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Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins

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Abstract

Studies of the impact of climate change on water resources usually follow a top to bottom approach: a scenario of emissions is used to run a GCM simulation, which is downscaled (RCM and/or statistical methods) and bias-corrected. Then, this data is used to force a hydrological model. Seldom, impact studies take into account all relevant uncertainties. In fact, many published studies only use one climate model and one downscaling technique. In this study, the outputs of an atmosphere-ocean regional climate model are downscaled and bias-corrected using three different techniques: a statistical method based on weather regimes, a quantile-mapping method and the method of the anomaly. The resulting data are used to force a distributed hydrological model to simulate the French Mediterranean basins.

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These are characterized by water scarcity and an increasing human pressure, which cause a demand in assessments on the impact of climate change hydrological systems. The purpose of the study is mainly methodological: the evaluation of the uncertainty related to the downscaling and bias-correction step. The periods chosen to compare the changes are the end of the 20th century (1970-2000) and the middle of the 21st century (2035-2065). The study shows that the three methods produce similar anomalies of the mean annual precipitation, but there are important differences, mainly in terms of spatial patterns. The study also shows that there are important differences in the anomalies of temperature. These uncertainties are amplified by the hydrological model. In some basins, the simulations do not agree in the sign of the anomalies and, in many others, the differences in amplitude of the anomaly are very important. Therefore, the uncertainty related to the downscaling and bias-correction of the climate simulation must be taken into account in order to better estimate the impact of climate change, with its uncertainty, on a specific basin. The study also shows that according to the RCM simulation used and to the periods studied, there might be significant increases of winter precipitation on the Cévennes region of the Massif Central, which is already affected by flash floods, and significant decreases of summer precipitation in most of the region. This will cause a decrease in the average discharge in the middle of the 21st in most of the gauging stations studied, specially in summer. Winter and, maybe spring, in some areas, are the exception, as discharge may increase in some basins.

Key words: Hydrology, simulation, regional climate, impacts, Mediterranean, uncertainty, downscaling

1. Introduction

The Mediterranean basin is a quasi-closed sea with a marked orography on its periphery and a high urbanization of its coastline. Its climate is characterized by mild winters and hot and dry summers. The marked orography often triggers intense events that may cause flash floods and the hot and dry weather in summer causes low flows to be long and severe. In this context, for planning purposes, it is important to evaluate the possible impacts of climate change on water resources in such a region.

Global climate models (GCM) are the main tool used to study the future climate. According to Giorgi and Lionello (2008), the study of several GCM simulations shows “a robust and consistent picture of climate change over the Mediterranean emerges, consisting of a pronounced decrease in precipitation, especially in the warm season, except for the northern Mediterranean areas (e.g. the Alps) in winter.”. It is also expected that the variability increases. In fact, according to Giorgi (2006) the Mediterranean basin is one of the planet’s hot-spots of climate change.

However, GCMs do not have enough resolution to study the regional and local scales. Their current resolution of 300 km (Solomon et al., 2007) misses most of the important relief surrounding the Mediterranean basin. Furthermore, at this scale, they are often biased. This obliges us to downscale the outputs of these models.

The usual strategy in impact studies has a top to bottom structure. Global socio-economic assumptions are made (Nakicenovic et al., 2000), which are then used to force GCMs, which are then downscaled and unbiased. This downscaling can be dynamical (computationally expensive) or statistical (less

26 expensive) (Mearns et al., 1999). If the chosen method is dynamical, a lim-
27 ited area atmospheric model, which can simulate in more detail the climate
28 on a smaller area, is forced at the edges of the domain by the outputs of a
29 GCM (Hewitson and Crane, 1996). These models are known as regional cli-
30 mate models (RCM) and have a typical resolution of 50 km or 25 km. Often,
31 dynamical and statistical downscaling methods are presented as mutually
32 exclusive, but, in fact, as it will be seen in further sections, they can be used
33 together.

34 The resolution of a RCM is not enough for most hydrological models, thus
35 they need to be further downscaled and bias-corrected (Christensen et al.,
36 2008) to produce atmospheric forcings at the adequate resolution (10 km)
37 (Wood et al., 2004). Thus it is necessary to further downscale the output of
38 these models and to develop methods to reconstruct the regional climate in
39 relation to climate on a larger scale.

40 In these studies, the emission scenario and the GCM are the main sources
41 of uncertainty (Boé, 2007; Maurer and Hidalgo, 2008). But, unfortunately,
42 each step of the downscaling procedure also has associated uncertainty. All
43 these uncertainties add up and constitute a cascade of uncertainty that must
44 be taken into account. Thus, a complete impact study must look at all kinds
45 of uncertainty. Many studies, have focused on the uncertainty related to
46 the GCM (Hamlet and Lettenmaier, 1999; Maurer and Duffy, 2005; Wilby
47 et al., 2006; Christensen and Lettenmaier, 2007; Minville et al., 2008) but
48 fewer studies have focused on uncertainties related to downscaling to the
49 resolution of the impact model (Dibike and Coulibaly, 2005; Khan et al.,
50 2006; Boé et al., 2007), which might also be important and is often neglected.

51 Within this study we look at the impacts of climate change on the French
52 Mediterranean basins. Our goal is to force the hydrological model SIM with
53 three atmospheric forcings representing the climate of the future. These forc-
54 ings are build from the same RCM simulation using three different methods
55 of downscaling and bias-correction. This should enable us to estimate the
56 hydrological response to climate change, and to estimate the uncertainties
57 related to the last step of downscaling and bias-correction of the climate
58 simulation.

59 **2. The French Mediterranean context**

60 [Figure 1 about here.]

61 This article is focused on the French Mediterranean region. Figure 1
62 shows the French Mediterranean basin, plus some rivers that do not reach
63 the Mediterranean sea but are Mediterranean in climatological terms. These
64 are situated on the Massif Central.

65 The largest French Mediterranean basin is the Rhône. Two of the main
66 tributaries of the Rhône are alpine and have a very important nival compo-
67 nent. These tributaries are also heavily influenced by hydropower produc-
68 tion. But, in our context, we are more interested in the small basins that
69 are tributaries of the Rhône or flow into the Mediterranean sea and are of
70 Mediterranean climate. To name a few: Aude, Hérault, Gardon, Ardèche,
71 Huveaune and Var. These basins have sizes ranging from 373 km^2 for the
72 Huveaune up the 6074 km^2 for the Aude and play a very important role for
73 the water supply for agriculture, industry and cities, as well as to contribute
74 freshwater to the sea. In some of these basins, there are some karstic sys-

75 tems, which are difficult to model, but are important for water supply. The
76 French Mediterranean basins undergo long dry periods and may therefore be
77 especially susceptible to the effects of climate change.

78 [Figure 2 about here.]

79 [Table 1 about here.]

80 Figure 2 shows the climatology of temperature and precipitation for the
81 period 1970-2000 on the area. Column SFR of Table 1 (section Precipita-
82 tion) shows the observed averages of annual and seasonal precipitation. In
83 the coastal areas, annual precipitation does not exceed 1.4 mm d^{-1} . Pre-
84 cipitation increases with altitude, in particular on the northern part of the
85 French Alps, Jura and Cévennes (up to 4.1 mm d^{-1}). Precipitation on the
86 Cévennes is mainly due to Mediterranean storms that occur from September
87 to December. These storms are intense and are often associated to catas-
88 trophic floodings. The evolution of these storms in the context of climate
89 change is of high interest.

90 **3. Methodology**

91 In this study, three different methods are used to downscale and bias-
92 correct the outputs of one single RCM simulation, using a gridded database
93 of observations. In the next sections, the gridded database, the RCM and
94 the downscaling methods are described.

95 *3.1. Gridded database of observations*

96 SAFRAN (Durand et al., 1993) produces an analysis of near surface at-
97 mospheric parameters at a resolution of 8 km using observations from the

98 automatic, synoptic and climatological networks of Météo-France and a first
99 guess from a large scale operational weather prediction model. The analy-
100 sis is made using optimal interpolation for most of the parameters, but for
101 incoming solar radiation and downward infrared radiation, SAFRAN uses a
102 radiative transfer scheme (Ritter and Geleyn, 1992). A more detailed de-
103 scription of SAFRAN is found in Quintana-Seguí et al. (2008).

104 3.2. *Climate scenario*

105 The model SAMM (Sea Atmosphere Mediterranean Model) Somot et al.
106 (2008) is a coupling between the atmospheric model ARPEGE-Climate (Gibelin
107 and Déqué, 2003) and the model of the Mediterranean Sea OPAMED (Somot,
108 2005; Somot et al., 2006). SAMM is the first AORCM (Atmosphere-Ocean
109 Regional Climate Model) dedicated to the Mediterranean. The maximum
110 resolution of the ARPEGE model on the Mediterranean region is of 50 km,
111 OPAMED's is about 10 km. For the 21st century the simulation is done using
112 the scenario of emissions IPCC SRES A2 (high economic and demographic
113 growth, Nakicenovic et al. (2000)). The simulation covers a period of 139
114 years: 1961-2099.

115 Regarding temperature at 2 m, the anomalies (2070-2099 vs 1961-1990)
116 obtained by this model are consistent with previous estimates (PRUDENCE¹).
117 In summer, increases of 4 to 5 °C are expected in south-eastern France. For
118 rainfall, an increase in winter precipitation in northern Europe and a decrease
119 in the Mediterranean region are expected. The model shows, in the area of
120 interest, a decrease of 0.5 mm d⁻¹ in summer, which is important considering

¹<http://prudence.dmi.dk>

121 the average, which in summer is between 1 and 2 mm d⁻¹.

122 *3.3. Downscaling methods*

123 *3.3.1. Statistical downscaling*

124 The first method used for the downscaling of the RCM was developed by
125 Boé et al. (2006); Boé (2007); Pagé et al. (2008). This method is a weather
126 typing approach in which the large scale variables simulated by the model
127 (surface pressure and temperature) are used to relate days from the future
128 and days from the past according to their weather type. This allows to build
129 a database of future climate based on fine scale information coming from an
130 database of observations (Sec. 3.1). The learning period is 1981-2005.

131 First, a limited number of discriminant weather types for rainfall in France
132 is established. This classification is done for three seasons (winter, spring-
133 summer and autumn). Between 8 and 9 weather types are defined for each
134 season. To take into account the intra-type variations (which may be impor-
135 tant), an index of precipitation is built using regressions between the distance
136 of a day to the center of the type and the precipitation analyzed by SAFRAN.
137 For temperature, an index over the domain is also calculated. This way, a
138 day of the SAFRAN database is associated with each day simulated by the
139 climate model, taking into account the weather type and the previously cal-
140 culated indices. In addition, a further correction on the temperature can be
141 made if the index of temperature of the day in SAFRAN is very different
142 from the day simulated by the general circulation model (as in the end of
143 the 21st century). The method was optimized to be applied to the whole of
144 France, not only the South-East. Therefore the results in this region are not
145 optimal, as its climate has some particularities comparing to the rest of the

146 country (it is more variable, dryer in summer, etc.).

147 This method has some limitations, which are characteristic of the statis-
148 tical downscaling techniques. It is supposed that the large-scale variable is
149 a good predictor of the variable of interest at fine-scale. Also, it is supposed
150 that the link between these two variables is stable in a changing climate.
151 This hypothesis is not verifiable and, in fact, it may be false. Finally, for
152 precipitation, the method is not able to produce extreme phenomena outside
153 those which are present in the database of observations, which covers a the
154 period 1970-2008 (but the hydrological model, forced with such downscaled
155 data, can produce discharges outside historical values because the frequencies
156 will certainly change).

157 However, the method has some important advantages too. All the vari-
158 ables of the chosen day are coherent between each other and the daily cycle
159 of each variable is realistic. Within the same day, there is a very good spatial
160 coherence. Finally, the method does not need a RCM. It can be directly
161 applied to a GCM.

162 We will refer to this method as WT (weather typing).

163 *3.3.2. Quantile mapping*

164 The second method used to downscale the climate simulation is based on
165 quantile mapping (QM) (Wood et al., 2004; Déqué et al., 2007; Boé et al.,
166 2007). Comparing to the previous one, the main difference of this method
167 is that it uses the model outputs for all the variables at the fine scale (those
168 needed to force SIM: precipitation, temperature, wind speed, humidity, solar
169 radiation and downward atmospheric radiation). It corrects their distribution
170 to eliminate systematic errors. If the previous method ignored the outputs

171 of the model at the fine scale and used the large scale variables, with this
172 one the opposite is done, the information provided by the model at the large
173 scale is ignored and the information at the small scale is used.

174 The correction is made at the resolution of SAFRAN (8 km). For each
175 cell, a correction is calculated for each percentile of the distribution of each
176 variable of interest at the daily time step, by comparing the observed distri-
177 bution to that of the closest model cell:

- 178 • The correction was calculated for each season for the period August
179 1970 - July 2006.
- 180 • Between percentiles and at the extremes, the correction function is
181 linearly interpolated.
- 182 • To interpolate the variables to the hourly time step (from the daily time
183 step), which is necessary for the hydrological model, a mean daily cycle
184 is calculated for each variable using SAFRAN. For the temperature, the
185 correction is calculated for the daily maximum and minimum, hence
186 the daily cycle is modified according to these two variables.
- 187 • Finally, some tests were done to verify that the resulting forcings are
188 physically realistic, for example, that the values of incoming solar radi-
189 ation are within physical limits, taking into account the solar constant
190 and the attenuation by the atmosphere.

191 This method relies on the hypothesis that the correction function is con-
192 stant in time, which is not verifiable. In particular, the method does not
193 distinguish the causes of the bias of the model. For example, the bias of

194 precipitation of the climate model ARPEGE depends on the type of atmo-
195 spheric circulation. If this circulation changes in the future, that seems very
196 likely, the correction may be inappropriate. Unlike the previous method, the
197 QM method ignores the outputs of the climate model that are simulated the
198 best (large scale) and each variable is corrected separately. Consequently to
199 this last point, there is no physical coherence between the different corrected
200 variables. However, to calculate corrections of one variable, conditioned to
201 the corrections of other variables, a new hypothesis would need to be estab-
202 lished, which might also be arbitrary and introduce new problems. Another
203 key point is that the method does not correct the spatial pattern of the model
204 (in percentile), so that, for example, the area where a 99th percentile rain
205 takes place is as big as the model's grid cell, which is not realistic enough,
206 even if the intensities are corrected. Furthermore, the extrapolation of the
207 function to the extremes is based on an arbitrary assumption (linearity), the
208 daily cycles are not very realistic, and the method should only be used for
209 high resolution simulations, which is the case in our study (50 km).

210 But the advantages are also important. The method is quite simple and
211 easy to implement. For present climate, the method does not degrade the
212 variables that are correctly simulated by the model and, also for present
213 climate, there is no bias at all over the reference period (1970-2000).

214 *3.3.3. Anomaly*

215 This last method is the simplest one of the methods used in this study. It
216 consists of superposing the mean climatological anomaly estimated using a
217 GCM or RCM to a high resolution observed dataset. This method has been
218 widely used in the literature, therefore it allows comparison with previous

219 studies (Hamlet and Lettenmaier, 1999; Etchevers et al., 2002; Caballero
220 et al., 2007; Jyrkama and Sykes, 2007; van Roosmalen et al., 2009) and
221 the evaluation of the gains obtained in using more elaborated downscaling
222 methods. From now on, the method will be called AN.

223 The method was implemented as follows:

- 224 • The anomalies were calculated for temperature, precipitation, humid-
225 ity, wind speed and atmospheric IR radiation.
- 226 • The anomalies were calculated comparing the periods: 2035-2065 and
227 1970-2000.
- 228 • They were calculated on a monthly basis.
- 229 • Relative anomalies were used. The ratio was calculated as follows :
230 $r = \langle x \rangle_{future} / \langle x \rangle_{present}$, where x is the variable of interest.
231 Afterwards the ratio was applied to the SAFRAN series of present
232 climate.
- 233 • The anomaly of temperature was calculated for the daily maximum and
234 minimum. A linear interpolation between the ratio of the maximum
235 and the minimum was used to correct each value of temperature of the
236 corresponding day. The anomaly was calculated in Kelvin.
- 237 • The anomaly of precipitation was calculated for total precipitation.
238 Afterwards, the solid and liquid phases were separated using tem-
239 perature. If $T > 0,7^{\circ}\text{C}$, then the precipitation was liquid, otherwise,
240 solid.

241 • After the anomaly of specific humidity was calculated, the series were
242 corrected, using temperature, to avoid it to be higher than the value
243 at saturation.

244 The method, as described is very simple to implement, but its limitations
245 are important: only the mean climatological change is taken into account
246 and the spatial variability is only taken into account at the resolution of the
247 climate model. As a consequence, when using this method, only changes on
248 the mean can be studied, the study of extremes and variability are therefore
249 excluded.

250 3.3.4. Validation

251 [Figure 3 about here.]

252 [Figure 4 about here.]

253 *Precipitation.* Table 1 compares the annual and seasonal averages for the re-
254 gion produced by QM and WT with SAFRAN. QM, as expected, reproduces
255 the same averages as SFR, on the contrary, WT is dryer for all seasons (-7%
256 for the annual average, -9% in autumn). Figure 3 shows the geographical
257 distribution of the differences in mean annual precipitation between the WT
258 method and SAFRAN. It shows that the greater differences are located on
259 the relief of the Massif Central and are within the range $(-1, -0.5) \text{ mm d}^{-1}$,
260 which is around $(-20, -8)\%$ depending on the grid cell. Therefore, the dryness
261 of WT is mainly due to the method's lack of skill to reproduce the precipi-
262 tation patterns in this area, which certainly is related to the difficulty of the
263 method to discriminate the synoptic situations that produce high precipita-
264 tion in this region. This is confirmed by panel (a) of Figure 4, which shows

265 that the probability of having intense precipitations is smaller according to
266 WT than to QM and SAFRAN. Panels (b) and (c) show that WT has diffi-
267 culties to reproduce both long dry and wet spells and that QM overestimates
268 wet spells. This might be due to the fact that the spatial scale of precipita-
269 tion events in this region is smaller than the size of the grid cell of the RCM
270 or, simply, because the model does not reproduce the wet spells well.

271 *Temperature.* Table 1 shows that, for the period 1970-2000, QM is cooler
272 than SAFRAN (-0.4°C) and WT is warmer ($+0.4^{\circ}\text{C}$). The differences are
273 not very important, but can be considered surprising in the case of QM, as it
274 is expected that QM to reproduce the distribution of SAFRAN. This bias is
275 probably due to the choice of 1970-2006 as the training period for QM, that
276 differs from 1970-2000, that is used for the comparison.

277 3.3.5. Conclusion

278 The assumptions and hypotheses made when applying these methods are
279 very different, specially when comparing WT with the other two methods.
280 These hypotheses are often difficult to verify and sometimes have obvious
281 weaknesses. If the results obtained are comparable, it will be a sign of ro-
282 bustness, otherwise, it will be a sign that more emphasis must be done on
283 the uncertainty related to the downscaling methods.

284 4. Description of the hydrological model

285 In this study, a recent version (Quintana Seguí et al., 2009) of the SAFRAN-
286 ISBA-MODCOU (SIM) model (Habets et al., 2008) is used. This model is the
287 result of combining the SAFRAN meteorological analysis, the ISBA surface

288 scheme and the MODCOU hydrogeological model. Only the main features
289 of the model are described in this paper.

290 ISBA (Noilhan and Planton, 1989; Boone et al., 1999) is a soil-vegetation-
291 atmosphere transfer (SVAT) scheme. It is used to simulate the exchanges
292 in heat, mass and momentum between the continental surface (including
293 vegetation and snow) and the atmosphere. There are several versions of
294 ISBA, ranging from a two layer force-restore method (Deardorff, 1977), to
295 a more detailed diffusion version (Boone, 2000; Habets et al., 2003). SIM is
296 implemented using the three layered force-restore version (Boone et al., 1999)
297 with the 3-layer snow scheme of Boone and Etchevers (2001). The version
298 used in this study (Quintana Seguí et al., 2009) also includes an exponential
299 profile of hydraulic conductivity to better reproduce the dynamics of water
300 in the soil (Decharme et al., 2006).

301 The hydrogeological model MODCOU calculates the temporal and spa-
302 tial evolution of the aquifer at several layers, using the diffusivity equation
303 (Ledoux et al., 1989). Then it calculates the interaction between the aquifer
304 and the river and finally it routes the surface water to the rivers and within
305 the river using an isochronistic algorithm. It calculates river discharge with
306 a time step of three hours. The time step used to calculate the evolution
307 within the aquifer is 1 day. In the version of SIM used in this study, the
308 aquifers are only simulated in two basins: the Seine (3 layers) and the Rhône
309 (1 layer) basins.

310 **5. Results**

311 Two periods of 30 years were selected to compare present and future
312 climate. For present climate, it was chosen to study the period August 1970

313 - July 2000. The period selected for the future is: August 2035 - July 2065.

314 The significance of the anomalies is evaluated using an adaptation of the
315 Student test that does not require the assumption of the equality of the
316 variances of the compared samples. This adaptation is often referred to as
317 the Welch's test (Welch, 1947).

318 *5.1. Analysis of downscaled meteorological variables*

319 *5.1.1. Precipitation*

320 [Figure 5 about here.]

321 [Figure 6 about here.]

322 [Figure 7 about here.]

323 Table 1 compares the anomalies produced by the three methods. It shows
324 that AN and QM always agree in the sign of the anomaly, whereas WT dif-
325 fers in winter. The three methods agree in a decrease of annual precipitation
326 between 3% and 4%. They also agree in a more important decrease of pre-
327 cipitation in summer (between 12% and 16%). The differences are mainly
328 found in winter, where WT presents a positive anomaly whereas the other
329 two methods a negative one. In autumn WT presents no anomaly and AN,
330 in the other extreme, an anomaly of -6%.

331 Figure 5 shows that AN and QM produce quite similar geographical pat-
332 terns, which was expected, as QM can be regarded as an evolution of AN.
333 These methods predict a diminution of precipitation on most of the region,
334 but also an increase near the Mediterranean coast and the maritime Alps.
335 These anomalies are only significant near the Massif Central and in a region
336 between the Alps and the Rhône. On the other hand, the spatial structure of

337 the mean calculated by WT is different. In this case, the anomaly is wetter
338 on a larger area and dryer on the swiss part of the Alps. The changes are
339 significant mainly in the upper alpine region, towards Switzerland, where
340 the anomaly is negative. This first comparison shows that the differences
341 between methods can be important.

342 The anomalies of precipitation produced by QM and AN are also similar
343 for the four seasons. On the other hand, the spatial patterns of the anomalies
344 produced by WT are quite different geographically, but their intensities are
345 comparable to those of the other methods. Their geographical pattern is more
346 similar in winter (Fig. 6) and autumn (not shown). In winter, it is expected
347 that precipitation will increase in the southern part of the Mediterranean
348 region, specially on the relief of the Massif Central, where the changes are
349 significant (Fig. 7). The AN method is less sensitive to this change on the
350 relief, as the changes are probably related to the strong events (extremes)
351 usually found in this part of the basin. Another region where differences
352 are important in winter, according to WT and QM, is the swiss part of the
353 basin, but the changes are not significant. In spring (not shown), according
354 to QM and AN, a significant diminution of precipitation is expected between
355 the Cevennes and the Rhône river. In contrary, WT produces a different
356 picture. In this case, the anomalies are positive in a large area, but they
357 are not significant. Differences in sign are also found in autumn. During
358 this period, as in spring, AN and QM are dryer than WT, which produces a
359 positive anomaly over half of the region, but the anomalies are not significant
360 for any of the methods. Summer (Fig. 6) is the period with more significant
361 changes (Fig. 7), according to the three methods. The anomalies are mainly

362 negative, but, again, the spatial structure of these anomalies is different,
363 depending on the method used.

364 *5.1.2. Temperature*

365 The anomalies of temperature are very homogeneous throughout the re-
366 gion (not shown). For the annual average, the three methods show an im-
367 portant degree of coincidence (Table 1): the average anomaly for the whole
368 region is almost identical (between 1.5°C and 1.7°C). According to WT, the
369 anomaly is warmer in the northern part. According to AN the North-South
370 gradient presents an opposite trend. The study of the summer average shows
371 that the anomalies produced by AN and QM are more important than the
372 anomaly of WT. In the first case, the average anomaly is of 2.2°C and in
373 the second it is of 1.4°C. These differences are mainly due to the choice of
374 the temperature index in WT, which was calculated at the scale of Europe.
375 SAMM produces an important increase of summer temperature in France,
376 which contrasts with a milder increase in Europe, which is the reference
377 increase for WT.

378 *5.2. Hydrological impacts*

379 *5.2.1. Water balance*

380 Table 1 shows the total runoff (the addition of surface and subsurface
381 runoff) and evapotranspiration obtained by each of the simulations and ag-
382 gregated to the whole area of interest. The context is of a diminution of
383 precipitation, specially in summer and an increased precipitation, specially
384 on the Cévennes area, in winter. Due to an increased temperature, evap-
385 otranspiration increases (except in summer, as there is not enough water
386 available). This translates in a decrease of runoff, mainly in spring and sum-

387 mer. The agreement in this respect is relatively good, specially in summer,
388 but the magnitude of the change in spring goes from -7% to -15%. For
389 evapotranspiration, the relative anomalies are lower than for runoff, but the
390 discrepancies between methods are evident: there is no agreement in the sign
391 of the change for the annual mean. In fact, the methods only agree in the
392 sign of spring and summer anomalies, but the differences in magnitude are
393 important. In conclusion, the differences between methods are more impor-
394 tant for runoff and evapotranspiration than for precipitation. Therefore, the
395 hydrological model amplifies the uncertainties.

396 *5.2.2. Discharge*

397 [Figure 8 about here.]

398 [Figure 9 about here.]

399 [Figure 10 about here.]

400 [Figure 11 about here.]

401 The analysis starts on Figure 8, which shows histograms of the anomalies
402 of discharge for all the stations. The three methods agree in that, for most
403 of the stations, the anomaly of the annual average is negative or zero. In
404 winter most of the anomalies are positive according to the three methods.
405 AN is the simulation that presents more stations with positive anomaly. In
406 spring there is some disagreement. On the one hand, according to AN, most
407 stations will have negative anomalies. On the other hand, WT presents a
408 more balanced picture. In summer the agreement is quite important, all the
409 methods present anomalies that attain -40%, even -50% in some cases. QM

410 and AN are the driest. In autumn, the three methods present also a quite
411 negative picture, but not as dry as in summer.

412 Figure 9 presents the geographical distribution of the anomalies of the
413 annual average. On the first look, the three methods present a similar picture,
414 specially on the Saône (the northern part of the Rhône basin), but there is
415 less agreement on the rest of the region. AN presents the most different
416 pattern, as it shows negative anomalies on most of the Massif Central. On
417 the contrary, QM and WT present points of positive anomaly (up to 30%)
418 on some basins of the Massif Central. According to WT, the area of positive
419 anomaly on the Massif Central is larger and also presents some positive
420 anomalies on the south eastern extreme of the area. WT disagrees with
421 the other methods on the east part of the region, where it is dryer. If the
422 stations are compared one to one, there are differences in sign in some stations
423 and differences in magnitude that can attain 30%. These uncertainties are
424 important.

425 Figure 10 shows the seasonal anomalies for winter and summer (autumn
426 and spring are not shown, but they are described in the text). The patterns
427 are more similar in summer and winter, and less in autumn and spring.
428 Fig. 11 shows the significance of the changes. In winter, there are positive
429 anomalies on many stations. AN presents some important positive anomalies
430 ($> 80\%$) and WT presents more moderate changes. But these anomalies
431 are not very significant. In spring, there are some important differences in
432 sign on the area of the Massif Central and in the South East part of the
433 region. According to AN the anomalies are significant on many stations, but
434 according to the other methods, the anomalies are not as significant. The

435 difference in number is important. In summer, there are no differences in
436 sign, but, if the magnitude of the change is considered, there are important
437 differences towards the western part of the area, where AN and QM present
438 anomalies that attain -60%, whereas WT is more moderate. In summer these
439 anomalies are significant in a large area. In autumn there are differences in
440 sign on the Alps, but, as in winter, the differences are not very significant.
441 This is probably due to the fact that September, October, November and
442 December are the months that present more variability.

443 **6. Discussion and conclusion**

444 There are many sources of uncertainty in impact studies. The main source
445 is related to the GCM simulation(Boé, 2007), which is often taken into ac-
446 count, but many studies don't take into account the uncertainties related
447 to the final step of downscaling and to the bias-correction of GCM or RCM
448 simulations. In this study, the uncertainties related to this last step were
449 assessed.

450 Relating precipitation, it was shown that the methods produce similar
451 long term annual averages, but there are important differences. Mainly, the
452 spatial patterns differ. Also, the study shows that the differences between
453 methods depend on the season. For each method, the geographical area
454 where the anomalies are significant is different, reinforcing the idea that
455 these methods are an important source of uncertainty. Nevertheless, these
456 comparisons also show that there are some agreements. According to the
457 RCM simulation used and to the period studied, there might be significant
458 increases of winter precipitation on the Cévennes region of the Massif Central,
459 where present day flash flood are known to be severe, and significant decreases

460 of summer precipitation in most of the region, which could reinforce the risk
461 of fire. But, it is not possible to locate the changes with precision, which
462 makes decision making difficult to water managers.

463 The study of temperature, shows that there are important differences
464 between the methods, specially in summer, where AN and QM are more than
465 one degree warmer. This differences affect many hydrological processes. This
466 is an important source of uncertainty, as there are threshold effects related
467 to this variable.

468 In terms of evapotranspiration and runoff, the methods present important
469 differences in long term averages over the region. These differences are further
470 propagated to the simulated discharge. For example, in some basins, for some
471 seasons, the methods don't agree in the sign of the anomaly and in basins in
472 which the methods agree in the sign, there are sometimes differences of up to
473 30% in the intensity of the anomaly. Therefore, it is not possible to determine
474 the intensity of the anomaly in a specific gauging station, even given the large
475 scale characteristics of the climate change. Nevertheless, some geographical
476 and seasonal patterns emerge. A decrease in the average discharge at the
477 middle of the century is expected in most of the stations for most of the
478 year. Winter and, maybe spring, in some areas, are the exception. Annual
479 discharges may increase in some stations located near the Massif Central.
480 There is more agreement in winter and summer than in autumn and spring.
481 The anomalies are more significant in summer.

482 The methods QM and WT were developed to better take into account
483 the changes on the extremes, as the AN method is only useful to study the
484 changes on the mean. Nevertheless, the study shows that these methods

485 produce also significantly different means.

486 From the methodological point of view, it can be argued that this study
487 overestimates the uncertainty related to the downscaling methods, as it is
488 known that the WT method was not optimized for the Mediterranean region
489 of France, as its area of application was the whole country. Its difficulties to
490 reproduce strong precipitation events on the Cévennes are a good example.
491 Nevertheless, when applying such methods a compromise is always done.
492 Every optimization favors some regions and disfavors other ones. The dis-
493 favored regions are usually those where small scale processes are important,
494 like the Mediterranean region of France. Therefore, the authors think that
495 it is worth taking into account this kind of uncertainty. Most studies do not
496 optimize their methods to areas with particularities, and particularities are
497 not rare in the world.

498 The study shows that the downscaling and bias-correction of the RCM
499 is a crucial step when only one climate model is used to study the impacts
500 of climate change on small basins where many threshold effects are present.
501 Therefore, the selection of methods and the treatment of uncertainties have
502 important effects on the conclusions drawn from the methodology applied,
503 even on annual or seasonal averages. It is expected that the results would be
504 more scattered for the extremes.

505 Generally, the uncertainty related to the downscaling and bias-correction
506 is lower than the uncertainty related to the emissions scenarios and climate
507 modeling. But more work should be done to analyze if the uncertainties an-
508 alyzed in this study increase the total uncertainty, when all the uncertainties
509 (emissions scenario, GCM, RCM, downscaling, hydrological model, ...) are

510 taken into account. It would also be interesting to focus on the extremes.

511 A broader conclusion of this work is that impact studies should analyze
512 and explain all the uncertainties related to the methodology used, without
513 neglecting any single step of the procedure. If all the uncertainties can not
514 be explored, the results of the study should be taken with caution, without
515 overselling them. Furthermore, there are also many other sources of un-
516 certainty, which are seldom studied and explained, for example: feedbacks
517 between the changing climate and vegetation, human adaptations to the new
518 climate (changes in agriculture, water management practices, urbanization,
519 etc.) and other human induced changes of the systems, which might be more
520 important than climate change itself. A lot of work is still to be done in
521 the field climate projections and uncertainties, specially in the context of
522 hydrological systems, which are affected by so many external influences.

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531 **References**

532 Boone, A., 2000. Modélisation des processus hydrologiques dans le schéma de
533 surface isba: Inclusion d’un réservoir hydrologique, du gel et modélisation

- 534 de la neige. Ph.D. thesis, Université Paul Sabatier (Toulouse III).
- 535 Boone, A., Calvet, J. C., Noilhan, J., 1999. Inclusion of a Third Soil Layer
536 in a Land Surface Scheme Using the Force-Restore Method. *Journal of*
537 *Applied Meteorology* 38, 1611–1630.
- 538 Boone, A., Etchevers, P., 2001. An intercomparison of three snow schemes
539 of varying complexity coupled to the same land surface model: Local-scale
540 evaluation at an alpine site. *Journal of Hydrometeorology* 2, 374–394.
- 541 Boé, J., 2007. Changement global et cycle hydrologique : Une étude
542 de régionalisation sur la france. PhD thesis, Université Paul Sabatier
543 (Toulouse III).
- 544 Boé, J., Terray, L., Habets, F., Martin, E., 2006. A simple statistical-
545 dynamical downscaling scheme based on weather types and conditional
546 resampling. *Journal of Geophysical Research* 111 (D23).
- 547 Boé, J., Terray, L., Habets, F., Martin, E., 2007. Statistical and dynamical
548 downscaling of the seine basin climate for hydro-meteorological studies.
549 *International Journal of Climatology* 27 (12), 1643–1655.
- 550 Caballero, Y., Voirin-Morel, S., Habets, F., Noilhan, J., LeMoigne, P.,
551 Lehenaff, A., Boone, A., Jul. 2007. Hydrological sensitivity of the Adour-
552 Garonne river basin to climate change. *Water Resources Research* 43,
553 W07448.
- 554 Christensen, J. H., Boberg, F., Christensen, O. B., Lucas-Picher, P., Oct.
555 2008. On the need for bias correction of regional climate change projec-

556 tions of temperature and precipitation. *Geophysical Research Letters* 35,
557 L20709.

558 Christensen, N. S., Lettenmaier, D. P., Jul. 2007. A multimodel ensemble
559 approach to assessment of climate change impacts on the hydrology and
560 water resources of the colorado river basin. *Hydrol. Earth Syst. Sci.* 11 (4),
561 1417–1434.

562 Deardorff, J. W., 1977. A parameterization of ground-surface moisture con-
563 tent for use in atmospheric prediction models. *J. Appl. Meteor.* 16, 1182–
564 1185.

565 Decharme, B., Douville, H., Boone, A., Habets, F., Noilhan, J., 2006. Impact
566 of an exponential profile of saturated hydraulic conductivity within the
567 ISBA LSM: simulations over the rhône basin. *Journal of Hydrometeorology*
568 7, 61–80.

569 Dibike, Y. B., Coulibaly, P., Jun. 2005. Hydrologic impact of climate change
570 in the saguenay watershed: comparison of downscaling methods and hy-
571 drologic models. *Journal of Hydrology* 307 (1-4), 145–163.

572 Durand, Y., Brun, E., Mérindol, L., Guyomarc’h, G., Lesaffre, B., Martin, E.,
573 1993. A meteorological estimation of relevant parameters for snow models.
574 *Ann. Glaciol.* 18, 65–71.

575 Déqué, Rowell, Lüthi, Giorgi, Christensen, Rockel, Jacob, Kjellström,
576 de Castro, van den Hurk, May 2007. An intercomparison of regional cli-
577 mate simulations for europe: assessing uncertainties in model projections.
578 *Climatic Change* 81 (0), 53–70.

- 579 Etchevers, P., Golaz, C., Habets, F., Noilhan, J., Aug. 2002. Impact of a
580 climate change on the rhone river catchment hydrology. *Journal of Geo-*
581 *physical Research* 107 (D16), 4293.
- 582 Gibelin, A., Déqué, M., 2003. Anthropogenic climate change over the
583 Mediterranean region simulated by a global variable resolution model. *Cli-*
584 *mate Dynamics* 20 (4), 327–339.
- 585 Giorgi, F., Apr. 2006. Climate change hot-spots. *Geophysical Research Let-*
586 *ters* 33, L08707.
- 587 Giorgi, F., Lionello, P., Sep. 2008. Climate change projections for the
588 mediterranean region. *Global and Planetary Change* 63 (2-3), 90–104.
- 589 Habets, F., Boone, A., Champeaux, J. L., Etchevers, P., Franchistéguy, L.,
590 Leblois, E., Ledoux, E., Moigne, P. L., Martin, E., Morel, S., Noilhan,
591 J., Quintana Seguí, P., Rousset-Regimbeau, F., Viennot, P., Mar. 2008.
592 The SAFRAN-ISBA-MODCOU hydrometeorological model applied over
593 france. *Journal of Geophysical Research* 113, D06113.
- 594 Habets, F., Boone, A., Noilhan, J., Jul. 2003. Simulation of a scandinavian
595 basin using the diffusion transfer version of ISBA. *Global and Planetary*
596 *Change* 38 (1-2), 137–149.
- 597 Hamlet, A. F., Lettenmaier, D. P., 1999. Effects of climate change on hy-
598 drology and water resources in the Columbia river basin. *Journal of the*
599 *American Water Resources Association* 35 (6), 1597–1623.
- 600 Hewitson, B., Crane, R., Nov. 1996. Climate downscaling: techniques and
601 application. *Climate Research* 07 (2), 85–95.

- 602 Jyrkama, M. I., Sykes, J. F., May 2007. The impact of climate change on
603 spatially varying groundwater recharge in the grand river watershed (Ont-
604 tario). *Journal of Hydrology* 338 (3-4), 237–250.
- 605 Khan, M. S., Coulibaly, P., Dibike, Y., Mar. 2006. Uncertainty analysis of
606 statistical downscaling methods. *Journal of Hydrology* 319 (1-4), 357–382.
- 607 Ledoux, E., Girard, G., de Marsilly, G., Deschenes, J., 1989. Spatially
608 distributed modeling: conceptual approach, coupling surface water and
609 ground water. Kluwer Academic, Dordrecht, pp. 435–454.
- 610 Maurer, E. P., Duffy, P. B., Feb. 2005. Uncertainty in projections of stream-
611 flow changes due to climate change in california. *Geophysical Research*
612 *Letters* 32, L03704.
- 613 Maurer, E. P., Hidalgo, H. G., Mar. 2008. Utility of daily vs. monthly large-
614 scale climate data: an intercomparison of two statistical downscaling meth-
615 ods. *Hydrol. Earth Syst. Sci.* 12 (2), 551–563.
- 616 Mearns, L. O., Bogardi, I., Giorgi, F., Matyasovszky, I., Palecki, M., 1999.
617 Comparison of climate change scenarios generated from regional climate
618 model experiments and statistical downscaling. *Journal of Geophysical Re-*
619 *search* 104 (D6), 6603–6621.
- 620 Minville, M., Brissette, F., Leconte, R., Aug. 2008. Uncertainty of the im-
621 pact of climate change on the hydrology of a nordic watershed. *Journal of*
622 *Hydrology* 358 (1-2), 70–83.
- 623 Myers, P., Haines, K., Josey, S., 1998. On the importance of the choice of

624 wind stress forcing to the modeling of the Mediterranean Sea circulation.
625 Journal of Geophysical Research 103 (C8).

626 Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenham, J., Gaffin, S.,
627 Gregory, K., Grübler, A., Jung, T., Kram, T., La Rovere, E., Michaelis, L.,
628 Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl,
629 A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S.,
630 Swart, R., van Rooijen, S., Victor, N., Z., D., 2000. IPCC Special Report
631 on Emissions Scenarios. Cambridge University Press, Cambridge, United
632 Kingdom and New York, NY, USA. 599pp.

633 Noilhan, J., Planton, S., 1989. A simple parameterization of land surface
634 processes for meteorological models. Monthly Weather Review 117, 536–
635 549.

636 Pagé, C., Terray, L., Boé, J., 2008. Projections climatiques à échelle fine sur
637 la france pour le 21ème siècle : les scénarii SCRATCH08. Technical Report
638 TR/GMGC/08/64, CERFACS, Toulouse, France.

639 Quintana-Seguí, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F.,
640 Baillon, M., Canellas, C., Franchisteguy, L., Morel, S., 2008. Analysis of
641 Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis
642 over France. Journal of Applied Meteorology and Climatology 47, 92–107.

643 Quintana Seguí, P., Martin, E., Habets, F., Noilhan, J., Feb. 2009. Improve-
644 ment, calibration and validation of a distributed hydrological model over
645 france. Hydrol. Earth Syst. Sci. 13 (2), 163–181.

- 646 Ritter, B., Geleyn, J. F., 1992. A comprehensive radiation scheme for nu-
647 merical weather prediction models with potential applications in climate
648 simulations. *Mon. Weather Rev.* 120, 303–325.
- 649 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.,
650 Tignor, M., Miller, H., 2007. *Climate Change 2007: The Physical Science*
651 *Basis. Contribution of Working Group I to the Fourth Assessment Report*
652 *of the Intergovernmental Panel on Climate Change [(eds.)]. Cambridge*
653 *University Press, Cambridge, United Kingdom and New York, NY, USA.*
- 654 Somot, S., 2005. *Modélisation climatique du bassin méditerranéen : vari-*
655 *abilité et scénarios de changement climatique. Ph.D. thesis, Université Paul*
656 *Sabatier, Toulouse, France.*
- 657 Somot, S., Sevault, F., Deque, M., 2006. Transient climate change scenario
658 simulation of the Mediterranean Sea for the 21st century using a high-
659 resolution ocean circulation model. *Clim. Dyn.*, 27 (7-9), 851–879.
- 660 Somot, S., Sevault, F., Déqué, M., Crepon, M., 2008. 21st century climate
661 change scenario for the mediterranean using a coupled atmosphere-ocean
662 regional climate model. *Global and Planetary Change In Press, Accepted*
663 *Manuscript.*
- 664 van Roosmalen, L., Sonnenborg, T. O., Jensen, K. H., Mar. 2009. Impact of
665 climate and land use change on the hydrology of a large-scale agricultural
666 catchment. *Water Resources Research* 43, W07448.
- 667 Vrac, M., Stein, M. L., Hayhoe, K., Liang, X., 2007. A general method for

668 validating statistical downscaling methods under future climate change 34,
669 L18701.

670 Welch, B. L., 1947. The generalization of "student's" problem when several
671 different population variances are involved. *Biometrika* 34 (1-2), 28–35.

672 Wilby, R., Whitehead, P., Wade, A., Butterfield, D., Davis, R., Watts, G.,
673 Oct. 2006. Integrated modelling of climate change impacts on water re-
674 sources and quality in a lowland catchment: River kennet, UK. *Journal of*
675 *Hydrology* 330 (1-2), 204–220.

676 Wood, Leung, Sridhar, Lettenmaier, 2004. Hydrologic implications of dy-
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678 *Climatic Change* 62 (1), 189–216.

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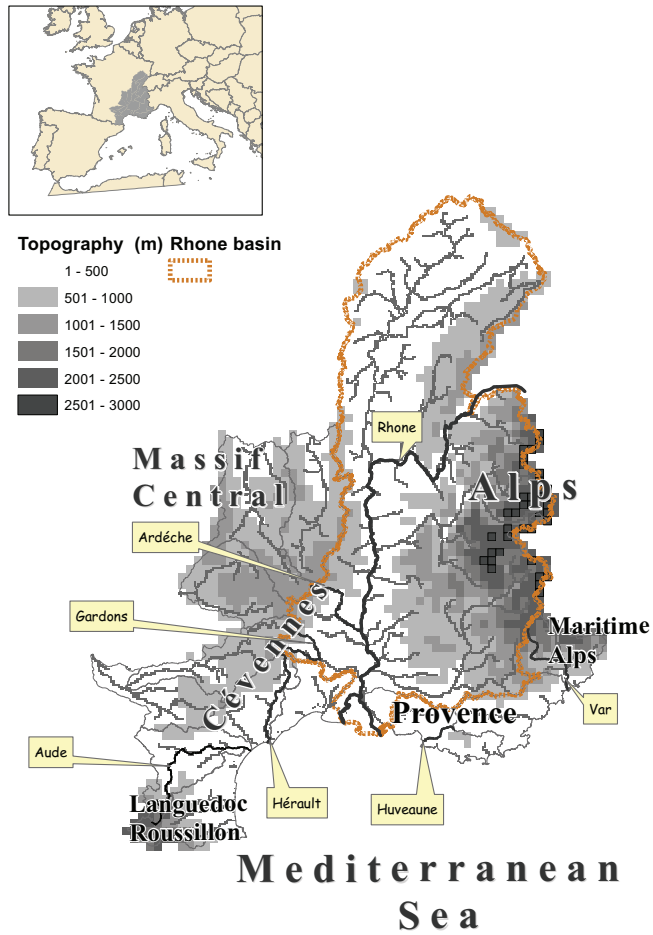
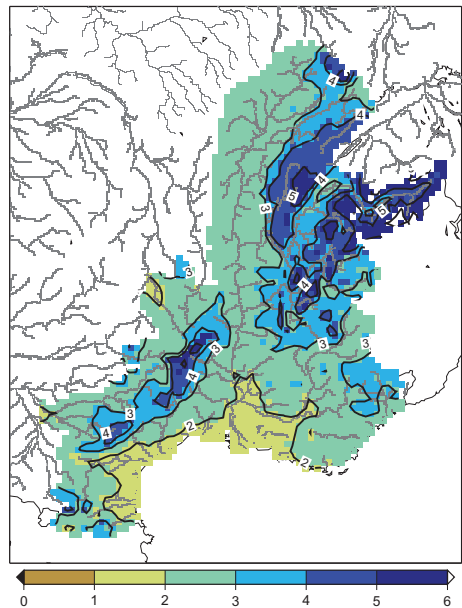
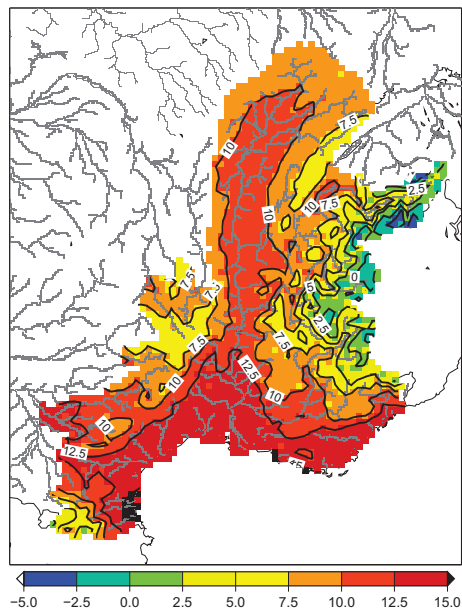


Figure 1: Topographical map of the area of study.



(a) Precipitation



(b) Temperature

Figure 2: Mean annual precipitation (mm d^{-1}) and temperature ($^{\circ}\text{C}$) in the area of study for the period 1970-2000 as reproduced by the SAFRAN meteorological analysis.

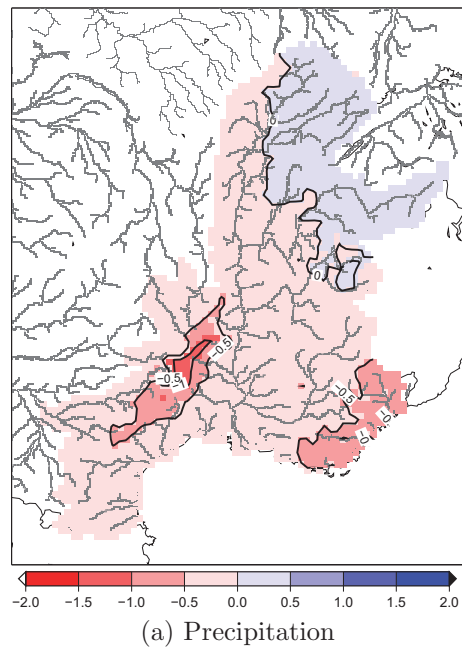
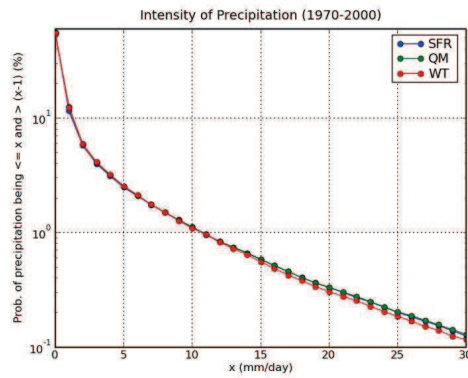
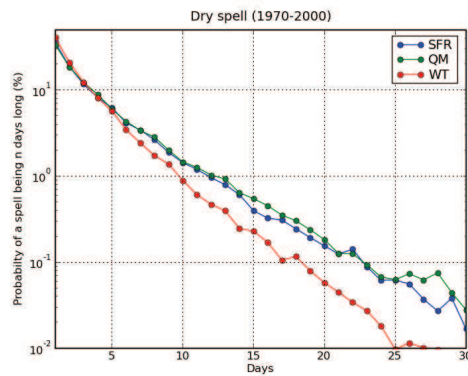


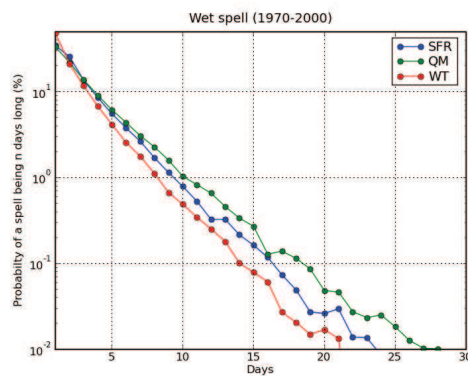
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(a)



(b)



(c)

Figure 4: Panel (a) shows the distribution of the intensities of precipitation in mm d^{-1} . Panels (b) and (c) show the lengths of dry and wet spells. A day is dry if daily precipitation is equal to zero, otherwise it is wet. In both cases the probability is calculated using all the grid cells of the area of interest. SFR corresponds to SAFRAN, QM to the quantile mapping downscaling method and, finally WT corresponds to the weather typing method.

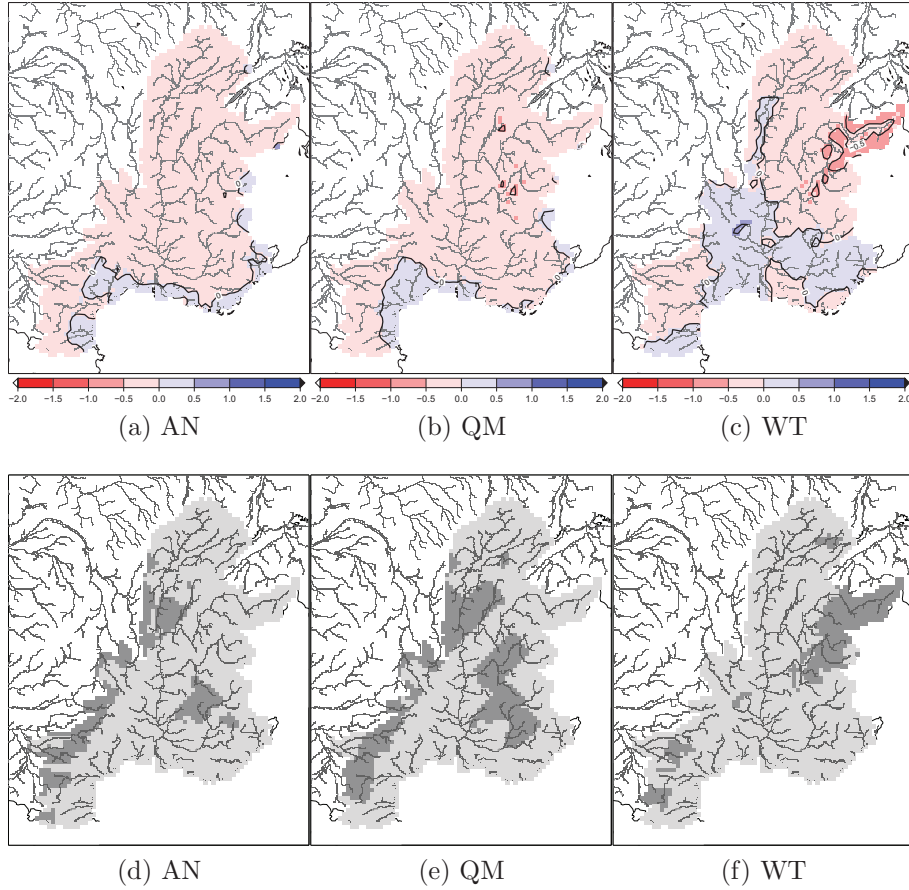


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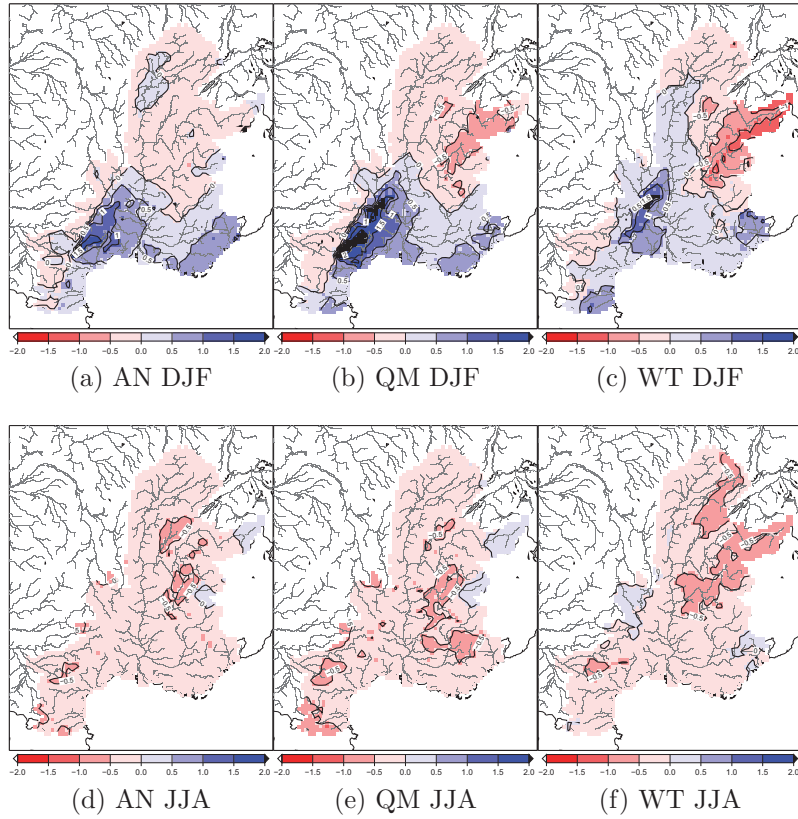


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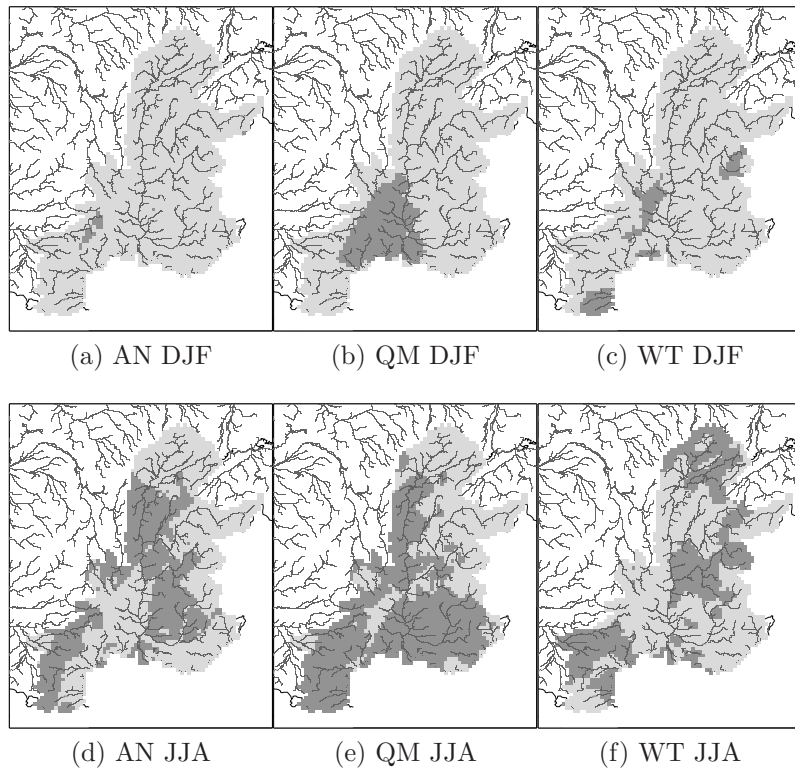


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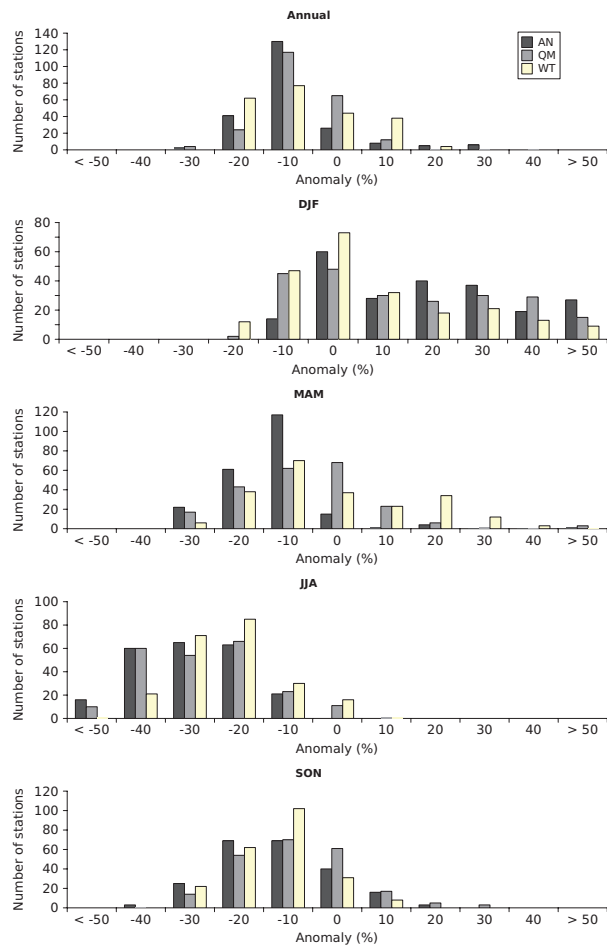


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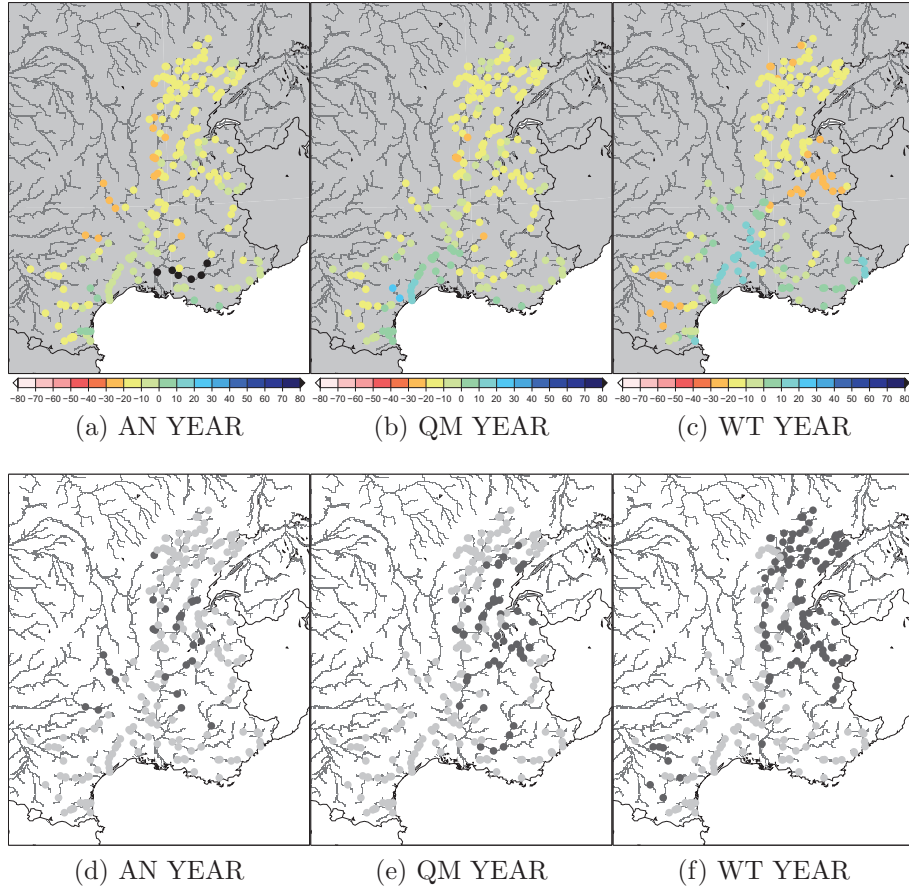


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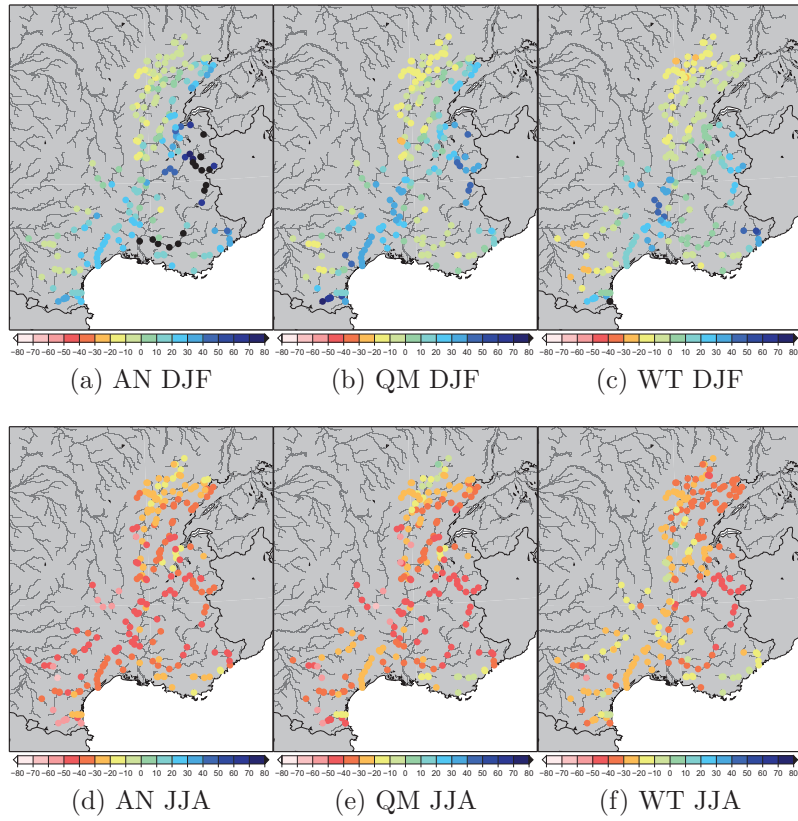


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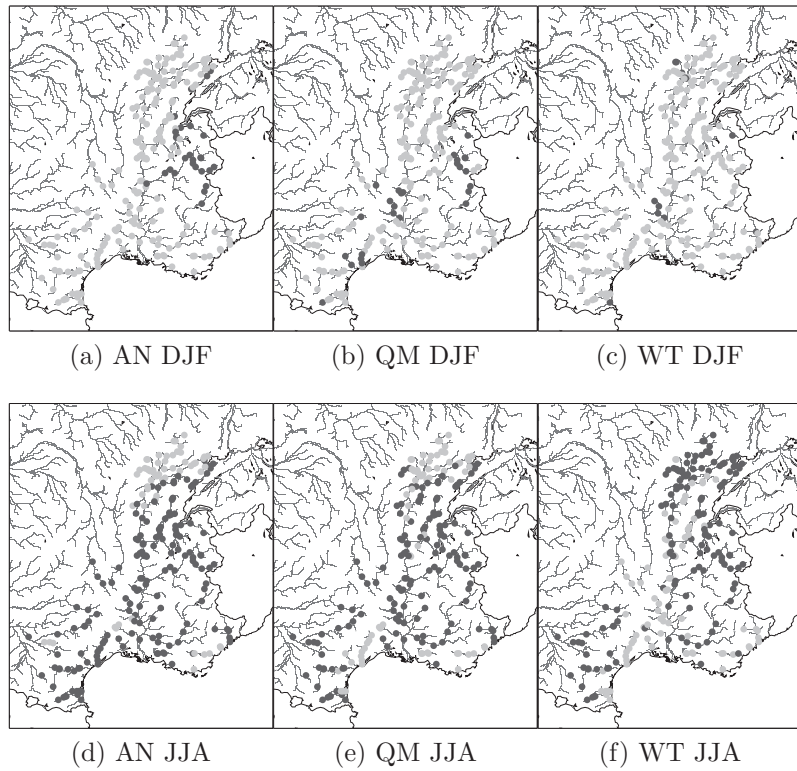


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723 **List of Tables**

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725 (mm d^{-1}) and evapotranspiration (mm d^{-1}) on the Mediter-
726 ranean region of France for the end of the 20th century and the
727 middle of the 21st and their corresponding anomalies. SFR
728 corresponds to the SAFRAN gridded database, QM to the
729 quantile mapping method, WT to weather typing and AN to
730 the method of the anomaly. 46

	Precipitation			Temperature			Total Runoff			Evapotranspiration		
1970-2000												
Year	SFR	QM	WT	SFR	QM	WT	SFR	QM	WT	SFR	QM	WT
Year	3.0	3.0	2.8	9.3	8.9	9.7	1.6	1.5	1.3	1.4	1.6	1.6
DJF	3.1	3.1	2.9	2.2	1.6	2.2	1.9	1.9	1.5	0.3	0.4	0.5
MAM	2.9	2.9	2.8	8.0	7.7	8.4	2.0	1.8	1.5	1.7	1.9	1.9
JJA	2.5	2.5	2.4	17.1	17.0	17.9	1.4	1.2	1.2	2.8	2.8	2.7
SON	3.5	3.5	3.2	9.7	9.4	10.1	1.3	1.2	0.9	1.0	1.1	1.1
2035-2065												
Year	AN	QM	WT	AN	QM	WT	AN	QM	WT	AN	QM	WT
Year	2.9	2.9	2.7	10.8	10.6	11.2	1.5	1.3	1.2	1.5	1.5	1.6
DJF	3.3	3.2	2.8	3.7	3.4	3.9	2.1	1.9	1.5	0.3	0.5	0.5
MAM	2.7	2.7	2.7	9.3	9.1	9.7	1.7	1.6	1.4	1.8	2.0	2.2
JJA	2.2	2.1	2.1	19.3	19.2	19.3	1.0	0.8	0.8	2.7	2.5	2.5
SON	3.3	3.4	3.2	11.0	10.7	11.7	1.1	1.0	0.8	1.0	1.0	1.2
Difference												
Year	AN	QM	WT	AN	QM	WT	AN	QM	WT	AN	QM	WT
Year	-3%	-3%	-4%	+1.5	+1.7	+1.5	-6%	-13%	-8%	+7%	-6%	0%
DJF	+6%	+3%	-3%	+1.5	+1.8	+1.7	+11%	0%	0%	0%	+25%	0%
MAM	-7%	-7%	-4%	+1.3	+1.4	+1.3	-15%	-11%	-7%	+6%	+5%	+16%
JJA	-12%	-16%	-13%	+2.2	+2.2	+1.4	-29%	-33%	-33%	-4%	-11%	-7%
SON	-6%	-3%	0%	+1.3	+1.3	+1.6	-15%	-17%	-11%	0%	-9%	+9%

Table 1: Average precipitation (mm d^{-1}), temperature ($^{\circ}\text{C}$), total runoff (mm d^{-1}) and evapotranspiration (mm d^{-1}) on the Mediterranean region of France for the end of the 20th century and the middle of the 21st and their corresponding anomalies. SFR corresponds to the SAFRAN gridded database, QM to the quantile mapping method, WT to weather typing and AN to the method of the anomaly.