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Evolution of flood generating processes under climate change in France

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Abstract

The impact of climate change on floods varies spatially, and often the observed trends in flood characteristics can be explained by differentiated changes in flood-generating processes. This study explores changes in flood magnitude and flood-generating processes under different climate change scenarios for a large number of basins in France. It is based on an unprecedented exercise to model the impacts of climate change on hydrology, using a semi-distributed model (GRSD) applied to 3727 basins with 22 Euro-CORDEX bias-corrected climate projections using two greenhouse gas emission scenarios (RCP4.5 and RCP8.5). Annual maxima of daily simulated streamflow were extracted for the period 1975-2100, resulting in a set of over 10 million flood events, and a trend analysis was carried out on both flood magnitudes and flood generating processes. The trends in flood magnitude are contrasted, with increasing trends only in the northern regions of France, although multi-model convergence rarely exceeds 60 %. The highest increases are observed for the rarest floods and under the RCP8.5 scenario. A classification of floods according to their generating process revealed that floods linked to soil saturation represent more than half of all floods in France. The relative change in the importance of the different flood-generating processes is not spatially homogeneous and varies by region. The proportion of floods linked to soil saturation excess is decreasing while the proportion of floods linked to infiltration excess related to extreme rainfall is increasing, particularly in the southern Mediterranean regions. Both the frequency and magnitude of floods linked to snowmelt processes are decreasing in mountainous areas. On the contrary, the most extreme floods associated with rainfall on dry soils tend to increase, in line with the increase of rainfall intensity. Overall, trends in antecedent soil moisture conditions are as important as trends in intense rainfall to explain flood hazard trends in the different climate projections. This study shows how important it is to decipher the changes in the different flood generating processes in order to better understand their evolution in different hydroclimatic regions.

1- Introduction

The impact of climate change on floods is uncertain, or unknown, in many regions of the world (Intergovernmental Panel On Climate Change (IPCC), 2023). In particular, it has been shown that competing changes in flood-generating processes can modulate, or even offset, changes in flood hazards (Ivancic and Shaw, 2015; Sharma et al., 2018; Tramblay et al., 2019; Brunner et al., 2021; Zhang et al., 2022). For example, in the context of an increase in intense rainfall events in some temperate and arid regions, the concomitant drop in soil moisture, resulting in lower runoff coefficients, could result in a lack of trend in flood magnitude (Wasko and Nathan, 2019; Ho et al., 2022; Tramblay et al., 2023; Scussolini et al., 2023). Similarly, the large decline in the frequency of snowmelt-induced floods in many regions may compensate for the increasing proportion of floods caused by rainstorms, resulting in the absence of trends in overall flood hazards in numerous regions worldwide where snowmelt is prevalent (Zhang et al., 2022). To comprehend the evolution of floods, it is essential to analyze not only their severity but also to consider in detail whether the processes that underpin them are also changing (Tarasova et al., 2019; Kemter et al., 2020; Blöschl, 2022a, b; Jiang et al., 2022; Tarasova et al., 2023; Kemter et al., 2023; McMillan et al., 2025). This is particularly salient given that trends in extreme rainfall do not generally translate into the same trends in floods (Ivancic and Shaw, 2015; Sharma et al., 2018; Wasko et al., 2023). Numerous studies have focused on understanding and categorizing floods according to the hydroclimatic mechanisms

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behind their generation (Tarasova et al., 2019; Stein et al., 2020; Kemter et al., 2023). We can distinguish studies that use seasonality to categorize the various causal mechanisms based on their temporal proximity (Berghuijs et al., 2016, 2019; Tramblay et al., 2021) from other studies that use different hydrological criteria, predominantly thresholds on precipitation intensity, snowmelt, or soil moisture levels, to differentiate between different types of floods (Froidevaux et al., 2015; Tarasova et al., 2018; Kim et al., 2019; Tarasova et al., 2020; Stein et al., 2020, 2021; Tramblay et al., 2022; Tarasova et al., 2023; Tramblay et al., 2023).

To provide future flood projections, it is necessary to use hydrological models to translate climate projections into hydrological projections, i.e. providing simulated streamflow values for the future. Such a modeling chain, which is generally constituted by greenhouse gas concentration scenarios, global (GCM) and regional (RCM) climate models, bias-correction methods, and hydrological models, necessarily suffers from uncertainties (Clark et al., 2016). The evolution of our society is inherently unpredictable, and thus, climate scenarios describe its evolution through greenhouse gas concentrations (Meinshausen et al., 2020). These concentrations, in turn, influence climate model outputs, which are subject to uncertainties related to process representation and climate variability (Knutti and Sedláček, 2013). Additionally, bias-correction methods and hydrological models are affected by process representation uncertainties (Teutschbein and Seibert, 2012; Maraun et al., 2017). Furthermore, their application in an extrapolation mode may compromise their temporal transferability. Indeed, these models and methods are generally calibrated, optimized, and evaluated over well-known past periods. With climate projections, they are used under potentially very different conditions, with unprecedented air temperatures, and possiblyvery different precipitation regimes, which may alter their transferability. This issue has been extensively documented in the context of hydrological modeling (Brigode et al., 2013; Thirel et al., 2015b; Dakhlaoui et al., 2017), and various protocols have been proposed to assess the robustness of these models (Klemeš, 1986; Thirel et al., 2015a). It is important to note that models of varying complexity exist, depending on their spatial discretization and the processes included in the equations, as well as the use of automatic parameter optimization (Hrachowitz and Clark, 2017). For large-scale studies, at the regional or even the global scale, most often the hydrological models are not calibrated for all stations but sometimes only in a subset of basins (Alfieri et al., 2015; Roudier et al., 2016; Do et al., 2020; Di Sante et al., 2021; Zhang et al., 2022). Nevertheless, all types of models can suffer from robustness issues (Santos et al., 2025). However, it has been shown that the relative uncertainty associated with hydrological modeling is typically lower for high flows, which are the focus of this study, in comparison to low flows (Vidal et al., 2016; Lemaitre-Basset et al., 2021).

This study analyzes a large ensemble of hydrological projections based on climate projections for a diverse set of basins in France, which represents a range of varied physiographic properties. The aim is to investigate the future evolution of flood events, both in terms of magnitude and flood-generating processes. The methodology enables a multi-factorial analysis of floods and the processes underlying their generation, leading to a better understanding of which factors most influence flood trends. By distinguishing the hydro-climatic drivers regionally, we identify those that may either increase or decrease future flood risks.

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2- Data and Methods

2.1 Hydrological model

The GRSD model, a semi-distributed rainfall-runoff model based on the lumped GR4J model structure (Perrin et al., 2003) and the CemaNeige snow model (Valéry et al., 2014), has been chosen for this study. The rationale behind this choice is its capacity to be applied to a very large range of hydro-meteorological conditions and numerous basins across the world, as shown by the GR4J or GRSD applications in Brazil (Kuana et al., 2024), Nepal (Nepal et al., 2017), Iran (Jahanshahi et al., 2025), Haiti (Bathelemy et al., 2024), Chile (Abbenante et al., 2024), Australia (Stephens et al., 2019), and France (De Lavenne et al., 2019; Lemaitre-Basset et al., 2024), as well as its large number of applications in the context of climate change (Chauveau et al., 2013; Cornelissen et al., 2013; Tian et al., 2013; Fabre et al., 2016; Stephens et al., 2018; Givati et al., 2019; Thirel et al., 2019; Tarek et al., 2021; Wasko et al., 2023; Poncet et al., 2024). The GRSD model calibration and simulation were applied within the airGR and airGRiwrm open-source R packages (Coron et al., 2017; Dorchies, 2022).

GR4J is a four-parameter rainfall-runoff model consisting of two conceptual stores: a production store and a routing store, whose flows are routed to the river after transformation by a unit hydrograph. While the GR4J model is applied on a sub-catchment spatial scale, and the simulated streamflow is routed from upstream to downstream with a lag function (de Lavenne et al., 2019), the CemaNeige snow model uses an additional sub-division of each sub-catchment into five zones of equal area to better describe the process heterogeneities linked to the topography (Valéry et al., 2014). GRSD provides daily streamflow simulation covering 3727 simulation points in France, and different variables have been extracted: the total, solid, and liquid precipitation, the soil water index (SWI, i.e. the ratio between water content and the storage capacity of the production store), and the snowmelt discharge (SMD, i.e the water flow resulting from snowpack melting). The GRSD model has been calibrated over the 1976-2019 period, using the Kling-Gupta Efficiency criterion (Gupta et al., 2009) applied on squared-root transformed streamflow, against the observed streamflow of 611 gauging stations in France considered as nearly natural (Strohmenger et al., 2023), using the SAFRAN (Vidal et al., 2010) reanalysis as meteorological input. To simulate streamflow over the remaining - ungauged - stations, parameters were transferred from neighbor gauged catchments to the target ungauged catchments following Oudin et al. (2008), and these parameter sets were used to produce pseudo-observed streamflow on the ungauged stations, on which the GRSD model was subsequently calibrated (Sauquet et al., 2024, 2025).

2.2 Climate simulations

The GRSD model was thereafter applied using as inputs climate projections from the Explore2-Climat-2022-ADAMONT dataset (Corre et al., 2025), available on the French national climate data portal (*DRIAS - les futurs du climat* - www.drias-climat.fr). This ensemble is derived from the 12-km resolution EURO-CORDEX ensemble (Jacob et al., 2018; Vautard et al., 2021), which consists of regional climate model simulations that downscale global climate model simulations over Europe from the CMIP5 (5th phase of the Coupled Model Intercomparison Project, (Taylor et al., 2012)). For this study, we use the 11 GCM/RCM pairs for which both emission scenarios (RCP4.5 and RCP8.5) are available (Table T1 in supplementary materials). The outputs of the climate models were statistically adjusted over

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mainland France, against the 8- km resolution SAFRAN reanalysis (Vidal et al. 2010). The bias correction method consists of a quantile mapping relying on seasonal weather regimes (ADAMONT method, Verfaillie et al., 2017). In the following, we use the daily rainfall data and the variables used to compute evapotranspiration (temperature, relative humidity, wind, radiation) from these bias adjusted simulations. These data are available from 1975-2100 at the daily time scale with an 8-km spatial resolution and have been aggregated at the catchment scale.

Several studies describe the future climate changes in France based on these projections (Marson et al., 2024). Overall, they show a shift towards hotter and drier summers, as well as an expansion of temperate climate in mountainous regions (Strohmenger et al., 2024). Despite variations in the magnitude of warming depending on the scenario, time horizon, or level of warming considered, all studies identify common features. These include spatial contrasts, with stronger warming projected in the south, east, and mountainous regions compared to the Atlantic coast, showing a gradient of about 1°C. Seasonal contrasts are also consistent, with warming more pronounced in summer than in winter (with also a difference of 1°C). Regarding precipitation, all studies highlight the limited agreement among models on the annual average, which is linked to the influence of internal variability and to France's geographical position, which places it in a transition zone between Northern Europe, where precipitation is projected to increase, and the Mediterranean region, where it is projected to decrease (Terray and Boé, 2013; Coppola et al., 2021). On a seasonal scale, however, projections are more consistent. In winter, median changes show an increase in rainfall (particularly in the northern regions) alongside a notable decrease in snowfall, especially in the low- and mid-mountain ranges. In summer, projections indicate a decrease in rainfall (particularly in the southern half). These changes in precipitation combined with increased evaporation due to warming, lead to a decrease in water resources availability and, consequently, a marked drying of the soil. In terms of intense rainfall (characterized by the annual maximum daily rainfall), the climate models show large dispersion regarding the direction of future changes (Tramblay et al., 2024), except for the long-term horizon under the RCP8.5 scenario or for high levels of warming (e.g., +4°C on average across France), where they tend to agree on an increase, particularly in the northern part of France

2.3 Extraction of flood events

From this dataset, we focused on the annual maximum of daily streamflow that has been extracted for each simulation point. For each station, a time series of 124 values, between 1976 and 2099 considering hydrological years starting in September, is available and described thereafter as the Annual Maximum Flood (AMF) series, referred to as 'floods' to improve readability. This sampling results in a total of 10,167,256 flood events. To estimate the base flow contribution, that is the proportion of direct runoff from rainfall and/or snowmelt, we applied a base flow filter (Lyne and Hollick, 1979) to compute the direct streamflow fraction. To extract the characteristics of the events in terms of rainfall and snowmelt, we computed the antecedent cumulative rainfall and snowmelt for each AMF value, and this aggregation stops if a day has rainfall below 1 mm or if a maximum of seven days is reached. Thus, this duration estimated for each event is extracted and hereafter referred to as the time of concentration, which may differ for each event. This time window of seven days is chosen given the size of the basins considered in the present study (from 64 to 111 570 km²) and also to be consistent with previous studies using similar approaches (Ivancic and Shaw, 2015; Stein et al., 2020).

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For each simulated flood event, we extracted: the antecedent soil moisture (i.e. SWI, between zero and one) one day before the flood date, the concentration time (in days), the total and maximum daily rainfall (mm) during the event, the fraction of the total flood streamflow being direct streamflow (%), and the total snowmelt discharge (mm) during the event.

2.4 Classification of flood events

The flood event classification was determined using a decision tree that had previously been applied in Europe and the USA (Kemter et al., 2020, 2023) to estimate the importance of five different flood-generating processes in each catchment, namely long rain, short rain, snowmelt, rain and snowmelt, and soil moisture excess. This classification is based on the catchment and climatic conditions occurring during the period defined by the time of concentration before the day of the flood peak. The rationale behind the choice of this classification over others (e.g. Tarasova et al., 2019) is that it does not rely on fixed quantities for the different variables, and notably precipitation extremes, compared to other classification schemes (Stein et al., 2020; Tramblay et al., 2022, 2023). Indeed, in a climate change context, these quantities could vary over time, notably those related to extreme rainfall that are inherently difficult to estimate precisely using climate simulations at these spatial and temporal resolutions (8 km, daily).

The flood event classification from Kemter et al. (2023) is adapted using the following sequential rules:

1. If the snowmelt is larger than the rainfall, the event is classified as ‘snowmelt’,
2. If the snowmelt is larger than 25 % of the rainfall, the event is classified as ‘rain and snowmelt’,
3. If antecedent soil moisture before the event is larger than the soil moisture threshold, the event is classified as ‘soil water excess’,
4. If during the event, the daily maximum rainfall exceeds 75 % of the total rainfall, the event is classified as ‘short rain’,
5. Else, the event is classified as ‘long rain’.

In the present study, we estimated the soil moisture threshold for each basin to identify flood events related to soil moisture excess. Considering specific soil moisture thresholds for each basin is undoubtedly more realistic than using a single soil saturation threshold for all basins, as done in other studies. The approach used herein has been applied previously (Tarasova et al., 2018; Tramblay et al., 2022) and is data-based, since there is no method for estimating these thresholds a priori from catchment characteristics. It relies on the extraction of all streamflow events above the 10th percentile of the whole streamflow time series between 1975 and 2005, fitting an exponential function to the soil moisture/runoff relationship, and then to identify the inflection point in the soil moisture/runoff relationship (i.e., the max slope of the curve). Here, we apply the Pruned Exact Linear Time method (Killick et al., 2012) to detect a change point (i.e., the soil moisture threshold, figure S1) in the exponential fit.

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2.5 Trend detection

To check for trends, the entire annual time series between 1976 and 2099 was considered. The rationale for using trend detection over the whole record is that floods in many regions are strongly impacted by multidecadal variability, notably in Europe (Hodgkins et al., 2017; Lun et al., 2020; Blöschl et al., 2020), making it difficult to detect climate change response using the standard approach of comparing historical and future time windows of about 30 years. Two approaches are applied to detect these trends. First, a quantile regression (Koenker and Bassett, 1978), is applied to check the presence of trends in the 2-year flood and in the 20-year flood. The significance of these trends at the 5 % level is then assessed using a bootstrap method (Efron, 1979). In this case, the magnitude of the trend is given by the slope of the regression. We also applied a variant of the Mann-Kendall test adjusted for serial correlation in the data (Hamed and Ramachandra Rao, 1998), and the Sen slope (Sen, 1968) method to estimate the magnitude of the trends. The Mann-Kendall test was applied to the different flood event characteristics, as well as the relative frequencies of the different flood event types. In that latter case, 20-year sliding windows were used to compute these frequencies, using a similar approach as in Tarasova et al. (2023). Given that some processes are not relevant to all basins (e.g. snowmelt), we applied the trend detection test only if a minimum of 20 occurrences for the given flood process is present in the data sample over the 1975-2100 period. To present the trend detection results, we considered the multi-model index of agreement (MIA) (Tramblay and Somot, 2018) that describes the model convergence towards an increase (1) or a decrease (-1) for a given indicator. The objective is to identify robust changes, where all model projections converge towards the same result.

3- Results and discussion

3.1 Changes in flood characteristics

Flood trends are analyzed here using the quantile regression technique, which distinguishes the change signal for AMF corresponding to 2-year (Q50) and 20-year (Q95) return periods. The results presented in Figure 1 show the convergence of the different simulations under the RCP4.5 and RCP8.5 scenarios with the MIA index. The figure shows a contrasting signal, with a relatively good convergence of the models towards an increase in Q50 and Q95 in the northern half of France and an absence of consensus for trends or even a decrease in some areas for the southern regions, that is more marked under RCP8.5. Overall, convergence at the country level is rather weak, with the median MIA value around 0.5 (Figure S2). Convergence between models is slightly greater for Q50 rather than Q95, expressing a larger uncertainty for rarest floods. In terms of magnitude (Figure 2), trends are more marked for the rarest floods (median change +28 % with RCP4.5, +34 % with RCP8.5), than for the most frequent floods (median change +20 % with RCP4.5, +27 % with RCP8.5). Overall, the projected changes between Q50 and Q95 are more correlated under the RCP8.5 than under the RCP4.5. This north/south contrast in the projections is consistent with previous findings using observational data (Blöschl et al., 2019; Tramblay et al., 2019).

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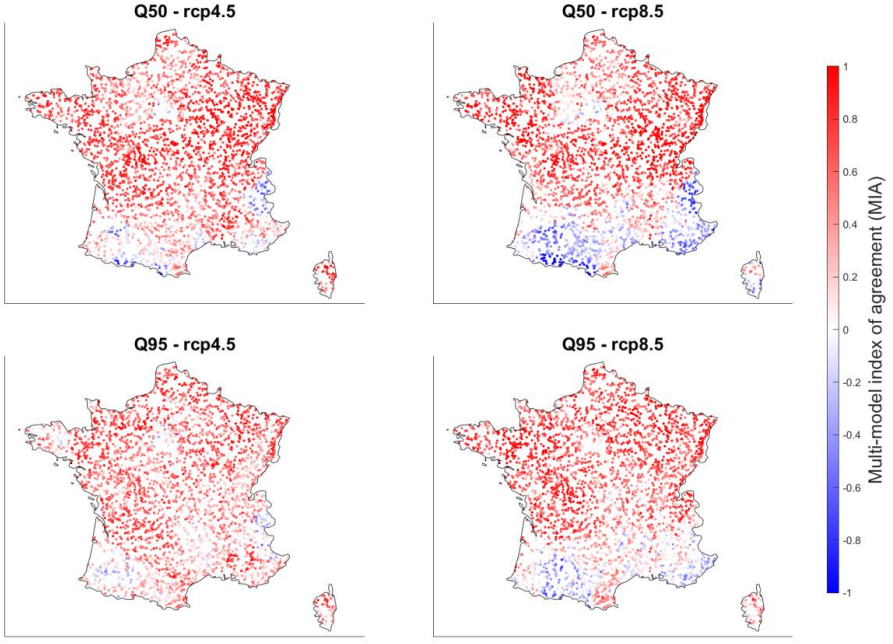

Figure 1: Maps of the multi-model index of agreement for the Q50 (2-year flood) and Q95 (20-year flood) for the 3727 simulation points, for the RCP4.5 and RCP8.5.

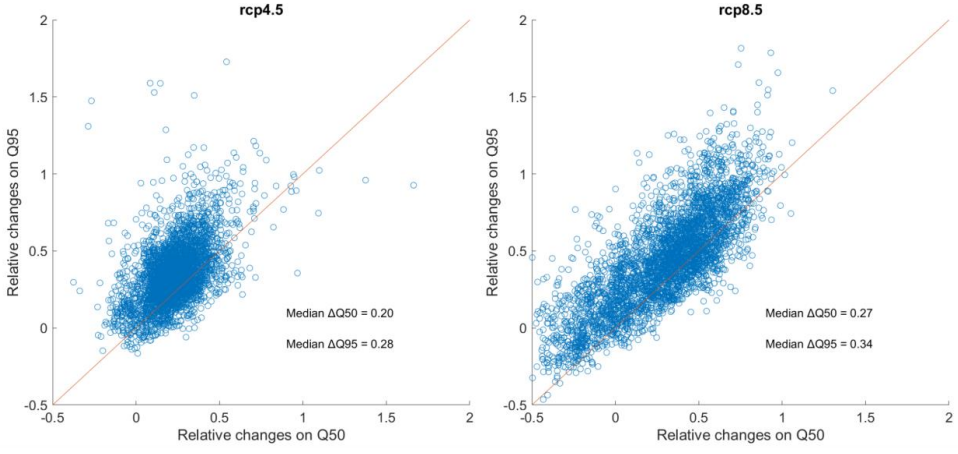

Figure 2: Comparison of the mean multi-model magnitude of significant trends on 2-year (Q50) and 20-year (Q95) floods under the RCP4.5 and RCP8.5.

This analysis of flood trends is complemented by trends in various indicators calculated during floods: maximum daily rainfall during the episode, initial soil moisture conditions, fraction of flood discharge from direct runoff, and contribution of snowmelt to flooding. The trends are shown for the RCP4.5 and RCP8.5 scenarios in Figure 3, with a general increase in maximum

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daily rainfall during floods, though less marked in southern France. The trends in antecedent soil moisture are more contrasted, with a good convergence of models towards an increase, more marked for RCP8.5, in the northern half of France and particularly in the eastern region. On the opposite, antecedent soil moisture decreases in the mountainous regions of the Alps and Pyrenees, and around the Mediterranean Sea. For the fraction of direct runoff, there is a slight trend towards an increase in RCP4.5, and a noticeable trend towards an increase in RCP8.5, in the western regions. Finally, the contribution of snowmelt to flood flows is decreasing wherever this component influences floods. Thus, it is interesting to note that in a context of increasing rainfall intensity, outside Mediterranean regions, we observe an increase in flood magnitude, that is associated either with an increase in initial soil saturation conditions, in eastern France, or with an increase in the fraction of direct runoff, in western France. It is also worth noticing that the spatial pattern of soil moisture trends seems to mimic flood trends more closely than extreme rainfall trends, as observed in other regions of the world (Wasko and Nathan, 2019).

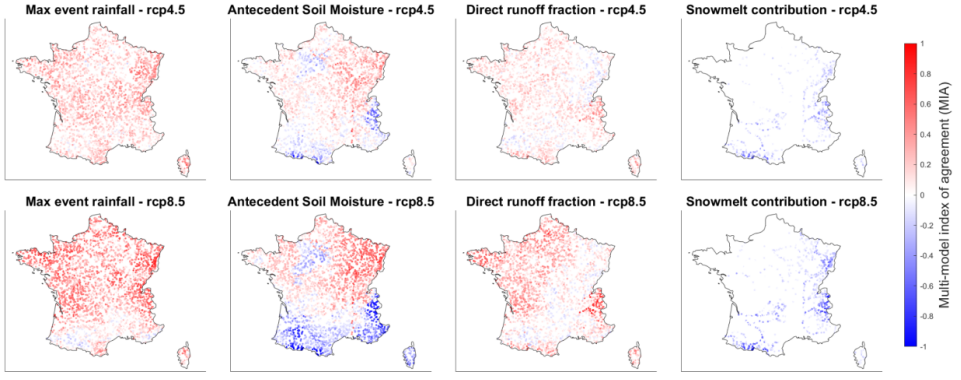

Figure 3: Multi-model index of agreement of the trends in maximum rainfall during floods, antecedent soil moisture conditions, direct streamflow fraction, and snowmelt fraction, under the RCP4.5 and RCP8.5 with ADAMONT

3.2 Classification of flood-generating processes

The floods extracted from the various simulations were classified according to the different categories; snowmelt, rain and snowmelt, soil water excess, short rain, and long rain. The result of this classification from the multimodel ensemble during the historical period 1975-2005 is presented in Figure 4, which shows the relative contribution of these different flood types for each station. Events linked to soil saturation are predominant, accounting for more than 50 % of floods in France. Long precipitation events are responsible for almost 25 % of floods and are mainly located in the north-west and south of France. It should be noted that most of these events also correspond to soil saturation processes, although in this case, the soil saturation occurs not before but during these events. Indeed, Figure S3 shows that during these long rain events, the largest floods are only associated with SWI values above 0.6, and that the modal value of SWI maxima is close to 0.75 and 0.8, corresponding to the value of the soil saturation threshold most frequently found in French basins (Figure S1). Snowmelt-

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related events, caused by snowmelt or a mixture of rain and snowmelt, account for around 11 % of the total number of floods, mainly for mountainous areas and central-eastern regions. Lastly, short rain events account for less than 10 % of the events, with a spatial distribution very similar to that of long rain. In terms of magnitude, when all the standardized floods for the different processes are grouped, short rain events show the highest magnitude, followed by soil water excess and long rain events, which have similar magnitudes (Figure 5a).

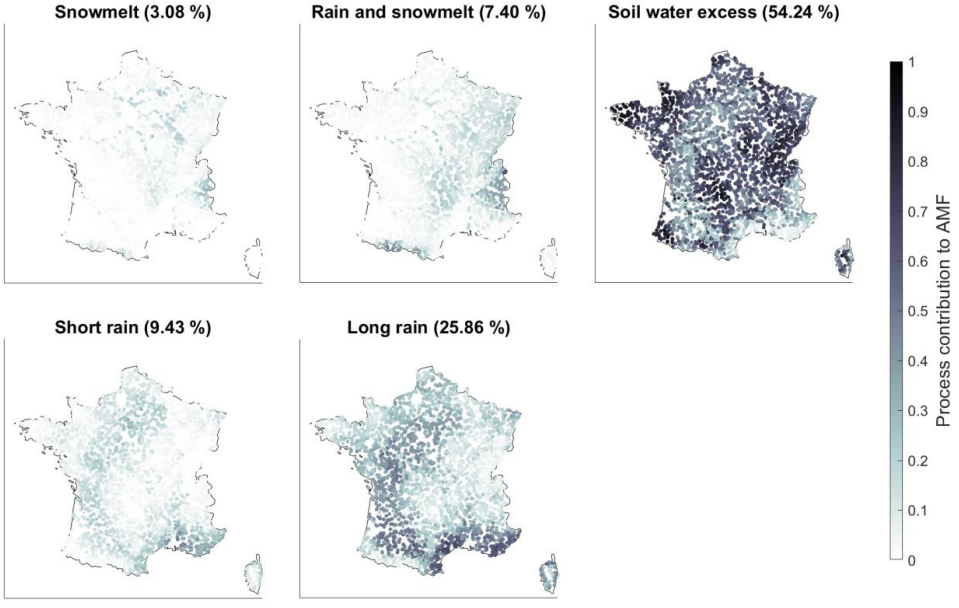

Figure 4: Relative proportion of the different flood-generating processes for each basin during the historical period 1975-2005. The average contribution of each process to the total number of floods is given in the titles of the sub-plots in percentages.

As these results are obtained with an ensemble of bias-corrected climate projections, the results have also been extracted for each GCM/RCM couple independently to check the consistency between results. Over the historical period, the classifications obtained with the different climate models show a very high degree of consistency in the proportions of the different classes between models (Figure S4). This result was quite expected given that the RCM simulations are bias-corrected using the same reference. The results of this classification are also very consistent with previous studies in Europe applying similar classification schemes but with different datasets and a different methodology. For instance, Berghuijs et al. (2019) have found that 49 % of floods are driven by soil water excess in Western Europe, and about 22 % of floods are driven by maximum annual rainfall. Tarasova et al. (2023) obtained similar results in their pan-European study using slightly different classes, with 11 % of rain on dry soils, 67 % of rain on wet soils, and 21 % of rain-on-snow events in Atlantic regions, and for the Mediterranean region, with 25 % of rain on dry soils, 59 % of rain on wet soils, and 15 % of rain-on-snow events. In both regions, the proportion of snowmelt-only driven floods was equivalent to 1 % only.

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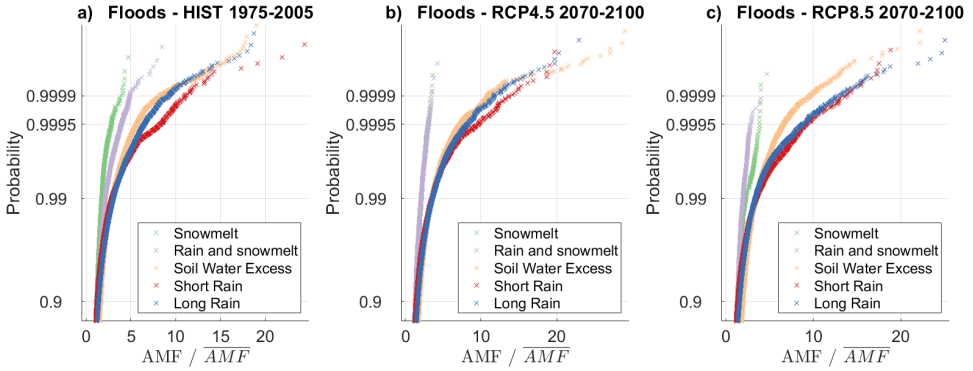

Figure 5: Distribution of floods all basins together, for the different types of floods during the historical period 1975-2005, and for 2070-2100 under RCP4.5 and RCP8.5

3.3 Changes in flood-generating processes

The direction of changes in the contribution of the various flood-generating processes in RCP4.5 and RCP8.5 is shown in Figure 6. Given the low frequency of snowmelt-only events, it is difficult to draw robust conclusions about changes in these events. However, there is a general decrease in snowmelt or rain-and-snowmelt-induced floods in both scenarios. This applies both to the mountain ranges of the Alps and the Pyrenees and to regions located from the center of France to the northeast. There is also an increase in the contribution of events linked to soil saturation, especially in the northeast, that is more widespread spatially for RCP4.5 than for RCP8.5. Floods induced by short rains and long rains are increasing in areas where soil water excess events are decreasing, most importantly in the southern regions and the Alps. It should be noted that the change in rain and snowmelt events shows a very similar spatial distribution compared to the trends for events linked to soil water excess. Indeed, the spatial correlations between changes in soil water excess events on the one hand, and rain and snowmelt events on the other hand, are significant (-0.6 for RCP4.5 and -0.67 for RCP8.5). This means that where the proportion of events linked to the combination of rain and snowmelt is reducing, these events tend to be replaced by floods associated with saturated soils. Similarly, there are significant correlations between changes in the proportion of soil water excess events and the proportion of short rain or long rain events (correlations of -0.31 between changes in soil water excess and changes in short rain, -0.4 with changes in long rain under RCP4.5, and respectively -0.54 and -0.45 under RCP8.5 - yet the magnitude of these correlations remains small). We can therefore see that in regions where the proportion of floods related to saturated soils is decreasing, the proportion of floods associated with short rain or long rain is increasing, particularly in southern regions. This result shows that these shifts, previously observed in historical records (Jiang et al., 2022; Tarasova et al., 2023; Tramblay et al., 2023), are likely to amplify under the two emission scenarios considered herein.

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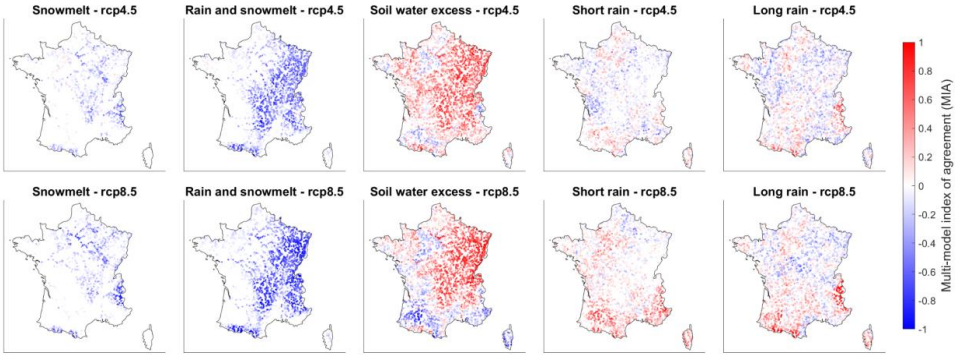

Figure 6: Multi-model index of agreement for the trends in the contributions of the different flood-generating processes, under the RCP4.5 and RCP8.5

The trends in the flood quantiles (Q50 and Q95) and the trends in the five flood-generating processes have been clustered for the two RCP separately, using the Ward linkage method, commonly used in hierarchical clustering, together with silhouette plots to identify the optimal number of clusters (Kaufman and Rousseeuw, 1990). This classification results in four spatial clusters as shown in Figure 7. Cluster 1 includes mountain basins in the Alps and Pyrenees, where Q50 and Q95 show mostly declining trends, or an absence of trends, linked to a sharp decrease in snowmelt-related events and an increase in events caused by short rain and long rain. Cluster 2 includes basins located in southern regions, where there is no trend or a decrease in floods, associated with a drop in events linked to soil saturation and an increase in events caused by short rain and long rain. Cluster 3 and 4 gather the stations in the northern half of France, where flooding trends are on the rise, but with a sharp decrease in snowmelt-related flooding in the east (cluster 4), while in the west (cluster 3) there is an increase of the proportion of intense rainfall (short rain) on dry soils, associated with an increase in direct runoff, as already shown in the previous sections. The spatial organization of the different clusters is very similar under the two scenarios RCP4.5 and RCP8.5, with one notable difference concerning cluster 2, corresponding to Mediterranean events in the South of France, which has a much more marked northward extension under the RCP8.5 scenario. Overall, it should be noted that this spatial distribution is strongly reminiscent of the different climatic zones observed in France (Strohmenger et al., 2024), with the western and coastal regions under a temperate oceanic climate, the center and east of France with a more continental climate, the southern part corresponding to areas with a Mediterranean climate, and finally the mountain regions of the Alps and the Pyrenees.

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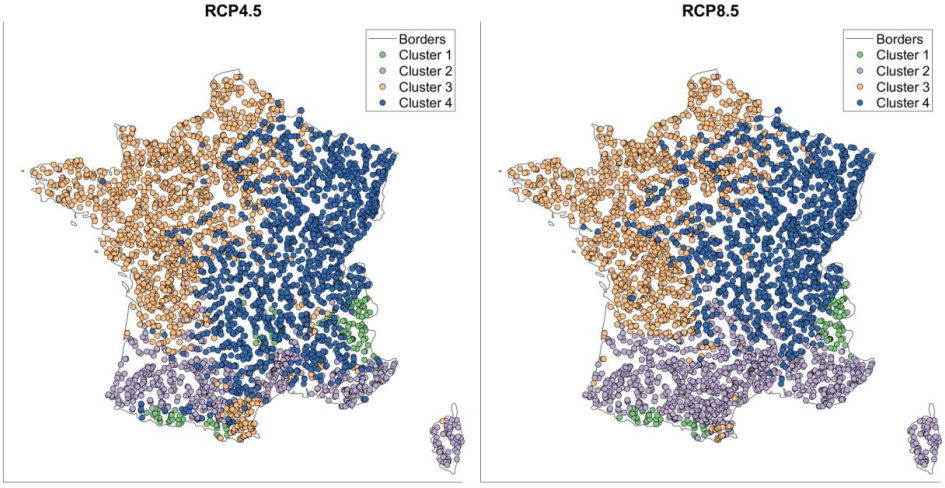

Figure 7: Regional clusters of the trends in flood magnitudes and flood-generating processes

3.4 Regional drivers of change for flood hazard in future projections

The magnitude of floods will change differently, depending on their generating processes. When aggregated over France, the magnitude of snowmelt-related events is projected to decrease (Figures 5b and 5c), while soil water excess events increase slightly. It is mainly the magnitude of the rarest and most intense short rain and long rain events that are increasing. Marked differences between future and historical distributions are mainly projected for events associated with non-exceedance probabilities greater than 0.95 (i.e. floods corresponding to a 20-year return period and beyond). However, this overall assessment at the country level hides regional differences depending on the flood-generating processes. If we look by region and by flood process (supplementary figures S5 and S6), we observe that this increase in the magnitude of the rarest floods (i.e. the distribution tails), only affects the northern regions of France, clusters 3 and 4, and events linked to short rains and long rains, which are flood events linked to rainfall on dry soils, and also the events related to soil water excess. Under the RCP4.5, the flood distributions in the different regions for the different flood generating process are similar between 1975-2005 and 2070-2100 (figure S5), except for some of the most extreme events as mentioned above. For the RCP8.5, there are more marked changes, notably with a shift of the flood distribution towards lower values for the cluster 1 (mountainous regions), and to a lesser extent for the cluster 2 (Mediterranean regions). On the opposite, there are distribution shifts towards increased flood magnitudes for most processes in the clusters 3 and 4.

Another important question that arises when analyzing the impact of climate change on floods is to understand which factors have the greatest influence on flood trends in different climate projections. Given that 11 climate projections are available here for RCP4.5 and RCP8.5, we can calculate for each model the correlations between flood trends and the trends in the three factors most commonly recognized as flood triggers (Wasko and Nathan, 2019, Zhang et al., 2022) at the event scale (antecedent soil moisture conditions, snowmelt contribution, and maximal rainfall) and the trends for floods with 2-year (Q50) and 20-year (Q95) return periods.

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The results of this correlation analysis are presented in Figure 8 for each of the four regions identified by the clustering of Figure 7. For the first cluster, i.e. the mountain areas, there are strong positive correlations between snowmelt trends and Q95 flood trends, but much more contrasting correlations with Q50. For clusters 2 to 4, the patterns are quite similar. A striking result is that the correlations between trends in floods and trends in SWI are at least equivalent, if not superior, to the correlations with trends in intense rainfall for the different climate projections. This result is not region-specific, and it should also be noted that correlations with SWI are almost systematically stronger for frequent floods (2-year), than for rarer floods (20-year). To a lesser extent, correlations are also weaker between trends in rainfall intensity and the flood trends for the rarest floods, than for trends in the most frequent floods. This result should however be interpreted with caution given the uncertainties inherent in estimating intense rainfall in climate models. These results imply that the trends projected for the various processes can, to a large extent, explain the trends in flooding in France, and that the evolution of soil saturation plays a role equivalent to that of the evolution of intense rainfall in the various regions to explain the trends in flood hazard in the different climate projections.

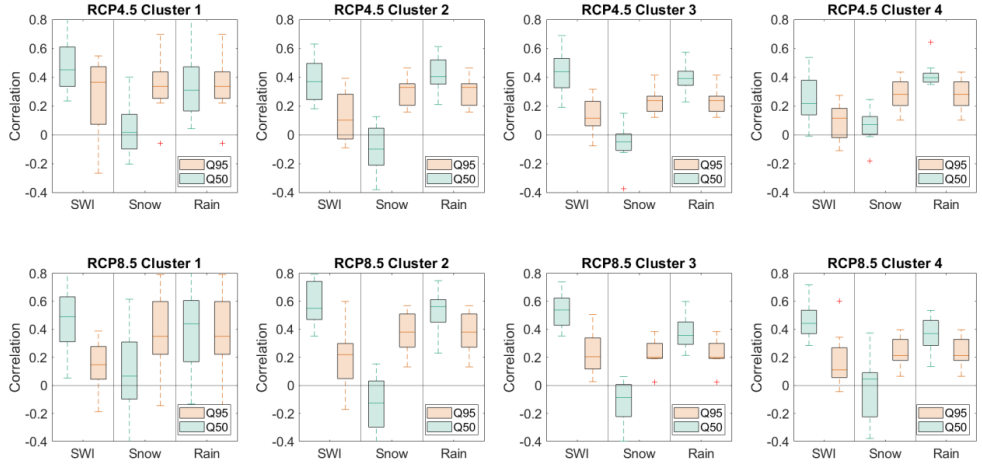

Figure 8: Correlations between the trends in event antecedent soil moisture (SWI), snowmelt contribution (Snow) and maximum rainfall (Rain), and the trends in 2-year (Q50) and 20-year (Q95) floods. The boxplots represent the ranges of the correlation coefficients obtained for each climate projection under the RCP4.5 (top row) and RCP8.5 (bottom row).

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4. Conclusions

Flood trends show a contrasting signal in the different regions, with a fairly good consistency towards an increase in floods in northern France and an absence of signal in southern regions. In line with the uncertainty in future precipitation changes, it should be emphasized that multi-model agreement remains fairly weak in most basins for increasing or decreasing trends in flood hazard. In terms of magnitude, trends are more marked for rare floods (20-year return period) than for frequent floods (2-year return period). Trends in initial moisture conditions show a spatial distribution quite similar to that of floods, with an increase mainly in northern regions and a decrease in antecedent soil moisture in the south. These changes tend to mimic the seasonal precipitation changes, with an increase in winter precipitation in the north and a decrease in summer precipitation in the south. The magnitude of rainfall events increases everywhere, most markedly in the northern half of France, while the contribution of snowmelt decreases everywhere in the mountain ranges, consistently with the projected decrease in snowfall as indicated by climate projections. A classification of floods by process reveals that floods linked to soil saturation account for more than half of all floods in France, and that this proportion is increasing in the north-east of the country while decreasing in the south. The relative changes in the importance of the different flood generating processes is not spatially homogeneous and varies by region. The analysis highlights that flooding trends can be decomposed into several distinct signals linked to different flooding processes, and that the multi-model uncertainty concerning these trends varies according to the process considered. Trends in soil saturation play as important a role as trends in intense rainfall in different regions to explain changes in flood hazard in the different climate simulations.

Overall, in regions where the proportion of floods linked to saturated soils is decreasing, the proportion of floods linked to short or long rains is increasing, particularly in the south. Both the frequency and magnitude of floods linked to snowmelt processes are declining in areas where these processes operate, namely mountainous areas and the north-eastern regions. On the contrary, the flood magnitudes associated with rainfall on dry sols (short rain and long rain floods) tend to increase, in line with the increase of maximum event rainfall in the different scenarios. The trends in the RCP8.5 scenario are both more pronounced and allow better discrimination between regions. The changes seem fairly consistent with the distribution of French climatic zones: floods tend to increase in the continental climate zone, with an increase in soil water content leading to an increase in the number of flood events linked to soil saturation. In the temperate oceanic zone, flooding is also on the rise, but this time in connection with the increased intensity of intense rainfall. In the Mediterranean regions, there is no marked trend in flooding, with declining soil moisture and uncertain trends in rainfall intensity. Lastly, in mountainous regions, there are drastic changes in flood-generating conditions, with a marked drop in snowmelt and an absence of trends, or even a decline, in flooding.

In terms of perspectives for this study, there are a number of points to note. The first is that the analysis carried out here is based on a daily time step, which is unsuitable for the analysis of flash floods, which occur, for example, in Mediterranean regions with high hourly rainfall intensities. For small basins, where only until recently high-resolution convection-permitting models (Lucas-Picher et al., 2021) are able to tackle this problem by improving the modeling of small-scale convective rainfall events (Kay, 2022; Poncet et al., 2024), there is not yet a large ensemble of model runs available to assess the uncertainties in the projections. It should

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be stressed out that the results obtained herein are unlikely to be transposable to flash floods, and large convection-permitting model ensembles would be required to replicate such an analysis for flash floods. Another important aspect is that this study is based on natural hydrology processes in relation to climate change. However, changes in land use (Rogger et al., 2017; Yang et al., 2021) or the construction of infrastructures, such as dams (Zahar et al., 2008; Grill et al., 2019; Blöschl, 2022b), can greatly modulate the risk of flooding. However, this type of non-climate-related change is very difficult, if not impossible, to take into account in such a large scale and multi-basin study. Nevertheless, at more local scales, and in close interaction with land-use planning and water management stakeholders, such multi-criteria analyses could be carried out to better distinguish between climatic and non-climatic influences on the evolution of flood risk.

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Data availability

All the data of this study is available freely in open access. The bias-corrected climate model simulations are available at: https://www.drias-climat.fr/. The hydrological model simulations are available at: https://www.drias-eau.fr/ . The discharge measurements over France are available at: https://www.hydro.eaufrance.fr/ . The SAFRAN database is available at: https://meteo.data.gouv.fr/datasets/donnees-changement-climatique-sim-quotidienne/

All the technical reports of the Explore2 project are available in the repository: https://entrepot.recherche.data.gouv.fr/dataverse/explore2

Code availability

The bias-correction method for climate simulations is available at: https://github.com/yrobink/SBCK-python

The hydrological model codes are available at: https://inrae.github.io/airGRiwrm/ and https://hydrogr.github.io/airGR/

Author contributions

YT designed the study and performed the experiments. GT, LS, ran the GRSD model simulations, LH managed the database, LC generated the climate scenarios, GE and ES contributed to the methodology and YT wrote the paper with contributions from all the authors.

Competing interest declaration

The authors declare that they have no conflict of interest.

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