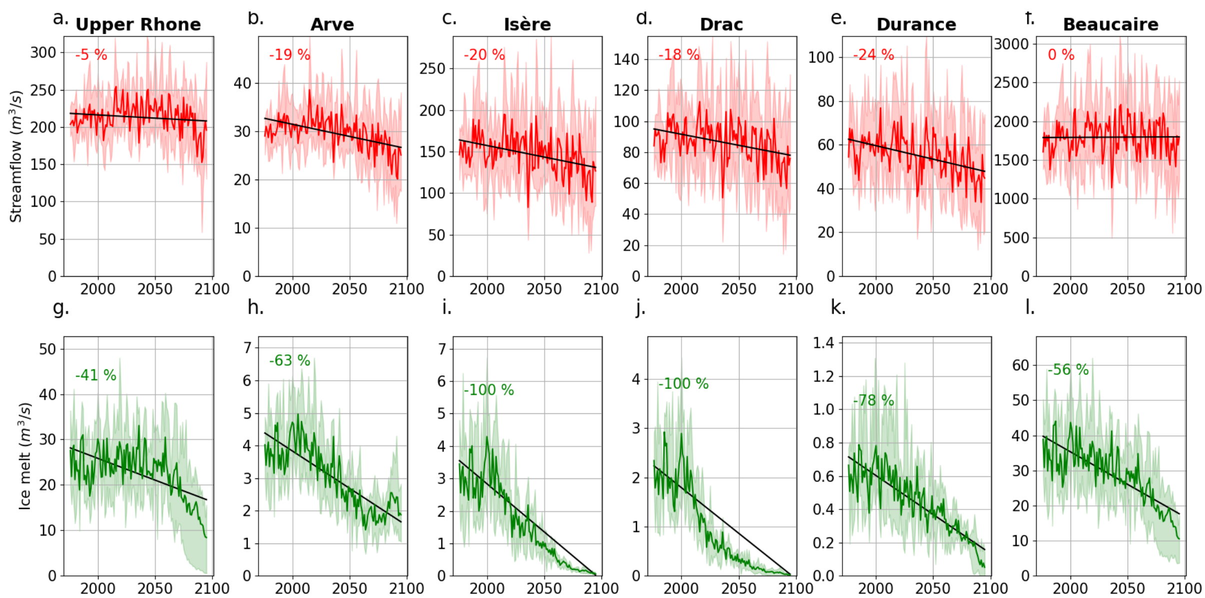

Figure 12: evolution of mean (lines) and range (shades) of (a-f) annual streamflow and (g-l) annual icemelt simulated by J2000-Rhône-glaciers using 5 climate chains under RCP 8.5 scenario.

The average icemelt decrease is expected to reach 41 % in the upper Rhône, with a large uncertainty (± 34 %), but still significant in most climate projections (Table S4). In the other subbasins the decrease reaches 63% (± 11 %) in the Arve, 78 % in the Durance (± 3 %) and 100% in the Isère and Drac subbasins. The peak water is expected to pass earlier in the southern subbasin with an average in 2014 (± 13 yrs) in the Durance subbasin (non significant), 2023 (± 2 yrs) in the Drac, 2037 (± 9 yrs) in the Isère, 2040 (± 5 yrs) in the Arve and 2053 (± 12 yrs) in the Upper Rhône. The decrease of icemelt from Isère and Durance rivers are transferred downstream along the Rhône river reaching -50% (±18%) at Beaucaire, contributing to attenuate the increase of annual streamflow south of the Rhône at Valence (Fig. S5).

Seasonally, the results from the 5 glacierized subbasins show a shift of the hydrological regimes to rain-influenced behaviors with an increase of winter streamflow but a dramatic decrease of summer streamflow (Fig. 13). The winter streamflow is

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approximately 25 % of the summer streamflow in the Arve and upper Rhône subbasins in the historical period. This number increases up to 50 % by the end of the century. The same behaviour is transferred downstream from the confluence Rhône-Arve at Rhône at Pougny (Fig. S6). In the Isère and Drac subbasins, the nival hydrological regime will clearly become pluvial with a yearly peak that may happen in the middle of the winter (Fig. 13). This change will contribute to enhance the pluvial regime in the Rhône River downstream from the Saône (Fig. S6).

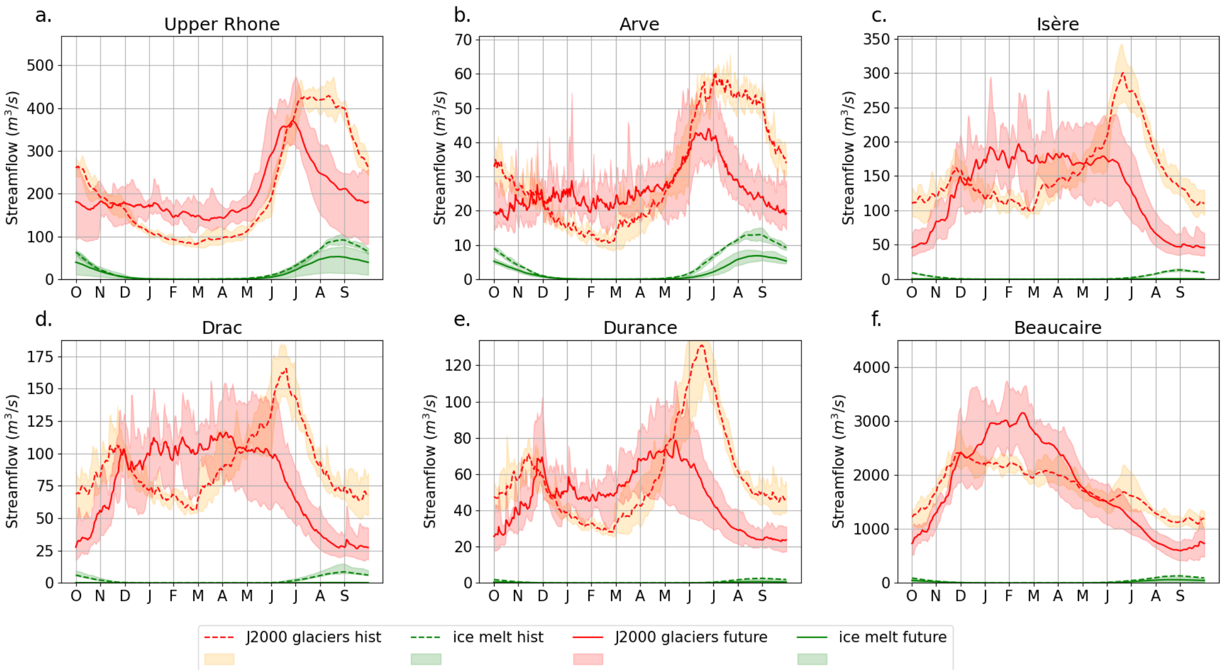

Figure 13: mean (lines) and range (shades) of seasonal streamflow (red) and icemelt (green) for the period 1976-2005 (dashed lines) and the period 2066-2095 (solid lines).

To understand what drives the change of streamflox, the contribution of precipitation, snowmelt, icemelt and evapotranspiration changes to the total change of these three four between (1976-2005) and the future period (2066-2095) was calculated. The results suggest that the decrease of annual streamflow is mainly driven by a decrease of precipitation, but icemelt contributes 30 % to the overall decrease in the Arve catchment, 25 % in the upper Rhône, 13 % in the Drac, 12 % in Isère and 3% in Durance. An increase of actual evapotranspiration is projected for the upper Rhône and the Arve subbasins and is contributing respectively 20 and 34 % to the overall streamflow decrease. In the Isère the evapotranspiration contributes only 5 % and is expected to decrease in the Drac and Durance. This decrease of evapotranspiration despite the warming may be due to a lack of water due to the summer decrease of snowmelt, icemelt and precipitation that limits the actual evaporation despite a higher potential evapotranspiration.

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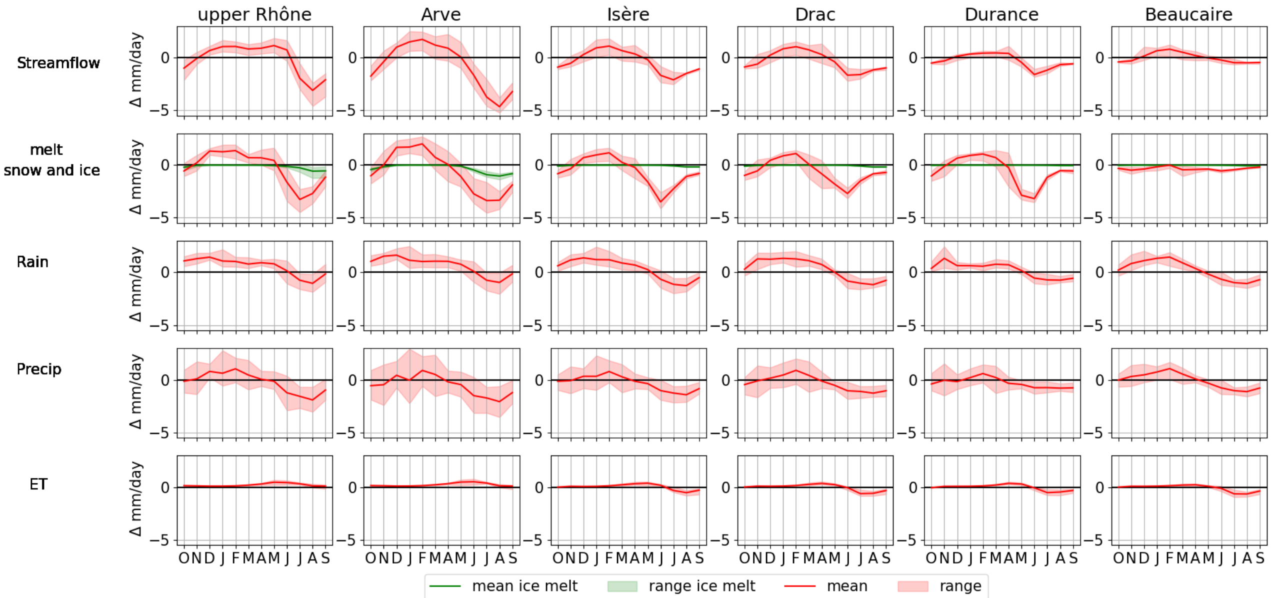

Figure 14: 5-models average (lines) and range (shades) of the change of streamflow and driving processes between the future (2066-2095) and the historical periods (1976-2005). (ET = actual evapotranspiration)

Seasonally, Fig. 14 suggests that the increase of winter streamflow is mainly associated with an increase of snowmelt and rainfall (including precipitation that formerly fell as snow and now reaches the ground as rain). The larger snowmelt is a dominant process in the upper Rhône, Arve and Durance catchments while the increase of rainfall is the driving mechanism in Isère-Drac (Fig. 14). These results are likely due to the large snowfall remaining in the high elevation upper Rhône and Arve, while further south and at lower elevation the warmer average temperature allows a large increase in rainfall. In the Durance subbasin, the increase of precipitation remains low, so that the increase in rainfall is mostly due to a shift from snowfall to rainfall.

The change of streamflow, icemelt and icemelt contribution to streamflow between 1976-2005 and 2066-2095 was also shown for the 48 stations in the summer months (July to september) (Fig. 15). The results confirm a large decrease in summer streamflow in all stations. Interestingly, the decrease of streamflow is very variable between stations in the upper Rhône with some stations showing a 60% decrease of streamflow in summer and the lowest decrease reaching -4% (±29%). The coefficient of variation between models is also larger in the upper Rhône (Fig. 15a). Regarding icemelt, a very large and consistent decrease between models is expected in all the French Alps (Fig. 15b) with a decrease of 100% in almost all subbasins but lower in Durance (-70% ±9%) and in the Arve at Sallanches (-45% ±9%). In the upper Rhône, some subbasins with low glacier cover in the current period also show a decrease close to 100%. The stations upstream from Rhône at Oberwald show a decrease close to 70% with a variability between models close to 20%. A low decrease is shown on

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average in the highly glaciated subbasins, and Massa at Blaten bei Naters even show an average increase of 45%, but with a very large variability (±58%). This lower icemelt decrease and the large variability has an impact downstream even though the evolution is clearly negative on average in the Upper Rhône at Porte du Scex (-39% ±28%), and downstream along the Rhône River.

In the Isère, Drac and Durance subbasins the decreasing of icemelt is larger than the decreasing of streamflow resulting in a decreasing in icemelt contribution, with high confidence between models. The Arve subbasin is interesting with a decrease of icemelt contribution at Chamonix (-11 percentage point ±9.5) but an increase at Sallanches (+1.9 pp ±7.5), even though the variability between models is very large. Contrasting results are shown in the upper Rhône with a decrease upstream from Rhône at Oberwald and an increase in Massa at Blatten (+10.5 pp ±6), Lonza at Blatten (+9.5 pp ±13), Vispa at Visp (+1.5 pp ±8) and Drance at Martigny (0.7 pp ±2). In these stations the decrease of streamflow is stronger than the change of icemelt, and this is transferred downstream.

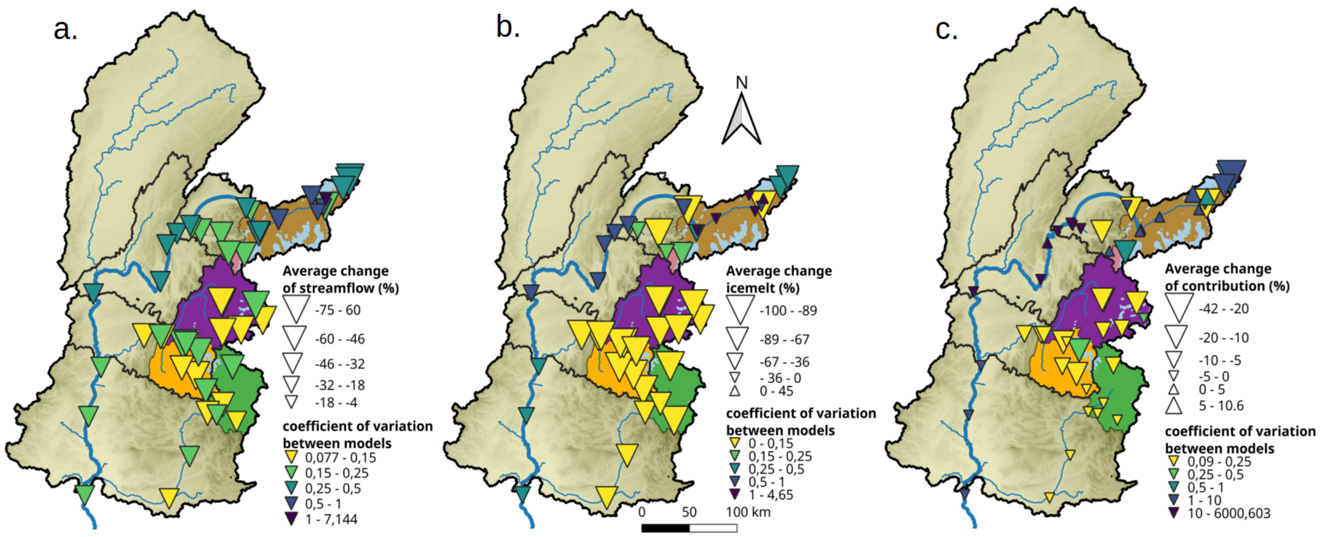

Figure 15: change of streamflow (a), icemelt (b) and icemelt contribution to streamflow (c) between the historical (1976-2005) and the future period (2066-2095) in July to September (JAS)

4. Discussion

4.1 Benefits of using J2000-Rhône-glaciers

In this work, a significant change of the hydrological regime of the Rhone river and its sub-bassins is projected by the end of the 21st century under the RCP 8.5 scenario, with an increase of winter streamflow and a very large decrease of summer streamflow. These results were shown in a large number of previous studies using hydrological modeling in the Alps (Confortola et al., 2013; Dayon et al., 2018; Fatichi et al., 2014; Hanus et al., 2021, 2024; Hanzer et al., 2018; Laurent et al.,

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2020; Milano et al., 2015; Muelchi et al., 2021; Sauquet et al., 2026). A previous study in the entire Rhône basin has shown a glacier melt contribution (rain on ice, snow melt and icemelt) close to 6 % annually in the 1990-2019 period (Hanus et al., 2024), in line with what we found for the 1976-2022 period (5.5 %). In August the contribution was higher (35 %) compared to our study (26.5 %). By the end of the 21st century the glacier contribution in August is projected to decrease dramatically in Hanus et al. (2024) reaching only 10% while our study points towards an end-of-century value remaining high (19.5 % ± 7 %) despite only considering climate projections with the most extreme RCP. These results are very encouraging because the method of Hanus (2024) on a global scale differs greatly from our method, making a direct comparison between contributions challenging (Weiler et al., 2018). In the Arve catchment we found that the annual glacier contribution to streamflow changes from 38% in the historical period to 21 % (± 2.5 %) at the end of the century under the RCP8.5 scenario, lower than a previous study (Laurent et al., 2020).

The added value of using J2000-Rhône-glaciers rather than hydrological models without glacier evolution (Sauquet et al 2025) is not straightforward when looking at general model performance metrics only (Fig. 8). However, contrary to most models used for example in the same subbasins in Explore 2 (Sauquet et al., 2026), our study shows specifically the respective contribution of icemelt, snowmelt and rainfall to the change of the overall streamflow in a very large number of subbasins in the Rhône basin. The share of icemelt and snowmelt has been validated in the observation period using reference snow data from reanalyses and observations, and mass balance estimations from the glacier model OGGM and from observations. The icemelt is generally decreasing, corroborating what was previously found in the Alps including the upper Rhône (Fatichi et al., 2014; Freudiger et al., 2021; Hanus et al., 2021; Muelchi et al., 2021). However, we found a large uncertainty between models in the upper Rhône subbasin and downstream along the Rhône river (Fig. 15). In the Massa at Blatten subbasin the uncertainty is very large, which was previously found (Fatichi et al., 2014) and the icemelt is even increasing which corroborates a previous study on a subbasin containing the Aletsch glacier (Freudiger et al., 2021).

The change in summer icemelt contribution is not very clear in basins with high amounts of ice remaining at the end of the 21st century, possibly because streamflow is also significantly decreasing due to a large decrease in summer precipitation (Fig. 14). The large change of projected streamflow and its impacts on ice melt contribution uncertainties emphasise the benefit of assessing the contribution of icemelt to the projected streamflow and not relative to the observed streamflow. (Huss and Hock, (2018) calculated for example the glacier runoff change relative to the observed basin runoff that is not changing with time, while streamflow may greatly change in the future due to other factors than icemelt (Fig. 14).

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4.2 Future improvement in J2000-Rhône-glaciers

4.2.1. Meteorological data

The data used in this study is based on the SAFRAN meteorological reanalysis, which is a gridded dataset developed on the French territory (Vidal et al., 2010). SAFRAN was later adapted to transnational basins by estimating meteorological data using the closest point. Therefore the meteorological data in the Swiss part are uncertain mainly because they are far away from the French border. Mostly, precipitation is overestimated in the Valais Region because the French Alps located on the western side of the mountain range receive a larger amount of precipitation compared to the Valais at similar elevation (MeteoSwiss, 2025). The calibrated parameter *precip_mult_low* corrects this problem but it assumes a consistent bias between closest SAFRAN grids and the actual snowfall in the Valais region. A consistent dataset covering all the French and Swiss part of the basin should be used in future studies.

The bias of the meteorological data may be an issue mainly in mountainous regions. The underestimation of streamflow during the snowmelt period (Fig. 9), is in line with an underestimation of snowmelt compared to S2M (Fig. 5) - a reanalysis that could itself be prone to an underestimation of snow accumulation at high elevation (Vernay et al., 2022). The underestimation of snowfall is a well known issue, especially in locations affected with strong winds like the high mountains, as precipitation gauges fail to capture solid precipitation in these conditions (Prein and Gobiet, 2017). This problem was partially resolved by increasing snowfall amounts in high elevation with the parameter *precip_mult_high*. This correction was very relevant to improve the overall estimation of glacier melt, since the icemelt depends on the timing of snowmelt.

4.2.2 Snow and ice melt rates

In this study, a large number of observations were used to calibrate the parameters of the snow and glacier modules, or to evaluate the simulated snow and icemelt. This calibration was done per basin (Upper Rhône, Arve, Isère, Drac, Durance), which means that all HRUs of each basin share the same set of parameters. During the validation we notice a large difference between glaciers certainly due to topographic factors governing the intrinsic variability of the parameters, especially the degree-day factors (Fig. 7). So the estimated degree day factor is only an average for each subbasin and is not representative of each glacier included in this subbasin. The scale of J2000-Rhône-glaciers does not allow to go into a glacier-scale level of details, but gives satisfactory results at a subbasin scale.

In this study the degree day factor (DDF) was also kept constant in time, even though it could probably vary with time. It has been especially shown that snow DDF decreases with climate change because snow melts earlier when its albedo is higher and the available energy is lower (Ismail et al., 2023). The icemelt seems to stay too large at the end of the 21st century compared to the ice volume retreat from ALPGM (Fig. S7) indicating possibly an overestimation of the DDF factor.

It seems that the DDF for ice may decrease with climate change (Fig. S7). One of the solutions could be to update DDF to keep the amount of icemelt consistent with ALPGM. But the evolution of DDF is complex, as DDF was shown to be larger with higher elevation (Ismail et al., 2023) where glaciers will remain in the future. The evolution of ice DDF in the context of climate change needs further investigation and could greatly improve the hydrological models in mountainous environments.

4.2.3 Evolution of landuse

In J2000-Rhône-glaciers, the glacier surfaces are prescribed every year, so that glacier retreat is taken into consideration in the hydrological model. It improved the previous version of J2000 used for glacio-hydrological applications in the Himalaya (Nepal et al., 2014). A question linked to this glacier retreat is associated with the land cover that is left when the glacier disappears (Bosson et al., 2023). In our study, HRUs with glaciers in the historical period have similar properties as bare rocks. However, the vegetation is colonizing these areas that are likely to become prairies or even forest, increasing the interception, the evapotranspiration or the infiltration. Therefore, the possibility of changing the HRUs properties in a transient way is increasingly needed and would allow to integrate scenarios of landuse change in J2000. The change in land use will also have implications for the ratio of the streamflow components (Runoff, Interflow, Baseflow). With the permafrost thaw accelerating and these new ecosystems emerging, it is likely that the groundwater will become increasingly important (Rogger et al., 2017). The groundwater, especially associated with glacier melt, is not well understood in mountainous regions (Van Tiel et al., 2024) and the model J2000 represents groundwater in a very simplistic way. With glacier retreat, it is increasingly important to also improve the representation of the groundwater component in hydrological models.

4.2.4. Anthropogenic influence

J2000-Rhône-glaciers used in this study simulates the behavior of natural streams, while most rivers are heavily influenced by dams and diversions. It is therefore challenging to calibrate the model with streamflow observations. For example the peak of streamflow observed in the Drac catchment in January (Fig. 9) is likely associated to a dam operation allowing to sustain the streamflow in this period. Even though dams and diversions are not integrated in this version of the model, our study already shows how the change of hydrological regimes may be problematic for dam management. In many rivers investigated in this study, the period of winter low flows will tend to disappear due to the increase of the rainfall to snowfall ratio. But the most concerning part is the dramatic decrease of streamflow in summer months due to the combination of a precipitation decrease and a reduction of snow and icemelt. The current operations consisting of retaining the water excess in summer to sustain the winter streamflow will no longer be possible in a future climate. It would be very interesting to integrate dams in J2000-Rhône-glaciers in future simulations and work on scenarios of future dam management, similarly to what was done with J2000-Rhône-classic (Branger et al. 2023).

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5. Conclusion

For the purpose of this study, a glacier module with dynamical glacier surfaces was integrated in the J2000 hydrological model and run in the Rhône Basin. SAFRAN reanalysis has been used as input meteorological data in the past period to calibrate and validate J2000-Rhône-glaciers in terms of snow processes, glacier mass balance and streamflow. The parameters fitted in the past and the climatic projections from five climate models under the scenario RCP 8.5 were used to simulate the future evolution of streamflow and the contribution of melting. The main results of this study can be summarized as follow:

(1) A satisfactory representation of streamflow, snow processes and glacier mass balance in J2000-Rhône-glaciers in most near-natural subbasins. The benefit of using a large number of datasets of different sorts to fit the parameters related to snow and glacier processes was clearly shown.

(2) A general decrease of icemelt in the period 1976-2095 reaching -100% in the Isère at Grenoble and Drac at Fontaine, -63% (±11 %) in the Arve at Sallanches, -78% in the Durance at Espinasses (± 3 %). A large inter-model variability is shown in the upper Rhône -41% (± 34 %), due to a high variability in the highly glaciated subbasins. This variability is transferred to the Rhône downstream but the decrease is consistent between models at the outlet in Beaucaire -56% (± 21 %). The evolution of icemelt was stable in the past but it is starting to decrease earlier in the South with a peak water around 2014 (± 13 yrs) in the Durance at Espinasses and later in the Upper Rhône at Porte du Scex (2053 (± 12 yrs))

(3) A great change in the future hydrological regimes in all subbasins of the Rhône Basin with an increase of winter streamflow and a dramatic decrease of summer streamflow associated with a change of precipitation regime, and timing of snowmelt. The change of icemelt will also contribute to the decrease of summer streamflow in the Arve subbasin and in the highly glaciated subbasins of the Upper-Rhône.

(4) The contribution of icemelt to the summer streamflow is projected to significantly decrease between 1976-2005 and 2066-2095 in the Isère at Grenoble (-6.5pp ±1) , the Drac at Fontaine (-8pp ±1.5) and Durance at Espinasses (-1.7pp ±0.4) subbasins. The evolution is less clear in the Arve at Sallanches (+1.9pp ±7.4) and the Upper Rhône at Porte du Scex (-0.8pp ±7.4) mainly due to a large variability in the highly glaciated subbasins that will be transferred all along the Rhône River to the outlet at Beaucaire (-1.2 ±2.45).

This study gives a new interesting insight into the future evolution of icemelt contribution to streamflow in a large area of the Alps and along the Rhône River. It emphasises that the decrease of summer streamflow, that is very consistent between subbasins and models, is expected to be driven mainly by a change of precipitation or snowmelt. Despite a decrease of icemelt, the contribution to the total streamflow is very uncertain in the highly glaciated subbasins due to a large inter-model variability of streamflow change and glacier extent. These results need to be further explored by future studies, using for instance more reliable meteorological data in the Swiss part. The existing European reanalyses such as CERRA, or the future reanalysis ARRA have for example a better resolution than SAFRAN and are consistent between the French and Swiss parts. Other projected glacier surface dataset could also be used to confirm the results found using ALPGM and GloGEMflow, and to further improve the reliability between icemelt and the change of glacier area. A simple glacier model could also be directly integrated in J2000. Other scenarios of climate change such as RCP4.5 and the scenarios from CMPI6 could also be used. Finally, how planners will adjust to the change of hydrological regime and mainly a dramatic decrease of summer streamflow is a fundamental question. In the highly glaciarized watersheds, the uncertainty in the future projections remains large but the use of multi-source cryospheric datasets in the calibration-validation processes is increasingly important to improve the reliability of the results.

Code and data availability

The J2000 simulations of hydrological processes computed in 1975-2022 with SAFRAN reanalyses and computed in 1975-2095 with the 5 climate models, will be made available shortly in a repository

Supplement link

Supplementary materials are made available by Copernicus

Author contributions

JB, AL and OC developped the JAVA scripts for the J2000 glacier module, GD made the OGGM simulations, LM extracted MOD10A2 data, FB did the founding acquistion, the supervision and was the project administrator. OC performed the simulations, designed and carried out the analyzes, and prepared the manuscript with review and editing from all co-authors.

Competing interests

The authors declare that they have no conflict of interest

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