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Influence of multidecadal hydroclimate variations on hydrological extremes: the case of the Seine basin

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Abstract. The multidecadal hydroclimate variations of the Seine basin since the 1850s are investigated. Given the scarcity of long term observations of hydrological variables, a hydrometeorological reconstruction is developed based on an method that combines the results of a downscaled long-term atmospheric reanalysis and local observations of precipitation and temperature. This method improves the representation of daily flows as well as at longer time steps. This reconstruction provide therefore an interesting tool to study the multidecadal hydroclimate variability of the Seine basin, as well as its possible influence on extreme hydrological events. Based on this reconstruction, it is shown that the Seine river flows, groundwater and soil moisture, have been influenced by multidecadal variations from the 1850s. Spring precipitations play a central role by directly influencing the multidecadal variability of spring flows, but also soil moisture and groundwater recharge, which then modulate summer river flows. Groundwater controls a large part of the multidecadal variations in river flows, particularly in summer and fall. These hydroclimate variations seem to influence extreme hydrological events. The positive multidecadal phases indeed appear to be more conducive to flooding, with twice as many flood days as in the negative phases while the negative multidecadal phases seems to influenced the droughts intensity. These hydroclimate variations over the Seine basin are driven by anomalies in large scale atmospheric circulations, which themselves appear to be influenced by sea surface temperature anomalies over of the North Atlantic Ocean and the North Pacific Ocean.

1 Introduction

The future impacts of climate change on the hydrological cycle could have major socio-economic consequences (Pachauri et al., 2014). In France, important hydrological changes are expected at the end of the 21st century, with for example a strong reduction of river flows in summer (Dayon et al., 2018). For adaptation purposes, an adequate characterization of the uncertainties in impact projections is crucial.

Internal climate variability is a major source of uncertainties in future projections, especially over the coming decades (Deser et al., 2012) and regarding hydrological variables (Hawkins and Sutton, 2009; Hingray and Saïd, 2014; Terray and Boé, 2013). Internal variations at decadal to multidecadal time-scales are especially important in that context, as they may modulate the mean hydroclimate state on several decades. They may temporarily reinforce or reduce, or even reverse especially over the coming decades, the long-term impacts of climate change.

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The studies cited above that characterized the uncertainties due to internal variability in climate and/or hydrological projections are model-based, and therefore rely, at least implicitly, on the hypothesis that climate models provide a realistic representation of the decadal to multidecadal internal climate variability, which is not granted (e.g. Qasmi et al. 2017). Efforts to better evaluate the capacity of climate models to reproduce correctly the multidecadal hydroclimate variability are therefore necessary. As a first and mandatory step, it is necessary to characterize such multidecadal variations in the observations, a work that has been undertaken in recent years.

Sutton and Dong (2012) showed that over the 20th century, the Atlantic Multidecadal Variability (AMV; Schlesinger and Ramankutty, 1994; Kerr, 2000; Deser et al., 2010; Cassou et al., 2018), the main mode of multidecadal variability of the North Atlantic, characterized by basin-wide variations of sea surface temperatures (SST), may impact the European climate through changes in large scale circulation. Large multidecadal variations are observed in mean river flows and glaciers over France and are likely associated with the AMV (Boé and Habets, 2014; Marti et al., 2014). These variations seem to strongly modulate secular trends in river flows (Dieppois et al., 2016). Additionally, the AMV could influence extreme hydrological events, with the existence of multidecadal variations in extreme precipitation and river flows in Europe, including France (Willems, 2013). Giuntoli et al. (2013) also showed a statistical link between droughts severity of some French rivers and the averaged SSTs of the North Atlantic on the second half of the 20th century, which are influenced by the AMV, as well as external anthropogenic forcings.

It is difficult to go further in the understanding of multidecadal hydrological variations only based on observations. Long-term observations of river flows are rare, with very few stations starting before 1900 for example, and they may suffer from non-climatic anthropogenic influences as well as temporal inhomogeneities. The other variables of the hydrological cycle, such as evapotranspiration, soil moisture or snow cover, are virtually not observed on such long time scales, which makes it very difficult to understand the mechanisms at play.

To move forward, long-term hydrometeorological reconstructions based on hydrological modelling have been developed (e.g Kuentz et al. 2015; Caillouet et al. 2016). Due to the scarcity of meteorological observations in the early 20th century (Minvielle et al., 2015), the meteorological forcing needed for hydrological modelling may be obtained by downscaling, for example statistical downscaling, of a long-term atmospheric reanalysis (e.g. Caillouet et al. 2016). This approach presents two main limitations. First, the quality of reconstructions depends on the quality of the reanalyses. As the density of assimilated observations (e.g. surface pressure in the Twentieth Century Reanalysis (20CR) (Compo et al., 2011) from the National Oceanic and Atmospheric Administration (NOAA)) strongly evolves over time, potential unrealistic trends and/or low frequency variations may exist in the reanalyses (Krueger et al., 2013; Oliver, 2016; Bonnet et al., 2017). Second, this approach is far from optimal, as it does not make use of the long-term meteorological observations that may exist. Indeed, even if they are scarce, long-term observations of precipitation and temperature exist and provide a very valuable and independent source of information.

Given these limitations, following the same general idea as Kuentz et al. (2015), Bonnet et al. (2017) presented a new method that combines available long-term monthly observations of precipitation and temperature with the results of a statistical downscaling method applied to long-term atmospheric reanalyses. Based on the hydrometeorological reconstructions over

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France obtained with this method, Bonnet et al. (2017) showed in particular that the multidecadal variations in river flows over France are mainly of climatic origin. They also showed that other variables of the hydrological cycle, such as snow cover and soil moisture, also exhibit variations at multidecadal time scales.

In this study, we build upon the methodology developed in Bonnet et al. (2017) and target two main improvements. First, the reconstruction is extended back in the past in order to assess more robustly the multidecadal variations over France. Given data availability, the reconstruction of Bonnet et al. (2017) began in 1900. Focusing on the Seine basin (Figure 1) we are able to extend back the reconstruction to 1850s. It is important because the shortness of the instrumental record is one of the main difficulties that exist in the study of multidecadal variability. It leads to large sampling uncertainties (e.g. Qasmi et al. 2017) and makes it difficult to characterize robustly the observed multidecadal variations. Additionally, we improve the method to better capture daily variability and therefore extreme events such as floods and droughts, in order to study their potential multidecadal variations.

This study has three main objectives: (i) to characterize the hydroclimate variations of the Seine basin since the 1850s, (ii) to study the hydrological and climatic mechanisms that cause these variations and (iii) to investigate the influence of these multidecadal variations on extreme hydrological events.

The data, models, hydrometeorological reconstruction and methods used are presented in section 2. The hydrometeorological reconstruction is then evaluated against observations in section 3. From this reconstruction, the hydroclimate variations of the Seine basin are characterized in section 4, and the hydrological mechanisms associated with these variations are analysed. The link between these multidecadal variations and extreme hydrological events (e.g. floods and droughts) is then explored in section 5. In section 6, the climatic mechanisms underlying the hydrological multidecadal variations over the Seine basin are analysed. Finally, the conclusions of this study are summarized in section 7, and some perspectives are discussed.

2 Data, models and Methods

2.1 Observations

Daily river flows at 136 gauging stations over the Seine basin (Figure 1) from the national HYDRO database (www.hydro.eaufrance.fr) are used for the evaluation of the reconstruction. These river flows series of variable lengths all start before 1970 and may contain missing values. Some of the stations are very likely influenced by human activities (e.g. dams or water abstraction). Additionally, these series are not homogenized, and therefore not necessarily free of measurement artifacts. The interpretation of observed variations at any single station must therefore be carried out carefully. Two long-term series, starting before 1900, are also available and used for the analysis of the link between extreme events and multidecadal hydroclimate variations, one at Paris Austerlitz (43800km^2) and one at Aisy-sur-Armançon (1350km^2) (Figure 1).

A long series of piezometric heights is also used to evaluate the hydrological reconstruction (Figure 1). The Beauce groundwater table at Toury, which has been monitored from the 1870s, is one of the few long piezometric measuring stations in France (Nicolas et al., 2013).

Different meteorological observations are used for the reconstruction. Monthly homogenized series of temperature and precipitation over the Seine basin from the Série Mensuelle de Réference (SMR, monthly series of reference) data set, developed by Météo-France (Moisselin et al., 2002) are used. 17 stations are available for precipitation and 4 for temperature, from 1885 to 2005. A long series of monthly precipitation at Paris (Slonosky, 2002), available since the late 17th century, is also used for the periods not covered by the SMR observations series at Paris, from 1852 to 1885 and from 2005 to 2008.

Daily temperature and precipitation series from the Série Quotidienne de Réference (SQR, daily series of reference) data set between 1885-2003 are also used (Moisselin and Dubuisson, 2006). They are not homogenized. The number of station varies greatly in time, from a few 2 to around 60 for precipitation and from one to seven for temperature.

2.2 The Safran-Surfex-AquiFR hydrometeorological system

The hydrological reconstruction is based on the French AquiFR hydrogeological modelling plateform (Vergnes et al., 2019). AquiFR couples several hydrogeological models over France to the Surfex land surface model (Masson et al., 2013). The ISBA (Noilhan and Planton, 1989) component of the Surfex modular land surface model, used for example in the French CNRM-CM5 coupled climate model (Voldoire et al., 2013), computes the water and energy exchanges at the interface between the soil, the vegetation and the atmosphere. In this study, the version 8.1 of Surfex is used, with the multilayer version of ISBA (Decharme et al., 2013). The surface runoff and the drainage simulated by Surfex then routed through multi-layer aquifers and rivers of the Seine basin by AquiFR.

Over the Seine basin, the EauDyssée hydrogeological model (Saleh et al., 2011) is used in the AquiFR plateform. This hydrogeological model is an improved version of the Modcou hydrogeological model used in Bonnet et al. (2017). Unlike Modcou, the EauDyssée hydrogeological model implemented in AquiFR includes the simulation of river water levels, allowing for a better estimation of water exchanges between groundwater and rivers (Saleh et al., 2011). The water transfers in the unsaturated zone are improved (Philippe et al., 2011), which can be important considering that the unsaturated zone can be reach 60 meters in the Seine basin, implying a delay in the groundwater recharge. Finally, AquiFR uses a 6-layer representation of the aquifers (Viennot et al. 2009, https://www.metis.upmc.fr/ aqui-fr/#_Documents), compared to the 3 layers used in Modcou (Rousset et al., 2004). AquiFR has therefore a more realistic representation of groundwater and water exchanges between groundwater and rivers compared to the version of Modcou used in Bonnet et al. (2017). Water abstractions can also be taken into account by AquiFR. However, in order to focus only on climatic influences, the reconstruction used in this study does not take these water abstraction into account. In any case, water abstractions of the late 19th and early 20th centuries are not knownmostly unknown prior to 1980.

The Safran analysis, based on about thousands observation stations collected by Météo-France and an optimal interpolation algorithm, provides the seven atmospheric variables necessary to force the Surfex-AquiFR system (liquid and solid precipitation, incoming longwave and shortwave radiation fluxes, 10m wind speed, 2m specific humidity and temperature), at the hourly time step, on an 8km grid, from 1958 to present. This analysis is described and evaluated in Quintana-Segui et al. (2008) and Vidal et al. (2010). Safran is used in our study to run a reference simulation with the Surfex-AquiFR system. The differ-

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ences between the reconstruction and the Safran-Surfex-AquiFR simulation only depend on the quality of the reconstructed meteorological forcing.

2.3 The Seine hydrometeorological reconstruction

A new hydrological reconstruction is developed over the Seine basin, improving on the method presented in Bonnet et al. (2017), with two main objectives: (i) to increase the study period to the 1850s, in order to characterize more robustly the multidecadal hydroclimate variations, and (ii) to improve the representation of river flows, particularly at the daily time scale, to obtain a better representation of extreme events such as droughts and floods in order to study their multidecadal variations.

To extend the study period, the long-term atmospheric reanalysis NOAA 20CRv2c (Compo et al., 2011), which begins in 1851, is used. This reanalysis is based on a global atmospheric model, using observed sea-ice (COBE-SST2; Hirahara et al. 2014) and sea surface temperature (SODAsi.2) as boundary conditions, and with the assimilation of surface and sea level pressure observations. 56 members, sampling the reanalysis uncertainties are available.

The main idea of the Bonnet et al. (2017) method is to use a stochastic statistical downscaling method to downscale a long-term atmospheric reanalysis such as NOAA 20CRv2c and then to constrain the downscaling results using available local observations. An ensemble of potential trajectories of precipitation and temperature over France at high resolution is generated thanks to the stochastic downscaling method. Then, the trajectory the closest to the monthly observed homogenized series of precipitations and temperature (see section 2.1) is selected.

To improve the representation of the daily variability of the Seine reconstruction in this study, a daily constraint is added before the monthly constraint described above. In order to create an ensemble of trajectories large enough to find satisfactory trajectories at the daily time scale, the 56 members of the NOAA 20CRv2c reanalysis are downscaled. The same downscaling method as in Bonnet et al. (2017) is used here. It is based on the analog method (Lorenz, 1969) at the daily time scale. Four predictors are used: precipitations, surface temperature, sea level pressure and specific humidity at 850 hPa. For each day Dn of the reconstruction period (1852-2008), the 50 best analog days Ai=1. . . 50 in the learning period (1958-2008) with the most similar large-scale atmospheric state (as characterized by the 4 predictors) are searched. The local variables of interests of the analog days Ai=1. . . 50 from the Safran analysis are finally used to estimate the potential local states of the day Dn. With this approach, all the variables necessary for hydrological modelling are obtained on the Safran grid from 1852 to 2008.

Here, the 50 best analog days of each of the 56 downscaled NOAA 20CRv2c members are conserved, which results in 2800 potential analog days for each day of the reconstruction period (with potentially similar analog days in the different members). As each analog day corresponds to a day of the learning period, the corresponding daily map of precipitation and temperature from Safran are selected and compared to the daily station observations (see section 2.1) after regridding. Reggriding consists in selecting the Safran grid point the closer to each observation station. Note that the number of stations vary on the 1852-2008 period: the comparison is done each day of the reconstruction on the available stations. The comparison is based on the following approach:

(i) The average daily bias in mean precipitation averaged over the Seine basin is calculated for the 2800 analog days, and the 60 analog days with the lower bias are conserved.

(ii) The spatial root mean square errors for to the 60 analog days are calculated for temperature. For precipitation the error to the cubic power rather than to the square power is used, in order to give more weight to strong values of precipitation, and the absolute value is then used .

(iii) The daily series of the precipitation and temperature errors obtained are then standardized over the whole period and added, with a weight of 1 for precipitation and 0.5 for temperature. Different tests have been conducted to choose the best combination of weights. Each day of the reconstruction period, the 3 analog days (out of 60) with the lower errors are finally conserved.

Based on these 3 selected analog days, a monthly constraint is then applied as in Bonnet et al. (2017). The interest of also using a monthly constraint after the daily constraint is that monthly data are homogenized contrary to daily data and therefore it allows for a better representation of low-frequency variations.

To sum up, the hydrometeorological reconstruction developed on the Seine basin is constrained on a daily basis over the period 1885-2003 by observations of precipitation and temperature (SQR), on a monthly basis over the period 1885-2005 by homogenized observations of precipitation and temperature (SMR), and over the periods 1852-1884 and 2005-2008 by a monthly series of precipitation at Paris (Slonosky, 2002) (see section 2.1 for more details about the observations used).

During the development of the reconstruction, mean climatological biases were found on reconstructed precipitations and incoming shortwave radiation. These mean climatological biases are simply corrected based on Safran as reference before forcing the hydrological model.

The meteorological forcing obtained on the 1852-2008 period with the approach described in this section is used to force the Surfex-AquiFR hydrogeological model to obtain the hydrological reconstruction.

2.4 Method

In order to extract the multidecadal variations from the interannual series, a Lanczos low-pass filter (Duchon, 1979) with a cutoff frequency of 30 years and 31 weights is applied. No padding at the ends of the series is applied: the first 15 years and the last 15 years of the unfiltered series are considered as missing values in the filtered series.

In order to focus on multidecadal variations, long-term trends are removed before most of the analyses shown in this study. As it is very unlikely for the trend to be linear on the very long period analyszed in the paper, non-linear long-term trends are computed using an ensemble empirical mode decomposition algorithm (EEMD; Wu and Huang 2009). This algorithm decomposes a series into a sum of signals that characterize the different temporal variability scales that compose this series. The interest of this method is that it is adaptive to the signal studied and non-parametric. Intrinsic mode functions (IMFs), with a zero average, are built up over time, from the lowest to the highest frequencies. The algorithm also extracts a non-linear trend adapted to the series and the period concerned.

In order to avoid an artificial skill induced by the annual cycle when calculating daily or monthly correlations between the observations and the reconstruction, the series are deseasonalized beforehand. For daily series, a centered running average of 31 days is applied first to limit the noise in the computed annual cycle. Then, the climatological average is calculated for each days of the year. For monthly series, the annual cycle is simply calculated by the climatological average of each month.

In this paper, winter means December-January-February (DJF), spring means March-April-May (MAM), summer means June-July-August (JJA) and fall means September-October-November (SON).

3 Evaluation of the Seine reconstruction

3.1 Mean river flows

The daily and monthly river flows variations are well represented in the Seine reconstruction. The medians of the correlations with observations are respectively of 0.7 and 0.97 for daily and monthly river flows (Figure 2). At the monthly time scale, the river flows variability is even almost as well reproduced as in the reference simulation (Figure 2). For most gauging stations, the representation of daily and monthly river flows is improved in the Seine reconstruction compared to the reconstruction developed over France by Bonnet et al. (2017) (Figure 2). Some low correlations are still seen at a few stations (Figure 2). These stations are identical in the reconstructions and in the reference simulation, showing that this issue is not due to the reconstructed meteorological forcing. Non-climatic anthropogenic influences (e.g. dams, pumping or land use changes) that are not taken into account by the hydrological model, or measurement artifacts may be responsible for these lower correlations. Alternatively, they may be due to hydrological modelling, especially since these lower correlations are seen for small catchments (not shown).

To go further in assessing the reconstruction, the two long observations of available flows in the Seine basin are compared to the reconstructed river flows (Figure 3). The reconstruction correctly reproduces interannual variability of both long-term river flows observations (Figure 3a-b). River flows in 1910, influenced by an exceptional flood, are underestimated at Paris while it is rather correctly reproduced at Aisy-sur-Armançon. The multidecadal variability of observed flows is also quite well reproduced by the reconstruction (Figure 3c-d). For the Seine at Paris, these variations are underestimated at the beginning of the 20th century and underestimated at the end (Figure 3c). Differences in long-term trends, with a much stronger negative trend in the observed series compared to the reconstruction (not shown), are probably at the origin of these differences. The meteorological forcing variables of the reconstruction that can be evaluated, and in particular precipitation, do not show an unrealistic trend (not shown). It is possible that measurement artifacts, or non-climatic anthropogenic influences, not taken into account in the reconstruction, influenced the long-term variability of the observed river flows in this highly anthropized region.

Multidecadal river flows variations at Paris and at Aisy-sur-Armançon are in phase, with a strong positive multidecadal phase around 1920 and a negative phase around 1890 and 1960.

3.2 Annual maximum of daily river flows

The interannual variability of the annual maximum value of daily river flows of the Seine at Paris is well captured in the Seine reconstruction, with a correlation of 0.88 with the observations on the 1900-2005 period (Figure 4). The correlation is consistent over time, with a correlation of 0.92 over the 1900-1960 period, and of 0.89 over the 1960-2005 period. On the later period, the correlation between the reconstruction and the observation is close to the correlation obtained with the reference simulation (r=0.95).

A negative bias exists in the Seine reconstruction until the 1960s (Figure 4). As a result, the magnitude of the exceptional 1910 flood is largely underestimated in the reconstruction, even if this event remains the strongest one of the reconstruction. The bias is far less pronounced in the reconstruction after 1960 and in the reference simulation, as a result of a decrease of the observed annual maximum values of daily river flows. The construction of large reservoirs over the Seine basin upstream from Paris that started in the 1960s, whose objectives include flood control, may be the cause of this decrease.

3.3 Piezometric levels

In France, long-term observations of piezometric levels (measure of the head of a groundwater table) are very rare. The measurements at the Toury sugar plant, which have monitored the Beauce groundwater table from the beginning of the 20th century, is especially interesting in this context. The Beauce aquifer is a limestone aquifer from the Oligocene, and it is drained by rivers mainly at its borders. The observed piezometric level at Toury shows strong multidecadal variations, with a positive phase around the 1920-1940 period, preceded by a negative phase in the early 20th century and followed by a negative phase in the 1950s (Figure 5). Strong decadal peaks are also seen after 1950, consistent with Flipo et al. (2012). The evolution of the Beauce groundwater is therefore generally consistent with that of river flows (Figure 3) at multidecadal time scales.

The Seine reconstruction reproduces quite well the interannual variations of piezometric heads at Toury, with a correlation of 0.74 over the 20th century. The intensity of these variations is however strongly underestimated, by a factor 2, both in the reconstruction and in the reference simulation. This might be linked to a coarse representation of the aquifer complexity (Violette, personnal communication). A partially captive part of the aquifere is not represented in the model. This part of the aquifere amplifies the flow time and, therefore, the memory of the aquifer.

4 Multidecadal hydroclimate variations on the Seine basin

4.1 Characterization

Annual river flows of the Seine at Poses (Figure 1) from the reconstruction show strong multidecadal variations during the 20th century (Figure 6), consistently with the observed variations over France described in Boé and Habets (2014). The length of the reconstruction allows to show that multidecadal variations are also present before the 20th century, with in particular a strong negative phase around 1885-1905. Phased multidecadal variations also exist for the seasonal averages, with the strongest

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absolute variations seen in spring and winter. Note however that as climatological flows are smaller in summer and early fall, the multidecadal variations seen in these seasons are also important.

To better understand the mechanisms at the origin of the multidecadal hydroclimate variations on the Seine basin, a composite analysis between dry and wet multidecadal periods identified on the river flows of the Seine at Poses is conducted for the main hydrological variables (Figure 6). The positive phases are defined as the 1910-1930 and 1975-1995 periods, and the negative phases are defined as the 1885-1905 and 1940-1960 periods. The use of four 20-year periods thanks to the length of the reconstruction makes the analysis of these variations more robust in comparison to previous works (e.g. Boé and Habets 2014 and Bonnet et al. 2017).

Most simulated stations on the Seine basin show strong river flows variations between the negative and positive multidecadal phases (Figure 7a-e-i-m). The relative differences are stronger in summer and spring, as large as 40% for some stations, and significant almost everywhere. The differences are weaker in winter but still significant for most of the stations. In autumn, only a few stations show significant changes between the positive and negative multidecadal phases, although some stations still show strong variations of 30%.

In spring, the river flows variations are concomitant with strong and significant precipitation variations over the entire Seine basin (Figure 7f). During the negative multidecadal phases, spring precipitation is on average 20% lower than during the positive phases. These precipitation anomalies also lead to significant soil moisture anomalies, between 5 and 10% (Figure 7g). The evapotranspiration does not show significant differences between the negative and positive multidecadal phases of the Seine river flows (Figure 7h), likely because it is energy-limited rather than water-limited in this region in spring.

Except for a small area in the south east of the catchment in fall, no significant differences in precipitation are noted except in spring. The significant river flows variations in winter and summer therefore cannot be explained by concomitant precipitation variations alone, suggesting that hydrological processes are at play.

In winter, the negative multidecadal phases of the Seine river flows are characterized by significantly lower evapotranspiration than in the positive phases (Figure 5d). Negative temperature anomalies, close to 0.8K and significant over the whole basin (not shown), are likely the cause of these evapotranspiration anomalies. As the evapotranspiration anomalies are negative during the dry phases, they are not responsible for the river flows anomalies and they actually tend to moderate them. The soil moisture presents significant variations between the negative and positive phases over a part of the Seine basin in winter (between 5 and 10%) (Figure 7c). They are probably related to differences of precipitation, between 10 and 15%, even if they are not significant.

Large, and significant over a large part of the catchment, soil moisture anomalies between positive and negative multidecadal phases, between 10 and 15%, are noted in summer (Figure 7k). The absence of significant precipitation and evapotranspiration anomalies in summer suggest that the persistence of soil moisture anomalies from spring to summer (e.g. Boé and Habets 2014) is responsible for the multidecadal variations of summer soil moisture.

Two important conclusions arise from the previous analysis. (i) Significant multidecadal variations of soil moisture exist in spring and summer from the mid-19th century, with potential important societal consequences, for example regarding agriculture, which is highly developed over the Seine catchment. (ii) Large and significant multidecadal variations in summer and

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winter river flows exist, which cannot be explained by concomitant variations in precipitation. Hydrological mechanisms that could be responsible for these variations are now investigated.

4.2 Role of groundwater table

In the Seine basin, the groundwater-river exchanges plays an important role in sustaining summer flows on the Seine catchment (Rousset et al., 2004). Interestingly, the groundwater-river exchanges over the Seine basin show strong multidecadal variations over the past 150 years for all seasons (Figure 8). These variations are in phase with the multidecadal variations in river flows and their amplitude is large (compare Figure 6 and Figure 8), pointing to an important role of groundwater dynamics in multidecadal river flows. We calculated the standard deviation of filtered river flows series (as in Figure 6) before and after the removal of the groundwater-river exchanges shown in Figure 8. The standard deviation is 64% lower in summer, 52% lower in autumn, 41% lower in spring and 38% lower in winter after the removal of the contribution of groundwater. Groundwater-river exchanges are therefore the dominant driver of multidecadal variations in summer and autumn flows, with also an important influence in winter and spring. The multidecadal variations in groundwater recharge and therefore levels are very likely explained by the multidecadal variations seen in late winter and early spring precipitations.

4.3 Role of soil moisture

Groundwater-river exchanges roughly explain 2/3 of the strong multidecadal river flows variations that exist in summer, pointing to the role of other mechanism(s). As seen in Figure 7k, a large part of the basin in summer is characterized by significant negative soil moisture anomalies during negative multidecadal river flows phases. Soil moisture anomalies may impact river flows through the modulation of the partitioning of precipitation between runoff and infiltration (e.g. Boé and Habets 2014). Consistently, the ratio between total runoff and precipitation is significantly lower over a large part of the basin, where the soil moisture anomalies are significant, during the dry multidecadal phases (Figure 9). As suggested by Bonnet et al. (2017) for the Loire Basin (see Figure 1), positive multidecadal anomalies of spring soil moisture due to anomalous precipitations persist in summer, especially over the upstream part of the catchment, and then influence summer river flows by favoring runoff against infiltration.

5 Influence of multidecadal river flow variations on extreme events

5.1 Links with floods and droughts

The improvements to the reconstruction described in section 2.3 allows for a better representation of high-frequency variations compared to previous works (Bonnet et al. 2017, see Figure 2) and therefore of extreme events, such as floods and droughts. To assess the influence of multidecadal hydroclimate variations on extreme hydrological events, the ratios of the number of flood (drought) days during positive and negative multidecadal phases are calculated. A flood day is simply defined here as a day with flows larger than the 95th percentile computed on the four multidecadal phases considered: 1910-1930, 1975-1995,

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1885-1905 and 1940-1960 for the flood season, from November to April. Conversely drought days are defined as days with flows lower than the 5th percentile at the same periods considering the whole year.

Floods are on average twice as likely to occur during a positive multidecadal phase of the Seine river flows, and up to three times more likely for some stations (Figure 10a). During the flood season, the positive multidecadal phases of the Seine river flows are characterized by higher mean precipitations, wetter soils (Figure 7) and higher groundwater levels (not shown). Such anomalies favor the occurrence of floods. The positive multidecadal phases are also characterized by a higher number of intense precipitations (not shown), which also favor the occurence of flood. This results is consistent with Willems (2013), which highlighted the existence of multi-decadal variations in observed intense precipitation, correlated to intense river flows. The results from the reconstruction are consistent with the ones from the two long series of observed flows available on the Seine basin (Seine at Paris and Armançon at Aisy-sur-Armançon, see triangles in Figure 10a).

Regarding drought days, a large number of stations have a ratio between one and two (Figure 10b). It is the case for the observations at Aisy-sur-Armançon, with a ratio of 1.1 consistents with the reconstruction in that region. The multidecadal hydroclimate variability of the Seine basin does not seem to strongly influence this type of events for many stations. Some stations, notably in the central part of the catchment, still show a ratio close or superior to two, pointing to an influence of multidecadal hydroclimate variations on droughts there. It may be due to the multidecadal variations seen in groundwater-river exchanges (Figure 8), which may impact low flows. For the observations at Paris, droughts are more than four times more likely to happen during a negative multidecadal phase of the Seine flows, whereas there are only twice more likely to happen based on the reconstruction. This result must, however, be taken with caution as the observations at Paris are influenced by human activities.

5.2 The 1921 and 1949 droughts

To go a little further in the understanding of the influence of multidecadal hydroclimate variability on droughts, we focus on two major droughts of the last 150 years: the 1921 and 1949 events. The 1921 drought, the most severe hydrological drought of the Seine basin since the 1850s in our reconstruction (not shown), occurred in the middle of a strong positive multidecadal phase of the Seine river flows (Figure 6). The 1949 drought, which is the second longest and third strongest hydrological drought of the Seine basin according to the hydrometeorological reconstruction (not shown), occurred in the middle of a negative multidecadal phase of the Seine river flows. Considering 20-year periods around these events, the average climatic conditions during which these events developed are therefore very different. Groundwater levels are very high in the decades around 1921 compared to the decades around 1949 (Figure 11d), with therefore higher groundwater-river exchanges (Figure 11c). The same applies to river flows (Figure 11b).

For both droughts, precipitations are below the climatological average from the autumn of the previous year (i.e. n-1) and extremely small in February, March, April of the year n. Between October of year n-1 and December of year n, the year 1921 has a lower average precipitation than 1949, with averages of 1.25 and 1.50 mm/j respectively. These average precipitation are well below the climatological average. The groundwater levels at the end of 1920, partly because of the multidecadal variations previously described, are very high in the autumn 1920, while the heads are already below average in the autumn

1948. In both cases, the level falls down during the drought, but they remain not extreme in 1921, while extremely low values are reached from the spring 1949. As a result, the water to river exchanges in 1921 remain above those of 1949 by between 17 and 83 m^3/s from august of the year n-1 to September of the year n (Figure 11c-d). Despite the lower groundwater-river exchanges, the rivers flows of the 1949 event generally remain above those of the 1921 drought from the autumn of the year n-1 to spring of the year n. The larger groundwater-river exchanges in 1921 allowed by the high levels during this period thanks to multidecadal hydroclimate variations contributed to moderate the severity of the hydrological drought, while in 1949 groundwater-river exchanges contributed to increase its severity. The 1921 drought could have been even worse should it had occurred during a dry multidecadal phase such as the 1949 drought, pointing that an even worse event is possible even without anthropogenic climate change.

6 Role of large-scale circulation and influence of ocean variability

Strong multidecadal hydroclimate variations on the Seine basin from the 1850s have been highlighted in the previous section. They are mainly linked to variations in precipitation and therefore the question is now to understand the origin of these precipitation variations.

Large-scale atmospheric circulation shows significant differences between the positive and negative hydroclimatic phases identified in section 4.1 (Figure 12a). The negative multidecadal phases of the Seine river flows are characterized by significantly higher pressures over northern Europe, and significantly lower pressures over North Africa. This circulation pattern leads to lower westerlies over Western Europe and therefore to negative precipitation anomalies over the Seine basin. Large scale circulation therefore likely explains a large part of multidecadal variations in precipitation.

The persistence of significant atmospheric circulation anomalies on decades suggests the existence of a slower external forcing acting on the atmosphere. Because of its inertia, the ocean is a good candidate. Significant variations of sea surface temperature in the North Atlantic are visible between the multidecadal phases of the Seine river flows. During the negative phases, the North Atlantic basin is characterized by significant warmer surface temperatures, around 0.4 to 0.7°C, especially in the subpolar gyre and the tropical North Atlantic (Figure 12). These SST anomalies suggest that the Atlantic Multidecadal Variability, the main mode of variability at these time scales in this region, is at the origin of these multidecadal variations of atmospheric circulation. This result is consistent with Sutton and Dong (2012) and Boé and Habets (2014).

Significant variations of SST between the negative and positive multidecadal phases of the Seine river flows are also observed in the North Pacific. The SSTs there are significantly warmer during the negative multidecadal phases of the Seine river flows compared to the positive phases. The North Pacific basin could therefore also influence the multidecadal variations of French river flows.

Boé and Habets (2014) highlighted the existence of a lag between the AMV and river flow variations in France, with the AMV in advance of several years. Interestingly, considering a 10-year time lag in the composite analysis (with the SST leading), temperature anomalies in the North Atlantic and North Pacific are much higher than with no lag (Figure 12c). The physical origin of this lag is still unknown. It could be the sign of a retroaction between SSTs and the atmospheric circulation. In any

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case, this analysis confirms with a longer period that the lag noted previously in Boé and Habets (2014) with the AMV is a robust feature.

7 Conclusions and perspectives

In this study, a new hydrometeorological reconstruction focused on the Seine basin is presented. The method improves upon the one described in Bonnet et al. (2017). It leads to a better representation of daily river flows. This reconstruction is therefore suitable to study the multidecadal variability of hydrological extremes such as floods or droughts. The reconstruction is extended back to 1852. The longer study period compared to previous works (e.g. Bonnet et al. 2017) allows for a more robust characterization of multidecadal hydrological variations.

We show the existence of strong multidecadal variations in river flows over the Seine catchment since the 1850s. Consistently with previous studies over France (Boé and Habets (2014) and Bonnet et al. (2017)), strong variations are noted in spring. For many stations, even stronger variations are noted in summer. Significant multidecadal variations are also noted in winter thanks to the longer period studied here.

Multidecadal variations in spring precipitations play a major role, as in previous studies over France. Spring precipitations directly impact river flows of the same season and also river flows in the other seasons through different hydrological processes. Spring precipitations lead to variations of soil moisture in spring that persist until summer and modulate the runoff-to-precipitation ratio in summer. Precipitations variations in late winter and spring play on groundwater recharge and then on river flows during all seasons through groundwater-river exchanges. Both the multidecadal variations in soil moisture in spring and summer and in groundwater may have important societal impacts, for example with regards to agriculture. Interestingly, the variations in summer river flows are much larger than seen in Bonnet et al. (2017). These differences are likely both due to the longest period studied here and potentially to the different hydrogeological model used, with a different representation of aquifers.

The multidecadal hydroclimate variations over the Seine basin are due to large-scale atmospheric circulation anomalies, themselves associated with sea surface temperature anomalies in the North Atlantic. It confirms the link between the AMV and French hydro-climate variations seen in previous studies on shorter periods, pointing to its robustness. Interestingly, an impact of the North Pacific, not described before, seems also to exist. The fact that multidecadal hydroclimate variations are present before the 20th century, which is a period where anthropogenic forcings were very small, reinforce the idea that they are of internal origin and not forced by greenhouse gases or sulphate aerosols.

An interesting new result is that the multidecadal variations previously described for the mean hydroclimate may influence extreme events. The positive multidecadal phases seem to be more conducive of flooding. Over large parts of the catchment the probability of floods is more than doubled during wet multidecadal phases. Although these events are mainly the result of exceptional weather conditions, the average state of the hydrological system, e.g. soil moisture or groundwater influenced by the multidecadal hydroclimate variability, may amplify or reduce the magnitude of these events. The influence of multidecadal variations on hydrological droughts is and more regional. Still, we have illustrated for two major droughts of the 20th century, that of 1921 and that of 1949, how multidecadal hydroclimate variations, through their impact on groundwater, may have reduced the intensity of the 1921 drought and increased the intensity of the 1949 drought.

Although the reconstruction developed in this study is an interesting tool for studying the past variability of the hydrological cycle over the Seine basin, it is obviously not perfect. Multidecadal (and interannual) variations of the piezometric levels at Toury are strongly underestimated. Although this is a one-point measurement, it is possible that this underestimation exists for the entire Beauce aquifer, which would imply an underestimation of the multidecadal variability of river flows in the reconstruction, especially in summer when the role of groundwater is particularly important. This underestimation seems to be due to hydrological modelling, and could come from a too simple representation of the limestone aquifer that neglects some confined parts . It would be interesting to confirm this hypothesis.

Even if it is not the object of this study, an important difference of long-term trends in river flows exists between the reconstruction and the observations for the Seine at Paris. The origin of these differences is not understood currently. The meteorological variables used as forcing for the reconstruction, and precipitations in particular, don't show an unrealistic trend (not shown) and therefore the trends in river flows from the reconstruction may not be unrealistic. As the Seine basin is highly anthropized, it is possible that non-climatic anthropogenic influences, which are not taken into account in the reconstruction, are responsible for the large negative trend in the observed series. It is something worth investigating in the coming years.

The origin of the hydroclimate variability over the Seine basin seems to be a teleconnection with SSTs of the North Atlantic and potentially of the North Pacific. Such teleconnections are still poorly understood. The Decadal Climate Projection Project (Boer et al., 2016) of the Coupled Model Intercomparison Project Phase 6 (Eyring et al., 2016) proposes some dedicated numerical experiments to tackle these questions. The study of their results will hopefully allow some progresses in our understanding of the physical origin of multidecadal hydrological variations over France.

Given the large multidecadal hydroclimate variations described in this study, it is crucial to assess whether climate models reproduce them correctly and therefore if the uncertainties due to internal variability are correctly captured in current projections. It may not be the case. For example, Qasmi et al. (2017) show that climate models may have difficulties to capture some properties of the AMV. Simpson et al. (2018) suggest that current climate models may have some issues to capture the multidecadal variations of the atmospheric jet over the North Atlantic in late winter / early spring, which would have consequences for the French hydroclimate. Understanding the potential consequences of these issues for the uncertainties in hydroclimate projections is now crucial.

Competing interests. The authors declare that there are no conflicts of interest regarding this work.

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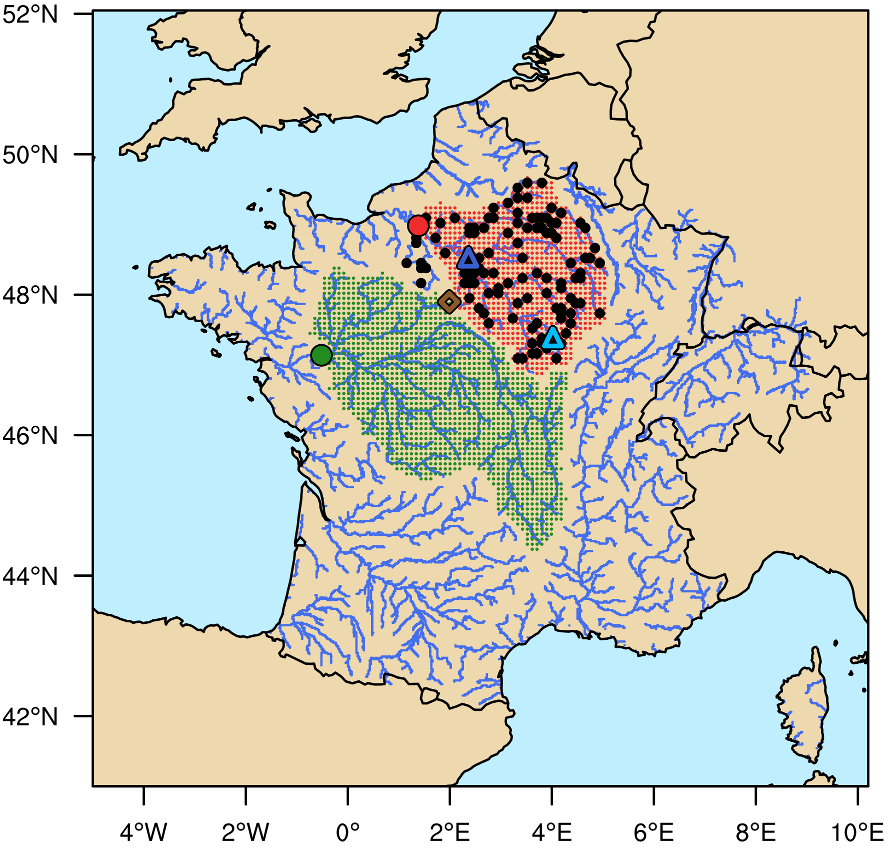

Figure 1. Location of the Seine catchment (red area) corresponding to the Seine at Poses station, considered as the outlet (red dot), and of the Loire catchment (green area) for the Loire at Montjean sur Loire station (green dot). Location of hydrometric stations both observed and simulated (black circles), and of the two long-term river flows observations available: the Paris Austerlitz station (dark blue triangle) and the Aisy-sur-Armançon station (light blue triangle). Location of the long-term piezometric level at Toury (brown rhombus).

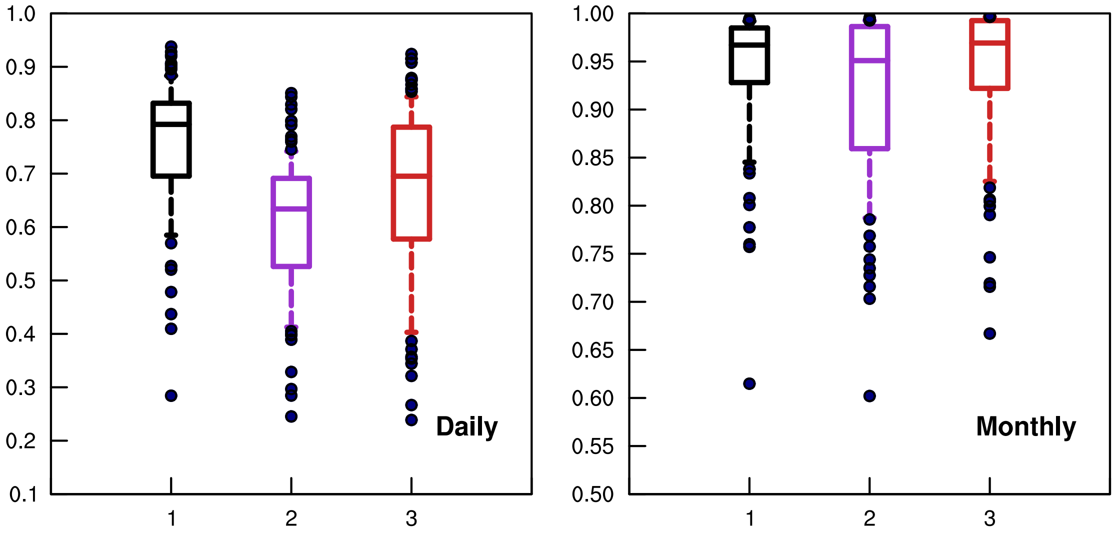

Figure 2. Spatial distribution of the correlations between (left) daily and (right) monthly observations of river flows and the (black) reference simulation (Safran-IsbaSurfex-AquiFR), (purple) the 20CRpt reconstruction used in Bonnet et al. (2017) and (red) the Seine reconstruction. The correlations are calculated on the 1958-2005 period and the series have been deseasonalyzed beforehand. The boxplots show the 10th percentile/25th percentile/median/75th percentile and the 90th percentile. The blue dots are the value below/above the 10th and the 90th percentiles.

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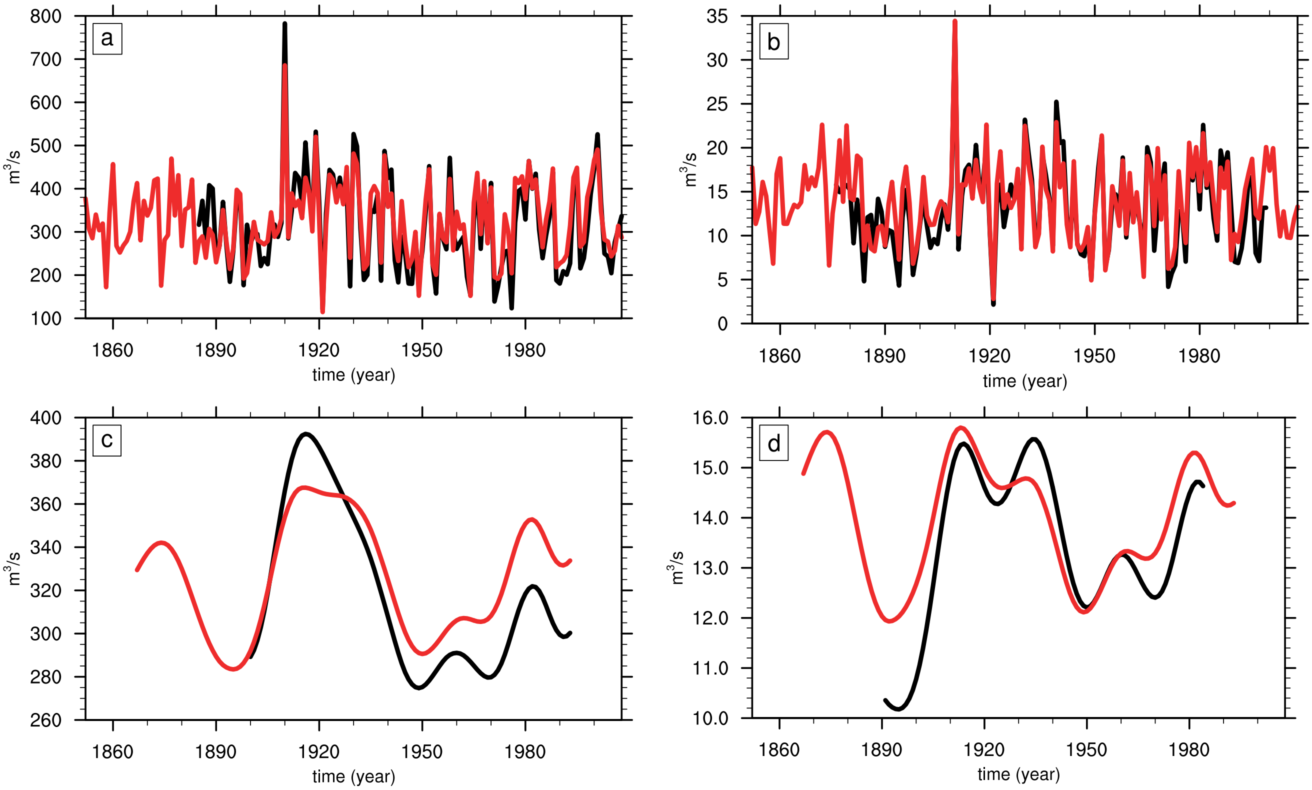

Figure 3. Annual series of river flows for the (a) Seine at Paris station and (b) Aisy-su-Armançon station (see Figure 1). (c) and (d): annual low-pass filtered series of river flows for the same stations of (a) and (b). Black: the observations. Red: the Seine reconstruction.

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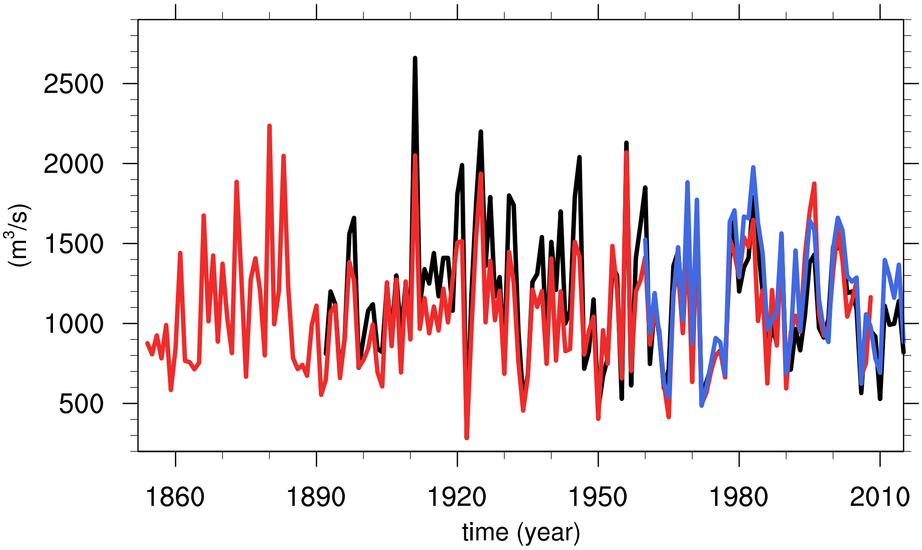

Figure 4. Annual maximum of daily river flows at the Seine at Paris station for the observations (black), the Seine reconstruction (red) and the reference simulation (based on Safran-Surfex-AquiFR).

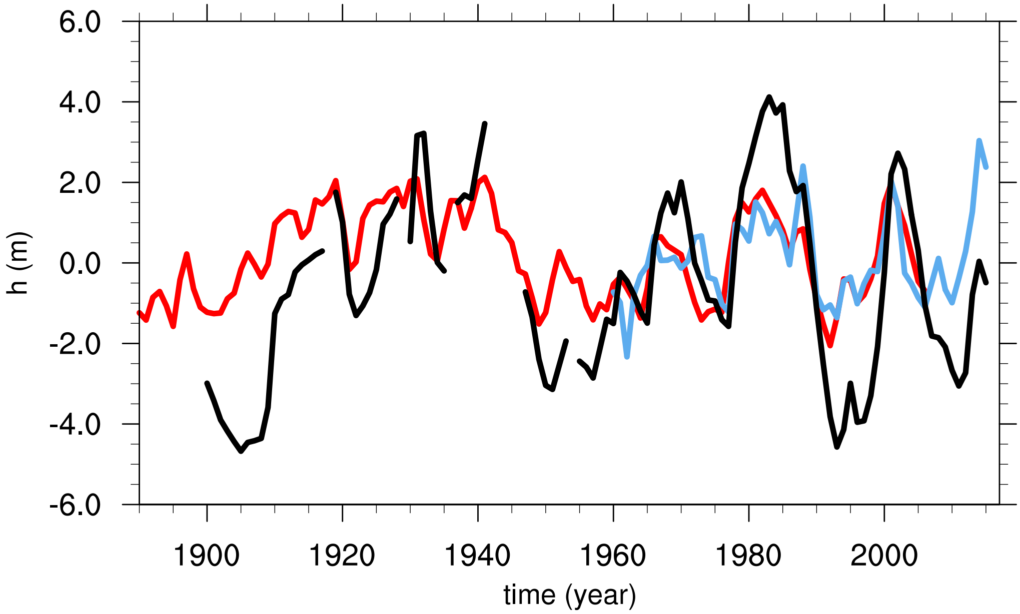

Figure 5. Annual anomalies of the piezometric levels of the Beauce groundwater table at Toury. The reference period is 1960-2005. Black: Observations. Red: the Seine reconstruction. Blue: the reference simulation (Safran-Surfex-AquiFR).

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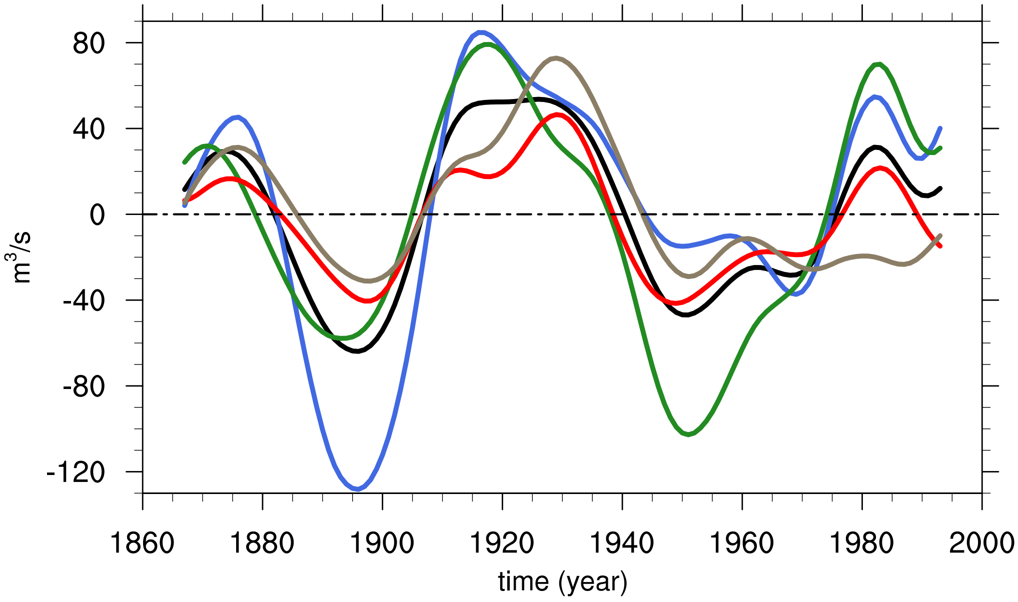

Figure 6. Low-pass filtered interannual anomalies of the Seine river flows at the Poses station. Black: annual, blue: winter, green: spring, red: summer and brown: autumn. The annual mean over the whole period is 446m3/s.

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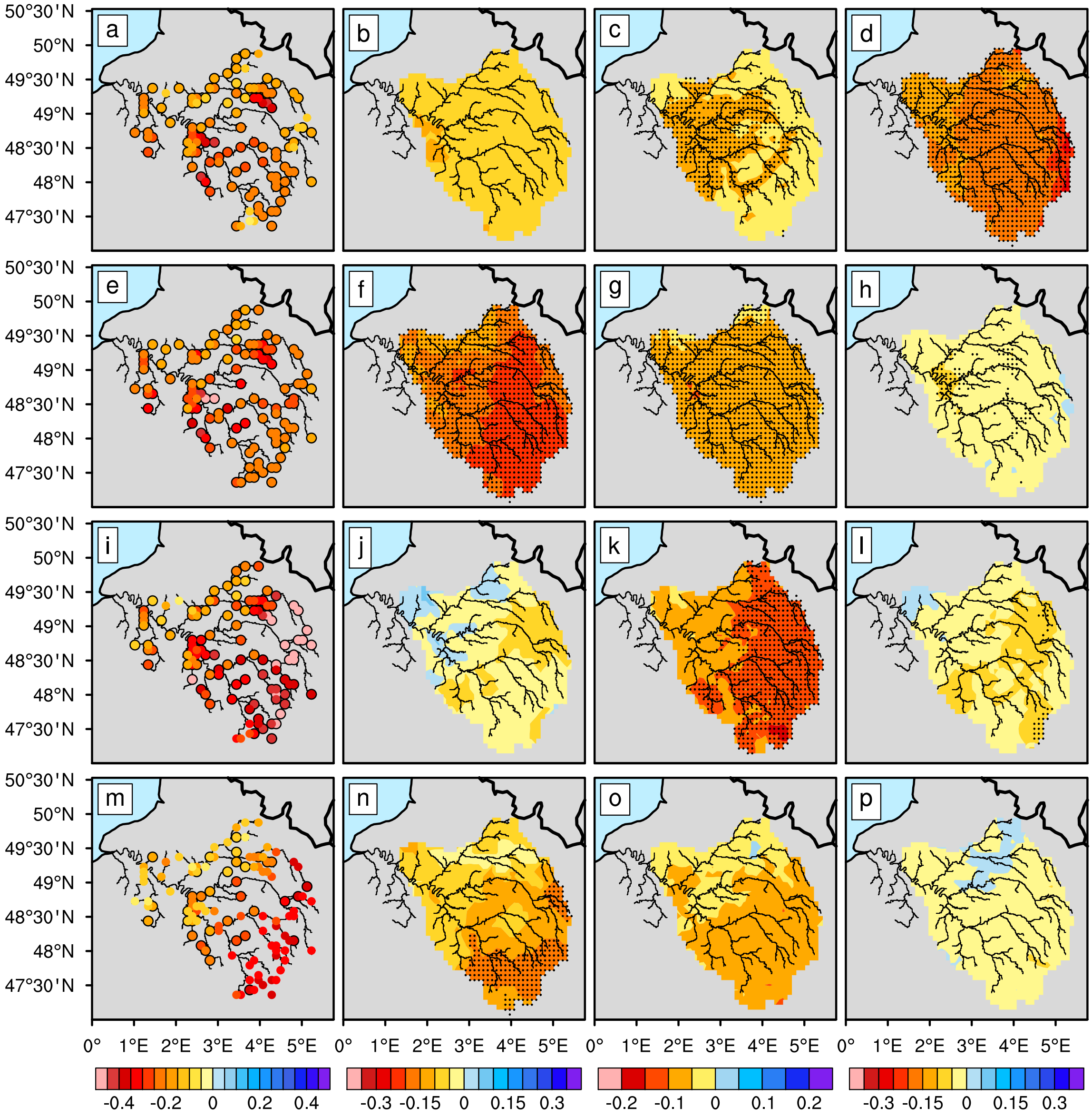

Figure 7. Relative differences of detrended (a-e-i-m) simulated river flows, (b-f-j-n) precipitations, (c-g-k-o) soil wetness index (SWI) and (d-h-l-p) evapotranspiration between the negative multidecadal phases of the Seine river flows (1885-1905 and 1940-1960) and the positive phases (1910-1930 and 1975-1995). The reference is calculated as the average of these four periods. (a-b-c-d) winter, (e-f-g-h) spring, (i-j-k-l summer) and (m-n-o-p) autumn. Simulated river flows, precipitations, SWI and evapotranspiration come from the Seine reconstruction. Black circles and dots show where the differences are significant with $p<0.05$ based on a t-test.

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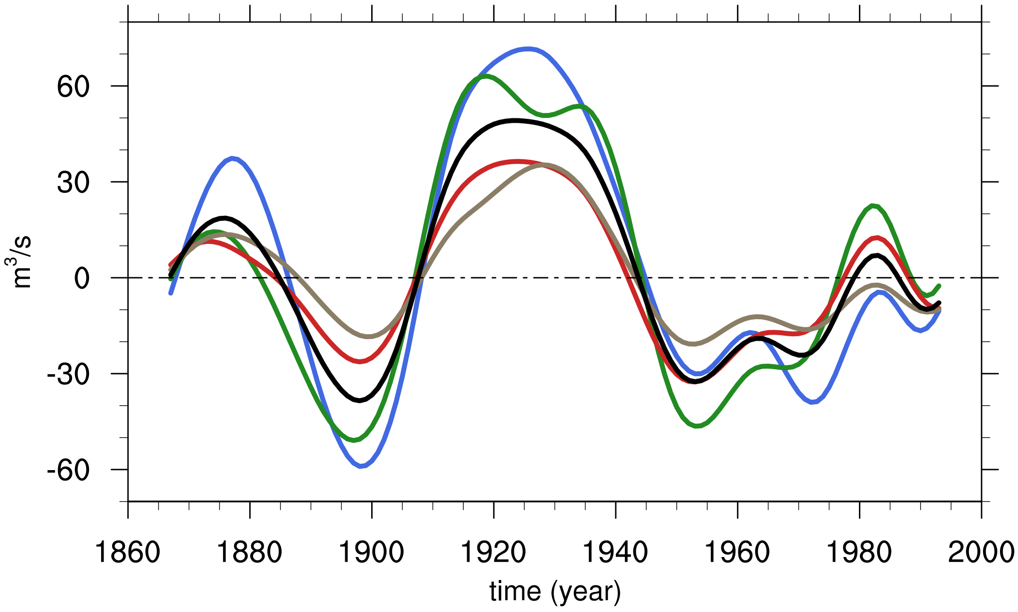

Figure 8. Annual low-pass filtered anomalies of the (black) annual, (blue) winter, (green) spring, (red) summer, (brown) autumn average groundwater-river water exchanges over the Seine basin in the reconstruction. The reference period is 1852-2008.

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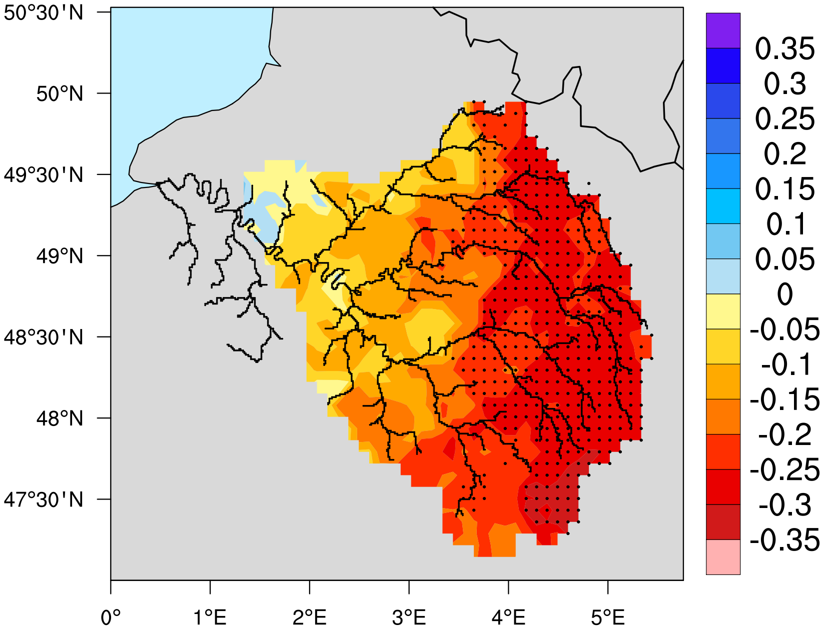

Figure 9. Relative differences of the ratio between the total runoff and precipitation of the reconstruction, calculated in summer between the negative multidecadal phases of the Seine river flows (1885-1905 and 1940-1960) and the positive phases (1910-1930 and 1975-1995). The reference for the calculation of the relative anomalies is calculated as the average of these four periods. Dots show where the differences are significant with $p<0.05$ based on a t-test.

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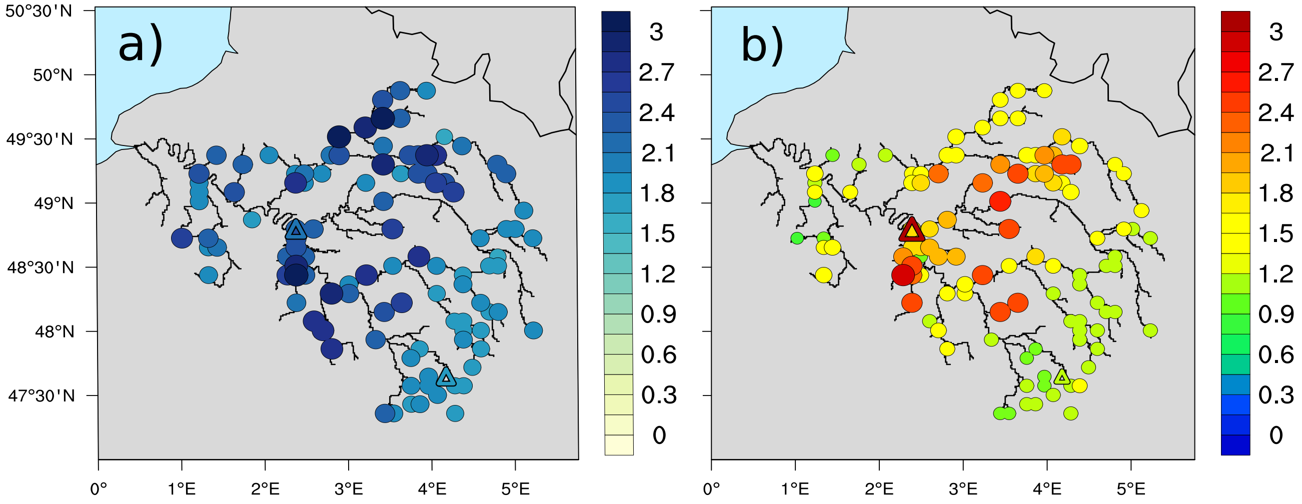

Figure 10. (a) Ratio of the number of the day with a river flow rates equal or greater of the 95th percentile between the positive multi-decadal phases of the Seine river flows (1910-1930 and 1975-1995) and the negative phases (1885-1905 and 1940-1960) calculated with the reconstruction (dots), and for the two long term observations (triangles, see figure 1). The ratio is calculated for the days in the months of November to April , which corresponds to the flood period. The reference period is 1852-2009. (Right) same as (b) for, and with the inverse of the ratio the number of the day with a river flow rates equal or lower of the 5% percentile. All days of the year are considered.

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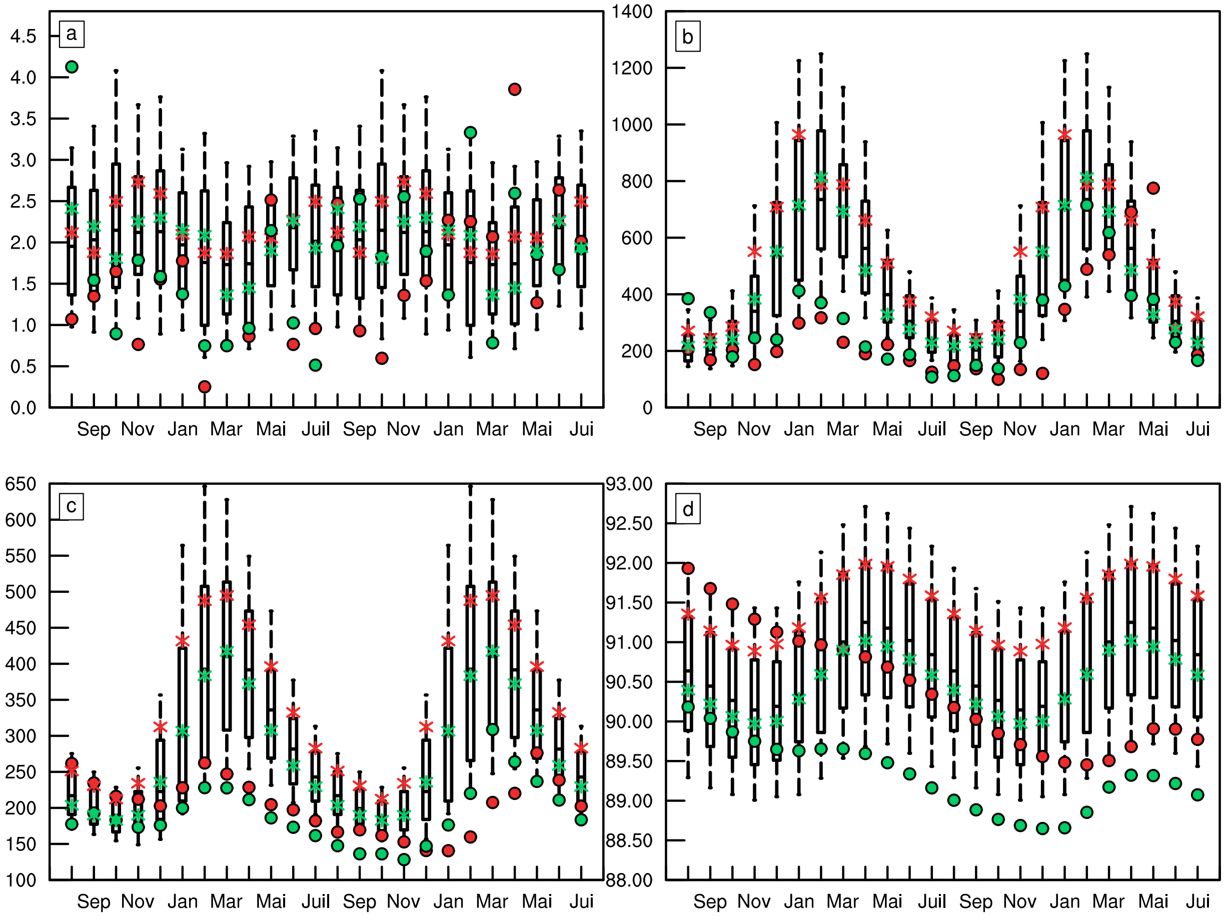

Figure 11. a) Evolution of monthly precipitation (mm/j) over the Seine basin from august 1920 to July 1922 (red dots) and from August 1948 to July 1950 (green dots). The boxplots represent the climatological monthly distributions calculated over the 1852-2008 period. Red (green) crosses represent the monthly average of the 1910-1930 (1940-1960 period). (b) The same for river flows at the Poses stations (m3/s), (c) water exchanges between groundwater and rivers (m3/s) and (d) the piezometric levels (m) of the unconfined part of the aquifer. The data come from the Seine reconstruction. Boxplots are defined as: 10th percentile, 25th percentile, median, 75th percentile and 90th percentile.

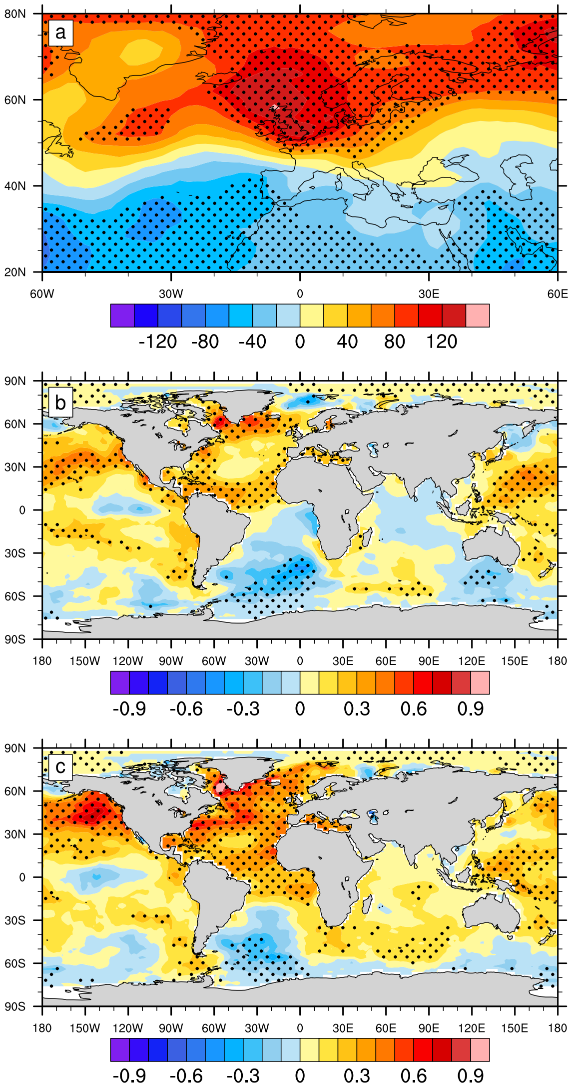

Figure 12. Differences of the (a) detrended pressure at sea level (SLP) (Pa), (b) detrended sea surface temperature (SST) (K) between the negative multidecadal phases of the Seine river flows (1885-1905 and 1940-1960) and the positive phases (1910-1930 and 1975-1995). (c): same as (b) considering a lag 10 years earlier over the periods. SLP comes from the NOAA 20CRv2c reanalysis. SST comes from the ERSSTv5 reconstruction (Huang et al., 2017). The trends are calculated with the EEMD method and removed for each grid points. Dots indicate where the differences are significant with $p<0.05$ (based on a t-test)