

Future Projection of Extreme Temperature, Precipitation and Runoff Indices in the Aga-Foua-Djilas Basin (Senegal) under Global Warming

Philippe Malick Dione^{1*}, Cheikh Faye¹

¹ Department of Geography, U.F.R. Sciences et Technologies, Assane Seck Univesity of Ziguinchor, Laboratory of Geomatics and Environment, Ziguinchor, Senegal, pm.d11@zig.univ.sn, cheikh.faye@univ-zig.sn

* Corresponding author

Abstract

Senegal is facing a growing challenge of severe climate and hydrological extremes as global warming accelerates. Developing countries, and Senegal in particular, are severely affected by these extreme climatic events due to their low adaptive capacity. Using the Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset, the study sought to ascertain how the Aga-Foua-Djilas basin's extreme temperature, precipitation, and runoff indices might react in the future to global warming below the levels predicted by the Shared Socioeconomic Pathways (SSP), SSP 126, SSP 370, and SSP 585 scenarios. Daily temperature, precipitation and runoff data from the Inter-Sectoral Impact Intercomparison Project (ISIMIP) are used in the study. Extreme temperature and precipitation indices as well as Indicators of hydrologic alteration (IHA) are calculated. The results show that future climate warming scenarios may cause a substantial decline in precipitation intensity and days of extremely heavy precipitation, which could account for the fall in total annual precipitation. As temperatures rise and precipitation decreases, the extreme flow indices will trend downward. The rainfall deficit will cause a decline in the medians of the minimum and annual flows over 1, 3, 7, 30, and 90 days for the upcoming period. Consequently, changes in climatic extremes are expected to increase the probability of severe extreme events. Therefore, climate change will influence future trends in the alteration of hydroclimatic variables in the watershed, making their study essential.

Key words:

climate change,
CMIP6,
flood, drought,
IHA

1 INTRODUCTION

Global warming has been linked to increases in temperature and precipitation intensity throughout Africa in recent decades (Tan et al., 2021; Thoeun, 2015). Due to their significant effects on many hydrological systems, these changes raise the danger of regional water events including droughts and floods (François et al., 2019; Kundzewicz et al., 2014). Severe droughts have the potential to drastically lower freshwater supply and agricultural yields, resulting in socioeconomic losses (Balti et al., 2020). Consequently, quantifying the impact of climate change on extreme precipitation and resulting extreme flows is important for developing better adaptation, more effective mitigation and greater resilience to water-related hazards.

Globally, hydrological cycles are being profoundly altered by climate change, contributing to more frequent floods and droughts, as well as changes in river flow patterns (Hirabayashi et al., 2013; Intergovernmental Panel on Climate Change (IPCC), 2023). This situation has a significant impact on water resources, river ecosystems, and human activities (Döll et al., 2018; Vörösmarty et al., 2010).

It is crucial for understanding the climate of the past, projecting future climate change, making policy

decisions, and signing international agreements (Yang & Jiang, 2017)]. Numerous studies on temperature and precipitation extremes have been conducted in various regions using the CMIP model as a basis. Some studies show that global warming is causing an increase in the frequency of extreme precipitation events around the world. (Papalexiou & Montanari, 2019). In Africa, extreme flows are sensitive to extreme climatic events. Numerous studies have assessed the impact of climate change on extreme flows in various river basins on the African continent (Rameshwaran et al., 2021). The changes reported vary from place to place.

Based on a new approach integrating CWatM, ISIMIP, CMIP6 and IHA indicators, this study aims to assess the impact of climate change on extreme flows in tropical regions. Projections of future temperature, precipitation and extreme flow indices in the Aga-Foua-Djilas are made for the period 2021-2100. In addition, variations in temperature, precipitation and extreme flow indices for the near future (2021-2040), the medium future 1 (2041-2060), the medium future 2 (2061-2080) and the far future (2081-2100) of the 21st century are analyzed in relation to the reference period (1985-2014).

2 MATERIALS AND METHODS

Study area

The Aga-Foua-Djilas watershed is located in the northern and north-western part of the Sine-Saloum delta (Fig. 1). In Senegal, the Sine-Saloum basin is one of the country's largest drainage basins. A system of rias drains it, with Sine and Saloum being the two principal ones. Many small low-lying areas crisscross the basin, and each winter, despite the ongoing drought, they drain significant amounts of run-off water. It covers the latitude range of 14°15'N to 14°25'N and the longitude range of 16°37'W to 16°53'W. Its perimeter is 115.7 km, and its total area is 317.5 km².

The Aga-Foua-Djilas watershed lies in the coastal North Sudanian domain (Sagna, 2005). During the period 1991-2020, the basin recorded average annual temperatures of between 27 and 28°C and total rainfall ranging from 550 to 700 mm/year (Dione, 2024).

In terms of geographical features, the highest points are situated in the northern and northwestern regions, with elevations ranging from 23 to 42 meters, encompassing 11.94% of the area. These elevations indicate the plateaus, which represent the highest sections of the topographic sequence. The middle elevations (12 to 23 m) make up 56.76% of the watershed's total surface area, which is over half. They create the linking inclines and serve as the areas of change between higher and lower elevations. They are situated at the heart of the basin. The bottommost regions of the topographical sequence have elevations between -8 to 12 meters and make up 31.30% of the watershed. They align with the lower areas along the water drainage system. They are larger in size in the southeastern section of the watershed, especially near the point where water flows out.

Data

Daily data on temperature, precipitation, and runoff are accessible through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (<https://www.isimip.org>), which serves as a comprehensive framework for evaluating climate change impacts across multiple scales and sectors (Lange, 2019). ISIMIP aims to improve the accuracy and scope of climate change research by integrating various global impact models, including global hydrological models. The ISIMIP3b protocol, designed to provide bias-corrected climate projections (Lange, 2019) from five climate models contributing to the IPCC Sixth Assessment Report, offers simulations at a spatial resolution of 0.5° × 0.5°. This protocol was specifically developed to support the IPCC Special Report on the 1.5°C global warming target (Frieler et al., 2017). Following the ISIMIP3b simulation protocol (www.isimip.org/protocol/#isimip3b), all general circulation model simulations were conducted at a spatial resolution of 0.5° × 0.5°. Among the five global climate models available on the ISIMIP platform, only MRI-ESM2-0 and its CWatM outputs (Burek et al., 2020) were utilized to characterize runoff in the study basin. Meanwhile, precipitation simulations were based on four climate models: GFDL-ESM4, CESM2-WACCM, CNRM-CM6-1-HR f2, and MRI-ESM2-0.

Methods

The data were first assessed for the Aga-Foua-Djilas basin and corrected using the modified quantiles method, which produced better results compared to other methods. The climate stations in Mbour (for temperature) and Fatick (for rainfall) were used for validation. These are the two climate stations closest to the watershed (Fig. 2.) The bias correction results show a correlation coefficient of over 0.70 for temperature (compared to 0.63 for the raw data) and 0.80 for precipitation (compared to 0.76 for the

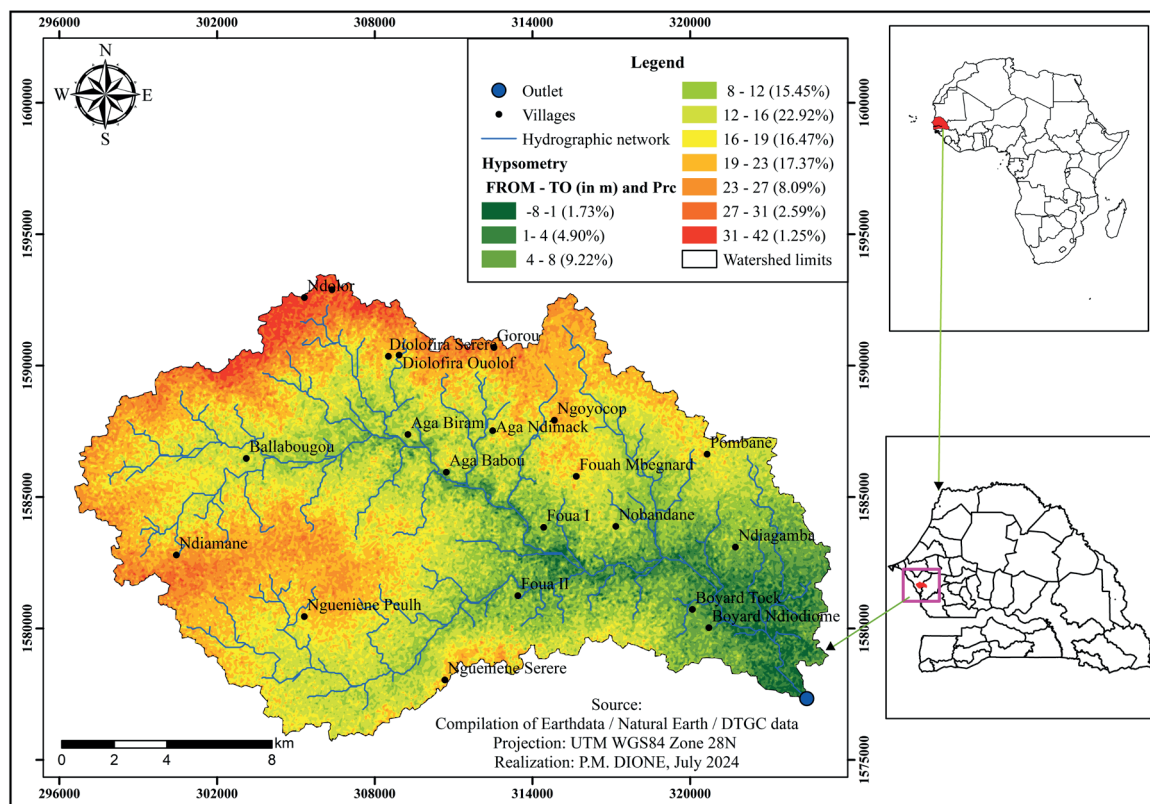


Fig.1: Aga-Foua-Djilas watershed presentation (Dione & Faye, 2025)

raw data) between the multi-model ensemble results and the observed data. Fig. 3 presents a comparison between observed, simulated, and bias-corrected data.

In this study, four extreme temperature indices and six extreme precipitation indices were selected, considering the fundamental meteorological characteristics of the Aga-Foua-Djilas basin. These indices have been widely recognized by the Expert Team on Climate Change Detection and Indicators (ETCCDMI) (Karl et al., 1999; Zhang et al., 2011) and have been extensively utilized in climate-related research (Akinsanola et al., 2021; Dong & Dong, 2021; Sun et al., 2021). The extreme climatic indices were computed using the ClimPACT2 tool (<https://github.com/ARCCSS-extremes/climpact2/>), which was released on August 1, 2023.

Methods for characterizing the daily variability of future temperatures in the basin

Future projections from the SSP126, SSP370, and SSP585 scenarios were used to compute a set of extreme temperature indices (Table 1). These indices include TN90p (annual percentage of days with a minimum temperature above the 90th percentile), TNx (annual maximum of daily minimum temperatures), TX90p (annual percentage of days with a maximum temperature above the 90th percentile), and TXx (annual maximum of daily maximum temperatures).

The Shared Socioeconomic Pathways (SSP) scenario families illustrate different levels of adaptation and mitigation challenges for societies (O'Neill et al., 2014). SSP1 emphasizes international

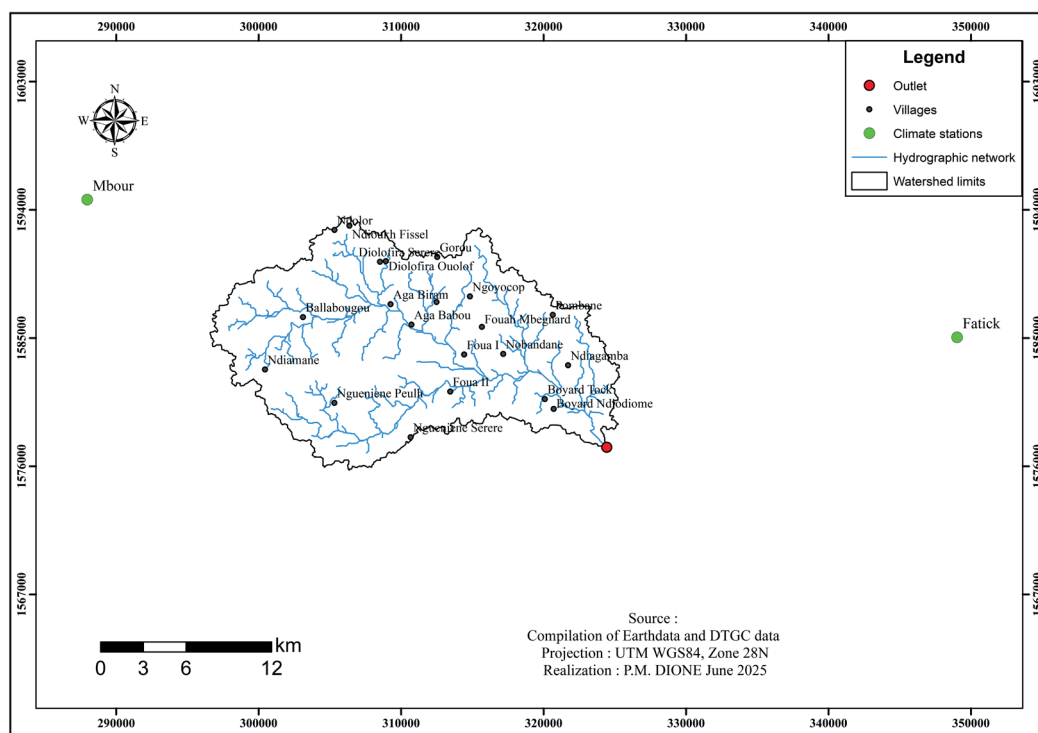


Fig. 2: Location of the Mbou and Fatick climate stations

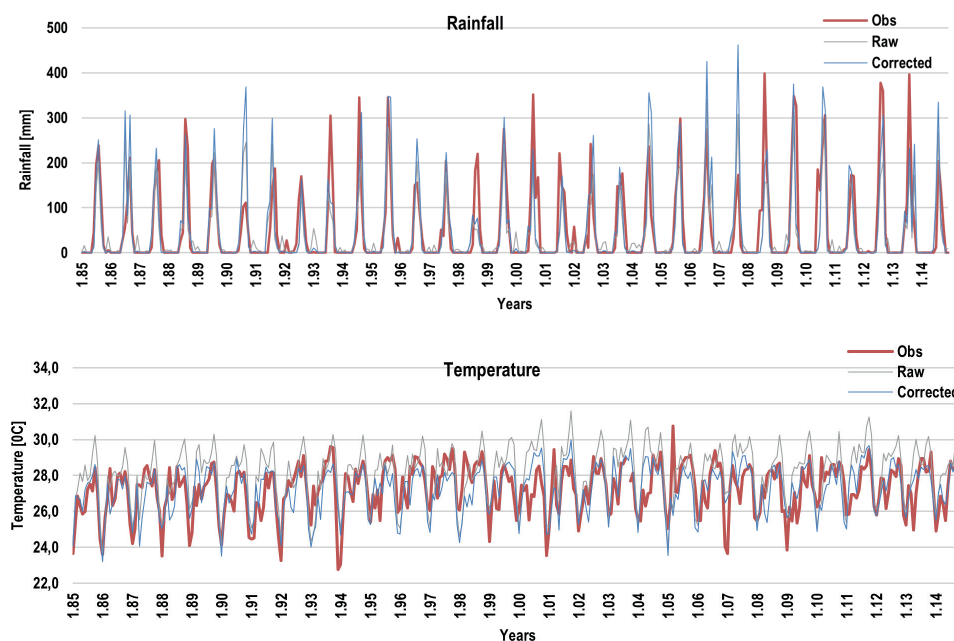


Fig. 3: Comparison of observed, simulated and corrected precipitation and temperature data

cooperation and sustainable development, aligning with the „Proaction“ pathway. SSP2 follows a trajectory of continuity with existing trends, resembling the „Inertia“ pathway. SSP3 reflects a context of geopolitical competition, characterized by slow economic growth and industrial policies, similar to the „Retrenchment“ pathway. SSP5 is associated with rapid development in emerging economies, driven by high energy consumption, corresponding to the „Growth at all costs“ pathway.

To facilitate analysis, the future projection period was divided into four 20-year intervals, starting in 2021: 2021–2040 (horizon 2030 or early 21st century), 2041–2060 (horizon 2050 or mid-21st century), 2061–2080 (horizon 2070), and 2081–2100 (horizon 2090 or late 21st century). This approach takes advantage of the model's long projection range, simplifying trend analysis. Precipitation data from 1985 to 2014 served as the reference period to assess the distribution of the four precipitation indices in the Aga-Foua-Djilas basin. The choice of this period (1985–2014) as the reference for these projections based on CMIP6 is linked to the fact that it corresponds to the last 30-year period fully covered by historical climate model simulations (Eyring et al., 2016). Being centered on the year 2000, it makes it possible to represent a recent climate without including future or extremely hot post-2015 years. This choice also facilitates comparison between observations and modelling within a methodologically consistent framework (Teah & Centre canadien des services climatiques, 2023).

Methods for characterizing the daily variability of future rainfall in the basin

Using projections from the SSP126 and SSP585 scenarios, a set of extreme precipitation indices commonly employed in climate studies (Bodian, 2014; Dos Santos et al., 2011; Xu et al., 2015) were calculated (Table 2). These indices include total annual precipitation on days exceeding the 99th percentile (r99p), maximum consecutive annual precipitation over three days (rx3days) and five days (rx5days), the Daily Rainfall Intensity Index (SDII), the maximum number of consecutive days with precipitation ≥ 1 mm (CWD), and the annual count of days with precipitation ≥ 10 mm (r10mm).

As with temperature, extreme precipitation for the 2021–2100 period is subdivided into four 20-year intervals: 2021–2040 (horizon 2030 or early 21st century), 2041–2060 (horizon 2050 or mid-21st

century), 2061–2080 (horizon 2070), and 2081–2100 (horizon 2090 or late 21st century). The distribution of these six precipitation indices in the Aga-Foua-Djilas basin is analyzed for each future period in comparison to the reference period (1985–2014).

Methods for characterizing the variability of future runoff using Indicators of hydrologic alteration (IHA) indices

The IHA method, developed by The Nature Conservancy (Richter et al., 1996) employed to evaluate the key hydrological characteristics influenced downstream of dams (Magilligan & Nislow, 2005) and the alteration of river hydrological regimes. This approach utilizes mean daily flow data to calculate 33 ecologically significant hydrological parameters, which are categorized into five groups (François et al., 2019; Kundzewicz et al., 2014). These categories include: (i) monthly average flow, (ii) annual extreme flow, (iii) timing of annual extreme flow, (iv) frequency and duration of high and low pulses, and (v) flow change rate and frequency (Richter et al., 1998). For this study, only the indices from Group 2 (Annual extreme flow) are presented (Table 3).

The method requires approximately twenty years of flow data, both before and after changes to the hydrological regime of the watercourse. The RVA method, which relies on the IHA, is a widely used approach for assessing hydrological changes in river ecosystems (Huang et al., 2019; Richter et al., 1996). In this study, the number of rises and falls of the parameter used in the RVA method was replaced with the number of hydrological changes. The IHA values for each indicator in each hydrological year were calculated using the mathematical approach described in previous research (Barbalić & Kuspilić, 2014) and the results were then used to evaluate hydrological alterations using the histogram comparison technique.

Mann Kendall test

Trends in extreme temperature, precipitation and flow series are determined by the Mann Kendall test, and the Kendall Tau used to determine the magnitude of the trend.

Offer comprehensive details to enable independent replication of the work. Summarize methods that are already published, providing references. If directly quoting from a previously published method, use quotation marks and cite the source. Describe any modifications made to existing methods.

Tab. 1. Definitions of selected extreme temperature indices

Index	Index name	Definition
TN90p	Warm nights	Annual percentage of days where TN > 90th percentile
TNx	Max of Tmin	Maximum annual value for daily minimum temperatures
TX90p	Hot days	Annual percentage of days where TX > 90th percentile
TXx	Max de Tmax	Maximum annual daily temperatures

Tab. 2. Definitions of selected extreme precipitation indices

Index	Index name	Definition
R99p	Days of extreme rain	Total annual precipitation in days > 99th percentile
Rx3days	Maximum rainfall over 3 days	Maximum consecutive annual precipitation over 3 days
Rx5days	Maximum rainfall over 5 days	Maximum consecutive annual precipitation over 5 days
SDII	Daily rainfall intensity index	Ratio of total annual rainfall to the number of wet days (≥ 1 mm)
CWD	Consecutive rainy days	Maximum number of consecutive days with rainfall ≥ 1 mm
r10mm	Number of days with very heavy rainfall	Annual number of days with rainfall ≥ 10 mm

3 RESULTS

Daily climate analysis using indices

Daily variability of future temperatures in the basin

Table 4 and Fig. 4, 5, and 6 present the results of the four extreme temperature indices for the different future periods, compared with the base period, along with the observed trends of change in the Aga-Foua-Djilas basin.

The highest daily maximum (TXx) and minimum (TNx) temperatures are projected to rise from 2021 to 2100. Compared to the reference period, with an average maximum temperature of 36.3°C, the daily maximum temperature (TXx) is projected to increase by approximately 5.08°C under SSP 126, 6.07°C under SSP 370, and 6.36°C under SSP 585 over the future period. For the mean minimum temperature, which is 27.2°C during the reference period, a decrease of -0.16°C is expected under SSP 126, while increases of 0.43°C under SSP 370 and 0.84°C under SSP 585 are anticipated. The changes become more pronounced towards the end of the century, with TXx values reaching up to 8.52°C and TNx values up to 2.38°C under SSP 585. However, for the periods 2021-2040 and 2041-2060, the trends

for TXx and TNx are generally lower compared to the reference period, as evidenced by the negative values observed during these periods.

In the Aga-Foua-Djilas basin, there have also been significant changes in the frequency of warm nights (TN90p) and warm days (TX90p). Compared with the reference period, average warm days (TX90p) have increased by 4.4% under SSP 370 and 4.77% under SSP 585 over the future period, and warm nights (TN90p) by 0.67% under SSP 126, 3.9% under SSP 370 and 5.48% under SSP 585 over the future period. The changes are greater towards the end of the century, with TX90p values of up to 201% and TN90p values of up to 211% under SSP 585. On the other hand, over the periods 2021-2040 and 2041-2060, the trends in TX90p and TN90p are often downwards compared with the reference period, as can be seen from the negative values noted for them.

The analysis of the Mann-Kendall test results for the four extreme temperature indices selected for the future period at the outlet of the Aga-Foua-Djilas basin (Table 5) reveals statistically significant upward trends at a 0.05 level of significance. However, the magnitude of change is highest under SSP 585, followed by SSP 370 and SSP 126, indicating a more pronounced

Tab. 3. Summary of the IHA parameters and their hydrological significance: amplitude and duration of extreme annual conditions (Richter et al., 1998)

Categories	IHA parameter groups
Group 2: Annual extreme flow	Annual lows. average over 1 day
	Annual minimums. 3-day average
	Annual minimums. 7-day average
	Annual lows. 30-day average
	Annual minimums. 90-day average
	Annual; maximums. average over 1 day
	Annual maximum. 3-day average
	Annual maximum. 7-day average
	Annual maximum. 30-day average
	Annual maximum. 90-day average
	Number of days with no flow
	Base flow index: minimum flow over 7 days / average flow for the year

Tab. 4. Absolute and percentage changes in the four extreme temperature indices selected for the future period compared with the reference period at the outlet of the Aga-Foua-Djilas basin

SSP 126	TN90p (%)	TNx (°C)	TX90p (%)	TXx (°C)
2021-2040	-34.8	-0.46	-31.8	4.84
2041-2060	-5.14	-0.24	-18.1	5.05
2061-2080	20.1	-0.01	11.1	5.40
2081-2100	22.5	0.07	38.1	5.04
SSP 370	TN90p (%)	TNx (°C)	TX90p (%)	TXx (°C)
2021-2040	-87.5	-0.65	-88.0	4.76
2041-2060	-50.8	0.16	-61.9	5.47
2061-2080	20.5	0.82	30.0	6.83
2081-2100	134	1.39	138	7.20
SSP 585	TN90p (%)	TNx (°C)	TX90p (%)	TXx (°C)
2021-2040	-91.9	-0.46	-91.9	4.53
2041-2060	78.1	0.21	-69.5	5.72
2061-2080	-19.0	1.23	-20.5	6.69
2081-2100	211	2.38	201	8.52

Tab. 5. Average annual variations in the four extreme temperature indices selected for the future period. based on the Mann Kendall test at the outlet of the Aga-Foua-Djilas basin. with a 0.05 risk of error

Kendall Tau	TN90p (%)	TNx (°C)	TX90p (%)	TXx (°C)
SSP 126	0.407	0.367	0.478	0.170
SSP 370	0.776	0.694	0.790	0.562
SSP 585	0.823	0.790	0.804	0.725

warming trend in the most intensive emission scenario.

For Warm Nights (TN90p), Kendall's Tau is 0.407% per year under SSP 126, 0.776% per year under SSP 370 and 0.823% per year under SSP 585 and for Warm Days (TX90p), Kendall's Tau is 0.478% per year under SSP 126, 0.790% per year under SSP 370 and 0.804% per year under SSP 585. For the maximum annual value of daily minimum temperatures (TNx), Kendall's Tau is 0.367°C per year under SSP 126, 0.694°C per year under SSP 370 and 0.790°C per year under SSP 585, and for the maximum annual value of daily maximum temperatures (TXx), Kendall's Tau is 0.170°C per year under SSP 126, 0.562°C per year under SSP 370 and 0.725°C per year under SSP 585.

Fig. 7 illustrates the spatial distribution of extreme temperature indices over the entire future period (2021-2100). The spatial distribution differs according to the extremes. TN90p and TX90p (%), will have practically the same spatial evolution. They will increase from east-northeast to west-southwest under all scenarios. TXx (°C) will rise from east to west, while TXx (°C) will fall along the same gradient under all scenarios. Frequencies will be more severe under SSP 585.

The findings of this study indicate an increase

in the frequency and intensity of extreme warm temperatures, while extreme cold temperatures have shown a declining trend in the basin.

Daily variability of future rainfall in the basin

The variations in the six precipitation indices for the Aga-Foua-Djilas basin are summarized in Table 6 and Table 7. Future projections of these indices at the beginning, middle, and end of the 21st century, compared to the historical period (1985-2014), are illustrated in Fig. 8, 9, and 10 at the basin outlet. These Figures show that the wet index (CWD) will decrease considerably as a result of global warming over the future period (2015-2100), with decreases of around -22.1%, -28.7% and -30.9% respectively under SSP 126, SSP 370 and SSP 585. It remains the only index to show a uniform downward trend over all periods (near, medium and far future) and under all scenarios. As for the index of the number of days of very heavy precipitation (r10mm), although it will increase by around 21.5% under SSP 126, it will remain slightly down under SSP 370 (with -2.1%) and SSP 585 (with -2.38%). The trend in the four remaining indices, which is much more variable, is almost certain to continue into the middle of the 21st

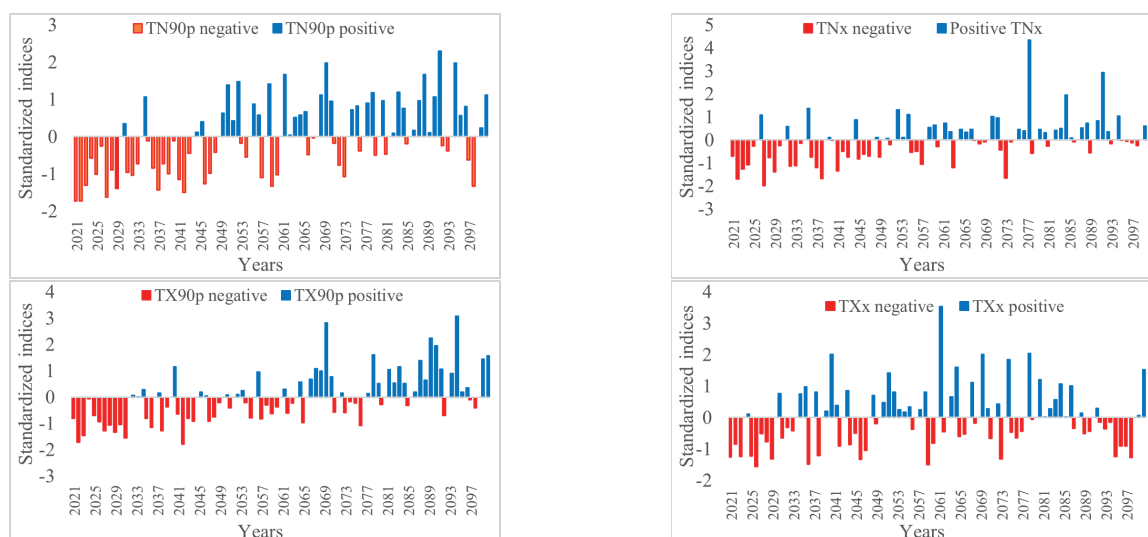


Fig. 4: Trend in standardized indices of the four extreme temperature parameters selected for the future period according to the SSP 126 scenario at the outlet of the Aga-Foua-Djilas basin

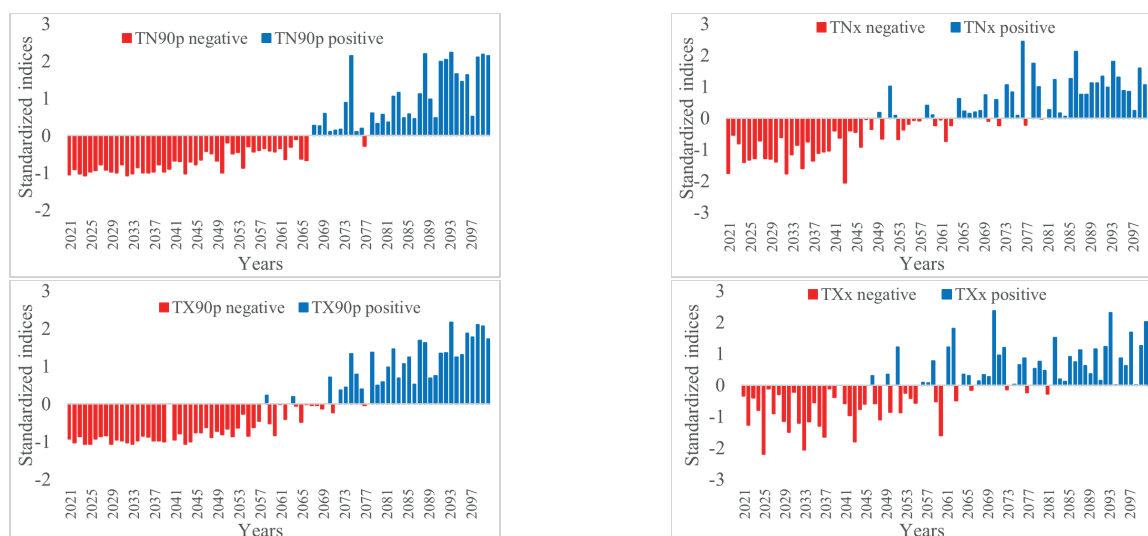


Fig. 5: Trend in standardized indices of the four extreme temperature parameters selected for the future period according to the SSP 370 scenario at the outlet of the Aga-Foua-Djilas basin

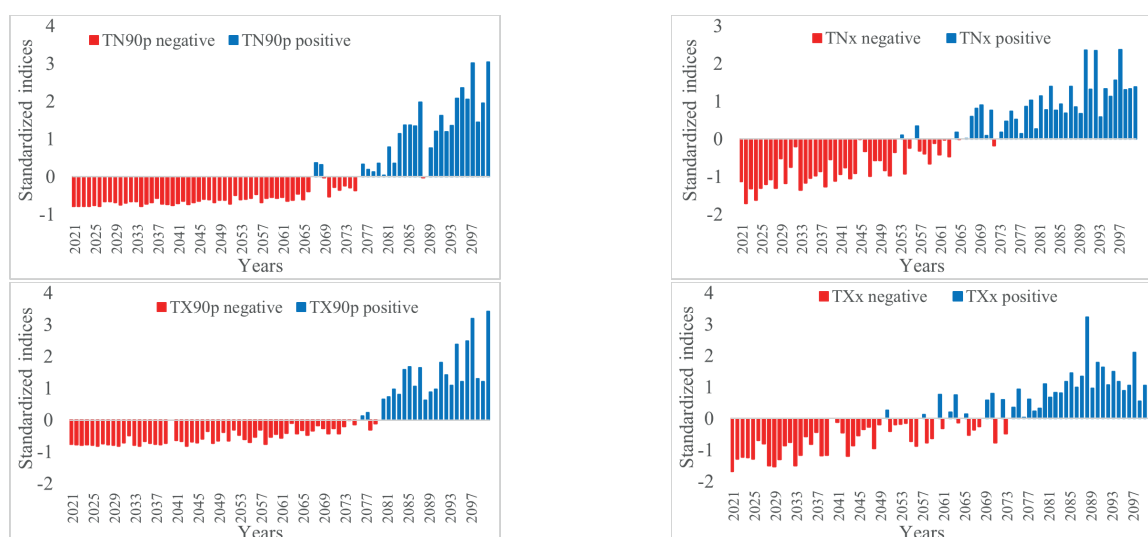


Fig. 6: Trend in standardized indices of the four extreme temperature parameters selected for the future period under the SSP 585 scenario at the outlet of the Aga-Foua-Djilas basin.

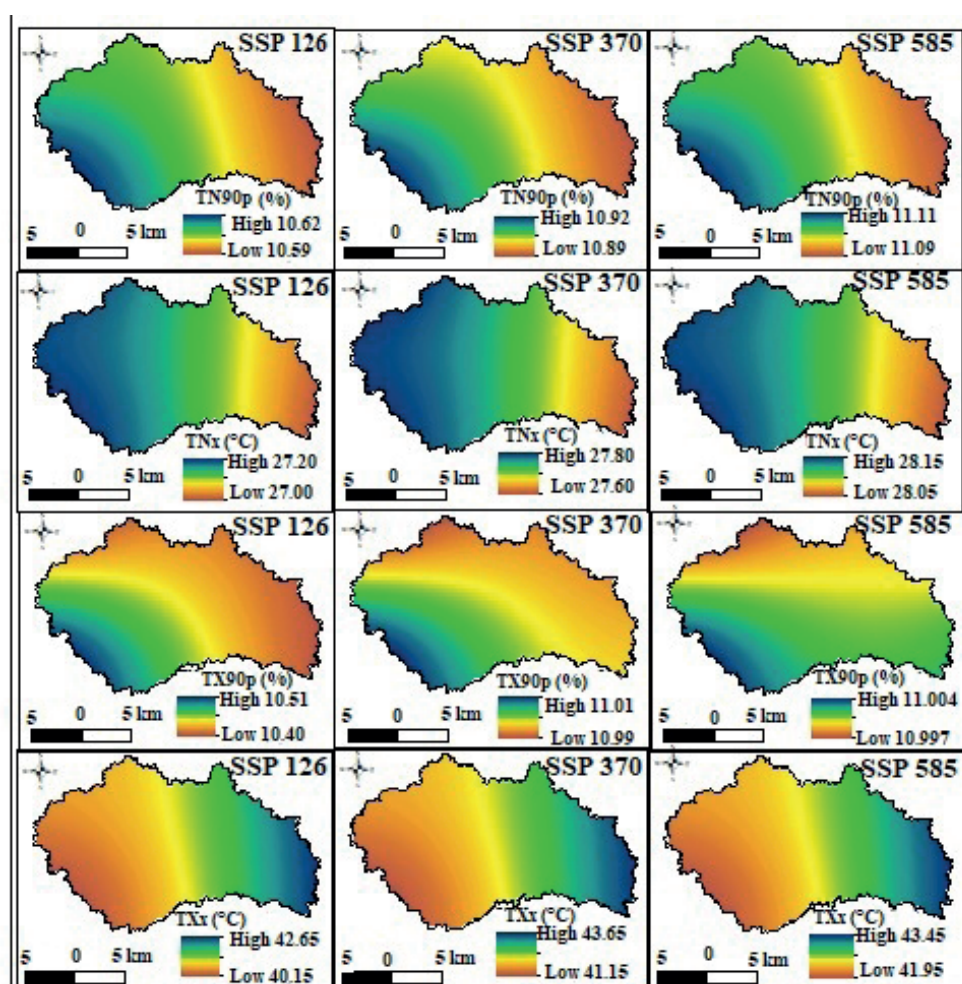


Fig. 7: Spatial distribution of selected temperature extremes in the Aga-Foua-Djilas watershed, over the period 2021-2100.

century. Rx3day shows the strongest growth over the period 2041-2060, with percentages of around 71.2%, 62.4% and 42.1% under SSP 126, SSP 370 and SSP 585 respectively. On the other hand, towards the end of the century (2081-2100), Rx3day will sometimes increase under SSP 126 (20.4%) and SSP 370 (5.12%), and sometimes decrease under SSP 585 (-17.4%). The trends observed for the other indices (R99p, Rx5day, and SDII) are generally consistent with

those of Rx3day, although the magnitude of changes may be relatively smaller. Additionally, variations in indices related to rainfall intensity (R10mm, Rx3day, Rx5day, and R99p) confirm an increase in both the intensity and frequency of heavy rainfall events in the Aga-Foua-Djilas basin around mid-century, followed by a decline towards the end of the 21st century. In addition, the SDII indicates a significant reduction in the average precipitation intensity per rainy day by

the end of the century, with decreases of up to 36.6% under SSP 370 and 46.3% under SSP 585. It should be noted, however, that the direction of change of certain indices (R95p, Rx3day, and SDII) under SSP 370 and SSP 585 differs from that under SSP 126. This shows that the overall intensity of precipitation in the Aga-Foua-Djilas basin under SSP 370 and SSP 585 is lower than that under SSP 126, but the number of precipitation days is likely to decrease.

Overall, climate projections indicate that the Aga-Foua-Djilas basin will experience increased humidity around the mid-21st century, followed by a marked drying trend towards the end of the century. Several extreme precipitation indices (R10mm, R99p, Rx3day, Rx5day, and SDII), which reflect precipitation intensity, indicate a significant decline in both the intensity and frequency of heavy rainfall events under SSP 585 by 2100. As a result, total precipitation in the basin is expected to decrease considerably in a warming climate. This trend is likely to heighten the risk of drought and increase the region's vulnerability to extreme weather events.

Under the SSP 126 scenario, the CWD at the end of the 21st century will increase by 0.059 days per year on average over the period 2015-2100, while over the same period it will decrease by -0.226 days per year under SSP 370 and -0.317 days per year under SSP 585. Unlike the CWD, the Man Kendall test indicates. A downward trend for all the other extreme precipitation indices under SSP 126 (-0.180 mm per year for R99p, -0.152 mm per year for Rx3days, -0.109 mm per year for Rx5days, -0.132 mm per year for SDII and -0.133 days per year for r10mm). Under SSP 370 and SSP 585, all trends are downwards. Under SSP 370, a decrease of around -0.132 mm per year, -0.261 mm per year, -0.311 mm per year, -0.308 mm/day per year, -0.226 days per year and -0.302 days per year respectively for R99p, Rx3days, Rx5days, SDII, CWD and r10mm. Under SSP 585, a decrease of around -0.220 mm per year, -0.351 mm per year, -0.355 mm per year, -0.404 mm /day per year, -0.317 days per year and -0.457 days per year respectively for R99p, Rx3days, Rx5days, SDII, CWD, r10mm. The rate of precipitation declines in the Aga-Foua-Djilas basin over the 21st century under SSP 585 is significantly higher than the other two SSP scenarios.

The Aga-Foua-Djilas basin is a region of significant agricultural production, where interannual variations in extreme precipitation indices throughout the 21st century directly influence downstream runoff and overall annual discharge. Therefore, projecting future

interannual changes in these indices is crucial for anticipating hydrological variability in the basin. This projection provides a clearer understanding of how extreme precipitation patterns may evolve under different SSP scenarios, offering valuable insights for water resource management and agricultural planning.

Fig. 11 illustrates the spatial distribution of precipitation indices across the different SSP scenarios, highlighting potential variations in rainfall patterns within the Aga-Foua-Djilas basin. All indices will follow the same spatial pattern, depending on the scenario. They will increase from northwest to south and southeast. Their frequencies will drop under SSP 370, and this drop will become more pronounced under SSP 585. The north, west and center of the basin will be more exposed.

Figures 7 and 11 show little spatial variability in temperature and precipitation indicators. This shows that there is a degree of climatic homogeneity across the watershed (Dione, 2024).

Daily variability of future runoff in the basin based on IHA indices

Tables 8 and 9 as well as Fig. 12 display the findings of the IHA tool's computation of the yearly minima and maximum flows' magnitude and duration for various time periods, such as one day, three days, seven days, thirty days, and ninety days, in addition to the number of days of base flow and zero flow. Understanding these indicators provides valuable insights for policymakers, water managers, hydrologists, and researchers on the impacts of human activities - such as land use changes and anthropogenic climate change - on rivers and groundwater resources. To characterize and measure changes in these extreme aspects linked to climate change, comparative analysis can be used.

Group 2 index hydrological impairment is seen as a high impairment. Only minimal annual extreme flows indicate low to moderate change; the other IHA indices for minimum annual extreme flows imply significant and severe alterations. Fig. 12 presents the time series for the Aga-Foua-Djilas basin, illustrating the median values along with the boundaries of the mean category (i.e., first and third quartiles), calculated based on the pre-impact reference period. It also highlights the maximum and minimum median values over 1-day, 3-day, 7-day, 30-day, and 90-day periods, comparing the pre-impact (reference period) and post-impact (future period) conditions.

Under the SSP 126 scenario, minimum and maximum flows at 1, 3, 7, 30 and 90 days will

Tab. 6. Percentage change in the six extreme precipitation indices selected for the future period compared with the reference period at the outlet of the Aga-Foua-Djilas basin

SSP 126	R99p	Rx3day	Rx5day	SDII	CWD	r10mm
2021-2040	30.2	55.0	44.4	48.4	-24.3	28.9
2041-2060	25.8	71.2	59.8	59.3	-18.9	46.1
2061-2080	29.9	46.6	41.8	34.7	-22.3	9.27
2081-2100	-57.2	20.4	18.5	26.6	-22.8	1.83
SSP 370	R99p	Rx3day	Rx5day	SDII	CWD	r10mm
2021-2040	106.3	82.1	76.9	51.9	-8.6	32.4
2041-2060	34.5	62.4	52.4	41.6	-33.1	6.9
2061-2080	-19.3	16.3	13.4	15.7	-30.6	-11.1
2081-2100	-37.1	5.12	-8.62	3.24	-42.3	-36.6
SSP 585	R99p	Rx3day	Rx5day	SDII	CWD	r10mm
2021-2040	74.6	90.8	87.1	63.7	-12.5	56.7
2041-2060	43.9	42.1	35.8	34.7	-20.8	14.0
2061-2080	-66.8	5.99	-3.93	2.61	-47.2	-33.8
2081-2100	-49.2	-17.4	-24.7	-6.4	-42.8	-46.3

increase significantly by 85.3% to 200% and 143% to 219% respectively over the period 2021-2060, while they will decrease significantly by -77.1% to -93% and -2.2% to -15.9% respectively over the period 2061-2100. Under the SSP 370 scenario, minimum and maximum flows at 1, 3, 7, 30 and 90 days will increase significantly from 249% to 311% and from 38.2% to 377%, respectively, over the period 2021-2060, while they will decrease significantly from -88.2% to -100% and from -14.5% to -76.2%, respectively, over the period 2061-2100. Under the SSP 585 scenario, minimum and maximum flows at 1, 3, 7, 30 and 90 days will increase significantly from 64.3% to 516% and from 163% to 411%, respectively, over the period 2021-2060, whereas they will decrease significantly from -100% and from -92.0% to -93.8%, respectively, over the period 2061-2100. There is a significant difference in the case of extremely high flows at maxima of 1, 3 and 7 days. There is a maximum for the case of extremely high flows at maxima of 1, 3 and 7 days, flows, showing that the extent of floods could increase in the near future and droughts could increase in the distant future.

Similar to the base flow index, a significant decrease is expected in the far future period, with reductions of up to -82.5% under SSP 126 and -100% under SSP 370 and SSP 585. This suggests that the future availability of water for freshwater supply is likely to decline sharply compared to current

levels. Consequently, water supply stress could be exacerbated if water consumption increases due to factors such as future population growth and the expansion of irrigated agriculture.

Zero-flow days, which are currently limited to 132 days in the reference period, are expected to increase significantly during the post-impact period (2021-2100). This increase, which could lead to considerable mortality of aquatic organisms and threaten the ecological quality and continuity of the ecosystem, is projected to reach 152 days under SSP 126, 212 days under SSP 370, and 206 days under SSP 585.

This makes perfect sense because, especially toward the end of the century, the reference era saw more precipitation than the subsequent period. The increase in zero-flow days, which can be attributed to both climate change and growing drought, is extremely disastrous for aquatic ecosystems. The findings show that climate change has an impact on the maximum and minimum flows on a daily, weekly, monthly, and quarterly basis in both positive and negative ways.

Significant differences were observed in the maximum and minimum annual flows between the reference and post-impact periods. The medians of the 1-, 3-, 7-, 30-, and 90-day annual minimum flows have increased due to climate change, while the medians of the maximum annual flows over the same timeframes have decreased sharply, largely due to the rainfall deficit. Under SSP 585, while the dispersion

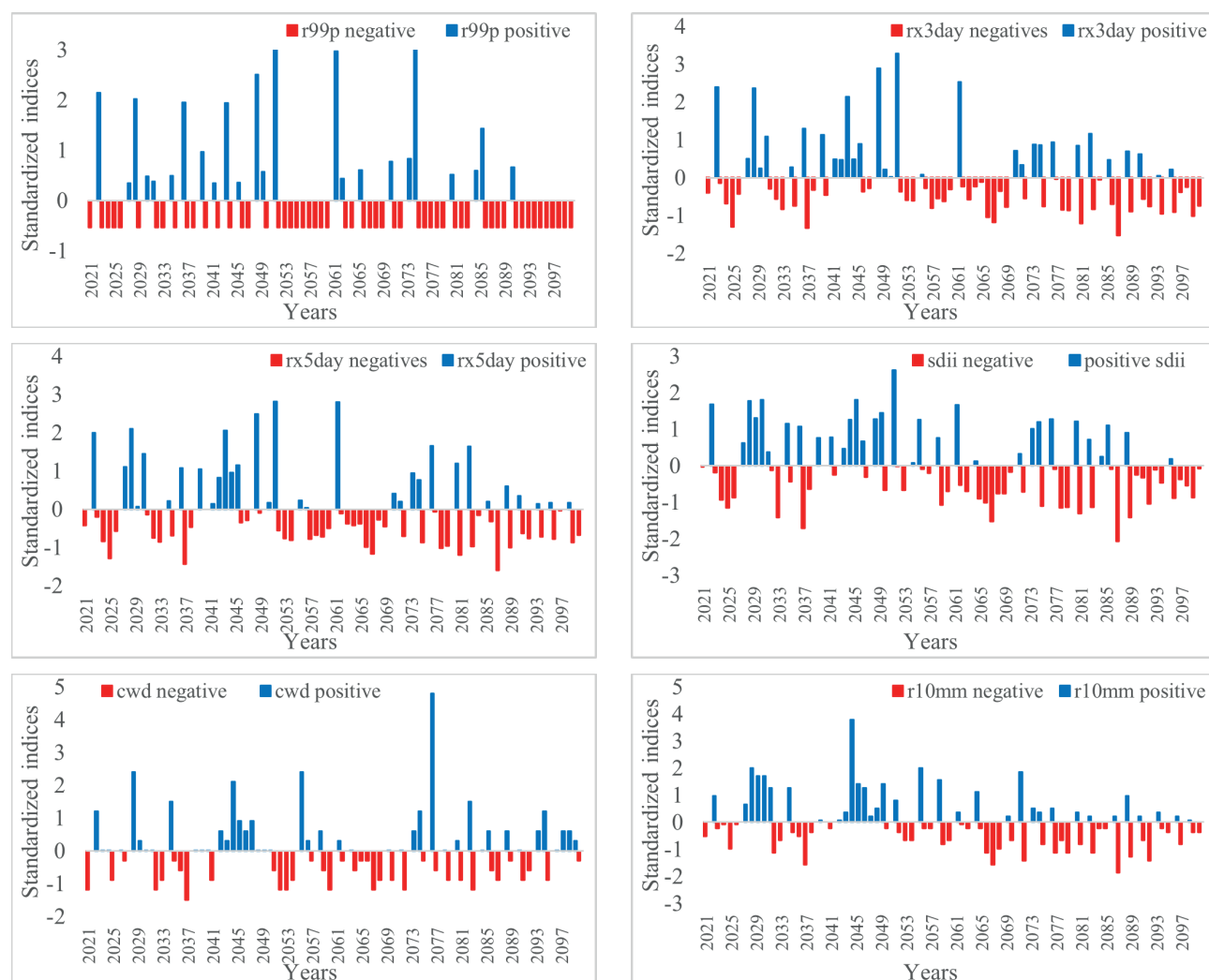


Fig. 8: Trends in standardized indices for the six extreme rainfall parameters selected for the future period under the SSP 126 scenario at the outlet of the Aga-Foua-Djilas basin

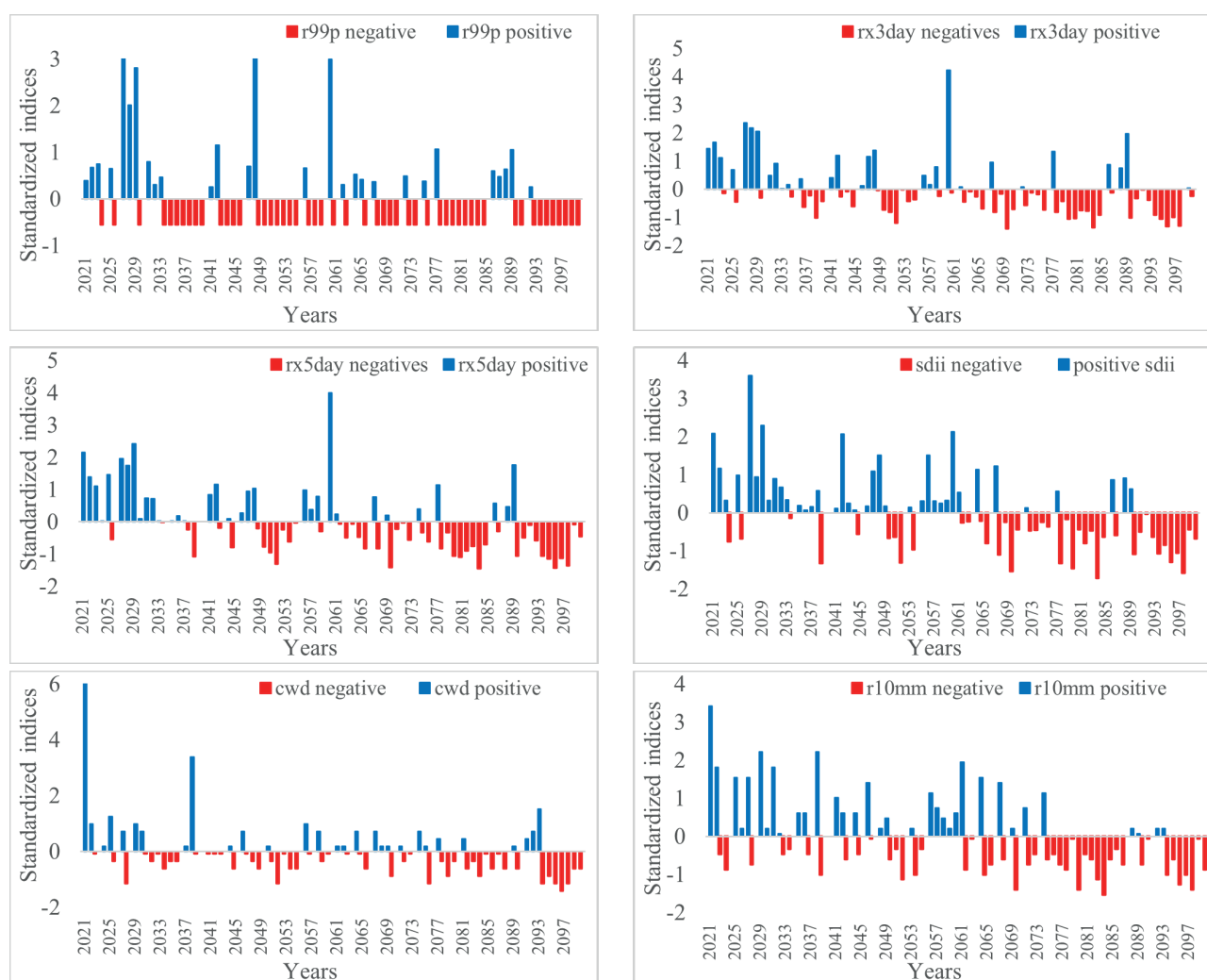


Fig. 9: Trends in standardized indices for the six extreme precipitation parameters selected for the future period under the SSP 370 scenario at the outlet of the Aga-Foua-Djilas basin

coefficients for minimum annual flows are zero, those for maximum annual flows during the future period range from 3.84 to 4.18, which are generally higher than the values observed in the reference period (ranging from 0.87 to 2.00). The base flow index is projected to be lower in the future period (zero) due to the impacts of climate change.

Under the SSP 126 scenario, the Mann Kendall test for minimum and maximum flows over 1, 3, 7, 30, and 90 days shows a statistically significant downward trend at the 0.05 risk level, with Kendall's tau ranging from -0.18 to -0.24. In the SSP 370 scenario, the minimum and maximum flows at these time intervals

indicate a significant decrease at the 0.05 risk level, with Kendall's tau ranging from -0.38 to -0.42. The SSP 585 scenario demonstrates the most pronounced downward trend, with Kendall's tau ranging from -0.42 to -0.56 for minimum and maximum flows at 1, 3, 7, 30, and 90 days. A statistically significant downward trend was also observed for base flow, with Kendall's tau values of -0.22, -0.41, and -0.39 for SSP 126, SSP 370, and SSP 585, respectively. In contrast, the number of zero-flow days showed a statistically significant upward trend, with Kendall's tau values of 0.21, 0.47, and 0.55 for SSP 126, SSP 370, and SSP 585, respectively (Table 8).

Tab. 7. Average annual variations in the six extreme precipitation indices selected for the future period. based on the Mann Kendall test at the outlet of the Aga-Foua-Djilas basin. with a 0.05 risk of error

Kendall Tau	R99p	Rx3day	Rx5day	SDII	CWD	r10mm
SSP 126	-0.180	-0.152	-0.109	-0.132	0.059	-0.133
SSP 370	-0.132	-0.261	-0.311	-0.308	-0.226	-0.302
SSP 585	-0.220	-0.351	-0.355	-0.404	-0.317	-0.457

Tab. 8. Average annual variations in the twelve extreme runoff indices selected for the future period based on the Mann Kendall test at the outlet of the Aga-Foua-Djilas basin with a 0.05 risk of error

Kendall Tau	1-day min	3-day min	7-day min	30-day min	90-day min	1-day max	3-day max	7-day max	30-day max	90-day max	Zero days	Base flow
SSP 126	-0.24	-0.24	-0.24	-0.23	-0.20	-0.18	-0.18	-0.18	-0.19	-0.19	0.21	-0.22
SSP 370	-0.42	-0.42	-0.42	-0.42	-0.45	-0.38	-0.38	-0.38	-0.38	-0.39	0.47	-0.41
SSP 585	-0.42	-0.42	-0.42	-0.42	-0.44	-0.56	-0.55	-0.55	-0.55	-0.56	0.55	-0.36

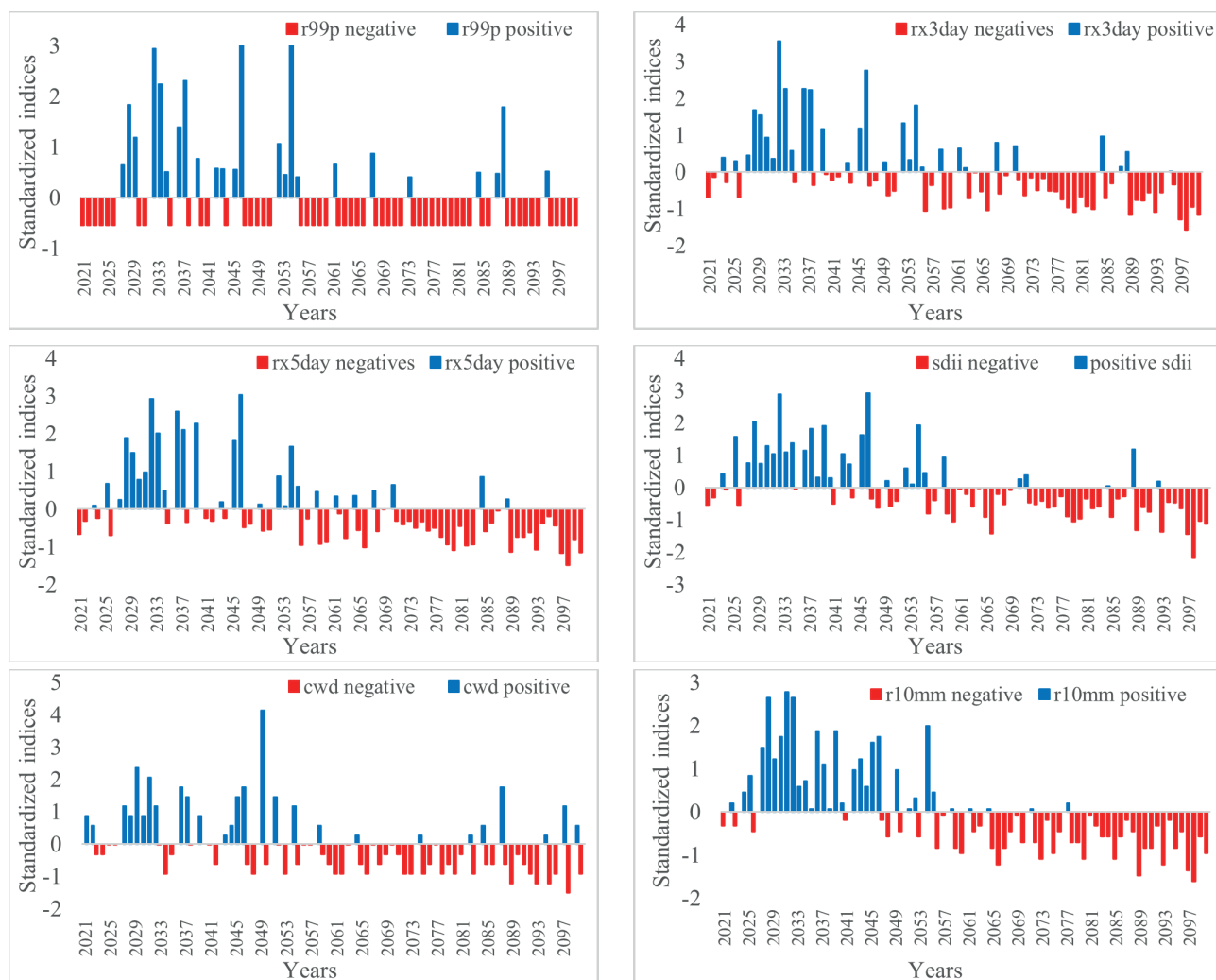


Fig. 10: Trends in standardized indices for the six extreme precipitation parameters selected for the future period under the SSP 585 scenario at the outlet of the Aga-Foua-Djilas basin

Tab. 9. Percentage change in the twelve extreme flow indices selected for the future period compared with the reference period at the outlet of the Aga-Foua-Djilas basin

SSP 126	1-day min	3-day min	7-day min	30-day min	90-day min	1-day max	3-day max	7-day max	30-day max	90-day max	Zero days	Base flow
2021-2040	113	109	105	94.6	85.3	193	192	188	157	143	-24.1	76.7
2041-2060	200	195	189	183	157	219	216	210	171	152	-26	69
2061-2080	-84.2	-84.5	-84.8	-81.2	-77.1	107	106	102	72.5	46.9	49.2	-75.0
2081-2100	-92.1	-92.2	-92.4	-93.0	-89.8	-2.2	-2.3	-2.9	-10.1	-15.9	61.6	-82.5
SSP 370	1-day min	3-day min	7-day min	30-day min	90-day min	1-day max	3-day max	7-day max	30-day max	90-day max	Zero days	Base flow
2021-2040	311	303	301	280	249	377	374	360	288	232	-44.7	159
2041-2060	-100	-100	-100	-100	-97.5	99.1	97.5	92.4	63.6	38.2	70.9	-100
2061-2080	-84.2	-84.5	-84.8	-85.9	-87.8	28.6	27.7	24.3	4.4	-14.5	78.7	-65.7
2081-2100	-100	-100	-100	-100	-100	-74.6	-74.5	-74.7	-75.2	76.2	138	-100
SSP 585	1-day min	3-day min	7-day min	30-day min	90-day min	1-day max	3-day max	7-day max	30-day max	90-day max	Zero days	Base flow
2021-2040	516	505	493	457	397	411	405	389	311	318	-52	181
2041-2060	89.5	88.8	88.0	78.9	64.3	385	377	350	241	163	-35	167
2061-2080	-100	-100	-100	-100	-100	-92.7	-92.8	-92.9	-93.3	-93.8	151	-100
2081-2100	-100	-100	-100	-100	-100	-92.1	-92.1	-92.0	-92.3	-92.9	160	-100

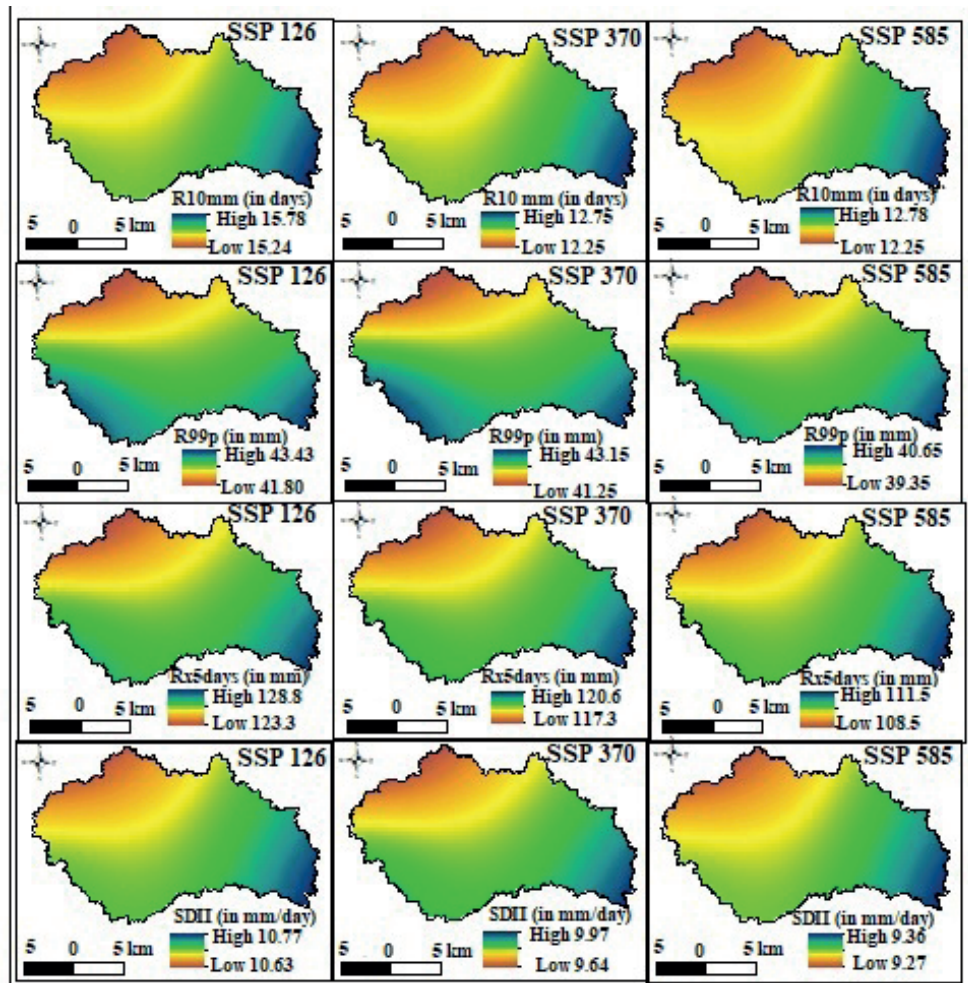


Fig. 11: Spatial distribution of selected extreme precipitation indices in the Aga-Foua-Djilas watershed, over the period 2021-2100

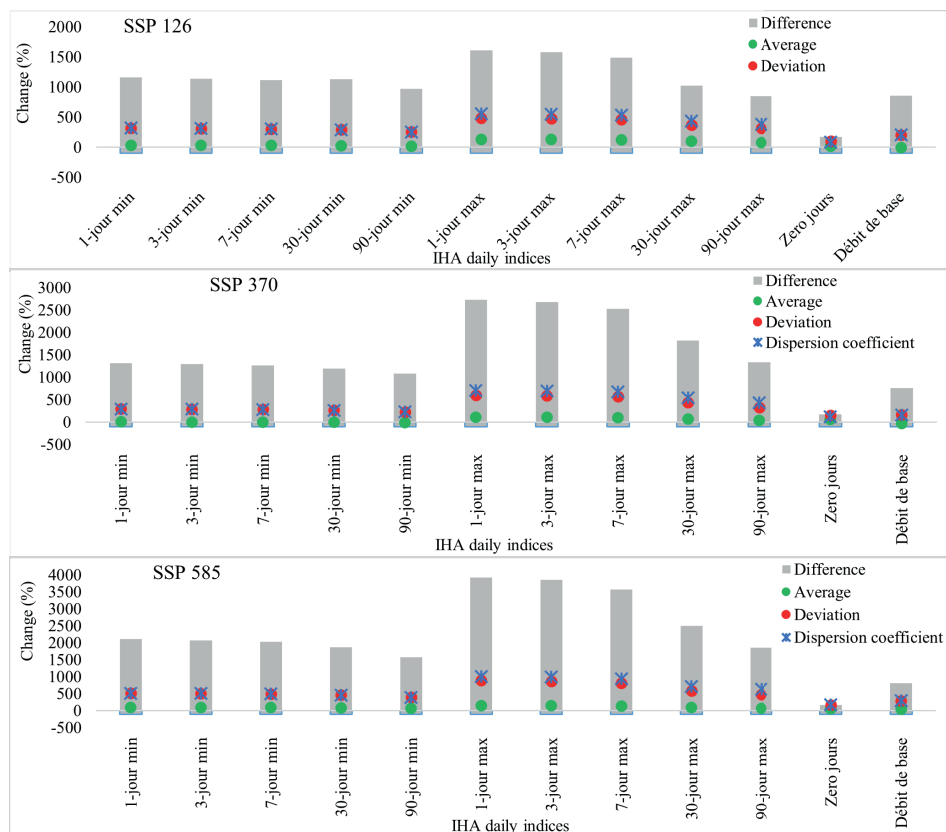


Fig. 12: Projected variations in hydrological extremes as indicated by IHA parameters of amplitude and duration between 1985-2014 and 2021-2100 according to the SSP 126, SSP 370 and SSP 585 scenario at the outlet of the Aga-Foua-Djilas basin

4 DISCUSSION

Specific climate extremes are brought on by global warming, including a rise in the occurrence of extremely hot days and nights, as well as a reduction in the occurrence of cold days and nights (Intergovernmental Panel on Climate Change (IPCC) IPCC, 2007). Senegal is distinguished by variations in temperature and rainfall from year to year. In most parts of the nation, crop productivity is impacted by rainfall unpredictability. Droughts are supported by trends of increasing dry days and declining winter rainfall, whereas flood hazards have been influenced by the opposite patterns (Gedefaw et al., 2018). The results of this study indicate an increase in the frequency and intensity of extreme warm temperatures. This trend aligns with findings from other studies, where similar increases in extreme temperature indices have been observed in various regions, such as in Iran (Soltani et al., 2016). Similar results have been achieved in many other parts of the world (Intergovernmental Panel on Climate Change (IPCC), 2013).

Flash floods and prolonged droughts, which are direct responses of hydrological dynamics to climate change, have become more intense in many river basins (Gbohoui et al., 2021; Hirabayashi et al., 2013). The availability of freshwater is declining, disrupting aquatic ecosystems and reducing the ecological resilience of watersheds (Addor et al., 2014a; Gbohoui et al., 2021; Hirabayashi et al., 2013). In this context, the non-stationarity of river regimes makes water resource management planning complex and uncertain (Addor et al., 2014a).

Based on rainfall projections in the Aga-Foua-Djilas basin, the study's results demonstrated a declining trend and a wide range that would make long-term predictions of water availability extremely questionable. Despite its great agricultural potential, the Aga-Foua-Djilas basin's low average annual rainfall and the declining trend in extreme rainfall indices may cause problems with water utilization. The findings of this study's analysis of climatic trends based on SSP scenarios are consistent with earlier studies conducted in Senegal (Mbaye et al., 2019; Sadio et al., 2020; Diakhaté et al., 2022; Dione et al., 2023, 2025; Dione, 2024) and other parts of the world (Almazroui et al., 2021; Ortega et al., 2021; Phan & Nguyen, 2023).

The extreme runoff indices exhibited a consistent change in line with rainfall patterns, which aligns with findings from studies on the region. For instance, projections in West Africa (e.g., Senegal) indicate a decrease in median peak flows by 23% (Rameshwaran et al., 2021), and a similar trend has been noted for seasonal peak flows in the Upper Niger and Inner Niger Delta during the 2050s and 2080s (Thompson et al., 2017). Additionally, projections for the Senegal and Gambia river basins using six CMIP5 models (RCP4.5 and RCP8.5) suggest a decrease in river flows by the 2050s (Bodian et al., 2018). However, projections for the Niger River, based on 19 CMIP5 models (RCP2.6 and RCP8.5), show uncertainty about the future trend, although most models suggest an increase in flows (Aich et al., 2014).

For many scenarios, it was generally found that river flow diminishes in the future. The basin has a statistically significant tendency of rising temperature overall, as well as a statistically significant trend of falling discharge and precipitation over the coming years, according to the trend test results. The future trajectory of the catchment's hydroclimatic

variables will be impacted by climate change. It ought to have an impact on the future water supply for rain-fed farming, irrigation, and other purposes.

The analysis' findings offer a chance to comprehend the rise of extreme occurrences and the capacity of the CMIP6 model's outputs to estimate anticipated modifications. Several limitations are mentioned, affecting the current results, even though this study is among the first of its sort to apply the most recent CMIP6 GCMs across a small basin like the Aga-Foua-Djilas basin. These restrictions include the small number of models used at the time of study, the restricted statistical features applied, the restricted number of indices, and the absence of physical mechanism investigation to promote a deeper comprehension of extreme event occurrences. To help the various stakeholders make more informed judgments, it is still necessary to clearly characterize potential extremes by describing intensity, frequency, and duration. The underlying physical properties influencing the occurrence of extreme consequences predicted for pertinent policies, as well as the application of bias-corrected models to reduce inter-model biases, require more research.

We are conscious that there is some degree of uncertainty in every step of the climate risk assessment process, whether it be in the selection of hydrological measurements or climate and hydrological models. However, climate change estimates have been found to largely eliminate uncertainties arising from the selection or parameterization of hydrological models, as noted in previous reviews (Addor et al., 2014; Melsen et al., 2018). As a result, in this study, we have not evaluated uncertainty resulting from the selection or parameterization of hydrological models. Water management choices are predicated on the potential evolution of system-dependent characteristics in the face of future climate change (Ekström et al., 2018), therefore it is highly advantageous to understand each one's level of uncertainty. (Vigiak et al., 2018) found that while metrics pertaining to the time, length, and rate of change are questionable, those reflecting the magnitude of mean and high flows in the simulated flow were typically reliable. Additional research might be based on the preliminary evaluation of these actions and their potential impact on the aquatic system.

5 CONCLUSION

This study aimed to identify changes and trends in hydroclimatic extremes in the Aga-Foua-Djilas basin by analysing extreme indices related to temperature, precipitation, and runoff for the reference period of 1985-2014 and the future period of 2021-2100. Hydroclimatic change trends in climate extremes were assessed using trend detection methods based on observed data sets. The evaluation of temperature-related extreme indices indicated a general increase in temperature trends across the basin during the study period. Daily maximum and minimum temperature values showed an upward trend, and an increase in the frequency of warm days and nights was observed at most stations. Extreme hot temperatures were found to be increasing compared to extreme cold temperatures.

In contrast, trends in extreme precipitation and runoff indices showed a downward trajectory. As a result, extreme precipitation events are projected to become less frequent and intense toward the end of the century in the Aga-Foua-Djilas basin, leading to a rise in the likelihood of droughts. The

analysis suggests that future climate projections will significantly influence river flows, particularly extreme river flows. Specifically, due to rising temperatures and decreasing rainfall, extreme flow indices are expected to exhibit a downward trend, with declines in the medians of minimum and annual flows over 1, 3, 7, 30, and 90 days in the future period due to rainfall deficits.

Thus, the changes in climatic extremes are likely to increase the risk of severe extreme events, and climate change will influence the future evolution of trends in hydroclimatic variables within the catchment area, highlighting the importance of studying them. Projected changes in average and peak river flows could have severe consequences for human life, including significant damage to property, infrastructure, and the environment, loss of agriculture and wildlife, and worsening health conditions, which could impede socio-economic development in the region. Therefore, there is an urgent need for effective climate change mitigation and adaptation strategies at both regional and national levels.

This work is designed to provide crucial data to stakeholders and policymakers to develop adaptation pathways and plan for future changes across the region. Without well-planned and managed interventions, the impacts of climate change on the frequency and magnitude of floods and droughts in Senegal, compounded by population growth, could have detrimental effects on lives, livelihoods, and the environment in the coming decades. Overall, assessing the impacts of extreme hydroclimatic events on agriculture, water resources, and populations will equip decision-makers and policymakers with the necessary information to take proactive steps to address these risks. Consequently, the results of this study could help improve the understanding of current conditions of extreme hydroclimatic variations in Senegal.

REFERENCES

- Addor, N., Rössler, O., Köplin, N., Huss, M., Weingartner, R., & Seibert, J. (2014a). Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. *Water Resources Research*, 50(10), 7541–7562. <https://doi.org/10.1002/2014WR015549>
- Addor, N., Rössler, O., Köplin, N., Huss, M., Weingartner, R., & Seibert, J. (2014b). Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. *Water Resources Research*, 50(10), 7541–7562. <https://doi.org/10.1002/2014WR015549>
- Aich, V., Liersch, S., Vetter, T., Huang, S., Tecklenburg, J., Hoffmann, P., Koch, H., Fournet, S., Krysanova, V., Müller, E. N., & Hattermann, F. F. (2014). Comparing impacts of climate change on streamflow in four large African river basins. *Hydrology and Earth System Sciences*, 18(4), 1305–1321. <https://doi.org/10.5194/hess-18-1305-2014>
- Akinsanola, A. A., Ongoma, V., & Kooperman, G. J. (2021). Evaluation of CMIP6 models in simulating the statistics of extreme precipitation over Eastern Africa. *Atmospheric Research*, 254, 105509. <https://doi.org/10.1016/j.atmosres.2021.105509>
- Almazroui, M., Ashfaq, M., Islam, M. N., Rashid, I. U., Kamil, S., Abid, M. A., O'Brien, E., Ismail, M., Reboita, M. S., Sörensson, A. A., Arias, P. A., Alves, L. M., Tippet, M. K., Saeed, S., Haarsma, R., Doblas-Reyes, F. J., Saeed, F., Kucharski, F., Nadeem, I., ... Sylla, M. B. (2021). Assessment of CMIP6 Performance and Projected Temperature and Precipitation Changes Over South America. *Earth Systems and Environment*, 5(2), 155–183. <https://doi.org/10.1007/s41748-021-00233-6>
- Balti, H., Ben Abbes, A., Mellouli, N., Farah, I. R., Sang, Y., & Lamolle, M. (2020). A review of drought monitoring with big data: Issues, methods, challenges and research directions. *Ecological Informatics*, 60, 101136. <https://doi.org/10.1016/j.ecoinf.2020.101136>
- Barbalić, D., & Kuspilić, N. (2014). Trends of indicators of hydrological alterations. *GRAĐEVINAR – Journal of the Croatian Association of Civil Engineers*, 66(7), 613–624. <https://doi.org/10.14256/JCE.1003.2014>
- Bodian, A. (2014). Caractérisation de la variabilité temporelle récente des précipitations annuelles au Sénégal (Afrique de l'Ouest). *Physio-Géo*, Volume 8, 297–312. <https://doi.org/10.4000/physio-geo.4243>
- Bodian, A., Dezetter, A., Diop, L., Deme, A., Djaman, K., & Diop, A. (2018). Future climate change impacts on streamflows of two main West Africa river basins: Senegal and Gambia. *Hydrology*, 5(1), 21. <https://doi.org/10.3390/hydrology5010021>
- Diakhaté, M., Mbaye, M. L., Camara, I., & Barry, M. B. (2022). Projected Changes in the Rainfall Annual Cycle over the Senegal River Basin Using CMIP5 bias-Corrected Simulations. *American Journal of Environmental Protection*, 10(1), 41–46. <https://doi.org/10.12691/env-10-1-5>
- Dione, P. M. (2024). Dynamique des ressources en eau et des terroirs dans le bassin versant d'Aga-Foua-Djilas face à la variabilité climatique et au changement climatique [Thèse de Doctorat Unique]. Université Assane Seck.
- Dione, P. M., & Faye, C. (2025). Water resources and community dynamics in the Aga-Foua-Djilas watershed (Senegal) : local perceptions and lowland management challenges. *Larhyss Journal*, ISSN 1112-3680, 61, 53–79. <https://larhyss.net/ojs/index.php/larhyss/article/view/16731/998>
- Dione, P. M., Faye, C., & Sadio, C. A. A. S. (2023). Hydrological Impacts of Climate Change (Rainfall and Temperature) and Characterization of Future Drought in the Aga Foua Djilas Watershed. *Indonesian Journal of Social and Environmental Issues (IJSEI)*, 4(3), 353–375. <https://doi.org/10.47540/ijsei.v4i3.1218>
- Dione, P. M., Faye, C., & Tolche, A. D. (2025). Projection of future temperature and precipitation in the Aga-Foua-Djilas basin in Senegal using the CMIP6 multi-model ensemble. *Journal of Materials and Environmental Science*, 16(2), 256–281. https://www.jmaterenvironsci.com/Document/vol16/vol16_N2/JMES-2025-1602016-Dione.pdf
- Döll, P., Trautmann, T., Gerten, D., Schmied, H. M., Ostberg, S., Saeed, F., & Schleussner, C.-F. (2018). Risks for the global freshwater system at 1.5°C and 2°C global warming. *Environmental Research Letters*, 13(4), 044038. <https://doi.org/10.1088/1748-9326/aab792>
- Dong, T., & Dong, W. (2021). Evaluation of extreme precipitation over Asia in CMIP6 models. *Climate Dynamics*, 57(7-8), 1751–1769. <https://doi.org/10.1007/s00382-021-05773-1>
- Dos Santos, C. A. C., Neale, C. M. U., Rao, T. V. R., & da Silva, B. B. (2011). Trends in indices for extremes in daily temperature and precipitation over Utah, USA. *International Journal of Climatology*, 31(12), 1813–1822. <https://doi.org/10.1002/joc.2205>

- Ekström, M., Gutmann, E. D., Wilby, R. L., Tye, M. R., & Kirono, D. G. C. (2018). Robustness of hydroclimate metrics for climate change impact research. *Wiley Interdisciplinary Reviews (WIREs): Water*, 5(4), e1288. <https://doi.org/10.1002/wat2.1288>
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- François, B., Schlef, K. E., Wi, S., & Brown, C. M. (2019). Design considerations for riverine floods in a changing climate – A review. *Journal of Hydrology*, 574, 557–573. <https://doi.org/10.1016/j.jhydrol.2019.04.068>
- Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., ... Yamagata, Y. (2017). Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geoscientific Model Development*, 10(12), 4321–4345. <https://doi.org/10.5194/gmd-10-4321-2017>
- Gbohoui, Y. P., Paturel, J. -E., Fowe, T., Karambiri, H., & Yacouba, H. (2021). Impacts des changements climatique et environnemental sur la réponse hydrologique du bassin du Nakanbé à Wayen (Burkina Faso) à travers le cadre de budyko. *Proceedings of the International Association of Hydrological Sciences*, 384, 269–273. <https://doi.org/10.5194/PIAHS-384-269-2021>
- Gedefaw, M., Yan, D., Wang, H., Qin, T., Girma, A., Abiyu, A., & Batsuren, D. (2018). Innovative Trend Analysis of Annual and Seasonal Rainfall Variability in Amhara Regional State, Ethiopia. *Atmosphere*, 9(9), 326. <https://doi.org/10.3390/atmos9090326>
- Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, 3(9), 816–821. <https://doi.org/10.1038/nclimate1911>
- Huang, X., Suwal, N., Fan, J., Pandey, K. P., & Jia, Y. (2019). Hydrological Alteration Assessment by Histogram Comparison Approach: A Case Study of Erdu River Basin, China. *Journal of Coastal Research*, 93(sp1), 139–145. <https://doi.org/10.2112/SI93-020.1>
- Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate Change 2007 – The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC*. Cambridge University Press.
- Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Karl, T. R., Nicholls, N., & Ghazi, A. (1999). *Clivar/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes: Workshop Summary*. *Climatic Change*, 42(1), 3–7. <https://doi.org/10.1023/A:1005491526870>
- Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., & Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, 59(1), 1–28. <https://doi.org/10.1080/02626667.2013.857411>
- Lange, S. (2019). Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geoscientific. Model Development*, 12(7), 3055–3070. <https://doi.org/10.5194/gmd-12-3055-2019>
- Magilligan, F. J., & Nislow, K. H. (2005). Changes in hydrologic regime by dams. *Geomorphology*, 71(1–2), 61–78. <https://doi.org/10.1016/j.geomorph.2004.08.017>
- Mbaye, M. L., Sylla, M. B., & Tall, M. (2019). Impacts of 1.5 and 2.0 °C Global Warming on Water Balance Components over Senegal in West Africa. *Atmosphere*, 10(11), 712. <https://doi.org/10.3390/atmos10110712>
- Melsen, L. A., Addor, N., Mizukami, N., Newman, A. J., Torfs, P. J. J. F., Clark, M. P., Uijlenhoet, R., & Teuling, A. J. (2018). Mapping (dis)agreement in hydrologic projections. *Hydrology and Earth System Sciences*, 22(3), 1775–1791. <https://doi.org/10.5194/hess-22-1775-2018>
- O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3), 387–400. <https://doi.org/10.1007/s10584-013-0905-2>
- Ortega, G., Arias, P. A., Villegas, J. C., Marquet, P. A., & Nobre, P. (2021). Present-day and future climate over central and South America according to CMIP5/CMIP6 models. *International Journal of Climatology*, 41(15), 6713–6735. <https://doi.org/10.1002/joc.7221>
- Papalexiou, S. M., & Montanari, A. (2019). Global and Regional Increase of Precipitation Extremes Under Global Warming. *Water Resources Research*, 55(6), 4901–4914. <https://doi.org/10.1029/2018WR024067>
- Phan, T. T. H., & Nguyen, H. A. (2023). Spatial and temporal distributions of temperature and rainfall on tropical islands of Vietnam. *Journal of Water & Climate Change*, 14(5), 1395–1412. <https://doi.org/10.2166/wcc.2023.342>
- Rameshwaran, P., Bell, V. A., Davies, H. N., & Kay, A. L. (2021). How might climate change affect river flows across West Africa? *Climatic Change*, 169(3–4), 21. <https://doi.org/10.1007/s10584-021-03256-0>
- Richter, B. D., Baumgartner, J. V., Braun, D. P., & Powell, J. (1998). A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research & Management*, 14(4), 329–340. [https://doi.org/10.1002/\(SICI\)1099-1646\(199807/08\)14:4<329::AID-RRR505>3.0.CO;2-E](https://doi.org/10.1002/(SICI)1099-1646(199807/08)14:4<329::AID-RRR505>3.0.CO;2-E)
- Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology*, 10(4), 1163–1174. <https://doi.org/10.1046/j.1523-1739.1996.10041163.x>
- Sadio, P. M., Mbaye, M. L., Diatta, S., & Sylla, M. B. (2020). Variabilité et changement hydroclimatiques dans le bassin-versant du fleuve Casamance (Sénégal). *La Houille Blanche*, 106(6), 89–96. <https://doi.org/10.1051/lhb/2021002>
- Sagna, P. (2005). *Dynamique du climat et son évolution récente dans la partie ouest de l'Afrique occidentale [Thèse de Doctorat d'Etat]*. Cheikh Anta Diop.

- Soltani, M., Laux, P., Kunstmann, H., Stan, K., Sohrabi, M. M., Molanejad, M., Sabziparvar, A. A., Ranjbar SaadatAbadi, A., Ranjbar, F., Rousta, I., Zavar-Reza, P., Khoshakhlagh, F., Soltanzadeh, I., Babu, C. A., Azizi, G. H., & Martin, M. V. (2016). Assessment of climate variations in temperature and precipitation extreme events over Iran. *Theoretical and Applied Climatology*, 126(3–4), 775–795. <https://doi.org/10.1007/s00704-015-1609-5>
- Sun, Q., Zhang, X., Zwiers, F., Westra, S., & Alexander, L. V. (2021). A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. *Journal of Climate*, 34(1), 243–258. <https://doi.org/10.1175/JCLI-D-19-0892.1>
- Tan, M. L., Juneng, L., Tangang, F. T., Chung, J. X., & Radin Firdaus, R. B. (2021). Changes in temperature extremes and their relationship with ENSO in Malaysia from 1985 to 2018. *International Journal of Climatology*, 41(S1), E2564–E2580. <https://doi.org/10.1002/joc.6864>
- Teah, L., & Centre canadien des services climatiques. (2023). Demandez à un expert en climatologie : naviguer dans les méandres des périodes de référence—DonneesClimatiques.ca. <https://donneesclimatiques.ca/demandez-a-un-expert-en-climatologie-naviguer-dans-les-meandres-des-periodes-de-reference/>
- Thoeun, H. C. (2015). Observed and projected changes in temperature and rainfall in Cambodia. *Weather and Climate Extremes*, 7, 61–71. <https://doi.org/10.1016/j.wace.2015.02.001>
- Thompson, J. R., Iravani, H., Clilverd, H. M., Sayer, C. D., Heppell, C. M., & Axmacher, J. C. (2017). Simulation of the hydrological impacts of climate change on a restored floodplain. *Hydrological Sciences Journal*, 62(15), 2482–2510. <https://doi.org/10.1080/02626667.2017.1390316>
- Vigiak, O., Lutz, S., Mentzafou, A., Chiogna, G., Tuo, Y., Majone, B., Beck, H., De Roo, A., Malagó, A., Bouraoui, F., Kumar, R., Samaniego, L., Merz, R., Gamvroudis, C., Skoulikidis, N., Nikolaidis, N. P., Bellin, A., Acuña, V., Mori, N., Ludwig, R.,... Pistocchi, A. (2018). Uncertainty of modelled flow regime for flow-ecological assessment in Southern Europe. *Science of The Total Environment*, 615, 1028–1047. <https://doi.org/10.1016/j.scitotenv.2017.09.295>
- Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, 467(7315), 555–561. <https://doi.org/10.1038/nature09440>
- Xu, Z. X., Yang, X. J., Zuo, D. P., Chu, Q., & Liu, W. F. (2015). Spatiotemporal characteristics of extreme precipitation and temperature: a case study in Yunnan Province, China. In *Proceedings of the International Association of Hydrological Sciences (PIAHS)*, 369, ISBN 978-1-5108-0898-0, 121–127. <https://piahs.copernicus.org/articles/369/121/2015/piahs-369-121-2015.pdf>
- Yang, K., & Jiang, D. (2017). Interannual climate variability change during the Medieval Climate Anomaly and Little Ice Age in PMIP3 last millennium simulations. *Advances in Atmospheric Sciences*, 34(4), 497–508. <https://doi.org/10.1007/s00376-016-6075-1>
- Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B., & Zwiers, F. W. (2011). Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews (WIREs): WIREs Climate Change*, 2(6), 851–870. <https://doi.org/10.1002/wcc.147>



Article first received: 10 April 2025
Article accepted: 15 July 2025