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# Multi-decadal river flows variations in France

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**Abstract**

In this article, multi-decadal variations in French hydroclimate are investigated, with a specific focus on river flows. Based on long observed series, it is shown that river flows in France generally exhibit large multi-decadal variations on the historical period, especially in spring. Differences of means between two 21 yr periods of the 20th century as large as 40 % are indeed found for many gauging stations. Multi-decadal spring river flows variations are associated with variations in spring precipitation and temperature. These multi-decadal variations in precipitation are themselves found to be driven by large-scale atmospheric circulation, more precisely by a multi-decadal oscillation in a sea level pressure dipole between western Europe and the East Atlantic. It is suggested that the Atlantic Multidecadal Variability, the main mode of decadal variability in the North Atlantic/Europe sector, controls those variations in large-scale circulation and is therefore the main ultimate driver of multi-decadal variations in spring river flows. Multi-decadal variations in river flows in other seasons, and in particular summer, are also noted. As they are not associated with significant surface climate anomalies (i.e. temperature, precipitation) in summer, other mechanisms are investigated based on hydrological simulations. The impact of climate variations in spring on summer soil moisture, and the impact of soil moisture in summer on the runoff to precipitation ratio, could potentially play a role in multi-decadal summer river flows variations. The large amplitude of the multi-decadal variations in French river flows suggests that internal variability may play a very important role in the evolution of river flows during the next decades, potentially temporarily limiting, reversing or seriously aggravating the long-term impacts of anthropogenic climate change.

## 1 Introduction

The role of internal low-frequency variations in the evolution of the climate system has received increasing attention recently, stemming from the societal need for relevant climate information on the next few decades for planning and adaptation in the context of climate change. Internal low-frequency variations can indeed temporarily either aggravate, moderate or even reverse the long-term impact of global warming. Current climate projections suggest that internal low-frequency variability is a major source of uncertainties on the coming decades (Hawkins and Sutton, 2009; Deser et al., 2010, 2012). For example, regarding precipitation change over France at the middle of the 21st century, uncertainties related to internal variability may be as large as uncertainties due to climate models (Terray and Boé, 2013).

The realism of those estimations of the impact of internal variability in future projections depends on the ability of climate models to simulate correctly low-frequency internal modes of variability. Unfortunately, current models generally present some moderate deficiencies in capturing the exact spatio-temporal characteristics of the observed low-frequency variations in the North Atlantic ocean, and serious difficulties in correctly capturing the associated hydroclimate impacts over land (Kavvada et al., 2013). This issue regarding hydroclimate variations is especially problematic since because of the multiplicity of the uses of water and the tensions that often already exist between demand and resources, low-frequency fluctuations in continental hydroclimate and in particular river flows may have particularly serious impacts for the society.

Some progresses are therefore to be made towards a better characterization and understanding of the low-frequency internal variations in the climate system, not only in the ocean which plays a central role in their existence, but also how they impact continental hydroclimate. Despite the shortness of the historical record when dealing with multi-decadal variations and despite the fact that observed variations are always the result of both internal and forced components, and therefore do not allow to readily disentangle the contributions of both sources of variability, observational studies remain crucial in that context. In this study, our objective is to characterize the low-frequency (multi-decadal) variations in the French hydroclimate and in particular river flows on the historical period, and to understand the associated mechanisms.





The main mode of multi-decadal variability in the North Atlantic-Europe sector is the Atlantic Multidecadal Variability (AMV, also known as Atlantic Multidecadal Oscillation; Kerr, 2000). The AMV is characterized by basin-wide variations in the North Atlantic sea surface temperature at multi-decadal time-scales (60–100 yr on the historical period, e.g. Schlesinger and Ramankutty, 1994; Kerr, 2000). Based on climate simulations, it is generally hypothesized that buoyancy-driven variations of the Atlantic Meridional Overturning Circulation (AMOC) intrinsic to the climate system largely drive the AMV (Delworth and Mann, 2000). However, whether the AMV is mainly an internal mode of variability or is to a large extent forced by external forcing remains somewhat controversial. On the one hand, paleoclimate data suggest that AMV-like variability is not limited to the historical period (e.g. Gray et al., 2004). Moreover, preindustrial control coupled climate simulations generally exhibit modes of variability whose spatio-temporal characteristics are relatively similar to the observed AMV (e.g. Knight et al., 2005). On the other hand, other studies point toward a potentially important role of climate forcing on observed multi-decadal variations in the North Atlantic on the historical period, as volcanic eruption (Ottera et al., 2010) or aerosols (Booth et al., 2012).

Independently of the driving mechanism(s) which is not the object of our study, current literature suggests a potential impact of the AMV on continental hydrological cycle over France, as it is the case in the USA (Endfield et al., 2001). At inter-annual time-scales, statistical relationships between drought severity for some French rivers and averaged North Atlantic sea surface temperatures (SST) have been found (Giuntoli et al., 2013). Regarding multi-decadal time-scales, on the historical period, positive phases of the AMV are significantly associated with larger temperature over France in spring and to a lesser extent in summer and with below average spring precipitation (Sutton and Hodson, 2005; Sutton and Dong, 2012). Physically, those changes in the surface climate are expected to lead to decadal river flows anomalies.

In this paper, after a description of the data and methods used (Sect. 2), multi-decadal variability in French river flows is characterized (Sect. 3). The mechanisms behind river flows variations in spring are described in Sect. 4. Hydro-meteorological



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simulations are analyzed in Sect. 5 in the objective to better understand multi-decadal variations in summer flows. Finally, conclusions and perspectives are given in Sect. 6.

## 2 Data, models, and methods

Daily river flows at 38 gauging stations over France are analyzed in this study. Data have been extracted from the national HYDRO database (http://www.hydro.eaufrance.fr/). Series at all selected gauging stations start before 1940 and cover at least 70 yr (the median length is 90 yr). Gauging stations with too much missing values have been discarded. When less than 3/4 of daily values are available during a given year (season), the corresponding annual (seasonal) mean is considered as missing. At most, 6 % of years are missing for the selected stations with that definition. The missing values as previously defined in the selected series are filled by the corresponding long-term climatological average. The use of this very crude approach is intentional. More sophisticated methods (e.g. temporal interpolation based on neighbor years etc.) might artificially enhance low-frequency variations.

The location of the gauging stations and the length of the corresponding river flows series are shown in Fig. 1. Stations are not uniformly distributed over France, with very few stations in the north while the central France is well covered.

Metadata indicate that river flows at some of the selected gauging stations are directly influenced by man (e.g. dams or water intakes). It has been decided not to discard those stations *a priori* because they may still provide valuable information, but we flagged them for the interpretation of the results (Fig. 1). Note also that this data-set is not homogenized and therefore stations in the "no or little influence" categories are not necessarily free from other artifacts (e.g. change in measurement). One has therefore to be cautious about the interpretation of variations at any particular station, and the focus of this study is on large-scale patterns of coherent variations. For most of the analyses described in this study, river flows series have been detrended by removing the long-term linear trend on the total period available for each series.





For precipitation, a large set of monthly homogenized time series aggregated by department to form 51 time series that sample a large portion of France, from Météo-France, is used (HPS as homogenized precipitation series, Moisselin et al., 2002). HPS data are available from 1900 to 2000. In complement to this data-set that does not cover the beginning of the 21st century, the Global Precipitation Climatology Center data-set (GPCC) is also used (full Data Reanalysis from 1901 to 2011, Rudolph and Schneider, 2005). This data-set is not optimized for variability study and is therefore *a priori* less suitable than HPS to study low-frequency fluctuations. Homogenized temperature series at different stations over France from Météo-France are also used in this study (Moisselin et al., 2002).

Precipitation and sea level pressure have been extracted from the 20th Century Reanalysis (20CR in the following, Compo et al., 2011). This data-set covers the 1871–2010 period. The only observation assimilated by the 20CR system is sea level pressure (SLP). Observed sea surface temperature, sea ice cover, time-varying global mean $CO_2$ and volcanic aerosols concentration, and incoming solar radiation are used as forcing of the atmospheric model of the 20CR system. Some caveats are associated with 20CR data. SLP observations are very sparse at the beginning of the period (and well within the 20th century for some areas) and therefore the accuracy of the reanalysis is necessarily more limited then. As only SLP is assimilated, this reanalysis cannot in theory have the same level of accuracy as more classical reanalyses for variables that are not strongly controlled by large-scale circulation. On the other hand, temporal inconsistencies associated with changes in instruments (new satellites etc.) are avoided in 20CR. However, the change with time of the number of SLP observations assimilated may still result in artificial temporal variations (Krueger et al., 2013).

The HadSST3 sea surface temperature (SST) data-set (Kennedy et al., 2011a,b) from 1850 to 2012 is used to compute the AMV index. The AMV is defined as the low-pass filtered average of SST in the North Atlantic (in our case, the domain is 0–60° N, 75–7.5° W) with the impact of anthropogenic temperature rise removed. A linear trend has been commonly used (e.g. Enfield et al., 2001; Knight et al., 2005) to estimate the anthropogenic temperature increase in this context. However the trend is not expected to be linear, especially on a long period as the one studied here. The global average of SST is also commonly used as an estimator of the forced temperature rise (e.g. Trenberth and Shea, 2006). However, as there is very little observations outside the North Atlantic initially, the global average is expected to be biased towards the North Atlantic average at the beginning of the period. This procedure could therefore lead to an underestimation of the AMV variations in the early period. Here, the forced component is estimated by regressing the North Atlantic SST average on the observed $CO_2$ concentration in order to compute and remove a non-linear trend. As the other ones, this method has drawbacks, but it is important to note that results presented in this study are not crucially dependent on the way the anthropogenic temperature rise is removed when computing the AMV index. By definition in the following, by AMV we mean the de-trended and low-pass filtered AMV index.

Results of an hydro-meteorological simulation over France on the 1961–2012 period are also analyzed in this study. This simulation is based on the SAFRAN-ISBA-MODCOU (SIM) hydro-meteorological coupled system. SIM is described and evaluated against observations in Habets et al. (2008). SIM is the combination of three independent systems. SAFRAN (Durand et al., 1993), based on obervations, analyses the seven atmospheric variables at the hourly time step on a 8 km grid necessary to force the soil-vegetation-atmosphere transfer (SVAT) scheme ISBA. Those variables are liquid and solid precipitation, incoming long-wave and short-wave radiation fluxes, 10 m wind speed, 2 m specific humidity and temperature. A description and elements of validation of SAFRAN are given in Quintana Segui et al. (2008) and Vidal et al. (2010). ISBA (Noilhan and Planton, 1989) computes the surface water and energy budgets and then MODCOU (Ledoux et al., 1984) routes the surface runoff simulated by ISBA in the hydrographic network.

To extract the multi-decadal variations in the series analyzed in this study, a 19-weights Hamming window low-pass filter is used. For yearly data, the half-amplitude point is about a 18 yr period. Oscillations with period less than 9 yr are virtually elim-



inated. No padding is applied: the first 9 yr and last 9 yr of the unfiltered series are considered as missing in the filtered series.

To assess the significance of correlations computed from the low-pass filtered series, which exhibit a very high level of serial correlation, the test proposed by Ebisuzaki (1997) and applied in the same context for example by Enfield et al. (2001) is followed. The test is based on a Monte Carlo approach, with a randomization of phases in the frequency domain in order to generate random surrogate series with the same level of serial correlations than the original ones.

Through this paper, winter means December-January-February, spring means March-April-May, summer means June-July-August and autumn means September-October-November.

## 3 Multi-decadal variability in observed French hydro-climate

Simple visual inspection reveals important multi-decadal fluctuations in river flows for many of the gauging stations examined in this study, especially in spring. As an example, Fig. 2a shows that the Gave d'Ossau, a small river in south-western France (see Fig. 1), exhibits large decadal variations in spring and annual river flows, clearly discernible even in unfiltred series. Decadal minimums in the 1950s and 2000s contrast with maximums in the 1920s and 1970s. Spectral analysis confirms that the Gave d'Ossau exhibits strong multi-decadal variations, significant for periods roughly greater than 30 yr (Fig. 2b).

To quantify the importance of multi-decadal variations in river flows in France, the ratio of the standard deviation of low-pass filtered series to the standard deviation of unfiltered series is shown for the seasonal and annual averages (Fig. 3a). Seasonally, the importance of multi-decadal variations relatively to the total variability is generally much greater in spring. Large decadal variations are also seen in the annual series. Note that as the standard deviation of unfiltered series is greater for spring averages than for yearly averages, in absolute term, the multi-decadal signal is much larger in spring than in annual means (1.8 times larger in average over France, not shown).

A straightforward hypothesis to explain the multi-decadal variations in river flows is that they are driven by precipitation fluctuations. Figure 3b shows that spring precipitation over France indeed also exhibits large multi-decadal fluctuations. Multi-decadal variations for the other seasons are much weaker. Interestingly, the magnitude of multi-decadal variations in river flows is generally greater than in precipitation.

To assess whether the local multi-decadal fluctations of the Gave d'Ossau shown in Fig. 2a are part of a coherent larger scale signal, the relative differences in detrended river flows between the 1938–1958 and 1965–1985 periods, that roughly correspond respectively to decadal minimum and maximum for the Gave d'Ossau, are shown in Fig. 4. The largest multi-decadal differences in river flows are generally seen in spring, with a signal shared by virtually all gauging stations over France. Differences in 21 yr average as large as or even greater than 40 % are seen in spring between the two periods. Many stations also exhibit important decadal differences in summer (especially over western France) and winter, while the signal is generally weaker in autumn, except for few stations. At the annual level, differences as large as 30 % and greater than 25 % are noted for most stations in western and central France. Corresponding precipitation and temperature anomalies between the two periods are also depicted in Fig. 4. The smaller spring river flows in 1938–1958 compared to the 1965–1985 period are associated with strong negative precipitation anomalies over France (up to −30 %) and warmer temperature (up to 1 K). No significant differences in temperature nor precipitation are generally observed for the other seasons.

Multi-decadal fluctuations in river flows noted for the Gave d'Ossau in Fig. 2a in spring are therefore part of large scale hydroclimate perturbations over France and are likely caused to a large extent by precipitation variations. An additional driver could be the temperature. Indeed, as spring evapotranspiration in France tends to be energy-limited rather than water-limited, positive temperature anomalies at the inter-annual level in spring are expected to be associated with larger evapotranspiration. Following



this line of reasoning and supposing that this relation is still valid at multi-decadal timescales, larger temperatures in 1938–1958 would therefore be consistent with larger evapotranspiration, which would also result in smaller river flows. While multi-decadal variations in spring river flows could be explained by surface climate anomalies, the decadal differences in river flows observed in the other seasons are more puzzling as they are not associated with significant specific climate anomalies and in particular precipitation anomalies.

The multi-decadal changes in mean river flows noted previously are also associated with modifications of the statistical distribution of river flows, which could have important practical impacts. Indeed, for most of the stations examined here, the 1938–1958 period compared to the 1965–1985 period is associated with an important increase in the occurrence of moderately low daily river flows and decrease in the occurrence of moderately intense daily river flows (often equal or greater than 50 %, Fig. 5).

To assess whether multi-decadal variations in spring precipitation and river flows are in phase on the entire available periods, the correlations between low-pass filtered spring precipitation averaged over France and low-pass filtered spring river flows at each gauging stations are computed (Fig. 6a). Very high significant correlations are obtained for the great majority of the gauging stations. Note that the average of precipitation over France is used here because of the lack of precipitation data specific to each river basins on the whole period of interest. As shown in Fig. 6b, the multi-decadal variations in spring precipitation over France are very spatially coherent. Precipitation at each point is indeed highly correlated with spatially-averaged precipitation, except in south-eastern France. Because of the orography, precipitation there are known to be often associated with particular synoptic conditions compared to the rest of France. Overall, this analysis shows that in spring it is justified to focus on spatially-averaged precipitation over France to understand river flows variations as the precipitation signal is large-scale.

## 4 Mechanisms of spring hydroclimate variations

Based on the previous analyses and considering the straightforward physical link between precipitation and river flows, it appears highly likely that multi-decadal fluctuations in spring river flows are driven to a large extent by large-scale precipitation variations over France. Assessing the robustness of the multi-decadal signal seen in spring precipitation and understanding its physical causes are therefore crucial.

Averaged precipitation over France in spring from three data-sets (GPCC, HPS and 20CR) are depicted in Fig. 7. Very similar multi-decadal signals are visible for all three data-sets. GPCC and HPS data are not independent, as some stations used in GPCC are also used in HPS. However, the statistical treatment of raw data for the two data-sets is largely different. HPS is a priori more adapted to the study of low-frequency variations because of the homogenization procedure applied. The extremely small differences seen between multi-decadal precipitation variations in GPCC and HPS show the robustness of those features to the statistical pre-treatment of precipitation data and to the exact number and location of stations. Moreover, it shows that even if it is not homogenized, GPCC data can be used in the following analyses to estimate averaged precipitation over France, as it has the advantage to be available on a longer period compared to HPS.

Spring precipitation over France in 20CR exhibits a temporal pattern that is very similar to the one seen in HPS and GPCC, even if some limited differences exist, especially at the beginning of the record. This consistency with direct observations (GPCC, HPS) is noteworthy as 20CR provides an indirect and totally independent estimation of precipitation. Indeed, no observed precipitation is used in 20CR. Note that SLP observations, the only variable assimilated in 20CR, are much sparser in the early period of the reanalysis, which has an impact on the quality of 20CR data then (Compo et al., 2011). It likely explains to a large extent the limited discrepancies between 20CR and observed precipitation at the beginning of the 20th century. The fact that low-frequency



variations in spring precipitation are well captured by 20CR also suggests that they may be largely driven by SLP.

The previous analysis shows that the large multi-decadal variations seen in spring precipitation over the 20th century are a robust feature of French climate. Indirectly, it also reinforces the confidence in the general robustness of multi-decadal variations seen in river flows.

The multi-decadal variations in spring precipitation noted here are consistent with the results of Sutton and Dong (2012). Those authors also suggest that there is a link between the AMV and spring precipitation variations. In spring, the positive phase of the AMV is associated with an anomalous ridge over western and central Europe, between two anomalous negative SLP anomalies over the East Atlantic and north-eastern Europe (Sutton and Dong, 2012). This circulation pattern is expected to be associated with an increase in southerly flows over France, with an advection of warmer and drier air, and therefore with negative precipitation anomalies over France. Sutton and Dong (2012) define a SLP index to capture this potential impact of the AMV on atmospheric circulation on the North Atlantic/Europe sector in spring. A similar SLP index (SLPI) is used in our study.

As shown in Fig. 7, there is a very good anti-correlation between low-pass filtered SLPI and precipitation anomalies over France in spring. High and significant anti-correlations with precipitation series between −0.86 and −0.94 depending on the precipitation data-set (and therefore on the exact period) are noted. A positive value of SLPI corresponds to positive SLP anomalies over central/western Europe and negative anomalies over the East Atlantic and is associated, as physically expected, with negative precipitation anomalies over France. This result is a strong evidence that the multi-decadal variations in spring precipitation over France and therefore in river flows are driven by large-scale circulation.

Sutton and Dong (2012) suggest those large-scale circulation fluctuations are likely driven by the AMV. Figure 8 shows that there is indeed a strong covariability between the AMV and SLPI. However, this graph also suggests that the variations may not be exactly in phase. The AMV tends to lead SLPI. It is confirmed by Fig. 9a. Maximum correlations between the AMV and SLPI are found when the AMV leads SLPI by 5 or 6 yr. As expected a similar lag-relationship with the AMV is found for spring precipitation (Fig. 8b). It can be seen in Fig. 8 that the lag tends to vary on the period as it seems to be generally larger at the beginning of the 20th century. Obviously, one must keep in mind that when dealing with multi-decadal variations, 130 yr is a very short period to estimate robustly a potential small lag between two low-pass filtered series. One must therefore remain cautious about the interpretation of this lag between AMV and SLPI or its variation. In any case, this lag remains consistent with the idea that the AMV drives SLPI variations (rather than the opposite). From a physical point of view, it is possible that the lag noted is due to the evolution of the exact spatial pattern of SST anomalies in the North Atlantic during the phase of the AMV, and to the sensitivity of SLP to the precise SST pattern. Further work, based for example on dedicated numerical experiments with an atmospheric model forced by different SST patterns would be needed to demonstrate unambiguously that the AMV is the driver of SLPI multi-decadal fluctuations and to better understand the physical mechanisms responsible for the potential lag.

Given the well-understood link between precipitation and river flows (Fig. 6a) and as multi-decadal precipitation variations are driven by SLPI, multi-decadal variations in SLPI generally explain a large part of multi-decadal variations in spring river flows (Fig. 10b). Large anti-correlations with the annual mean are also generally noted.

Some significant correlations are also seen between SLPI (in spring) and river flows in summer or even in autumn. They are not straightforward to explain. Obviously, no direct causal relationship between atmospheric circulation in spring and river flows in summer is possible. The link between SLPI and summer flows might just be coincidental, as both may be independently impacted by the AMV through different mechanisms, or the decrease in spring precipitation (and/or increase in spring temperature) caused by SLPI has also an impact on summer flows, through memory effects associated with hydrological processes. This issue is examined in the next section.





## 5 Summer variations: hydro-meteorological simulations

The analyses described in the previous sections allow to understand the multi-decadal variations seen in spring river flows and to a certain extent in annual means. However, no explanation for multi-decadal variations in other seasons has emerged. Figure 4 shows that multi-decadal fluctuations, although less important than in spring (Fig. 3a), also exist for many gauging stations in summer for example. Those variations are puzzling as they are not directly associated with significant climate (i.e. precipitation and temperature) variations. In particular, except in south-eastern France, decades with below normal river flows are characterized by non-significant and moreover generally larger precipitation in summer (Fig. 4). If those variations are not directly caused by climate anomalies, they might be related to hydrological processes.

Negative precipitation anomalies associated with positive SLPI in spring are expected to lead to drier soils. Moreover, as explained previously, a modulation of spring evapotranspiration could also be envisaged given the decadal temperature variations noted in Fig. 4. Positive SLPI anomalies would be associated with increased evapotranspiration in spring and therefore a decrease in soil moisture. The negative soil moisture anomalies associated with the variations in precipitation and evapotranspiration in spring might then persist until summer, and in turn impact river flows. Indeed, over drier soils, a smaller fraction of precipitation results in runoff and more water is stored in the soil or is lost as evapotranspiration in the end. An impact of spring precipitation and evapotranspiration on summer flows through a modulation of aquifer levels could also theoretically be possible. However, deep aquifers are not expected to play an important role on river flows for many of the stations analyzed here (BRGM, 2006).

In this section, we focus on the possible bridge between spring climate variations and summer flows through a modulation of soil moisture. To study those mechanisms, the knowledge of hydrological variables such as soil moisture and evapotranspiration is needed. Observations of those variables with a correct spatio-temporal sampling do not exist, and therefore one has to use hydrological modelling in that context. Here, the SIM system described in Sect. 2 is used.

The availability of the meteorological forcing limits the SIM hydrological simulation over France to the 1961–2012 period (and therefore limits the analyses to 1970–2003 when low-pass filtered series are involved). This is obviously a very short period to study low-frequency variability. On such a short period it is difficult to disentangle the impact of internal multi-decadal variations from the one of potential long-term trend associated with increase in greenhouse gases (GHG) concentration. Also, for such a short sample of time, it is difficult to reach significance levels for statistical tests involving low-pass filtered series. The objective of this section therefore remains modest: we want to evaluate the general plausibility of the mechanism previously described rather than demonstrate unambiguously its role. Note that as shown in Fig. 8, the period 1961–2012 mostly corresponds to a negative phase of the AMV, starting in the 1960s and ending in the 1990s. On this period, SLPI follows a very similar temporal pattern.

First, spring, summer and annual simulated river flows by SIM are compared to observations, at the interannual level (1961–2012 period) and after low-pass filtering (1970–2003 period), to assess the ability of SIM to capture observed river flows variations (Fig. 11). For the vast majority of the stations studied here, the model captures the interannual variability in river flows well. Correlations lower than 0.70 are seldom found. Regarding low-frequency variations, the model also performs well, except at a few stations, especially in summer. It is not clear whether deficiencies in the hydrological model, direct anthropogenic influences on river flows or some measurement issues, explain those poor correlations. Note that as SIM does not take into account direct human influence on river flows (dams, pumping etc.) the fact that simulated river flows are most of the time consistent with observed river flows suggest that direct anthropogenic influences are not dominant in the interannual and multi-decadal fluctuations on the period simulated here for most stations. As river flows are generally well simulated and as the precipitation forcing is derived from observations, the previous



analysis suggests that the evolution of the other components of the continental water cycle are very likely also well simulated by SIM for most of the stations.

The central element of the hypothesis tested in this section is that soil moisture at the end of spring can impact river flows in summer through a modification of the part of precipitation that contributes to runoff. Figure 12a shows the link between the soil wetness index (SWI, the difference between the volumetric water content of the soil column and the wilting point divided by the difference between the field capacity and the wilting point) at the end of spring and the runoff to precipitation ratio simulated by SIM in summer for all the stations examined in this section, at the interannual and multi-decadal time-scales. A clear non linear relation exists. Dry soils in spring are associated with very small runoff to precipitation ratio in summer, while for SWI at the end of spring close to one, most of precipitation is transformed into runoff. To confirm the link between the SWI at the end of spring and the runoff to precipitation ratio in summer for each individual stations, the rank correlations at the interannual level between those two quantities are shown in Fig. 12b. The impact of detrending is very limited, pointing towards the robustness of the relationship at the interannual level.

Now that it is clear that the basic mechanism is effective at the interannual level, multi-decadal variations in soil moisture at the end of spring are investigated. First, the link between SLPI and spring evapotranspiration and soil moisture at the end of spring are studied. As the objective here is to study the relationships between variables at multi-decadal time-scales, it is necessary to remove the potential effect of long-term anthropogenic climate change as done previously by detrending the data for the long observed series studied. However, as the trends in simulated variables are estimated on a short period, they may not only capture the effect of long-term anthropogenic climate change but also the potential impact of internal multi-decadal variations that we would like to isolate. Detrending the data may therefore lead to an underestimation of multi-decadal variations and bias the analyses. Not removing any trend avoid this issue, but if long-term anthropogenic climate change has an impact on the variables of the interest, keeping the trends could result in spurious relationships due to com-




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mon trends. As none of the approach is perfectly appropriate, in the following, both detrended and non detrended simulated hydrological variables are examined in order to assess the impact of this methodological issue.

As previously hypothesized, positive SLPI is generally associated with larger evapotranspiration in spring. Because of smaller precipitation and higher evapotranspiration, lower level of soil moisture at the end of the spring are therefore also associated with positive SLPI (Fig. 13). Although detrending simulated data does have an impact and results in smaller absolute correlation, especially for soil moisture, the general picture remains the same. It is also verified that there is a strong relationship between evapotranspiration in spring and soil moisture at the end of the spring (Fig. 14). This is true whether the variables are detrended or not before computing the correlations.

It is now tested whether soil moisture at the end of spring may have a non negligible impact on summer flows at the multidecadal time-scale. Large positive correlations are seen for most stations between low-pass filtered SWI at the end of spring and river flows in summer (Fig. 14). However, detrending the data has a large impact on the analysis for most of the stations in the Massif Central, while other stations maintain high correlations even after detrending. It is the case for the two stations of the Loire (the two northern stations in western France) and in south-western France. Those are also stations where large decadal variations in summer flows are observed (Fig. 4).

The results described in this section suggest that the AMV, through a modulation of SLPI, may also affect evapotranspiration over France in spring. Increased evapotranspiration and decreased precipitation lead to soil moisture depletion. Negative soil-moisture anomalies in spring lead to drier soils in summer with a potential influence on river flows in summer. This is a physically plausible mechanism, consistent with the decadal variations simulated at several stations in France in summer. For other stations, the fact that the link between the SWI at the end of spring and summer flows is very dependent on the presence or not of trends does not allow to conclude.

It is also important to note that it is possible that anthropogenic forcing plays an important role on the evolution of evapotranspiration in the late 20th and early 21st cen-



tury over some regions (Douville et al., 2012). GHG could be associated with positive evapotranspiration trends in spring, while dimming over Europe due to anthropogenic aerosols from the 1950s to the 1980s and then brightening (Wild, 2012), which is basically our period of interest in this section, could result in decadal fluctuations in evapotranspiration that would be somewhat in phase with SLPI and the AMV. The results described in this section should therefore be taken with great caution. Longer hydrological simulations on the entire 20th century would help to reach stronger conclusions. It would allow to better separate multi-decadal variations from anthropogenic trends and not to only rely on a short period potentially affected by external forcing at decadal time-scales.

## 6 Conclusions

Multi-decadal variability in river flows over France on the historical period has been investigated. Strong multi-decadal variations in observed river flows have been noted. Those variations are generally clearly more important in spring, and have been shown to be associated with multi-decadal variations in precipitation themselves driven by large-scale circulation. Those multi-decadal variations in large scale circulation can likely be interpreted as an atmospheric response to the SST anomalies associated with the AMV.

Considering those results in the context of current literature, it is somewhat surprising that such strong multi-decadal hydroclimatic variations over France, and especially regarding river flows, have received little attention so far. The amplitude of multi-decadal variations is very season-dependent, and often much larger in spring, especially for precipitation and temperature. Studies have often focused preferentially on winter and summer, with a major exception being Sutton and Dong (2012) who already described such multi-decadal variations in precipitation and temperature over France during spring and discussed their link with the AMV. Regarding rivers flows over France, such large and widespread multi-decadal variations have not been described before to the best of our knowledge. The links at the inter-annual time scale between what is called in those studies the AMO (but what is probably best called the North Atlantic SST (NASST) index as those studies don't deal with multi-decadal variations) and river flows in France have been studied by Oubeidillah et al. (2012) and Giuntoli et al. (2013). Oubeidillah et al. (2012) report no significant relationships between NASST and river flows in the Adour-Garonne basin, except for few gauging stations. Giuntoli et al. (2013) show significant relationships between hydrological drought severity at some gauging stations and the NASST index over France, but with a distinct north-south pattern (positive correlation in the north, negative in the south). Those results are however not contradictory with the results presented here, that suggest a major contribution of the AMV in the multi-decadal variations of French river flows, because these studies deal with interannual variability rather than multi-decadal variability, on a shorter period, and do not focus on the same seasons and/or aspect of river flows.

Although less important and less widespread than in spring, noticeable multi-decadal variations have also been noted in summer and winter for many stations. It has been suggested that the summer variations could be associated with climate variations in spring through soil moisture memory: smaller precipitation and larger evapotranspiration in spring would result in drier soils in summer which would then lead to smaller river flows in summer. Those results are however based on an hydrological simulation, short in the context of multi-decadal variability, and are therefore subject to caution. Note also that locally, a modulation of snowmelt and/or of the solid to liquid precipitation ratio by the AMV could potentially exist and impact flows of nival rivers. Although such processes are taken into account in the hydrological modeling, this mechanism has not been investigated in our study.

Because soils tend to be well moistured (above field capacity) in winter in any case, a comparable bridge from spring climate to the next winter through soil moisture memory is highly unlikely. Deep aquifers could play a similar role with potential longer memory but it remains very hypothetical and, anyway, it is not a good explanation for many





stations in this study as the impact of deep aquifers on flows is very small for many stations investigated here. The variations noted in winter therefore remain to be explained.

Some important caveats apply to our study. River flows data used are not homogenized and we choose to use all available stations with long series to have the largest possible data-set, even if some of them are known to be influenced by direct anthropogenic effects, as those influences do not necessarily affect their decadal variations. The large-scale and very consistent signal that appears over France, especially in spring, suggests that those multi-decadal river flows variations are generally robust. If direct anthropogenic influences or measurement artifacts can locally artificially generate low-frequency variations in river flows, it is indeed highly unlikely for those artificial influences to be in phase over entire France. Moreover, it has been shown that multi-decadal variations in spring river flows are strongly associated with multi-decadal variations in precipitation (and temperature). High confidence can be attached to the existence of such multi-decadal variations in precipitation. They are very consistently seen in homogenized and unhomogenized precipitation data, and independently in precipitation from the 20CR reanalysis that does not assimilate precipitation observations. The consistency between simulated and observed river flows during the period for which the hydrological simulation exists is also an element that gives confidence in the reality of the variations seen in river flows on this period, as direct anthropogenic effects are not included in the model.

Long hydrological simulations on the whole 20th and early 21st centuries would be really useful for the same reason. Such simulations would also help to better characterize the multi-decadal variations in other components of the continental hydrological cycle (soil moisture, evapotranspiration) and would be very useful to better understand the mechanisms at the origin of the decadal variations, especially in summer and winter. Efforts to reconstruct the meteorological forcing on a long period to do such hydrological simulation are necessary in that context.

The existence of large multi-decadal variations in river flows has to be kept in mind when interpreting the results of trend analyses. In order to maintain a correct spatial sampling, trend analyses often have to rely on relatively short time periods. Strong multi-decadal variations can seriously impact such short-term trends as noted by Hannaford et al. (2013) and Giuntoli et al. (2013), and one has therefore to remain careful when trying to attribute short-term trends.

From a more applied perspective, it is clear that large multi-decadal variations in river flows may also have some practical implications, for example regarding hydropower production.

To fully grasp the importance of those multi-decadal variations in river flows, it is interesting to put them into the climate change context. Boé et al. (2009) and Chauveau et al. (2013) give an estimate of the multi-model climate change signal projected in French river flows from an ensemble of CMIP3 models. At the middle of the 21st century (2046–2065 average), the ensemble mean change (which is generally seen as the "best estimate" of the climate change signal) over France is generally of the order of −15 to −30 % in spring, and −25 to −35 % for yearly average. Figure 4 in this study therefore suggests that decadal differences might be as large or even greater than the climate change signal in the middle of the 21st century in spring, and often not far from what is simulated at the annual level in the climate change context. If one supposes that historical multi-decadal variations have mainly an internal origin, internal low-frequency variability is therefore expected to be a very important actor in shaping the future evolution of river flows in France during the coming decades. It could potentially temporarily reverse the long-term effect of global warming or strongly enhance the climate change signal, depending of its phasing. Note that as said in the introduction, a debate currently exists about the nature of the AMV. If the AMV is not mainly a natural mode of variability there is no reason to expect it to continue in the future climate in the absence of adequate external forcing. The mainstream view is still that the AMV is largely an internal mode of variability.

If decadal variations are mostly internal, they have to be taken into account in climate change projections and in adaptation policies to climate change as potential uncertainties. As one cannot simply suppose that those variations will have the same amplitudes



in the perturbed climate as on the historical period (the amplitude of low-frequency variations is not necessarily independent of the mean climate state, and additionally, 150 yr at most is a very short period to estimate robustly the amplitude of multi-decadal variations) one has to rely on multiple members of climate projections to estimate those uncertainties. Whether climate models are able or not to capture realistically the magnitude of low-frequency variations in the continental hydroclimate (or in the climate variables necessary to statistically or dynamically downscale climate models to force hydrological models) remains to be demonstrated and will be the object of future work.

Finally, because the multi-decadal variations in French river flows are likely due to internal climate variability, and especially since they are related to the AMV, one could hope to try to predict those variations thanks to decadal climate predictions (Goddard et al., 2013). However, the skill of current decadal predictions regarding continental variables such as precipitation and temperature is generally limited even for small lead times, but more work is needed to better characterize the potential decadal predictability for river flows.

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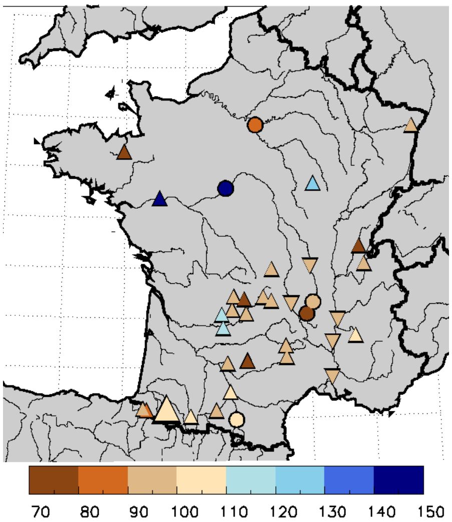


**Fig. 1.** Location of the gauging stations whose data are analyzed in this study. The length of the record in years is given by the color-scale. The symbol gives an indication on the potential direct human influence on the hydrological regime for each station. Upward triangle: no or little influence (74 % of stations); circle: strong influence (13 % of stations); downward triangle: strong influence on low-flows (13 % of stations). The large triangle in southwestern France corresponds to the Gave d'Ossau at Oloron-Sainte-Marie (see Fig. 2.)



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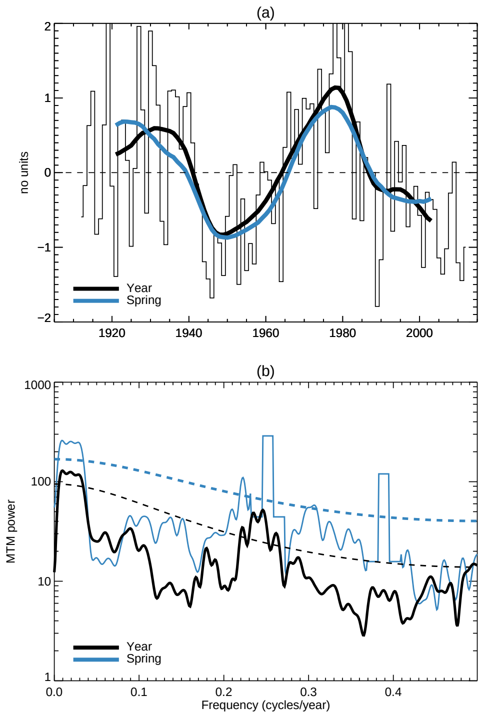


**Fig. 2. (a)** Standardized river flows of the Gave d'Ossau at Oloron-Sainte-Marie (Oloron-Ste-Croix). Bars: annual means. Thick lines: low-pass filtered spring and annual series. **(b)** Multi-taper method (MTM) spectrum (Mann and Lees, 1996; Ghil et al., 2002) of spring and annual river flows of the Gave d'Ossau (thick line) and associated 0.05 significance level relative to the estimated noise background (dashed line). The Gave d'Ossau at Oloron-Sainte-Marie is shown in Fig. 1 with a larger triangle.

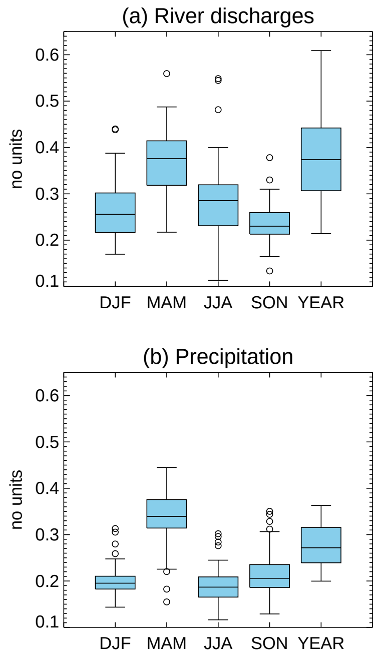


**Fig. 3.** Boxplots of the ratio of the standard deviation of low-pass filtered seasonal and annual river flow series to the standard deviation of the corresponding unfiltered series at the different stations. The series have been linearly de-trended prior to the analyses (the linear trend is computed on the longest possible period for each station). **(a)** River flows, **(b)** precipitation. On the boxplots, the 25th and 75th centile, and the median of the data are shown by the lines. The whiskers are defined by the minimum and maximum values in the sample, or by 1.5 times either the 25th and 75th centile. In that case, values greater than 1.5 times the 25th or 75th centile are shown with a circle.



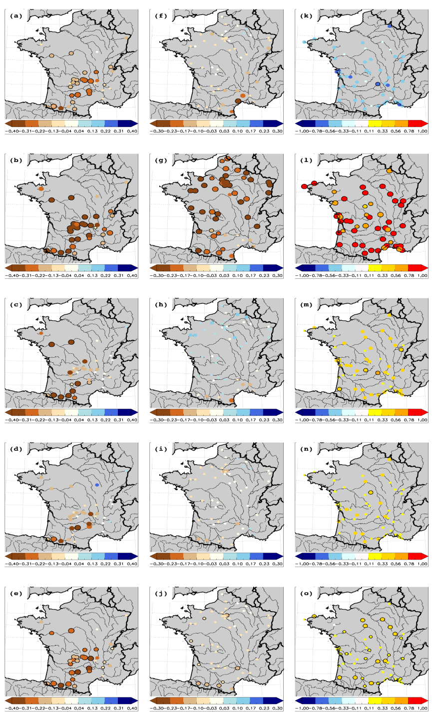

**Fig. 4.** Relative differences in de-trended river flows between the 1938–1958 and 1965–1985 periods. The reference is the 1938–1985 average. **(a)** winter, **(b)** spring, **(c)** summer, **(d)** autumn, **(e)** year. **(f–j)** Same as **(a–e)** but for de-trended precipitation. **(k–o)** Differences in de-trended temperature between the 1938–1958 and 1965–1985 periods. Black circles show where the differences are significant with $p < 0.1$.




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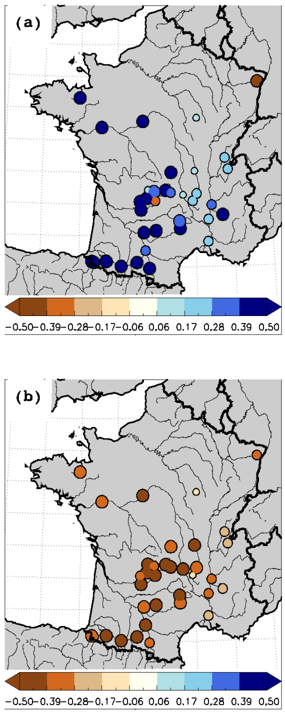


**Fig. 5.** Relative changes between the 1938–1958 and 1965–1985 periods in the percentage of days in a year with river flows **(a)** lower than the 20th percentile and **(b)** greater than the 80th percentile. The percentiles are computed on the total period available for each station. The reference to compute the relative changes is 20 %.





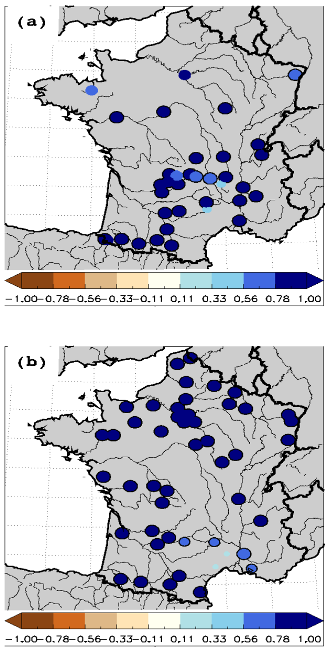


**Fig. 6. (a)** Correlation between low-pass filtered spring precipitation averaged over France (GPCC data) and low-pass filtered spring river flows at the different gauging stations. The correlation is computed on the longest possible period for each gauging station. **(b)** Correlation between low-pass filtered spring precipitation averaged over France (GPCC data) and low-pass filtered spring precipitation at different locations (HPS data), 1910–1991 period. The use of different data-sets for local precipitation and France average is intended to highlight the consistency of precipitation data-sets. Linear trends have been removed from the series prior to the analyses. Black circles show where the correlations are significant with $p < 0.1$.



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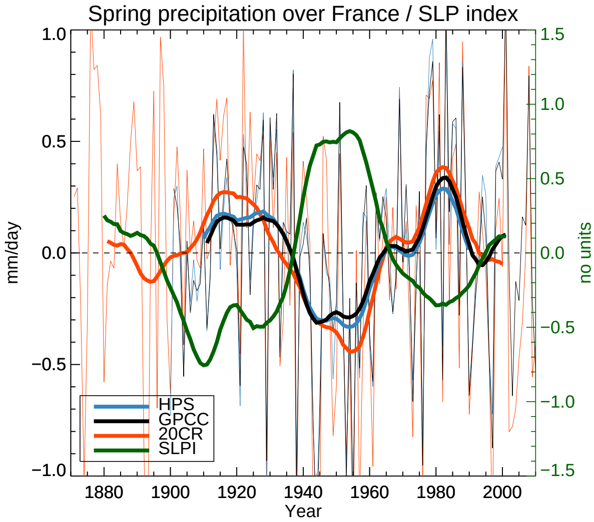


**Fig. 7.** Average spring precipitation over France from three data-sets (HPS, GPCC, 20CR) and standardized SLP index. The SLP index (SLPI) is defined as the difference of averaged SLP on the region 35–60° N, 12–25° E and averaged SLP on the region 20–45° N, 40–12° W. The series have been linearly de-trended and low-pass filtered. The correlations between low-pass filtered precipitation series (HPS, GPCC, 20CR) and SLPI on the respective maximum overlapping periods are: −0.94 ($p < 0.01$), −0.89 ($p < 0.01$), −0.86 ($p < 0.05$). The correlations between low-pass filtered precipitation series from the three data-sets on the common 1910–1991 period are: 0.99 (HPS/GPCC), 0.97 (HPS/20CR) and 0.96 (GPCC/20CR).



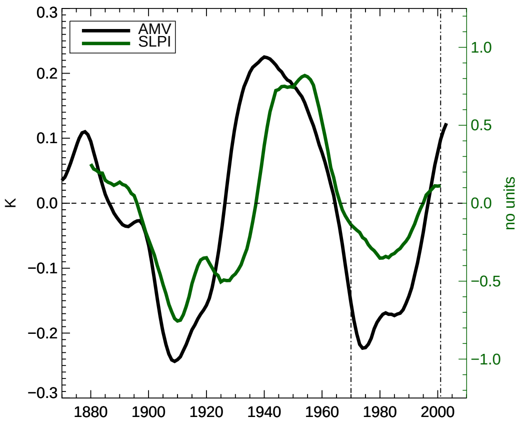


**Fig. 8.** Low-pass filtered standardized SLPI and AMV index. The vertical lines delimit the period used for analyses described in Sect. 5.




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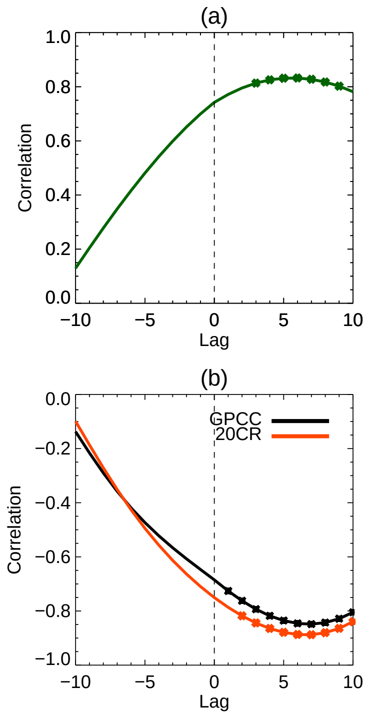


**Fig. 9.** Lag-correlations between the AMV index and low-pass filtered **(a)** SLPI in spring, **(b)** averaged precipitation over France in spring (from GPCC and, to have a longer period, from 20CR) for different lags in years. Positive lags mean that the AMV leads. Crosses show where the correlations are significant with $p < 0.1$.





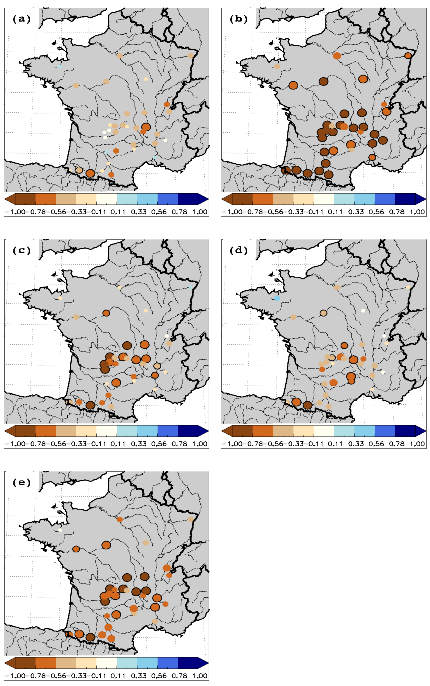


**Fig. 10.** Correlation between low-pass filtered SLPI in spring and low-pass filtered river flows at different gauging stations: **(a)** winter, **(b)** spring, **(c)** summer, **(d)** automn, **(e)** year. The series have been linearly de-trended prior to the analyses. Note that the correlations are computed on the longest possible period for each gauging stations (and therefore not on the exact same period everywhere). Black circles show where the correlations are significant with $p < 0.1$.



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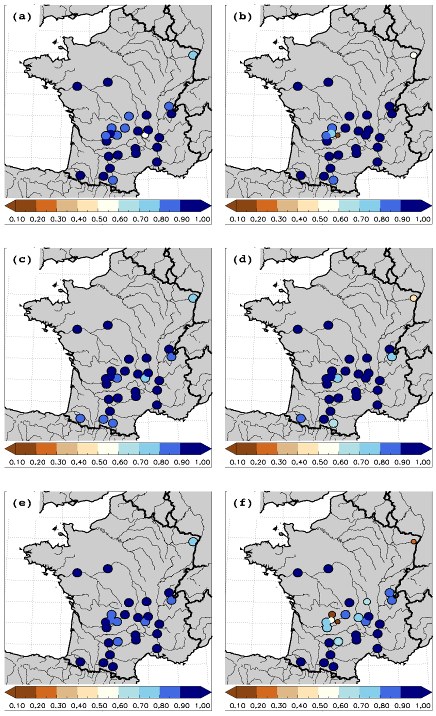


**Fig. 11.** Correlation between simulated and observed river flows, 1961–2012: **(a)** annual means, **(c)** spring, **(e)** summer. Correlation between low-pass filtered simulated and observed river flows, 1970–2003: **(b)** annual means, **(d)** spring, **(f)** summer.



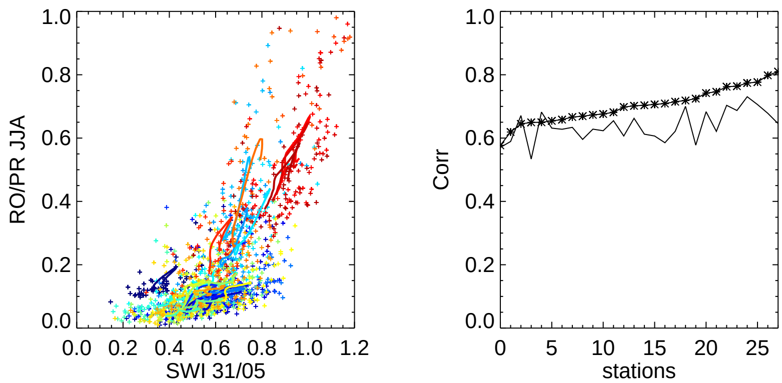


**Fig. 12. (a)** Runoff to precipitation ratio in JJA as a function of the SWI at the end of spring. Each color corresponds to a simulated station of Fig. 11. The points are interannual values while the lines correspond to low-pass filtered data. **(b)** Spearman rank correlation between runoff to precipitation ratio in JJA and the SWI at the end of spring at the interannual level. The stars show the values for raw data and the line the values for detrended data. Stations have been ranked according to the correlation for raw data.

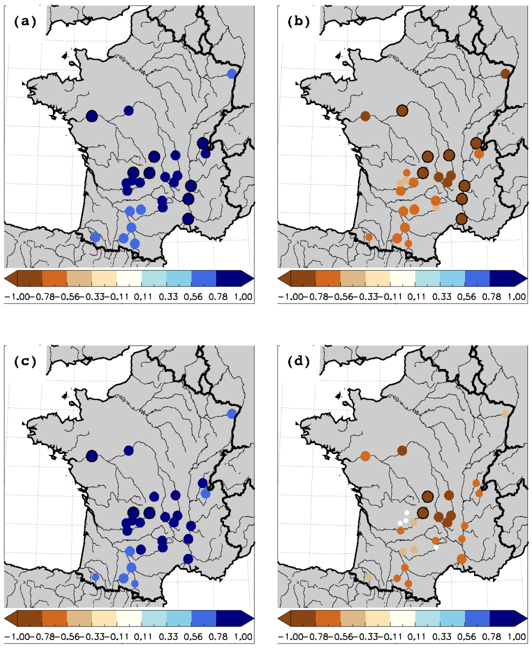


**Fig. 13.** Correlation between low-pass filtered and de-trended SLPI (the linear trend is computed on the 1871–2010 period) and low-pass filtered simulated **(a)** evapotranspiration in spring, **(b)** soil wetness index at the end of spring (31 May). **(c)** and **(d)** same as **(a)** and **(b)** except that evapotranspiration in spring and soil wetness index at the end of spring (31 May) have been de-trended before computing the correlations. Black circles show where the correlations are significant with $p < 0.1$.





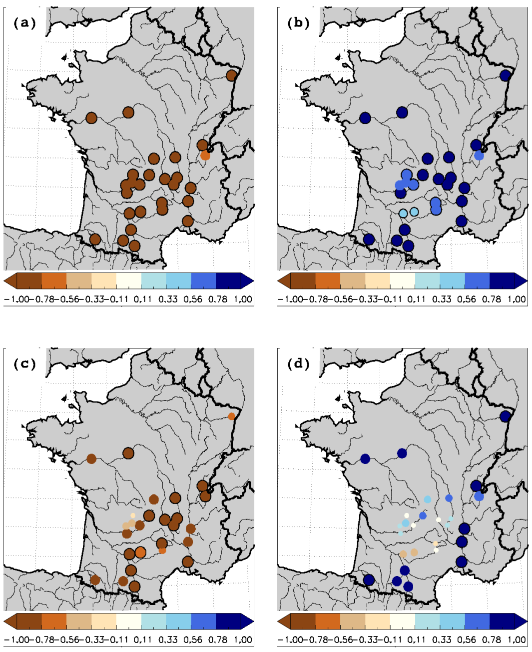


**Fig. 14. (a)** Correlation between low-pass filtered simulated evapotranspiration in spring and soil wetness index at the end of spring (31 May). **(b)** Correlation between low-pass filtered soil wetness index at the end of spring (31 May) and low-pass filtered simulated summer river flows. **(c)** and **(d)** same as **(a)** and **(b)** respectively except that all the variables have been de-trended before computing the correlations. Black circles show where the correlations are significant with $p < 0.1$.