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

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A Appendix : Data, models and methods

Climate models data

We study the impacts of climate change on the hydrological cycle over France with CMIP5 GCMs (Taylor et al. (2012) and Table 1), used for the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5, Stocker et al. (2013)). Historical simulations, from 1850 to 2005, and radiative concentration pathways simulations (RCP, van Vuuren et al. (2011)), from 2006 to 2100, are used.

Historical simulations are driven by the main anthropogenic (e.g. greenhouse gases, anthropogenic aerosols) and natural (e.g. volcanic aerosols and solar activity) forcings observed or estimated during the historical period (Meinshausen et al., 2011). The 21^{st} century projections are driven by four emissions scenarios, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The RCP2.6 scenario corresponds to a strong mitigation of emissions with a maximum concentration reached in 2050, equivalent to a CO_2 concentration of 443 ppm, and negative emissions from 2070, leading to a concentration of 421 ppm by 2100. The RCP4.5 and the RCP6.0 are two scenarios of stabilization of emissions by the end of the 21^{st} century while the RCP8.5 scenario corresponds to an important increase in GHG concentrations until the end of the 21st century, with an equivalent CO_2 concentration of 936 ppm in 2100.

The ensemble of GCMs used in the study (Table 1) have been limited by the availability, at the beginning of the study, of the data necessary for our statistical downscaling method. Our approach requires climate variables at a daily time step, which are not always available on the CMIP5 database and often limited to the 1950-2005 period for the historical simulations. Additionally, we decided to use a single GCM by modelling center in order to limit the inter-model dependency (Leduc et al., 2016). For example, only the IPSL-CM5A-MR is used among all the GCMs developed by the Institut Pierre Simon Laplace modelling center.

Hydrological system

The evolution of the continental hydrological cycle over France is simulated with the Isba-Modcou hydrometeorological system. A description of the full Safran-Isba-Modcou system is given by Habets et al. (2008). Safran (Quintana-Seguí, 2008; Vidal et al., 2010) is a near-surface analysis based on surface observations and an optimal interpolation algorithm that provides the seven near-surface atmospheric variables at the hourly time step on a 8 km grid over France necessary to drive Isba-Modcou (air temperature at 2 meters, wind at 10 meters, specific humidity, solid and liquid precipitations, solar radiation, infrared radiation)

Isba computes the surface water and energy budgets. Since Habets et al. (2008), Isba has been modified following Boone et al. (2000) and Decharme et al. (2011). A soil multilayer diffusion scheme has been introduced and the heat and mass transfers are now explicitly solved on 14 vertical layers. In mountainous areas, elevation tiles are used in order to better describe the altitude variability within a grid mesh. This version has been evaluated in various climatic conditions: for a continental regime (Boone et al., 2000), in Scandinavia (Habets et al., 2003), in the south-west of France (Decharme et al., 2011) and over France (Decharme et al., 2013).

Modcou is a distributed hydrogeological model which first routes the surface runoff through the hydrographic network following an isochronous algorithm at a 3 hours time step. Then, the temporal and spatial evolutions of the piezometric levels are computed, at a daily time step, using the diffusivity equation (Ledoux et al., 1989; Rousset et al., 2004) in regions where groundwater are represented (Seine and Rhone basins). In regions where aquifers are not simulated by Modcou, a system of conceptual reservoir following Artinyan et al. (2008) in plains and following Lafaysse et al. (2011) in mountains is included to represent slow sub-surface flows, which in particular ensures minimum low flows during the dry season. River-aquifer exchanges are calculated at a daily time-step where groundwater are represented. In a final step, river streamflows are calculated at a 3 hours time step.

Statistical downscaling method

The statistical method used to downscale the CMIP5 GCMs is described in Dayon et al. (2015). It is based on the analog method (Lorenz, 1969; Zorita et al., 1995) which consists in a re-sampling of high-resolution observed atmospheric states, and therefore maintains the spatial and inter-variables consistency. Daily observed large-scale atmospheric states are chronologically associated with corresponding observed high-resolution states on a learning period. The large-scale predictors (sea level pressure (SLP), near-surface air temperature (SAT), specific humidity at 850 hPa (HUS850), moisture flux at

850 hPa (QFX850) and Total Totals Index (TTI)) come from the European Center for Medium-Range Weather Forecast (ECMWF) reanalysis-Interim (ERA-Interim - Dee et al. (2011)) and high resolution atmospheric observations come from the near-surface analysis Safran. Given the availability of ERA-Interim and Safran, the learning period is 1979-2010. Each day, the large-scale state from a climate simulation to be downscaled is compared to the observed ones on the learning period. Based on a chosen metric, the most similar observed large-scale climate state is identified. Finally, the associated high-resolution state is selected as an estimate of the high-resolution state for the corresponding day of the climate simulation. The high-resolution state is defined as the seven atmospheric variables from Safran necessary for hydrological modelling.

The main limitation of the analog method is its inability to produce a state that has not been observed on the learning period. Due to the large variance of daily precipitation, this limitation does not prevent to capture correctly mean precipitation changes (Dayon et al., 2015). As the mean temperature change is large compared to the variance of temperature, especially with the RCP8.5 scenario, the simple resampling of days from the learning period would lead to an underestimation of future warming (not shown). Air temperature is therefore corrected after downscaling, as specific humidity and downward long wave radiation in order to maintain the inter-variable consistency as in Etchevers et al. (2002).

Air temperature and specific humidity are both conjointly corrected in order to reproduce as closely as possible their future mean increase as simulated by the GCMs. First, the distribution of the differences between the mean over France of each variables simulated by the GCM and obtained with the downscaling method is computed. Then, the two variables are corrected when the differences between the mean over France simulated by the GCM and the mean over France downscaled with the analog method for both variables is smaller (greater) than the 5^{th} (95^{th}) percentile of the difference calculated on the historical period. The correction is applied spatially on the Safran grid. The joint correction of specific humidity and temperature ensures no spurious change in relative humidity. The downward long wave radiation at surface is also corrected to take into account the temperature correction, following Etchevers et al. (2002). The precipitation phase is recalculated after the air temperature correction using the same critical temperature (0.5°C) as the one used in Safran.

Note that the SLP used as predictor in the statistical downscaling method is corrected with a simple approach. The annual cycle of SLP is removed at each grid cell before computing the comparison metric. With this simple approach, the associated biases in other variables, such as wind or moisture flux for example, are not corrected. In the end, the biases in downscaled winter precipitation are reduced thanks to the correction (not shown) but important biases still remain. More complex bias-correction approaches for GCMs predictors could have be considered to further reduce winter biases but it is a complex issue with an high risk of loss of inter-variables physical consistency after correction.

Hydrological projections based on three CMIP5 GCMs have been done with and without the corrections described above, in order to evaluate the sensitivity of projected hydrological changes to these corrections (not shown). The differences are generally very small except for the catchments strongly influenced by snow, where the correction of temperature has an important impact on the precipitation phase, and therefore on streamflow changes.

Table 1: CMIP5 models and experiments used in this study (Taylor et al., 2012) with the respective number of members.

Models	historical	rcp26	rcp45	rcp60	rcp85
ACCESS1-3	1		1		1
bcc-csm1-1-m	1	1	1	1	1
BNU-ESM	1		1		1
CanESM2	5	5	5		5
CNRM-CM5	1	1	1		
CSIRO-Mk3-6-0	1		1	1	1
IPSL-CM5A-MR	3	1	1	1	1
MIROC5	5		3	1	3
NorESM1-M	3	1	1	1	1
Total	19	9	15	5	14

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