



HAL
open science

Low Flows in France and their relationship to large scale climate indices

I. Giuntoli, Benjamin Renard, Jean-Philippe Vidal, A. Bard

► **To cite this version:**

I. Giuntoli, Benjamin Renard, Jean-Philippe Vidal, A. Bard. Low Flows in France and their relationship to large scale climate indices. *Journal of Hydrology*, 2013, 482, p. 105 - p. 118. 10.1016/j.jhydrol.2012.12.038 . hal-00833431

HAL Id: hal-00833431

<https://hal.science/hal-00833431v1>

Submitted on 12 Jun 2013

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Low flows in France and their relationship to large scale climate indices

I. Giuntoli^{a,*}, B. Renard^a, J-P. Vidal^a, A. Bard^a

^a*Irstea, UR HHLY, Hydrology-Hydraulics Research Unit,
3 bis quai Chauveau - CP 220, F-69336 Lyon, France*

Abstract

This study explores the relationship between low flows and large scale climate variability in France. To this aim, a national low flow reference network of near-natural catchments, consisting of 236 gauging stations, was set up. A subset of 220 daily streamflow records for the period 1968-2008 was used to detect trends in a number of severity and timing drought indices. In addition to testing temporal trends, correlations with four climate indices were also evaluated: the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) and the frequency of two Weather Patterns corresponding to circulation types associated to wet (WP2) and dry (WP8) conditions over France. Due to their specific dynamics, NAO and WPs were also analyzed seasonally.

Results show a consistent increase of drought severity in southern France. Correlations with NAO and AMO show a similar spatial pattern. Addition-

*Corresponding author. Tel: +44 1491 692550.
Present address: Centre for Ecology & Hydrology, Wallingford, UK.
Email address: ignazio.g@gmail.com (I. Giuntoli)

ally, significant relationships with WPs were found throughout France, with the exception of the Mediterranean coast. Timing indices appear to be less related to large scale climate indices, whereas some evidence of negative temporal trends was found (e.g. earlier drought start).

To assess the robustness of the above relationships, a subset of 28 stations with longer records was studied over a 60 year period (1948-2008). The results show that, when shifting the time window of the analysis, the correlations between low flow indices and climate indices remain stable, whereas those with respect to time do not.

Seasonal climate indices appear to have stronger links with low flow indices than their annual counterparts. For instance, the summer NAO shows a strong link with severity indices in the northern half of the country. This link is found again for the winter WP2.

The above results indicate that temporal trends should only be used for descriptive purposes, whereas seasonally lagged climate indices are potential candidates as predictors of summer low flows.

Keywords: low flows, trend analysis, correlation analysis, North Atlantic Oscillation, Atlantic Multidecadal Oscillation, Weather patterns

1 **Research Highlights**

2

- 3 1. Trend analysis for low flows in France, based on 220 stations over the
4 period 1968-2008.
- 5 2. Correlations with large-scale climate variability (AMO, NAO, weather

6 patterns).

7 3. Unlike correlations with climate indices, temporal trends are not stable
8 when changing the period of analysis.

9 4. Lagged correlations could be used for seasonal forecasting.

10 **1. Introduction**

11 Understanding the temporal variability of low flows is of paramount im-
12 portance for water resources management, hydrological risk assessment, hy-
13 dropower production, agriculture and other economic activities. This vari-
14 ability depends on catchment characteristics (e.g. size, geology, altitude)
15 as well as external forcings (e.g. climate forcings and direct anthropogenic
16 disturbances). In particular, the impact of large-scale climate variability
17 and change has drawn significant attention over the years (e.g. Kiely, 1999;
18 Kingston et al., 2006; Bouwer et al., 2008; Lavers et al., 2010).

19 This paper aims to study the temporal variability of low flows in France, in
20 relation to large-scale climate variability.

21 *1.1. Trend analyses*

22 At the European scale, the most complete low flow trend analysis to date
23 was performed by Stahl et al. (2010), based on 441 catchments with more
24 than 40 years of data. Results revealed a consistent spatial pattern of change,
25 with generally negative trends (i.e. more severe droughts) in South and East
26 Europe, and positive trends elsewhere. However, this general picture shows
27 variations, depending on the hydrological regime of the studied catchments
28 (rainfall vs. snowmelt-dominated regime). At the scale of France, the study
29 of Renard et al. (2008), based on 90 stations over the period 1960-2000,
30 showed no consistent trends in most parts of the country, with some regional
31 exceptions in the Pyrenees and the Alps.

32 *1.2. Relationship with large-scale climate variability*

33 Correlations analyses with indices quantifying large-scale climate vari-
34 ability have been performed by many authors. For the European region, the
35 most relevant modes of climate variability appear to be the North Atlantic
36 Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO).

37 The NAO represents a pattern of North Atlantic climate variability. It can
38 be quantified by an index defined as the normalized pressure difference be-
39 tween two stations: one over the Azores subtropical high, and one over the
40 Iceland polar low (Hurrell, 1995). The positive phase of the NAO (NAO+)
41 corresponds to a strong pressure gradient and is characterized by stronger-
42 than-average westerlies associated with warm and wet winters over Northern
43 Europe, and to a drier weather into the Mediterranean. Conversely, the
44 negative phase (NAO-) is associated with cold and dry winters in North-
45 ern Europe, and moist air (increased precipitations) into the Mediterranean
46 (Hurrell and VanLoon, 1997).

47 During positive and negative NAO phases, prevailing atmospheric condi-
48 tions have an impact on river hydrology. Pociask-Karteczka (2006) proposed
49 a review of the main links detected between the NAO and river hydrology.
50 Several studies have been carried out at the European scale. Shorthouse and
51 Arnell (1997) have shown that during winter positive NAO phases, winter
52 streamflows are generally higher in Northern Europe, and, inversely, lower in
53 Southern Europe. Similarly Bouwer et al. (2008) confirm that hydrological
54 regimes that are most sensitive to NAO variations are located at the North-

55 ern and Southern extremities of Europe, i.e. in the Scandinavian and in the
56 Iberian peninsulas. Wrzesinski and Paluszkiwicz (2011) classified European
57 river profiles according to the dependence between streamflow and the inten-
58 sity of the NAO.

59 These general results have been confirmed by studies focusing on specific re-
60 gions, e.g. Scandinavia (Kingston et al., 2006) or the British Islands (Wilby
61 et al., 1997; Kiely, 1999; Stahl et al., 2001). Moreover, several lagged links,
62 particularly interesting for their potential use in seasonal forecasting, have
63 been highlighted. In England and Wales, a negative phase of winter NAO
64 is generally followed by a negative anomaly of fall streamflows (Wedgbrow
65 et al., 2002). Conversely, positive phases of winter NAO are usually associ-
66 ated with the following characteristics:

- 67 • In Iceland, positive anomaly of mean annual streamflow of the following
68 year (Jónsdóttir et al., 2004).
- 69 • In the Alps, low streamflows during the spring snowmelt (Stahl et al.,
70 2001).
- 71 • In Central Europe, low streamflows in late summer / beginning of
72 the fall (Limanówka et al., 2002; Kaczmarek, 2003; Pociask-Karteczka
73 et al., 2003).
- 74 • In several regions of Southern Europe, pronounced summer droughts,
75 as for instance in the Iberian Peninsula (Stahl et al., 2001; Trigo et al.,

76 2004; Vicente-Serrano and Cuadrat, 2007), in Romania (Stefan et al.,
77 2004) or in the downstream Danube (Rimbu et al., 2002, 2004).

78 In France, the impact of the NAO on hydrological regimes remains unclear.
79 Cassou (2004) investigated how atmospheric and oceanic systems are linked
80 to the NAO, but without specific focus on hydrological regimes. Massei et al.
81 (2010) is one of the few studies on hydrological impacts of the NAO in France,
82 in which the covariation between the NAO and the Seine catchment stream-
83 flows is analyzed.

84 The AMO represents a pattern of Atlantic multidecadal climate variability,
85 and refers to detrended anomalies in the Sea Surface Temperature (SST)
86 in the North Atlantic Ocean. These anomalies are explained by fluctua-
87 tions in the thermohaline circulation in the North Atlantic and account for a
88 leading large scale pattern of multidecadal variability in surface temperature
89 (Knight, 2005). Differently from the NAO, the AMO is characterized by
90 longer positive or negative phases that may persist for 20 to 40 years. There
91 have been mainly two warm (1860-1880, 1930-1960) and two cool (1905-1925,
92 1965-1990) phases since 1860. The AMO amplitude has been increasing since
93 about 1990 and from 1995 onward seems to be in its warm phase (Enfield
94 et al., 2001).

95 Many prominent examples of regional multidecadal climate variability have
96 been related to the AMO (Knight et al., 2006), for instance the frequency
97 of Atlantic hurricanes (Goldenberg et al., 2001; Trenberth and Shea, 2006;
98 Enfield and Cid-Serrano, 2009) or the occurrence of Sahel droughts (Rowell

99 et al., 1995; Rowell, 1996). The AMO has also been shown to affect North
100 American and European summer climate (Sutton and Hodson, 2005): a positive
101 AMO anomaly is related to decreased mean sea level pressure over the
102 whole North-Atlantic basin, along with lower rainfall over the US and in-
103 creased rainfall in North West Europe.

104 In North America, the influence of this climate index on the temporal vari-
105 ability of streamflow and precipitation has been studied extensively. Enfield
106 et al. (2001) studied the impact of the AMO on rainfall and river flows in
107 the continental US, finding that the warm phases are associated with negative
108 anomalies on the majority of the country. McCabe et al. (2008) looked
109 specifically at US droughts, showing that warm AMO phases are associated
110 with more frequent or longer droughts in the Midwest, and with less intense
111 droughts in Florida and in the North West. Assani et al. (2011) found a link
112 between the warm phase of the AMO and rainfall and streamflow deficit in
113 Quebec.

114 In Europe in general, the influence of AMO on temporal variability of stream-
115 flow has received less attention. Regarding the evolution of glaciers in the
116 Swiss Alps, Huss et al. (2010) showed that the AMO is inversely correlated to
117 the glaciers' mass balance: a positive AMO is associated with Alpine glacier
118 mass loss, whereas during negative AMO periods glaciers experience reduced
119 mass loss or even mass gain. In France, in particular, the impact of the AMO
120 remains largely unknown. Noteworthy is the study by Tourre et al. (2011),
121 who found the AMO index to have an effect on temperatures variability in

122 the Paris region and on grape harvest dates in the Burgundy region.
123 The NAO and the AMO describe climate variability on a relatively broad
124 scale. Considering that this study focuses on France and on rather small
125 catchments, we also decided to use local climate variability indices. More-
126 over, the literature indicates that the influence of NAO and AMO is stronger
127 at the ends of the European continent (South and North). France is located
128 right in the middle of the two areas of influence which are affected by oppo-
129 site effects.

130 Weather patterns (WPs, or "circulation patterns" when defined by air pres-
131 sure only) are often used to describe the atmospheric situation over a region
132 as a categorical variable, which has potential to reveal important information
133 about the climatic mechanisms driving drought development (Fleig et al.,
134 2011). As region-specific indices, they are potentially more explanatory than
135 the NAO and the AMO when it comes to link climate variability to hydrology.
136 Weather patterns are widely used in atmospheric sciences for grouping
137 similar synoptic weather situations which lead, for a given geographical area,
138 to similar meteorological conditions. Numerous methods of weather pat-
139 tern classification are available (see e.g. Huth et al., 2008; Fleig et al., 2010;
140 Philipp et al., 2010, and the COST733 European action for reviews and
141 comparisons).

142 A number of studies revealed the interest in classifying weather patterns in
143 hydrology. Several authors have shown the link between the rainfall distribu-
144 tion and weather patterns (Littmann, 2000; Boé and Terray, 2008; Lorenzo

145 et al., 2008; Martínez et al., 2008; Garavaglia et al., 2010, 2011). Similar
146 relations exist with hydrological variables (Samaniego and Bárdossy, 2007;
147 Petrow et al., 2009), and, more specifically, with low flows [e.g. Stahl and
148 Demuth (1999) in Germany; Pongrácz et al. (2003) in Central Europe; Fleig
149 et al. (2011) in Denmark and the UK].

150 For this study, we used the weather patterns defined by Garavaglia et al.
151 (2010), which result from a classification of atmospheric circulation patterns
152 relevant to French climatology. The classification uses a limited number (8)
153 of typical but contrasted synoptic situations described by geopotential fields.
154 The data is assigned to the 8 WP classes according to geopotential heights
155 between 700 and 1000 hPa. Note that, although the assignment rule is solely
156 based on geopotential information, precipitation data is also used to deter-
157 mine the number of classes and to initialize the clustering algorithm (see
158 Garavaglia et al. (2010), for more details).

159 *1.3. Objectives and outline of the paper*

160 This paper aims to study the temporal variability of low flows in France,
161 in relation to large-scale climate variability. The specific objectives are the
162 following:

- 163 • Describe a reference dataset of 220 gauging stations suited to the mon-
164 itoring of climatic effects on low flows in France.
- 165 • Update the trend analysis previously performed by Renard et al. (2008)

166 by considering more gauging stations, thus providing an extended pe-
167 riod of analysis and a markedly improved spatial coverage.

- 168 • Move beyond the sole trend analysis by attempting to link low flow
169 variability with large-scale climate variability.

170 This analysis contributes to the extended literature discussed in previous
171 sections, thus improving the understanding of the role of climate variability
172 on low flow regimes. In particular, specific points of interest are:

- 173 • The analysis is based on an extended dataset of thoroughly inspected
174 daily series, providing a remarkable temporal and spatial extent.
- 175 • The analysis uses hydrological indices describing drought events based
176 on daily data rather than monthly or seasonally averaged discharges.
177 This is of interest for a more event-based description of low flows, in
178 particular in terms of timing and severity.
- 179 • The analysis uses several climate indices describing distinct modes of
180 variability, at inter-annual and seasonal time scales.
- 181 • The analysis has a nation-wide spatial extent, thus contributing to a
182 better understanding of the role of climate in low flow variability in
183 France.

184 The remainder of this paper is organized as follows. Section 2 describes
185 the data and methods used in this analysis, including the reference gauging

186 stations network (section 2.2), the definition of hydrological (section 2.3) and
187 climate (section 2.4) indices, and the statistical trend and correlation testing
188 procedures (section 2.5). Section 3 describes the main results of this analysis,
189 both in terms of temporal trends and correlations with climate indices. The
190 consequences and perspectives of these results are discussed in section 4,
191 before summarizing the main findings in section 5.

192 **2. Data and methods**

193 *2.1. Data requirements*

194 The analysis of low-flows variability is based on hydrological time series,
195 recording river discharges at gauging stations. The importance of good-
196 quality datasets can not be overemphasized, as recently recalled by Hannah
197 et al. (2011). Given the various forcings controlling low flows, disentangling
198 the effects of measurement errors, anthropogenic disturbances and climate
199 variability/change, is a tremendous challenge. When understanding the role
200 of climate in low flow variability is the main interest, the most tractable so-
201 lution is to select gauging stations where non-climatic factors of change can
202 be minimized (if not discarded). In particular, this requires selecting gaug-
203 ing stations suited to low flow measurements (e.g. with a gauging section
204 enabling a stable rating curve), controlling near-natural catchments where
205 anthropogenic disturbances are negligible. Moreover, long series spanning
206 several decades are necessary if trends and relationships with large-scale cli-
207 mate variability are to be identified.

208 Many studies in the literature have analyzed low flow variability based on
209 such datasets. In general, these studies can be classified into two categories:
210 (i) trend analyses, reporting the magnitude and significance of temporal
211 trends in hydrological variables (e.g. Stahl et al., 2001; Burn and Elnur,
212 2002; Birsan et al., 2005; Hannaford and Marsh, 2006; Renard et al., 2008,
213 amongst many others); (ii) correlation analyses, linking temporal variabil-
214 ity of hydrological variables to various indices quantifying large-scale climate
215 variability (e.g. Kingston et al., 2006; Vicente-Serrano and Cuadrat, 2007;
216 McCabe et al., 2008; Assani et al., 2011, amongst many others).

217 *2.2. French Reference Low Flow Network*

218 Several countries have set up reference gauging networks in order to mon-
219 itor the evolution of hydrological regimes and to assess the impact of climate
220 variability and change (Whitfield et al., 2012). The UK, for instance, has set
221 up a reference network of 120 relatively undisturbed catchments (Bradford
222 and Marsh, 2003) which was used to assess trends in low flows (Hannaford
223 and Marsh, 2006) and floods (Hannaford and Marsh, 2008). Similarly the
224 French National Agency for Water and Aquatic Environments (ONEMA)
225 set up a project for creating a nationwide reference network of trustworthy
226 gauging stations from relatively undisturbed catchments aiming at monitor-
227 ing the evolution of low flow regimes. Daily streamflow time series from the
228 French Banque HYDRO Archive (Ministry of Environment) were selected in
229 order to meet the following criteria: (a) at least 40 years of daily records; (b)

230 the gauging station controls a catchment with no appreciable direct human
231 influence on river flow; (c) data quality is suitable for low flow analysis.

232 The first selection of gauges, based on the Banque HYDRO metadata, were
233 thoroughly inspected so that stations of low quality or not meeting the cri-
234 teria were discarded. In particular, all time series were visually screened one
235 by one in search of visual inhomogeneities. Moreover, they underwent a sta-
236 tistical trend and step-change analysis on a number of streamflow indices,
237 based on the Mann-Kendall trend test (Mann, 1945; Kendall, 1975) and the
238 Pettitt step-change test (Pettitt, 1979). Suspicious changes and trends were
239 noted and checked through an exchange with the data providers aiming at
240 linking anomalies to particular events (e.g. rating curve change, construc-
241 tions affecting the river, occurrence of specific extreme events, change of the
242 station location). If the change was linked to a specific cause, the station
243 was excluded from the data set.

244 Finally, the Benchmark Low Flow Network¹ comprises 236 gauging stations
245 whose time availability is shown in figure 1a. Figure 1b shows the number of
246 stations available per year. The period 1968-2008 provides the best trade-off
247 for data availability in time and space. Consequently, a subset of 220 stations
248 available over the period 1968-2008 was used in this study.

249 Figure 2 shows the location of the selected stations. The majority of gaug-

¹A subset of 209 stations is also suitable for flood analyses (Giuntoli et al., 2012). Part of this dataset is currently being transferred to the Global Runoff Data Center (GRDC, <http://grdc.bafg.de/>).

250 ing stations control catchments with a rainfall-dominated hydrological regime
251 (184), while 36 catchments have a snowmelt or mixed (snowmelt-rainfall) hy-
252 drological regime, mostly in the Pyrenees and in the Alps. Figure 1c shows
253 the distribution of catchments areas. The selected catchments are in general
254 relatively small, 85% of catchments being smaller than 1000 km².

255 *2.3. Low flow indices*

256 Low flow indices were extracted from the daily streamflow series in order
257 to quantitatively summarize the main properties of hydrological droughts:
258 summer low flows due to low precipitation and high evapotranspiration for
259 rainfall regimes; winter low flows due to snow and ice storage for snowmelt
260 and mixed regimes. Different hydrological years were defined for the two
261 types of regime in order to locate low flow periods roughly in the middle
262 of the year. For rainfall-dominated gauges the year starts in February and
263 ends in January of the following calendar year. For snowmelt-dominated
264 and mixed gauges the hydrological year was set to start in May ending in
265 April of the following calendar year. Low flows events were pooled using
266 a low flow threshold, which was set for each station to the quantile Q15
267 of the interannual flow duration curve (corresponding to the flow that is
268 exceeded for 85% of the period of record, as in e.g. Tallaksen and Van Lanen
269 (2004)). This quantile results from the trade-off between having a sufficiently
270 low threshold to characterize low flows, while avoiding having years with no
271 threshold crossing. All indices were extracted yearly. For snowmelt and

272 mixed regimes, analyses (not shown) were made considering two distinct low
273 flow periods (May+6months, November+6months): because the number of
274 these stations is small we decided to avoid this distinction and adopt yearly
275 indices as we did for rainfall dominated gauges.

276 Preliminary analyses (not shown) suggested that the following six indices
277 provide complementary drought information (Figure 3):

- 278 1. the annual mean discharge (A Mean)
- 279 2. the annual minimum discharge (A Min)
- 280 3. the annual volume deficit below a low flow threshold (Vol. Def.)
- 281 4. the drought start (Start)
- 282 5. the drought center (Center)
- 283 6. the drought end (End)

284 Indices 1-3 describe the drought severity, while indices 4-6 describe the
285 drought timing. The volume deficit index (3) is equal to the sum of the
286 volume deficits over the whole year. Timing indices 4-6 were adapted from
287 the concept of "center of mass" proposed by Stewart et al. (2005): indices
288 Start, Center and End correspond to the day when the volume deficit reaches
289 10%, 50%, 90% of its annual value, respectively. Timing indices are expressed
290 in number of days after the year start.

291 *2.4. Climate indices*

292 In order to study the relationship between hydrological and climatic vari-
293 ability, climate indices can be used to quantify the main modes of climate

294 variability relevant to the French region. The indices selected for this study
295 are two well-known large scale climate indices, the NAO and the AMO,
296 and two weather patterns corresponding to frequent synoptic situations over
297 France.

298 *2.4.1. AMO*

299 The time series for the unsmoothed AMO monthly index was downloaded
300 from the US National Oceanic and Atmospheric Administration web site ².
301 This monthly time series was averaged over hydrological years, yielding the
302 annual series shown in Figure 4a. Two AMO series were used, correspond-
303 ing to averaging over the two distinct hydrological years considered for the
304 hydrological indices (see section 2.3 - only the February-January averaged
305 series is shown in Figure 4a).

306 *2.4.2. NAO*

307 The time series for the NAO monthly index as defined by Jones et al.
308 (1997) (normalized pressure difference between Gibraltar and Reykjavik sta-
309 tions) was downloaded from the Climate Research Unit web site ³. Similarly
310 to the AMO, averaging over the hydrological year yields the annual NAO se-
311 ries, as shown in Figure 4b for February-January. However, unlike the AMO
312 index, the within-year variability of the NAO is not negligible compared with
313 interannual to interdecadal variations. Consequently, seasonal NAO indices

²<http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data>

³<http://www.cru.uea.ac.uk/cru/data/nao/>; accessed September 2011

314 were also used, by averaging monthly values over the four boreal seasons:
315 winter (DJF), spring (MAM), summer (JJA) and fall (SON).

316 *2.4.3. Weather Patterns*

317 A daily times series of WP occurrence was provided by Electricité de
318 France (EDF, French Power Company) for the period 1953-2008 (as in Gar-
319 avaglia et al., 2010). In this series, each day is assigned a WP value between
320 1 and 8 according to the weather pattern. WP indices can then be derived
321 by counting the frequency of each WP within a given time-frame (a hydro-
322 logical year or one of the four seasons). Two weather patterns were used
323 in this study: WP2, associated with Atlantic westerly circulations yielding
324 wetter-than average conditions over most of France, except in the South the
325 Mediterranean and the Massif Central regions; and WP8, associated with
326 anticyclonic situations yielding drier-than-average conditions over the whole
327 country. These specific patterns were chosen because they are the two most
328 frequent (23 and 28% of days for WP2 and WP8, respectively) and are hence
329 likely to play an important role in the development of drought events. Fig-
330 ure 4c-d show the WP2 and WP8 indices, corresponding to the standardized
331 annual frequency of WP2- and WP8-days (standardization was obtained by
332 subtracting the mean and dividing by the standard deviation computed over
333 the whole period of record 1953-2008). Similarly to the NAO, seasonal in-
334 dices were also derived by restricting the computation of WP frequencies to
335 the four boreal seasons.

336 *2.5. Trend and correlation tests*

337 As in other studies (Stahl et al., 2010; Wilson et al., 2010), this paper
338 aims to present the overall regional patterns of streamflow evolution and
339 variability. To this aim, the existence of trends in the hydrological indices
340 defined in section 2.3 was evaluated. Moreover, correlations between hydro-
341 logical indices and climate indices (section 2.4) were explored.

342 Since the distribution of hydrological indices may be difficult to elucidate
343 (it may vary from one index to the next, and from station to station),
344 non-parametric testing procedures were used. The Mann-Kendall trend test
345 (Mann, 1945; Kendall, 1975) was used for evaluating the presence of trends
346 in the low flow indices series. The modification suggested by Hamed and
347 Rao (1998) to account for potential autocorrelation was implemented. Cor-
348 relations between hydrological and climate indices were tested using the
349 Kendall's tau test (Kendall, 1938). This test evaluates whether the Kendall's
350 tau between two variables (here, climate index X vs. hydrological index Y)
351 significantly differs from zero. The Kendall's tau is a rank-based alternative
352 to the Pearson linear correlation coefficient, which may be more relevant for
353 non-linear associations and/or markedly non-Gaussian data.

354 Both tests are based on ranks and therefore do not make any assumption
355 on the distribution of data. Note that the Mann-Kendall test is a particular
356 case of the Kendall's tau test, obtained by replacing the climate index X
357 by a time index (e.g. $1, \dots, n$). From this point of view, the trend analysis
358 can be considered as a particular correlation analysis with the time used as

359 covariate in lieu of the climate index.

360 The analysis was carried out in three steps:

- 361 1. Correlations between *annual* climate indices and hydrological indices
362 were sought for 220 stations over the period 1968-2008.
- 363 2. Same as 1. for a subset of 28 long series covering the period 1948-
364 2008. Three periods of analysis were considered: 1948-1988 (40 years),
365 1968-2008 (40 years) and 1948-2008 (60 years). The objective was to
366 assess the stability of detected trends and correlations when changing
367 the period of analysis. Note that data were not available before 1953
368 for correlations with WPs.
- 369 3. Correlations between *seasonal* climate indices (NAO, WP2 and WP8)
370 and hydrological indices were sought for 220 stations over the period
371 1968-2008. This analysis was performed in order to evaluate the exis-
372 tence of lagged correlations (e.g. between a characteristic of the sum-
373 mer drought and a climate index computed over the preceding winter)
374 which are of interest for seasonal forecasting purposes. For the ma-
375 jority of the stations (rainfall regime), the hydrological year starts in
376 February and low flows occur mainly in the summer (June-August), so
377 the seasons with a lag are primarily the winter, and to a lesser extent,
378 spring and fall. For the remainder of the stations (mixed and snowmelt)
379 the hydrological year starts on May. For mixed regime stations, low
380 flow periods are in summer and winter, so the lagged seasons are the
381 preceding winter and spring, and the fall of the same year. For purely

382 snowmelt stations, the main low flow period is fall through winter, so
383 the lagged seasons are the preceding winter and spring, and the summer
384 or the same year.

385 For each station, the values of hydrological indices are considered as missing
386 for years with more than 10% of missing daily data.

387 **3. Results**

388 The results are presented through maps of the spatial variability of the
389 trends/correlations, as in Figure 5. Significant correlations are shown with
390 color dots, blue (negative correlation) and red (positive correlation) for rain-
391 fall regime, green (negative correlation) and brown (positive correlation) for
392 snowmelt regime. The distinction is made because the two regime types are
393 calculated over different hydrological years. The legend shown in Figure 5
394 applies to all figures of this section.

395

396 *3.1. Year-to-year links: annual climate indices*

397 The results for year-to-year links between climate and low flow indices
398 are presented at the hydrological year scale (period 1968-2008). Figure 5
399 shows the results of the Kendall tests for, on the one hand, the three severity
400 indices (annual mean flow, annual minimum flow, volume deficit) and, on the
401 other hand, the four annual climate indices and time. On the first column of
402 this figure the temporal evolution is shown. The next neighboring columns

403 describe the association with the climate indices. Moreover, Table 1 gives
404 the percentages of significant correlations (at 10% error level).

405 In terms of temporal evolution, the first column of Figure 5 highlights a
406 distinct North-South pattern: significant trends toward more severe low flows
407 were detected for many stations in the Southern half of France, while most
408 stations of the Northern half show no significant trends. The new study
409 confirms the trend towards more severe droughts that was found in South-
410 Western France by Renard et al. (2008), but this trend is now more clearly
411 apparent over all Southern France.

412 The most striking results are the consistent correlations detected between
413 the hydrological indices and the weather patterns WP2 and WP8. These
414 correlations are found over the whole territory with the exception of the
415 Mediterranean coastal region. They are highly significant for the annual
416 mean flow, a little less for the annual minimum flow and the volume deficit,
417 but preserving a remarkable spatial homogeneity. The sign of the correlations
418 is sound with the interpretation of the indices WP2 and WP8: a high value of
419 WP2 corresponds to a high frequency of wet weather "western circulation",
420 leading to high values of annual mean and minimum flow, and low values for
421 volume deficit. A similar reasoning applies to the WP8, corresponding to a
422 dry weather.

423 Correlations were also detected for the AMO. The spatial pattern is similar
424 to the one observed for temporal trends (first column), especially in the
425 mountainous areas of the Pyrenees (South-West) and the Cevennes (Center-

426 South). This is particularly interesting, and suggests that, for these regions,
427 detected temporal trends could partly result from the correlation with the
428 AMO. Indeed, the AMO has seen an overall pronounced increase in the study
429 period (1968-2008, see 4a). A hydrological index correlated with the AMO
430 would be expected to have a similar temporal trend. Nonetheless, if this
431 trend does stem from the AMO, it may disappear over a longer period, with
432 the AMO's variability. This possibility will be examined further with the
433 stability of correlations assessed over different periods (following section).
434 The correlations with the NAO are mainly found for the center of France. In
435 particular, a cluster of significant correlations was detected with the annual
436 mean flows for the Cevennes (Center-South) region.
437 Results for the three timing indices are shown in Figure 6. On the whole,
438 correlations with climate indices are less prominent compared to the previous
439 severity indices. In particular, the influence of NAO and AMO is weak and
440 does not have a specific spatial pattern. Correlations with WP2 and WP8 are
441 more numerous, especially for the drought start and end, and are spatially
442 coherent: years with high frequencies of dry weather WP8 correspond to an
443 earlier drought start (in the Center and in Brittany), and a later drought end
444 (in the North and the Pyrenees), and inversely for WP2. Figure 6 also shows
445 that a number of temporal trends exist for drought timing (first column), the
446 drought start in particular, but the spatial pattern does not match any of
447 the climate indices patterns. This suggests that temporal trends in drought
448 timing are not affected by climate variability.

449 *3.2. Year-to-year links: stability of hydro-climatic links*

450 A subset of 28 long series, covering the period 1948-2008, was used to
451 assess the stability of detected correlations for different time periods. Figure
452 7 shows temporal trends detected over the periods: (i) 1948-1988 (40 years);
453 (ii) 1968-2008 (40 years, same as the analysis in the previous section); (iii)
454 the entire period 1948-2008 (60 years).

455 For simplicity the results shown are limited to three hydrological indices:
456 annual mean flow, drought start, and volume deficit. Temporal trends are
457 visibly not stable from one period to the next: for the annual mean flow,
458 for instance, the 1948-1988 analysis suggests a positive trend, but this trend
459 is reversed over the subsequent period 1968-2008, and fades away over the
460 entire period 1948-2008. When comparing the periods lasting to 2008, what
461 is detected in the short period 1968-2008, is barely found in the long period
462 1948-2008, or, in the case of Volume Deficit, detections are not found in the
463 same areas. The same lack of stability is observed in the other hydrological
464 indices.

465 The analysis was also carried out using the climate indices. For the AMO
466 (results not shown) the regions where this index has an influence (Pyrenees,
467 Cevennes) are underrepresented among the available data set of 28 stations.
468 No clear correlation pattern was therefore detected consistently over the dif-
469 ferent periods.

470 The results for the NAO are more conspicuous (Figure 8): the correlations
471 detected over the three periods remain consistent. The influence of the NAO

472 on annual mean flows in the center of France remains visible over the three
473 periods. For the drought indices the influence is much smaller, but still con-
474 sistent over the three periods.

475 Lastly the results for the WP8 show a good stability of the correlations
476 (Figure 9): the correlations WP8-annual mean flow and WP8-volume deficit
477 remain consistent no matter the period of analysis. Similar results were found
478 for the WP2 index (not shown).

479 The lack of stability of temporal trends stands in contrast with the fairly
480 good stability of correlations with climate indices (when they exist) and ac-
481 counts for an important result which leads to several remarks. Firstly, this
482 result confirms that the detected temporal trends should not be extrapolated
483 into the future, or at least not on the basis of the results presented in this
484 study. Conversely, although more stations and longer periods are required to
485 corroborate this hypothesis, the fact that the links climate-hydrology remain
486 stable, is per se an indication of the suitability of climate indices to explain
487 the temporal variability of hydrological regimes.

488 As discussed in section 3.1, the temporal trends detected on hydrological
489 regimes could originate (at least partly) from a dependence to large scale
490 climate variability, on the basis of the following rationale: (i) hydrological
491 indices depend on climate indices; (ii) some climate indices have a strong
492 temporal inertia, which can create apparent trends on short periods of a few
493 decades (especially for the AMO); (iii) some temporal trends detected on
494 hydrological indices could indeed result, at least in part, from the inertia of

495 the climate indices.

496 *3.3. Lagged links: seasonal climate indices*

497 Correlations between low flow indices and seasonal climate indices are
498 now presented with specific focus on lagged correlations (e.g. a winter or
499 spring climate index with a high correlation with summer droughts). This
500 type of correlation can pave the way for seasonal forecasting applications.

501 Figure 10 shows the Kendall test results between the six hydrological indices
502 (rows) and the four seasonal NAO series (columns). As highlighted in section
503 1.2, the winter NAO (first column), during its positive phase, is associated
504 with higher flows in Northern Europe (Shorthouse and Arnell, 1997), and
505 conversely, with more pronounced droughts in the Iberian Peninsula (Vicente-
506 Serrano and Cuadrat, 2007). None of these links are visible in France: all
507 severity indices (annual mean and minimum flows and volume deficit) are
508 scarcely correlated to winter NAO. Some correlations are detected for timing
509 indices but in a dispersed fashion. Contrary to what is observed in Northern
510 and Southern Europe, it appears that French hydrological regimes are barely
511 influenced by winter NAO.

512 The next noticeable result is the strong link between summer NAO and
513 severity indices (annual minimum flow and volume deficit) detected for the
514 Northern half of the country. This prominent link opens new interesting
515 perspectives for seasonal forecasting. This point will be further discussed in
516 the discussions section.

517 Overall, the seasonal scale allows highlighting correlations more prominently
518 than at the annual scale. When looking at severity indices, the annual scale
519 (Figure 5) does not show the compelling correlations found at the seasonal
520 scale (Figure 10) for the summer NAO. It is thus convenient to consider this
521 mode of variability at the finer scale of seasons.

522 The results obtained for the seasonal WP2 are shown in Figure 11. The large
523 number of lagged correlations detected for the Northern half of the country
524 between winter/spring WP2 and the hydrological indices of drought severity
525 (and the timing indices to a lesser extent) is not surprising: it occurs during
526 a period of high flows when groundwater storages have been replenished
527 by winter precipitation. As discussed previously, this result brings about
528 interesting perspectives for seasonal forecasting. This is especially true for
529 the WP2, as lagged correlations provide information on upcoming low flows
530 without the need to predict the climate index.

531 As for the WP2, numerous correlations are detected between seasonal WP8
532 and the hydrological indices (Figure 12). However, unlike WP2 and summer
533 NAO, the correlations are not limited to the Northern half of France but
534 stretch out to the South as well. The most pronounced correlations are:

- 535 • The annual mean flow and the fall WP8, mainly in the center of France
536 and in Brittany (North West).
- 537 • The drought severity indices and winter/spring/summer WP8, over
538 the majority of the country, except the Pyrenees, the Alps and the

539 Mediterranean coast.

- 540 • The drought timing indices and WP8. The drought start is strongly
541 correlated with the spring/summer WP8, whereas for the drought cen-
542 ter and end the strongest correlation is with the fall WP8.

543 **4. Discussion**

544 The results of the analysis demonstrate that the response of low flows to
545 climate large-scale variability varies spatially and temporally. This section
546 discusses the consequences of these findings, both in terms of limitations and
547 opportunities.

548 *4.1. Trends vs. climate-induced oscillations*

549 When considering temporal trends, drought severity increases in South-
550 ern France, and this result is in agreement with those of Stahl et al. (2010).
551 However, correlations with the AMO and NAO indices follow a similar spa-
552 tial pattern (although with less detections), suggesting that, to a certain
553 extent, trends in drought severity could result from the low-frequency vari-
554 ability of AMO and NAO. Conversely, drought timing indices show numerous
555 downward trends, whereas correlations with AMO, NAO and WPs are less
556 pronounced and do not show a similar spatial pattern.

557 In the stability of hydro-climatic links analysis (section 3.2) we assume that,
558 if oscillating/quasiperiodic trends exist, they are found in the hydrological
559 indices, and they are the result of oscillating/quasiperiodic trends in climate

560 indices. Interestingly, the reversed temporal trends detected over different
561 time windows from long series, are similar to those seen in a comparable
562 analysis conducted by Hannaford and Buys (2012) in the UK. The authors
563 assessed trends via a moving window trend analysis and found trends shift-
564 ing from largely positive to negative around 1965, suggesting that large-scale
565 atmospheric circulation changes may be responsible.

566 These observations highlight the difficulties in distinguishing between long-
567 term trends and low-frequency variability based on relatively short series.
568 This is problematic because operational consequences (e.g. updating fre-
569 quency analysis procedures to account for non-stationarity) very much de-
570 pend on the actual type of evolution affecting the data. This ambiguity also
571 reemphasizes the fundamental distinction between trend detection and at-
572 tribution (IPCC, 2007, chapter 1.3.3.), or similarly, between correlation and
573 causality. In this study, no causal relationship can be formally inferred from
574 the results, since only correlations (whether with time or with climate in-
575 dices) are investigated. At the most, the lack of stability of temporal trends
576 suggests that climate indices are better candidates to explain the temporal
577 variability of low flows - but without demonstrating that it *causes* it. Merz
578 et al. (2012) discuss this issue in further depth and propose avenues to move
579 forward in the direction of attribution, which is in our opinion an important
580 challenge to tackle.

581 *4.2. Frequency analysis and the iid hypothesis*

582 The dependence of low flow regimes to large-scale climate variability may
583 be problematic for standard frequency analyses approaches. As a matter of
584 fact, standard methods assume independent and identically distributed (iid)
585 observations. This hypothesis is inadequate if the distribution of low flow
586 variables depends on some climate indices, as shown in this study.

587 The most problematic case occurs when this dependence is on a low-frequency
588 mode of variability (e.g. the AMO). Indeed, the representativeness of hydro-
589 logical series spanning over a few decades might be questionable due to the
590 inertia of climate variability (see the discussion by e.g. Jain and Lall, 2001).
591 There is, therefore, a distinct possibility to under- or over-estimate the actual
592 hydrological risk, depending on the available record period.

593 This hurdle is well known for some areas of the world, where the impact of
594 low-frequency climate variability on hydrological regimes is well documented.
595 In the United States, regime shifts characterizing global climate oscillations
596 and their potential impact in hydrology have been reported around 1970 (e.g.
597 McCabe and Wolock, 2002; Mauget, 2003). In particular, Collins (2009)
598 reported that, along the United States east coast, increasing flood magni-
599 tudes occurred in 1970, and are concurrent with a phase change in the low
600 frequency variability of the NAO. The authors suggest that, when known,
601 hydroclimatic shifts should be considered when the affected flow records are
602 used for hydrological frequency analyses.

603 In Australia, the impact of the Interdecadal Pacific Oscillation (IPO) on hy-

604 drology has been extensively reported (e.g. Franks, 2002; Franks and Kuczera,
605 2002), amongst other modes of climate variability (e.g. Keim and Verdon-
606 Kidd, 2009). In order to overcome these difficulties, innovative frequency
607 analysis approaches have been proposed (e.g. Micevski et al., 2006a,b; Thyer
608 and Kuczera, 2000, 2003a,b; Verdon-Kidd and Kiem, 2010), and could be
609 adapted to the context of France. In particular, such approaches explicitly
610 integrate the role of climate variability, and attempt to make the best use of
611 available long series at a regional scale.

612 *4.3. Seasonal forecasting*

613 The results obtained with seasonal climate indices yield interesting per-
614 spectives in terms of seasonal forecasting, which is a valuable tool for e.g.
615 water resources management, hydropower management, and agriculture. For
616 instance, the summer NAO has strong links with drought severity over north-
617 ern France. This implies that, if one can predict the summer NAO, one can
618 therefore infer drought severity for the same summer. This option is fairly
619 limited by the overall prediction skill of the NAO, which is only satisfactory
620 for periods of 1-2 weeks (Johansson, 2007). A better option would be to use
621 the observed value of winter/spring WP2 and WP8, which could enable a
622 direct seasonal forecast of the summer drought severity.

623 Developing such a seasonal forecasting system would require moving beyond
624 the detection approach used in this study (which constitutes, however, a valu-
625 able preliminary step to identify compelling climate indices). It could build

626 on the numerous examples of seasonal forecasting systems based on statisti-
627 cal relationships with large-scale climate variability existing in the literature
628 (e.g. Sharma, 2000a; Sharma et al., 2000; Sharma, 2000b; Wilby et al., 2004;
629 Westra et al., 2008; Lima and Lall, 2010; Gong et al., 2011). Moreover, in-
630 vestigating the role of additional climate indices might be valuable, since for
631 instance the Mediterranean region displayed very few links with the climate
632 indices used in this study. In particular, alternative WP classifications might
633 be of interest (e.g. Cassou et al., 2004, 2005). The joint use of several com-
634plementary climate indices may also improve predictability.

635 Lastly, using statistical relationships between hydrological indices and large-
636 scale climate variability is not the sole approach to seasonal forecasting. In
637 particular, an alternative is to use an atmospheric model to produce fore-
638 casts of climate forcings, and to use them as inputs of a hydrological model
639 to produce hydrological forecasts (e.g. Ceron et al., 2010; Soubeyroux et al.,
640 2010; Singla et al., 2012, for applications in France).

641 *4.4. Impact of climate change on hydrological droughts*

642 Another potential application of the hydro-climatic relationships high-
643 lighted in this study pertains to projecting the impact of climate change on
644 low flows. The standard approach to this problem is to force a hydrological
645 model with future forcings (e.g. precipitation, temperature) projected by
646 a General Circulation Model (GCM), possibly after a downscaling or bias-
647 correction procedure (see e.g. Vidal and Hendrickx, 2010; Hendrickx and

648 Sauquet, 2012, for examples in France). A drawback of this approach is the
649 difficulty to reliably reproduce some key variables for catchment hydrology
650 (in particular, precipitation, Vidal and Wade, 2008). Moreover, the ability
651 of hydrological models to extrapolate beyond the range of forcing conditions
652 used for its calibration remains unclear (e.g., Merz et al., 2011).

653 An alternative approach would be to directly use the statistical relationships
654 detected between hydrological and climate indices (similarly to seasonal fore-
655 casting, but without the requirement of asynchronicity). In other words,
656 this approach would imply to directly downscale streamflow indices from cli-
657 matic information. It could be beneficial provided that GCMs can reproduce
658 atmospheric circulation and SST more reliably than forcings like precipita-
659 tion. Moreover, it would imply that the statistical relationships held under
660 climate change, which is the underlying hypothesis of any statistical down-
661 scaling method. Tisseuil et al. (2010) propose a review of such approaches
662 and discuss why they have been so scarcely used compared to the standard
663 approach. The interest of directly downscaling streamflow therefore deserves
664 some evaluation, at least for temporally integrated indices such as the annual
665 mean flow. For instance, the strong relationships detected between the mean
666 annual flow and WP2/WP8 (Figure 5) might be used for future projections.
667 For finer characteristics (e.g. annual minimum flow or volume deficit), the
668 use of a hydrological model might be more difficult to circumvent.

669 **5. Conclusions**

670 The present study aimed at performing a trend analysis for low flows
671 in France and increase our understanding of the climate factors that affect
672 the temporal variability of hydrological regimes. The main results can be
673 summarized as follows:

- 674 • **Drought Severity:** temporal trends show a North-South geographical
675 split, with an increase of drought severity in the southern half of France.
676 A similar spatial pattern is observed for correlations with the AMO and
677 the NAO. Consequently, it cannot be excluded that at least part of the
678 temporal trends detected on drought regimes results from large scale
679 climate variability and on its inertial behavior. Moreover, the frequency
680 of the WP2 (Atlantic low pressure) and WP8 (high pressure) weather
681 patterns seems to play a predominant role in the temporal variability of
682 drought regimes over most of the country, except for the Mediterranean
683 coastal region.

- 684 • **Drought Timing:** a large number of temporal trends were detected,
685 especially for the drought start (occurring earlier in the year). However,
686 unlike drought severity, the correlations with the AMO and the NAO
687 do not bring about a similar spatial pattern. Furthermore, the role of
688 the weather patterns WP2 and WP8 is less pronounced. As a result,
689 the temporal trends detected on drought timing do not seem to be
690 linked to large scale climate variability.

691 In addition, the analysis carried out on a subset of longer series (60 years of
692 data over the period 1948-2008) shows a quite good stability of the correla-
693 tions with climate indices (when present), whereas temporal trends are much
694 less robust, sometimes even contradictory, over different time periods. This
695 result reveals the suitability of climate indices for explaining the temporal
696 variability of hydrological regimes, and suggests that these indices are more
697 relevant in the light of predictability than temporal trends.

698 Lastly, the use of seasonal climate indices allows for the identification of some
699 specific hydro-climatic links. The main findings are the following:

- 700 • The use of seasonal NAO, WP2 and WP8 make some of the correla-
701 tions stand out more prominently than their annual counterparts. This
702 highlights the importance of considering these modes of variability at
703 a finer scale (seasons).
- 704 • Notwithstanding the literature, especially at the Northern and South-
705 ern boundaries of Europe, the winter NAO shows very little correlation
706 with drought severity. Thus France seems located in an area of weak
707 influence of winter NAO.
- 708 • Several relationships based on seasonal climate indices are lagged, mean-
709 ing that summer droughts are linked to the climate index of previous
710 seasons. This result paves the way for interesting seasonal forecasting
711 applications.

712 **6. Acknowledgments**

713 This project was funded by the French National Agency for Water and
714 Aquatic Environments (ONEMA). The hydrological time series were down-
715 loaded from the Banque Hydro database. We thank the data providers
716 (DREAL, CNR, EDF, DDE, DDAF, SPC, SN and CA) for their invaluable
717 assistance during data validation. Finally, we thank the three reviewers
718 for their constructive and helpful comments.

719 Assani, A.A., Landry, R., Laurencelle, M., 2011. Comparison of interannual
720 variability modes and trends of seasonal precipitation and streamflow in
721 southern Quebec (Canada). *River Research and Applications* .

722 Birsan, M.V., Molnar, P., Burlando, P., Pfaundler, M., 2005. Streamflow
723 trends in switzerland. *Journal of Hydrology* 314, 312–329.

724 Boé, J., Terray, L., 2008. A Weather-Type Approach to Analyzing Win-
725 ter Precipitation in France: Twentieth-Century Trends and the Role of
726 Anthropogenic Forcing. *Journal of Climate* 21, 3118–3133.

727 Bouwer, L.M., Vermaat, J.E., Aerts, J.C.J.H., 2008. Regional sensitivities of
728 mean and peak river discharge to climate variability in Europe. *Journal of*
729 *geophysical research* 113.

730 Bradford, R., Marsh, T., 2003. Defining a network of benchmark catchments
731 for the uk. *Proceedings of the Institution of Civil Engineers, Water and*
732 *Maritime Engineering* 156, 109–116.

- 733 Burn, D.H., Elnur, M.A.H., 2002. Detection of hydrologic trends and vari-
734 ability. *Journal of Hydrology* 255, 107–122.
- 735 Cassou, C., 2004. Du changement climatique aux régimes de temps :
736 l'Oscillation Nord-Atlantique. *La Météorologie* 45, 21–32.
- 737 Cassou, C., Terray, L., Hurrell, J.W., Deser, C., 2004. North atlantic winter
738 climate regimes: Spatial asymmetry, stationarity with time, and oceanic
739 forcing. *Journal of Climate* 17, 1055–1068.
- 740 Cassou, C., Terray, L., Phillips, A.S., 2005. Tropical atlantic influence on
741 european heat waves. *Journal of Climate* 18, 2805–2811.
- 742 Ceron, J.P., Tanguy, G., Franchisteguy, L., Martin, E., Regimbeau, F., Vi-
743 dal, J.P., 2010. Hydrological seasonal forecast over france: feasibility and
744 prospects. *Atmospheric Science Letters* 11, 78–82.
- 745 Collins, M., 2009. Evidence for Changing Flood Risk in New England Since
746 the Late 20th Century. *Journal of the American Water Resources Associ-
747 ation* 45, 279–290.
- 748 Enfield, D.B., Cid-Serrano, L., 2009. Secular and multidecadal warmings in
749 the North Atlantic and their relationships with major hurricane activity.
750 *International Journal of Climatology* 30, 174–184.
- 751 Enfield, D.B., Mestas-Nuñez, A.M., Trimble, P.J., 2001. The Atlantic Mul-
752 tidecadal Oscillation and its relation to rainfall and river flows in the con-
753 tinental U.S. *Geophysical Research Letters* 28, 2077–2080.

- 754 Fleig, A.K., Tallaksen, L.M., Hisdal, H., Hannah, D.M., 2011. Regional
755 hydrological drought in north-western Europe: linking a new Regional
756 Drought Area Index with weather types. *Hydrological Processes* 25, 1163–
757 1179.
- 758 Fleig, A.K., Tallaksen, L.M., Hisdal, H., Stahl, K., Hannah, D.M., 2010.
759 Inter-comparison of weather and circulation type classifications for hydro-
760 logical drought development. *Physics and Chemistry of the Earth, Parts*
761 *A/B/C* 35, 507–515.
- 762 Franks, S.W., 2002. Identification of a change in climate state using regional
763 flood data. *Hydrology and Earth System Sciences* 6, 11–16.
- 764 Franks, S.W., Kuczera, G., 2002. Flood frequency analysis: Evidence and im-
765 plications of secular climate variability, new south wales. *Water Resources*
766 *Research* 38.
- 767 Garavaglia, F., Gailhard, J., Paquet, E., Lang, M., Garçon, R., Bernardara,
768 P., 2010. Introducing a rainfall compound distribution model based on
769 weather patterns sub-sampling. *Hydrology and Earth System Sciences* 14,
770 951–964.
- 771 Garavaglia, F., Lang, M., Paquet, E., Gailhard, J., Garçon, R., Renard, B.,
772 2011. Reliability and robustness of rainfall compound distribution model
773 based on weather pattern sub-sampling. *Hydrology and Earth System*
774 *Sciences* 15, 519–532.

- 775 Giuntoli, I., Renard, B., Lang, M., 2012. Floods in France, in: Kundzewicz,
776 Z.W. (Ed.), Changes in flood risk in Europe. IAHS Press, pp. 199–211.
- 777 Goldenberg, S.B., Landsea, C.W., Mestas-Nunez, A.M., Gray, W.M., 2001.
778 The recent increase in Atlantic hurricane activity: causes and implications.
779 Science 293, 474–479.
- 780 Gong, G., Wang, L., Lall, U., 2011. Climatic precursors of autumn streamflow
781 in the northeast United States. International Journal of Climatology 31,
782 1773–1784.
- 783 Hamed, K.H., Rao, A.R., 1998. A modified Mann-Kendall trend test for
784 autocorrelated data. Journal of Hydrology 204, 182–196.
- 785 Hannaford, J., Buys, G., 2012. Trends in seasonal river flow regimes in the
786 UK. Journal of Hydrology 475, 158–174.
- 787 Hannaford, J., Marsh, T., 2006. An assessment of trends in UK runoff and low
788 flows using a network of undisturbed catchments. International Journal of
789 Climatology 26, 1237–1253.
- 790 Hannaford, J., Marsh, T.J., 2008. High-flow and flood trends in a network of
791 undisturbed catchments in the UK. International Journal of Climatology
792 28, 1325–1338.
- 793 Hannah, D.M., Demuth, S., van Lanen, H.A.J., Looser, U., Prudhomme, C.,
794 Rees, G., Stahl, K., Tallaksen, L.M., 2011. Large-scale river flow archives:

795 importance, current status and future needs. *Hydrological Processes* 25,
796 1191–1200.

797 Hendrickx, F., Sauquet, E., 2012. Impact of business-as-usual water manage-
798 ment under climate change for the ariège river basin (france). *Hydrological*
799 *sciences Journal*. In preparation. .

800 Hurrell, J., 1995. Decadal trends in the north atlantic oscillation: Regional
801 temperatures and precipitation. *Science* 269, 676–679.

802 Hurrell, J., VanLoon, H., 1997. Decadal variations in climate associated with
803 the north atlantic oscillation. *Climatic Change* 36, 301–326.

804 Huss, M., Hock, R., Bauder, A., Funk, M., 2010. 100-year mass changes in
805 the Swiss Alps linked to the Atlantic Multidecadal Oscillation. *Geophysical*
806 *Research Letters* 37, 1–5.

807 Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynova, M.,
808 Kysely, J., Tveito, O.E., 2008. Classifications of atmospheric circulation
809 patterns recent advances and applications, in: Gimeno, L., GarciaHerrera,
810 R., Trigo, R.M. (Eds.), *Trends and Directions in Climate Research*. Black-
811 well Publishing, Oxford. volume 1146 of *Annals of the New York Academy*
812 *of Sciences*, pp. 105–152.

813 IPCC, 2007. *Climate Change 2007: The Physical Science Basis*. Contribution
814 of Working Group I to the Fourth Assessment Report of the Intergovern-
815 mental Panel on Climate Change. Technical Report.

- 816 Jain, S., Lall, U., 2001. Floods in a changing climate: Does the past represent
817 the future? *Water Resources Research* 37, 3193–3205.
- 818 Johansson, A., 2007. Prediction Skill of the NAO and PNA from Daily to
819 Seasonal Time Scales. *Journal of Climate* 20, 1957–1975.
- 820 Jones, P.D., Jonsson, T., Wheeler, D., 1997. Extension to the north atlantic
821 oscillation using early instrumental pressure observations from gibraltar
822 and south-west iceland. *International Journal of Climatology* 17, 1433–
823 1450.
- 824 Jónsdóttir, J., Uvo, C., Snorrason, A., 2004. Multivariate analysis of Ice-
825 landic river flow and its relation to variability in atmospheric circulation,
826 in: XIII Nordic Hydrological Conference, 8-12 August 2004, Tallinn, Es-
827 tonia.
- 828 Kaczmarek, Z., 2003. The impact of climate variability on flood risk in
829 Poland. *Risk analysis* 23, 559–566.
- 830 Keim, A., Verdon-Kidd, D.C., 2009. Climatic drivers of victorian streamflow:
831 Is enso the dominant influence? *Australian Journal of Water Resources*
832 13.
- 833 Kendall, M., 1975. Rank correlation methods. Griffin, London.
- 834 Kendall, M.G., 1938. A new measure of rank correlation. *Biometrika* 30,
835 81–93.

- 836 Kiely, G., 1999. Climate change in Ireland from precipitation and streamflow
837 observations. *Advances in water resources* 23, 141–151.
- 838 Kingston, D.G., Hannah, D.M., Lawler, D.M., McGregor, G.R., 2006. In-
839 teractions between large-scale climate and river flow across the northern
840 North Atlantic margin, in: IAHS-AISH publication. International Associ-
841 ation of Hydrological Sciences, pp. 350–355.
- 842 Knight, J.R., 2005. A signature of persistent natural thermohaline circulation
843 cycles in observed climate. *Geophysical Research Letters* 32, 2–5.
- 844 Knight, J.R., Folland, C.K., Scaife, A.A., 2006. Climate impacts of the
845 Atlantic Multidecadal Oscillation. *Geophysical Research Letters* 33, 1–4.
- 846 Lavers, D., Prudhomme, C., Hannah, D.M., 2010. Large-scale climate, pre-
847 cipitation and British river flows: Identifying hydroclimatological connec-
848 tions and dynamics. *Journal of Hydrology* 395, 242–255.
- 849 Lima, C.H.R., Lall, U., 2010. Climate informed monthly streamflow fore-
850 casts for the brazilian hydropower network using a periodic ridge regression
851 model. *Journal of Hydrology* 380, 438–449.
- 852 Limanówka, D., Nieckarz, Z., Pociask-Karteczka, J., 2002. The North At-
853 lantic Oscillation impact on hydrological regime in Polish Carpathians, in:
854 ERB and Northern European FRIEND Project 5 Conference, Demanovska
855 dolina, Slovakia.

- 856 Littmann, T., 2000. An empirical classification of weather types in the
857 Mediterranean Basin and their interrelation with rainfall. Theoretical and
858 applied climatology 66, 161–171.
- 859 Lorenzo, M.N., Taboada, J.J., Gimeno, L., 2008. Links between circulation
860 weather types and teleconnection patterns and their influence on precipita-
861 tion patterns in Galicia (NW Spain). International Journal of Climatology
862 28, 1493–1505.
- 863 Mann, H., 1945. Nonparametric tests against trend. Econometrica 13, 245–
864 259.
- 865 Martínez, C., Campins, J., Jansà, A., Genovés, A., 2008. Heavy rain events
866 in the western mediterranean: an atmospheric pattern classification. Ad-
867 vances in Science and Research 2, 61–64.
- 868 Massei, N., Laignel, B., Deloffre, J., Mesquita, J., Motelay, A., Lafite, R.,
869 Durand, A., 2010. Long-term hydrological changes of the Seine River flow
870 (France) and their relation to the North Atlantic Oscillation over the period
871 1950-2008. International Journal of Climatology 30, 2146–2154.
- 872 Mauget, S.A., 2003. Multidecadal Regime Shifts in US Streamflow, Precipi-
873 tation, and Temperature at the End of the Twentieth Century. Journal of
874 Climate 16, 3905–3916.
- 875 McCabe, G.J., Betancourt, J.L., Gray, S.T., Palecki, M.A., Hidalgo, H.G.,

- 876 2008. Associations of multi-decadal sea-surface temperature variability
877 with us drought. *Quaternary International* 188, 31–40.
- 878 McCabe, G.J., Wolock, D.M., 2002. A step increase in streamflow in the
879 conterminous United States. *Geophysical Research Letters* 29, 2185.
- 880 Merz, B., Vorogushyn, S., Uhlemann, S., Delgado, J., Hundedcha, Y., 2012.
881 Hess opinions "more efforts and scientific rigour are needed to attribute
882 trends in flood time series". *Hydrol. Earth Syst. Sci. Discuss.* 9, 1345–1365.
883 HESSD.
- 884 Merz, R., Parajka, J., Blöschl, G., 2011. Time stability of catchment model
885 parameters: Implications for climate impact analyses. *Water Resources*
886 *Research* 47, W02531.
- 887 Micevski, T., Franks, S.W., Kuczera, G., 2006a. Multidecadal variability in
888 coastal eastern australian flood data. *Journal of Hydrology* 327, 219–225.
- 889 Micevski, T., Kuczera, G., Franks, S., 2006b. A bayesian hierarchical regional
890 flood model, in: Australia, E. (Ed.), 30th Hydrology and Water Resources
891 Symposium, Engineers Australia, Launceston, Tas, Australia.
- 892 Petrow, T., Zimmer, J., Merz, B., 2009. Changes in the flood hazard in Ger-
893 many through changing frequency and persistence of circulation patterns.
894 *Natural Hazards and Earth System Science* 9, 1409–1423.
- 895 Pettitt, A.N., 1979. A non-parametric approach to the change-point problem.
896 *Applied Statistics* 28, 126–135.

- 897 Philipp, A., Bartholy, J., Beck, C., Erpicum, M., Esteban, P., Fettweis,
898 X., Huth, R., James, P., Jourdain, S., Kreienkamp, F., Krennert, T., Lyk-
899 oudis, S., Michalides, S.C., Pianko-Kluczynska, K., Post, P., Alvarez, D.R.,
900 Schiemann, R., Spekat, A., Tymvios, F.S., 2010. Cost733cat-a database of
901 weather and circulation type classifications. *Physics and Chemistry of the*
902 *Earth* 35, 360–373.
- 903 Pociask-Karteczka, J., 2006. River Hydrology and the North Atlantic Oscil-
904 lation: A General Review. *AMBIO: A Journal of the Human Environment*
905 35, 312–314.
- 906 Pociask-Karteczka, J., Nieckarz, Z., Limanówka, D., 2003. Prediction of
907 hydrological extremes by air circulation indices. *Water Resources Systems-*
908 *Water Availability and Global Change*, IAHS Publ. 280, 134–141.
- 909 Pongrácz, R., Bogardi, I., Duckstein, L., 2003. Climatic forcing of droughts:
910 a Central European example. *Hydrological Sciences Journal* 48, 39–50.
- 911 Renard, B., Lang, M., Bois, P., Dupeyrat, A., Mestre, O., Niel, H., Sauquet,
912 E., Prudhomme, C., Parey, S., Paquet, E., Neppel, L., Gailhard, J., 2008.
913 Regional methods for trend detection: Assessing field significance and re-
914 gional consistency. *Water Resources Research* 44.
- 915 Rimbu, N., Boroneant, C., Buta, C., Dima, M., 2002. Decadal variability of
916 the Danube river flow in the lower basin and its relation with the North
917 Atlantic Oscillation. *International Journal of Climatology* 22, 1169–1179.

- 918 Rimbu, N., Dima, M., Lohmann, G., Stefan, S., 2004. Impacts of the North
919 Atlantic Oscillation and the El Niño-Southern Oscillation on Danube river
920 flow variability. *Geophysical Research Letters* 31, 2–5.
- 921 Rowell, D.P., 1996. Variability of summer rainfall over tropical north Africa
922 (1906-92): Observations and modelling - Further analysis of simulated
923 interdecadal and interannual variability of summer rainfall over tropical
924 north Africa - Reply to comments. *Quarterly Journal of the Royal Mete-
925 orological Society* 122, 1007–1013.
- 926 Rowell, D.P., Folland, C.K., Maskell, K., Ward, N.M., 1995. Variability of
927 summer rainfall over tropical north Africa (1906-92): Observations and
928 modelling. *Quarterly Journal of the Royal Meteorological Society* 121,
929 669–704.
- 930 Samaniego, L., Bárdossy, A., 2007. Relating macroclimatic circulation pat-
931 terns with characteristics of floods and droughts at the mesoscale. *Journal
932 of Hydrology* 335, 109–123.
- 933 Sharma, A., 2000a. Seasonal to interannual rainfall probabilistic forecasts
934 for improved water supply management: Part 1 - a strategy for system
935 predictor identification. *Journal of Hydrology* 239, 232–239.
- 936 Sharma, A., 2000b. Seasonal to interannual rainfall probabilistic forecasts
937 for improved water supply management: Part 3 - a nonparametric proba-
938 bilistic forecast model. *Journal of Hydrology* 239, 249–258.

939 Sharma, A., Luk, K.C., Cordery, I., Lall, U., 2000. Seasonal to interan-
940 nual rainfall probabilistic forecasts for improved water supply manage-
941 ment: Part 2 - predictor identification of quarterly rainfall using ocean-
942 atmosphere information. *Journal of Hydrology* 239, 240–248.

943 Shorthouse, C., Arnell, N., 1997. Spatial and temporal variability in Euro-
944 pean river flows and the North Atlantic Oscillation. FRIEND 97 - Regional
945 Hydrology: Concepts and Models for Sustainable Water Resource Manage-
946 ment, IAHS Publ. 246.

947 Singla, S., Céron, J.P., Martin, E., Regimbeau, F., Déqué, M., Habets, F.,
948 Vidal, J.P., 2012. Predictability of soil moisture and river flows over france
949 for the spring season. *Hydrology and Earth System Sciences* 16, 201–216.

950 Soubeyroux, J.M., Vidal, J.P., Baillon, M., Blanchard, M., Ceron, J.P., Fran-
951 chisteguy, L., Regimbeau, F., Martin, E., Vincendon, J.C., 2010. Charac-
952 terizing and forecasting droughts and low-flows in france with the safran-
953 isba-modcou hydrometeorological suite. *Houille Blanche-Revue Interna-*
954 *tionale De L Eau* , 30–39.

955 Stahl, K., Demuth, S., 1999. Linking streamflow drought to the occurrence of
956 atmospheric circulation patterns. *Hydrological Sciences Journal* 44, 467–
957 482.

958 Stahl, K., Demuth, S., Hisdal, H., Santos, M., Verissimo, R., Rodrigues,
959 R., 2001. The North Atlantic Oscillation (NAO) and the drought, In:

- 960 Assessment of the Regional Impact of Droughts in Europe. Final Report,
961 ARIDE .
- 962 Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L.M., van Lanen, H.a.J.,
963 Sauquet, E., Demuth, S., Fendekova, M., Jódar, J., 2010. Streamflow
964 trends in Europe: evidence from a dataset of near-natural catchments.
965 Hydrology and Earth System Sciences 14, 2367–2382.
- 966 Stefan, S., Ghioca, M., Rimbu, N., Boroneant, C., 2004. Study of meteorolo-
967 gical and hydrological drought in southern Romania from observational
968 data. International Journal of Climatology 24, 871–881.
- 969 Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward Earlier
970 Streamflow Timing across Western North America. Journal of Climate 18,
971 1136–1155.
- 972 Sutton, R.T., Hodson, D.L.R., 2005. Atlantic Ocean forcing of North Ameri-
973 can and European summer climate. Science (New York, N.Y.) 309, 115–8.
- 974 Tallaksen, L.M., Van Lanen, H.A.J., 2004. Hydrological Drought: processes
975 and estimation methods for streamflow and groundwater. volume 48. El-
976 sevier.
- 977 Thyer, M., Kuczera, G., 2000. Modeling long-term persistence in hydrocli-
978 matic time series using a hidden state markov model. Water Resources
979 Research 36, 3301–3310.

980 Thyer, M., Kuczera, G., 2003a. A hidden markov model for modelling long-
981 term persistence in multi-site rainfall time series 1. model calibration using
982 a bayesian approach. *Journal of Hydrology* 275, 12–26.

983 Thyer, M., Kuczera, G., 2003b. A hidden markov model for modelling long-
984 term persistence in multi-site rainfall time series. 2. real data analysis.
985 *Journal of Hydrology* 275, 27–48.

986 Tisseuil, C., Vrac, M., Lek, S., Wade, A.J., 2010. Statistical downscaling of
987 river flows. *Journal of Hydrology* 385, 279–291.

988 Tourre, Y., Rousseau, D., Jarlan, L., Le Roy Ladurie, E., Daux, V., 2011.
989 Western European climate and Pinot noir grape-harvest dates in Bur-
990 gundy, France, since the 17th century. *Climate Research* 46, 243–253.

991 Trenberth, K.E., Shea, D.J., 2006. Atlantic hurricanes and natural variability
992 in 2005. *Geophysical Research Letters* 33, 1–4.

993 Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis,
994 S., Esteban-Parra, M.J., 2004. North Atlantic oscillation influence on pre-
995 cipitation, river flow and water resources in the Iberian Peninsula. *Inter-
996 national Journal of Climatology* 24, 925–944.

997 Verdon-Kidd, D.C., Kiem, A.S., 2010. Quantifying drought risk in a nonsta-
998 tionary climate. *Journal of Hydrometeorology* 11, 1019–1031.

999 Vicente-Serrano, S., Cuadrat, J., 2007. North Atlantic oscillation control of

- 1000 droughts in north-east Spain: evaluation since 1600 A.D. *Climatic Change*
1001 85, 357–379.
- 1002 Vidal, J., Hendrickx, F., 2010. Impact of climate change on hydropower:
1003 Ariège, France, in: Fung, F., Lopez, A., New, M. (Eds.), *Modelling the*
1004 *Impact of Climate Change on Water Resources*. Wiley-Blackwell, pp. 148–
1005 161.
- 1006 Vidal, J.P., Wade, S.D., 2008. Multimodel projections of catchment-scale
1007 precipitation regime. *Journal of Hydrology* 353, 143–158.
- 1008 Wedgbrow, C.S., Wilby, R.L., Fox, H.R., O'Hare, G., 2002. Prospects for
1009 seasonal forecasting of summer drought and low river flow anomalies in
1010 England and Wales. *International Journal of Climatology* 22, 219–236.
- 1011 Westra, S., Sharma, A., Brown, C., Lall, U., 2008. Multivariate stream-
1012 flow forecasting using independent component analysis. *Water Resources*
1013 *Research* 44.
- 1014 Whitfield, P.H., Burn, D.H., Hannaford, J., Higgins, H., Hodgkins, G.a.,
1015 Marsh, T., Looser, U., 2012. Reference hydrologic networks I. The status
1016 and potential future directions of national reference hydrologic networks
1017 for detecting trends. *Hydrological Sciences Journal* , 1–18.
- 1018 Wilby, R., O'Hare, G., Barnsley, N., 1997. The North Atlantic Oscillation
1019 and British Isles climate variability, 1865-1996. *Weather* 52, 266–276.

1020 Wilby, R.L., Wedgbrow, C.S., Fox, H.R., 2004. Seasonal predictability of the
1021 summer hydrometeorology of the river thames, uk. Journal of Hydrology
1022 295, 1–16.

1023 Wilson, D., Hisdal, H., Lawrence, D., 2010. Has streamflow changed in
1024 the Nordic countries? – Recent trends and comparisons to hydrological
1025 projections. Journal of Hydrology 394, 334–346.

1026 Wrzesinski, D., Paluszkiewicz, R., 2011. Spatial differences in the impact of
1027 the North Atlantic Oscillation on the flow of rivers in Europe. Hydrology
1028 Research 42, 30.

Table 1: Percentage of gauges with positive and negative correlations with error level 10%.

Correlation	Time		AMO		NAO		WP2		WP8	
	Pos.	Neg.								
Drought severity										
A _{Mean}	0.0	25.9	3.2	13.6	0.5	25	80	0.0	0.0	90.5
A _{Min}	3.6	16.8	7.3	12.7	0.5	8.6	24.5	0.5	0.0	38.6
Vol. Def.	18.2	3.2	12.7	6.4	8.6	0.0	0.0	33.6	53.6	0.5
Drought timing										
Start	0.0	30.5	3.2	11.8	0.0	5.5	13.6	0.0	0.0	31.4
Center	0.9	25.9	1.8	2.7	0.9	3.6	3.2	0.9	1.8	5.0
End	1.8	15.9	3.6	6.8	2.7	1.8	0.5	14.1	20.5	0.0

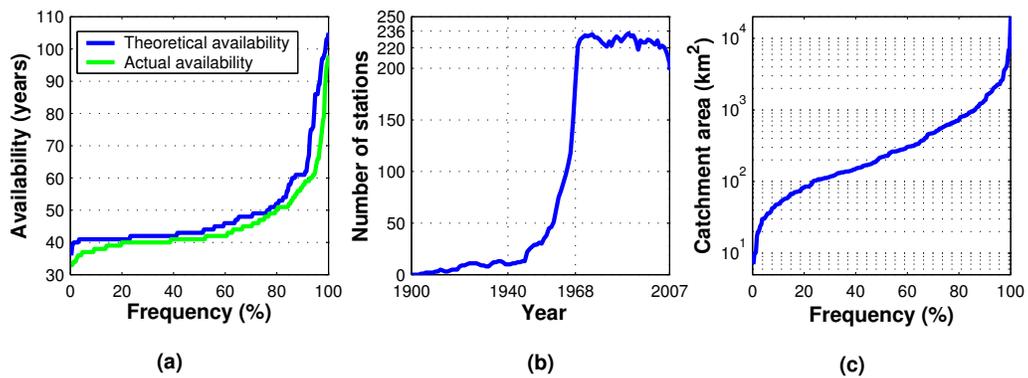


Figure 1: Properties of the dataset used in this study. (a) Distribution of the time series length. The "theoretical availability" refers to the life duration of the gauging station, while the "actual availability" holds once years with more than 10% of missing values are left out. (b) Number of stations available per year. (c) Distribution of catchment areas.

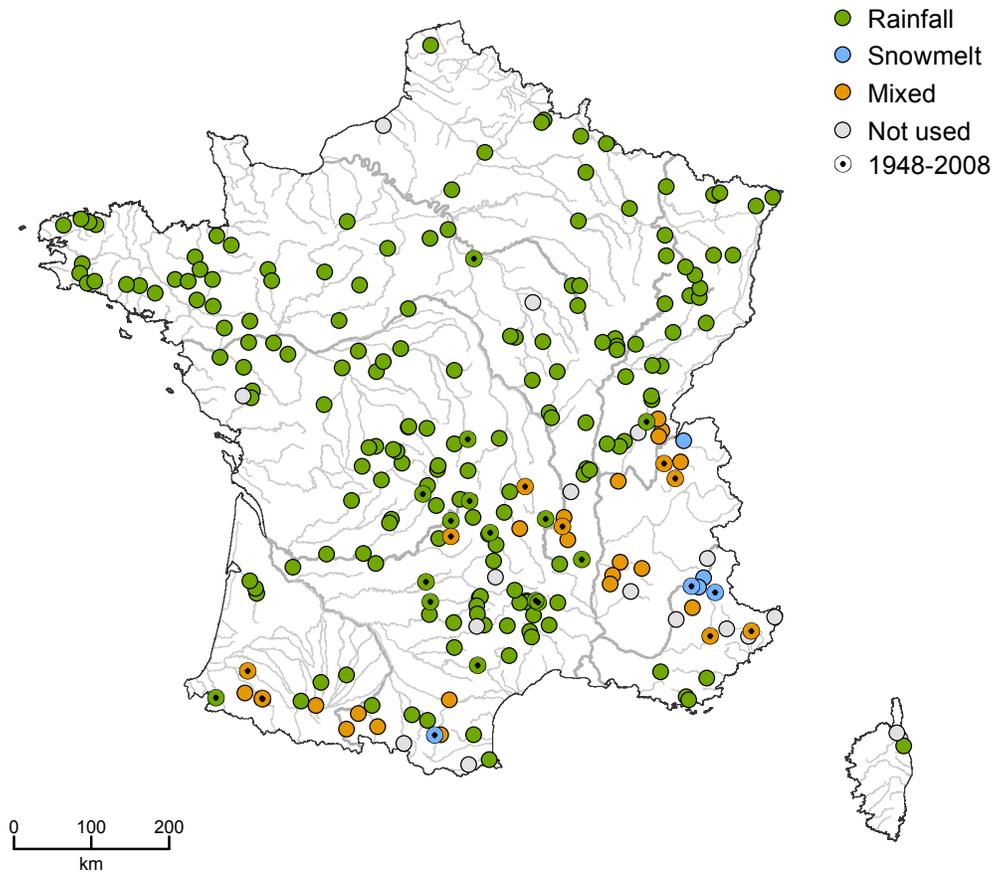


Figure 2: Location of gauging stations and hydrological regime of associated catchments. Stations in gray (16) are part of the benchmark network, but were not used in this study due to insufficient coverage over the period 1968-2008. Stations "1948-2008" (28) provide additional coverage.

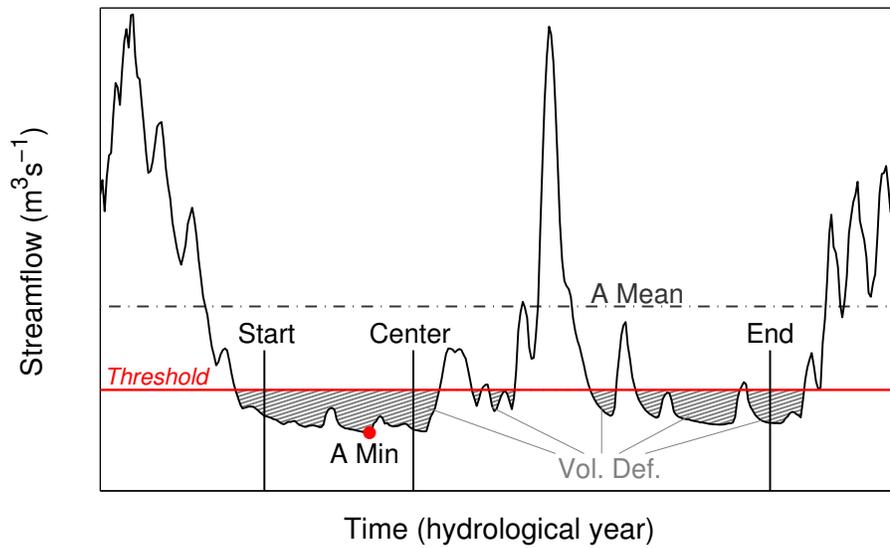


Figure 3: Schematic of drought indices.

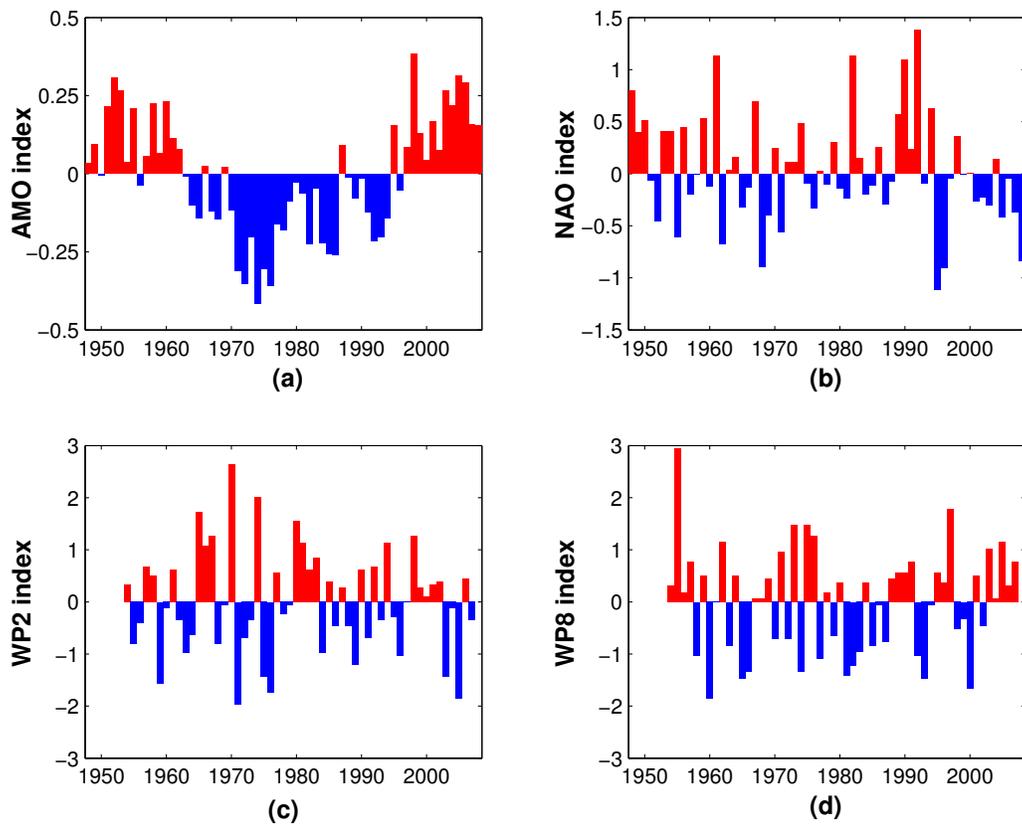


Figure 4: Time series of climate indices at the annual scale. (a) AMO; (b) NAO; (c) WP2; (d) WP8. Hydrological years corresponding to the rainfall regime (February - January) are used here.

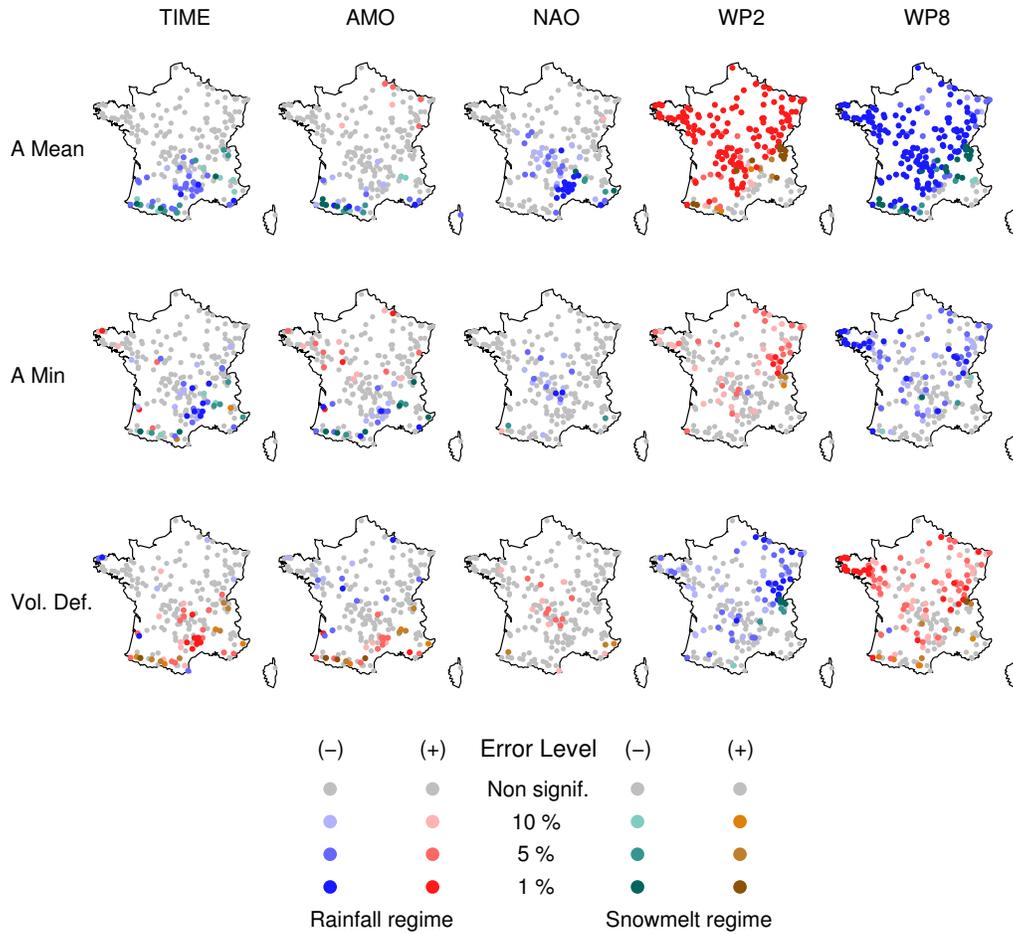


Figure 5: Results of the correlation analysis carried out on an annual basis: severity drought indices (rows) vs. climate indices (columns).

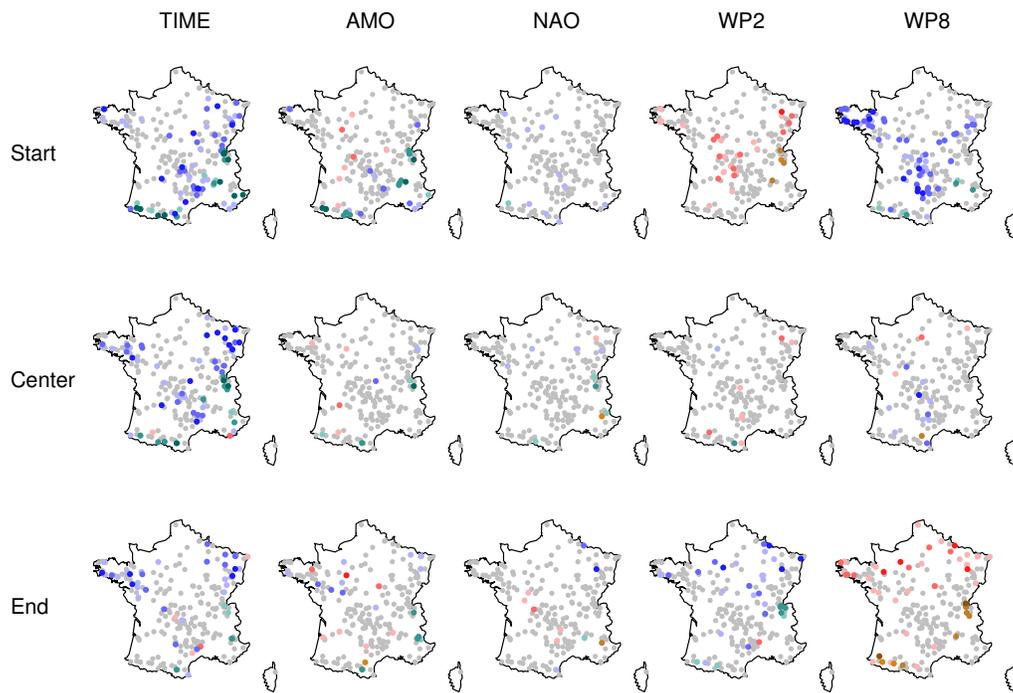


Figure 6: Results of the correlation analysis carried out on an annual basis: timing drought indices (rows) vs. climate indices (columns). Legend as in Figure 5.

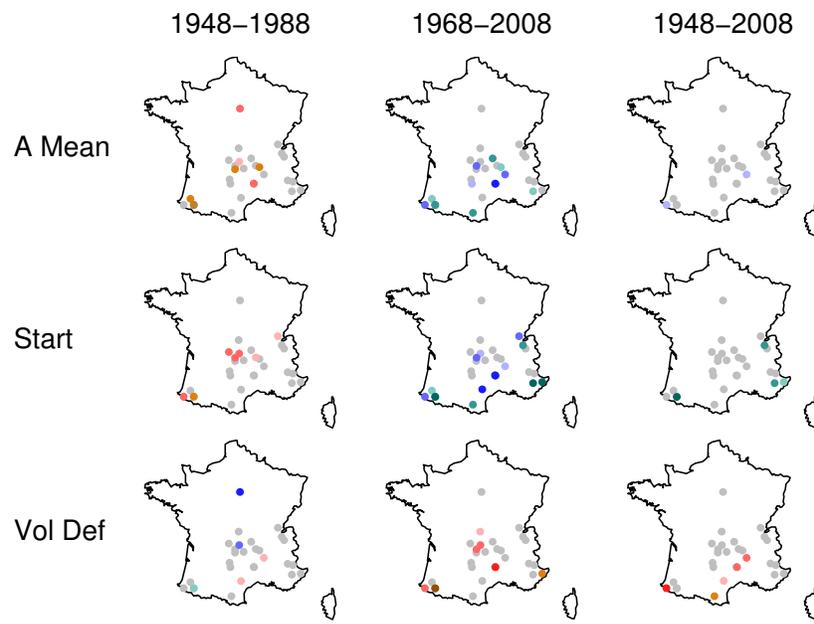


Figure 7: Results of the correlation analysis with respect to time, for three drought indices and three periods 1948-1988, 1968-2008, and 1948-2008. Legend as in Figure 5.

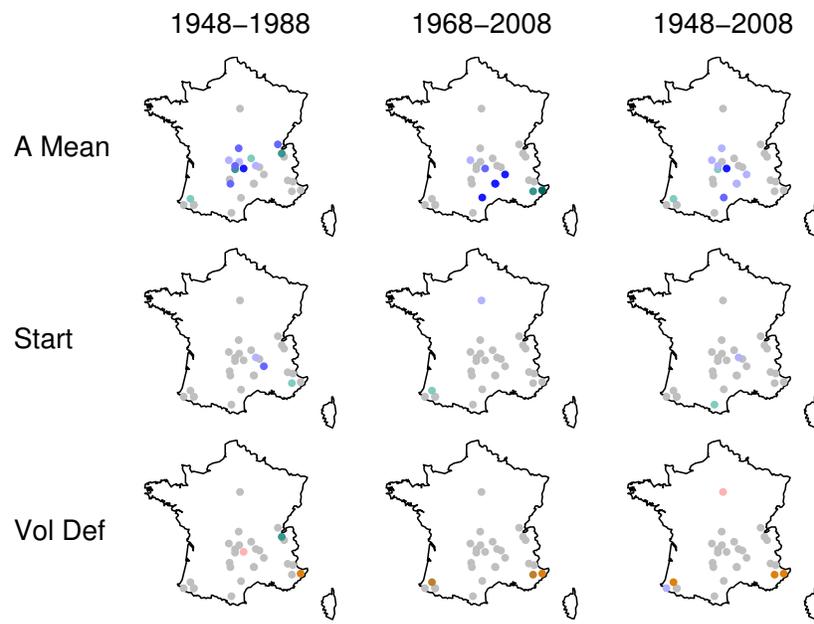


Figure 8: Results of the correlation analysis with respect to NAO, for three drought indices and three periods 1948-1988, 1968-2008, and 1948-2008. Legend as in Figure 5.

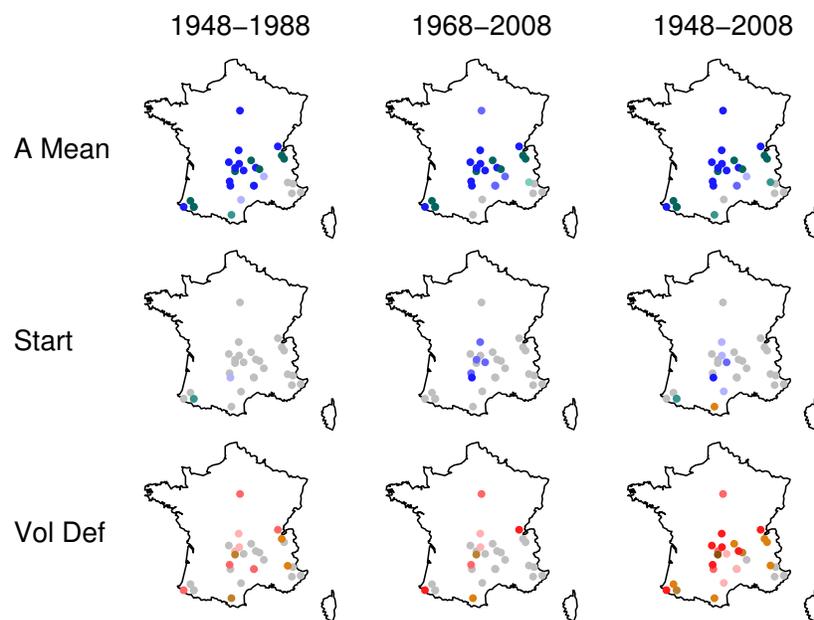


Figure 9: Results of the correlation analysis with respect to WP8, for three drought indices and three periods 1948-1988, 1968-2008, and 1948-2008. Legend as in Figure 5.

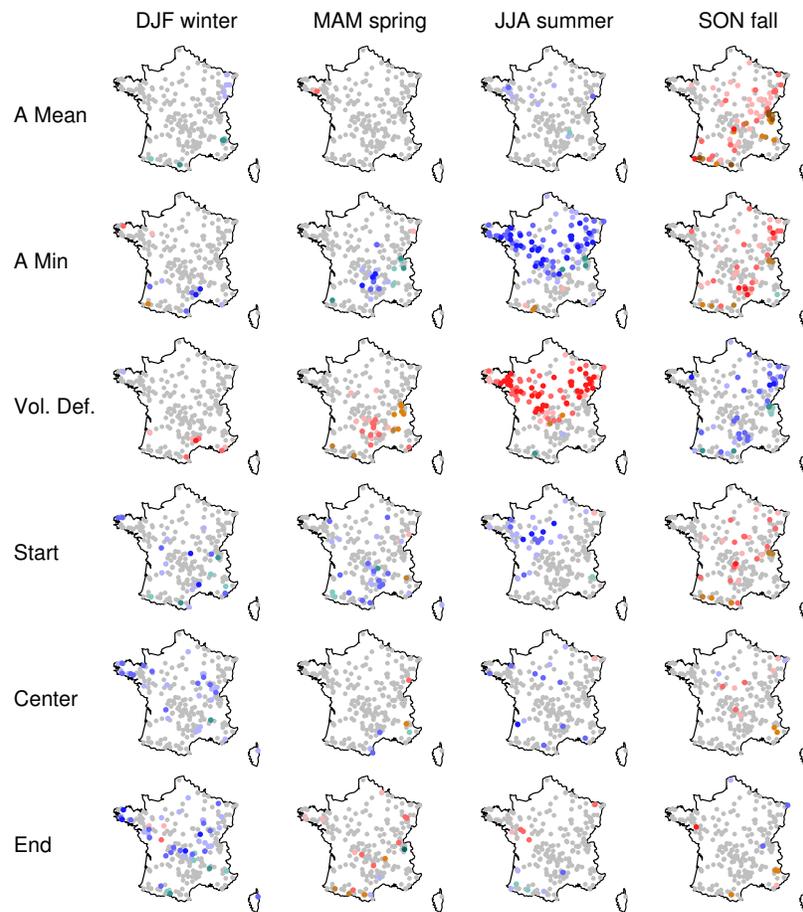


Figure 10: Results of the correlation analysis with respect to seasonal NAO. Legend as in Figure 5.

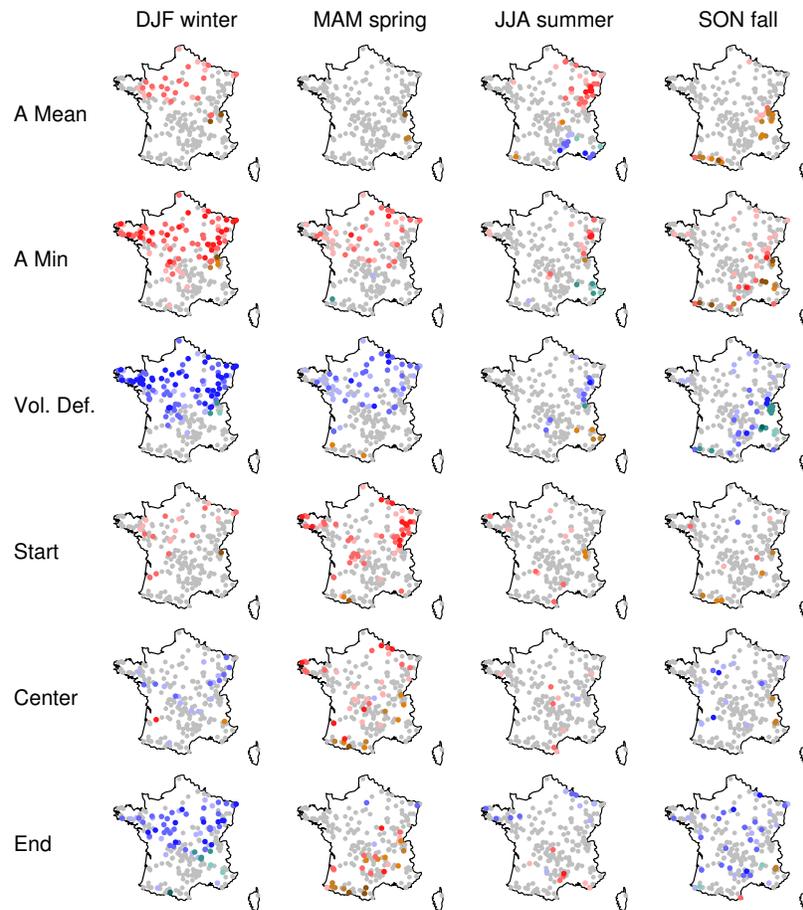


Figure 11: Results of the correlation analysis with respect to seasonal WP2. Legend as in Figure 5.

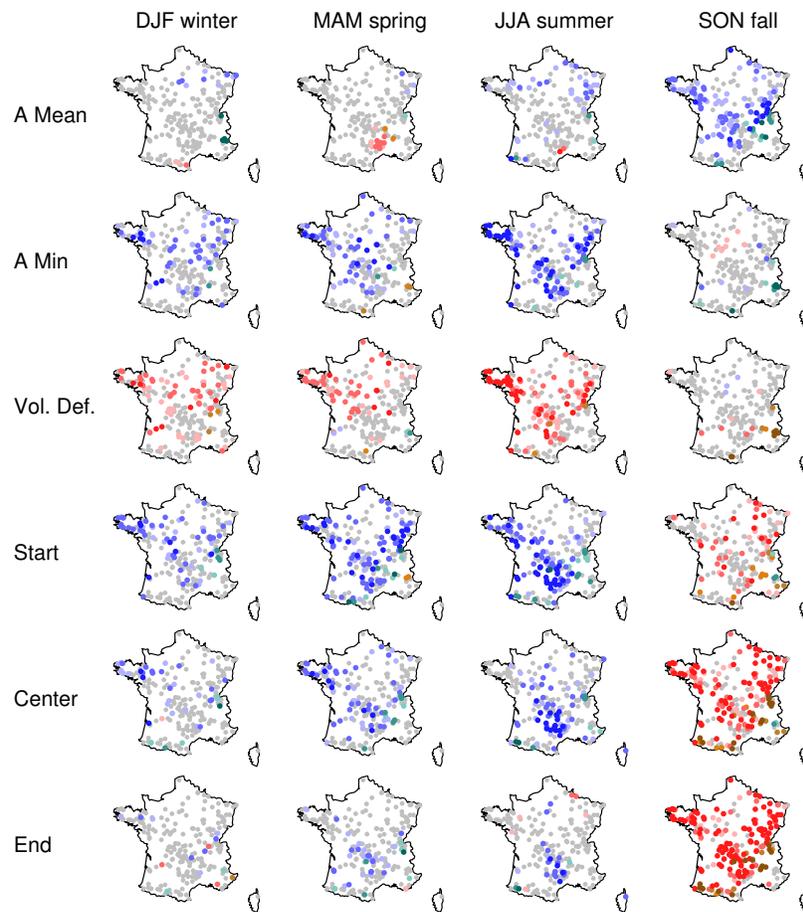


Figure 12: Results of the correlation analysis with respect to seasonal WP8. Legend as in Figure 5.