C. R. Geoscience 350 (2018) 141–153

Contents lists available at ScienceDirect

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Review paper

Impacts of climate change on the hydrological cycle over France and associated uncertainties

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ARTICLE INFO

Article history:
Received 3 February 2018
Accepted after revision 6 March 2018
Available online 4 April 2018

Handled by Didier Roche

Keywords:
Climate change
Impacts
France
Regional hydrology
Hydrological cycle changes

ABSTRACT

This study deals with the evolution of the hydrological cycle over France during the 21st century. A large multi-member, multi-scenario, and multi-model ensemble of climate projections is downscaled with a new statistical method to drive a physically-based hydrological model with recent improvements. For a business-as-usual scenario, annual precipitation changes generally remain small, except over southern France, where decreases close to 20% are projected. Annual streamflows roughly decrease by 10% (±20%) on the Seine, by 20% (±20%) on the Loire, by 20% (±15%) on the Rhone and by 40% (±15%) on the Garonne. Attenuation measures, as implied by the other scenarios analyzed, lead to less severe changes. However, even with a scenario generally compatible with a limitation of global warming to two degrees, some notable impacts may still occur, with for example a decrease in summer river flows close to 25% for the Garonne.

1. Introduction

Several studies point to an impact of anthropogenic forcings on the recent evolution of the water cycle at large scales (Bindoff et al., 2013), for example on precipitation (Zhang et al., 2007) or evapotranspiration (Douville et al., 2012). Over France, significant negative trends have been noted on river flows during the last decades of the 20th century in summer (Giuntoli et al., 2013) but as they occur in the context of large multi-decadal variations of probable internal origin (Boé and Habets, 2013), no robust attribution can be made.

A few studies projected the future evolution of the continental hydrological cycle over the entire France (Boé et al., 2009; Chauveau et al., 2013). Both were based on the previous generation of global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al., 2007) and emissions scenarios. These studies generally agree, on a decrease in river flows, especially pronounced in summer and autumn, when it can reach 30% by the middle of the 21st century. Chauveau et al. (2013) note an important role of hydrological models in the uncertainties of hydrological impacts over France, especially in summer, consistent with Hattermann et al. (2017) and Donnelly et al. (2017) at the global and regional scales. Projected hydrological changes are also impacted by uncertainties due to emissions scenarios and to the downscaling methodologies. Some studies on specific catchments over France provide a finer characterization of the changes and of their uncertainties Habets et al. (2013a) and Lafaysse and Hingray (2014).

As all these studies over France are mainly based on statistical downscaling (SD) as a method to obtain from the

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https://doi.org/10.1016/j.crte.2018.03.001

low-resolution climate models the high-resolution climate forcing necessary for hydrological modelling, they suffer from a common conceptual difficulty (Maraun et al., 2010). SD is based on the strong hypothesis that the statistical relationship remains valid in future climate conditions, which cannot be strictly verified. It is therefore possible that part of what is generally considered as uncertainties related to SD methods are, in fact, errors caused by the limited temporal transferability of some methods.

In this study, the results of new hydrological projections over France are described. A new version of the Isba–Modcou hydrometeorological system (Decharme et al., 2011; Habets et al., 2008), with a higher resolution on mountains areas, and a more realistic representation of water and energy transfers in the soil is used. Its results are compared to the ones of a second hydrological model: Mordor (Garçon, 1996, 1999). Given the limited completeness of the Euro-Cordex (Jacob et al., 2013) ensemble of regional climate models (RCMs) projections at the beginning of our study, we also use a SD approach. It has been evaluated within an innovative framework to test the transferability hypothesis previously mentioned (Dayon et al., 2015). The last generation of GCMs (Coupled Model Intercomparison Project Phase 5, CMIP5, Taylor et al., 2012) with new emissions scenarios are used, including a scenario corresponding to a limitation of global warming close to the objective of the Paris climate agreement (Schleussner et al., 2016).

The preliminary applications of the methods necessary for our study are presented in Section 2. Projected hydrological changes are described in Section 3. Our results are compared to previous studies and the uncertainties due to hydrological modelling are discussed in Section 4. Finally, our conclusions and research perspectives are given in the last section. Data, models and methods are introduced in the appendix.

2. Application of Isba–Modcou and of the downscaling method

2.1. Present-day streamflows modelling

An evaluation of the ability of the new Isba–Modcou hydrometeorological system forced by Safran (SIM, see Appendix A) to simulate the streamflows for the four main French river basins is presented in Fig. 1. The observed and simulated seasonal cycles of streamflows are very similar for the Loire, the Seine, and the Garonne Rivers, except in summer. In summer, SIM generally overestimates the streamflows. Water withdrawals are not modelled in SIM, which may explain a part of the positive bias in summer. For the Loire and the Garonne, the biases in summer are also likely due to the conceptual reservoirs in Isba that help to sustain slow sub-surface runoff and are not calibrated (Appendix A). The Rhone hydrological regime is strongly impacted by dams, whose impacts are not simulated by Isba–Modcou, which very likely explain the large differences between observed and simulated river flows.

The ability of the SD method (Dayon et al., 2015 and see Appendix A) to capture the spatial and seasonal features of the regional climate necessary to simulate correctly river flows is evaluated with an Isba–Modcou simulation forced by the downscaling of ERA-Interim (Fig. 1). On the four river basins, the seasonal cycles of streamflows simulated by Isba–Modcou driven by the downscaling of ERA-Interim are very close to those simulated by SIM.

The negative bias in winter, compared to SIM, can be explained by a dry bias in precipitation due to the statistical downscaling method (around 5% in winter; Dayon et al., 2015). A negative bias in downscaled precipitation is seen throughout the year on the Seine (not shown). The downscaling method applied to realistic atmospheric predictors, such as the ones provided by ERA-Interim, and combined with the hydrological system Isba–Modcou therefore generally lead to a correct simulation of the hydrological cycle on the present period.

The ensemble mean and spread of the annual cycle of the streamflows simulated by Isba–Modcou driven by the downscaling of the GCMs, given in Table 1, Appendix A, on the historical period are also shown in Fig. 1. A systematic positive bias is noted, especially in winter (up to 30% relative to SIM on the Rhone and the Garonne Rivers). This bias is mostly due to a noticeable bias in downscaled precipitation in winter (not shown). The bias in downscaled precipitation in winter, not seen for the downscaling of ERA-Interim, is very likely due to biases in the zonal circulation of GCMs (not shown).

In summary, climatological biases in simulated river flows after the downscaling of GCMs exist, in winter mostly because of GCMs and in summer for some rivers, mostly because of the hydrological model. This is not necessarily an issue as we are interested in future changes. Indeed, a hydrological model with smaller biases in the current climate is not necessarily more robust to project future changes.

This question of the temporal transferability in the future climate of hydrological models has been addressed in several studies but is still a largely open issue. Conceptual hydrological models may be very sensitive to the calibration period (Brigode et al., 2015; Coron et al., 2012, 2015), which limits their transferability. On the other hand, Van Huijgevoort et al. (2014) show generally a good agreement of the performances of five global hydrological models on the 1971–2000 period and the most recent and warmer past (2001–2010), which reinforces the confidence in the transferability of these hydrological models to the future climate. Nevertheless, the relevance of those studies regarding climate change projections is mainly limited by the relative weakness of observed climate change signals compared to the ones expected by the end of the 21st century. For future studies, an interesting approach would be to use several hydrological models, ideally with different modelling approaches, associated with an ensemble averaging technique (Broderick et al., 2016; Seiller et al., 2012).

2.2. Downscaled precipitation changes over France

Downscaled annual precipitation changes are small at the end of the 21st century for the radiative concentration pathways 8.5 (RCP8.5) scenario (Moss et al., 2010) (Fig. 2c).

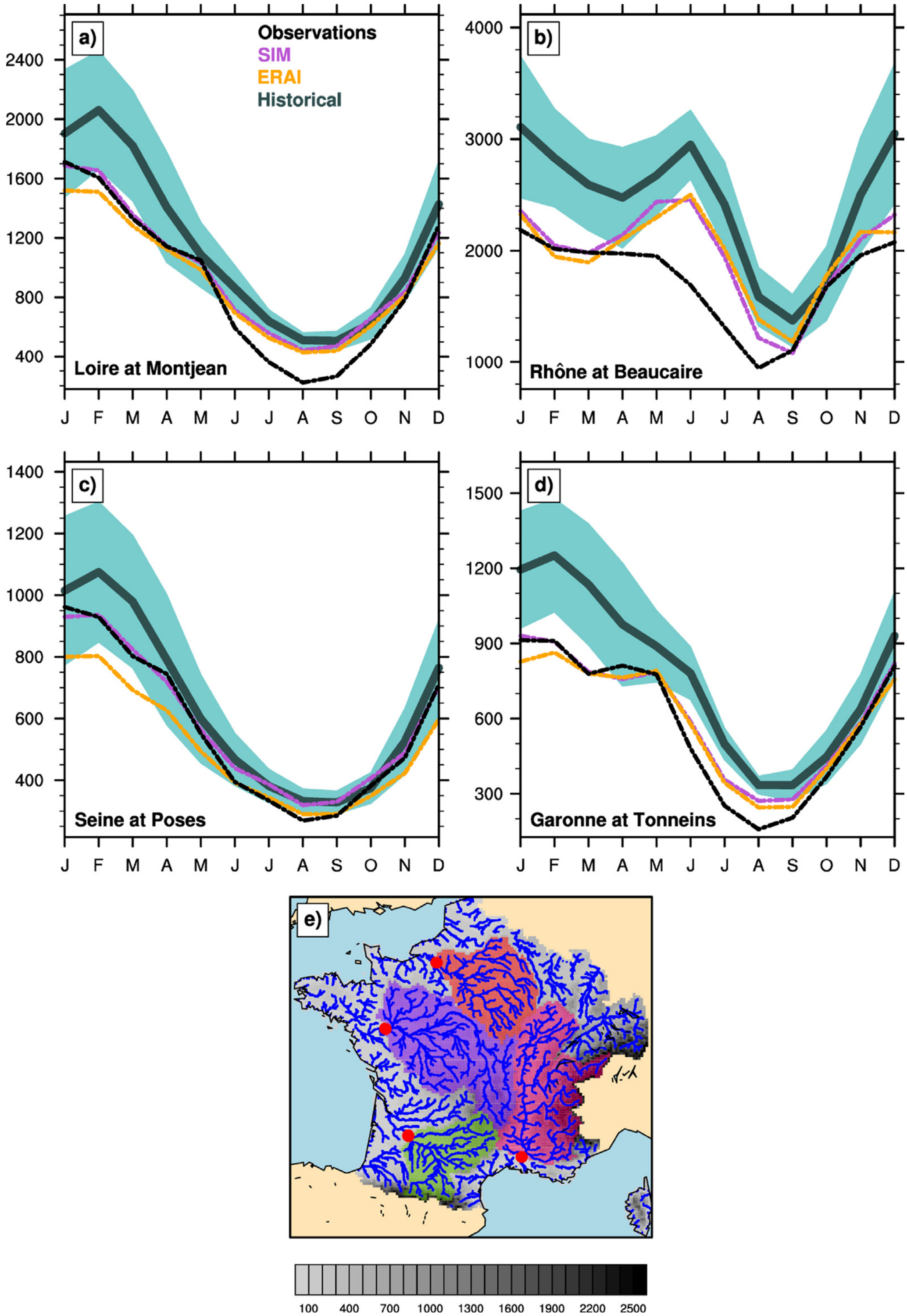

Fig. 1. (a–d) Climatological annual cycle of streamflows ($m^3 s^{-1}$) on the 1979–2005 period in the observations (black), the Safran–Isba–Modcou analysis (purple), as simulated by Isba–Modcou driven by the downscaling of the ERA-Interim reanalysis (yellow) and simulated by Isba–Modcou driven by the downscaling of the CMIP5 GCMs on the historical period (cyan). The shading represents the uncertainties range due to GCMs. It is estimated by a 1.64 standard deviation between the simulations, weighted by the number of members for each GCM. (e) Hydrographic network of the Modcou model and river basin of the four main French river in color: the Seine at Poses (red), the Loire at Montjean-sur-Loire (blue), the Rhone at Beaucaire (pink) and the Garonne at Tonneins (green). The stations where the streamflows are studied are marked by a red dot.

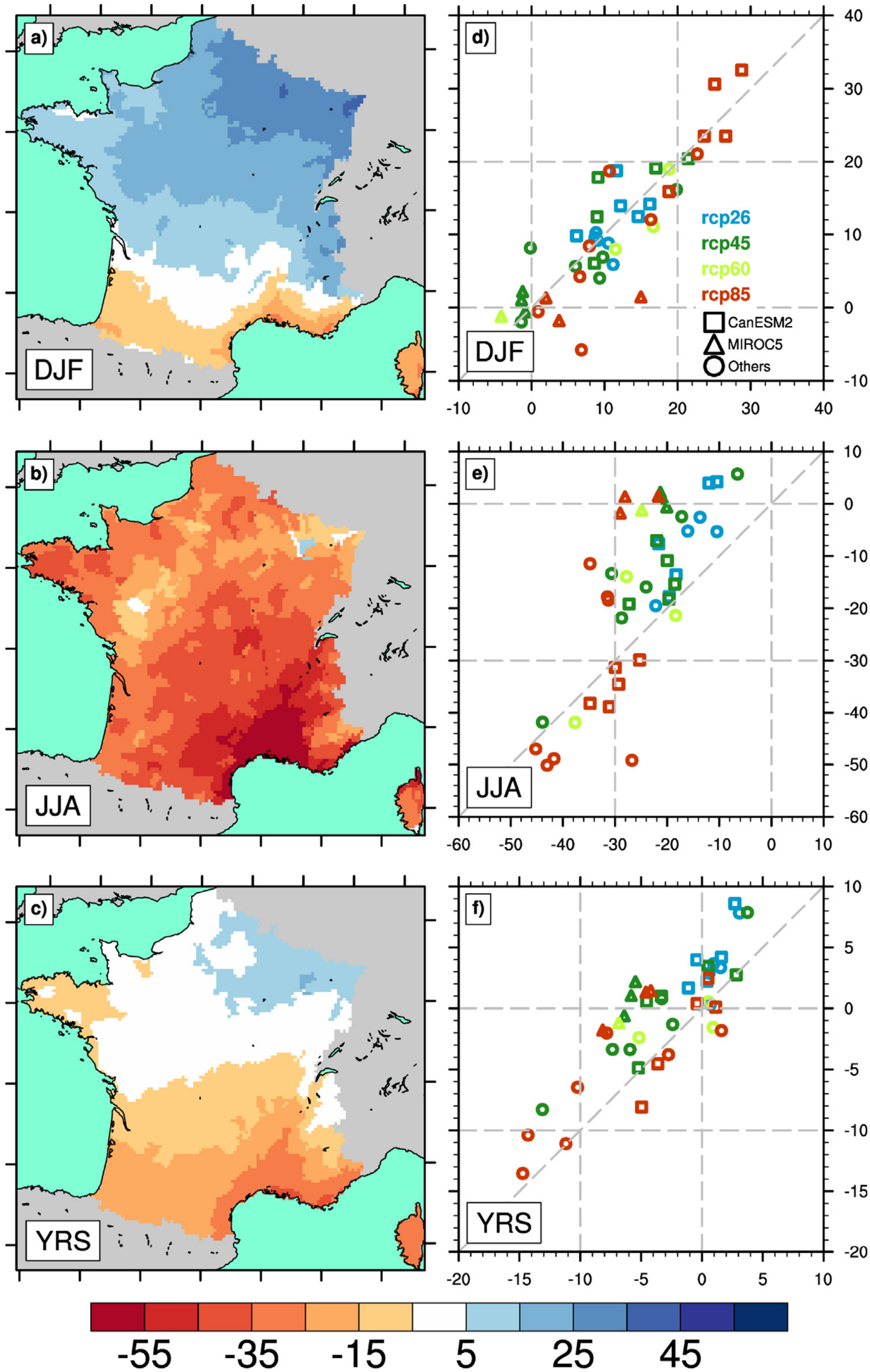

Fig. 2. (a–c) Ensemble mean of relative precipitation changes (%) between the 1960–1990 and 2070–2100 periods under the RCP8.5 scenario in winter (DJF), summer (JJA), and for the entire year (YRS). (d–f) Scatter plot of the relative precipitation changes over France simulated by GCMs (*y*-axis) against the corresponding relative downscaled precipitation changes (*x*-axis). Each color corresponds to a RCP scenario, and the symbols represent the simulations: squares are for simulations from CanESM2, triangles are for simulations from MIROC5, and circles for the other GCMs.

Annual changes are mainly the residual of seasonal changes of opposite signs. In winter, downscaled precipitation increases over a large part of France (Fig. 2a), especially in the Northeast (increase between 25% and 35%). Summer precipitation strongly decreases over the entire France, with maximum values in the South, especially in Mediterranean region (Fig. 2b). Almost all the downscaled GCMs agree on the sign of the changes in summer but there is a strong uncertainty on the magnitude of the decrease in precipitation (from 0 to −50%, Fig. 2e). Relative precipitation changes directly simulated by GCMs and from the SD of GCMs are compared on average over France (Fig. 2d–f). In summer, weak (strong) decreases simulated by GCMs are associated with more (less) severe decreases after downscaling. The inter-model variance and hence the uncertainties due to GCMs are therefore smaller after statistical downscaling in summer (Fig. 2e). It is surprising, considering that the SD method was able to capture the full range of projected changes by an ensemble of RCMs in the perfect model framework developed in Dayon et al. (2015). Given the period and the scenario used, the climate change signals were smaller in Dayon et al. (2015) than here. The SD method might be less skillful for larger signals. Alternatively, the perfect model framework of Dayon et al. (2015) and real-world downscaling differ in an important way: the statistical relation between predictors and precipitation used by the SD method comes from the models in the former but from observations in the latter. Further analyses would be needed to determine if the statistical relation between predictors and precipitations is somewhat biased in some GCMs.

Averaged precipitation changes over France from the limited ensemble of GCMs used here are generally consistent with precipitation changes simulated by wider ensembles of CMIP5 GCMs, both in terms of ensemble mean and spread (Stocker et al., 2013; Terray and Boé, 2013). It suggests that our results based on a sub-sample of CMIP5 GCMs are representative of the full ensemble.

3. Hydrological changes over France and associated uncertainties

This section presents the hydrological impacts over France as projected by the Isba–Modcou model driven by the downscaling of the CMIP5 models given in Table 1. Results are shown for the 21st century relatively to the 1960–1990 period. Note that with the experimental design adopted, only the impacts of climate change on the hydrological cycle are addressed, and not those associated with potential land use or water management changes.

3.1. Surface water balance

The seasonal and annual relative changes in precipitation, evapotranspiration and total runoff averaged over the four main French river basins are depicted in Fig. 3 for the different greenhouse gas (GHG) emissions scenarios. The multi-model ensemble mean is calculated and considered as the best estimator of the climate change signals. This approach is common (e.g., the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5); Stocker et al., 2013) and relies on the hypothesis that the errors from different GCMs partially cancel out (Knutti et al., 2010; Tebaldi and Knutti, 2007).

On the four river basins, projected changes in evapotranspiration are very similar. A strong relative increase in evapotranspiration is projected in winter (between 30% and 60% in ensemble mean) and in spring (between 30% and 40% in ensemble mean). In winter and early spring, the soils are generally climatologically moist, and evapotranspiration over France is generally limited by incoming energy at the land surface. Incoming energy at surface increases in the global change context and so does evapotranspiration. In summer, evapotranspiration decreases over the four river basins because of drier soils (not shown) caused by a decrease in precipitation in summer and an increase in evapotranspiration in spring and winter. This mechanism has been described and discussed in previous studies (Boé and Terray, 2008; Boé et al., 2009; Habets et al., 2013a).

The summer runoff decreases over the four river basins, for all emissions scenarios. For the RCP8.5 scenario, this decrease is consistent among all the GCMs and ranges from −20% to −60% in ensemble mean. More contrasted results are obtained in winter. On the Seine basin, the runoff slightly increases in ensemble mean, but the results are uncertain and range from a large increase (30%) to an important decrease (−20%) depending on the GCMs (Fig. 3a). On the Rhone basin, whose regime is strongly impacted by snowmelt, the runoff in winter increases for almost all the GCMs with the RCP8.5 scenario (Fig. 3b), because both total precipitation and the rainfall proportion increase over the Alps (not shown). On the Garonne and the Loire basins, the winter runoff decreases in ensemble mean for the RCP4.5, RCP6.0 and RCP8.5 scenarios (Fig. 3c and d). The decrease is more pronounced for the Garonne, where it is always greater than −20% for the RCP8.5 scenario.

The strong mitigation of GHG emissions associated with the RCP2.6 scenario would lead to much less severe changes in the hydrological cycle over France. However, large decreases in runoff would still occur with this scenario in summer (close to 30% for the Garonne).

3.2. Streamflows

Seasonal and annual changes in streamflows at the end of the 21st century are shown for the RCP8.5 scenario in Fig. 4a–c. A decrease in winter streamflows in the Southwest (between −20% and −30%) except for a few rivers in the Pyrenees, no changes or a slight increase in the Northeast (from −5% to 15%), and a strong increase in the Alps mountains (more than 50%) for some rivers, are projected (Fig. 4a). On mountain areas, warming induces a decrease in the solid-to-liquid precipitation ratio (not shown). It leads to a strong increase in streamflows, despite a moderate increase in precipitations in the Alps and to a slight increase in streamflows in the Pyrenees while precipitation decreases (Fig. 2a). Outside mountain areas, the pattern of changes in streamflows is similar to the pattern of precipitation changes (Fig. 2a). In the North of France in winter, the impact of the increase in

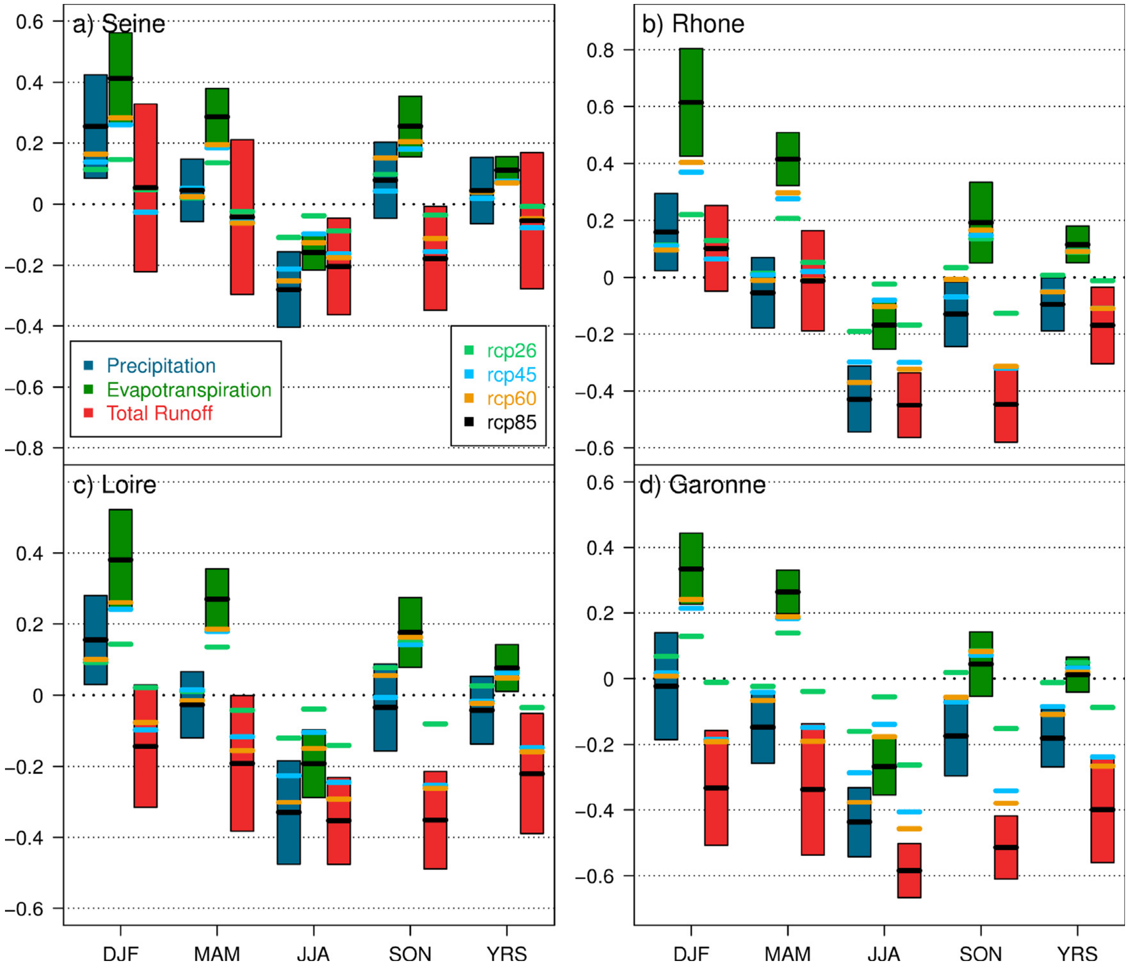

Fig. 3. Seasonal and annual relative changes (no units) of precipitation (blue), evapotranspiration (green), and total runoff (red) on the Seine at Poses (a), the Rhone at Beaucaire (b), the Loire at Montjean (c), and the Garonne at Tonneins (d) between the 1960–1990 and 2070–2100 periods. Each horizontal bar represents the ensemble mean and colored rectangles the estimation at [5–95%] of the uncertainty range due to GCMs for the RCP8.5 scenario, centered on the ensemble mean, estimated by a 1.64 standard deviation between simulations.

precipitation on river flows is limited by the increase in evapotranspiration (Fig. 3a).

In winter, the uncertainties due to GCMs generally range from 12% to 30% (Fig. 4d) and reach exceptionally high values in the Alps (above 45%). These large uncertainties in the Alps are probably due to an important sensitivity of streamflow projections to the inter-model spread in temperature changes through its impact on the precipitation phase.

In summer, a large decrease in streamflows is projected for all the French rivers with a meridional gradient (Fig. 4b), as for precipitation changes (Fig. 2a). The strongest decreases (generally greater than −55%) are expected in upstream parts of rivers in the Pyrenees and the Alps mountains because of both an earlier snowmelt in the future climate and a decrease in summer precipitations. The summer is the season when the uncertainties due to GCMs are the smaller (almost always less than 20%).

The temporal evolution of annual streamflow anomalies on the four main river basins for all the scenarios is shown in Fig. 5. The uncertainties ranges associated with climate projections are also represented for the RCP4.5 and RCP8.5 scenarios. The impact of the different emissions scenarios on streamflow anomalies is generally small until the 2030s. Strongest annual changes are projected with the RCP8.5 scenario (decreases in streamflows of 5–10% for the Seine, around 20% for the Loire and the Rhone, and up to 40% for the Garonne). With the strong mitigation of emissions of the RCP2.6 scenario, virtually no changes in annual streamflows are projected for the Loire, the Rhone and the Seine in ensemble mean. Only a small decrease (around −10%) is projected for the Garonne River at the end of the 21st century.

The uncertainties due to climate projections generally increase during the period for both scenarios for which they are shown (Fig. 5). At the end of the 21st century, the uncertainties due to climate projections are important compared to ensemble mean changes (around ±15% for the Loire, ±15% for the Rhone, ±20% for the Seine and ±15% for the Garonne).

Observed streamflows and those simulated by Isba–Modcou forced by the observed climate (SIM) are also

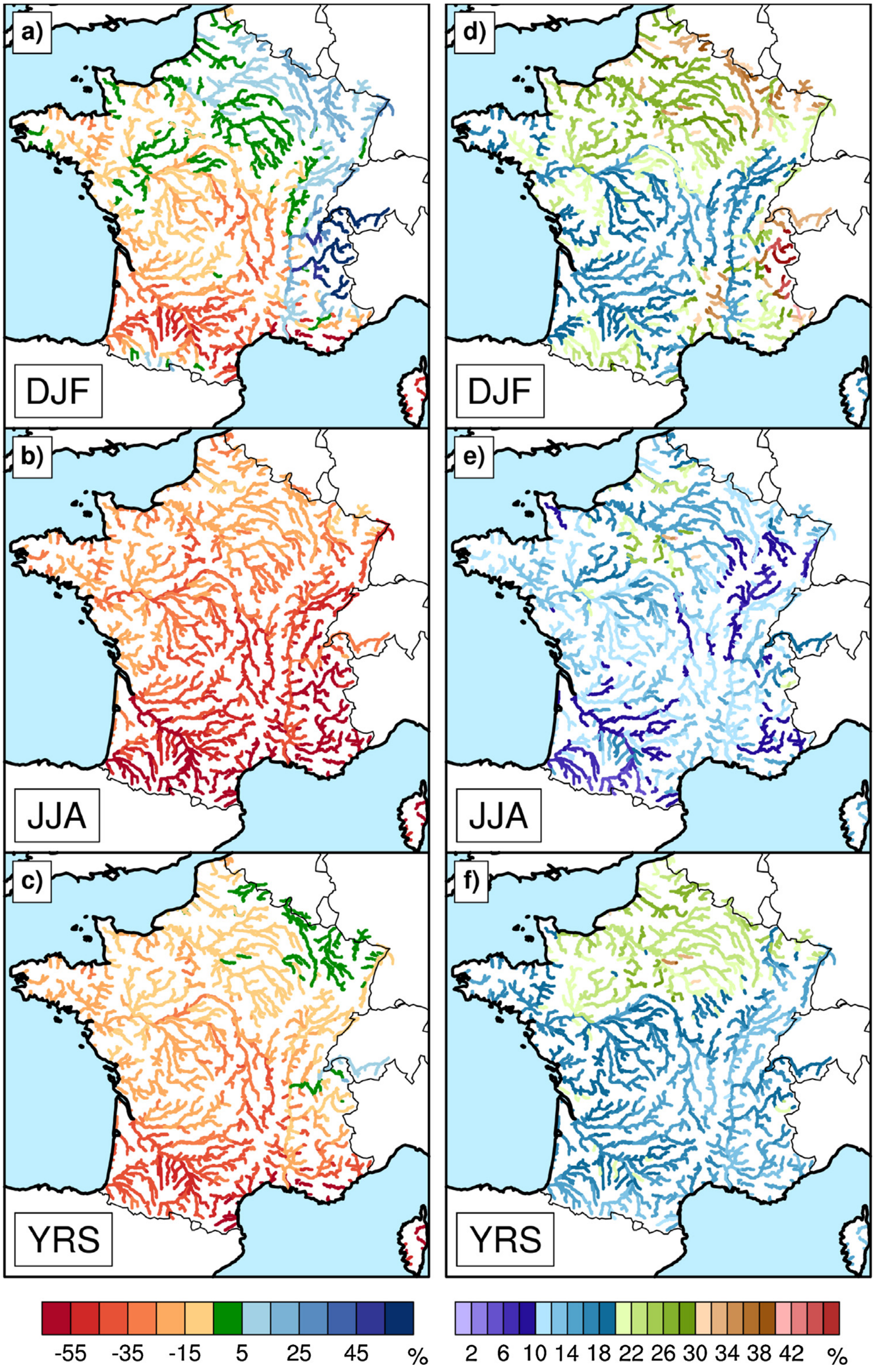

Fig. 4. (a–c) Ensemble mean of relative streamflow changes (%) between the 1960–1990 and 2070–2100 periods under the RCP8.5 scenario on the Modcou hydrographic network. (d–f) Estimation of the uncertainty range at [5–95%] due to GCMs, estimated by a 1.64 standard deviation between simulations.

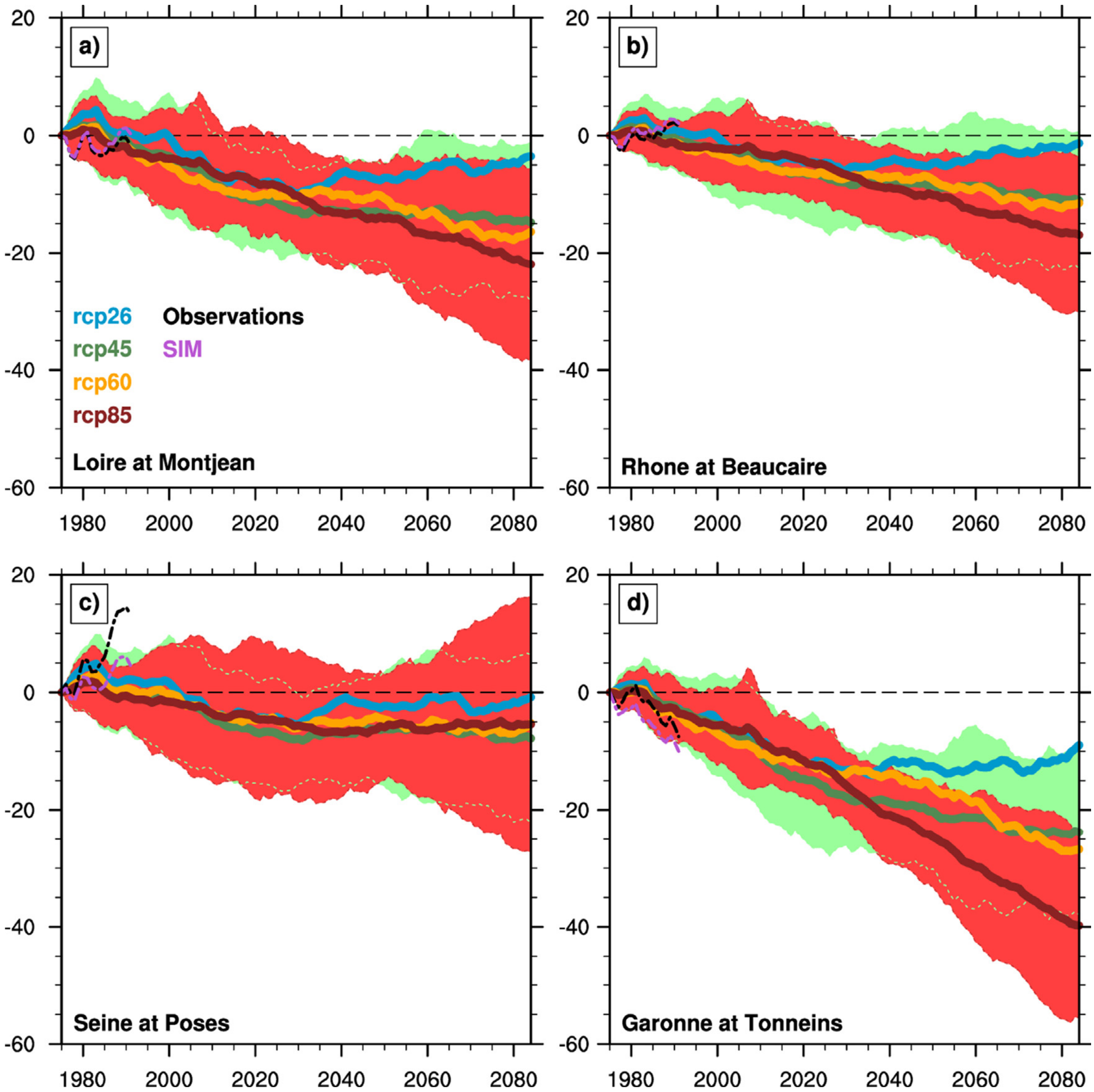

Fig. 5. Ensemble mean, weighted by the number of member for each GCM, of streamflow (%) evolution relative to the 1960–1990 period for the RCP2.6 (blue), the RCP4.5 (green), the RCP6.0 (yellow), and the RCP8.5 (red) scenario. The colored shadings represent the estimation at [5–95%] of the uncertainty range due to GCMs for the RCP4.5 and RCP8.5 scenario, estimated by a 1.64 standard deviation between simulations. Dashed lines are the streamflow evolution in observation (black) and in the Safran–Isba–Modcou analysis (purple). Data have been filtered with a 31-year running mean.

shown in Fig. 5 to assess to what extent the hydrological projections are consistent with the recent observed evolutions. Because of internal variability, it is only expected that the observations fall within the range of the projections. It is the case for the Loire and Rhone Rivers, where observed and SIM streamflows are also close to each other. For the Garonne, SIM and the observations agree on a strong decrease in river flows (close to 20% in 30 years) that is inside the range of projections. On the Seine basin, the observed river flows are outside the range of the projections, but it is not the case for SIM river flows. As the Isba–Modcou model does not take into account non-climatic anthropogenic influences (such as water withdrawal or land-use changes), the divergence between SIM and the observations might imply that non-climatic anthropogenic influences have impacted the Seine during the past decades. If it is not the case, it might imply that there is an issue with the Isba–Modcou system for this particular river, which would decrease our confidence in its future projections.

3.3. Snowpack

The analysis of streamflow projections in the previous section suggests that important changes in the solid-to-liquid precipitation ratio and snowmelt occur in mountain regions. Important impacts on snow cover are therefore expected. The evolution of snow mass above 400 m for the Pyrenees and the Alps is shown in Fig. 6 a and c. We define the annual snow mass as the average of snow mass per

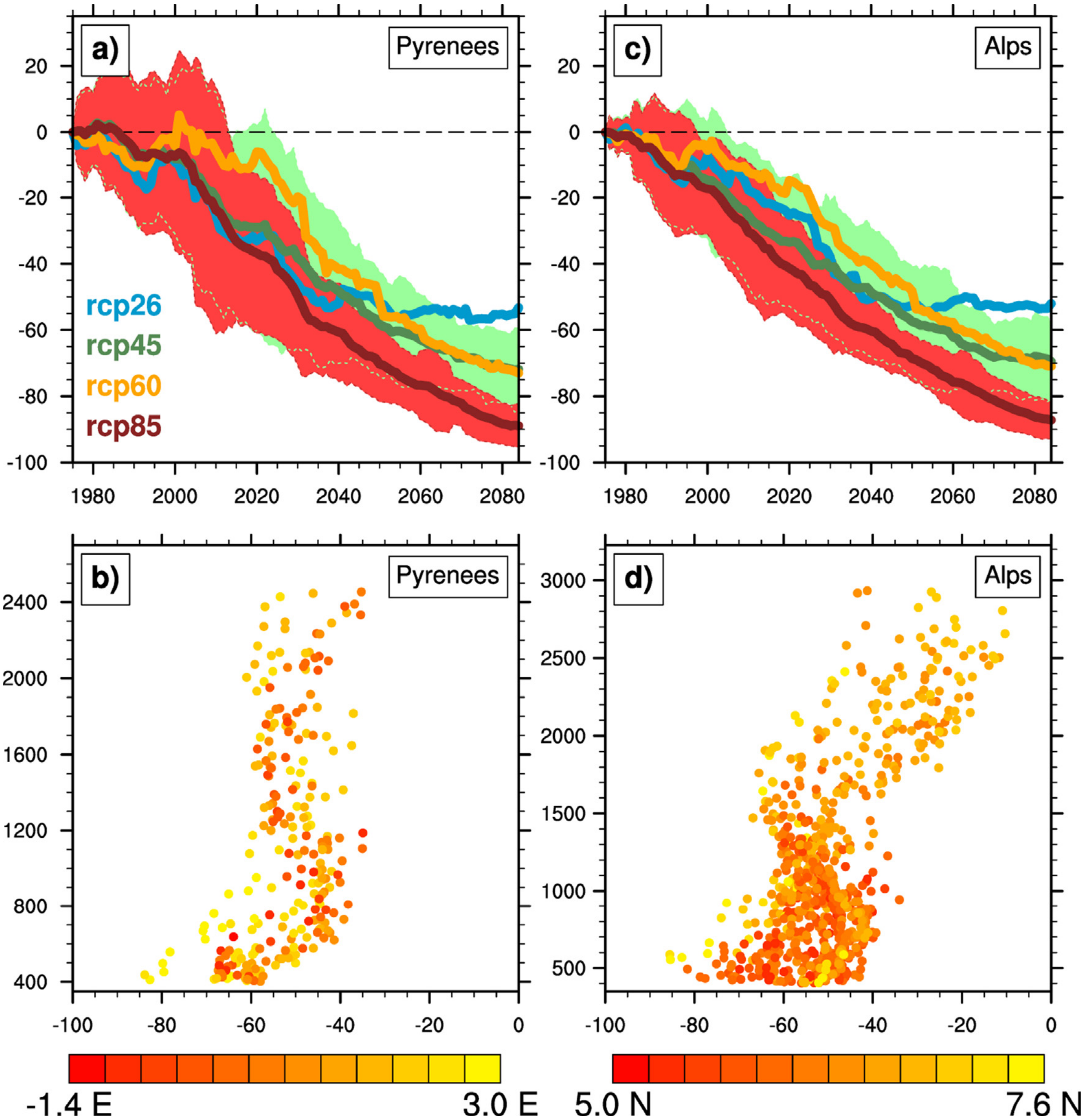

Fig. 6. Top: ensemble mean of the averaged annual snow mass evolution (%) relative to the 1960–1990 period for the RCP2.6 (blue), the RCP4.5 (green), the RCP6.0 (yellow), and the RCP8.5 (red) scenario on the Pyrenees mountains (a) and the French Alps moutains (c). The colored shadings represent the estimation at [5–95%] of the uncertainty range due to GCMs for the RCP4.5 and RCP8.5 scenario, estimated by a 1.64 standard deviation between simulations. Data have filtered with a 31-year running mean. Bottom: relative changes of the daily annual maximum of the snowpack (%) for the RCP4.5 scenario in each grid cell according to their respective altitude (m) on the French Pyrenees mountains (b) and the French Alps (d). The each dots are colored according to their longitude (latitude) in the Pyrenees (French Alps).

square meter over an hydrological year, defined here from August to July.

Projected snow mass changes are very large (Fig. 6a and c). Even with the strong mitigation of GHG emissions of the RCP2.6 scenario, a decrease of −50% in the ensemble mean of the annual snow mass is observed at the end of the 21st century for both mountain chains. The uncertainties due to GCMs decrease during the period and reach 10% at the end of the 21st century, mainly because the remaining snow cover is small in most projections at this point. Note that these results might be particularly sensitive to the sample of GCMs, as shown by the smaller snow mass changes obtained with the RCP6.0 scenario (for which only five GCMs are used, Table 1, Appendix A) during the 2000–2040 period compared to the less severe RCP4.5 scenario.

The ensemble mean of the relative changes in the annual maximum of daily snow mass are also represented against the altitude in Fig. 6b and d, for the RCP4.5 scenario at the end of the 21st century. The daily snow mass maximum is defined as the daily maximum of snow mass per square meter on a grid cell computed for each year. For the Pyrenees (Alps), the dots are colored according to the longitude (latitude) of the corresponding grid point as the mountain range is east–west (north–south) oriented.

In the Pyrenees, the daily snow mass maximum decreases by approximately 50% above 800 m over the entire chain (Fig. 6, b). Below this altitude, changes are stronger, generally between −60% and −70% and even close to −80% for the eastern part of the Pyrenees. Similarly, the changes are stronger at low altitudes over the Alps (Fig. 6d). Above 1500 m, it seems that a quasi-linear relation exists between the relative changes in snow mass daily maximum and the altitude, with smaller changes at high altitudes, especially in the Alps. For both mountain chains, except for the extreme East of the Pyrenees, no particular spatial pattern is discernible.

3.4. Droughts

The strongest hydrological changes over France are generally expected to occur in summer (Fig. 3, Boé et al., 2009; Chauveau et al., 2013) with a large general decrease in streamflows (Fig. 4b). Associated with these changes of the mean state, changes in the occurrence and the intensity of droughts are likely to occur (Vidal et al., 2012).

Here, we use a metric commonly used by French stakeholders to characterize hydrological droughts, the annual minimum of monthly streamflows with a return period of five years (QMNA5), and we adapt this metric to meteorological (PMNA5) and agricultural (SMNA5) droughts. The meteorological and agricultural droughts metrics are constructed as the QMNA5, but with precipitation and the Soil Wetness Index (SWI) respectively. Simple non-parametric estimates of the return period are used.

The QMNA5 strongly decreases over France (Fig. 7a), with changes generally as strong as the changes in mean streamflows in summer (Fig. 4b). The spatial patterns are also similar, with a meridional gradient. Stronger changes in meteorological droughts are projected, with a decrease greater than −55% in a large part of the South of the country. The large relative increase in PMNA5 in the Southeast of France is explained by very ow values in the present climate and a very small increase. The Alps is the region where the smallest decreases are generally projected. The small decrease in this region might be explained by orographic effects. In the North, the changes in the severity of meteorological droughts are also very important with decreases always greater than −35%. A strong increase in the severity of agricultural droughts is also noted (between 25% and 45%) quite homogeneously over the country.

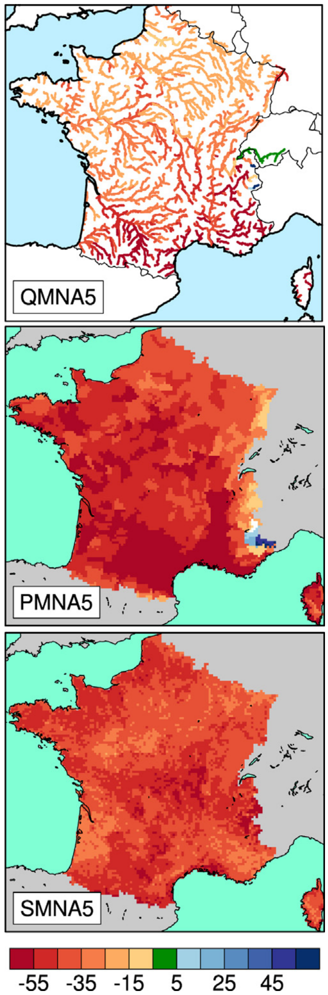

Fig. 7. Ensemble mean of the changes (%) in hydrological droughts (QMNA5), meteorological droughts (PMNA5), and agricultural droughts (SMNA5) between the 1960–1990 and 2070–2100 periods for the RCP8.5 scenario. See text for details.

4. Discussion

The uncertainties due to emissions scenarios and climate simulations characterized in the previous section are not the only ones to limit the precision of hydrological projections. The hydrological model may also play an important role in that context (Habets et al., 2013a). In order to assess to what extent the results shown in the previous sections are dependent on the hydrological model, projections based on the same atmospheric forcings have been done on 21 river basins with the Mordor hydrological model (Garçon, 1996, 1999). Mordor is a distributed and conceptual model and is therefore very different from Isba–Modcou in terms of approach. Annual and winter streamflow changes between 1979–2010 and 2070–2100 from Isba–Modcou and Mordor are highly correlated, but quasi-systematic differences exist (Fig. 8a). Annual streamflow decreases simulated with Mordor are generally less severe by roughly 10% than those simulated with Isba–Modcou. In winter, the changes projected by Mordor are indeed generally shifted by between 10% and 20%.

The uncertainties due to the hydrological models are generally much larger in summer. Changes may indeed vary by a factor two for some river basins depending on whether Mordor or Isba–Modcou is used. Some preliminary analyses (not shown) suggest that these differences are partly due to the estimation of evapotranspiration (especially in winter and spring) and to the soil reservoirs dynamics and associated slow sub-surface flows. Even if the large differences in summer have little impact regarding annual streamflow changes, these uncertainties

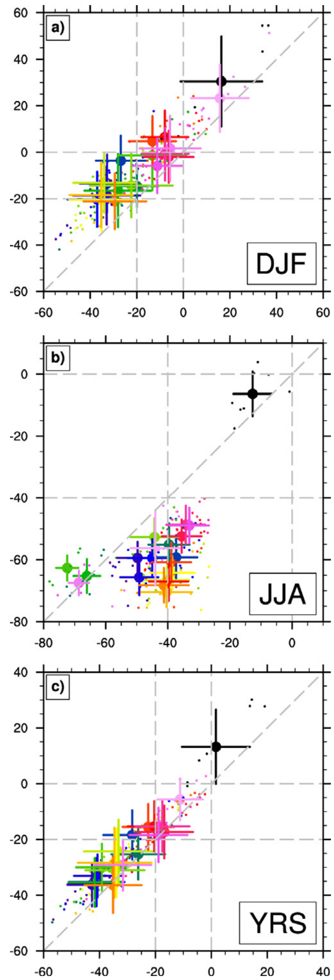

Fig. 8. Relative streamflow changes simulated by Mordor (*y*-axis) against relative streamflow changes simulated by the Isba–Modcou models (*x*-axis) between the 1979–2010 and 2070–2100 periods for the RCP8.5 scenario. One color represents a river basin, a small dot represents a simulation. One color circle represents the ensemble mean for a river basin and horizontal and vertical lines one standard deviation.

may be of great practical importance. Summer streamflows may indeed be important, for irrigation for example.

Only two hydrological models are used, which is not sufficient to provide a robust estimate of the actual uncertainties due to the hydrological modelling, as it has been done over northern France (Habets et al., 2013a) or at larger scales (e.g., Hagemann et al., 2013; Hattermann et al., 2017). These results still illustrate that large uncertainties in hydrological projections in summer are due to the hydrological models, of the same order as the ones due to climate models.

In this study, we do not take into account the potential non-climatic anthropogenic influences on river flows projections. Water use for irrigation and reservoir regulation will very likely evolve as a result of climate change, with potential additional impacts on the hydrological cycle. In the northern hemisphere, reservoirs may mitigate the increase of summer droughts thanks to an increase of stored volumes during the wet season (Wanders and Wada, 2015). Note, however, that the impact of reservoirs will be very dependent on how they are operated. For example, small farm dams over France used for irrigation are expected to lead to an additional decrease in river flows. The ability of these dams to fill up is also expected to decrease because of climate change (Habets et al., 2013b).

5. Conclusion

This study presents the hydrological changes projected over France based on state-of-the-art climate projections from the CMIP5 project, for four emission scenarios. The CMIP5 projections have been downscaled with a new statistical method (Dayon et al., 2015) whose transferability to the future climate has been carefully evaluated using a pseudo-reality framework. The downscaled climate projections have been used to drive a new version of the distributed and physically-based Isba–Modcou hydrological model (Decharme et al., 2011, 2013), with an improved representation of heat and water transfer in the soil and an higher resolution in mountainous areas.

An increase in precipitation in the northern part of France is generally projected in winter, but the exact pattern, intensity and sometimes sign of the changes are uncertain. A country-wide decrease in summer precipitation is very likely, but the inter-model spread in terms of intensity is large. The downscaled changes in precipitation are consistent with those obtained in previous studies with RCMs (Jacob et al., 2013; van Der Linden and Mitchell, 2009). A general increase in evapotranspiration is expected in winter and spring, as the energy available at surface increases, leading to a decrease in soil moisture. As additionally precipitation decreases in summer, evapotranspiration decreases in summer, because soil moisture is too low. This decrease in summer evapotranspiration is not sufficient to compensate for the decrease in summer precipitation, and streamflows severely decrease in summer. In winter, the pattern of streamflow changes generally follows the one of precipitation changes, with in particular a decrease in the Southwest and an increase in the Northeast. The key features of the changes are very similar to ones of previous studies (Ducharne et al. (2011) for the Seine or Boé et al. (2009) and Chauveau et al. (2013) for France and Donnelly et al. (2017) more recently). The main difference with some previous studies concern streamflow changes in winter in the Northeast of the country. The slight increase projected here compared to the decrease of around 20% shown in Ducharne et al. (2007), Boé et al. (2009), and Habets et al. (2013a) may be due to the differences in precipitation changes and therefore likely to the SD methods.

The uncertainties due to GCMs on streamflow changes are large throughout the year, especially in northern France, and greater in winter. The uncertainties due to the hydrological model are rather weak in winter, but large in summer. In summer, the slow sub-surface runoff associated with soil reservoirs plays an important role, and it is likely that the representation of these reservoirs in hydrological models leads to important differences in climatological streamflows in summer and their future changes. In this study, large aquifers are explicitly simulated by Modcou on some catchments (Seine and Rhone), which increases the reliability of the results of the projections in summer over these catchments, but others are not. In any case, progresses in the representation of delayed sub-surface flows that play a key role in summer are needed. Not surprisingly, the snow cover is very likely to strongly decrease over the Alps and the Pyrenees. The associated uncertainties due to GCMs and emissions scenarios are moderate. The changes in the mean hydrological cycle previously described are associated with a strong increase in the severity of meteorological, hydrological and agricultural droughts.

The Paris climate agreement has put forward the objective to limit global warming to 2 °C compared to the pre-industrial era and to pursue efforts to limit it to 1.5 °C (Schleussner et al., 2016) in order to prevent dangerous anthropogenic impacts on the climate system. An important novelty of our work is the characterization of hydrological changes at the watershed scale over France for the RCP2.6 scenario, which is mainly compatible with these objectives (Schleussner et al., 2016).

Our study clearly shows the benefits of strong mitigation policies, with a major reduction of the hydrological impacts over France with the RCP2.6 scenario compared to the business-as-usual RCP8.5 scenario. The decrease of annual streamflows for the Garonne river are much smaller (−10% with the RCP2.6 scenario compared to −40% with the RCP8.5 scenario) as well as on the Loire and Rhone Rivers. However, even with the RCP2.6 scenario, important changes of the continental hydrological over France may occur. A large decrease of streamflows in the Southwest (close to 30% for the Garonne in summer) is indeed projected, as well as a large decrease in snow cover over the Pyrenees and the Alps (50% by the end of the 21st century). These results show that a 2 °C warming may not necessarily be considered as safe, and illustrate the interest to limit global warming to well below 2 °C.

In this study, we do not deal with the future changes in flood occurrence and intensity. The SD method, based on the resampling of days of the recent past cannot lead to daily precipitation events more intense than the observed maximum. Precipitation extremes are very likely to increase in the future climate for well understood physical reasons (Kendon et al., 2009), and this increase is likely to be underestimated with the SD method used here. Note that the previous studies over France (Boé et al., 2009; Chauveau et al., 2013) suffer from the same drawback. More work on the impacts of climate change on floods over France is therefore needed. High-resolution regional climate projections, such as the Euro-Cordex projections (Jacob et al., 2013), may be very useful in that context, but should be associated with bias correction methods able to deal adequately with extreme precipitation (Muerth et al., 2013; Teutschbein and Seibert, 2012), as well as to preserve the spatial and inter-variable consistency.

In this work, we have focused on the total climate uncertainty, without a separation of the uncertainties due to climate models and the ones due to internal climate variability. Some recent studies have shown that a strong multi-decadal variability exists in the observed river flows over France (Boé and Habets, 2013). This multi-decadal variability is expected to temporarily reinforce or partly hide the signal of climate change, with important consequences for adaptation. The extent to which current climate models and, consequently, hydrological projections capture the multi-decadal variability to its full extent remains a largely open question, and is the object of ongoing work.

Acknowledgements

This work was supported by the French National Research Agency (ANR) in the framework of its JCJC program (ECHO, decision No. ANR 2011 739 JS56 014 01). The authors thank the two reviewers, Stefan Hagemann and Ryan Teuling, for their constructive comments, which greatly helped improve the manuscript. The authors also acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and thanks are also due to the climate modelling groups for producing and making available their model output. For CMIP, the US Department of Energy's Program for Climate Model Diagnosis and Inter-comparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth SystemScience Portals. The European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim data used in this study have been obtained from the ECMWF data server. The authors would finally like to thank Météo France (Direction de la climatologie and CNRM/GAME) for providing the SAFRAN data and all the colleagues from Météo-France and Mines-ParisTech who have contributed to the development of the SAFRAN–ISBA–MODCOU system.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.crte.2018.03.001.

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