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Research papers

Multi-time-scale hydroclimate dynamics of a regional watershed and links to large-scale atmospheric circulation: Application to the Seine river catchment, France

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ABSTRACT

In the present context of global changes, considerable efforts have been deployed by the hydrological scientific community to improve our understanding of the impacts of climate fluctuations on water resources. Both observational and modeling studies have been extensively employed to characterize hydrological changes and trends, assess the impact of climate variability or provide future scenarios of water resources. In the aim of a better understanding of hydrological changes, it is of crucial importance to determine how and to what extent trends and long-term oscillations detectable in hydrological variables are linked to global climate oscillations.

In this work, we develop an approach associating correlation between large and local scales, empirical statistical downscaling and wavelet multiresolution decomposition of monthly precipitation and streamflow over the Seine river watershed, and the North Atlantic sea level pressure (SLP) in order to gain additional insights on the atmospheric patterns associated with the regional hydrology. We hypothesized that: (i) atmospheric patterns may change according to the different temporal wavelengths defining the variability of the signals; and (ii) definition of those hydrological/circulation relationships for each temporal wavelength may improve the determination of large-scale predictors of local variations.

The results showed that the links between large and local scales were not necessarily constant according to time-scale (i.e. for the different frequencies characterizing the signals), resulting in changing spatial patterns across scales. This was then taken into account by developing an empirical statistical downscaling (ESD) modeling approach, which integrated discrete wavelet multiresolution analysis for reconstructing monthly regional hydrometeorological processes (predictand: precipitation and streamflow on the Seine river catchment) based on a large-scale predictor (SLP over the Euro-Atlantic sector). This approach basically consisted in three steps: 1 – decomposing large-scale climate and hydrological signals (SLP field, precipitation or streamflow) using discrete wavelet multiresolution analysis, 2 – generating a statistical downscaling model per time-scale, 3 – summing up all scale-dependent models in order to obtain a final reconstruction of the predictand. The results obtained revealed a significant improvement of the reconstructions for both precipitation and streamflow when using the multiresolution ESD model instead of basic ESD. In particular, the multiresolution ESD model handled very well the significant changes in variance through time observed in either precipitation or streamflow. For instance, the post-1980 period, which had been characterized by particularly high amplitudes in interannual-to-interdecadal variability associated with alternating flood and extremely low-flow/drought periods (e.g., winter/spring 2001, summer 2003), could not be reconstructed without integrating wavelet multiresolution analysis into the model. In accordance with previous studies, the wavelet components detected in SLP, precipitation and streamflow on interannual to interdecadal time-scales could be interpreted in terms of influence of the Gulf-Stream oceanic front on atmospheric circulation.

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1. Introduction

In the present context of global change, considerable efforts have been deployed by the hydrological scientific community to improve our understanding of the impacts of climate fluctuations on water resources (Cloke and Hannah, 2011). Both observational and modeling studies have been employed extensively to characterize hydrological changes, variability and trends (Hannah et al., 2011; Wilson et al., 2013), which appears of primary importance when the question arises of disentangling "natural" and "human-induced" long-term hydrological variations and trends. For instance, streamflow records for the world's major rivers show large decadal to multidecadal fluctuations, with small secular trends for most rivers (Cluis and Laberge, 2001; Lammers et al., 2001; Mauget, 2003; Pekárová et al., 2003; Labat et al., 2004; Giuntoli et al., 2013), which are important to be considered in developing new future scenarios of water resources (e.g. Prudhomme et al., 2014). In addition to identifying and characterizing short- to long-term hydrological variations, improving the understanding of processes driving such changes is of crucial importance in order to determine, in particular, to what extent trends and long-term oscillations in hydrological variables are linked to large-scale climate variability. As mentioned in Laizé et al. (2014), this is vital to improve the skills of hydrological predictions, and prediction of the water cycle.

In Europe, several studies have focused on the investigation of trends and low-frequency variability in hydrological variables (Stahl et al., 2010; Gudmundsson et al., 2011; Kingston et al., 2011). Precipitation over northern Europe experienced upward trends ranging between 6 and 8% from 1900 to 2005 (Trenberth et al., 2007), and these trends are expected to persist over the 21st century (Christensen and Lettenmaier, 2007). Investigating low-frequency variability in streamflow at the pan-European scale, Gudmundsson et al. (2011) showed the existence of long-term oscillations originating from large-scale climate variations, the amplitude of which depended strongly on local watershed physical characteristics. Potential relationships of such low-frequency variability in European streamflow and large scale climate variations have been explored using climate indices, such as the North-Atlantic Oscillation (NAO) (Kiely, 1999; Massei et al., 2007, 2010; Mares et al., 2002; Trigo et al., 2004; Angulo-Martínez and Beguería, 2012; Kingston et al., 2006; Giuntoli et al., 2013; Fritier et al., 2012; Dieppois et al. 2013, 2016). The NAO is considered as a particularly relevant climate indicator over the North Atlantic-Europe sector because changes in NAO phases produce large changes in the mean wind speed and directions, redistributing heat and moisture fluxes from the Atlantic to Europe (Hurrell, 1995; Cassou et al., 2004; Hurrell and Deser, 2009). However, the links between NAO regimes (positive and negative NAO) and European hydroclimate are complex, as it is not constant over time and show seasonal as well as long-term temporal non-stationarity related to the position of NAO poles (Slonosky and Yiou, 2002; Raible et al., 2006; Fritier et al., 2012; Lehner et al., 2012; Dieppois et al., 2016). This is consistent with the conclusions drawn by some authors who pointed out that those circulation indices would likely constitute poor large-scale predictors of local hydrological variations as they do not necessarily capture the most consistent atmospheric pattern linked to observed hydrological variation (e.g., Lavers et al., 2010a; Lavers et al., 2010b). In France, Giuntoli et al. (2013) pointed out the difficulty to use climate indices (NAO, AMO/Atlantic Multidecadal Oscillation) as hydrological predictors. They nevertheless highlight better skills in predicting low-flow using weather patterns than using climate indices such as NAO or AMO. Yet, by studying the links between hydrological variations (precipitation and streamflow) on the Seine river watershed and the NAO index using spectral and multiresolution time series analyses, Massei et al. (2010) and Massei and Fournier (2012) demonstrated significant correlation at some interannual and interdecadal time scales, and thus highlighted potential skills for hydrological predictions. Boé and Habets (2014) and Dieppois et al. (2016) highlighted the critical role of multidecadal climate variability on hydrological variations over France. Such multidecadal fluctuations in hydrological variations are indeed likely to strongly modulate trend, as it has been the case from the mid-19th century in winter and spring (Dieppois et al., 2016). This also holds for the coming decades, as at the regional and local scales, internal climate variability is likely to be as important as anthropogenic climate changes in the middle and high latitudes (Deser et al., 2012, 2014). Therefore, to improve our prediction skills of hydrological variations, it appears of particular interest to determine the way hydrological and climatic signals oscillate together at different time-scales, and to develop new statistical downscaling strategies accounting for those low-frequency ($\geqslant$2 year up to multidecadal) time-scales of variability.

To address the above research gaps, this study builds on some previous work, which investigated high- to low-frequency oscillations in northern France/central England precipitation and streamflow (Fritier et al., 2012; Massei et al., 2010; Massei and Fournier, 2012; Dieppois et al., 2013; Dieppois et al., 2016). Here, we tested the potential value-added of combining discrete wavelet multiresolution decomposition and statistical downscaling for studying, understanding and predicting the links between precipitation or streamflow over the Seine river watershed with atmospheric circulation patterns using sea level pressure (SLP) in the Euro-Atlantic sector. We aimed at gaining new insights into the atmospheric patterns driving regional hydrology. In particular, the following hypotheses were tested: (1) do atmospheric patterns related to local hydrology remain unchanged whatever the different characteristic frequencies over which atmospheric and hydrological signals oscillate? (2) would accounting for time-scale-dependent characteristics of the large-scale circulation/local-scale hydrological variation relationships help improving the results of empirical statistical downscaling models of local or regional hydrology?

2. Data and methods

2.1. Hydro-climatological data

The Seine is one of the main French rivers (Fig. 1), with precipitation regime in the area is typically of pluvio-oceanic type. Its catchment area is $\sim$78,000 km^2 and comprises almost one third of the French population. With large regions devoted to agriculture and many large urban zones including Paris, it is heavily impacted by human activities. As a result such catchments are not classically considered as the most appropriate for investigating the linkages between hydrological and large-scale climate variability (Hannah et al., 2011). However, improving our understanding of such links for such basins appears crucial precisely because a huge amount of the population of the country depends on its water resources. As in many rivers in northern France, the Seine is sustained by major groundwater aquifers. In the case of the Seine River, these aquifers develop within the wide Paris basin syncline, which comprises several hydrogeological units, either confined or unconfined.

The Climatic Research Unit (CRU) data-set was used to estimate precipitation data. The CRU TS 3.21 rainfall field was produced on a 0.5° × 0.5° grid and derived from monthly rainfall provided by about 4000 weather stations distributed around the world over the last centuries (http://catalogue.ceda.ac.uk/uuid/3f8944800c-c48e1cbc29a5ee12d8542d for more explanations for this dataset).