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Convection-Permitting Regional Climate Simulations Reveal Stronger Drying and Snow Loss in Semi-Arid Mountainous Basins of Morocco

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ABSTRACT

Mountainous basins in semi-arid regions are among the most climate-sensitive environments, yet their hydro-climatic processes remain poorly represented by regional climate models. This study provides the first hydrological evaluation of a convection-permitting regional climate model (WRF3) with a spatial resolution of 3 km in mountainous basins of Morocco in North Africa, using a multi-model hydrological framework (HYPE and GR4J-CemaNeige). Results show that hydrological simulations forced by the convection-permitting WRF3 model provide a better agreement with observed streamflow and a set of different hydrological signatures than those forced by the coarser, convection-parameterized WRF20 model (20 km). Under the SSP5–8.5 scenario, the projections indicate precipitation decreases of 31%–62%, increases in potential evapotranspiration of 16%–27%, and streamflow reductions ranging from 64%–87%, depending on the climate forcing (WRF3 versus WRF20). There is a systematically stronger reduction in water resources in WRF3 projections than in WRF20 that is consistent across different basins. Snow contributions decline more strongly in simulations forced by the convection-permitting regional climate model (WFR3), leading to a shift from a snow-dominated to a predominantly rain-dominated hydrological regime. These results highlight the added value of high-resolution climate modelling in capturing fine-scale mountain processes, strengthening the confidence in climate-impact assessments, and also reveal the severe vulnerability of semi-arid mountainous water resources to future warming. The more pessimistic scenarios obtained with the convection-permitting regional climate model call for a reassessment of currently available scenarios for future water resources in semi-arid mountainous regions obtained with coarse resolution climate models.

1 | Introduction

Mountain regions are susceptible to climate variability and change because their water resources depend strongly on precipitation patterns, snow accumulation and snowmelt-driven runoff. These regions act as critical 'water towers' for downstream populations, providing drinking water, irrigation supply, hydropower production and ecological support (Beniston et al. 2018; Viviroli et al. 2007). In the Moroccan Atlas, mountain catchments supply more than half of the national renewable water resources (Boudhar et al. 2009; Tramblay and Somot 2018), making robust climate projections essential for future planning.

However, producing reliable scenarios in complex terrain is particularly challenging, as steep gradients modulate local climate and hydrology, and small-scale processes exert a disproportionate influence on extremes such as flash floods, droughts and rapid snowmelt events (Beniston 2003; Hock et al. 2019).

Global climate models (GCMs), operating at coarse spatial resolutions of tens to hundreds of kilometres, are unable to explicitly simulate these fine-scale processes, especially deep convection and orographic enhancement. This limitation results in large uncertainties in precipitation intensity, variability and spatial structure over mountains (Giorgi 2019; Prein et al. 2015). Regional climate models (RCMs) provide improved detail through dynamical downscaling, typically at 10–50 km resolution, but they still rely on parameterized convection, a major source of bias in simulating short-duration, intense rainfall and hydrological extremes (Kendon et al. 2021; Lucas-Picher et al. 2021). As a result, traditional RCMs struggle to capture the localised convective storms that frequently drive peak flows and flood hazards in mountain basins such as those of the Moroccan High Atlas (Driouech et al. 2021; Tramblay and Somot 2018).

Advances in computational capabilities have recently enabled convection-permitting regional climate models (CPRCMs or CPMs), operating at grid resolutions of 1–4 km, to explicitly resolve deep convection without parameterization, with this technical evolution being closely tied to progress in high-performance computing (Schär et al. 2020; Berthou et al. 2019; Folwell et al. 2022; Kendon et al. 2019). Coordinated efforts such as the CORDEX-FPSCONV ensemble further demonstrated the maturity of kilometre-scale regional climate modelling and its benefits for representing precipitation processes (Ban et al. 2021; Pichelli, Coppola, Sobolowski, et al. 2021; Pichelli, Coppola, Sobolowski, et al. 2021). These models represent a major shift in climate modelling, offering significantly improved representation of precipitation extremes, the diurnal cycle of convection, mesoscale storm organisation and fine-scale orographic processes (Ban et al. 2021; Prein et al. 2015). While this added value has been demonstrated mainly in Europe and North America, particularly for heavy rainfall, flash floods, high-impact storms, and snow processes, applications in the Global South remain scarce (Ban et al. 2014; Coppola et al. 2020; Kendon et al. 2021; Poncet et al. 2024, 2025).

This rapidly growing literature highlights a marked geographic imbalance: very few studies have explored CPM behaviour in African mountain regions, despite their high vulnerability to climate change and limited observational data (Lucas-Picher et al. 2021; Pichelli, Coppola, Sobolowski, Ban, et al. 2021; Pichelli, Coppola, Sobolowski, et al. 2021). Only recent contributions have begun to address hydrological impacts using CPM-derived projections. For example, Ascott et al. (2023) applied rainfall projections from a convection-permitting model to lumped hydrological catchment models in East Africa, demonstrating both the feasibility and the relevance of CPMs for hydroclimatic assessments on the continent.

This research gap is especially critical in North Africa. Mountain basins in Morocco exhibit strong orographic precipitation gradients, frequent convective storms, and complex snow dynamics, all of which are highly sensitive to warming. Multiple studies show declining snowpack, shifts in seasonal runoff, and future reductions in streamflow under high-emission scenarios (Boudhar et al. 2009; Marchane et al. 2015; Tramblay and Somot 2018). Yet, these assessments almost exclusively rely on conventional RCMs, and their ability to represent mountain hydroclimate remains limited by unresolved convection. To date, no hydrological impact study has evaluated the performance of a convection-permitting RCM over the Atlas Mountains or any other mountain range in Africa, representing a major knowledge gap for regional water-resource planning.

The RegIPSL regional climate model developed by the Institute Pierre-Simon Laplace (IPSL)-offers a new opportunity to address this gap through its convection-permitting configuration at 3 km resolution (Shahi et al. 2022). By explicitly resolving convective processes and fine-scale topographic effects, RegIPSL-CPM has the potential to improve the realism of precipitation fields and hydrological inputs in mountainous areas. High-resolution climate information is particularly valuable for hydrological models, as runoff generation, snow accumulation and melt, soil moisture dynamics, and peak flows are strongly influenced by local precipitation patterns and elevation gradients. Studies have shown that snowmelt can contribute up to 40%–50% of annual flow in Atlas basins (Boudhar et al. 2009; Marchane et al. 2015), making a realistic simulation of snow and precipitation essential for accurate streamflow modelling.

The present article addresses this gap by providing the first hydroclimatic evaluation of the convection-permitting RegIPSL regional climate model in the High Atlas Mountains of Morocco. Two configurations of the model are examined: a 3 km convection-permitting run (WRF3), which explicitly resolves deep convection, and a 20 km configuration (WRF20) that relies on parameterized convection. After describing these configurations, we evaluate the quality of their raw and bias-corrected climate simulations using basin-scale diagnostics, and two hydrological models (GR4J and HYPE) are used to produce hydrological simulations with WRF3 and WRF20, both for historical and future periods.

2 | Data and Methods

2.1 | Study Area and Observational Data

The study was conducted in the Ourika River Basin, located in the High Atlas Mountains of Morocco (Figure 1b,c), within the broader regional climate model (RCM) domain shown in Figure 1a. This is the only watershed in Morocco that has snow depth measurements, which can be used to estimate the water equivalent and also rain gauge data distributed within the watershed. The basin covers an area of approximately 580 km^2 and exhibits a complex hydroclimatic regime shaped by steep elevation gradients, strong orographic effects, and a combination of rainfall- and snowmelt-driven runoff. These characteristics make it an ideal testbed for evaluating the hydrometeorological performance of the convection-permitting RegIPSL regional climate model and its suitability as a driver for hydrological impact modelling, particularly under high-emission scenarios where changes in precipitation phase, timing, and intensity are expected to be strongly amplified. Snowmelt and seasonal

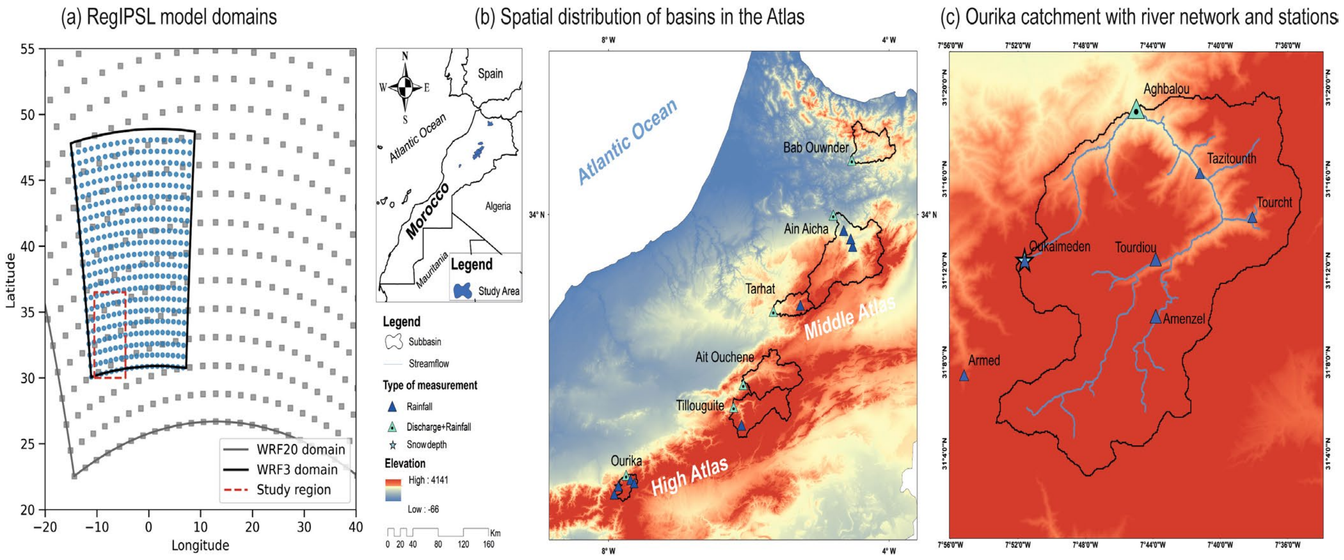

FIGURE 1 | Study area and model configuration. (a) RegIPSL model domains showing the 20 km (WRF20) and 3 km (WRF3) grids, with the study region indicated. (b) Spatial distribution of the selected basins across the Atlas Mountains over elevation (m), including the Ourika basin and additional basins used in the multi-basin analysis. (c) Detailed map of the Ourika catchment showing elevation, river network, and monitoring stations, including rainfall gauges, the Aghbalou discharge station, and the Oukaïmeden snow station used for SWE estimation.

precipitation constitute major contributors to streamflow and groundwater recharge, reflecting the broader challenges of water availability in semi-arid mountain environments.

Daily discharge observations at the Aghbalou hydrometric station, located at the outlet of the basin (Figure 1c), were obtained from the Tensift Hydraulic Basin Agency (ABHT) and cover the period 1992–2014. These data were used for hydrological model calibration and evaluation.

Daily areal precipitation fields were reconstructed using ordinary kriging based on seven rainfall stations distributed throughout the basin (Armed, Amenzel, Tourcht, Tourdiou, Aghbalou, Tazitounth and Oukaïmeden), with records covering the period 1989–2014. The interpolation followed standard geostatistical procedures: (i) quality control and homogenisation of station records, (ii) computation of an experimental variogram and fitting of a theoretical model (spherical) and (iii) interpolation onto a regular 28-point grid covering the basin, followed by spatial averaging to obtain basin-wide precipitation estimates (Cressie 1993; Goovaerts 1999; Isaaks and Srivastava 1989; Matheron 1963).

To account for the solid precipitation component, snow depth observations from the Oukaïmeden station (3250 m a.s.l.) were converted to snow water equivalent (SWE) using an empirical relation calibrated for the High Atlas (Boudhar et al. 2009), which has been successfully applied in previous studies in the Ourika basin (Marchane et al. 2017). This conversion provides a continuous daily SWE time series, used here as a proxy for snowfall occurring at high elevations. The resulting SWE contribution was incorporated into the basin-scale precipitation time series to compensate for the absence of snowfall measurements at lower-elevation rain gauges. Therefore, the method does not rely on a single value for the entire basin, but on a time-varying SWE signal integrated into the precipitation forcing. Due to data limitations, the SWE series was assumed to be representative of high-altitude areas within the basin. This approach allows the main snow accumulation and melt dynamics to be captured in the hydrological simulations, which is essential for reproducing late-winter and spring runoff in high-mountain basins.

2.2 | Climate Modelling Approach

In this study, regional climate simulations produced with the RegIPSL modelling framework are used to investigate hydroclimatic processes over the High Atlas Mountains. RegIPSL is an evolution of the MORCE-MED system (Drobinski et al. 2012) and is based on the non-hydrostatic WRF-ARW Version 4 atmospheric model coupled with the ORCHIDEE land-surface scheme (Skamarock et al. 2019; Krinner et al. 2005). Detailed descriptions of the model architecture and its physical components are provided in previous studies (Drobinski et al. 2012; Skamarock et al. 2019; Krinner et al. 2005). Recent applications of the coupled RegIPSL framework in convection-permitting regional climate simulations are described in Pichelli, Coppola, Sobolowski, et al. (2021); Pichelli, Coppola, Sobolowski, et al. (2021).

RegIPSL allows simulations at kilometre-scale resolution, which is particularly relevant in mountainous regions where steep topographic gradients exert a strong control on temperature and precipitation patterns. This capability arises from the non-hydrostatic dynamical core of WRF combined with the detailed land-surface representation provided by the ORCHIDEE model, which together enable a more realistic simulation of atmosphere–land interactions in complex terrain. The benefits of increased spatial resolution and convection-permitting configurations in complex mountainous terrain have been widely documented in the literature (Ban et al. 2014; Prein et al. 2015; Lucas-Picher et al. 2021; Shahi et al. 2022). While convection-permitting regional climate simulations have been applied in some African studies (e.g., Stratton et al. 2018; Senior et al. 2021;

TABLE 1 | Summary of the physical and numerical settings for the WRF-ARW Version 4 configurations of WRF20 and WRF3 within the RegIPSL regional climate model.

Description	WRF20 simulation	WRF3 simulation
Dynamic solver	ARW	ARW
Horizontal grid spacing	20 km	3 km
Grid dimensions	301 × 193	581 × 651
Vertical levels	46 (top 50 hPa)	46 (top 70 hPa)
Integration time	90 s	10 s
Radiation (shortwave and longwave)	RRTMG scheme (integration timestep = 30 min)	RRTMG scheme (integration timestep = 5 min)
Microphysics	WRF single-moment (WSM) 5-class scheme	Thompson scheme
Atmospheric surface layer	MYNN surface layer	MYNN surface layer
Land surface	ORCHIDEE	ORCHIDEE
Planetary boundary layer (PBL)	MYNN 2.5 level TKE scheme	MYNN 2.5 level TKE scheme
Cumulus	Kain-Fritsch scheme	No cumulus scheme is used

Chen et al. 2024), their hydrological evaluation and application to mountainous basins in Africa remain unexplored.

The climate simulations used in this study were produced within the framework of the European Climate Prediction (EUCP) Horizon 2020 project using the RegIPSL regional climate model forced by the IPSL-CM6A-LR global climate model (CMIP6, r1i1p1f1). Three types of simulations are considered. First, evaluation simulations (EVAL), covering the period 2000–2009 and forced by the ECMWF ERA-Interim reanalysis, are specifically designed to assess the ability of the regional climate model to reproduce observed hydro-climatic conditions. Second, historical simulations (HIST), covering the period 1996–2005 (including 1 year of spin-up), are used to represent present-day climate conditions and serve as a baseline for climate change analysis. Third, future climate projections (SSP5–8.5) for the mid-century period (2041–2050) are used to assess the climate-change signal relative to the historical baseline. End-of-century simulations were not available within the EUCP convection-permitting simulation framework used in this study. The focus on the mid-century period is nevertheless relevant, as it corresponds to time horizons commonly considered for near-term climate adaptation and water-resource planning. Hourly climate outputs generated by RegIPSL were aggregated to daily values prior to hydrological modelling, and precipitation and temperature were bias-corrected before hydrological coupling using the CDF-t method (Michelangeli et al. 2009; Vrac et al. 2016), as described in Section 2.3, to reduce systematic errors.

The resulting modelling framework allows a direct comparison between the 20 and 3 km simulations and enables an assessment of how differences in the representation of convection and orographic processes influence hydrological outcomes. This includes evaluating streamflow performance, snow accumulation and melt dynamics, peak-flow behaviour, and key hydrological signatures such as flashiness, baseflow contribution, and the timing of runoff. In this framework, the high-resolution RegIPSL simulations provide hydroclimatic inputs that can be evaluated within the hydrological modelling chain for mountainous basins, without assuming a priori added value at the scale of small headwater catchments. Given the study design (single model and limited number of simulations), the results should be interpreted as indicative rather than generally applicable to provide future scenarios. Nevertheless, this framework allows for exploring the sensitivity of runoff processes to changes in the representation of convection and orographic effects, which are key controls on hydrology in data-scarce mountain regions (Ban et al. 2014; Lind et al. 2020; Skamarock et al. 2019). A detailed summary of the model configurations, parameterizations, and domain characteristics is presented in Table 1.

2.3 | Bias Adjustment

Climate simulations typically contain systematic biases in precipitation and temperature that limit their direct use in hydrological modelling, especially in mountainous regions where water balance components are highly sensitive to errors in both variables (Christensen et al. 2008; Ehret et al. 2012; Teutschbein and Seibert 2013; Maraun et al. 2017). To address these limitations, this study applies a daily bias-correction procedure based on the cumulative distribution function–transform (CDF-t) method (Michelangeli et al. 2009; Vrac et al. 2012), which has proven effective for adjusting climate simulations before hydrological applications. CDF-t aligns the simulated and observed distributions while allowing their shapes to evolve between the reference and future periods, making it better suited than traditional stationary quantile-mapping approaches under non-stationary climate conditions. Previous work has shown that CDF-t preserves climatic trends, improves the correction of extremes, and provides more robust adjustments of phase-dependent variables such as rain–snow partitioning (Maraun 2016; Menapace et al. 2025; Michelangeli et al. 2009).

In the Ourika Basin, where multiple gauges exist, precipitation observations were taken from a basin-averaged daily rainfall series derived from the kriging interpolation of the seven stations described in Section 2.1. This basin-scale precipitation series was used as the observational reference for the bias-adjustment procedure.

For temperature, the absence of reliable high-elevation measurements in the region necessitates the use of a gridded reference dataset. ERA5 near-surface air temperature was therefore used as a spatially consistent proxy dataset for the bias-adjustment procedure. ERA5 was not used for the evaluation of the regional climate simulations themselves, but only to provide a reference temperature series required for the CDF-t correction. Although reanalysis products may present limitations in complex mountainous terrain, ERA5 offers continuous spatial coverage and temporally consistent fields, which makes it a practical reference dataset for statistical correction in data-scarce mountain regions (Hersbach et al. 2020; Beck et al. 2021).

The WRF20 and WRF3 outputs from RegIPSL are first aggregated to daily resolution and averaged across the basin using area-weighted extraction of the model grid cells intersecting the catchment boundaries. This procedure produces basin-scale daily time series of precipitation and temperature that are consistent with the hydrological modelling framework used in this study. The CDF-t transformations were then calibrated using the observed precipitation series derived from the kriging interpolation of the rain-gauge network. Bias correction was therefore applied to the basin-averaged time series, ensuring that the statistical properties of the climate forcing match the observed hydroclimatic variability at the basin scale while preserving the climate-change signal simulated by the regional climate model. Spatial patterns of precipitation and temperature for both model resolutions are provided in Supporting Information (Figure S3) for reference.

Precipitation is corrected using a two-step occurrence–intensity approach: the frequency of wet days is adjusted using a 0.1 mm threshold, followed by CDF-t applied to positive precipitation values to ensure non-negativity and realistic scaling of intensities. Temperature is bias-corrected using the CDF-t method in its additive form, which aligns simulated and observed distributions while preserving the climate-change signal simulated by the model. The calibrated transformations are subsequently applied to both the historical and future simulations, ensuring internal consistency across all periods.

All computations are implemented using the XSBCK package (Robin and Vrac 2021; DOI: 10.5281/zenodo.7985173), which ensures full reproducibility of the statistical adjustments.

2.4 | Hydrological Modelling

To evaluate how the climate simulations translate into hydrological responses, two rainfall–runoff models are employed: the semi-distributed HYPE (Hydrological Predictions for the Environment) model (Lindström et al. 2010) and the lumped conceptual GR4J model coupled with the CemaNeige snow module (Perrin 2002). Using both models is essential for assessing structural uncertainties in hydrological modelling, particularly in mountainous regions where runoff generation depends on complex interactions between precipitation phase, snow dynamics, subsurface processes and topographic controls. Previous studies have highlighted the need for such multi-model strategies to obtain more robust inferences under changing climate conditions (Fatichi et al. 2016; O'Connell and Todini 1996). These two models have already been successfully implemented and evaluated over the same High Atlas basins in a previous study, demonstrating their suitability for snow-influenced hydrological regimes and their ability to reproduce the main components of the mountain water balance (Lahnik et al. 2025).

HYPE offers a semi-distributed, process-oriented framework capable of representing spatial heterogeneity across sub-basins. It has been widely applied across diverse regions, including the Baltic Sea basin (Arheimer et al. 2012), continental Europe (Donnelly et al. 2016), West Africa (Andersson et al. 2017), South Asia (Pechlivanidis and Arheimer 2015) and in global-scale applications (Arheimer et al. 2020). In this study, HYPE's global configuration (World-Wide HYPE) is specifically adapted to the Atlas Mountains by integrating local physiographic, climatic, and hydrological information derived from basin topography, land cover, soil properties and observed streamflow. The model is implemented at a daily time step, consistent with the temporal resolution of the climate forcing used in this study. In HYPE, snow accumulation and melt are represented through a temperature-based routine integrated within the model's semi-distributed structure. This adaptation enhances the representation of snow accumulation and melt, groundwater–surface water interactions, and event-scale precipitation–runoff responses, which are particularly important in high-elevation headwater catchments (Donnelly et al. 2016; Gelfan et al. 2017; Gosling et al. 2017).

GR4J-CemaNeige complements HYPE by offering a conceptual modelling structure with a snow module specifically designed to represent snow accumulation and melt using temperature-based formulations and elevation-dependent partitioning between rainfall and snowfall (Perrin et al. 2003; Valéry et al. 2014). Its simplicity and parsimony have made it highly effective in basins where snow contributes significantly to seasonal water availability. Furthermore, GR4J-CemaNeige has already proved suitable for Moroccan mountain hydrology, with successful applications in several High Atlas basins and strong performance in simulating seasonal regimes driven by snowfall and spring melt (Boumenni et al. 2017; Hajhouji et al. 2020, 2018). The availability of user-friendly tools such as the airGR package (Coron et al. 2017) facilitates rigorous calibration and reproducible workflows.

2.5 | Hydrological Signatures

To complement classical performance metrics commonly used in hydrological modelling, such as the Nash–Sutcliffe Efficiency (NSE), the Kling–Gupta Efficiency (KGE), or relative bias, a set of hydrological signatures was analysed to assess whether the climate–hydrology modelling chain reproduces key runoff processes in a physically consistent manner. Hydrological signatures provide a process-oriented perspective on streamflow

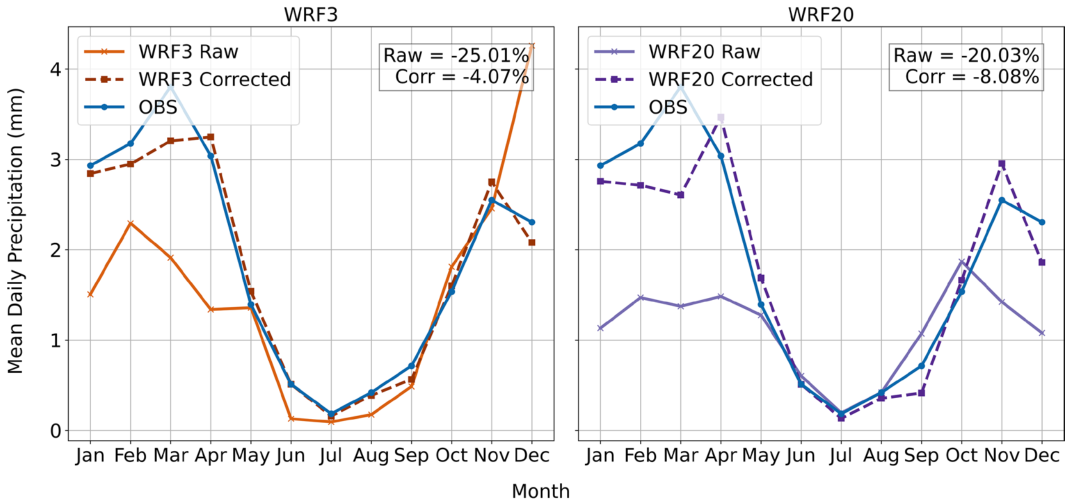

FIGURE 2 | Comparison of monthly precipitation simulated by the RegIPSL model at convection-permitting (WRF3, 3 km) and parameterized-convection (WRF20, 20 km) resolutions, before and after bias correction, against observations over the 2000–2009 period.

dynamics and allow the evaluation of model behaviour beyond simple error statistics, particularly in mountainous basins where runoff is influenced by rapid precipitation–runoff responses, snow accumulation and melt, groundwater contributions and seasonal timing (Lyne 1979; Baker et al. 2004; Blume et al. 2007; Eckhardt 2005; McMillan et al. 2020; Olden and Poff 2003; Sawicz et al. 2011; Teutschbein and Seibert 2013; Yilmaz et al. 2008).

In this study, signatures were computed at a daily time step over complete hydrological years using observed discharge, as well as simulations from the HYPE and GR4J-CemaNeige models forced by bias-corrected RegIPSL climate simulations. The analysis includes indicators describing runoff variability, baseflow contribution, precipitation–runoff conversion, and seasonal timing of discharge. This multi-metric approach enables a process-based evaluation of model behaviour and provides additional insight into the sensitivity of hydrological responses to climate forcing and model structure.

The detailed definitions and formulations of the hydrological signatures used in this study are provided in the Supporting Information (Section S2).

3 | Results

3.1 | Evaluation of RegIPSL Climate Simulations (EVAL Period)

3.1.1 | Precipitations

The monthly precipitation cycle was evaluated for the EVAL (2000–2009) simulations of WRF3 (3 km) and WRF20 (20 km), before and after CDF-t bias correction (Figure 2), using catchment-averaged precipitation series derived from the RegIPSL grid cells intersecting the Ourika basin. Both raw configurations underestimate precipitation during the wet season (November–April), with annual biases of −25% for WRF3 and −20% for WRF20. This negative bias likely reflects the difficulty of simulating precipitation over steep mountain terrain, where residual smoothing of topography, imperfect representation of orographic uplift, and limitations in the simulation of localised convection and solid precipitation may reduce simulated totals. In addition, the observational reference is based on a basin-averaged series reconstructed from seven rain gauges, including the high-altitude Oukaïmeden station, and complemented by a SWE-derived contribution to account for snowfall. After applying CDF-t, residual biases decrease markedly to −4% and −8%, respectively. WRF3 reproduces the seasonal structure of precipitation more accurately than WRF20, particularly the autumn and spring maxima, even before correction. WRF20 maintains a spring underestimation despite bias-adjustment. Overall, CDF-t substantially improves the monthly climatology for both configurations, while the added value of explicit convection in WRF3 remains evident for capturing seasonal variability. Bias correction modifies distributional statistics but does not influence event timing, and the physical advantages of high-resolution modelling remain essential for hydrological applications in mountainous terrain.

The evaluation presented here concerns the EVAL simulations only, which are used to calibrate the bias-correction procedure over the observational period. The resulting CDF-t transformation is then applied to the HIST and SSP5–8.5 simulations used for the climate-change analysis.

3.1.2 | Evapotranspiration

The monthly cycle of potential evapotranspiration (PET) was derived from daily temperatures of the EVAL simulations (WRF3 and WRF20), before and after CDF-t correction, and compared with a reference based on ERA5 2-m temperature (Figure 3). Daily temperatures were spatially averaged at the basin scale and converted to PET using the Oudin formulation (Oudin 2004), with the same method applied to all datasets so that differences in PET reflect differences in temperature forcing rather than differences in the PET formulation itself. ERA5 was used here as a pragmatic gridded reference dataset for temperature correction in the absence of reliable high-elevation observations, although its coarse resolution does not fully resolve the strong topographic gradients of the basin. Before correction, both configurations underestimate PET throughout the year, with the largest deficits from March to September, reflecting a cold bias in simulated temperatures over complex terrain. WRF3 reproduces the phase and amplitude of the seasonal cycle more accurately than WRF20, indicating a better representation of temperature variability over mountainous terrain. After applying CDF-t, PET estimates from both configurations become very close to the ERA5-based reference, so that the corrected curves are partly superimposed in Figure 3. The correction reduces mean biases, restores the seasonal amplitude, and aligns summer maxima, confirming that temperature biases strongly influence PET estimates at these timescales. Although the Oudin formulation does not explicitly represent all energy-balance controls relevant in high-altitude environments, it provides a simple and coherent basis for comparing the temperature-driven evaporative demand derived from the different climate forcings.

3.2 | Hydrological Performance Under Observed and Simulated Forcings

3.2.1 | Benchmark Simulations Using Observation-Based Forcings

To establish an independent benchmark, the GR4J-CemaNeige and HYPE models were first forced with observation-based data. Both models were calibrated against daily discharge observations from the Aghbalou hydrometric station, located at the outlet of the Ourika basin, over 2000–2009, identical to the evaluation time window of the EVAL climate simulations. The discharge record covers the 1992–2014 period, allowing validation over two independent periods: 1992–2000 and 2010–2014. Performance was assessed using the Kling–Gupta Efficiency (KGE), which provides an integrated measure of correlation, bias and variability (Gupta et al. 2009). GR4J-CemaNeige yields higher KGE values than HYPE across all analysed periods. The KGE values in validation are higher for 2010–2014 than for the calibration period (Figure 4). This

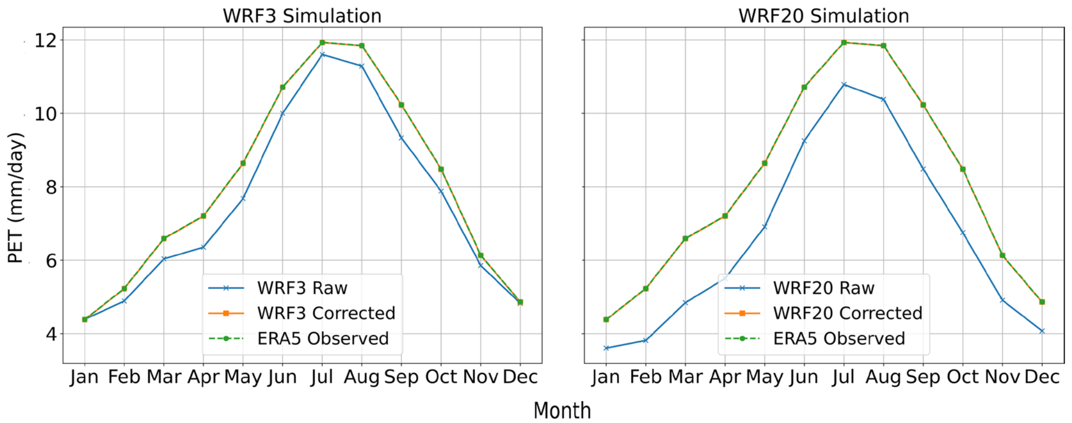

FIGURE 3 | Monthly cycle of potential evapotranspiration (PET) simulated from WRF3 (3 km) and WRF20 (20 km) temperature outputs, before and after bias correction, compared with ERA5 reference data.

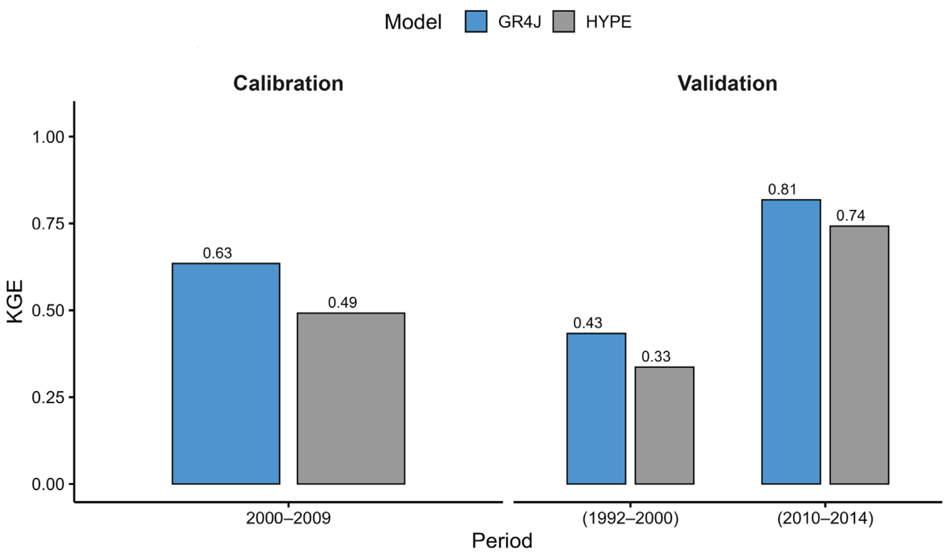

FIGURE 4 | Kling–Gupta efficiency (KGE) values for the GR4J-CemaNeige and HYPE hydrological models forced with observed meteorological data, during the calibration period (2001–2009) and two validation periods (1992–2000 and 2010–2014).

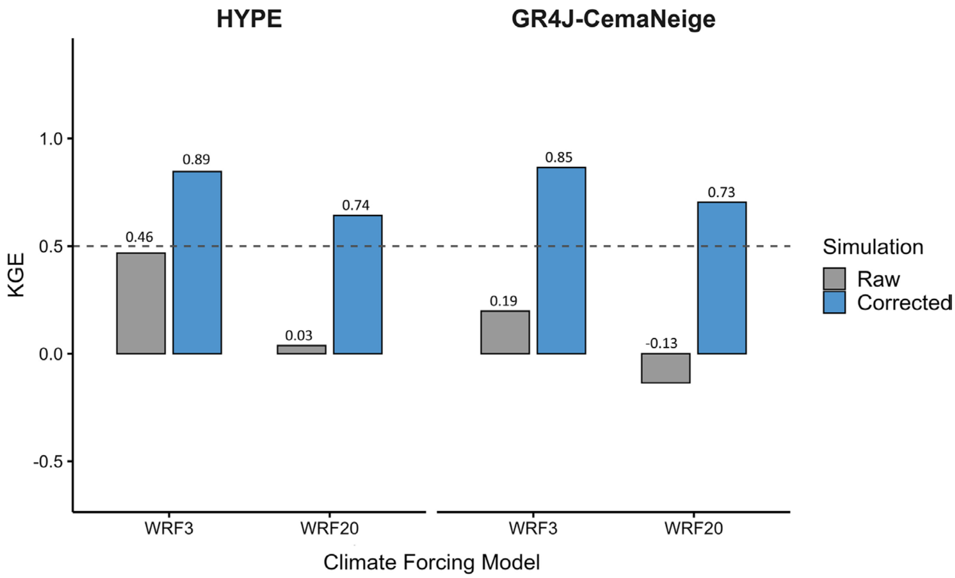

FIGURE 5 | Hydrological performance of the HYPE and GR4J-CemaNeige models forced with raw and bias-corrected climate simulations (EVAL period) from WRF3 (3 km) and WRF20 (20 km) over the 2001–2009 period.

difference is primarily attributable to the shorter duration of the 2010–2014 period, which includes the flood events of 2014 (El Khalki et al. 2018), that are better simulated than low-flow years. In contrast, the 1992–2000 validation period spans a broader range of hydro-climatic conditions, leading to lower but more representative performance estimates. Observation-forced simulations are therefore used as a reference for evaluating simulations driven by raw and bias-corrected EVAL climate forcings in subsequent sections.

3.2.2 | Influence of Climate Bias Correction on Simulated Hydrological Responses

- Performance metrics

To isolate the impact of climate forcing on hydrological simulations, GR4J-CemaNeige and HYPE were rerun over 2001–2009 using raw and CDF-t–corrected EVAL forcing from WRF3 (3 km) and WRF20 (20 km). Hydrological parameters were kept fixed at their observation-based calibration values, ensuring that performance changes arise solely from differences in climate inputs. KGE results (Figure 5) display a consistent response across climate forcings. Bias correction leads to higher KGE values for both hydrological models, with larger improvements for WRF20, consistent with its stronger initial biases. For a given bias-correction approach, simulations driven by WRF3 generally yield higher KGE values than those driven by WRF20. In addition, raw WRF3 forcings already produce positive KGE values, in some cases comparable to those obtained with bias-corrected WRF20. Differences between GR4J-CemaNeige and HYPE responses across forcings are present but remain moderate and do not indicate a systematic contrast in sensitivity to their inputs.

- Hydrograph dynamics

Observed and simulated hydrographs (Figure 6) highlight clear differences between model resolutions. Raw WRF20 simulations strongly underestimate spring peak flows and intensify summer low flows, indicating insufficient precipitation and an under-represented snow contribution. Raw WRF3 simulations better reproduce seasonal timing, although HYPE tends to overestimate the spring peak. Bias correction markedly enhances the hydrological realism of the simulations. Corrected WRF20 reduces annual volume deficits and improves seasonal dynamics, while corrected WRF3 closely matches observed hydrographs for both hydrological models in terms of amplitude and timing. Remaining discrepancies in late-summer likely reflect under-captured light rainfall, the absence of anthropogenic withdrawals in the models, and uncertainties in high-elevation snow processes. Overall, these findings confirm that bias correction is essential for hydrological applications, particularly for WRF20, and that the added value of explicit convection in WRF3 persists after correction. GR4J-CemaNeige provides robust snow-related timing, while HYPE is more sensitive to precipitation variability. Corrected WRF3 offers the most consistent hydrological simulations and forms a reliable basis for subsequent process-based evaluations.

3.3 | Sensitivity of Hydrological Signatures

Convection-permitting models are known to better capture orographic precipitation patterns, sub-daily variability, and extremes than parameterized-convection configurations. Using bias-corrected forcings, our results confirm this added value: corrected WRF3 systematically yields lower RMSEs than corrected WRF20 for both hydrological models and for all analysed signatures (Figure 7). Threshold precipitation (TP) shows a clear improvement under WRF3 for HYPE and GR4J-CemaNeige, consistent with a better representation of intense rainfall and non-linear runoff generation. The Centre of Timing (CT) shows one of the largest reductions in RMSE under WRF3, particularly for GR4J-CemaNeige, indicating improved agreement in the seasonal timing of simulated streamflow. This improvement is most likely linked to

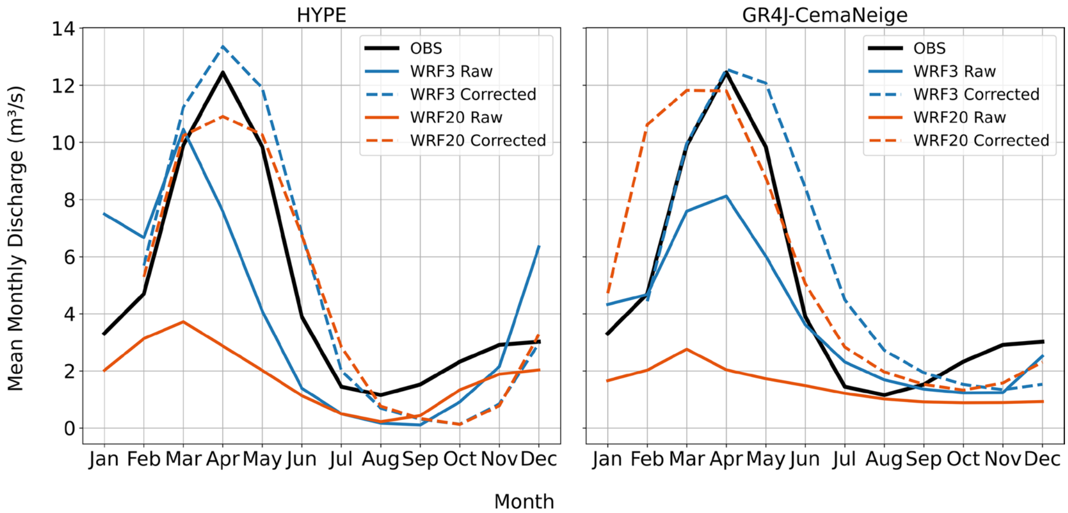

FIGURE 6 | Effect of bias correction applied to simulated precipitation and temperature from the RegIPSL climate model (EVAL period, 2000–2009) for the WRF3 (3 km) and WRF20 (20 km) configurations on monthly streamflow simulated by HYPE and GR4J-CemaNeige. OBS denotes the observed discharge measured at the Ourika gauging station and is shown as a reference.

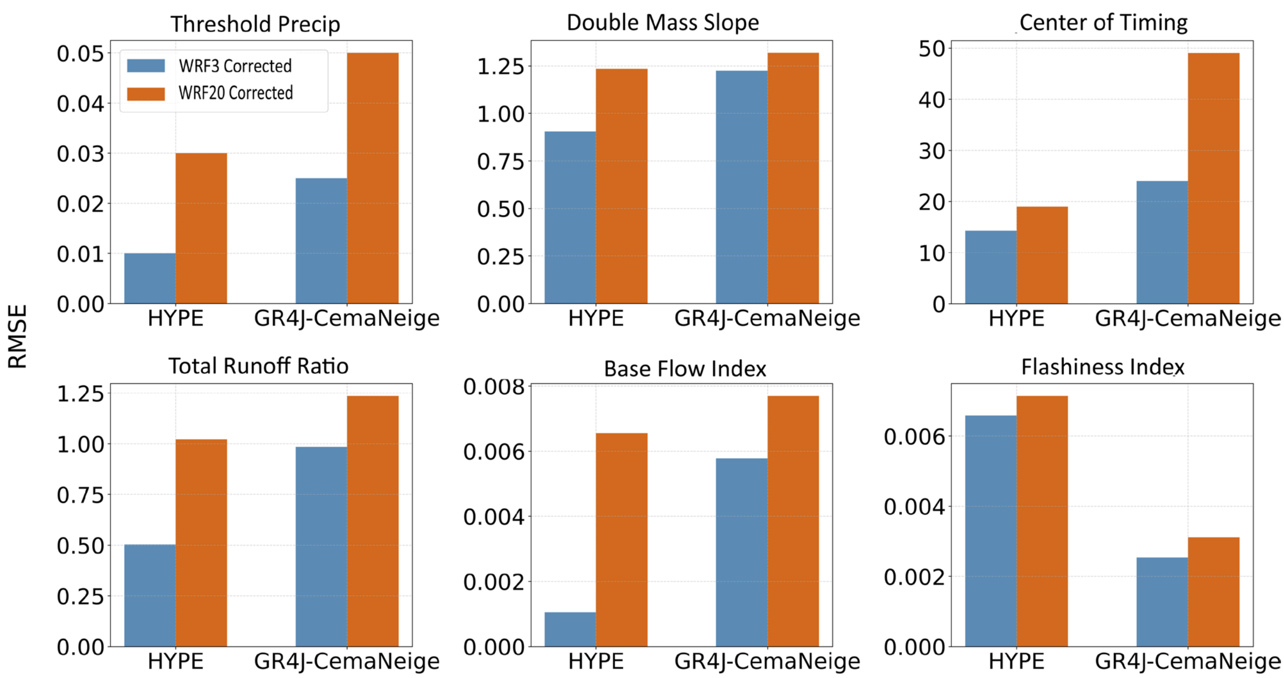

FIGURE 7 | Root mean square error (RMSE) of eight hydrological signatures simulated by the HYPE and GR4J-CemaNeige models, forced with bias-corrected precipitation from the WRF3 (3 km) and WRF20 (20 km) climate simulations.

the finer spatial resolution of WRF3, which allows a more detailed representation of temperature gradients and precipitation variability in complex terrain. Base flow index (BFI) errors are also reduced with WRF3, particularly with HYPE, indicating a better representation of slow-flow contributions once snow processes and temperature corrections are accounted for. The total runoff ratio (TRR) benefits from WRF3 through reduced volume biases, in line with improved precipitation distributions after CDF-t correction. Double mass slope (DMS) improvements are more moderate but remain consistent across models. Flashiness Index (FI) shows smaller yet systematic reductions in error, reflecting more realistic transitions between quick flow and baseflow conditions. Overall, corrected WRF3 outperforms corrected WRF20 for all hydrological signatures, with a pronounced advantage for timing- and extreme-sensitive metrics (CT, TP) and more moderate gains for integrative indicators (DMS, FI). GR4J-CemaNeige particularly benefits from WRF3 for snow-influenced signatures (CT, BFI) due to its explicit snow module. These results highlight the operational value of convection-permitting climate models for improving both intensity- and timing-related hydrological processes in mountainous basins.

3.4 | Future Hydro-Climatic Projections (SSP5-8.5)

3.4.1 | Future Evolution of Precipitation

Future precipitation changes under the high-emission scenario SSP585 were assessed using bias-corrected EVAL simulations from WRF3 (3 km) and WRF20 (20 km), and compared with the historical period (Figure 8). Both configurations project a significant decline in precipitation, but the magnitude of the signal varies strongly with model resolution. WRF3 projects a sharp annual decrease of −62.2%, with the most pronounced reductions during the wet season (November–April). From May onward, precipitation becomes nearly absent, indicating a severe disruption of seasonal recharge and a high risk of future water-stress conditions in mountain basins. WRF20 also shows a substantial decline but of lower magnitude (–30.9% annually). The seasonal cycle is attenuated but still identifiable, with reduced, but not collapsed, wet-season peaks. This contrast highlights the sensitivity of projected hydro-climatic changes to model resolution and the representation of orographic processes. Overall, two key conclusions emerge. Convection-permitting WRF3 provides a more realistic representation of fine-scale precipitation processes, but it also yields a markedly stronger climate-change signal. At the same time, the pronounced divergence between WRF3 and WRF20 highlights the importance of relying on multi-model frameworks to properly characterise uncertainty in future water availability assessments.

3.4.2 | Future Evolution of Potential Evapotranspiration

Seasonal changes in potential evapotranspiration (PET) under the SSP585 scenario were evaluated using bias-corrected EVAL simulations from WRF3 (3 km) and WRF20 (20 km), and compared with the historical period (Figure 9). Both configurations project a marked increase in annual PET, reaching +26.9% with WRF3 and +16.7% with WRF20, reflecting strengthened atmospheric evaporative demand. The rise is strongest from April to September, when warming and increased atmospheric aridity amplify evaporative losses while precipitation sharply declines. WRF3 shows the most pronounced intensification, with summer PET peaks approaching 12 mm day^{-1}, consistent with its finer representation of orographic temperature gradients. These changes indicate earlier and stronger seasonal evaporative maxima and prolonged summer dryness. Differences between WRF3 and WRF20 highlight the sensitivity of PET projections

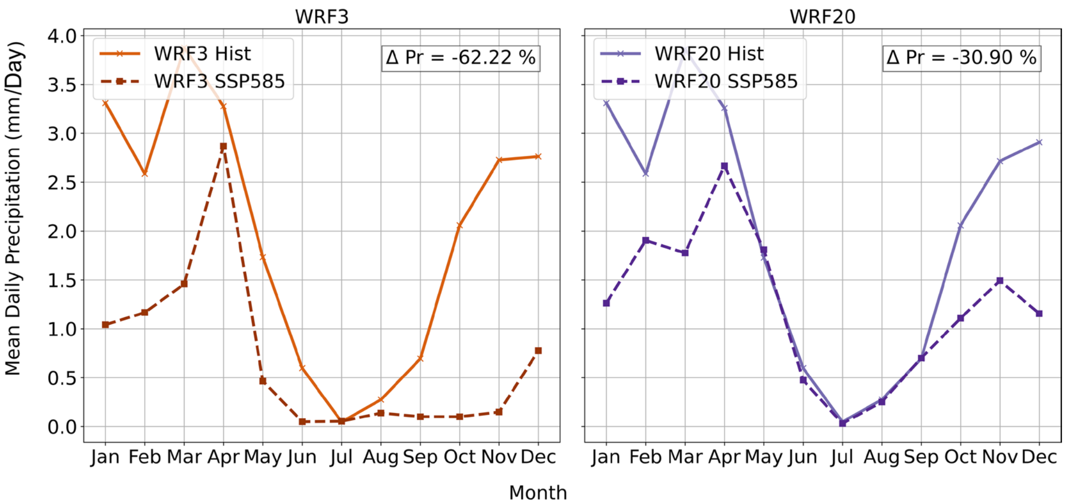

FIGURE 8 | Seasonal evolution of precipitation in the Ourika basin under the SSP585 scenario, compared with the historical period, for the WRF3 (3 km) and WRF20 (20 km) configurations.

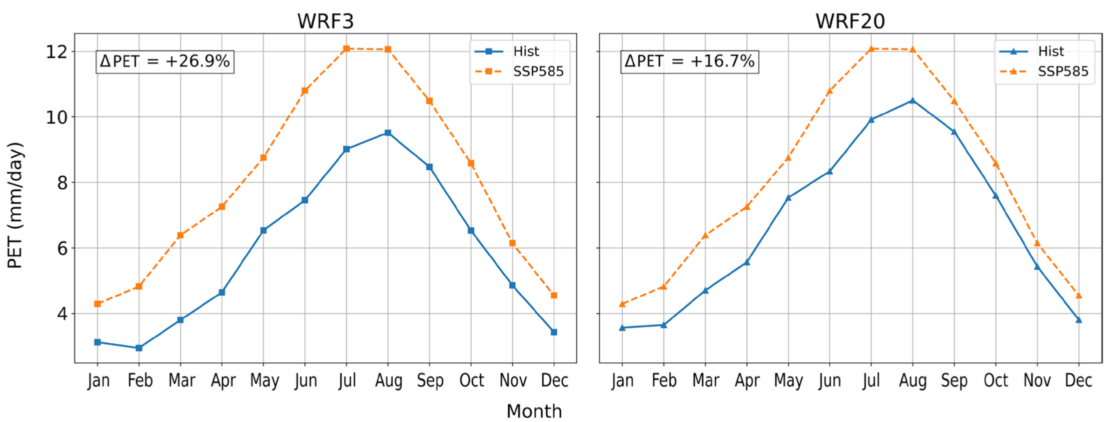

FIGURE 9 | Seasonal evolution of potential evapotranspiration (PET) in the Ourika basin under the SSP585 scenario, compared with the historical period, for the WRF3 (3 km) and WRF20 (20 km) configurations.

to model resolution and reinforce the need to account for inter-model uncertainty. Combined with the projected decline in precipitation, the substantial increase in PET points to heightened water scarcity risks in High Atlas basins under future climate conditions.

3.4.3 | Future Evolution of Streamflow

Monthly streamflow projections provide a direct assessment of how combined changes in precipitation and evaporative demand reshape hydrological regimes. In the snow-influenced Ourika Basin, the two hydrological models, HYPE and GR4J-CemaNeige, offer complementary insights due to their differing structures and representations of snow processes. Under the SSP585 scenario, both models project a severe reduction in future streamflow compared with the historical period (Figure 10a). The decline is strongest during the spring high-flow season (March–June), when meltwater typically sustains most of the runoff. With WRF3 forcing, streamflow decreases by −84.5% with HYPE and −87.8% with GR4J-CemaNeige. Under WRF20, reductions are weaker but still substantial (about −65% for both

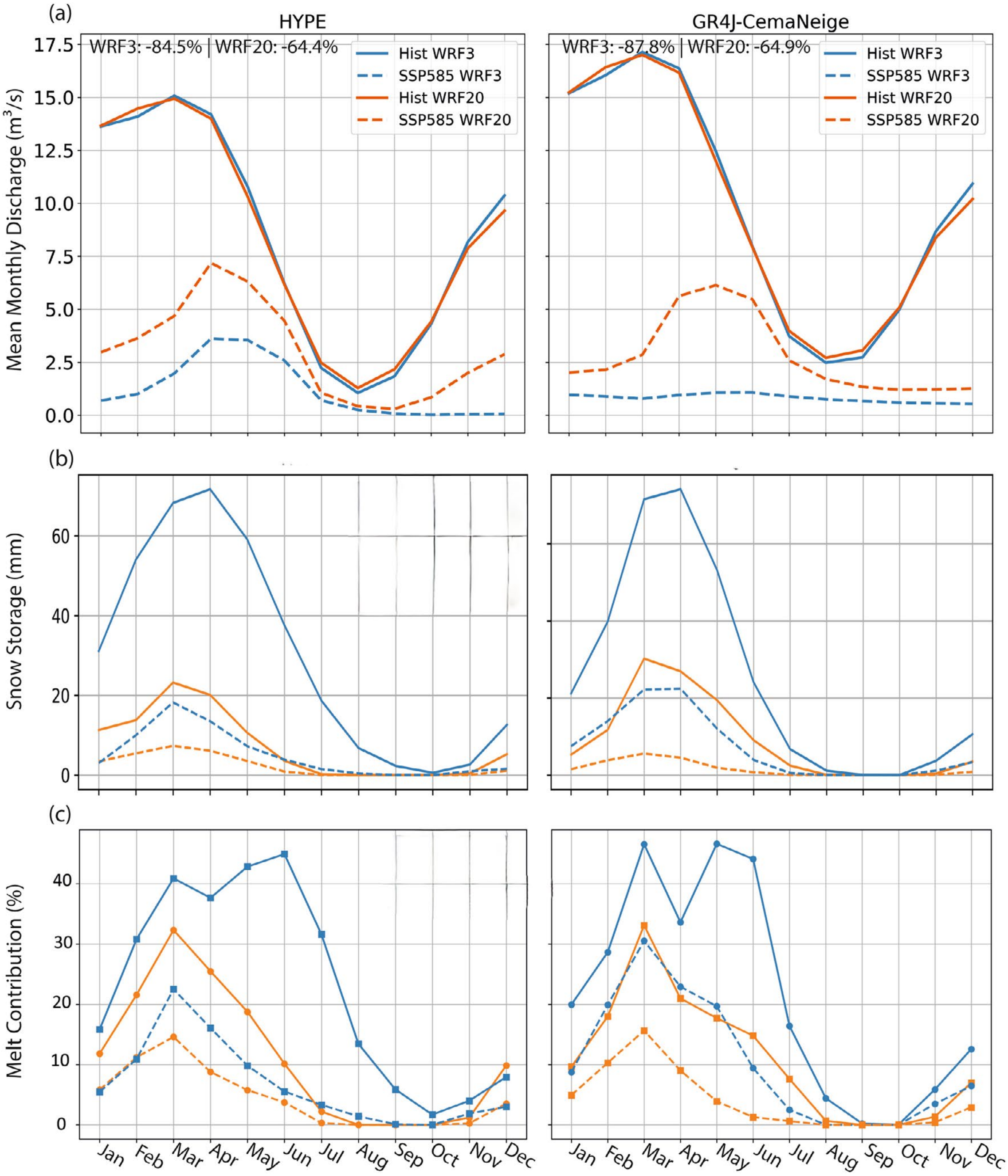

FIGURE 10 | Seasonal evolution of key hydrological variables in the Ourika basin simulated by the HYPE and GR4J-CemaNeige models forced by RegIPSL climate simulations at 3 km (WRF3) and 20 km (WRF20) resolution for the historical period (1996–2005) and the SSP5–8.5 scenario (2041–2050). Panels show (a) mean monthly discharge, (b) snow storage and (c) snowmelt contribution. The left column corresponds to HYPE simulations and the right column to GR4J-CemaNeige. Historical and future simulations are shown for both climate model configurations, allowing comparison of seasonal dynamics and projected changes under different resolutions and forcing conditions.

models). These contrasts confirm that climate model resolution strongly influences the magnitude of hydrological change. The hydrological models also respond differently. GR4J-CemaNeige, which represents snow accumulation and melt explicitly, shows a stronger sensitivity to snowpack loss, amplifying the decline in spring runoff. HYPE reproduces the same overall trend but with slightly lower magnitude, reflecting its more aggregated structure and less detailed snow representation. Overall, the projected decrease in streamflow reflects the combined influence of (i) sharply reduced precipitation, (ii) higher evaporative demand and (iii) a weakened snow contribution. The effect of evaporative demand should, however, be interpreted in light of the temperature-based Oudin formulation used in this study, which provides a coherent PET estimate for comparative hydrological modelling but does not explicitly represent all atmospheric controls on evapotranspiration. These mechanisms suggest a major intensification of water-stress conditions in the basin. The following sections further examine changes in snow storage and snowmelt timing, which are central to understanding the future hydrological regime in high-mountain basins.

3.4.4 | Future Evolution of Snow Storage

The annual cycle of snow storage in the Ourika Basin was simulated using HYPE and GR4J-CemaNeige forced with WRF3 (3 km) and WRF20 (20 km) climate data (Figure 10b). Under historical conditions, both models reproduce a clear seasonal snow accumulation, with a maximum in March–April followed by melt extending into early summer. For both hydrological models, WRF3 systematically simulates higher snow storage than WRF20 throughout the accumulation period. Under the SSP5–8.5 scenario, snow storage decreases substantially for all configurations, with near-zero values reached earlier in the year. While absolute snow storage remains higher in WRF3 than in WRF20, the relative reduction between historical and future periods is larger for WRF3, reflecting differences in simulated accumulation levels and temperature forcing. Differences between HYPE and GR4J-CemaNeige are apparent in the magnitude and timing of snow storage, but both models show a consistent response to warming. This reduction reflects the combined effects of rising temperatures, earlier melt onset, and a shift from snowfall to rainfall during winter. The loss of snow as a natural seasonal reservoir has major implications for spring and summer water availability. In snow-dominated mountain basins such as Ourika, diminished storage translates into reduced seasonal buffering capacity and heightened vulnerability to hydrological drought.

3.4.5 | Future Evolution of Snowmelt

The contribution of snowmelt to total streamflow was assessed using HYPE and GR4J-CemaNeige driven by WRF3 and WRF20 climate forcings (Figure 10c). Historically, snowmelt accounts for a substantial share of spring discharge, ensuring the transition between winter snowfall and early-summer water availability. GR4J-CemaNeige tends to attribute a larger fraction to snowmelt than HYPE probably due to its more detailed snow representation. Future projections show a pronounced decline in snowmelt contribution, especially during the spring peak period. This reduction arises from both diminished snow storage and earlier, faster melt under higher temperatures. As a result, snowmelt occurs sooner in the year and contributes less to spring flows. Differences between model configurations persist: WRF3 generally produces stronger reductions than WRF20, driven by its finer representation of warming intensification at high elevations. GR4J-CemaNeige also projects higher absolute contributions than HYPE, but both converge toward a strong downward trend under SSP585. These results confirm the high sensitivity of mountain hydrology to warming. The decreased role of snowmelt will weaken seasonal flow regulation, exacerbate late-summer water deficits, and increase inter-seasonal variability, adding pressure on water-dependent sectors.

4 | Discussion

The joint analysis of climate simulations, hydrological responses, and future projections shows that model resolution is key to represent hydro-climatic processes in mountains (Prein et al. 2015, 2016; Kendon et al. 2017; Poujol et al. 2025). This is consistent with the fact that the convection-permitting configuration WRF3 generally provides a more realistic hydroclimatic forcing than the 20 km configuration, as reflected by its improved seasonal precipitation cycle, lower errors in hydrological signatures, and better agreement with observed streamflow (Prein et al. 2016; Lucas-Picher et al. 2021). Previous studies in mountain regions have similarly shown that convection-permitting models can improve the representation of orographic precipitation, temperature gradients and snow-related processes (He et al. 2019; Lucas-Picher et al. 2021; Pichelli, Coppola, Sobolowski, et al. 2021; Pichelli, Coppola, Sobolowski, et al. 2021; Stuart et al. 2025). Raw RegIPSL simulations nevertheless exhibit substantial errors in both precipitation and temperature, particularly for extremes, which is consistent with the known limitations of regional models in complex terrain (Alexander et al. 2006; Giorgi and Lionello 2008).

CDF-t correction clearly improves the statistical agreement with the available observational reference (Alexander et al. 2006; Tramblay et al. 2016), but it does not erase the differences between WRF3 and WRF20. It should nevertheless be noted that precipitation observations in this high-mountain environment are themselves affected by uncertainty, including possible gauge undercatch and incomplete representation of solid precipitation (Sevruk 1996; Dahri et al. 2018). In this study, the reference dataset is based on a basin-averaged series reconstructed from seven rain gauges, including the high-altitude Oukaïmeden station, and complemented by a SWE-derived contribution to partly account for snowfall. Bias correction should therefore be interpreted as an adjustment toward the best available observational reference rather than toward an error-free estimate of precipitation. Hydrological simulations confirm that these contrasts in climate forcing directly shape runoff responses (Clark et al. 2008; Rogger et al. 2012). When driven by bias-corrected WRF3 data, both HYPE and GR4J-CemaNeige reproduce more realistic regimes than with WRF20, especially for peak-flow timing, low-flow seasonality, and the transition between snow-dominated and rain-dominated periods (Chaponnière et al. 2008; Boudhar et al. 2009). Improvements in hydrological signatures, such as the centre of timing, baseflow index, runoff ratio, or threshold precipitation, show that WRF3 better captures both the phasing and the non-linear response of mountainous catchments (Merz and Blöschl 2008; Blöschl et al. 2011). The fact that two structurally different hydrological models converge toward the same direction of change under WRF3 increases confidence that the signal is not an artifact related to a particular hydrological model structure (Clark et al. 2008; Hrachowitz et al. 2013). Indeed, even if HYPE and GR4J-CemaNeige models differ in their representation of storage, routing, and snow processes, they respond consistently to differences in climate forcing between WRF3 and WRF20.

For future projections, WRF3 reveals a much stronger drying and snow-loss signal under SSP585, consistent with observed trends in hydro-climatic extremes (Tramblay and Somot 2018). This raises an important question as to whether these changes are robust or location-specific. Since WRF3 produces substantially more pessimistic scenarios than WRF20 in the Ourika basin, we extended the analysis to a subset of additional High Atlas basins (Figure 1b; see also Supporting Information, Section S1) to assess whether this signal is regionally consistent. These basins were selected based on their robust hydrological performance in a previous study (Lahnik et al. 2025), although they have lower observational coverage than the Ourika basin, with generally only one rain gauge per basin and no snow measurements. For these basins, the same modelling framework was applied to analyse changes in precipitation, evapotranspiration, snow storage, snowmelt contribution, and streamflow under historical and SSP585 conditions. Although the limited observations do not allow the same level of historical evaluation as in Ourika, the comparison of future changes relative to the historical baseline provides an important regional perspective. Despite differences in size, elevation, and hydro-climatic regime, all tested basins show (Table 2) a consistent signal of amplified aridification under WRF3, with stronger reductions in winter and spring precipitation, higher evaporative demand, reduced snow storage, and a more pronounced decline in annual runoff than with the WRF20 model, consistent with regional climate change projections for the Mediterranean region (Ragab and Prudhomme 2002; Giorgi and Lionello 2008). This multi-basin comparison indicates that the severe changes obtained for the Ourika basin are not an isolated anomaly, but part of a broader regional pattern emerging from the high-resolution climate forcing. However, these results should still be interpreted in light of the limited observational constraints outside the Ourika basin and the absence of additional climate model realisations and scenarios.

These findings have several implications. First, they strengthen the case for using convection-permitting regional models in mountain impact studies: the improved representation of orographic precipitation and snow processes translates into more physically consistent hydrological responses at the basin scale (Prein et al. 2015; Kendon et al. 2017). Second, the systematic differences between WRF3 and WRF20 underline that intermediate-resolution RCMs without explicit convection may underestimate the severity of hydro-climatic change in complex terrain (Poujol et al. 2025), especially when snowpack acts as a key seasonal reservoir. At the same time, several limitations exist. An important methodological limitation concerns the spatial and temporal aggregation applied to the climate forcing: WRF20 and WRF3 outputs are aggregated to daily resolution and averaged at the sub-basin scale, which ensures consistency with the hydrological models used here but inevitably smooths part of the fine-scale variability, particularly in the convection-permitting configuration. The present framework should therefore be interpreted as a basin-scale assessment of the hydrological implications of high-resolution climate forcing, rather than as a full exploitation of kilometre-scale hydroclimatic heterogeneity. A finer hydrological discretization, or the use of more physically based distributed hydrological models, could allow a more explicit propagation of small-scale precipitation and temperature

TABLE 2 | Relative changes (%) in precipitation (Pr), evapotranspiration (ETP), streamflow (Q), and snow water equivalent (SWE) for five Atlas Mountain basins under the SSP5–8.5 scenario, using hydrological models HYPE and GR4J-CemaNeige forced by WRF3 (3 km) and WRF20 (20 km) simulations.

Basin	Forcing	Pr (%)	ETP (%)	Q-HYPE (%)	Q-GR4J (%)	SWE-HYPE (%)	SWE-GR4J (%)
Ourika	WRF3	−62.2	+26.9	−84.5	−87.4	−82	−79
	WRF20	−30.9	+16.7	−64.5	−64.9	−64	−60
Tarhat	WRF3	−35.6	+11.2	−58.3	−29.5	−81.7	−70.3
	WRF20	−2.2	+6.3	−34.6	−1.6	−74.2	−69.5
Bab Ouwnder	WRF3	−57.6	+10.2	−83.1	−87.6	−86.4	−71.3
	WRF20	−1.7	+2.7	−62.8	−70.6	−76.1	−66.7
Tillouguite	WRF3	−50.9	+22.4	−68.5	−69.0	−91.2	−84.6
	WRF20	−10.5	+13.4	−45.9	−41.8	−89.1	−59.8
Ait Ouchene	WRF3	−39.9	+7.3	−61.4	−66.2	−81.8	−76.0
	WRF20	−7.6	+1.3	−48.0	−50.0	−74.7	−64.2
Ain Aicha	WRF3	−46.7	+24.7	−85.0	−29.0	−73.5	−76.1
	WRF20	−18.1	+18.8	−61.8	−25.2	−69.2	−74.3

Note: Values represent percentage differences between future (2041–2050) and historical (1996–2005) periods.

variability into runoff simulations. Likewise, future work could also explore a more direct use of runoff simulated by the land-surface component of the regional climate model (Di Sante et al. 2021), in order to better exploit the native spatial resolution of convection-permitting simulations. However, such developments currently remain limited by data availability and modelling constraints in the Moroccan Atlas.

In addition, convection-permitting simulations remain computationally demanding, constraining ensemble size, simulation length, and the exploration of multiple emission scenarios. Such limitations complicate the construction of simulation sets that would allow a fuller investigation of the effects of model structure, boundary conditions and scenario uncertainty. At present, there is no comprehensive CPRCM model ensemble for Africa. Also, despite bias correction, residual errors persist in precipitation and temperature fields, and their evaluation is limited by the scarcity of high-elevation observations. In such mountainous environments, the available observations are themselves affected by representativeness limitations and cannot be considered as error-free references, whereas the regional climate simulations provide spatially continuous and physically consistent fields. Anthropogenic water uses and groundwater abstractions are also not explicitly represented, implying that simulated low flows likely underestimate the combined effects of climate change and water demand. Moreover, projections rely on a single high-emission scenario, a single global climate model, and two relatively short 10-year periods, which do not capture the full range of possible future hydro-climatic trajectories.

Overall, the discussion emerging from this work is twofold. On the one hand, convection-permitting regional models such as WRF3 provide a more credible physical basis for assessing climate-change impacts in mountain basins than conventional RCMs, and the multi-basin consistency of the signals they produce argues strongly for their wider use in water-resource assessments. On the other hand, the severity of the projected drying, snowpack loss, and runoff decline calls for caution in interpretation, systematic multimodal comparisons, and closer coupling with observational networks and water-management models. These results are also consistent with previous work highlighting the strong sensitivity of snow hydrology in the Moroccan Atlas Mountains to climate variability and warming (Barnett et al. 2005; Boudhar et al. 2009; Hanich et al. 2022). Together, these findings point toward an Atlas Mountain hydrology that is both more vulnerable and more strongly affected by climate change than suggested by coarser-scale models, with major implications for long-term planning of reservoirs, irrigation systems, and drought-risk management in Morocco's mountain water towers.

5 | Conclusion

This study provides an assessment of the hydrologic performance of the convection-permitting version of the RegIPSL regional climate model over the Ourika basin and additional representative catchments of the High Atlas Mountains, a region where water resources depend critically on orographic precipitation, snow accumulation and melt processes. By comparing a 3-km convection-permitting configuration (WRF3) with a 20-km parameterized-convection configuration (WRF20), and by integrating both into two structurally distinct hydrological models (HYPE and GR4J-CemaNeige), the analysis demonstrates the decisive role of model resolution in shaping both present-day simulations and future projections. Results show that high-resolution modelling substantially improves the representation of seasonal precipitation patterns and snow-related processes. These improvements propagate to the hydrological models, which reproduce streamflow dynamics, snow storage, and melt timing more realistically when driven by WRF3. Hydrological signatures confirm this added value for different indicators representative of the hydrological regime. Future projections under SSP585 indicate profound hydro-climatic changes, combining a marked decline in precipitation, a strong increase in evaporative demand, and a drastic reduction in spring streamflow and snow contribution. These changes are amplified when using high-resolution convection-permitting forcing, highlighting the high sensitivity of mountain hydrology to warming.

Overall, the findings underline the scientific and operational relevance of convection-permitting regional climate models for impact studies in complex terrain. Their enhanced physical realism strengthens confidence in future water-availability assessments and provides a more robust foundation for adaptation strategies related to water resources, flood management and drought preparedness. Despite computational constraints and remaining uncertainties, advances in high-resolution climate modelling offer promising avenues for improving climate-impact projections and supporting decision-making in mountain regions facing rapidly evolving hydro-climatic conditions.

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Data Availability Statement

Precipitation and discharge data were provided by the Agence du Bassin Hydraulique du Tensift (ABHT; https://www.abht.ma), the Agence du Bassin Hydraulique de l'Oum Er Rbia (ABH Oum Er Rbia; www.abhoer.ma), and the Agence du Bassin Hydraulique du Sebou (ABHS; https://www.abhsebou.ma), and are available upon request from the respective agencies. The RegIPSL simulation used in the present work is available upon request from Sophie Bastin. The ERA5 reanalysis data can be obtained from: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Additional High Atlas basins used for the multi-basin analysis. **Data S2:** Hydrological signatures used in the analysis. **Data S3:** Spatial patterns of climate simulations. **Figure S3:** Seasonal spatial distribution of precipitation and temperature simulated by the RegIPSL model at 20 km (WRF20) and 3 km (WRF3) resolution over the High Atlas region. Panels (a, b) show precipitation and (c, d) temperature. The Ourika basin and additional basins used in the multi-basin analysis are indicated for reference. These maps illustrate differences in spatial patterns between model resolutions, while the analysis in this study is conducted at the basin scale.