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Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios

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Abstract. Drought events develop in both space and time and they are therefore best described through summary joint spatio-temporal characteristics, such as mean duration, mean affected area and total magnitude. This paper addresses the issue of future projections of such characteristics of drought events over France through three main research questions: (1) Are downscaled climate projections able to simulate spatio-temporal characteristics of meteorological and agricultural droughts in France over a present-day period? (2) How such characteristics will evolve over the 21st century? (3) How to use standardized drought indices to represent theoretical adaptation scenarios? These questions are addressed using the Isba land surface model, downscaled climate projections from the ARPEGE General Circulation Model under three emissions scenarios, as well as results from a previously performed 50-yr multilevel and multiscale drought reanalysis over France. Spatio-temporal characteristics of meteorological and agricultural drought events are computed using the Standardized Precipitation Index and the Standardized Soil Wetness Index, respectively, and for time scales of 3 and 12 months. Results first show that the distributions of joint spatio-temporal characteristics of observed events are well simulated by the downscaled hydroclimate projections over a present-day period. All spatio-temporal characteristics of drought events are then found to dramatically increase over the 21st century, with stronger changes for agricultural droughts. Two theoretical adaptation scenarios are eventually built based on hypotheses of adaptation to evolving climate and hydrological normals, either retrospective or prospective. The perceived spatio-temporal characteristics of drought events derived from these theoretical adaptation scenarios show much reduced changes, but they call for more realistic scenarios at both the catchment and national scale in order to accurately assess the combined effect of local-scale adaptation and global-scale mitigation.

1 Introduction

Global climate projections for Europe under the A1B greenhouse gases emissions scenario (Nakićenović et al., 2000) suggest a drying of the southern part of the continent, with a large decrease in both precipitation and soil moisture between the end of the 20th century and the end of the 21st century (Meehl et al., 2007b; Dai, 2011a). When looking at the sub-continental scale and more specifically at France, it appears that while the decrease in summer precipitation is shared by the majority of general circulation models (GCMs), there is a large uncertainty in the evolution of winter precipitation over this country (Christensen et al., 2007b). However, Wang (2005) found that a majority of GCMs predict a soil moisture decrease over the major part of France under the A1B emissions scenario all year round, but more pronounced in summer. Burke et al. (2006) found a decrease in the Palmer Drought Severity Index (PDSI, Palmer, 1965) for most of Europe, including France, from simulations with the Hadley Centre GCM under the A2 emissions scenario. Sheffield and Wood (2008) also found a significant increase

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in the frequency of long-term soil moisture deficits over this area based on a multi-model and multi-scenario analysis. Using two multimodel ensembles, Burke and Brown (2008) showed that Southern Europe (including France) should be subject to an increase in moderate drought as a result of a doubling in CO_2 concentrations.

Regional climate projections performed over Europe confirmed this future drying trend over France. Based on results from the PRUDENCE project (Christensen et al., 2007a), Beniston et al. (2007) found an increase in the annual maximum length of dry spells for the French Mediterranean area for the 2080s under the A2 emissions scenario, and Blenkinsop and Fowler (2007) found an increase in the frequency of long droughts (defined as negative 6-month cumulative precipitation anomalies) over most of Western Europe. Using multi-model regional projections under the A1B scenario from the more recent ENSEMBLES project (van der Linden and Mitchell, 2009), Heinrich and Gobiet (2012) found a significant decrease, between 1961–1990 and 2021–2050, in the 3-month Standardized Precipitation Index (SPI3, McKee et al., 1993) in summer over a region covering most of France. They also found a similarly significant decrease for both self-calibrated versions of the Palmer Z-Index and Palmer Drought Severity Index (Palmer, 1965; Wells and Goddard, 2004) for all seasons except winter. The length, magnitude and area of drought events identified with Palmer indices are all projected to increase, together with the frequency of SPI3 and SPI12 events, still according to Heinrich and Gobiet (2012).

At the scale of France, results from the IMFREX project (IMFREX, 2005; Planton et al., 2008) showed a 50 % increase in the maximum number of consecutive dry days in summer between the end of the 20th century and the end of the 21st century, and for the most part of the country as simulated by two regional climate models under the A2 emissions scenario. All the above mentioned studies strongly suggest a decrease in water resource availability over France, but they lack some detailed information that would help define adaptation strategies for France, in terms of spatial and temporal resolution.

The CLIMSEC[1] project (Soubeyroux et al., 2011) looked at the evolution of spatio-temporal characteristics of drought events in France by (1) forcing a high-resolution land-surface scheme and a hydrogeological model with various downscaled climate projections over France and (2) computing standardized drought indices based on precipitation, soil moisture and river flows (see Vidal et al., 2010b). Joint spatio-temporal characteristics are particularly useful when trying to understand the development of drought events and such analyses are being performed more often, mainly for the assessment of past events (Andreadis et al., 2005; Sheffield et al., 2009; Vidal et al., 2010b; van Huijgevoort et al., 2011; Corzo Perez et al., 2011). Moreover, standardized drought indices like the SPI proved particularly adapted to joint spatial and temporal analyses (Lloyd-Hughes, 2012).

This paper presents some results from the CLIMSEC project and addresses three research questions:

1. Are downscaled climate projections able to simulate spatio-temporal characteristics of meteorological and agricultural droughts in France over a present-day period?

2. How such characteristics will evolve over the 21st century?

3. How to use standardized drought indices to represent theoretical adaptation scenarios?

The first question is addressed by considering the spatio-temporal characteristics of drought events from a previously performed reanalysis over a 50-yr period as a reference for past droughts in France (Vidal et al., 2010b). This drought reanalysis has been performed at different levels of the hydrological cycle (precipitation and soil moisture, considered here, but also river flows) and at different time scales (only 3 and 12 months are considered here) with standardized indices similar to the SPI. It has been built thanks to the Safran high-resolution atmospheric reanalysis (Vidal et al., 2010a) which was used to force the Isba Land Surface Model (LSM) (Noilhan and Mahfouf, 1996). The drought reanalysis is compared here to a corresponding drought analysis derived from a present-day control run of the ARPEGE GCM (Gibelin and Déqué, 2003), downscaled with a weather-type method (Boé et al., 2006), and used to force the Isba LSM.

The second question about the evolution of spatio-temporal drought characteristics is studied through downscaled 21st century transient runs of the same ARPEGE GCM under 3 different emissions scenarios, which were also used to force the Isba land surface scheme. The evolution of standardized indices allowed us to derive spatio-temporal characteristics of drought events during the whole 21st century.

In order to address the third question, theoretical adaptation scenarios were constructed from GCM-derived time series of standardized indices. The effect of these adaptation scenarios on spatio-temporal drought characteristics can thus be assessed and compared to the choice of the emissions scenarios.

Section 2 presents the Safran atmospheric reanalysis over France, the downscaled climate projections and the Isba LSM. Section 3 describes the methods used for identifying and characterizing spatio-temporal drought events, and introduces the theoretical adaptation scenarios developed for this study. GCM-based drought characteristics are validated against characteristics from the reanalysis over the present-day period in Sect. 4, and their evolution throughout the 21st century is described in Sect. 5, as conditioned by both emissions scenarios and theoretical adaptation scenarios. Results are finally discussed in Sect. 6.

[1] http://www.cnrm-game.fr/projet/climsec

Table 1. Difference in mean annual temperature (in °C) averaged over France of two future time slices under three emissions scenarios with respect to the 1961–1990 control run (adapted from Pagé et al., 2008).

	B1	A1B	A2
2046–2065	+1.3	+2.1	+2.2
2081–2100	+1.8	+2.7	+3.6

2 Data

2.1 The Safran atmospheric reanalysis

Safran is an atmospheric analysis system that computes vertical profiles of the atmosphere for climatically homogeneous zones, by combining large-scale fields and ground observations through Optimal Interpolation. The algorithm, its validation and its application over France are detailed by Quintana-Seguí et al. (2008). Safran hourly outputs of liquid and solid precipitation, air temperature, specific humidity, wind speed, visible and infrared radiations are interpolated from 605 climatically homogenous zones over France onto a 8-km regular grid (8602 cells) to provide atmospheric forcings for land surface schemes. Vidal et al. (2010a) have applied and thoroughly validated Safran over the period 1958–2008. In particular, reanalysed precipitation has been found of high quality over the whole period compared to both dependent and independent observations. This 50-yr high-resolution atmospheric reanalysis over France is thus used in the present study as a reference for present-day precipitation data.

2.2 Downscaled climate projections

21st century simulations from the Météo-France ARPEGE GCM are used in the present study. This variable resolution atmospheric model, fully described by Gibelin and Déqué (2003), has a stretched grid with a pole over the Western Mediterranean with a 50 km resolution over France. This particular version (V4.6) has been recently used in the ENSEMBLES project (van der Linden and Mitchell, 2009). Four simulations are considered in this study: (1) a control run over the 1958–2000 period, and (2) three 21st-century simulations starting on the first of January 2000 and forced by three different greenhouse gas emissions scenarios. Sea surface temperature forcings are taken from the CNRM-CM3 coupled model (Salas-Mélia et al., 2005) used in the Coupled Model Intercomparison Project phase 3 (CMIP3, Meehl et al., 2007a). Radiative forcings (greenhouse gases and sulfate aerosol concentrations) are based on observations till 2000, then on one of the three emissions scenarios (B1, A1B and A2) taken from the Special Report on Emissions Scenarios (SRES, Nakićenović et al., 2000).

Table 2. The same as Table 1, but for mean annual precipitation (in mm). 1961–1990 values are close to 910 mm in the reanalysis dataset.

	B1	A1B	A2
2046–2065	−70	−90	−130
2081–2100	−130	−210	−230

The ARPEGE simulations have been further statistically downscaled with a weather type method initially developed by Boé et al. (2006) for the Seine basin and later extended to the whole of France (Boé, 2007; Boé et al., 2009). This downscaling method has been compared to other statistical and dynamical methods in terms of hydrological impacts over the Seine basin (Boé et al., 2007) as well as over French Mediterranean basins (Quintana-Seguí et al., 2010, 2011). Outputs from the statistical downscaling method are gridded data with the same spatial and temporal resolution as the Safran reanalysis, and for the same variables.

Pagé et al. (2008) give an overall assessment of climate changes derived from the statistically downscaled projections used here, and France-averaged annual changes in temperature and precipitation for the middle and end of the 21st century are recalled, respectively in Tables 1 and 2. Table 1 shows a growing increase in temperature throughout the 21st century, more pronounced for higher-range emissions scenarios. Seasonal variations also indicate a larger warming in summer for the more distant time slice (see Pagé et al., 2008). Similarly, Table 2 shows a drying trend through the 21st century, once again more pronounced for higher-range emissions scenarios. These statistically downscaled climate projections from ARPEGE V4.6 are currently being disseminated to the French impact community through the DRIAS project (Lémond et al., 2011).

Outputs considered here for drought assessment are monthly gridded total precipitation for the control run and each of the 3 climate projections.

2.3 The Isba land surface model

The land surface scheme Isba computes water and energy budgets at the soil-vegetation-atmosphere interface (Noilhan and Mahfouf, 1996). This scheme is used in Météo-France numerical weather prediction and climate models. The configuration of this highly modular scheme is the same as the one used by Habets et al. (2008) and Vidal et al. (2010b) for long-term simulations over France, with a 8-km resolution of soil and vegetation parameters. Isba is based on a three-layer force-restore model and explicit multilayer snow model and it includes subgrid runoff and drainage schemes. Soil and vegetation parameters are derived from the Ecoclimap database (Masson et al., 2003). Safran, Isba and the Modcou hydrogeological model constitute a hydrometeorological suite that is used for drought and low-flow analysis, in reanalysis context or medium-range and seasonal forecasting (Soubeyroux et al., 2010). The Isba output relevant for the present study is the Soil Wetness Index (SWI) defined as

$$\mathrm{SWI} = \frac{w_{\mathrm{tot}} - w_{\mathrm{wilt}}}{w_{\mathrm{fc}} - w_{\mathrm{wilt}}} \quad (1)$$

where w_{tot} is the volumetric water content of the simulated soil column, w_{fc} the water content at field capacity and w_{wilt} the water content at wilting point. Soil moisture products from Isba have been extensively validated against in-situ measurements (Habets et al., 1999; Paris Anguela et al., 2008; Albergel et al., 2008) as well as various satellite products (Baghdadi et al., 2007; Rüdiger et al., 2009).

Isba had been previously run with forcings from the 1958–2008 Safran reanalysis in order to derive a 50-yr SWI reference dataset over the Safran 8-km grid (see Vidal et al., 2010b). In this study, Isba has also been run over France with forcings from each downscaled climate projection. Snowpack, soil temperature and soil moisture values have been initialised using a 2-yr spin-up (first year repeated three times).

Outputs used here are monthly gridded SWI values for the control run and each of the 3 climate projections.

3 Methods

3.1 Drought characterisation

3.1.1 Drought indices

A large number of drought indices have been developed over the last decades (see Mishra and Singh, 2010, for a recent review) in order to characterize one of the three main drought types (meteorological, agricultural and hydrological) as defined by Wilhite and Glantz (1985). However, only some of them have been used in a climate change context. The main meteorological drought index used in climate change impact studies is the Standardized Precipitation Index (SPI, McKee et al., 1993), which transforms distributions of cumulative precipitation over n months to a standard normal distribution. It has been recently promoted by the World Meteorological Organization as the reference index for meteorological droughts (Hayes et al., 2011), and it has been applied to various parts of the world, like India (Mishra and Singh, 2009), Greece (Loukas et al., 2008), Korea (Kwak et al., 2011), the USA (Wang et al., 2011) or the UK (Vidal and Wade, 2009). For assessing climate change impacts on agricultural droughts, the most commonly used index is based on modelled soil moisture percentiles, either directly from GCM runs at the global scale (Sheffield and Wood, 2008) or from off-line runs of land surface schemes at smaller scales (Wang et al., 2009, 2011; Mishra et al., 2010).

As shown by Vidal et al. (2010b), characterizing drought events can lead to quite different results depending on both the variable and the time scale considered for building standardized indices. The time scale corresponds to the duration over which the total precipitation (in the case of SPI) is standardized. More and more climate change impact studies take advantage of the potential of SPI to work at different time scales (see for example Dubrovsky et al., 2008; Vidal and Wade, 2009; Vasiliades et al., 2009; Mishra and Singh, 2009; Heinrich and Gobiet, 2012), and we chose here to look at time scales of 3 and 12 months for characterizing short and long droughts, respectively. Moreover, we considered not only meteorological droughts through total precipitation and the SPI, but also agricultural droughts through soil moisture and the Standardized Soil Wetness Index (SSWI). This index is built through a standardisation method similar to the one used for SPI, simply replacing total precipitation over n months by SWI values – computed by the Isba land-surface model – averaged over n months. It allows to assess changes in droughts as a consequence not only of changes in precipitation like the SPI but also changes on other variables – among them temperature – through the computation of water and energy budgets at the soil-vegetation-atmosphere interface.

For each climate projection, the standardisation is performed with reference to the control run climate in order to remove biases in GCM-derived control climate. The reference period for standardisation is 1961–1990 (actually 1 August 1961 to 31 July 1991) in line with WMO (2007) recommandations. For reanalysis data, the standardisation is performed with reference to the same period, which is different from Vidal et al. (2010b) who used the whole 1958–2008 reanalysis period. For both the SPI and the SSWI, the standardisation procedure makes use of kernel density estimates, notably in order to overcome issues of bimodal and bounded distributions of SWI (see Vidal et al., 2010b, for computation details). Standardized indices are computed locally for all 8462 grid cells over continental France.

To summarize, all 4 combinations of index and time scale (SPI3, SPI12, SSWI3, SSWI12) have been computed for (1) the 1958–2008 Safran-Isba reanalysis fields and (2) each of the 3 climate projections, taken each as the combination of the common control run and a future run in order to preserve the temporal continuity of events over the year 2000.

3.1.2 Spatio-temporal drought identification and description

Many climate change impact studies focused on changes in the probability of drought indices to be under a given threshold at the local scale (Ghosh and Mujumdar, 2007; Dubrovsky et al., 2008; Strzepek et al., 2010; Jung and Chang, 2012). Others attempted to assess changes in statistics of local-scale drought event characteristics, like the number of events (Hayhoe et al., 2007) or its combined effect with the average total magnitude of these events (Vidal and Wade, 2009). In parallel, some studies looked at the areal extent of drought as a spatial characteristic, but did not identify independent drought events (Sheffield and Wood, 2008; Mishra et al., 2010).

Some recent work however attempted to examine the evolution of spatio-temporal characteristics of drought events. Burke and Brown (2010) for example made use of predefined UK regions over which spatio-temporal characteristics of events (area in drought, duration and total magnitude) are computed from 12-month precipitation deficits. Mishra and Singh (2009) built severity-area-frequency curves based on SPI over a river basin in India. Still, in spite of existing spatio-temporal clustering algorithms applied to historical droughts (Andreadis et al., 2005; Lloyd-Hughes, 2012; Corzo Perez et al., 2011), no study looked at the evolution of such joint characteristics of individual drought events derived from hydroclimate projections.

Here we apply the clustering algorithm described by Vidal et al. (2010b) and previously applied over France for characterizing historical spatio-temporal meteorological and agricultural drought events from SPI and SSWI fields. A drought event is considered as a sequence of spatially contiguous and temporally continuous areas where the index is under a given threshold value. A threshold corresponding to a local 20 % probability ($\simeq -0.84$) has been chosen for identifying spatio-temporal drought events following Andreadis et al. (2005), Sheffield et al. (2009) and Vidal et al. (2010b). Two algorithm parameters for removing small clusters (less than 10 contiguous cells) and for merging consecutive clusters (overlapping area larger than 100 cells) have been fixed to values adopted by Vidal et al. (2010b). This algorithm has been applied to spatio-temporal fields of SPI3, SPI12, SSWI3 and SSWI12 derived from (1) the 1958–2008 Safran-Isba reanalysis and (2) each of the 3 climate projections described above.

Following Vidal et al. (2010b), summary statistics for a drought event include its mean duration, its mean area and its total magnitude. The *mean duration* of a spatio-temporal event is defined as the mean duration of all cells across the country affected by the drought at some time(s) during the event. The duration for each cell is taken here as the number of months when the index is lower than the threshold (in possibly separate periods). The *mean area* is defined as the mean drought-affected area during the event, and expressed as a percentage of the total area of France. The *total magnitude* is computed here as the sum over space and time of the index values in cells affected by the event, expressed in month by percent of France's area. In addition to these summary statistics, the *centroid* of each spatio-temporal event has been computed as the average centroid of clusters at each time step, weighted by the total magnitude of each cluster.

All algorithms have been implemented in the R software environment (R Development Core Team, 2011) and figures for this paper have been produced thanks to the ggplot2 package developed by Wickham (2009).

3.2 Theoretical adaptation scenarios and perceived characteristics

The marked projected changes in climate summarized in Tables 1 and 2 will hopefully lead to apply strategies for adapting the structure and the management of the various existing anthropogenic hydrosystems. Examples of such systems are headwater catchments with reservoirs for producing hydropower and/or sustaining low flows, or lowland catchments with irrigated crops. Without adaptation, such hydrosystems might not be able to fulfill their purposes, in terms of crop or hydropower production (see Vidal and Hendrickx, 2010, for an example of changes in hydropower production under business-as-usual management).

Three theoretical adaptation scenarios have been derived here based on the projections of drought indices. These scenarios are local-scale scenarios, and their consequences will here be studied at the national scale. The adaptation of an anthropogenic hydrosystem may be performed in many different ways and affects different aspects of the perception of a drought. The theoretical scenarios built here focus on the adaptation to the evolution of the median value of the variable of interest at the local scale (precipitation or soil moisture), thus to the evolution of the median value of the corresponding standardized drought index. In other words, according to these scenarios, the hydrosystem will be able to adapt to changes in the "normal" conditions, but not necessarily to changes in variability, seasonality or temporal patterns. Thus, such theoretical scenarios stay in line with the definition of standardized indices which are based on a departure from normals, but allow potential changes in such normals.

3.2.1 Adaptation scenarios

The first scenario, called *no adaptation* assumes that our perception of drought will not change in the future, i.e. that a given departure from the present-day normals will be perceived in the same way in the late 21st century than in the 1980s for example. The *drought index baseline*, i.e. zero by construction over the reference period, is therefore supposed to remain valid during the whole 21st century.

The two other scenarios assume that the anthropogenic hydrosystem under study will be able to adapt to new conditions. This assumption will be discussed in detail in Sect. 6. If the assumption holds, it should provide us with a perception of a given departure from normals that will be lowered in the future thanks to the adaptation performed. In terms of drought indices described in Sect. 3.1.1, it comes down to an evolution of the drought index baseline. The two scenarios implemented here exemplify two different strategies: adapt either (1) to *past* conditions, a strategy called here *retrospective* adaptation or (2) to *future* conditions, called here *prospective* adaptation.

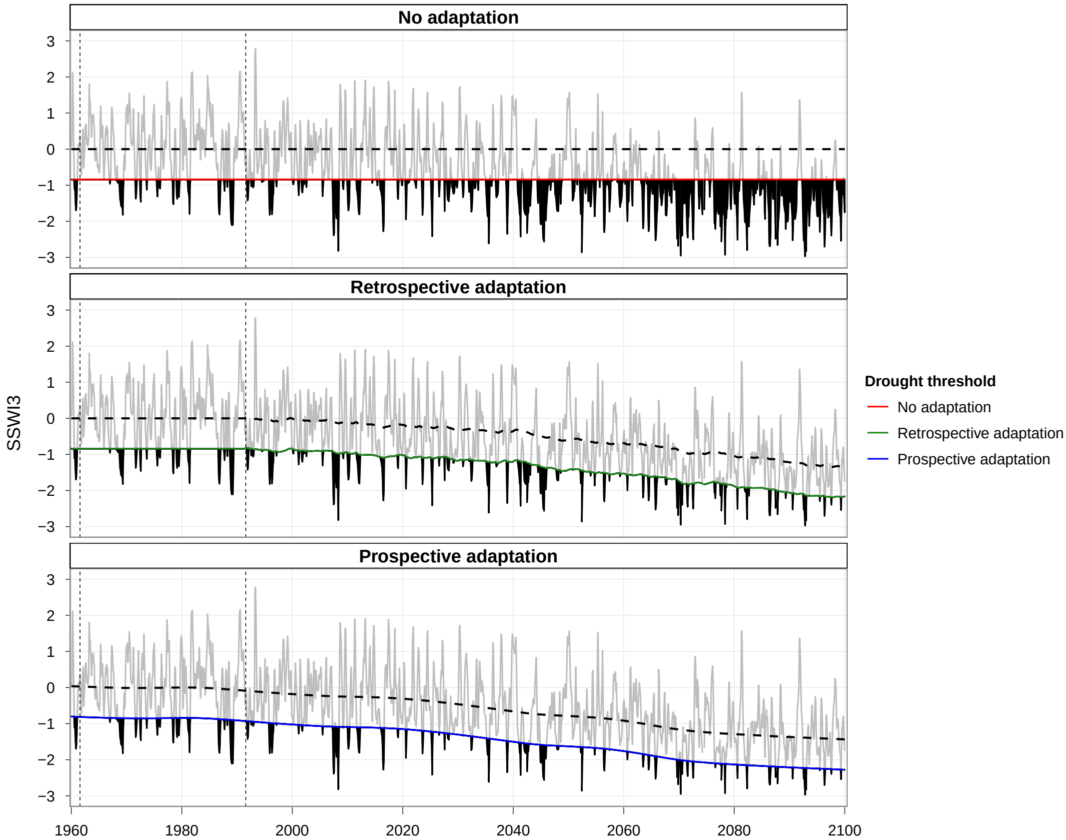

Fig. 1. Evolution of SSWI3 for a grid cell near Toulouse under the A1B scenario, and corresponding adaptation scenarios. Black filled areas correspond to local-scale drought events reaching the 20 % threshold. The dashed lines show the drought index baseline evolutions calculated for each adaptation scenario and described in Table 3. Coloured lines show the corresponding drought state threshold (see text for details). The reference period is framed by dashed vertical lines.

The *retrospective adaptation* scenario assumes that the hydrosystem is able to constantly adapt to antecedent climatic normals. These normals are thus reconsidered at each time step and the hydrosystem is adapted accordingly. In terms of drought indices, it is implemented as follows: the drought index baseline is taken as the mean of the preceding 30 yr of the index, starting right after the reference period. For a given date of the 21st century, this scenario is therefore theoretically independent from projections for the future (and associated uncertainties) as it relies only on antecedent and thus experienced conditions. In the applications considered here, this scenario however relies on the assumption that the hydroclimate projections will be valid and then considered as "experienced" until any date considered in the 21st century.

The *prospective adaptation* scenario assumes first that the future evolution of the normals are perfectly known and perfectly represented by the hydroclimate projection considered. In terms of drought indices, the evolution of the drought index baseline is represented by a smooth transient median value of the index time series. An approach with smooth splines was chosen here in order to get the intended smoothness. The theoretical constraint of a zero value over the whole 1961–1990 reference period was approached by optimizing the degree of freedom of the spline to get a minimum deviation from zero of the resulting spline curve over this period. This theoretical adaptation scenario assumes a quickest reaction to changes in climate, which could be advantageous in the case of rapid changes.

3.2.2 Implementation

In both actual adaptation scenarios, the drought index baseline is simply added to the reference value of the drought threshold, ($\simeq -0.84$, see Sect. 3.1.2), in order to generate a time-varying drought threshold. This way, the adaptation scenarios only take account of changes in average conditions and not in potential evolutions in variability. Table 3 summarizes the different drought index baseline computations adopted for the different theoretical adaptation scenarios. Figure 1 shows an example application of the three scenarios for estimating short agricultural droughts over a given grid cell.

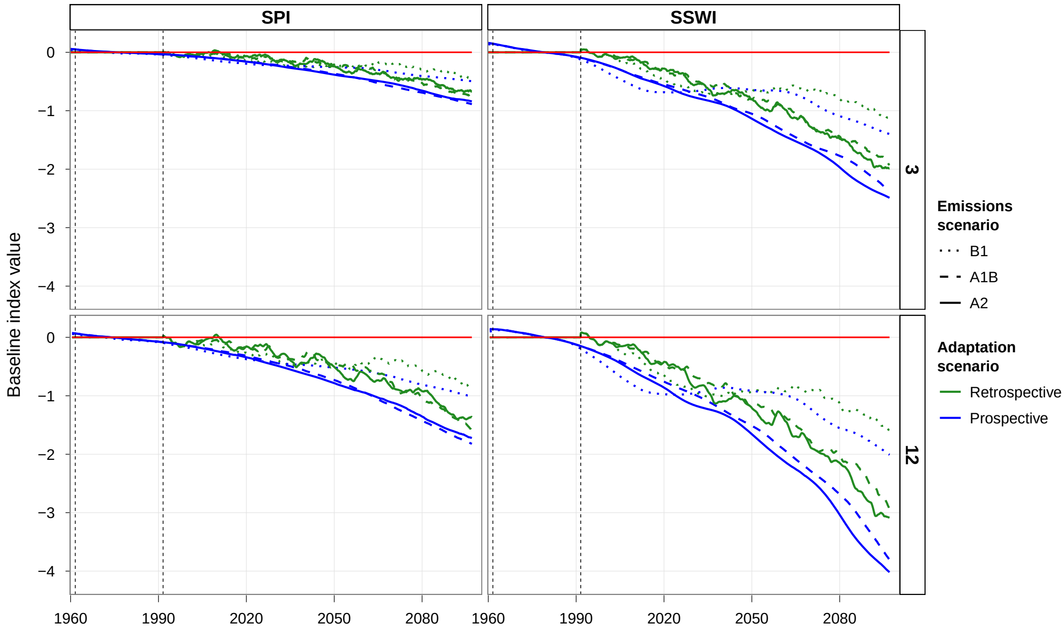

Fig. 2. Evolution of drought index baseline averaged over France, according to each adaptation scenario described in Table 3. Columns show the 2 different indices and rows show the 2 different time scales. The reference period is framed by dashed vertical lines.

Table 3. Adaptation scenarios.

Scenario	Drought index baseline
No adaptation	zero
Retrospective adaptation	running mean of previous 30 yr
Prospective adaptation	smooth spline optimised for minimal deviation from zero over the reference period

3.2.3 Implications for the evolution of drought characteristics

Figure 2 shows the temporal evolution of the drought index baseline averaged over France according to each emission and adaptation scenarios and for all 4 combinations of index and time scale. It shows a dramatic decrease of baseline values over the 21st century, more pronounced for more "pessimistic" emission scenarios, and more pronounced for the *prospective adaptation* scenario. This decrease is stronger for SSWI than for SPI, and also stronger for longer time scales. This is simply the result of a relatively small decrease in precipitation mentioned in Table 2 and a marked decrease in soil moisture resulting from an overall warming (see Table 1) and thus an increase in evaporation demand. The extremely low values reached at the end of 21st century correspond to a large drop of median cumulative precipitation or averaged soil moisture. These values correspond to probabilities as low as 15 % (for SSWI12 under the *retrospective adaptation* scenario and the A2 emissions scenario) in the distribution of these variables over the 1961–1990 reference period. This suggests that the theoretical scenarios constructed here may be hardly accessible in practice and thus represent an upper limit of adaptation efforts. This is further discussed in Sect. 6. It can also be seen in Fig. 2 that, by construction of the *prospective adaptation* scenario, the optimisation of the spline degree of freedom could not perfectly match the zero value over the reference period.

The spatio-temporal clustering algorithm has been also run on all 3 climate projections with the retrospective and prospective adaptation scenarios in order to derive spatio-temporal characteristics of drought events. Such characteristics cannot be interpreted as actual drought event characteristics as they are conditional on the adaptation scenario considered and they do not imply modifications in physical natural processes with respect to the *no adaptation* scenario. Therefore, in the remainder of the paper, they are described as *perceived* characteristics: the drought event characteristics would indeed be perceived as such by users of the anthropogenic hydrosystem if this system could have been modified according to the adaptation scenario considered.

4 Validation on present-day climate

This section aims at validating simulations against reanalysis over the 1958–2008 period in terms of spatio-temporal drought characteristics. Section 4.1 first examines the number of drought events identified in the reanalysis and in the simulations, and Sect. 4.2 focuses on drought characteristics defined in Sect. 3.1.2. The whole period covered by the reanalysis data has been chosen in order to have the longest possible common period with simulations. This is particularly important, as relatively few major spatio-temporal events occurred in a 50-yr period. Consequently, in this section, simulation B1 (resp. A1B and A2) will refer to outputs derived from the ARPEGE control run for the 1958–2000 period together with outputs from the B1 (resp. A1B and A2) ARPEGE run for the 2001–2008 period. The three simulations will therefore present limited differences over this present-day period, and these differences could only be interpreted as the consequences of internal variability, as very little impact of the choice of the emissions scenario could be possibly found during this short 8-yr period (see Hawkins and Sutton, 2011, for a larger-scale analysis of the different sources of uncertainty).

4.1 Number of drought events

Figure 3 plots the number of drought events identified in the reanalysis and in all 3 simulations over the 1958–2008 period. Together with the number of all events (top panel), the number of *major* events (bottom panel) is plotted, defined as events with a mean duration strictly higher than 1 month. Events during exactly 1 month – i.e. the time step of the analysis – are indeed not developing in time and have to be considered separately. Figure 3 shows that the total number of short (resp. long) meteorological droughts are slightly overestimated (resp. slightly underestimated) in the modelled climate. Such discrepancies may originate from spatial and/or temporal biases in either ARPEGE large-scale simulations or the downscaling method used here (see Sect. 2.2). A good agreement is reached for the number of both short and long agricultural droughts. When looking at the number of major events, the overestimation of short meteorological events is confirmed and this time it is accompanied with a similar overestimation of short agricultural events. Some explanations to such features will be proposed below when looking at drought event centroids. No bias can be found for long meteorological and agricultural droughts.

In the remainder of the paper, only *major* drought events will be considered.

4.2 Drought characteristics

This section aims at assessing how well the diversity of spatio-temporal droughts identified in the reanalysis are simulated over the present-day period. Figure 4 identifies each observed or simulated drought event jointly through its mean duration, mean area and total magnitude. It first reproduces features of observed events presented by Vidal et al. (2010b) as white and coloured full circles. When compared to the original figure (Vidal et al., 2010b, Fig. 10, p. 472) where colours identify specific major events in a consistent way with Fig. 4, some differences can be seen. For example, the 1976 drought (in red) appears here to affect a larger

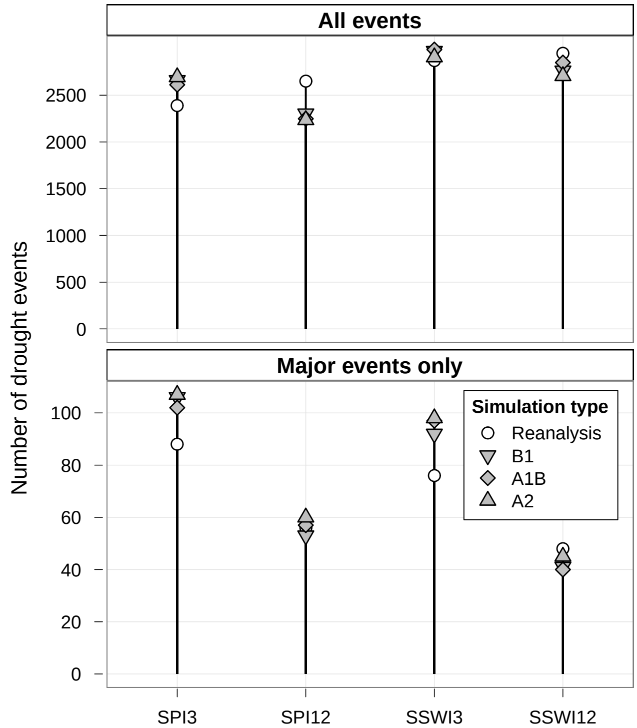

Fig. 3. Number of drought events identified over the 1958–2008 period, for reanalysis data and all 3 simulations. Top panel: all events; bottom panel: only major events (duration > 1 month).

part of France for both indices and both time scales. The 2003 drought (in orange) also appears here to last longer, at least when soil moisture deficits are concerned. These differences exemplify the impact of the selected reference period on spatio-temporal drought characteristics: 1961–1990 here, and the whole period covered by the reanalysis (1958–2008) in Vidal et al. (2010b). Figure 4 also plots as grey shapes the events identified in present-day simulations. Squares identify events with a maximum magnitude during the control run, i.e. before 2000. Triangles and diamonds denote events occurring between 2000 and 2008, depending on the choice of emission scenario. The scatter plot of observed events is generally well replicated in simulations, with appropriate combinations of small and large events. In particular, events similar to major observed ones like the 1976 SPI3 drought or the 2003 SSWI12 drought can be found in simulated climate. One interesting feature is that the 3 longest (and with highest magnitude) simulated events for SSWI3 are found to occur in the last years of the simulation, suggesting a downward trend in simulated soil moisture, possibly driven by an underlying upward trend in temperature. This is consistent with results from recent trend analyses in different versions of the PDSI (Dai, 2011a,b).

Figure 5 shows the centroid of observed (reanalysis) and simulated (control run + A2 emissions scenario) drought events over the 1958–2008 period. Results are very similar

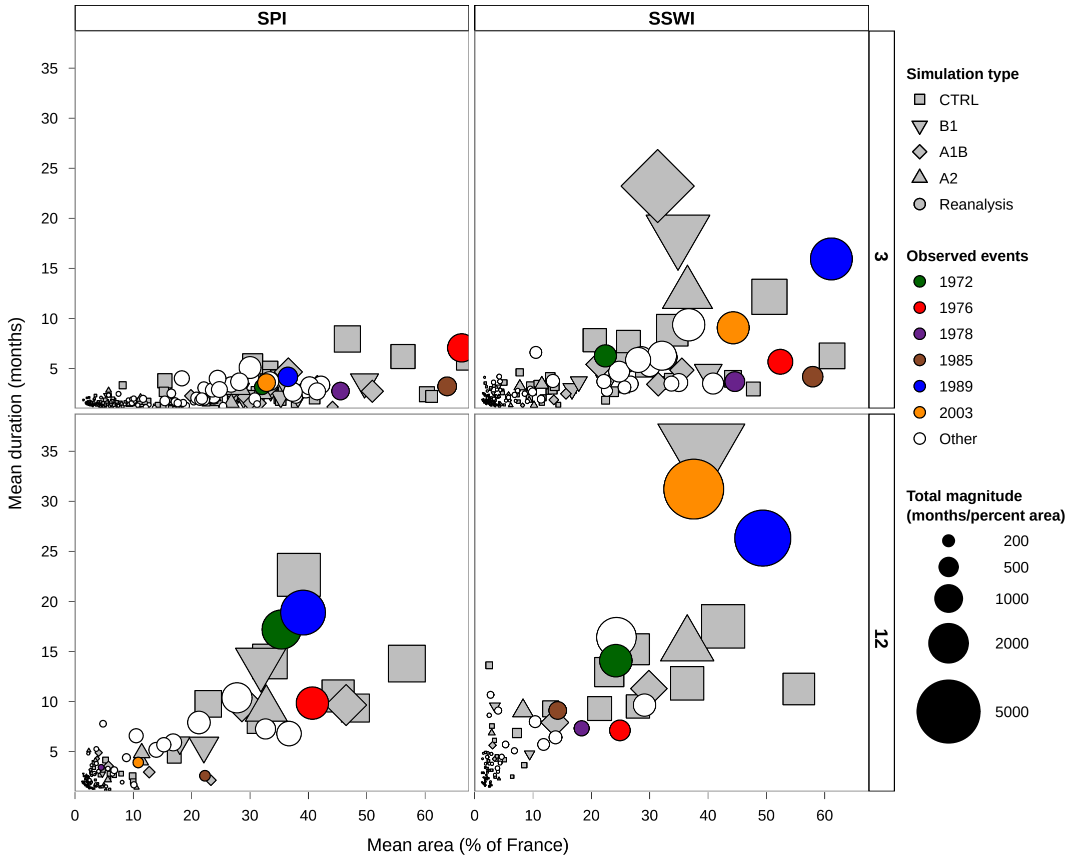

Fig. 4. Relation between mean area (in percent area of France), mean duration (in months) and total magnitude (in months by percent area of France) for all drought events identified during the 1958–2008 period with SPI (left column) and SSWI (right column), with time scales of 3 months (top panels) and 12 months (bottom panels). Circles show events from the reanalysis, whereas grey symbols represent events from downscaled ARPEGE simulations. Squares represent events from the downscaled ARPEGE 1958–2000 control run, and downward and upward triangles and diamonds represent events from one of the downscaled ARPEGE 2001–2008 simulation runs under the 3 emissions scenarios. Coloured circles identify the six major drought events from the reanalysis highlighted by Vidal et al. (2010b, Fig. 10, p. 472).

for the two other emissions scenarios (not shown). Centroids of events with high total magnitude are by construction found close to the geometrical centre of France, but many small events can be found in all different parts of the country, with for example, relatively large meteorological droughts restrained to the Mediterranean area or long agricultural droughts around Brittany. The overall distribution of locations is generally well replicated in the simulated sample of drought events, but specific differences can be seen. First the overestimation of SPI3 events noted in Fig. 3 can be attributed to a higher number of events located preferentially in the northern half of France, where much fewer events have been actually identified in the reanalysis. As expected, a similar feature is found for SSWI3 events. This could be linked to a bias in the latitude of the simulated storm tracks in the ARPEGE runs used here. Moreover, such a bias should be confined to a specific season as no bias appears for 12-month drought events. This hypothesis has however still to be confirmed.

4.3 Comparison of present-day distributions

The 2-sample Kolmogorov-Smirnov test (Massey, 1951) is used here to check the agreement between the observed (from the reanalysis) and simulated empirical distributions of each drought characteristics (duration, mean area, total magnitude x- and y-location of the centroid) over the 1958–2008 period. Results show that the H_0 hypothesis (the two samples come from the same distribution) cannot be rejected in any case, i.e. for each drought type and for each drought characteristic. Figure 6 shows the p-values for each test performed. It demonstrates that simulations correctly recreate the statistics of spatio-temporal drought characteristics over the present-day period, with p-values higher than 0.1 for nearly all combinations. The only dubious case with small p-values relates to the centroid latitude already discussed above, mainly for SPI3.

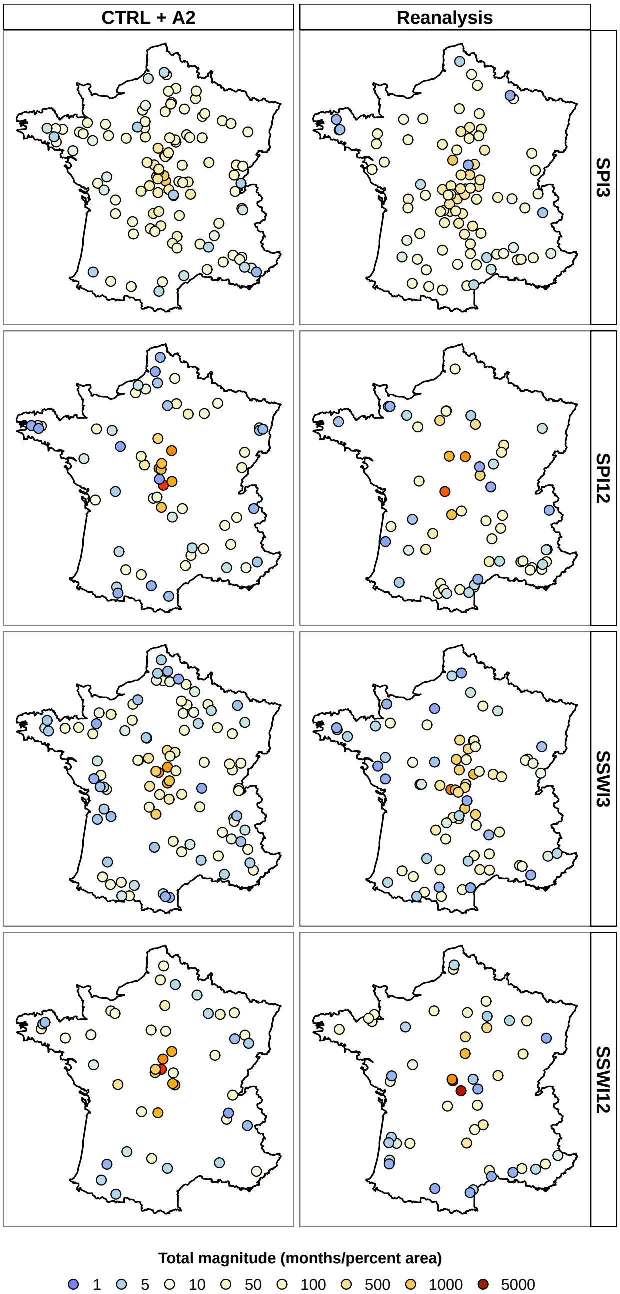

Fig. 5. Centroid of drought events identified over the 1958–2008 period, from the reanalysis (right panels) and from the (CTRL + A2) downscaled ARPEGE run. Colours denote different classes of total magnitude. The different rows show all four drought indices.

All above comments therefore give a relatively high confidence in the ability of downscaled climate projections to simulate spatio-temporal characteristics of drought events.

5 Projections in future climate

This section presents results of the evolution of simulated drought event characteristics during the end of the 20th century and the 21st century, conditional to the emissions scenario and the adaptation scenario selected.

5.1 Evolution of drought characteristics

Figure 7 jointly plots the mean area, mean duration and total magnitude of simulated short meteorological droughts over the 1958–2100 period, for all combinations of emissions and adaptation scenarios, following the approach already used in Fig. 4. Note, however, that here the y-scale is logarithmic to represent a larger range of durations. The whole simulation period has been cut into 20-yr time slices in order to get an idea of the long-term evolution of spatio-temporal characteristics. Colours in Fig. 7 identify the time slice when each event reaches its maximum magnitude. The first row corresponds to the *no adaptation* scenario and thus represent events as they are projected to happen with reference to present-day climate. The middle and bottom lines show the *perceived* characteristics of drought events conditional to the *retrospective* and *prospective* adaptation scenario, respectively. The three columns show the influence of the emissions scenario on drought characteristics. Figures 8–10 plot similar features for long meteorological droughts and short and long agricultural droughts, respectively.

When looking at the first row in Fig. 7, it appears that drought characteristics under the *no adaptation* assumption are projected to increase during the 21st century, with duration and magnitude values not encountered before 2000. The most intense events tend to appear in the last part of the 21st century, combining a mean duration of 20 months and a mean area of nearly 70 % of the country in both the A2 and A1B emissions scenario. The evolution appears to be more limited for the B1 emissions scenario. Considering one of the two adaptation scenarios leads to reduce the perceived characteristics of the largest events. Only few events are, for example, found to have a duration higher than 7 months, i.e. the duration of the longest event in the reanalysis (1976, see Fig. 4). The *prospective adaptation* scenario tends to give events with a reduced magnitude compared to the *retrospective adaptation* scenario, with small similar influences on duration and area.

Figure 8 shows a quite different picture for long meteorological droughts. Due to the longer time scale, events are far scarcer, and a few very large, long and intense events are found in the last decades of the 21st century under the *no adaptation* scenario, in particular under the A2 and A1B emissions scenarios. The order of magnitude encountered here (12-yr event affecting nearly 70 % of France) is far higher than in the panel of events from the reanalysis, where the worst event (1989, see Fig. 4) lasted for 20 months and concerned less than 45 % of the country. When considering

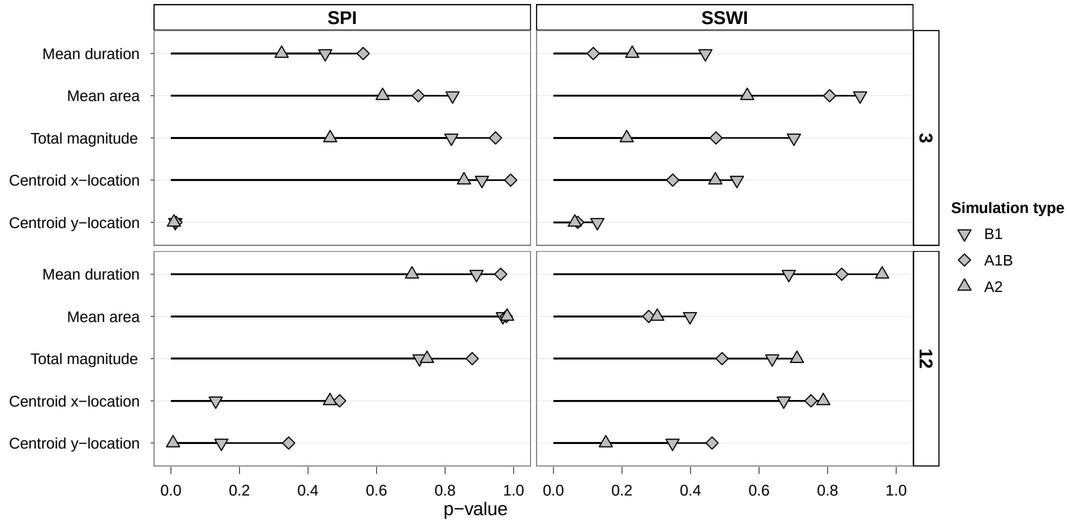

Fig. 6. Agreement between simulated and observed statistical distributions of drought characteristics (mean area, mean duration, total magnitude, centroid x- and y-location) over the 1958–2008 period. The agreement here is given as the p-value of the 2-sample Kolmogorov-Smirnov test between the observed distribution from the reanalysis and the corresponding distribution from a present-day simulation (CTRL + A2, A1B or B1) . Only "major events" are considered here (see Fig. 3). Columns show the 2 different indices and rows show the 2 different time scales.

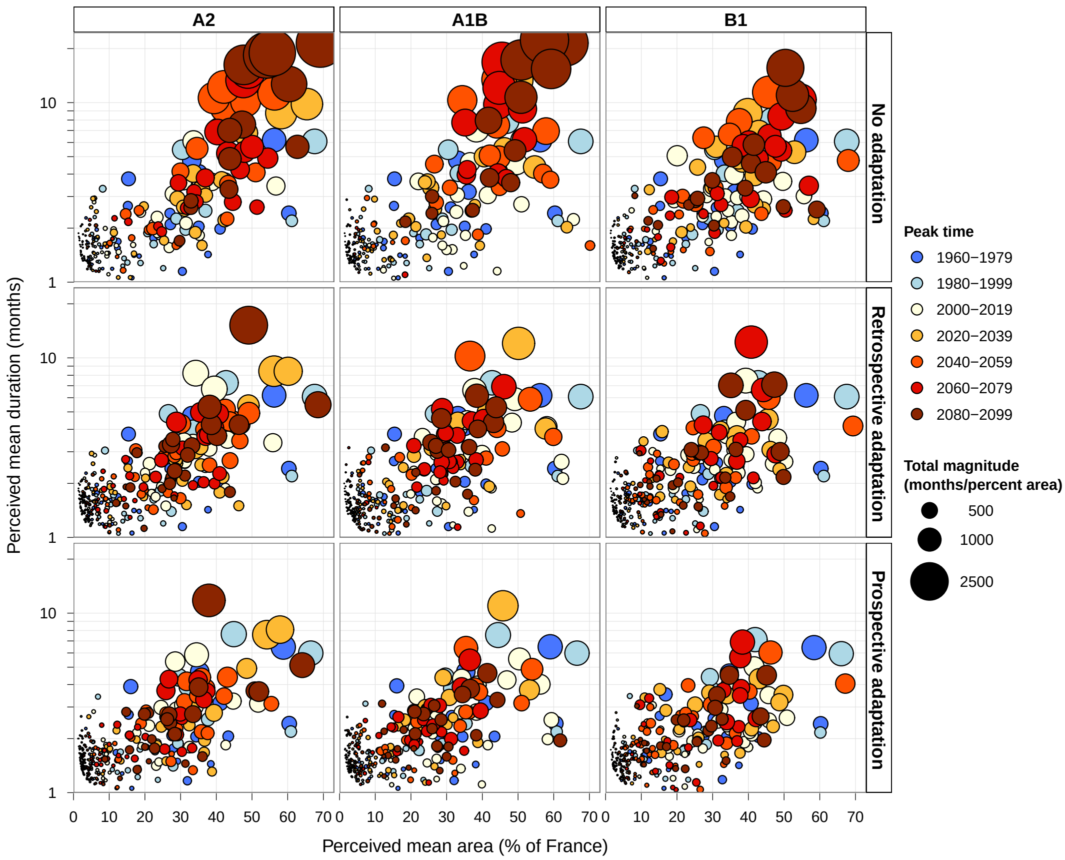

Fig. 7. Evolution of perceived spatio-temporal characteristics (mean area, mean duration and total magnitude) of short meteorological droughts, as defined by SPI3. Three emissions scenarios are considered along the columns, and three adaptation scenarios are considered along the rows.

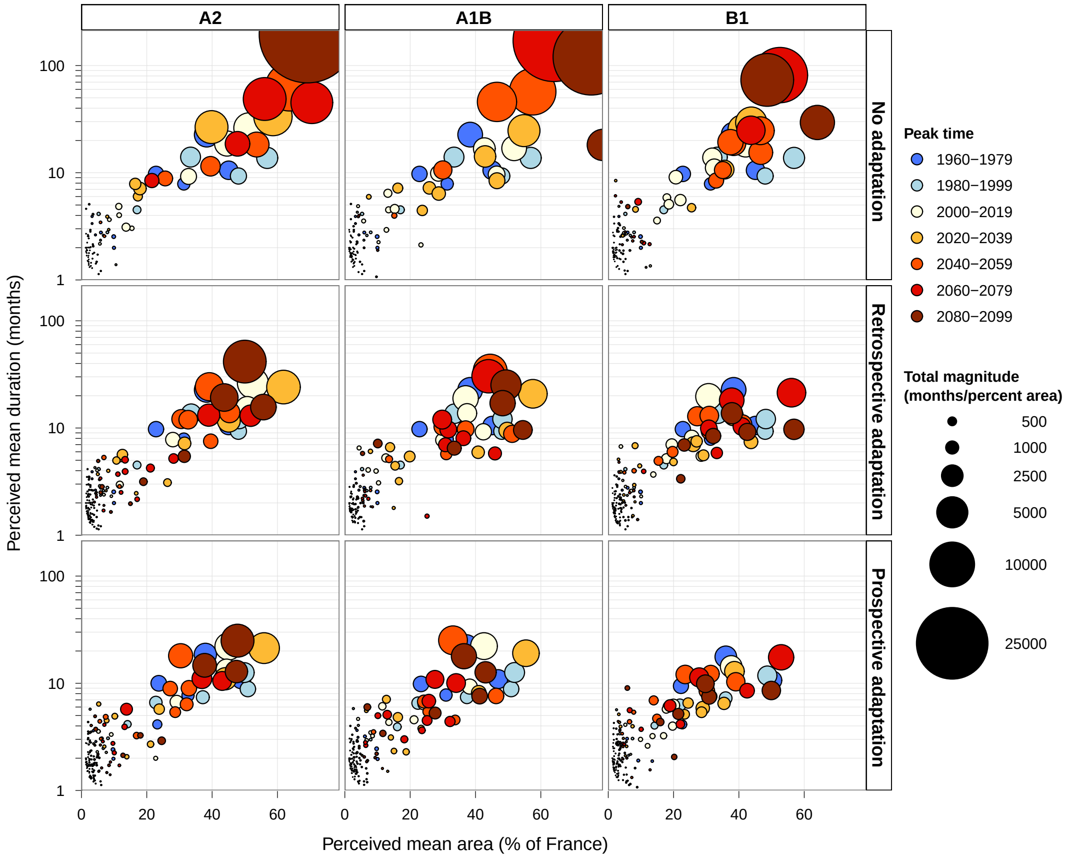

Fig. 8. As for Fig. 7, but for long meteorological droughts, as defined by SPI12.

adaptation scenarios, perceived drought characteristics are significantly lowered, even if some events still show areas larger than 50 % and/or durations longer than 20 months. The *prospective adaptation* scenario leads to somewhat more limited changes in all drought characteristics.

Figure 9 plots the evolution of short agricultural drought characteristics. The overall picture is very similar to long meteorological droughts, with events of even larger total magnitude. It can also be noted that these scatter plots show a higher dispersion for medium events compared to Fig. 8. Under the *no adaptation* scenario, only one event is found during the last 2 decades of the 21st century in both the A2 and A1B scenarios. This event covers the entire 20-yr period and concerns nearly 80 % of the country, which means that agricultural drought is projected to become the norm in France at the end of the 21st century. Under adaptation scenarios, the perceived mean duration of events is generally contained below 24 months and their perceived mean area under 60 %, when the worst event from the reanalysis (1989, see Fig. 4) reached 16 months and 62 %. However, one cannot exclude short events affecting more than 75 % of the country, as the one identified under the B1 emissions scenario in the mid-century.

Figure 10 plots the evolution of long agricultural drought characteristics. The picture depicted here under the *no adaptation* scenario is even more dramatic: the single events culminating in the last two decades of the century actually start much earlier, before the 2050s under the A2 and A1B scenarios, and before the 2070s under the B1 "optimistic" scenario. Other events larger than the two major ones identified in the reanalysis (1989 and 2003, see Fig. 4) can also be spotted earlier under the A2 and B1 emissions scenarios. Choosing the *retrospective adaptation* scenario enables to keep the perceived mean duration of events under 4 yr – which is already 1.5 times longer than the 2003 drought – and the perceived mean area under 60 %, where the 1989 drought affected "only" half of the country. Under the *prospective adaptation*, perceived drought characteristics are generally found to be within the range of events identified in the reanalysis.

5.2 Statistical assessment of the effect of adaptation comparison of present-day distributions scenarios

The non-parametric Mann-Kendall test for trends (Mann, 1945) is applied here in order to statistically assess the effect of adaptation scenarios on perceived drought characteristics.

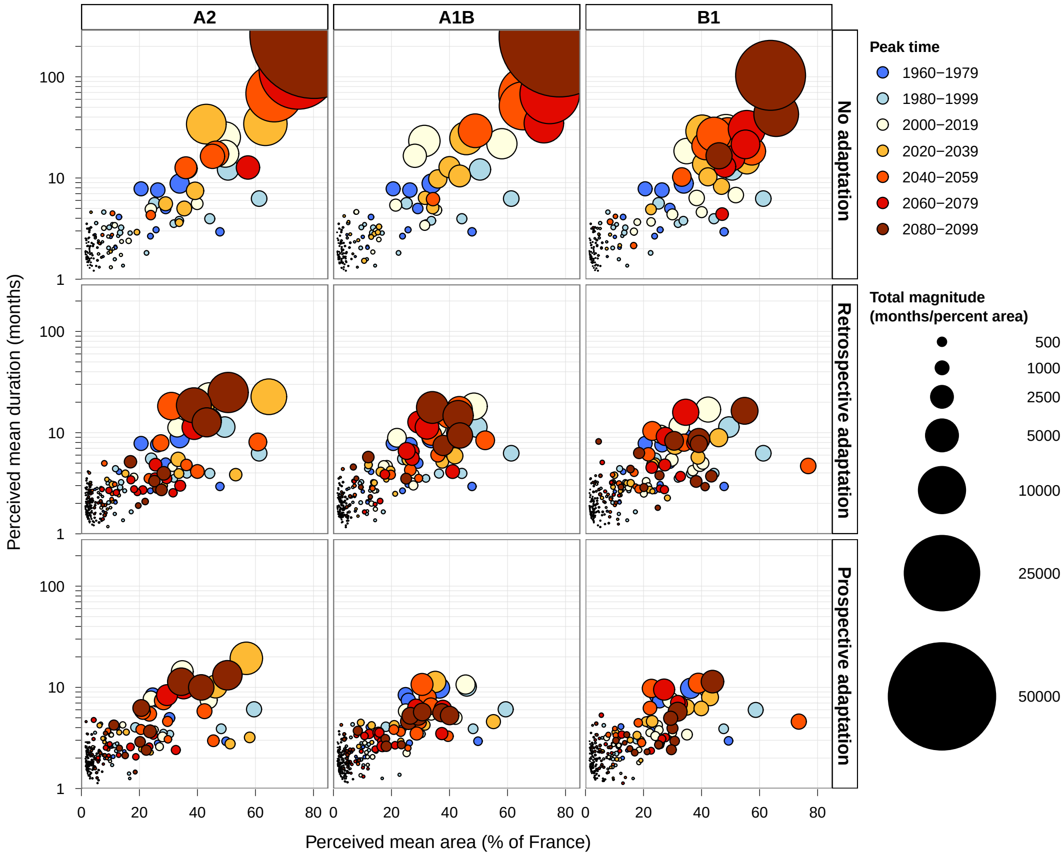

Fig. 9. As for Fig. 7, but for short agricultural droughts, as defined by SSWI3.

This widely used test in historical trend assessments (see for example Renard et al., 2008) is applied in this study to quantify the significance of trends in spatio-temporal drought characteristics (mean duration, mean area, total magnitude, centroid x- and y-location) for each combination of emissions scenarios and adaptation scenarios, over the whole simulation period (1958–2100). Figure 11 shows the p-values for the test for all variables and scenarios considered.

First, no trend can be found for the centroid location of drought events. The exception is a trend significant only at the 10 % level for the latitude in short agricultural droughts under the A2 emissions scenario and the *prospective adaptation* scenario. This trend is a southward trend (not shown), and as no corresponding trend appears in the *no adaptation* scenario, it is hard to conclude on its origin.

Under the *no adaptation* scenario, significant (upward, as shown in Figs. 7–10) trends can be found for all other characteristics of short drought events (both meteorological and agricultural). This is true for all emissions scenarios, but with much lower p-values for the A2 scenario. Some significant trends are additionally found for long meteorological droughts (mean duration and mean magnitude under the A2 scenario) and for long agricultural droughts (mean duration under the B1 scenario). The fact that fewer cases where significant trends are found for long droughts comes from the reduced number of spatio-temporal events for standardized indices with higher time scales.

When looking at adaptation scenarios, all these trends either disappear statistically or have their p-value increased. One exception is an increase in the magnitude of long agricultural droughts under the B1 emissions scenario and the *prospective adaptation* scenario with a p-value higher than 0.05. The difference in reduction of trend significance between the two adaptation scenarios appears only – for duration of short meteorological events and magnitude of short agricultural events – when looking at the A2 emissions scenario, which leads to the most rapid climate evolution over the 21st century.

6 Discussions

6.1 Uncertainties

This section aims at assessing the different sources of uncertainties in the modelling suite that may impact the results summarized above, for the *no adaptation* scenario.

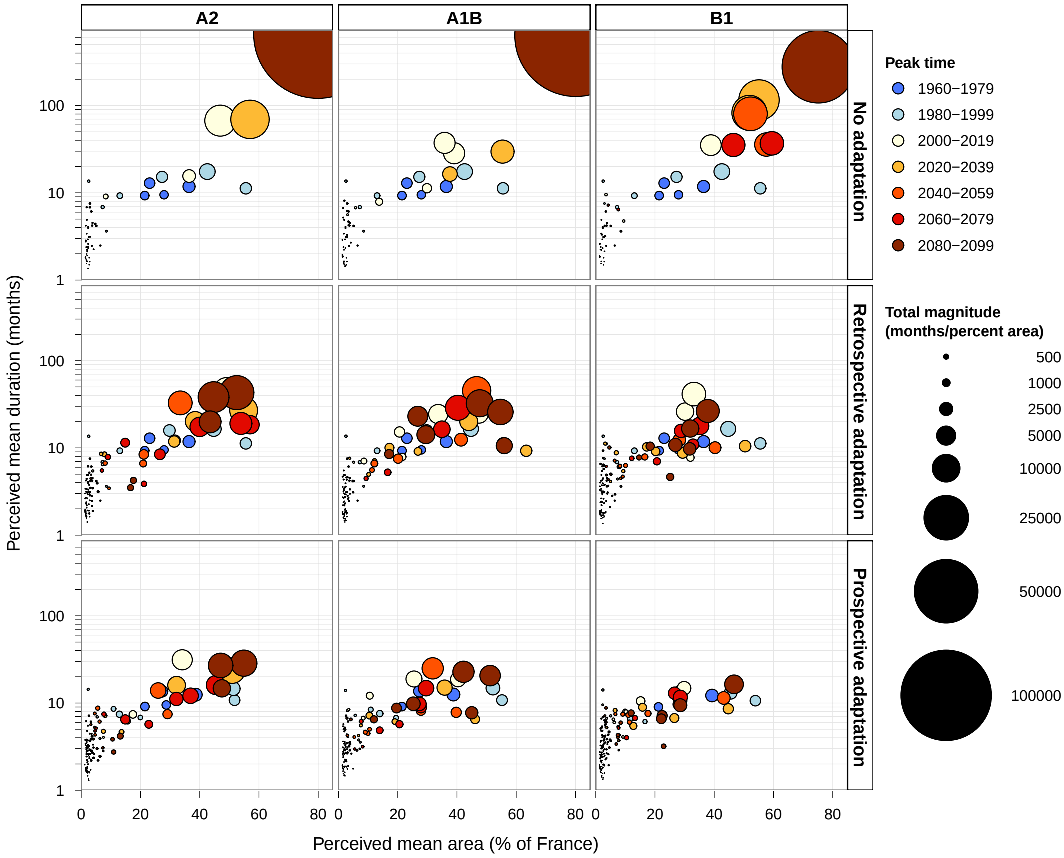

Fig. 10. As for Fig. 7, but for long agricultural droughts, as defined by SSWI12.

6.1.1 GCM and downscaling method

First, this particular paper considered neither a multi-GCMs nor a multi-downscaling method approach, as recommended for providing some information about the uncertainty in future climate projections (see, e.g. Vidal and Wade, 2009, for a multi-GCMs approach). Indeed, this study focused on the mitigation and adaptation effects on spatio-temporal characteristics of drought events, and results should obviously been taken as conditional on the choice of the GCM and downscaling method made here. Such multi-model approaches have however been used elsewhere in the ClimSec project and the impact of corresponding uncertainties on local-scale droughts have been quantified (Kitova et al., 2011). On top of the transient multi-SRES experiment used in the present study, two other experiments have been considered: (1) a time slice experiment (1961–2000 and 2046–2065) with 6 different GCMs under the A1B scenario and downscaled with the weather types downscaling method used here, and (2) a transient experiment with the ARPEGE GCM coupled with a model of the Mediterranean Sea (Somot et al., 2008) under the A2 emissions scenario, downscaled again with the same weather type method but also with a quantile-quantile approach (Déqué, 2007). Analysing the respective spread from all 3 experiments in the 2050s led to rank first the uncertainty in GCMs. Moreover, outputs derived from the ARPEGE GCM under the A1B scenario were found to be close to the multi-GCM average under the same emissions scenario.

6.1.2 Land surface model configuration, vegetation and land use

If the uncertainties discussed above are equally valid for meteorological and agricultural droughts, additional uncertainties can be mentioned for results associated with soil moisture simulations.

A potentially significant source of uncertainty may be found in the configuration of the land surface model (LSM). Indeed, simulated soil moisture has been shown to be highly model-dependent (Koster et al., 2009). However, in reconstructing historical droughts over the United States with 6 different LSMs, Wang et al. (2009) found that standardizing results lead to similar spatio-temporal patterns of soil moisture droughts. This result has been since confirmed by Fan et al. (2011) with LSMs at different resolutions and run in different conditions (interactively or offline), even if differences can be spotted in local intensities. Results obtained

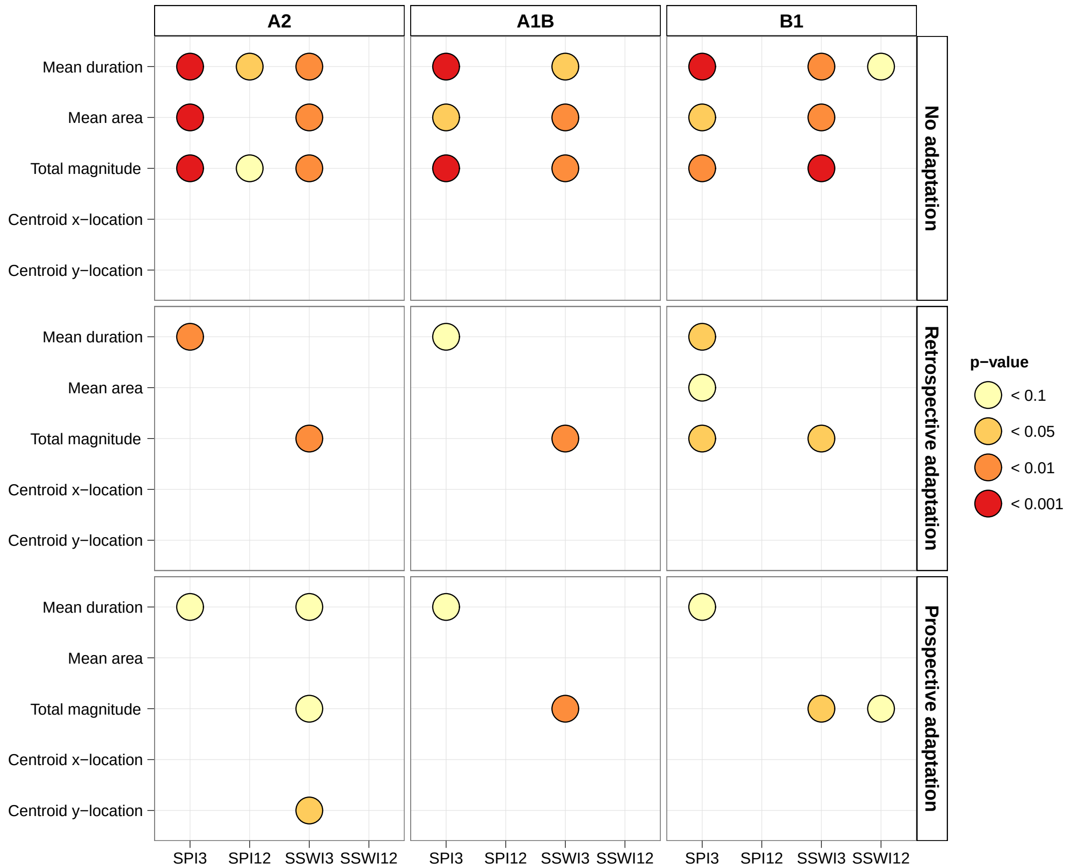

Fig. 11. Significance of the Mann-Kendall trend test (represented with the test p-value) on all combinations of drought indices and spatio-temporal characteristics, for the 3 emissions scenarios (columns) and for the 3 adaptation scenarios (rows).

here should therefore not be highly sensitive to the choice of a specific LSM for the present-day period. However, the situation may be quite different in the 21st century climate, as the LSM sensitivity to an increase in temperature could encompass a large range. This has been clearly shown on streamflow droughts by Williamson et al. (2011) with outputs from the WATCH project (Harding et al., 2012). 21st century trends in the Regional Deficiency Index (RDI, see Hannaford et al., 2011) for "Western and Central France" region are found to be quite different when driven by different GCMs, but also when considering different land surface models/global hydrological models. It therefore strongly suggests a potentially large uncertainty in LSM/GHM configuration. All combinations nevertheless show a massive drying trend similar to the one commented in the present paper, with a pronounced evolution in the second part of the 21st century.

The land surface simulations were performed here with static vegetation and land use parameters, as in most current off-line studies, with the notable exception of some other innovative work done within the WATCH project (Harding et al., 2012). Initiatives are underway in France (1) to account for spontaneous responses of vegetation to climate variability (Lafont et al., 2010) and CO_2 changes (Queguiner et al., 2011) using a vegetation-interactive version of the Isba LSM and (2) to model both historical and future water demand and water management at the catchment scale, through the recently completed IMAGINE2030 project[2] in the Garonne basin (Sauquet et al., 2009, 2010; Vidal and Hendrickx, 2010) and the R2D2-2050 project[3] in progress in the Durance basin (Southern Alps) (Sauquet, 2011).

6.2 Adaptation and mitigation scenarios

Results presented in Sect. 5 are conditional on both the emissions scenario and the adaptation scenario considered, and this section discusses the implications of such a conditioning as well as the possible interpretations of results.

6.2.1 Adaptation scenarios

The theoretical adaptation scenarios described in Sect. 3.2 have been constructed from time series of standardized

[2] http://www.irstea.fr/la-recherche/unites-de-recherche/hhly/hydrologie-des-bassins-versants/projet-imagine2030

[3] https://r2d2-2050.cemagref.fr/

drought indices. Consequently, they do not reflect in any case the actual capacity of anthropogenic hydrosystems at the scale of France to actually follow these scenarios. The two adaptation scenarios are indeed "perfect" in different ways: the *retrospective adaptation* scenario suggests that one can adapt continuously over the 21st century. Indeed, the drought index baseline is updated each month, which is far from being feasible, for example for irrigated crops (annual or seasonal time step) or forestry (decadal time step). Regarding the *prospective adaptation* scenario, it assumes that the transient projection of the drought index mean value corresponds exactly to how the median water availability will actually evolve, which is a very strong hypothesis. It has also to be noted that no seasonality of changes are taken into account in the theoretical adaptation scenarios, in spite of these specific changes being a key driver for managing anthropogenic hydrosystems, from hydropower production system to crop production. As mentioned above (see Sect. 3.2.3), they nevertheless provide information about the upper limit of adaptation efforts relative to present-day median values of water availability. Additionally, both theoretical scenarios fail to provide a satisfying adaptation to changes in interannual variability, as shown in Figs. 7–10 through the occurrence of several events far longer than the longest observed ones. It strongly suggests that adaptation efforts should not only concentrate on the evolution of median values of water availability, but also on potential changes in its interannual variability.

Different ways forward exist to derive realistic adaptation scenarios and many works have been dedicated to this task, for example in the case of crop production systems (see Olesen et al., 2011, for a recent review). Such adaptation efforts would require an integrated approach (Falloon and Betts, 2010), which would follow harmonized policies at the European level (Kampragou et al., 2011). Additionally, the regional to catchment-scale specificities have to be taken into account, with different priorities emerging from the local existing or projected resources, for example in the Alps (Beniston et al., 2011) or in the Mediterranean area (Iglesias et al., 2011). Different initiatives are underway in France to provide relevant adaptation strategies and assess the future balance of water demand and water availability: the R2D2-2050 project for example applies an integrated multidisciplinary approach to accurately represent the Durance anthropogenic hydrosystem, taking into account main biophysical processes, water management policy and decision-making aspects, and their interactions in time and space (Sauquet, 2011). Scenarios for future water demand and water management will be developed in close collaboration with local stakeholders (water agency, hydropower companies, water industry companies, etc.). In parallel, the Explore2070 study is currently underway to provide consistent and systematic national-scale adaptation strategies (de Lacaze, 2011).

6.2.2 Mitigation scenarios

First, the three emissions scenarios taken from the Special Report on Emissions Scenarios (SRES, Nakićenović et al., 2000) may be seen as proxies for actual mitigation scenarios. Even if no real mitigation scenario like the E1 scenario (Johns et al., 2011) developed in the ENSEMBLES project (van der Linden and Mitchell, 2009) was considered here, the 3 SRES scenarios represent different storylines regarding future global population growth, technological development, globalisation, and societal values. The B1 scenario describes a world steered towards globalised environmental stainability, leading to a stabilisation of CO_2 concentration of 550 ppm at the end of the century (see Meehl et al., 2007b, Fig. 10.26, p. 803). The A1B scenario corresponds to a globalised world with rapid economic growth and a balanced use of fossil and non-fossil energy sources leading to constantly growing CO_2 concentration up to more than 700 ppm in 2100. The A2 scenario describes a more heterogeneous world with a strong economic focus, and leads to exponentially growing CO_2 concentrations reaching 850 ppm at the end of the century.

Unsurprisingly, results from Sect. 5 show that emissions scenarios with lower greenhouse gas concentrations lead to the smaller changes, even if these changes are already dramatic. It would be useful to actually compare the respective or combined effects of local adaptation scenarios and global mitigation scenarios on future drought characteristics. The effects of mitigation scenarios on droughts at the European scale recently studied by Warren et al. (2012) could for example be combined with effects of local- or catchment-scale French adaptation scenarios.

7 Conclusions

This paper addresses the issue of spatio-temporal characteristics of future drought events in France. More specifically, it focuses on three research questions: (1) Are downscaled climate projections able to simulate spatio-temporal characteristics of meteorological and agricultural droughts in France over a present-day period? (2) How such characteristics will evolve over the 21st century? and (3) How to use standardized drought indices to represent theoretical adaptation scenarios?

The first question is addressed by studying droughts derived from a downscaled control run from the ARPEGE GCM. Results shown in Sect. 4 suggest that the diversity of spatio-temporal characteristics identified in the reanalysis over France is fairly well simulated in a GCM-derived climate, in terms of combinations of duration, affected area and total magnitude. These conclusions are furthermore valid for both meteorological and agricultural droughts with time scales of both 3 and 12 months, computed using standardized indices. Section 5 provides an answer to the second question, based on 21st century runs of ARPEGE under three emissions scenarios. All spatio-temporal characteristics of drought events are expected to dramatically increase over the century, with stronger changes for agricultural droughts. The third question is addressed by building two theoretical adaptation scenarios based on hypotheses of adaptation to evolving climate normals, either *retrospective* or *prospective*. These theoretical scenarios take advantage of the spatial consistency of the standardized drought indices to translate the corresponding hypotheses in terms of changes in spatio-temporal characteristics of drought events.

The present study thus provides a proof of concept (1) for assessing spatio-temporal characteristics of future drought events and (2) for deriving spatial theoretical adaptation scenarios using spatial consistency of standardized drought indices like the SPI. In order to have more robust information about the expected changes by providing corresponding estimates of uncertainty, this study could easily be extended to multimodel hydroclimate projections, derived from different GCMs, different downscaling methods as well as different land surface models. Moreover, realistic adaptation scenario could be translated into corresponding evolutions of local drought indices in order to derive projections of spatio-temporal characteristics of drought events, for example at the scale of a specific catchment or a water resource zone. Additionally, drought indices standardized with respect to a model control run as used here would also provide relevant information in a seasonal forecasting context, for example to have an insight on the spatio-temporal development of an ongoing drought. Such an application of standardized drought indices will be tested in the near future based on on-going works on seasonal hydrological forecasting (Céron et al., 2010; Soubeyroux et al., 2010; Singla et al., 2011).

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