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## Contrasting seasonal changes in total and intense precipitation in the European Alps from 1903 to 2010

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## 1           **Contrasting seasonal changes in total and intense precipitation in the** 2                               **European Alps from 1903 to 2010**

3  
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6  
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### 11           **Abstract**

12   Changes of precipitation over the European Alps are investigated with the regional climate  
13   model MAR applied with a 7-km resolution over the period 1903-2010 using the reanalysis  
14   ERA-20C as forcing. A comparison with several observational datasets demonstrates that the  
15   model is able to reproduce the climatology as well as both the inter-annual variability and the  
16   seasonal cycle of precipitation over the European Alps. The relatively high resolution allows to  
17   estimate precipitation at high elevations. The vertical gradient of precipitation simulated by  
18   MAR over the European Alps reaches 33% km<sup>-1</sup> (1.21 mm.day<sup>-1</sup>.km<sup>-1</sup>) in summer and 38%  
19   km<sup>-1</sup> (1.15 mm.day<sup>-1</sup>.km<sup>-1</sup>) in winter, on average over 1971-2008 and shows a large spatial  
20   variability. A significant (p-value<0.05) increase in mean winter precipitation is simulated in the  
21   North Western Alps over 1903-2010, with changes typically reaching 20 to 40% per century.  
22   This increase is mainly explained by a stronger simple daily intensity index (SDII) and is  
23   associated with less frequent but longer wet spells. A general drying is found in summer over the  
24   same period, exceeding 20 to 30% per century in the Western plains and 40 to 50% per century  
25   in the Southern plains surrounding the Alps, but remaining much smaller (<10%) and not  
26   significant above 1500 m.asl. Below this level, the summer drying is explained by a reduction of  
27   the number of wet days, reaching 20% per century over the Northwestern part of the Alps and  
28   30-50% per century in the Southern part of the Alps. It is associated to shorter although more  
29   frequent wet spells. Maximum daily precipitation index (Rx1day) takes its highest values in  
30   autumn in both the Western and the Eastern parts of the Southern Alps, locally reaching 50 to 70  
31   mm.day<sup>-1</sup> on average over 1903-2010. Centennial maxima up to 250 to 300 mm.day<sup>-1</sup> are  
32   simulated in the Southern Alps, in France and Italy, as well as in the Ticino valley in  
33   Switzerland. Over 1903-2010, seasonal Rx1day shows a general and significant increase at the  
34   annual timescale and also during the four seasons, reaching local values between 20% and 40%  
35   per century over large parts of the Alps and the Apennines. Trends of Rx1day are significant (p-  
36   value<0.05) only when considering long time series, typically 50 to 80 years depending on the  
37   area considered. Some of these trends are nonetheless significant when computed over 1970-  
38   2010, suggesting a recent acceleration of the increase in extreme precipitation, whereas earlier  
39   periods with strong precipitation also occurred, in particular during the 1950s/1960s.  
40

41



## 42 1. Introduction

43

44 The European Alps are often considered as the “water tower” of continental Europe (Beniston et  
45 al., 2018), hosting the headwaters of several major European rivers, such as the Rhine, the  
46 Danube, the Po, and the Rhône Rivers. Similar to other mountain regions of the world, this stems  
47 from both enhanced precipitation rates compared to surrounding lowlands, and by the specific  
48 role played by glaciers and the mountain snow cover in regulating the local and regional  
49 hydrological cycle (Wanner et al., 1997, Viviroli et al., 2008; 2019). The high population density  
50 and the presence of strong slopes makes these areas particularly prone to natural hazards such as  
51 landslides, floods and avalanches, which are strongly connected to meteorological conditions  
52 (e.g. Beniston M., 2006; Evin et al., 2019). There is widespread evidence from scientific studies  
53 addressing past and future climate conditions, that significant atmospheric warming, largely due  
54 to anthropogenic forcing (Hock et al., in press), has been and is projected to occur in the  
55 European Alps. This warming is estimated to 1.2°C per century over the 20th century (Auer et  
56 al., 2007), which is twice as large as global rates (Brunetti et al., 2009; Gobiet et al., 2014).  
57 Precipitation changes are more difficult to detect because of (i) the difficulty to observe and  
58 simulate this variable over mountainous areas, (ii) the stronger influence of internal variability  
59 and (iii) the spatial heterogeneity peculiar to complex topography areas.

60

61 The longest time series of observed precipitation in the European Alps are available in  
62 Switzerland and Italy, with station data that have been homogenized over the last 100 to 150  
63 years (i.e starting from 1900 and even before; Schmidli et al., 2002; Brugnara and Maugeri,  
64 2019). Such a long record is useful to investigate precipitation changes, but station data need to  
65 be considered carefully, because the spatio-temporal heterogeneity of the data availability might  
66 be a cause of spurious trends (e.g. Masson and Frei, 2016). Interpolation of station data can be  
67 used to produce gridded products, commonly used to investigate climate variability. For  
68 example, SAFRAN (Durand et al., 2009) and SPAZM (Gottardi et al., 2009) are two reanalyses  
69 covering the French Alps, HISTALP (Auer et al., 2007) and EURO4M (Isotta et al., 2014) are a  
70 reconstruction of the climate of the European Alps, and E-OBS is a dataset commonly used for  
71 model verification over Europe (Cornes et al., 2018). General Circulation Models (GCMs) are  
72 also widely used to investigate climate change processes and trends. However, their coarse  
73 resolution precludes accurate simulations of small scale processes typical of mountainous areas,  
74 such as those inducing the spatial heterogeneity of precipitation and snow cover. It is therefore  
75 difficult to study the Alpine climate variability with GCMs (Zubler et al., 2015). Due to their  
76 finer resolution (~25 to 1 km) and their more detailed parametrization for physical processes  
77 (e.g. precipitation microphysics, surface snow scheme), that can be developed and tuned  
78 specifically considering regional geographical features, Regional Climate Models (RCMs) are  
79 more adapted to simulate the mountainous climate and can be used to dynamically downscale  
80 global climate model or global reanalyses. They have been widely used to simulate the climate in  
81 mountainous areas, and in particular temperature (Smiatek et al., 2009), daily and sub-daily  
82 precipitation events (Torma et al., 2014; Pieri et al., 2015), precipitation trends (Giorgi et al.,  
83 2016) and snow cover (Steger et al., 2013). A fine resolution is critical to simulate correctly



84 precipitation. Increasing the resolution from  $0.44^\circ$  to  $0.11^\circ$ , Fantini et al. (2018) demonstrated  
85 that a RCM better captures the spatial pattern and the seasonal cycle of precipitation as well as  
86 its daily intensities and statistics. The improvement of the model performances allows currently  
87 to run RCMs at high resolution, typically 1 to 5 km, in non-hydrostatic configurations, resolving  
88 the convective processes, and allowing an accurate description of the snow cover in mountainous  
89 areas (e.g. Ban et al., 2014, 2015; Luthi et al., 2019). Such configuration is however challenging  
90 to run over more than one to two decades due to computational costs.

91

92 Internal climate variability in the North Atlantic basin induces large seasonal to multi-decadal  
93 variability of precipitation over Europe (Dell'Aquila et al., 2018). Using gridded observations,  
94 Efthymiadis et al. (2007) and Brunetti et al. (2006) described the spatiotemporal distribution of  
95 precipitation in the European Alps, highlighting higher interannual variability in the Southern  
96 compared to the Northern Alpine areas. Seasonally, higher interannual variability in winter and  
97 autumn compared to other seasons has also been observed in the European Alps (Brunetti et al,  
98 2009; Bartolini et al, 2009). At daily to interannual time scales, the variability of precipitation  
99 across the Alps is influenced by large-scale atmospheric circulations and particularly by the  
100 North Atlantic Oscillation (NAO). A general picture is that a positive phase of the NAO induces  
101 higher precipitation rates over the Northern Alps and lower ones over the Southern Alps, and  
102 vice versa for negative phases of the NAO. This general view nonetheless hides important  
103 heterogeneities, as local conditions can drive strong variations of local temperature, wind and  
104 moisture transport that may amplify or mitigate synoptical atmospheric patterns (Keiler et al.,  
105 2010). In addition, the NAO-precipitation relationship over the Alps is not stationary over the  
106 last two centuries (Brunetti et al., 2006). At decadal timescales, the Atlantic Multidecadal  
107 Variability (AMV) affects the precipitation rates over the Alps as suggested by Brugnara and  
108 Maugeri (2019) using correlations with station data. However, the compensating effects of the  
109 thermodynamical and dynamical signals of the AMV on the surrounding continents might induce  
110 a strong nonlinearity between the AMV and the precipitation rates in Europe (Qasmi et al.,  
111 2017).

112

113 Over the last decades, precipitation rates have been declining for any period of the year in the  
114 mediterranean area (Giorgi et al., 2008; Mariotti et al., 2015), a signal partly attributed to  
115 anthropogenic forcings (Hoerling et al., 2012) and associated with a significant surface drying  
116 (Douville et al., 2017). Precipitation trends during the last century are more contrasted over the  
117 Alps, with a decrease in the Southeastern Alps consistent with the drying of the mediterranean  
118 area (Schmidli et al., 2002; Auer et al., 2007; Brugnara and Maugeri, 2019) and an increase in  
119 the annual precipitation in the North Western Alps, mainly driven by a positive and significant  
120 trend in winter and at high elevation (Masson and Frei, 2014; 2016). Napoli et al. (2019)  
121 suggested that the contrasted trends of precipitation between high mountains and lowlands over  
122 the last decades is explained by the aerosol forcing that cools the atmosphere mainly at low  
123 elevations since the air quality is better at high elevations. The contrasted seasonal trends in  
124 precipitation needs to be considered separately since their sign can be different from one season  
125 to another one. In addition, precipitation trends emerge from the natural variability only when



126 considering long time series, typically one century (Schmidli et al., 2002). This result is  
127 consistent with previous studies claiming that precipitation rates did not show any significant  
128 trend in the Alps when considering shorter periods, as found in Durand et al. (2009) in the  
129 French Alps over the period 1958-2002.

130

131 Dry spells did not show any clear tendency over the last century in the Alps (Schmidli and Frei,  
132 2005; Brugnara and Maugeri, 2019), whereas the length of dry episodes increased in the  
133 Mediterranean area (Kuglitsch et al. 2010). On the other hand, Schmidli and Frei (2005)  
134 highlighted contrasting seasonal trends of the wet spell duration over the Swiss Alps, with a  
135 lengthening in winter and a shortening in summer. Using 104 rain gauge stations in Switzerland,  
136 Schmidli and Frei (2005) found an increase of the high quantiles of precipitation by 10% to 30%  
137 over 1901-2000, a result evidencing an increase of extreme precipitation in this area, that they  
138 relate to global climate change. Considering the annual maximum of daily precipitation  
139 (Rx1day), which is often used as an indicator of extreme precipitation, Brugnara and Maugeri  
140 (2019) found a similar signal in Switzerland over 1890–2017, whereas they could not highlight a  
141 clear trend of extreme precipitation in Northern Italy. Using a convection-resolving RCM at 2.2  
142 km resolution over the European Alps, Ban et al., (2015) confirmed the significant decrease in  
143 mean summer precipitation related to global warming, and also find an increase in extreme  
144 precipitation events that asymptotically intensifies following the Clausius-Clapeyron  
145 relationship. Using model data over the last 400 years and over the 21st century, Brönniman et  
146 al. (2018) pointed out that heavy precipitation change should thermodynamically increase with  
147 temperature increase at the daily timescale, following the Clausius-Clapeyron relationship.  
148 However, they evidenced a limitation of the available moisture in the atmosphere at the seasonal  
149 timescale, a signal that limits the increase of heavy precipitation during the summer, and induces  
150 a shift of heavy precipitation events from late summer to early summer and early autumn.

151

152 RCMs are limited-area models that can be forced laterally by atmospheric reanalysis, often  
153 available only for the last decades, such as the ECMWF reanalyses ERA40 (1958-2002, Uppala  
154 et al., 2004), ERA-Interim (1979-2019, Dee et al., 2011) and ERA5 (1950 onward, Hersbach and  
155 Dee, 2016). Recent reanalysis products available for the whole 20th century (e.g. ERA20C,  
156 1900-2010; Poli et al., 2016) now offer the possibility to apply RCMs over longer periods  
157 although such a reanalysis, assimilating few data, is less reliable than reanalysis built on the  
158 satellite era. Most of the observational and modeling data used to investigate climate change in  
159 the European Alps generally do not combine a daily resolution, a centennial availability and a  
160 fine spatial resolution, precluding investigations of changes in mean and extreme precipitation.  
161 This strongly limits the possibility to detect precipitation trends, especially when considering the  
162 large internal variability that may overwhelm long-term trends. In this study, daily precipitation  
163 variability and changes in the European Alps (referred to as the Alps in the rest of the text) are  
164 investigated over the period 1903-2010, using observational datasets as well as the regional  
165 climate MAR model applied with a resolution of 7 km and driven by the ERA20C reanalysis.  
166 The material and methods, including a description of the model MAR and different observational  
167 datasets are described in Section 2. The model outputs are compared with several observational



168 datasets in Section 3. Seasonal and annual trends of precipitation indices are estimated over  
169 1903-2010 in section 4. A discussion associated to the conclusions is presented in Section 5.

170

## 171 **2. Material and methods**

172

### 173 **2.1 The MAR model**

174

175 In this section we provide a succinct description of the atmospheric regional model MAR  
176 (<http://mar.cnrs.fr/index.php>), developed at ULiège (Belgium) and IGE (Grenoble). A more  
177 detailed description can be found in Gallée and Schayes (1994), Gallée (1995) and Gallée et al.  
178 (2001, 2005). MAR is a hydrostatic primitive equation model with a vertical coordinate defined  
179 as sigma coordinates. The radiative transfer through the atmosphere uses the radiative scheme of  
180 the ECMWF reanalysis (Morcrette, 2002). MAR includes a detailed scheme of clouds  
181 microphysics with six prognostic equations for specific humidity, cloud droplets concentration,  
182 cloud ice crystals (concentration and number), concentration of precipitating snow particles and  
183 rain drops. The convective adjustment is parameterised according to Bechtold et al. (2001).  
184 MAR is coupled to the one-dimensional land surface scheme SISVAT (Soil Ice Snow  
185 Vegetation Atmosphere Transfer, De Ridder and Schayes, 1997; Gallée et al., 2001) that  
186 includes a snow multi-layer scheme (Brun et al., 1992) including prognostic equations for  
187 temperature, mass, water content and snow properties (dendricity, sphericity and size) as well as  
188 an ice module (Lefebvre et al., 2003). As pointed out in Messenger et al. (2006), the physics of  
189 MAR can be adjusted to the region of interest and can be used with relatively high resolutions  
190 (40 to 7 km, finer resolutions would not be possible when using the hydrostatic configuration).  
191 MAR is a limited area model that offers the big advantage to be able to be forced by most of  
192 reanalyses (including ERA-20C) or CMIP5/CMIP6 global model outputs. MAR has been first  
193 designed for polar regions (Gallée, 1995), i.e. Antarctica (e.g., Gallée et al., 1996; Naithani, J. et  
194 al., 2002; Gallée et al., 2013, Amory et al. 2015; Agosta et al. 2019) and Greenland (Fettweis et  
195 al., 2017). It has also been applied over tropical regions (Messenger et al., 2004) to investigate the  
196 precipitation variability (Gallée, 2004). MAR has also been used to simulate the climate at  
197 midlatitudes (e.g. Wyard et al., 2016), and in particular to study changes of precipitation over  
198 Europe (Doutreloup et al., 2019). It has been applied over various mountainous areas, e.g.  
199 Himalaya (Ménégoz et al., 2013), Svalbard (Lang et al., 2015), Kerguelen archipelago (Favier et  
200 al., 2016; Verfaillie et al., 2019) and Antarctic peninsula (Datta et al., 2017).

201

### 202 **2.2 MAR configuration**

203

204 We used the version 3.9.0 of the MAR model, which is an open source code available at  
205 [mar.cnrs.fr/](http://mar.cnrs.fr/). Here, the model has been applied over the European Alps with a domain that  
206 extends from 43.5°N to 48°N and 5°E to 13°E and includes 140 x 90 grid points, at 7 km  
207 horizontal resolution. This configuration is based on 24 levels in the atmosphere, 7 levels in the  
208 soil, and the snow cover is described with a number of layers varying from 1 to 20. Here, MAR  
209 is laterally forced with the 6-hourly outputs of the ERA-20C reanalysis and its dynamical and



210 physical schemes are applied with a time step of 60s. ERA-20C is one of the first reanalyses  
211 available from 1900 to 2010, assimilating surface pressure and near-surface winds over the  
212 ocean and forced by SST reconstructions (Poli et al., 2016). By assimilating a limited number of  
213 variables corresponding to those available relatively homogeneously over 1900-2010, the  
214 ERA20-C reanalysis is expected to be homogeneous over this period, with a limited risk of  
215 including spurious trend. However this reanalysis is probably less accurate than other products  
216 assimilating also humidity and temperature in the free troposphere, a weakness that could induce  
217 model biases also in regional experiments as evidenced by Fettweis et al. (2017) over Greenland.  
218 MAR has already been successfully tested with the ERA20-C reanalysis as boundary conditions  
219 over Europe (Wyard et al., 2017; 2018). After a spin-up of 2 years, the model in general and the  
220 surface component in particular are supposed to reach an equilibrium. Therefore, the first years  
221 have been excluded from this analysis that hence focuses on the period 1903-2010.

222

### 223 **2.3 Observational datasets**

224

225 Observational data sets are used in this study for two objectives: first, a comparison between the  
226 model outputs and the different precipitation datasets have been conducted over 1971-2008, a  
227 period for which all the datasets are available (Section 3). Second, an analysis of the trends of  
228 several precipitation indices is described using the MAR experiments and the MeteoSwiss  
229 station data available since the beginning of the 20th century (Section 4). In addition to the  
230 MeteoSwiss station data, the following datasets have been considered:

231

#### 232 **HISTALP**

233 The HISTALP (“Historical instrumental climatological surface time series”) is the first long-  
234 term database of meteorological data collected in the European Alps, initiated in the 1990s (Auer  
235 and Bohm, 1994) and completed later on (Auer, et al., 2007). This dataset is available for air  
236 temperature at 2 meters, surface pressure, precipitation, sunshine duration and cloudiness  
237 through two different configurations: a first one including monthly homogenized time series of  
238 local measurements, with the first observations available from 1760 for temperature and 1800 for  
239 precipitation and a second one provided as a 1° gridded version. The gridded version, used in our  
240 study, is available from 1800 to 2014.

241

#### 242 **EURO4M-APGD**

243 The Alpine Precipitation Grid Dataset (EURO4M-APGD, Isotta et al., 2014) is a 5kmx5km grid  
244 analysis of daily precipitation, extending over the European Alps and covering the period 1971-  
245 2008. It is based on rain-gauge networks, encompassing more than 8500 stations from Austria,  
246 Croatia, France, Germany, Italy, Slovenia and Switzerland. This dataset was developed in the  
247 framework of the European Reanalysis and Observations for Monitoring (EURO4M) initiative  
248 and is simply named EURO4M thereafter.

249

250



251 **E-OBS**

252 E-OBS is provided by the ECA&D project under the Copernicus Climate Change Service (van  
253 den Besselaar et al., 2011). It is a daily gridded dataset over Europe for temperature and  
254 precipitation, produced from interpolation of local measurements at two available resolutions:  
255 0.25° and 0.1° (the highest resolution is used in this study). It is available from 1950 and updated  
256 each year, and is commonly used for model evaluation (e.g. Guillod et al., 2017). The version 19  
257 of E-OBS offers an estimate of the uncertainty related to the interpolation of local observations  
258 by providing a 100-member ensemble for each variable (Cornes et al., 2018).

259  
260 **SAFRAN**

261 The SAFRAN reanalysis combines large scale reanalyses and forecasts with in-situ  
262 meteorological observations, including precipitation, in order to provide a reanalysis of  
263 meteorological conditions in the French Alps, at the scale of massifs with a typical surface area  
264 of 1000 km<sup>2</sup> within which meteorological conditions are assumed to be homogenous but vary  
265 with elevation by steps of 300 m (Durand et al., 2009). Hence this reanalysis does not use a  
266 regular grid but focuses on the elevation dependency of meteorological conditions.

267  
268 **SPAZM**

269 The SPAZM dataset is a gridded product at a 1km resolution for minimum and maximum daily  
270 2m temperature and daily precipitation in the French Alps, available over the period 1948-2009  
271 and based on the interpolation of a dense network of rain gauges and temperature sensors from  
272 Météo-France and the French Company for Electricity (EDF; Gottardi et al., 2009). This dataset  
273 is provided with calibration parameters allowing to reproduce the stream flow observed in the  
274 Rhône valley with a hydrological model. These parameters are useful to correct the snowfall  
275 rates that are often underestimated in rain gauge measurements. The solid and liquid  
276 precipitation has been computed by considering 100% of solid precipitation below 0°C and  
277 100% of liquid precipitation above 2°C, considering daily temperature. A linear relationship for  
278 the ratio liquid/solid precipitation has been applied between 0°C and 2°C. Following the  
279 calibration suggested by Picouet (2012), we applied a correction factor for solid precipitation of  
280 1.5 in the Northern Alps and 1.3 elsewhere. The Northern Alps are defined here as the areas  
281 located north of Grenoble city (45.1885° N) and higher than 1000m asl. This apparently-  
282 arbitrary values have been developed and evaluated in the context of hydrological studies  
283 (Gouttevin et al., 2017).

284  
285 **2.4 Statistical analysis and indices**

286  
287 Mean and trends for the precipitation indices described in Table 1 are considered in this study,  
288 most of them selected from those recommended by the World Meteorological Organization  
289 (Peterson et al., 2001; [http://etccdi.pacificclimate.org/list\\_27\\_indices.shtml](http://etccdi.pacificclimate.org/list_27_indices.shtml)). When comparing  
290 MAR outputs with observational datasets based on a higher resolution (EURO4M, SPAZM),  
291 these ones are linearly interpolated onto the MAR grid. The gridded data are based on regular  
292 grids, except the SAFRAN data that is provided with a georeferenced polygon describing the





293 location of each massif. Correlation and Root Mean Square Error (RMSE) are computed to  
294 investigate the differences between datasets. The linear trends are computed with a linear least-  
295 square regression and a two-sided p-value is computed to test if the trends are significantly  
296 different from zero (Wald test with a t-distribution of the test statistic). Mean values and  
297 normalized trends (in percentage of the averaged values) are computed annually and seasonally  
298 for the precipitation rates and indices in the following sections. The seasons are computed by  
299 averaging indices over December-January-February (DJF) for winter, March-April-May (MAM)  
300 for spring, June-July-August (JJA) for summer, and September-October-November (SON) for  
301 autumn.

### 302 **3. Climatology of the MAR experiment and the observational datasets**

#### 303 **3.1 Spatial differences**

304 The Total Precipitation amount (TP) averaged over 1971-2008 simulated with MAR is shown in  
305 Figure 1a, with annual mean ranging between 300 and 3000 mm. In a general way, TP is  
306 stronger in the Northern than in the Southern Alps as expected due to the drier Mediterranean  
307 climate in the South. A comparison between the MAR experiment and the EURO4M reanalysis  
308 (Figure 1b) shows a good consistency between these two datasets in the lowlands (i.e. below  
309 500m asl), with positive or negative differences barely exceeding 20% in these areas. Above  
310 1500m, this difference is much higher with precipitation rates 40 to 80% higher in the MAR  
311 experiment than in the EURO4M dataset. Such a difference is significant with respect to the  
312 interannual standard deviation of precipitation that generally does not exceed 30% over the  
313 domain of application of MAR (Figure A1). The comparison between MAR and SPAZM  
314 (Figure 1c) shows similar differences in the lowlands as with EURO4M (~20%), but a better  
315 agreement at high elevation, with differences barely exceeding 40%. Correlation pattern between  
316 MAR and EURO4M is 0.59 and reaches 0.63 between MAR and SPAZM, suggesting a slightly  
317 better spatial consistency between these last two products. The precipitation rates estimated from  
318 SPAZM above 1500m asl are also higher in comparison with those provided by EURO4M  
319 (Figure 1d, differences ranging between 20% to 80%). As snowfall rates in SPAZM have been  
320 adjusted to fit the hydrological balance over the French Alps, this comparison suggests that the  
321 high precipitation rates simulated with MAR above 1500m asl may be realistic. Overall, TP  
322 simulated with MAR is relatively similar to TP estimated from SPAZM and show stronger  
323 values with respect to EURO4M data over the Alps.

#### 324 **3.2 Vertical gradients**

325 Vertical gradients of TP simulated with MAR are evidenced in Figure 2 (as yearly averages,  
326 considering both wet and dry days), including also a comparison with the SAFRAN reanalysis  
327 and the MeteoSwiss station data. In the MAR experiment, TP varies from 2 to 4 mm day<sup>-1</sup> at  
328 500m asl and from 3 to 5 mm day<sup>-1</sup> at 2500m asl in the Southern Alps, and from 2 to 4 mm day<sup>-1</sup>  
329 at 500m asl and from 3 to 6 mm day<sup>-1</sup> at 2500m asl in the Northern French Alps. The vertical  
330 gradient estimated from the SAFRAN dataset is smaller than those simulated by MAR. The large  
331 spread in the scatter plots of Figures 2a-b is explained by the spatial variability of the vertical



332 gradient of precipitation, which is stronger in MAR than in SAFRAN. Based on a comparison  
333 with high resolution numerical weather forecast model and glacier mass balance in mountain  
334 glaciers in the French Alps, it has been shown that SAFRAN most likely underestimates high  
335 elevation winter precipitation (above 2000m asl), which lends credence to the higher gradients  
336 simulated by MAR (Vionnet et al., 2019). MAR data are compared to the MeteoSwiss station  
337 data in Figure 2c-d. A difference between the two datasets in terms of vertical gradients is found  
338 both in winter (14% km<sup>-1</sup> for the local observations vs 43% km<sup>-1</sup> in the MAR data) and in  
339 summer (12% km<sup>-1</sup> for the local observations vs 20% km<sup>-1</sup> in the MAR data). These seasonally  
340 contrasted differences suggest a possible underestimation of the precipitation rates estimated  
341 from rain gauge measurements in relation with snowfall undercatch issues (Kochendorfer et al.,  
342 2017). However, the differences found in summer, i.e. a period with reduced snowfall rates, also  
343 suggests an overestimation of the precipitation rates at high elevation in the MAR experiment.  
344 Overall, it is difficult to accurately quantify the model biases at high elevation areas because of  
345 the scarceness of the observational data above 2000m asl whereas a large number of the MAR  
346 grid cells reaches an elevation ranging between 2000m asl and 3000m asl with a spatial  
347 resolution of 7km (Figure 2c-d). The vertical gradient of precipitation simulated by MAR over  
348 the entire domain of application reaches 38% km<sup>-1</sup> (1.15 mm.day<sup>-1</sup>.km<sup>-1</sup>) in winter and 33%  
349 km<sup>-1</sup> (1.21 mm.day<sup>-1</sup>.km<sup>-1</sup>) in summer (Figure 2e-f). Overall, the spatial patterns shown in  
350 Figure 2g-h for the MAR experiment and the MeteoSwiss station data suggest that MAR is able  
351 to reproduce the seasonal variations of precipitation rates, with large (small) values in summer in  
352 the Northeastern (Southwestern) Alps and an opposite pattern in winter.

### 353 **3.3 Interannual variability and seasonal cycle**

354 The temporal evolution of precipitation and its seasonal cycle over the period 1971-2008 is  
355 shown in Figure 3 for three sub-regions defined as the Southern Alps (SA, 43.5°N to 45.5°N and  
356 5°E to 7.5°E), the North Western Alps (NWA, 45.5°N to 47°N and 5°E to 7.5°E) and the  
357 Northeastern Alps (NEA, 45.5°N to 48°N and 7.5°E to 13°E), corresponding respectively to the  
358 orange, blue and purple boxes in Figure 1a. These boxes have been defined according to the data  
359 availability of the products used for comparisons as well as regional climatological conditions:  
360 SA is largely affected by the Mediterranean dry conditions, NWA precipitations rates are mainly  
361 related to Western low pressure systems, whereas NEA is more typical of a continental climate,  
362 with wetter conditions in summer than in winter. Over 1971-2008, precipitation rates estimated  
363 from the different datasets (EURO4M, SPAZM, E-OBS, HISTALP) show similar features. They  
364 range between 2 and 4 mm day<sup>-1</sup> in SA and take higher values in NWA and NEA, varying  
365 between 3 and 5 mm day<sup>-1</sup>. Table 2 includes the interannual correlations between the different  
366 datasets, that takes values above 0.8, except for HISTALP that correlates neither with EURO4M  
367 nor with MAR. The correlations between MAR and the observational datasets range between  
368 0.84 and 0.89, whereas the correlations among these different datasets systematically exceeds  
369 0.9, even reaching 0.99 and 0.97 for EURO4M versus SPAZM in SA and NWA. Such high  
370 correlation is probably due to the rain gauge network used to produce these gridded datasets that  
371 is partially common between the two products. Overall these correlation values suggest a correct  
372 interannual variability in the MAR experiment, but less realistic than those estimated from the



373 other observational datasets (except HISTALP). The model bias could be related to both model  
374 deficiencies and uncertainties in the ERA20C reanalysis used as boundary conditions. The  
375 difference between the MAR experiment and the observational products is similar in all the  
376 datasets, with a RMSE ranging between 0.26 and 1.14. RSME computed with HISTALP are  
377 comparable to the other ones, evidencing that HISTALP is able to provide an estimation of  
378 precipitation similar to the other products, even if the interannual variability is poorly  
379 reproduced in this dataset compared to the other ones (low correlation). No clear regional and  
380 data-dependant specificity in terms of RMSE is discernable in Table 2. It is worth noting that the  
381 uncertainty related to data interpolation in E-OBS (orange dashed lines) encompasses the time  
382 series corresponding to the other datasets. Such a large uncertainty is probably related to the low  
383 number of observations assimilated in E-OBS over the Alps in comparison with the large  
384 number of meteorological stations used to build EURO4M and SPAZM. It also points out the  
385 large uncertainty of such gridded products in mountainous areas. MAR is closer to SPAZM and  
386 EURO4M (smaller RMSE) than to HISTALP and E-OBS (higher RMSE), a finding giving  
387 confidence in the realism of the MAR simulation. The different datasets show specific seasonal  
388 cycles of precipitation (Figure 3, bottom), with two maximum values in spring and autumn in SA  
389 (Mediterranean climate), one maximum value in summer in NEA (continental climate) and a  
390 mix between these two regimes over NWA. Overall, the consistency between the different  
391 datasets is better in SA and NEA than over NWA, where more discrepancies among the datasets  
392 have been found. The comparison between model experiments and observational datasets gives  
393 confidence in the precipitation rates simulated with the MAR model forced here by ERA-20C.  
394 Longer simulations are therefore considered in the next section to investigate potential trends  
395 over the last century.

#### 396 **4. Precipitation trends in the Alps over 1903-2010**

##### 397 **4.1 Mean annual and seasonal precipitation**

398 No significant trend in precipitation rates is identified on average when considering the three  
399 Alpine sub-regions shown in Figure 3, a finding that could be explained by the shortness of the  
400 time series. The seasonal trends of mean precipitation (STP) are investigated now over a longer  
401 period, by considering in Figure 4 the MAR experiment (shaded) and the MeteoSwiss station  
402 data (dotted) over 1903-2010. The MeteoSwiss data is used here because it is available over the  
403 period covered by the MAR experiment (i.e. from 1903). Trends are contrasted both seasonally  
404 and altitudinally. In winter, there is a general positive trend in precipitation over the Alps (up to  
405 40% per century), contrasting with a drying simulated in the surrounding plains (~10% per  
406 century), both in the Po plain and in the Rhône valley (Figure 4a). In winter, the MAR  
407 experiment is consistent with the local observations showing an increase in precipitation over  
408 Switzerland, except in the southern part of this country, where some stations show a drying  
409 trend. However, when masking the non significant trends ( $p\text{-value} > 0.05$ , Figure 4c), only the  
410 positive trends of precipitation remain over the Alpine mountains, with values ranging between  
411 20 and 40% per century in the Northern French Alps and in the Southwestern Switzerland, at an  
412 elevation generally higher than 1500m asl. The MeteoSwiss data shows a significant increase in



413 precipitation at stations located further north in Switzerland, with a magnitude similar to the  
414 model values. In summer, a general drying is simulated over the whole model domain (Figure  
415 4b), with values exceeding 40 to 50% per century in the Po and the Rhône valleys. This signal is  
416 much less pronounced in the alpine areas located above 1500m asl, where the signal is generally  
417 not significant (Figure 4d). The drying is less pronounced over Switzerland in comparison with  
418 the Southern Alps. Considering Figure 4b, a drying and even a slight increase in precipitation  
419 (<10% per century) is found in the station data over the mountains of Southern Switzerland,  
420 whereas a drying is observed in the north of the country (10% to 20% per century). The summer  
421 trends locally observed in Switzerland are however barely significant (Figure 4d). Spring and  
422 autumn trends show intermediate patterns, with a drying pronounced in the plains, and a slight  
423 moistening in the mountainous areas (Figure 4e-f). The trends simulated and observed during  
424 spring and autumn are however smaller and barely significant, except in the Po plain where a  
425 drying is simulated by MAR and in the North of Switzerland where a significant moistening is  
426 significant at some stations (Figure 4g-h).

#### 427 **4.2 Wet spells**

428 Changes of the wet spell features are highlighted in Figure 5, showing the centennial summer  
429 and winter trends of WD (Figure 5a-b), SDII (Figure 5c-d), MNWS (Figure 5g-h) and MWSD  
430 (Figure 5e-f). In winter and over the Alps, the slight increase in WD, ranging between 0 and  
431 10% per century, is slightly contributing to the increase in the STP (Figure 5a), but this one is  
432 mainly explained by an increase in SDII by 10 to 30% per century (Figure 5c). These changes  
433 are associated with an increase in the MWSD by 10 to 20% per century (Figure 5e). Finally, the  
434 winter trend in the MNWS shows a different pattern from the previous ones (Figure 5g), with a  
435 consistent decrease over the Northern Alps and in particular over Switzerland, ranging between  
436 10 and 20% per century in both model and observational data. These changes suggest that the  
437 precipitation increase found in winter over the Alpine mountains is related to longer, more  
438 intense and less frequent wet spells. The agreement between the model and the observations is  
439 relatively good in winter. In summer, a large part of the drying is explained by a reduction of  
440 WD, reaching 10 to 20% in the north-western flank of the Alps, and exceeding 40 to 50% per  
441 century in all the Southeastern Alps (Figure 5b). The SDII shows smaller changes during this  
442 season (Figure 5d), that can be either positive or negative and barely exceeding 10% per century.  
443 A general decrease of MWSD is also found in summer (Figure 5f), especially pronounced over  
444 the Southeastern flank of the Alps and in the Po plain, a signal consistent between the model and  
445 the observations over Switzerland. Finally, the model shows a general increase in MNWS  
446 (Figure 5h) in summer, which is particularly strong over the Southeastern flank of the Alps. Over  
447 Switzerland, this signal is small and not consistent with the observations that show a minor  
448 reduction of MNWS. Overall, these results suggest that the decrease of the mean precipitation  
449 rates over the Alps in summer is explained by a dramatic reduction of WD, with shorter and  
450 more frequent wet spells without any clear change of SDII.

451



#### 452 4.3 Extreme precipitation

453 The means and the trends of extreme precipitation rates are described by considering Rx1day  
454 seasonally (Figure 6) and annually (Figure 7). Extreme precipitation shows contrasted seasonal  
455 and spatial climatological patterns (Figure 6a-c-e-g). In winter and spring, it takes higher values  
456 over the Southern Alps (both in France and in Italy) than in the Northern Alps (Figure 6a-c). In  
457 summer, extreme values are smaller in the Western Alps than in the Eastern Alps. The most  
458 intense events are found in autumn, in both the Western and the Eastern parts of the Southern  
459 Alps, with mean Rx1day ranging between 50 and 70 mm day<sup>-1</sup> in many areas (Figure 6g). Over  
460 Switzerland, the climatological pattern of Rx1day is consistent between the model and the  
461 observations, except for some local exceptions. In contrast with the trends of mean precipitation  
462 (Figure 4), there is a general increase in Rx1day (Figure 6b-d-f-h) that occurs over the four  
463 seasons and both in the plains and in the mountainous areas. The trend in the seasonal Rx1day  
464 over the period 1903-2010 takes values between 0 and 40% per century, and generally ranges  
465 between 20% and 40% per century over the Alpine mountain range. Such increase in  
466 percentages, suggests strong changes of local extreme, in particular in the regions where strong  
467 events are frequent in autumn (50 to 70 mm day<sup>-1</sup>, Figure 6g). The magnitude of the change in  
468 Rx1day is similar between the model and the observations, but the MeteoSwiss station data show  
469 more heterogeneous spatial trends, with some locations where the trends can be small and even  
470 slightly negative. The mean increase in Rx1day over the model domain reaches 10, 10, 6 and  
471 13% per century, respectively in winter, spring, summer and fall, confirming a constant increase  
472 in Rx1day for all the seasons.

473 The climatological mean of the annual Rx1day (Figure 7a) is dominated by the seasonal Rx1day  
474 computed in autumn that shows a similar pattern (Figure 6g). Centennial Rx1day (Figure 7b,  
475 maximum Rx1day computed over 1903-2010) shows a pattern similar to the annual average of  
476 Rx1day. The strongest centennial events are found in the Southern Alps, in France and Italy, as  
477 well as in the Ticino valley in Switzerland, with extreme values locally reaching 250 to 300 mm  
478 day<sup>-1</sup>. The annual trends are inspected in Figure 7c, highlighting a general increase in extreme  
479 precipitation. The significance of this trend is described in Figure 7d, where non-significant  
480 trends (p-value>0.05) are masked. The annual samples considered here are obviously larger than  
481 the seasonal samples, allowing to detect more efficiently significant trends. In that case, a good  
482 consistency is found between the model and the MeteoSwiss station, both of them showing only  
483 positive trends, ranging between 20 and 40% per century, and covering large parts of the Alps  
484 and the Apennines.

#### 485 4.4 Statistical significance of the trends

486 The large interannual to decadal variability of the climate in the Europe-North-Atlantic region,  
487 in relation with internal climate variability, makes precipitation trends challenging to detect in  
488 the Alps. When considering time series over 1971-2008, i.e. a relatively short period, there is no  
489 clear tendency of the mean precipitation over the Alps (Figure 3). By computing trends from the  
490 beginning of the 20th century, winter increase and summer decrease of mean precipitation



491 emerge from interannual to decadal variability over large areas (Figure 4 c-d). Similarly, the  
492 positive trends of the annual Rx1day are significant ( $p$ -value $<0.05$ ) over large areas of the Alps,  
493 in particular where the trends are positive and strong (i.e.  $>10\%$  per century), whereas all the  
494 negative and small trends in both the model data at the MeteoSwiss station data are not  
495 significant (Figure 7d). Figure 7e illustrates the trend of the annual Rx1day, considering the  
496 average of the MeteoSwiss data (purple), the model data integrated over Switzerland (blue) and  
497 the model data integrated over the whole model domain (red). In agreement with the patterns  
498 shown in Figure 7c-d, the mean trend in the annual Rx1day in Figure 7 is positive for both the  
499 model outputs and the observations, reaching 9.43, 8.74 and 8.40 mm day<sup>-1</sup> per century  
500 respectively for the MeteoSwiss data, the model over Switzerland and the model over the whole  
501 domain. The vertical bars in Figure 7e show the length of the time series required to identify a  
502 significant trend over the period 1903-2010, starting from 2010 and going back into the past.  
503 Time series has to be considered from 1961, 1932 and 1942 until 2010 to get significant trends  
504 ( $p$ -value $<0.05$ ) for the MeteoSwiss data, the model integrated over Switzerland and the model  
505 integrated over the whole domain respectively, which correspond to length of  $\sim 50$  to  $\sim 80$  years.  
506 We nonetheless see that shorter time series can lead to significant signals as evidenced in Figure  
507 7f showing the  $p$ -value computed to estimate the significant level of the trend. The three curves  
508 reach values below 0.05 during the years 1960-1970, highlighting significant trends of Rx1day  
509 over 1960-2010 for the observations and over 1970-2010 for the model data.

## 510 **5. Discussions and conclusions**

511

512 Previous work highlighted a temperature increase in the Alps over the last century, associated  
513 with an increase in precipitation over the Northern Alps in winter and a drying in summer  
514 (Schmidli et al., 2002; Auer et al., 2007; Masson and Frei, 2014; 2016; Brugnara and Maugeri,  
515 2019). The detailed features of climate change over the Alps remain however partly unknown, in  
516 particular because of the lack of observational data at high elevation, and observational issues  
517 with snow precipitation. In addition, the large internal variability of the climate system,  
518 especially pronounced in Europe, may overwhelm long-term trends that remain challenging to  
519 detect. Here, the MAR model has been used at a 7km resolution over the Alps, over the period  
520 1900-2010 laterally forced with the ERA-20C reanalysis. A comparison with several datasets  
521 (EURO4M, SPAZM, SAFRAN, E-OBS, HISTALP and local MeteoSwiss data) demonstrates  
522 that the model is able to reproduce the climatological precipitation rates as well as both the  
523 interannual variability and the seasonal cycle of precipitation over the Alps. The high resolution  
524 used in the MAR experiment allowed a relatively correct representation of the topography, with  
525 a large number of grid cells covering elevation between 2000m and 3500m, corresponding to  
526 areas with few available observations. The vertical gradient of precipitation in the Alps is  
527 estimated to 33% km<sup>-1</sup> (1.21 mm.day<sup>-1</sup>.km<sup>-1</sup>) in summer and 38% km<sup>-1</sup> (1.15 mm.day<sup>-1</sup>.km<sup>-1</sup>)  
528 in winter, with values stronger in the Northern Alps than in the Southern Alps. The spatial  
529 variability of this vertical gradient is large, being affected by the local climate conditions.

530

531 The model experiment confirms an increase in precipitation during the winter over the North  
532 Western Alps, above 500m asl and significant and more pronounced above 1500m asl, with local



533 values of 20% to 30% per century over the period 1903-2010. This increase in precipitation is  
534 related to stratiform precipitation, mainly explained by more intense precipitation during wet  
535 days, and it is associated to longer albeit less frequent wet spells, a result consistent with  
536 Schmidli and Frei (2005) over Switzerland. The model reproduces the general drying that  
537 occurred in summer during the same period, exceeding 40% to 50% per century in the lowlands,  
538 whereas it is much smaller (<10% per century) and not significant above 1500m asl. This drying  
539 is not related to a decrease of the intensity of precipitation, but it is explained by a dramatic  
540 reduction of the number of wet days, with shorter and more frequent wet spells. It is consistent  
541 with previous work suggesting that the Alpine region appears as an exception in a drying region,  
542 where local convective precipitation increases locally, in relation to surface warming and  
543 sufficient moisture available in the soil at high-elevation areas (Giorgi et al., 2016).

544

545 The model reproduces the observed climatological patterns of the seasonal maximum  
546 precipitation, and in particular the large values occurring in the Southern Alps in autumn,  
547 exceeding 50 and even 70 mm day<sup>-1</sup> on average over the period 1903-2010. Centennial events  
548 reaching 250 to 300 mm day<sup>-1</sup> are simulated in the Southern Alps, both in France and in Italy, as  
549 well as in the Ticino valley. The seasonal maximum of precipitation shows a general increase  
550 over this period and present during the four seasons, reaching values between 20% and 40% per  
551 century in the Alps. An increase of strong precipitation has been evidenced in previous studies  
552 over the European Alps in relation with higher temperature and moisture rates in the atmosphere  
553 following the Clausius-Clapeyron relationship (e.g. Ban et al., 2015). However, this increase  
554 might be modulated by the availability of moisture in the low troposphere and at the surface. The  
555 drying of the surface may act as a positive feedback enhancing warming signals, that has been  
556 identified as one of the causes of the Mediterranean amplification (Brogli et al., 2019).  
557 Bronnimann et al. (2018) suggested a limited increase in Rx1day during the summer in the Alps  
558 due to moisture limitation, pointing out a shift of this index typically observed at the end of the  
559 summer toward early summer and early autumn. Here, the MAR experiment shows an increase  
560 of Rx1day both annually and for all seasons, suggesting sufficient moisture available at the  
561 surface and in the low troposphere over 1903-2010 in the model experiment. This difference  
562 with Bronnimann et al. (2018) could be explained by a relatively high resolution (7km) in our  
563 model configuration as well as specific physical parameterisations. Nevertheless, the MAR  
564 experiment evidenced a significant increase in the Rx1day only in mountainous areas whereas no  
565 significant signal is not found in the lowlands. This result is consistent with Brugnara et al.  
566 (2019) who observed an increase in the Rx1day in the mountain areas of Switzerland, where  
567 enough moisture would be available, whereas the drying occurring in the Southern flank of the  
568 Italian Alps may prevent any increase in Rx1day.

569

570 In the MAR experiments, the trends of the seasonal maxima of precipitation integrated over the  
571 Alps are significant (p-value<0.05) only when considering long time series, typically 50 to 80  
572 years depending on the area considered. Some of these trends are nonetheless significant when  
573 computed over recent decades, from the 1960s/1970s to the 2000s. This suggests a recent  
574 acceleration of the increase in extreme precipitation, whereas earlier periods with strong



575 precipitation also occurred, in particular during the 1950s/1960s. These ones could be explained  
576 by internal climate variability and/or the non-linear response of the climate system to  
577 anthropogenic greenhouse gases and aerosols. In particular, the cooling related to aerosol  
578 forcing, which peaked during the 1970s/1980s (Koch et al., 2011) over Europe could have  
579 masked the warming related to greenhouse gases, and temporarily prevented changes of extreme  
580 precipitation. Further model investigations should be conducted to disentangle the variability of  
581 the Alpine climate related to internal variability and external forcings. This research is needed to  
582 anticipate possibly strong precipitation changes in the Alps under the accelerating global climate  
583 change.

584

#### 585 **Data availability:**

- 586 • MAR is accessible at <https://gitlab.com/Mar-Group>, and documented at <http://mar.cnrs.fr/>
- 587 • The outputs of the MAR experiments will be uploaded to a public server (EUDAT) if the  
588 paper is accepted and before publication.
- 589 • The scripts used in this study will be put on github if the paper is accepted.
- 590 • Alpine Precipitation Grid Dataset (EURO4M-APGD), Version 1, is available on-line at  
591 DOI:10.18751/Climate/Griddata/APGD/1.0
- 592 • ECAD can be downloaded at <https://www.ecad.eu/download/ensembles/ensembles.php>
- 593 • SAFRAN data are available upon request to [s2m.reanalysis@meteo.fr](mailto:s2m.reanalysis@meteo.fr). Work is in progress to  
594 release the data set on a public repository.
- 595 • The SPAZM dataset has been provided by EDF and Météo-France for this research. It could  
596 be made available to other researchers under a specific research agreement. Requests should  
597 be sent to [dtg-demandedonnees-hydro@edf.fr](mailto:dtg-demandedonnees-hydro@edf.fr)

598

599 **Author contributions:** All authors contributed to design the study. XF, MM and JB ran MAR  
600 experiments and produced the figures. MM wrote the manuscript and other authors contributed  
601 with suggested changes and comments.

602

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604

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617 package basemap (<https://matplotlib.org/basemap/>).





618 **Tables:**

619

Index	Unit	Description
TP	mm year-1	Total precipitation amount per year
STP	mm day-1	Total precipitation amount, including wet and dry days, seasonal or annual
WD	days	Number of wet days ( $\geq 1$ mm)
SDII	mm day-1	Simple daily intensity (TP/WD)
Rx1day	mm day-1	Maximum daily precipitation, seasonal or annual
MNWS	no unit	Mean number of wet spells per season
MWSD	days	Mean wet spell duration, averaged over a season (WD/MNWS)

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Table 1: Annual and seasonal precipitation indices analysed in this study. Precipitation is the sum of solid and liquid precipitation.

	Southern Alps (SA)	Northwestern Alps (NWA)	Northeastern Alps (NEA)
<b>MAR - EURO4M</b>	<b>C=0.89; RMSE=0.46</b>	<b>C=0.88; RMSE=0.37</b>	<b>0.85; RMSE=0.41</b>
<b>MAR - SPAZM</b>	<b>C=0.87; RMSE=0.26</b>	<b>C=0.85; RMSE=0.45</b>	-
<b>MAR - E-OBS</b>	<b>C=0.84; RMSE=0.69</b>	<b>C=0.86; RMSE=0.83</b>	<b>C=0.79; RMSE=0.90</b>
<b>MAR - HISTALP</b>	<b>C=0.02; RMSE=0.64</b>	<b>C=-0.10; RMSE=0.73</b>	<b>C=-0.22; RMSE=0.66</b>
EURO4M - SPAZM	C=0.99; RMSE=0.38	C=0.97; RMSE=0.62	-
E-OBS - SPAZM	C=0.93; RMSE=0.63	C=0.95; RMSE=1.14	-
E-OBS - EURO4M	C=0.94; RMSE=0.29	C=0.95; RMSE=0.54	C=0.93; RMSE=0.54
EURO4M - HISTALP	C=0.03; RMSE=0.68	C=-0.08; RMSE=0.74	C=-0.26; RMSE=0.67

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Table 2: Correlation Pearson coefficient computed over 1971-2008 (C) and Root Mean Square Error (RMSE) between the time series of precipitation data over 1971-2008 for the three different subareas described in Figure 1. All the correlations are significant ( $p$ -value $>0.1$ ), except those computed with the HISTALP data.



631 **Figure captions**

632

633 Figure 1: (a) Annual mean of precipitation (TC, mm year<sup>-1</sup>) over 1971-2008 in the Alps  
634 simulated with the model MAR applied with a resolution of 7km and laterally forced with ERA-  
635 20C. The colored boxes correspond to the Southern Alps (SA, orange), the Northwestern Alps  
636 (NWA, blue) and the Northeastern Alps (NEA, purple). Precipitation differences (%) between:  
637 (b) the MAR experiment and the SPAZM dataset, (c) the MAR experiment and the EURO4M-  
638 APGD observational gridded datasets, and the SPAZM and the EURO4M-APGD datasets. (c)  
639 and (d) are shown only for the area where the SPAZM data is available. The 1000 m-spaced  
640 black contours show the topography in the 7km-resolution model, starting from 500 m.asl and  
641 political frontiers are denoted with the black dashed lines. The pattern correlation between MAR  
642 outputs and observational data is 0.59 and 0.63 respectively with EURO4M and SPAZM (p-  
643 value<1e-200).

644

645 Figure 2: Precipitation (STP) averaged over 1971-2008 simulated by MAR and estimated from  
646 reanalyses and observations. (a-b-c-d-e-f) show precipitation as a function of the elevation over  
647 the Southern (a) and the Northern (b) French Alps in MAR experiments and SAFRAN  
648 reanalysis, and estimated over Switzerland from local meteorological stations and from the MAR  
649 grid cells covering Switzerland during summer (c) and winter (d). The vertical gradient averaged  
650 over the full domain are shown for winter (e) and summer (f). STP averaged over 1903-2010 in  
651 the MAR experiment (shaded, mm.day<sup>-1</sup>) and observed at MeteoSwiss stations in Switzerland  
652 (dots, observations available from the beginning of the XXth century) are shown for summer (g)  
653 and winter (h). In (g) and (h), the 1000 m-spaced black contours show the topography with a  
654 7km-resolution, starting from 500 m.asl and political frontiers are denoted with the black dashed  
655 lines.

656

657 Figure 3: Annual mean precipitation (mm day<sup>-1</sup>) averaged over the Southern Alps (SA), the  
658 Northwestern Alps (NWA) and the Northeastern Alps (NEA) over the period 1971-2008 (top  
659 row) and corresponding monthly averaged seasonal cycle over the same period (bottom row).  
660 The area covered by the SA, NWA and NEA domains can be visualized in Figure 1. MAR  
661 outputs and observational data sets EURO4M, SPAZM, HISTALP and E-OBS are shown (see  
662 text for details). E-OBS (orange solid line) is provided with an estimation of the observational  
663 uncertainty (orange dashed lines).

664

665 Figure 4: Seasonal linear trends (percent per century) of precipitation over 1903-2010 in winter  
666 (a-c), summer (b-d), spring (e) and autumn (f). 1000 m-spaced black contours show the  
667 topography in the 7km-resolution model, starting from 500 m.asl and frontiers are denoted with  
668 the black dashed lines. In (c-d) and (g-h), the trend is masked when its p-value is below 0.05  
669 (level of confidence is lower than 95%; white areas for the model outputs and station data  
670 excluded).

671



672 Figure 5: Winter and Summer 1903-2010 trends (percent per century) of WD (a-b), SDII (c-d),  
673 MWSD (e-f) and MNWS (g-h) simulated by the MAR model (shaded) and locally observed in  
674 Switzerland (dots). WD is computed as a percentage of the available daily data for observations.  
675 Any station from the observational network including missing data is excluded when computing  
676 the trends.

677

678 Figure 6: Seasonal mean (mm day<sup>-1</sup>, left) and trends (percent per century, right) over the period  
679 1903-2010 of the seasonal Rx1day simulated by MAR (shaded) and locally observed in  
680 Switzerland (dots) for Winter (a-b), Spring (c-d), Summer (e-f) and Autumn (g-h).

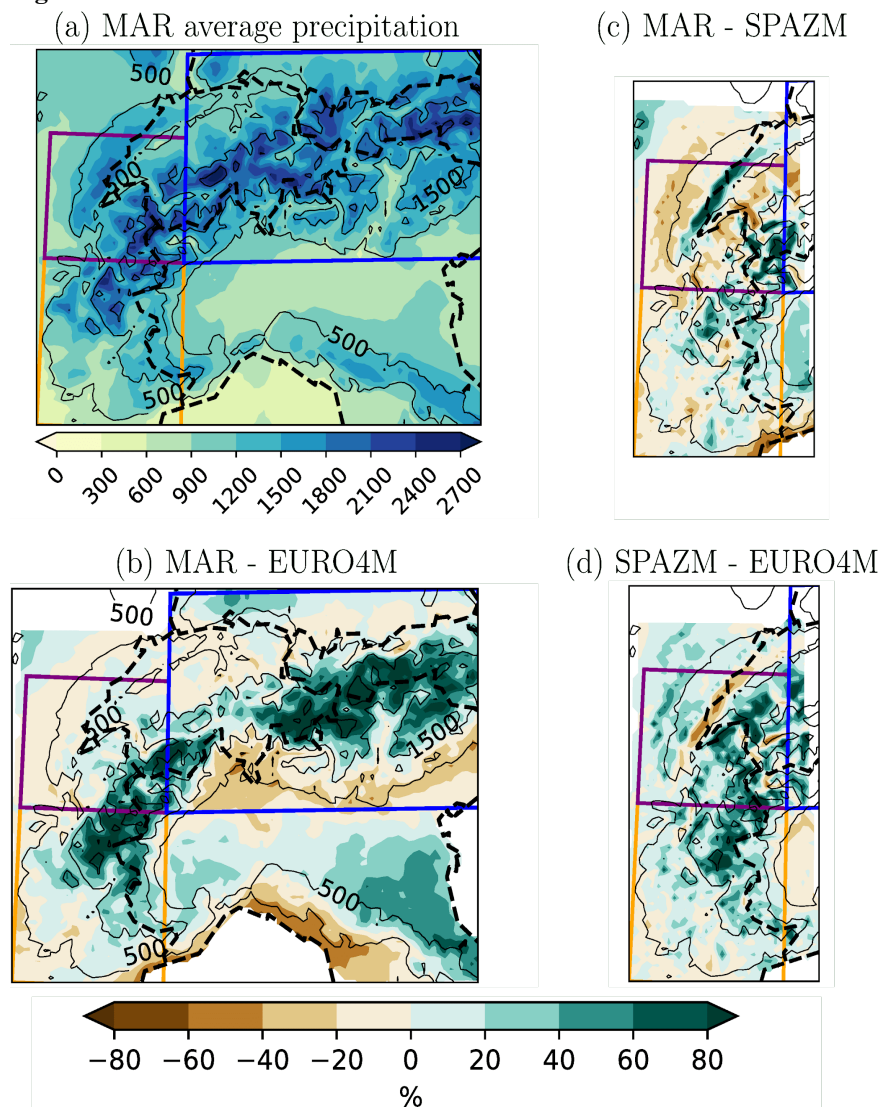
681

682 Figure 7: Mean (a) and maximum (b) of the annual Rx1day and its trend including (c) and  
683 excluding (d) the areas where the p-value is lower than 0.05, over 1903-2010. Annual Rx1day  
684 (e) and associated p-value of the trend (f) over the same period averaged over the model domain  
685 (red for the entire Alpine region and blue for the Swiss domain only) and for the MeteoSwiss  
686 network (purple, average of the MeteoSwiss data station available over 1903-2010). The vertical  
687 bars in (e) highlight the year before which the p-value never exceeds 0.05.

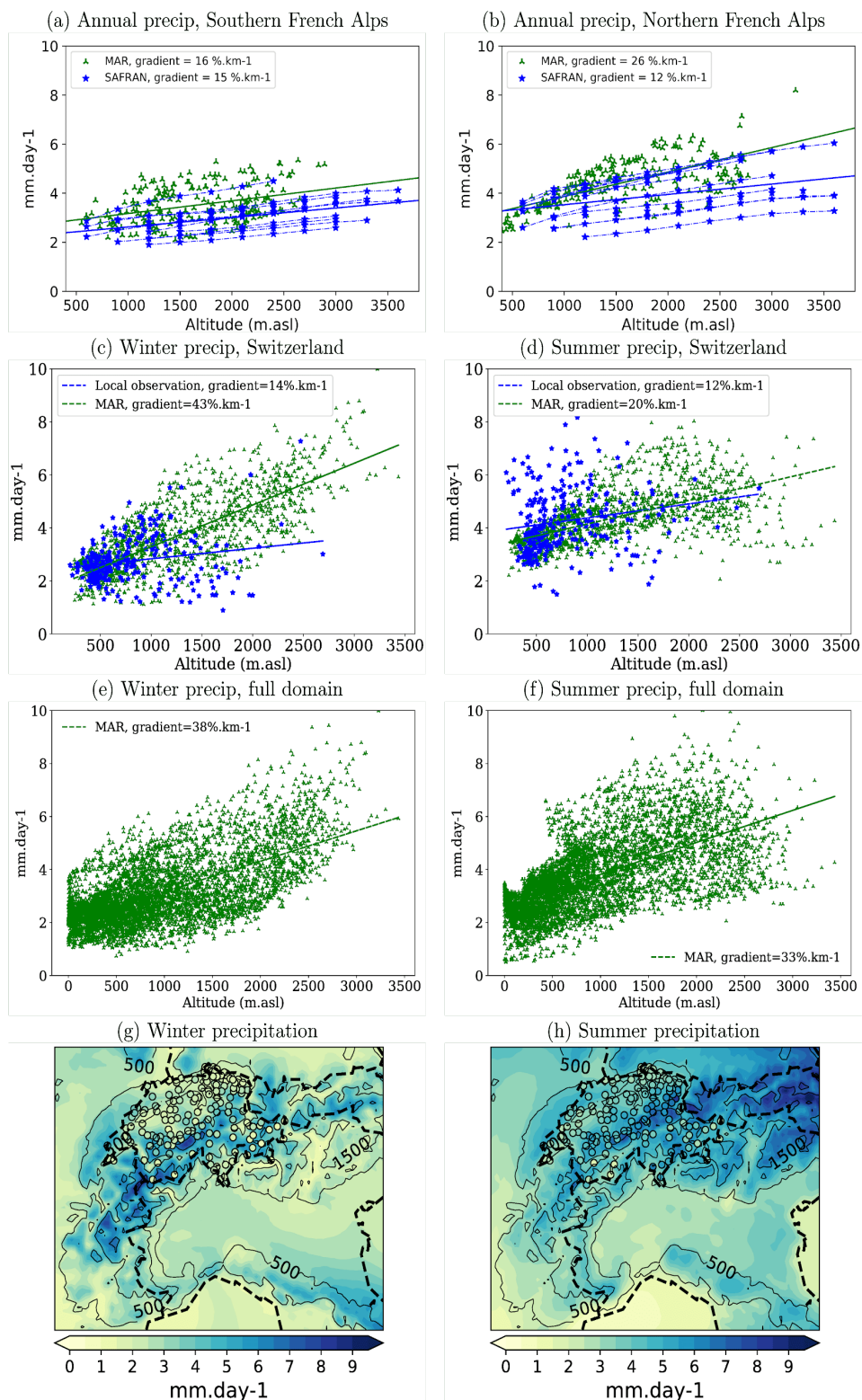
688



689 **Figures:**

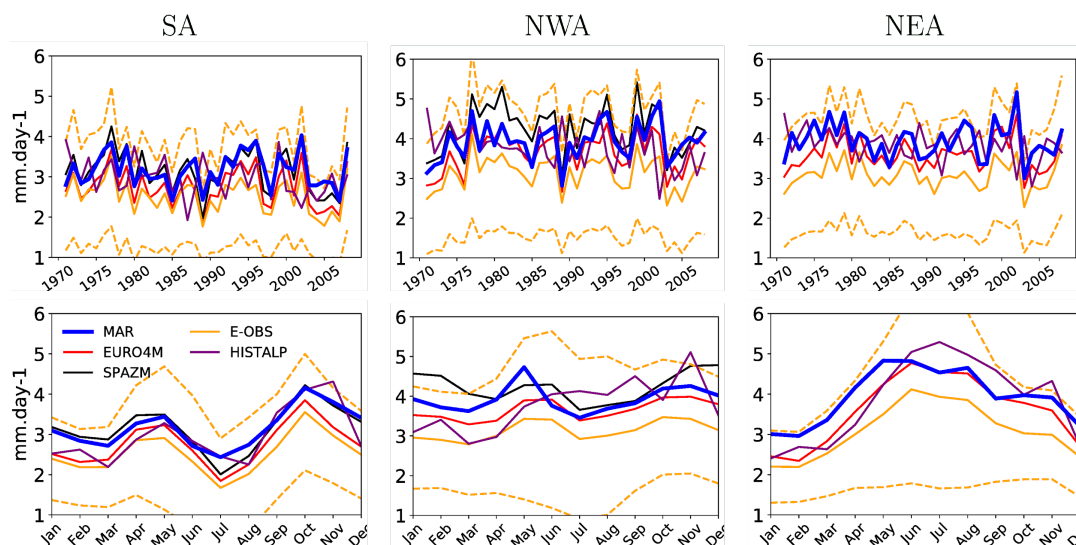


690  
691 Figure 1: (a) Annual mean of precipitation (TC, mm year<sup>-1</sup>) over 1971-2008 in the Alps  
692 simulated with the model MAR applied with a resolution of 7km and laterally forced with ERA-  
693 20C. The colored boxes correspond to the Southern Alps (SA, orange), the Northwestern Alps  
694 (NWA, blue) and the Northeastern Alps (NEA, purple). Precipitation differences (%) between:  
695 (b) the MAR experiment and the SPAZM dataset, (c) the MAR experiment and the EURO4M-  
696 APGD observational gridded datasets, and the SPAZM and the EURO4M-APGD datasets. (c)  
697 and (d) are shown only for the area where the SPAZM data is available. The 1000 m-spaced  
698 black contours show the topography in the 7km-resolution model, starting from 500 m.asl and  
699 political frontiers are denoted with the black dashed lines. The pattern correlation between MAR  
700 outputs and observational data is 0.59 and 0.63 respectively with EURO4M and SPAZM (p-  
701 value<1e-200).

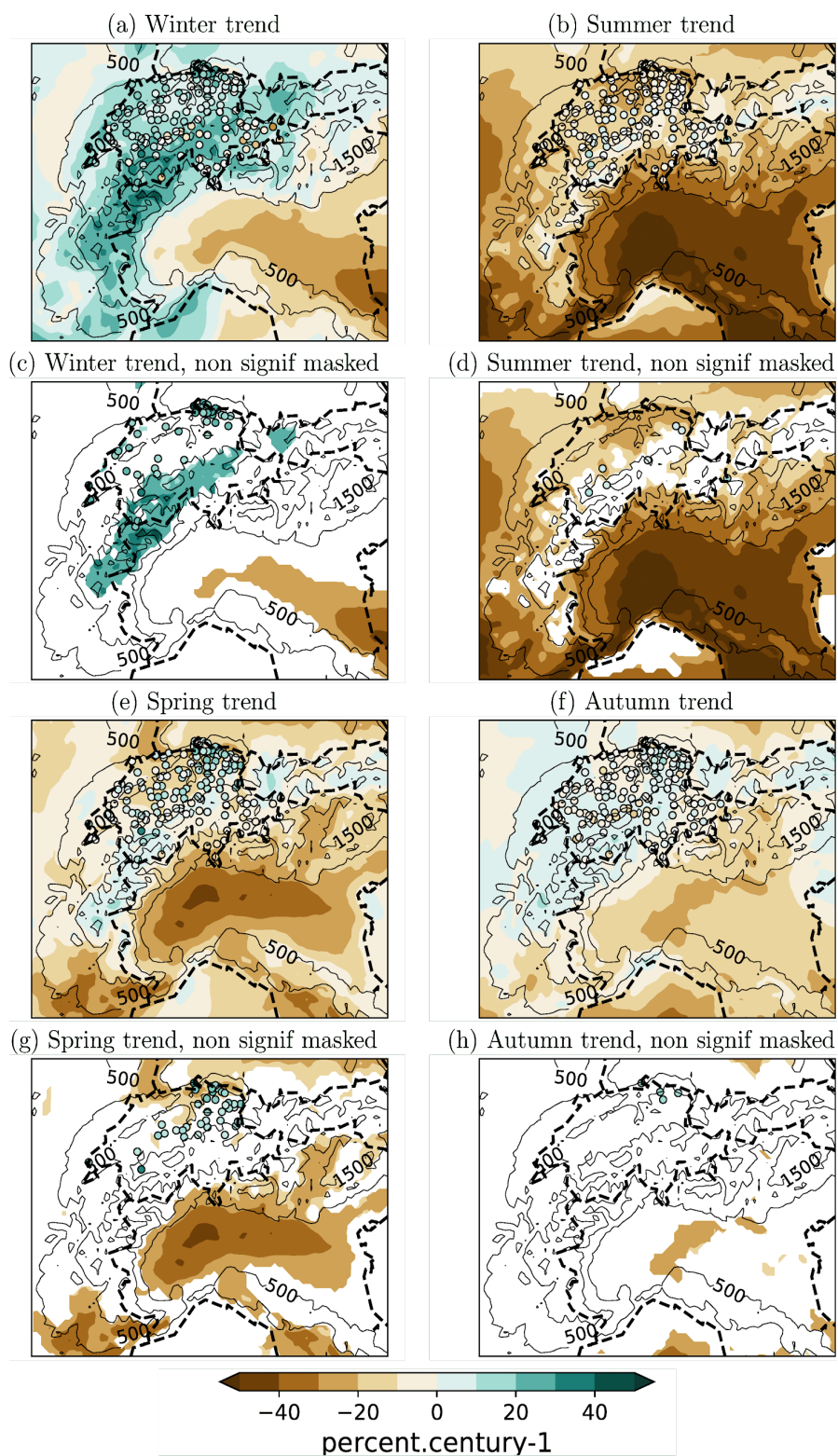




703 Figure 2: Precipitation (STP) averaged over 1971-2008 simulated by MAR and estimated from  
 704 reanalyses and observations. (a-b-c-d-e-f) show precipitation as a function of the elevation over  
 705 the Southern (a) and the Northern (b) French Alps in MAR experiments and SAFRAN  
 706 reanalysis, and estimated over Switzerland from local meteorological stations and from the MAR  
 707 grid cells covering Switzerland during summer (c) and winter (d). The vertical gradient averaged  
 708 over the full domain are shown for winter (e) and summer (f). STP averaged over 1903-2010 in  
 709 the MAR experiment (shaded, mm.day<sup>-1</sup>) and observed at MeteoSwiss stations in Switzerland  
 710 (dots, observations available from the beginning of the XXth century) are shown for summer (g)  
 711 and winter (h). In (g) and (h), the 1000 m-spaced black contours show the topography with a  
 712 7km-resolution, starting from 500 m.asl and political frontiers are denoted with the black dashed  
 713 lines.  
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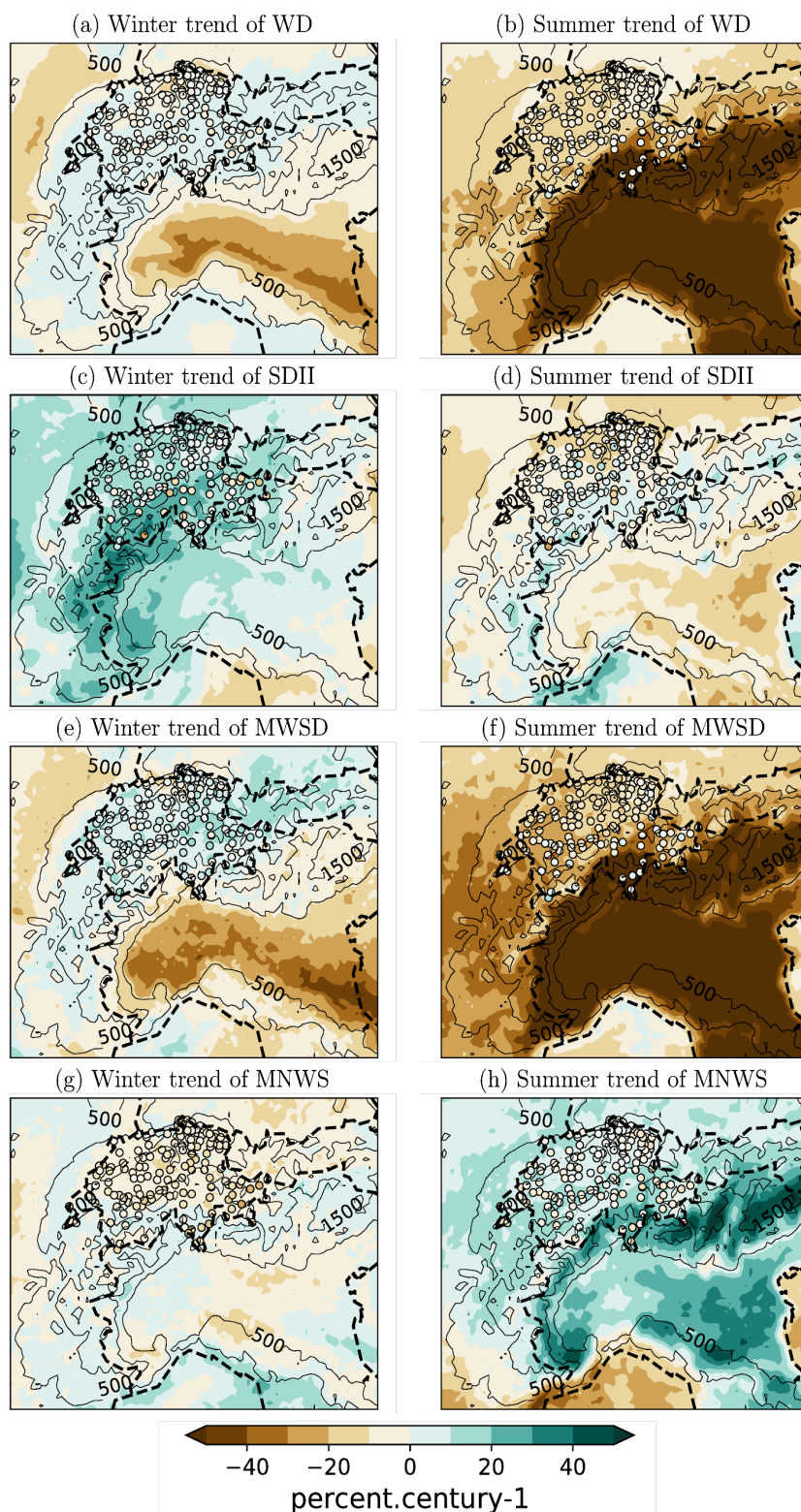
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 717  
 718 Figure 3: Annual mean precipitation (mm day<sup>-1</sup>) averaged over the Southern Alps (SA), the  
 719 Northwestern Alps (NWA) and the Northeastern Alps (NEA) over the period 1971-2008 (top  
 720 row) and corresponding monthly averaged seasonal cycle over the same period (bottom row).  
 721 The area covered by the SA, NWA and NEA domains can be visualized in Figure 1. MAR  
 722 outputs and observational data sets EURO4M, SPAZM, HISTALP and E-OBS are shown (see  
 723 text for details). E-OBS (orange solid line) is provided with an estimation of the observational  
 724 uncertainty (orange dashed lines).  
 725





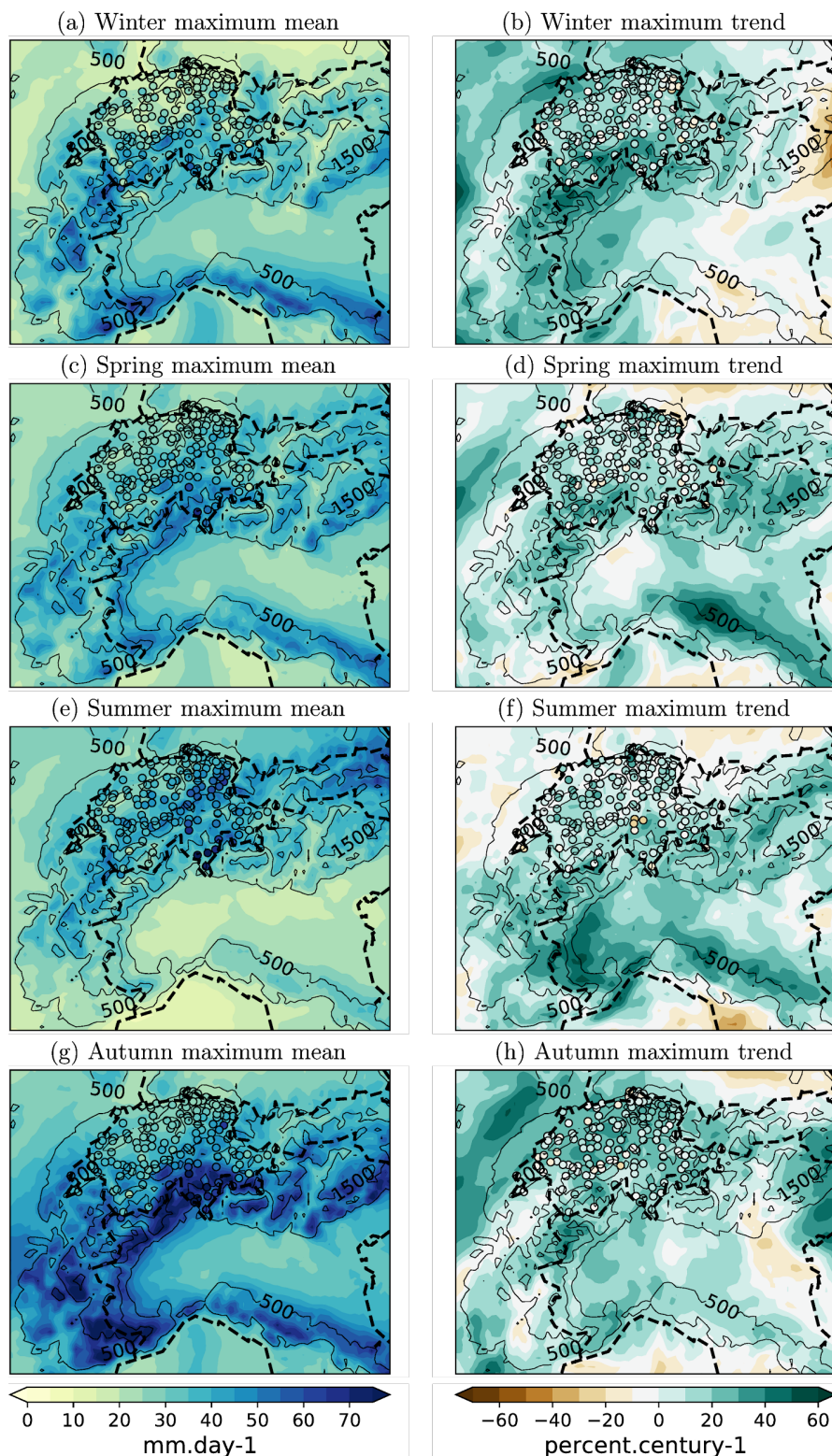
727 Figure 4: Seasonal linear trends (percent per century) of precipitation over 1903-2010 in winter  
728 (a-c), summer (b-d), spring (e) and autumn (f). 1000 m-spaced black contours show the  
729 topography in the 7km-resolution model, starting from 500 m.asl and frontiers are denoted with  
730 the black dashed lines. In (c-d) and (g-h), the trend is masked when its p-value is below 0.05  
731 (level of confidence is lower than 95%; white areas for the model outputs and station data  
732 excluded).







734 Figure 5: Winter and Summer 1903-2010 trends (percent per century) of WD (a-b), SDII (c-d),  
735 MWSD (e-f) and MNWS (g-h) simulated by the MAR model (shaded) and locally observed in  
736 Switzerland (dots). WD is computed as a percentage of the available daily data for observations.  
737 Any station from the observational network including missing data is excluded when computing  
738 the trends.  
739

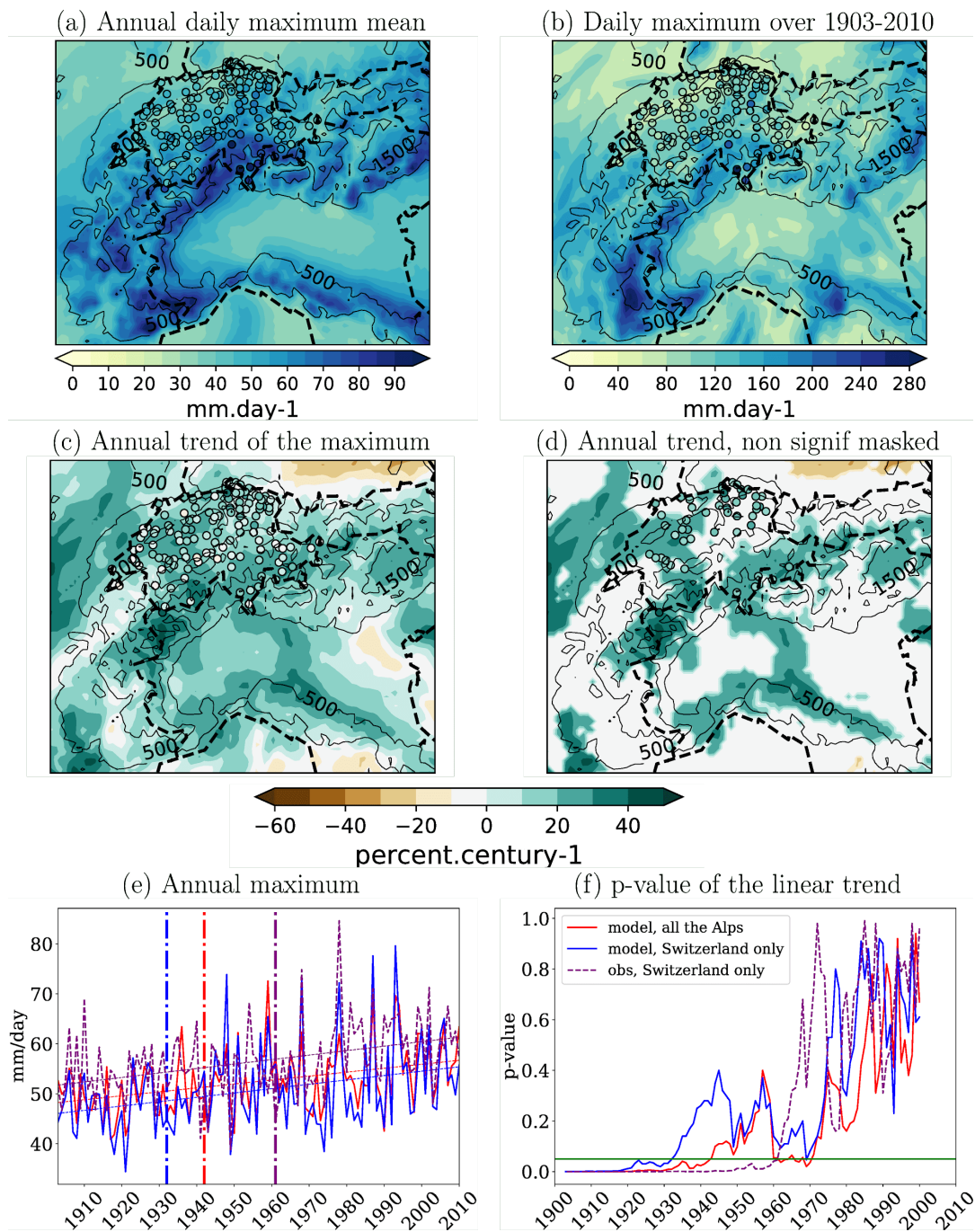




741 Figure 6: Seasonal mean (mm day<sup>-1</sup>, left) and trends (percent per century, right) over the period  
742 1903-2010 of the seasonal Rx1day simulated by MAR (shaded) and locally observed in  
743 Switzerland (dots) for Winter (a-b), Spring (c-d), Summer (e-f) and Autumn (g-h).  
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748 Figure 7: Mean (a) and maximum (b) of the annual Rx1day and its trend including (c) and  
749 excluding (d) the areas where the p-value is lower than 0.05, over 1903-2010. Annual Rx1day  
750 (e) and associated p-value of the trend (f) over the same period averaged over the model domain  
751 (red for the entire Alpine region and blue for the Swiss domain only) and for the MeteoSwiss  
752 network (purple, average of the MeteoSwiss data station available over 1903-2010). The vertical  
753 bars in (e) highlight the year before which the p-value never exceeds 0.05.



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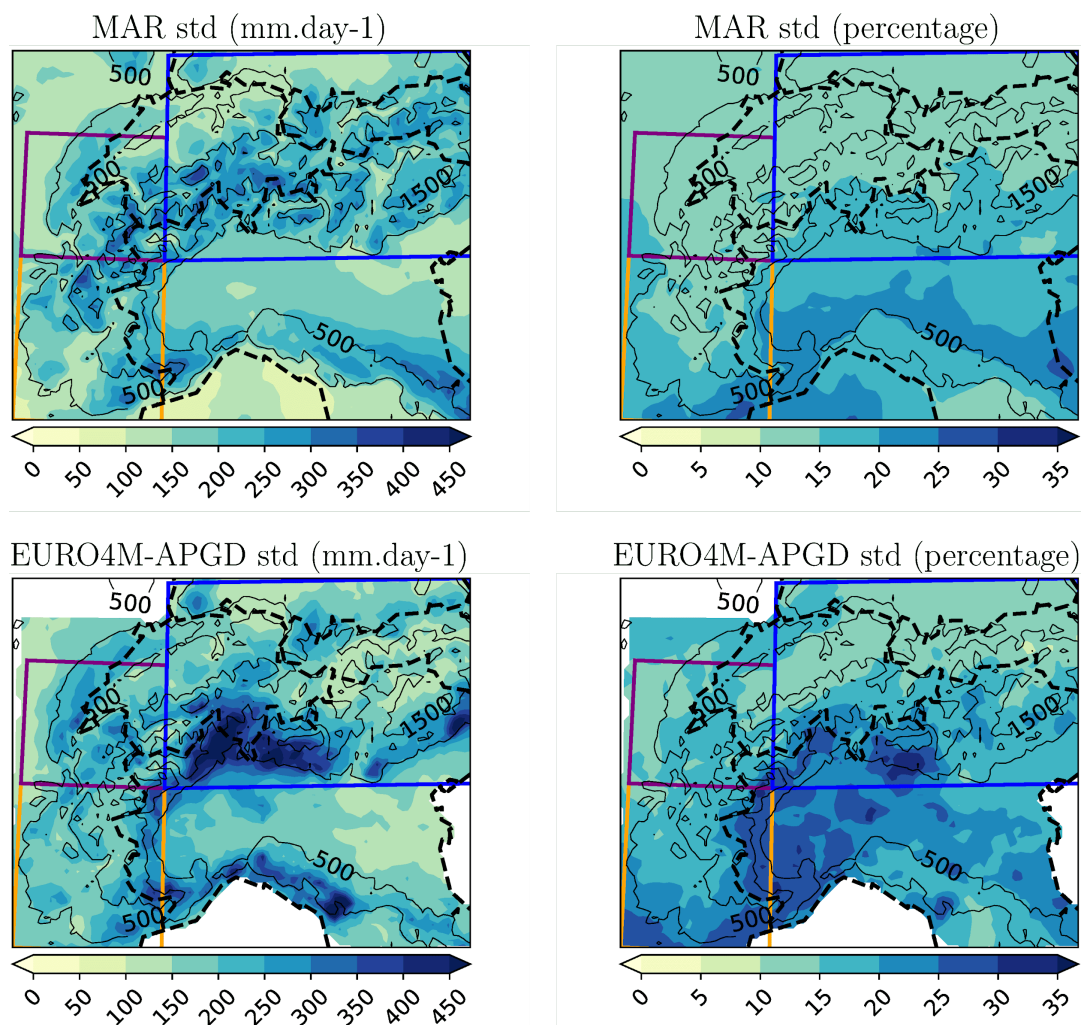
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1003 Appendix  
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Figure A1: Standard deviation of annual precipitation over 1971-2008, in mm.day-1 (left) and in percent (right), in the MAR experiment (top) and in the EURO4M-APGD dataset (bottom).