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Review paper

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

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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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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).