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Potential and limitations of convection-permitting CNRM-AROME climate modelling in the French Alps

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Convection permitting climate modelling is a promising avenue for climate change research and services especially in mountainous regions. Work is required to evaluate the results of high resolution simulations against relevant observations, and put them in a broader context against coarser resolution modelling frameworks. Here we evaluate numerical simulations with the convection permitting regional climate model CNRM-AROME ran at 2.5 km horizontal resolution over a large pan-Alpine domain in the European Alps, using either the ERA-Interim or climate model output as boundary conditions.

This study analyses annual and seasonal characteristics of 2m temperature, total precipitation, solid fraction of precipitation and snow depth at the scale of the French Alps under past and future climate conditions. The results are compared with the local reanalysis S2M, and raw or adjusted, with the ADAMONT method, simulations of the regional climate model CNRM-ALADIN driven either by the ERA-Interim reanalysis or the CNRM-CM5 global climate model.

The study highlights generally similar differences in past and future climate between the datasets, as well as obsta-

cles to the use of some CNRM-AROME outputs as they stand. These consist of excessive accumulation of snow on the ground above 1800 m a.s.l., as well as lower temperature values at same elevations than the S2M reanalysis and the ADAMONT-adjusted outputs.

Besides these obstacles, CNRM-AROME simulations present several advantages compared to the raw CNRM-ALADIN outputs. Among them, a significantly smaller cold bias, more realistic values of accumulated precipitations, as well as a better representation of the spatial variability of the different variables investigated, which always stand closer to the reference data than in the CNRM-ALADIN outputs. As suggested by many studies, CNRM-AROME could even produce more realistic accumulated precipitations at high elevation than the S2M reanalysis taken as our reference and consequently than the ADAMONT-adjusted projections, but the lack of a reliable set of high-resolution observations at high elevation remains an obstacle to their evaluation.

KEYWORDS

CP-RCM, Mountain, Climate change, AROME, Snow

1 | INTRODUCTION

Over the past decades, climate projections applied to assess regional climate change mainly came from the combined use of general circulation model (GCM) dynamically downscaled by regional climate models (RCM). International efforts such as EURO-CORDEX have lead to the production of 12 km resolution simulations from multiple GCM/RCM pairs and their use for various applications (Jacob et al., 2014; Beniston et al., 2018). Within this framework, the use of adjustment methods and statistical downscaling are necessary to exploit them, which is especially true in mountainous environments where the complex topography leads to significant deviations between model outputs and observational datasets (Hock et al., 2019). For example, the statistical adjustment method ADAMONT was applied to the Alps and Pyrenees using the SAFRAN meteorological reanalysis as a reference observation dataset for processing multiple EURO-CORDEX GCM/RCM pairs (Verfaillie et al., 2017, 2018; Evin et al., 2019). However, such approaches neglect several key physical processes playing a role in shaping climate change patterns in mountainous regions and the assumption of the stationarity of the bias corrections between present and future climate remains questionable.

Convection permitting regional climate models (CP-RCMs) are increasingly considered as a potent step forward in climate change studies, holding amongst others promising potentials in mountain regions Prein et al. (2013). Indeed, such models have shown added-value concerning the representation of precipitation over complex terrain, whether

16 it concerns their spatial or temporal characteristics, in particular on the sub-daily time scale, particularly in summer
17 (Keller et al., 2016). The representation of extremes, as well as rainfall accumulation in high relief against lower-
18 resolution RCMs such as ALADIN (Spiridonov et al., 2005) which do not resolve explicitly deep convection, have
19 also been demonstrated (Lind et al., 2016; Ban et al., 2021).

20 In this context, the high-resolution AROME numerical weather prediction model (Seity et al., 2011) is now used for
21 climate simulations. The first applications of the AROME model as a climate model (also referred to as CNRM-AROME)
22 were carried out to analyze the evolution of extreme precipitation in the South-East of France under climate change
23 (Déqué et al., 2016). More recently, climate simulations using AROME with a 2.5 km horizontal grid spacing were
24 conducted over the pan-Alpine domain. This was carried out within the CP-RCMs multi-model study project defined
25 in the Flagship Pilot Study « Convection » of EURO-CORDEX described by Coppola et al. (2020). CNRM-AROME
26 simulations have, *inter alia*, demonstrated their added-value in their capacity to represent Mediterranean extreme
27 precipitation events in the fall season (Fumière et al., 2020; Caillaud et al., 2021).

28 Although studies including CNRM-AROME simulations have mainly focused on the precipitation added-value of CP-
29 RCMs, Lüthi et al. (2019) have shown that a CP-RCM model (COSMO) was able to improve remarkably the representa-
30 tion of the Swiss alpine snow cover components compared to coarser resolution simulations, in line with previous stud-
31 ies of snow cover within coarser resolution RCM (Terzago et al., 2017; Matiu et al., 2020) conclusions, which outlined
32 a clear added-value of using higher resolution climate models to represent snow related variables over mountainous
33 regions.

34 Increased horizontal resolution provided by the new generation of convection permitting climate models could there-
35 fore allow for approaching debated questions such as elevation dependent warming (Kotlarski et al., 2015; Rottler et al.,
36 2019), changes in the intensity of convective precipitations in mountain areas (Giorgi et al., 2016) or assess climate
37 change impacts at high elevations. Indeed, some studies have illustrated the interest of using CP-RCM in projected
38 climate change by comparing them to coarser RCM over the alpine region. For example, Lüthi et al. (2019) showed
39 that COSMO refined and enhanced projected reduction in snow water equivalent. Pichelli et al. (2021) showed that
40 an ensemble of CP-RCM compared to a coarser RCM ensemble can lead to a different change in the sign of the heavy
41 precipitation intensity change over some regions. Prior to the study of these complex climate processes, one needs to
42 assess the capacities of such models to represent climate characteristics over the targeted area. The added value and
43 limitations of CP-RCMs need to be quantified thoroughly, in a context where the scientific community faces strong
44 expectations from a number of societal spheres, especially in the context of extreme weather events and related nat-
45 ural disasters in mountain regions. Such an analysis is also a prerequisite for any use of the output of such models as a
46 forcing dataset for impacts studies in weather-sensitive sectors or applications (avalanche hazard, ski tourism, glacier
47 evolution, water resources, impacts on ecosystems etc.) which are currently mostly addressed, in state-of-the-art
48 studies, using adjusted GCM/RCM ensembles (e.g Spandre et al., 2019; Morin et al., 2021; Zekollari et al., 2019). The
49 main questions addressed here are :

- 50 • What are the seasonal climate characteristics of the outputs from CP-RCM CNRM-AROME over the French Alps ?
- 51 • Are these outputs bringing added-value compared to the results for the CNRM-AROME coarser resolution driving
52 RCM ?
- 53 • What are the differences between future changes in CNRM-AROME output across the 21st century, and results
54 of statistically adjusted projections, both driven by the same GCM/RCM pair ?

55 This study provides a case study of the CNRM-AROME CP-RCM output over the French Alps, focusing on the sur-
 56 face air temperature at 2 m, total amount and solid fraction of precipitation and snow depth at annual and seasonal
 57 integration time scales, as a function of location and elevation. The evaluation is carried out using multiple datasets,
 58 aggregated over climatically homogeneous geographical entities within which atmospheric and snow cover variables
 59 are allowed to vary with elevation, thereby providing a novel and robust approach to compare observations and cli-
 60 mate model outputs in mountainous areas. Analyses of CNRM-AROME output are carried in past and futur climate,
 61 and compared to the local reanalysis S2M, its raw driving RCM ALADIN, as well as statistically adjusted RCM ALADIN
 62 using the ADAMONT method.

63 2 | MATERIAL AND METHODS

64 Several datasets were used in this study, originating from model simulations and observations. Figure 1 provides an
 65 overview of all the datasets employed and combined, along with their corresponding time coverage. Individual models
 66 and datasets are described in detail in section 2.1.

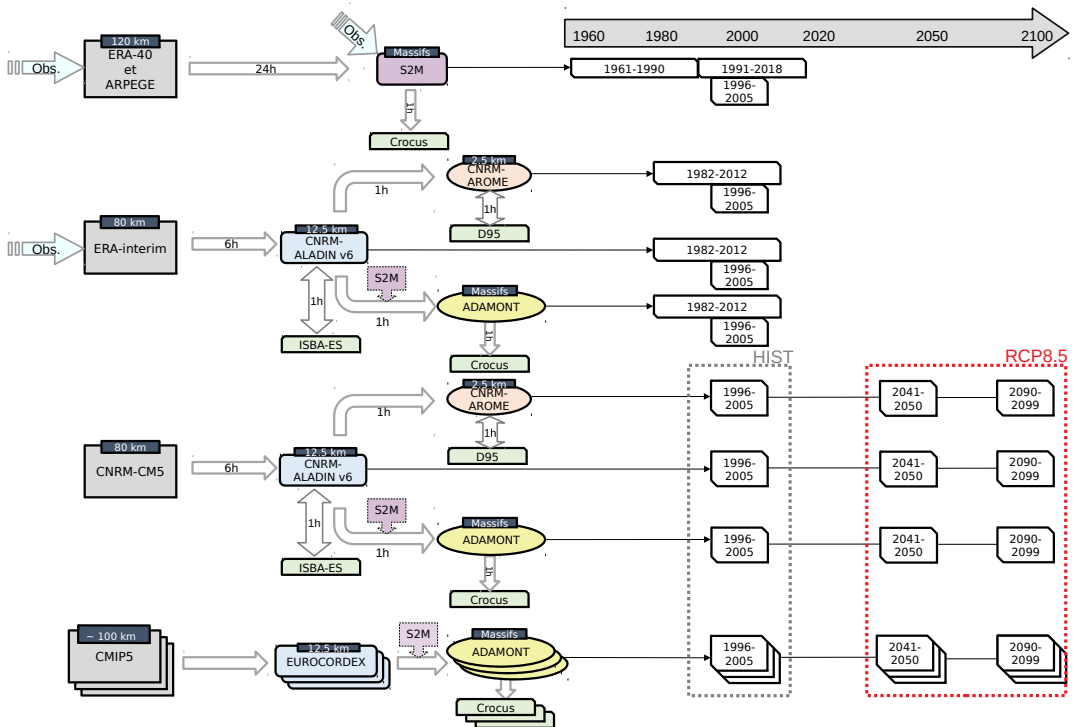


FIGURE 1 Overview of the datasets used in this study. In grey, the global reanalysis ERA-Interim or general circulation models (GCMs); in blue, regional climate models (RCMs) driven by global datasets; in orange, dynamically downscaled RCM (CP-RCM); in yellow, statistically downscaled RCM using the method ADAMONT ; in violet, reference dataset, here the regional reanalysis S2M ; in green, snow cover models providing snow cover variables through coupled or offline simulations. The wide arrows start from the models used to drive further, higher resolution models, with their forcing frequencies indicated in hours. Double wide arrows indicate the presence of a coupling between two components. The thin arrows point to the periods for which the datasets are used in this study.

67 2.1 | Data

68 2.1.1 | SAFRAN-Crocus (S2M) reanalysis

69 The SAFRAN reanalysis (Durand et al., 2009; Vernay et al., 2021) results from a combination of multiple meteorologi-
70 cal data coming from different observation sources (automatic stations, manual observations, radiosoundings ...) and
71 a synoptic guess from ERA-40 (Uppala et al., 2005) for the 1958-2002 period, and from the operational global NWP
72 model ARPEGE since 2002. It covers primarily in French mountain regions, using 23 massifs, in the French Alps, as
73 its basic geographical entity. For each massif, with a surface area of about 1000 km², meteorological and snow cover
74 conditions are assumed to depend only on the elevation, with data provided by 300 m-spaced elevation bands. The
75 SAFRAN reanalysis provides hourly values for air temperature, relative humidity or specific, liquid and solid precipita-
76 tion, wind speed and direction, incoming short and longwave radiation from 1958 to 2020. As part of the SAFRAN
77 - SURFEX/ISBA-Crocus - MEPRa reanalysis (S2M) (Vernay et al., 2019), atmospheric fields from SAFRAN are used
78 to drive the snow cover model Crocus (Vionnet et al., 2012), thereby providing daily snow cover information on the
79 same spatial scale. In this study, we only use snow cover simulations on flat terrain, and the S2M reanalysis is used
80 as a reference observation dataset, bringing together available information in a consistent and integrated manner.
81 Indeed, at the elevations where observations are available, S2M reanalyses do not suffer from systematic biases in
82 meteorological variables when compared to observations (due to the analysis process), and do not suffer from system-
83 atic biases in simulated snow depths (Vernay et al., submitted). However, it is known that S2M is affected by several
84 intrinsic limitations such as severe temporal heterogeneities of input observations affecting the quality of long-terms
85 trends (Vernay et al., submitted), a likely underestimation of precipitation at high elevation (typically above 3000 m
86 (Vionnet et al., 2019)), and a reported underestimation of incident solar radiation compared to in-situ observations
87 (Quéno et al., 2020).

88 2.1.2 | CNRM-ALADIN - RCM

89 We use the CNRM-ALADINv6 (ALADIN in the following) regional climate model (see Nabat et al. (2020) for further
90 details concerning its parametrizations schemes and configurations), which uses a 12.5 km horizontal grid spacing over
91 a large pan-European domain, 91 vertical levels and a 450 s internal time step. It is hydrostatic, which involves the
92 parametrisation of deep convection, using the PCMT (Prognostic Condensates Microphysics and Transport) scheme
93 (Piriou and Guérémy, 2016). The coupling with the land surface modeling system SURFEX8 (Decharme et al., 2019)
94 includes the snow cover model ISBA-ES, using a 12-layers snowpack discretisation scheme (Boone and Etchevers,
95 2001; Decharme et al., 2016), including an ad'hoc option for limiting unrealistic snow accumulation at high elevation.
96 ALADIN was driven by the ERA-Interim (Dee et al., 2011) reanalysis for the evaluation simulations, as well as the
97 CNRM-CM5 GCM output (Voltaire et al., 2013) for the historical and scenario (RCP8.5) simulations. In this work, the
98 ALADIN outputs are used as they stand, but also as the intermediate forcing dataset for the CNRM-AROME model
99 and as input to the statistical adjustment method ADAMONT.

100 2.1.3 | Statistical adjustment ADAMONT

101 The ADAMONT method (Verfaillie et al., 2017) is a statistical adjustment method used to adjust spatially and disag-
102 gregate daily outputs from RCM, using a reference dataset at hourly resolution. It uses a quantile mapping approach,
103 meaning that the quantile distribution of each variable from the RCM is corrected based on the quantile distribution
104 of a reference dataset over an common past period. It then creates correction tables for each adjusted points, which

105 are then applied to the output of the climate projections of the same RCM.

106 In this study, the ADAMONT method was applied to the outputs from CNRM-ALADIN, as well as 19 other GCM/RCM
107 model pairs from the EURO-CORDEX ensemble, using the S2M meteorological fields (see Section 2.1.1) as reference
108 observations. The output from the ADAMONT-adjusted GCM/RCM model output was used to drive corresponding
109 Crocus snow cover simulations.

110 2.1.4 | CNRM-AROME - CP-RCM

111 The CNRM-AROME (AROME in the following) model corresponds to the numerical weather forecast model AROME
112 developed at CNRM (Seity et al., 2011; Termonia et al., 2018), used operationally since December 2008 at Météo-
113 France. This study relies on simulations carried out with CNRM-AROME (cycle 41t1) at 2.5 km horizontal grid spacing
114 Caillaud et al. (2021); Ban et al. (2021); Pichelli et al. (2021). This version of the model was the one used opera-
115 tionally for NWP at Météo-France from 2015 to 2018 (see Termonia et al. (2018) for further details concerning its
116 parametrizations schemes and configurations).

117 A key difference of this kilometeric resolution model is its dynamic core, the non-hydrostatic spectral version used by
118 the ALADIN model (Bénard et al., 2010), with a semi-lagrangian advection scheme and a semi-explicit time discretisa-
119 tion. This makes it possible to explicitly resolve deep convection. CNRM-AROME includes a coupling with SURFEX
120 7.3, which provides a detailed representation of continental surfaces with an high resolution topography. The snow-
121 pack model used in CNRM-AROME is the single layer D95 model (Douville et al., 1995). It models the snowpack
122 as one layer which evolves according to snowfall, evaporation/sublimation and melting. The albedo is a decreasing
123 function of age of the snow, and the density is treated as a prognostic variable, which increases exponentially with
124 time and decreases with new snowfall (Martin, 2005).

125 2.2 | Methods

126 2.2.1 | Geographical domain

127 The study focuses on the French Alps, using AROME simulations ran over the pan-Alpine domain (ALP-3), as shown
128 on Figure 2. CNRM-ALADIN simulations used in this study were performed for two different domains called MED-11
129 and EUR-11 (see <https://cordex.org> for further details concerning the domains). The French Alps are in both cases
130 located at the center of the domain, which leads to negligible differences in the topographical representation of the
131 French Alps.

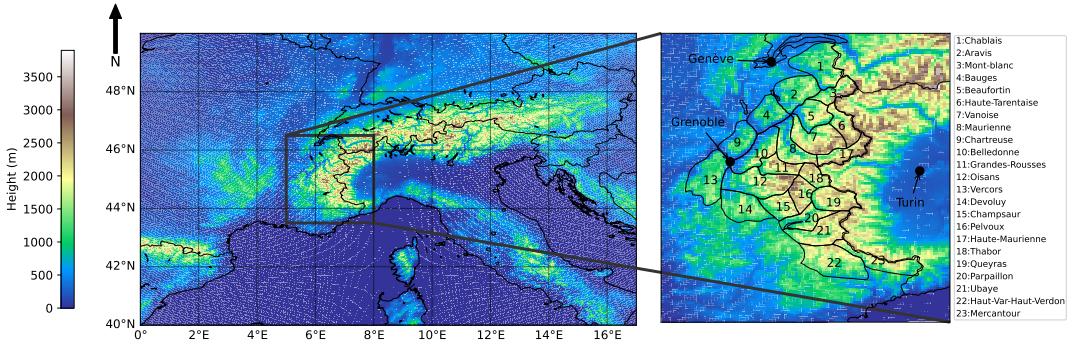


FIGURE 2 Geographical setting of the study. On the left side, AROME topography over the ALP-3 domain. On the right side, a zoom in of AROME topography covering the French Alps, on which the contours of the S2M massifs are superimposed.

132 **2.2.2 | Aggregation of AROME and ALADIN simulation over the S2M massifs**

133 We used the S2M geometry, by massifs and elevation bands, as a reference for carrying out comparisons and eval-
 134 uations. For each modelling system used, grid points were attributed to each massif according to their geographical
 135 coordinates and grouped by elevation slices into 300m width slices, by gathering data for grid points from 150m
 136 below to 150m above for each 300m elevation band.

137 We focus on the elevation bands from 900m to 2700m (i.e., including grid points from 750m to 2850m elevation),
 138 where a sufficient number of grid points are represented (see Figure 3), from ALADIN and AROME simulations.

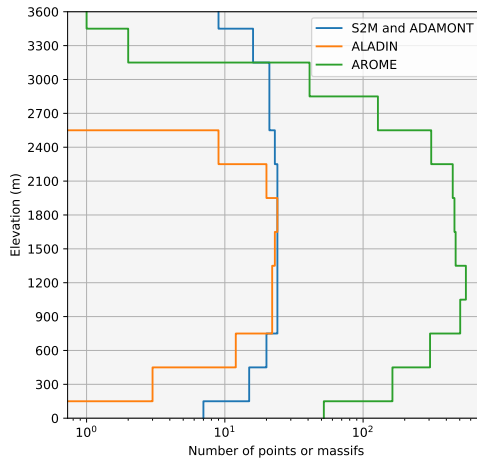


FIGURE 3 Altitudinal repartition of the number of points/massifs per 300m elevation band ($z \pm 150$ m) for AROME and ALADIN, and massifs for S2M and ADAMONT.

139 Note that for Figures 5 and 7 (as well as figures A1 to A4), data points are displayed for all ALADIN and AROME grid

140 points within the elevation band investigated (1800 m +/-150 m for Figures 5 and 7, 1200 m and 2400 m \pm 150 m for
141 Figures A1 to A4) , in order to depict potential intra-massif geographical patterns. Grid points were also displayed
142 outside the domain investigated to provide a more complete sight of the spatial coverage of grid points within the
143 corresponding elevation band.

144 2.2.3 | Description of indicators and spatial aggregation

145 We computed indicators characterizing the main features of mountain regions climatology, based on 2m air temper-
146 ature, total precipitation, solid precipitation fraction and snow depth, at seasonal (September to November SON for
147 fall, December to February DJF for winter, March to May MAM for springtime and June to August JJA for summer)
148 and annual time scales. We focused, in particular, on seasonal and annual mean air temperature, total precipitation,
149 mean solid precipitation fraction and snow depth. Note that annual values for mean solid precipitation fraction and
150 snow depth were taken for the time period from December to May (winter and springtime).

151 For all indicators described above, we computed spatial averages covering the entire French Alps, taking the average
152 over the 23 massifs (equal weight given to each massif, given their comparable individual surface area), after a first
153 aggregation of gridded datasets within each massif and elevation band. This provides robust estimates of the meteo-
154 rological and snow conditions for the entire French Alps in a consistent and comparable way, although this masks out
155 spatial variability within the region when using such aggregated values. Several results are provided here at 1800 m
156 elevation (representing the data contained in the 1800 m \pm 150 m band), covering most of the French Alps presenting
157 for all datasets a large number of massifs and points (see Figure 3) and relevant to study climate variability and long
158 term in meteorological and snow conditions in the French Alps (Durand et al., 2009). Results for other elevations are
159 provided and discussed when relevant, and included in supplements.

160 2.2.4 | Implementation of the simulations and evaluation strategy

161 Figure 1 provides an overview of all the datasets used in this study and the time periods relevant to each of them.
162 We used ALADIN simulations driven by two different global driving datasets: ERA-Interim (for the evaluation period
163 1982-2012) and CNRM-CM5 (for the historical period 1996-2005 and future time periods 2041-2050 and 2090-
164 2099 using the RCP8.5 greenhouse gas concentration scenario).In both cases and for the same time period, ALADIN
165 simulations were used as an intermediate driving RCM for AROME simulations over the ALP-3 domain (see Figure 2).
166 ALADIN simulations driven by ERA-Interim were performed over the MED-CORDEX (MED-11) domain (Ruti et al.,
167 2016) using spectral nudging (von Storch et al., 2000; Radu et al., 2008). Spectral nudging enables to constrain large-
168 scale conditions inside the nesting domain, and therefore to remain closer to the driving dataset. For further details
169 concerning the spectral nudging applied to the ALADIN simulations used in this study, see Nabat et al. (2020).

170 ALADIN simulations driven by CNRM-CM5 were carried out over the EURO-CORDEX domain (EUR-11). For climate
171 projections, AROME simulations were produced over 10 years time slices 1996-2005, 2041-2050 and 2090-2099.
172 This high resolution simulation framework is in line with the choice done within the EURO-CORDEX Flagship Pilot
173 Study Convection (Coppola et al., 2020). All ALADIN model runs, as well as 19 other GCM/RCM pairs from the EURO-
174 CORDEX ensemble, were used as input to the ADAMONT statistical adjustment method using S2M meteorological
175 fields as reference meteorological datasets over the 1980-2012 period. In this case, one grid point for each RCM was
176 used for each massif (the closest to the barycenter of each massif), similar to the approach taken by Verfaillie et al.
177 (2018).

178 **3 | RESULTS**

179 We first describe AROME multi-annual seasonal characteristics over the evaluation period, spanning from 1982 to
 180 2012, across different elevations, averaged over the French Alps, as well as at finer spatial scale to look at geographical
 181 patterns over the different regions. AROME simulations are compared to ALADIN raw outputs, and the S2M reanal-
 182 ysis. Then, change across the 21st century (differences between end and beginning of century) for the RCP8.5 are
 183 investigated using similar indicators, and compared to ALADIN raw outputs and statistically adjusted ALADIN outputs
 184 with ADAMONT method. The analysis also includes a summary table of annual mean values at 1800 m, covering all
 185 datasets at all periods available, allowing the comparison of the effects of using different driving datasets.

186 **3.1 | Past climate conditions**

187 We first focus on the comparison of the various datasets for the time period from 1982-2012, for all indicators at
 188 the seasonal scale. Figure 4 shows the elevation profiles, per season, averaged over the 1982-2012 period for the
 189 ERAi/ALADIN/AROME (AROME) and ERAi/ALADIN (ALADIN) simulations, as well as the S2M reanalysis (S2M). ADA-
 190 MONT profiles are not displayed in the figures below. Indeed, by design, the differences between ADAMONT and
 191 S2M are very small for all variables represented, but larger differences between AROME, ALADIN and S2M can be
 192 seen. In the Figure 5, the three first rows display the 30 years average values for all the grid points included within the
 193 1800m elevation band (1800m +/-150m), inside and also outside the S2M massif border for ALADIN and AROME.
 194 The two last rows show the differences of the 30 average values between ALADIN and S2M, AROME and S2M.

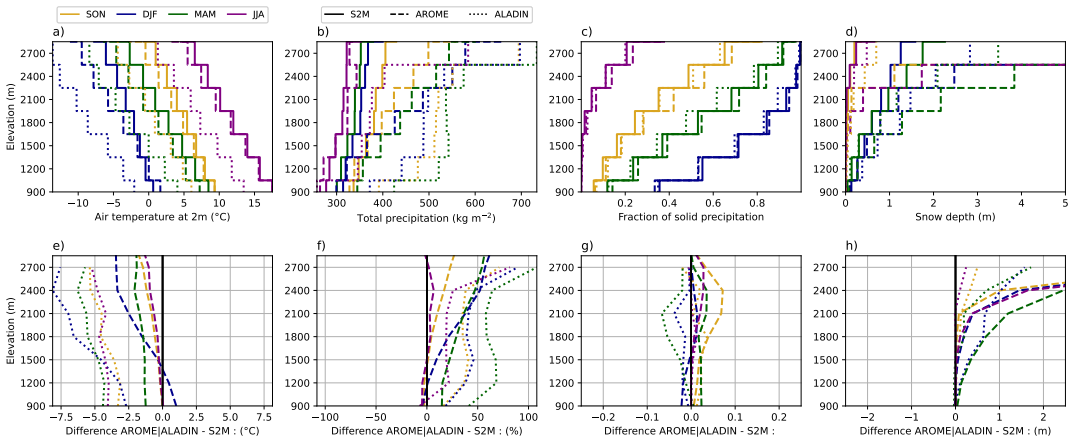


FIGURE 4 Time-averaged elevation profiles over the period 1982-2012, for 4 variables at the seasonal scale: a) air temperature, b) total precipitation, c) solid precipitation fraction, and d) snow depth. On the second line, (e), (f), (g), (h), the respective differences between the datasets AROME - S2M (dashed) and ALADIN - S2M (dotted).

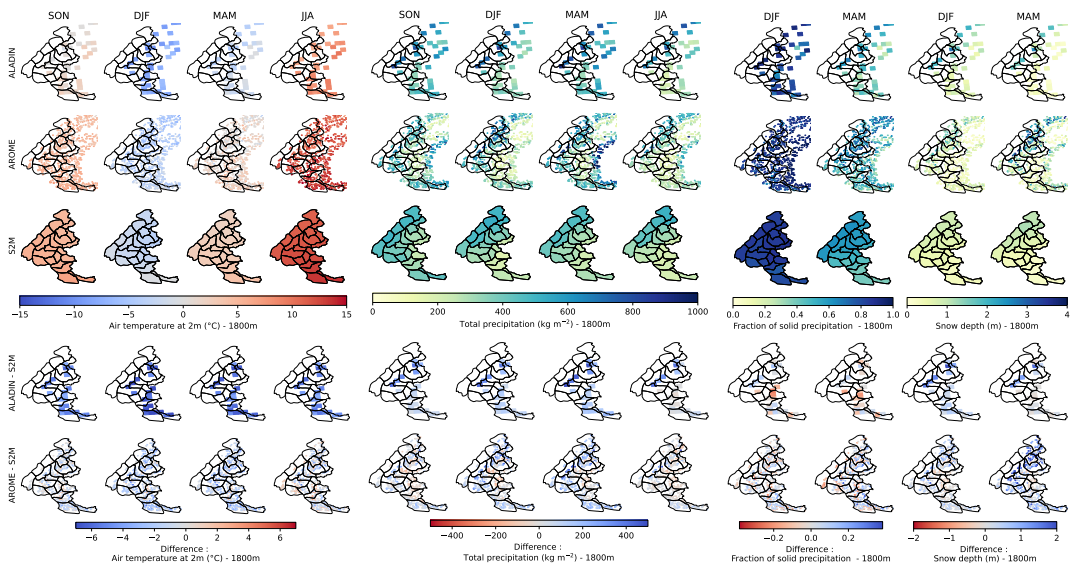


FIGURE 5 Simulation results at 1800 m elevation (representing grid point values within the 1800 m \pm 150 m elevation band for AROME and ALADIN, inside and outside the S2M massif border) for the three datasets and their seasonal values over the period 1982-2012, for 4 variables: air temperature, total precipitation, solid precipitation fraction, and snow depth. Columns correspond to the different seasons. The three first rows present the different models: ALADIN, AROME and S2M, while the fourth and the fifth ones correspond to the differences between ALADIN and S2M, and AROME and S2M, respectively.

195 | Air temperature

196 On Figure 4.a-e, AROME and ALADIN simulations generally show lower temperatures than S2M for all seasons, and
 197 the differences increase with elevation to various extents depending on the season. We note that for all seasons, the
 198 altitudinal profiles of the differences Figure 4.e are similar for AROME and ALADIN, with a shift of around 3 degrees
 199 warmer for AROME outputs, making them closer to the reanalysis. The differences and their increases with elevation
 200 are most pronounced in winter, with a difference of +1°C at 900 m for AROME, -2.5°C for ALADIN, reaching -3.5°C
 201 at 2700 m between AROME and S2M, -7.5°C between ALADIN and S2M (Figure 4.e). These increases are smaller
 202 in spring, with a difference of -1.5°C at 1200 m reaching -2°C at 2700 m for AROME, similar for ALADIN but 3°C
 203 colder. AROME and ALADIN summer and autumn profiles Figure 4.a exhibit the smallest differences and increases
 204 above 1500 m, from 0°C at 900 m to -1/-1.5°C at 2700 m for AROME and from -3/-4°C at 900 m to -5°C at 2700 m
 205 for ALADIN.

206 Figure 5 shows similar geographical patterns between S2M and both AROME and ALADIN simulations. The two last
 207 rows showing the differences of AROME and ALADIN against S2M data confirm that both datasets provide lower
 208 temperature values than S2M, particularly in winter (down to almost -6°C difference at some grid points), although
 209 several grid points show higher values in AROME than in S2M. This is observed at all elevations, except below 1200 m
 210 elevation where AROME simulations show higher temperature values than S2M.

211 | Total precipitation

212 Figure 4.b shows that precipitation amounts generally increase with elevation for S2M, ALADIN and AROME, and
213 are larger in the ALADIN simulations than AROME and AROME than S2M, both for all elevations, with differences
214 increasing with elevation. This behaviour is particularly marked in winter and spring, with seasonal accumulations at
215 2700 m 60% higher in AROME than in S2M, and up to 100% for ALADIN compared to S2M (see Figure 4.f). From
216 September to May in AROME outputs, and for all seasons in ALADIN, a strong elevation gradient can be observed,
217 resulting in accumulated values up to 80% larger at 2700 m than at 900 m. This gradient is less pronounced in the
218 S2M data, regardless of the season, as well as in AROME summer data, and is more continuous in AROME simulations
219 than in ALADIN profiles (Figure 4.b), almost vertical between 1500 m and 2400 m.

220 The annual distribution of precipitation is also different between the datasets. For the S2M data, the larger precipi-
221 tation total occurs during the autumn period (Figure 4.b), in spring for ALADIN, while AROME results indicate more
222 precipitations in spring for altitudes ranging from 900 m to 1800 m, and in winter above 2100 m.

223 In terms of geographical pattern, total precipitation values show similarities across the three datasets at 1800 m (also
224 valid at other elevations 1200 m and 2400 m, see Figures A1 and A2), with higher values on the north-western massifs,
225 whereas inner and southern parts of the French Alps receive less precipitations for most seasons, except in autumn,
226 where the southern part receive almost as much precipitation as the northern part, probably due to the occurrence of
227 mediterranean storms at this season. Higher precipitation values in AROME and ALADIN outputs, compared to S2M,
228 are also displayed in Figures 4 and 5, although AROME exhibits systematically lower precipitation values than S2M
229 in the inner Alps. ALADIN and AROME simulate extremely high precipitation amounts at very few grid points around
230 the Mont-Blanc massif for all season at intermediate and high elevation (Figures 5, A1 and A2), with values that can
231 reach 200% of S2M values.

232 | Fraction of solid precipitations

233 The fraction of solid precipitation, shown on Figure 4-c-g, displays only small differences between the AROME, AL-
234 ADIN and S2M dataset, not exceeding 0.06. We note based on Figure 4-g that AROME outputs show larger solid
235 fraction for all seasons above 1500 m, whereas ALADIN shows the contrary, and that both show their maximum differ-
236 ences with S2M within the 1500 m to 2400 m elevation bands. Figure 5 shows a similar pattern at 1800 m (and other
237 intermediate levels) for the three datasets, with more precipitations falling as snowfall in the northern part of the Alps,
238 whereas the southern part receives less solid precipitation in autumn and spring. Values for winter and summer are
239 relatively homogenous, with almost only snowfall and rainfall, respectively.

240 | Snow depth

241 Snow depth values simulated by the AROME show exceptionally high values from 2100 m and above, compared to
242 S2M rising above several meters on average (see Figures 4d-h). ALADIN simulates lower values of snow depth than
243 AROME, although the differences with S2M can be as much as double at high elevations. Figure 5 shows that at
244 1800 m elevation, AROME and S2M snow depth values are in broad agreement in terms of overall pattern. Figure 5
245 also shows that exceptionally high snow depth values are only found for few grid points at 1800 m. In fact, even at
246 elevation above 1800 m (see Figure A2), only few grid points keep spurious values of snow depths (also in fall season,
247 not shown here), whereas the others show no accumulation.

248 The exceptionally high AROME snow depth values are too large to be explained by differences in precipitation, solid
249 precipitation fraction and temperature alone. Some hypotheses are explored in the discussion, in order to explain
250 these outliers.

251 3.2 | Climate projections

252 In this section, we describe projected changes over the 21st century based on 10 years averages (2090-2099 minus
253 1996-2005) for AROME, ALADIN and ADAMONT, as well as differences between simulations (AROME - ADAMONT
254 and ALADIN - ADAMONT) for the same periods (1996-2005 and 2090-2099).

255 Figure 6.a-d and Figure 6.i-l respectively display simulated changes between 1996-2005 and 2090-2099 for AROME
256 and ADAMONT and for AROME and ALADIN, for the four variables investigated, as a function of elevation.

257 Figure 6.e-h and Figure 6.m-p respectively display the differences between AROME and ADAMONT, and between
258 AROME and ALADIN outputs, for 1996-2005 and 2090-2099, for the four variables investigated, as a function of
259 elevation

260 In Figure 7, the three first rows display the simulated change over the 21st century (between 1996-2005 and 2090-
261 2099) for all the grid points included within the 1800 m elevation band (1800m +/-150 m), inside and also outside the
262 S2M massif boundaries (for ALADIN and AROME). The two lowermost rows show the differences of simulated change
263 between 1996-2005 and 2090-2099 between ALADIN and ADAMONT, and AROME and ADAMONT, respectively

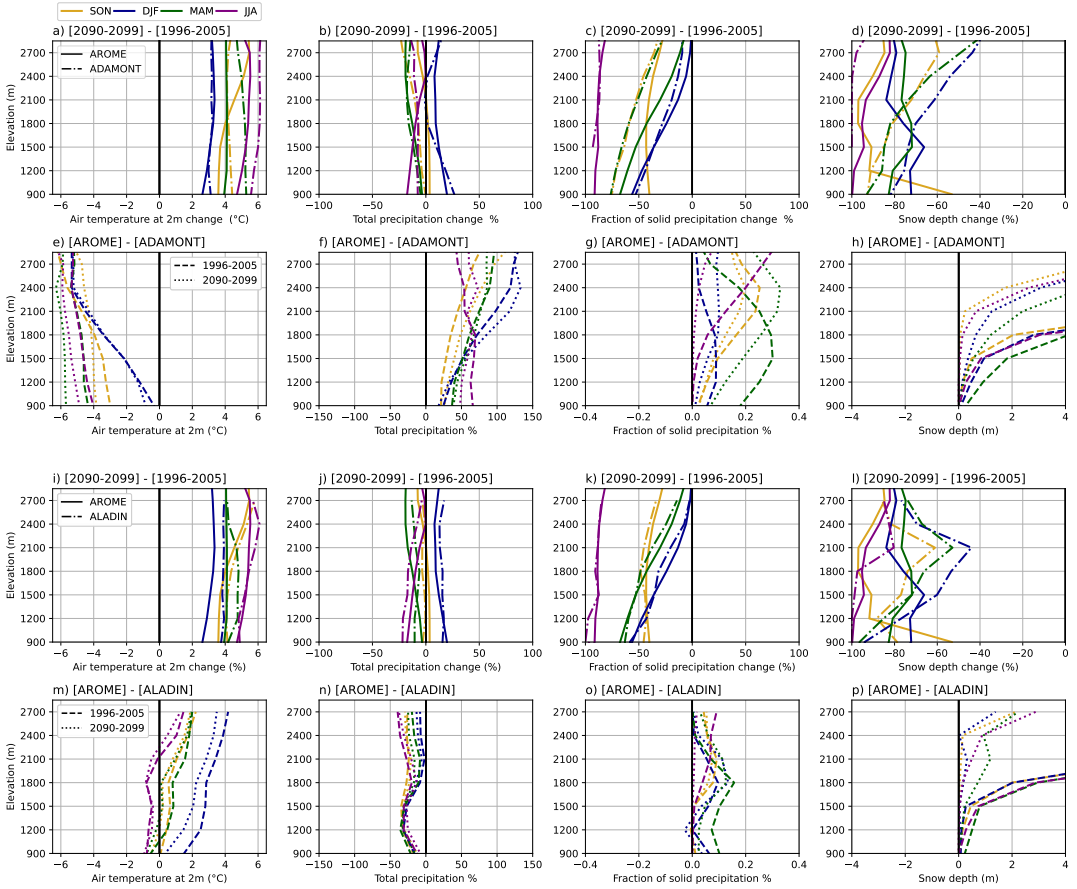


FIGURE 6 Altitudinal profiles, by season, for 4 variables: a-e-i-m) air temperature at 2m, b-f-j-n) total precipitation, c-g-k-o) solid fraction of precipitation, and d-h-l-p) snow depth. The first (third) line is the difference between the averages of the end-of-century (2090-2099) and beginning-of-century (1996-2005) periods, for the AROME data in solid line, and the ADAMONT (ALADIN) data in dashed line. The second (fourth) line represents the difference between the average of the AROME and ADAMONT (ALADIN) data for each of the periods at the beginning (dashed) and end of the century (dotted).

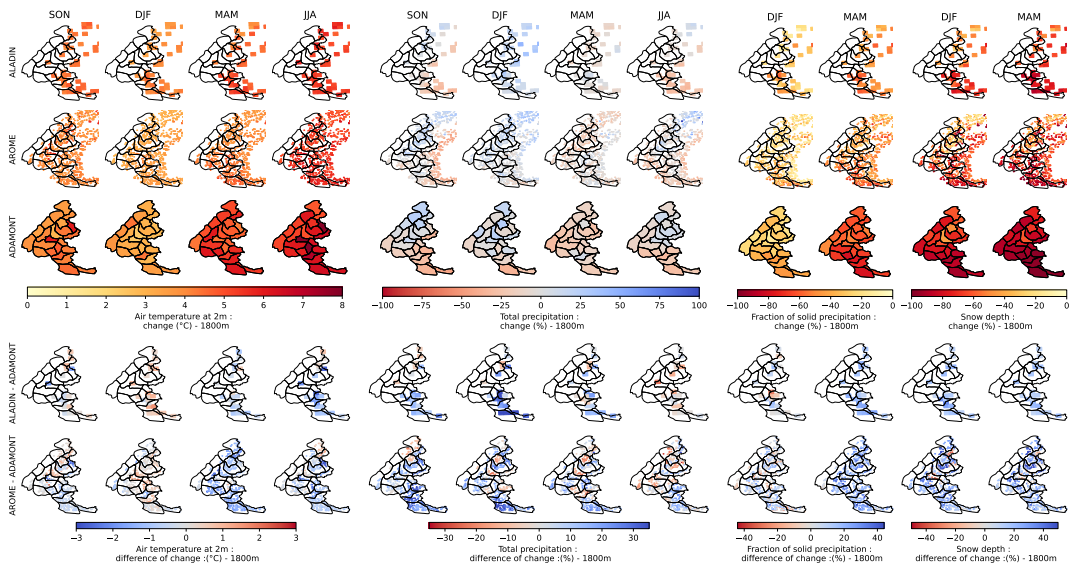


FIGURE 7 Simulation results at 1800 m (representing grid point values within the $1800\text{ m} \pm 150\text{ m}$ elevation band for AROME and ALADIN, inside and outside the S2M massif borders) for the three datasets ALADIN, AROME and ADAMONT. Values of the three first rows correspond to the change over the 21st century (differences between the seasonal averages of the end-of-century (2090-2099) and beginning-of-century (1996-2005) periods), for 4 variables: air temperature at 2m, total precipitation, solid fraction of precipitation, and snow depth. Columns correspond to the different seasons. The two last rows show the differences between ALADIN and S2M change values, and AROME and S2M change values, respectively.

264 | Air temperature

265 The air temperature changes between the end (2090-2099) and beginning (1996-2005) of the 21st century, displayed on Figure 6-a-i, show small altitudinal variations over the represented elevation range, with the same values for AROME and ADAMONT in winter (+3°C, 6-a), and 1°C warmer for ALADIN (6-i), which corresponds to the least warming season. For AROME, ALADIN and ADAMONT, the summer season shows the greatest mean warming, from 5.5°C to 6°C for ADAMONT, and around 1°C lower for AROME and ALADIN, regardless of the elevation. For ADAMONT, spring is the season that undergoes the most marked warming after summer, for all elevations, whereas AROME and ALADIN simulates that from 1800 m upwards, autumn shows a stronger warming reaching +5°C at 2700 m, almost similar to the summer value. Overall, AROME simulates the lower warming over the 21st century, on average around 1°C lower than ADAMONT for spring and summer and than ALADIN for winter and spring.

274 Figure 7 displays the temperature change geographical pattern at 1800 m, which is generally homogeneous for fall and winter seasons in AROME and ALADIN outputs, whereas in spring and summer the warming is, on average, 1°C larger in the south than in the north. The main differences between ALADIN, AROME and ADAMONT datasets, in terms of temperature change, are mainly related to the spatial heterogeneity in ADAMONT temperature changes. In spring and summer, almost all grid points show a smaller temperature change for AROME and ALADIN than for ADAMONT, whereas in winter season in the inner Alps, AROME shows higher temperature change than ADAMONT.

280 In terms of the differences between temperatures profiles, Figure 6-e shows that differences between AROME and ADAMONT CNRM-CM5 driven are similar to the ERAi driven ones but exacerbated (see Figure 4-f). However, differences between AROME and ALADIN Figure 6-m show for all seasons lower cold deviations that can be seen on

283 Figure 4-f. This is explained by the fact that simulations CNRM-CM5 driven for AROME are 3°C colder than ERAI
284 driven simulations for the 1996-2005 period at 1800 m (see Table 1), whereas a slight warming of 0.7°C is observed
285 for ALADIN ones.

286 | Total precipitation

287 Changes over the 21st century are shown in Figure 6-b-j and are rather small and heterogeneous in their seasonal
288 distribution. Total winter precipitation values in AROME and ALADIN at the end of the century are on average 15%
289 higher than at the beginning of the century (from +10% to +20% depending on elevation), a change that is only found
290 at low elevations for ADAMONT.

291 Spring and summer profiles (Figure 6-b-j) show rather similar trends for all datasets, with a general drying, slightly
292 oscillating along the elevations, from 0 to 20%. Fall season is the most contrasted between simulations, with no
293 change at all elevations in AROME and ALADIN, whereas ADAMONT presents similar trends that for summer or
294 spring, around 10-15%.

295 Figure 7 shows that precipitation changes are similarly distributed at 1800 m elevation between AROME and ADA-
296 MONT, both AROME and ADAMONT presenting much more discrepancy with ALADIN. Values for spring and summer
297 seasons show almost only negative changes at all elevations. In the fall and winter, AROME and ADAMONT changes
298 are roughly similar, with increases in the northern part and decreases in the southern part at all elevations in the fall,
299 but only at intermediate elevations for winter season (with increases almost everywhere at low and high elevations,
300 see Figures A3 and A4).

301 The differences between precipitation changes across the 21st century in AROME and ADAMONT depend strongly
302 on the massif, which is mostly due to the inter-massif heterogeneity in precipitation changes in ADAMONT.

303 Total precipitation amounts in AROME and ADAMONT climate projections Figure 6-f-n are larger than in ADAMONT
304 output, and the differences increase with elevation, similar to simulations for ERAI driven (see Figure 4-b-f). However,
305 the differences are larger when AROME and ALADIN are driven by CNRM-CM5 (from 50 to 70% in autumn and
306 summer to 125 to 150% of the ADAMONT totals in winter) than when forced by ERAI (at most 60% to 80% of the
307 S2M or ADAMONT totals).

308 | Fraction of solid precipitation

309 Figure 6-c-k shows a decrease in the solid fraction of precipitation regardless of the season and elevation, with similar
310 changes in ADAMONT, ALADIN and AROME. In winter, the relative differences between the end and beginning of
311 the century are around 50% at low elevation, then decrease in elevation, becoming almost zero at 2700 m. Changes
312 are strongest in summer, where the average solid precipitation fraction reach zero at low elevation and is reduced by
313 90% at high elevation, for both datasets. Changes are also large in autumn and spring, with a 50-75% reduction at
314 lower elevations, and 35% at 2700 m. These strong decreases in the fraction of solid precipitation are directly related
315 to the temperature increases.

316 Figure 7 shows the changes in the fraction of solid precipitation at 1800 m elevation, with a stronger decrease in the
317 southern part than the northern part, especially in autumn. The relative decrease is larger in ADAMONT results than
318 AROME and ALADIN for most of the grid points.

319 | Snow depth

320 Snow depth values at 1800 m and above in AROME and above 2400 m ALADIN projections are exceptionally high
 321 (Figure 6-h-p) compared to ADAMONT, similar to past simulations comparing AROME or ALADIN and S2M. These
 322 high values of snow depth may explain the different behaviours of change across the 21st century between ADA-
 323 MONT and AROME above 1500 m Figure 6-d-l) and between ADAMONT and ALADIN above 2100 m Figure 6-l).
 324 Indeed, whereas snow depth values show a relative decrease decreasing with elevation in ADAMONT, AROME and
 325 ALADIN show an increase with elevation starting from the elevation where they present high snow depth values
 326 which prevents any meaningful comparison to other projections or an analysis of future changes at these elevations.

327 Nevertheless, an analysis can be carried out at low and intermediate elevations (shown at 1800 m elevation on Figure
 328 7). At lower elevation (1200 m elevation on Figure A3), there is a relatively homogenous general decrease in snow
 329 depth values, whereas at intermediate (for AROME and ADAMONT and high elevations (for ADAMONT) relative
 330 changes are larger in the southern part of the Alps. At low and intermediate levels (below 1800 m), the decrease in
 331 snow depth values is larger in ADAMONT than in AROME for most of the grid points.

332 | Overall comparison between all datasets

Period	Dataset / Variable	Temperature at 2 m (°C) -annual mean-	accumulated precipitations (kg m ⁻²) -annual mean-	Fraction of solid precipitation -DJFMAM mean-	Snow depth (m) -DJFMAM mean-
1961-1990	S2M	4.3±0.6	1390±200	0.73±0.07	0.71±0.22
1991-2018	S2M	4.8±0.7	1390±170	0.67±0.06	0.56±0.18
1982-2012	S2M	4.6±0.5	1380±260	0.68±0.05	0.59±0.25
	ERA/ALADIN	-0.8±0.6	1910±200	0.63±0.07	0.99±0.19
	ERA/ALADIN/ADAMONT	4.7±0.5	1360±210	0.67±0.06	0.64±0.22
	ERA/ALADIN/AROME	3.6±0.7	1580±180	0.69±0.06	1.01±0.17
1996-2005	S2M	4.6±0.5	1380±320	0.68±0.05	0.54±0.20
	ERA/ALADIN	-0.8±0.5	1850±250	0.64±0.08	0.96±0.11
	ERA/ALADIN/ADAMONT	4.7±0.5	1300±240	0.67±0.06	0.61±0.19
	ERA/ALADIN/AROME	3.6±0.6	1540±210	0.69±0.04	1.00±0.11
	CNRM-CM5/ALADIN	-0.1±0.7	2630±300	0.73±0.03	1.50±0.60
	CNRM-CM5/ALADIN/ADAMONT	4.9±0.70	1330±290	0.66±0.06	0.60±0.40
	EUROCORDEX/ADAMONT	Q ₂₀ : 4.7 Q ₅₀ : 4.8 Q ₈₀ : 4.9	Q ₂₀ : 1260 Q ₅₀ : 1330 Q ₈₀ : 1350	Q ₂₀ : 0.57 Q ₅₀ : 0.66 Q ₈₀ : 0.68	Q ₂₀ : 0.52 Q ₅₀ : 0.57 Q ₈₀ : 0.60
	CNRM-CM5/ALADIN/AROME	0.7±0.8	2190±260	0.87±0.06	3.89±0.22
2041-2050	CNRM-CM5/ALADIN	1.2±0.6	2740±240	0.63±0.06	1.16±0.28
	CNRM-CM5/ALADIN/ADAMONT	6.3±0.6	1400±260	0.56±0.06	0.39±0.17
	EUROCORDEX/ADAMONT	Q ₂₀ : 5.9 Q ₅₀ : 6.5 Q ₈₀ : 7.0	Q ₂₀ : 1300 Q ₅₀ : 1400 Q ₈₀ : 1530	Q ₂₀ : 0.51 Q ₅₀ : 0.55 Q ₈₀ : 0.58	Q ₂₀ : 0.32 Q ₅₀ : 0.38 Q ₈₀ : 0.44
	CNRM-CM5/ALADIN/AROME	1.9±0.5	2300±120	0.76±0.02	2.42±0.07
2090-2099	CNRM-CM5/ALADIN	4.5±0.6	2560±180	0.45±0.09	0.60±0.40
	CNRM-CM5/ALADIN/ADAMONT	9.7±0.7	1280±190	0.41±0.09	0.15±0.21
	EUROCORDEX/ADAMONT	Q ₂₀ : 9.2 Q ₅₀ : 9.9 Q ₈₀ : 10.7	Q ₂₀ : 1040 Q ₅₀ : 1170 Q ₈₀ : 1350	Q ₂₀ : 0.28 Q ₅₀ : 0.31 Q ₈₀ : 0.38	Q ₂₀ : 0.06 Q ₅₀ : 0.10 Q ₈₀ : 0.13
	CNRM-CM5/ALADIN/AROME	5.0±0.8	2130±140	0.65±0.05	1.13±0.05

TABLE 1 Summary table of annual values (fraction of solid precipitation and snow depth values are averaged over the December to May period) and their interannual standard deviations at 1800 m elevation for the four variables analysed in this study, averaged over each period, for each of the datasets shown in Figure 1. The values in the "EUROCORDEX/ADAMONT" row correspond to the median (Q₅₀) and quantiles Q₂₀ and Q₈₀ of the multi-annual means of the ADAMONT-adjusted EUROCORDEX set consisting of 19 GCM/RCM pairs.

333 Table 1 provides annual mean values (for air temperature and total precipitation) and december to april values (for
 334 fraction of solid precipitations and snow depth) at 1800 m, over the French Alps for all datasets shown in Figure 1. All
 335 these values are averaged over their corresponding period in the table. This makes it possible to carry out a compact
 336 and quantitative comparison, complementary to the analysis performed in the previous sections and corroborating
 337 the results described previously, and summarized below:

- 338 • Lower temperature, in general, in ALADIN and AROME compared with ADAMONT or S2M, with a larger difference
339 in the raw ALADIN outputs.
- 340 • Higher amounts of total precipitation in ALADIN and AROME, compared to ADAMONT or S2M, also more pro-
341 nounced in ALADIN outputs.
- 342 • The fraction of solid precipitation is generally close or a bit higher in AROME and ALADIN than in S2M or ADA-
343 MONT datasets.
- 344 • Spurious high snow depth values are found in AROME simulation results, also found in ALADIN, but to a lesser
345 extent and at higher elevation.

346 All the datasets are available for the period 1996-2005, which makes it possible to compare the influence of the ERA-
347 Interim and CNRM-CM5 forcing in a similar climate context for both AROME and ALADIN simulations. Using the
348 GCM CNRM-CM5 reinforces the features described above, with colder values (except for ALADIN), greater amount
349 of precipitation, higher proportion of precipitations falling as solid, and therefore larger snow cover. This difference
350 could partly be due to the specificity of the GCM CNRM-CM5, leading to wetter and colder simulation compared to
351 ERA-Interim, but also to the specific characteristics of the ALADIN RCM, whose specific influence is limited due to
352 the spectral nudging in the run driven by ERAi. Natural climate variability, not entirely smoothed out in a 10 years
353 average could have some influence, with a chronology of meteorological events imposed by CNRM-CM5, forming a
354 colder and wetter sequence than that of ERAi.

355 The median and quantiles of the multi-annual means of the EURO-CORDEX ensemble adjusted by ADAMONT indi-
356 cate that the CNRM-CM5/ALADIN simulations are slightly colder and with higher precipitation than the median
357 of the ensemble, especially at the end of the century. This results in a higher proportion of solid precipitation and a
358 higher snow accumulation, even if this GCM/RCM pair remains overall close to the median of the ensemble for most
359 of its characteristics.

360 4 | DISCUSSION

361 This study analyzes a series of complementary climate simulations covering the French Alps, providing several oppor-
362 tunities to identify and discuss limitations and benefits of the CP-RCM AROME.

363 | Temperature differences between simulations

364 | ALADIN vs. AROME

365 There are large temperature differences, for all seasons, over all the elevations investigated, ranging from -1 to -5°C,
366 between ALADIN and AROME. Furthermore AROME results show significantly lower temperature values than S2M
367 (past climate) and ADAMONT (future climate), particularly in winter, with differences increasing with elevation.

368 These features are in line with numerous studies evaluating the EURO-CORDEX ensembles of simulations over an
369 extended alpine domain. Indeed, large negative temperature differences between the RCMs and reference datasets
370 over the Alpine region have been highlighted in Kotlarski et al. (2014); Smiatek et al. (2016); Terzago et al. (2017); Frei
371 et al. (2018). These studies showed that ALADIN simulations, using comparable versions to those used in this study,
372 lie systematically among the models showing the strongest cold biases, regardless of the season considered.

373 AROME simulations show a much lower «cold bias» compared to ALADIN , for all elevations and seasons. This be-
374 haviour was also observed in Lind et al. (2020) over Scandinavia, comparing ALADIN and AROME simulations, but
375 to a much lesser extent. The differences in results between the studies could be due to climatic differences induc-
376 ing different model behaviors, depending on the elevation and the region investigated (between 0 m and 1000 m for
377 Scandinavia, a lower elevation range than for the French Alps).

378 To the best of our knowledge, few studies have so far shown such a significantly lower cold bias over mountainous
379 regions between a RCM and a CP-RCM . Nevertheless, the generalized RCM cold biases in the Alps has led to some
380 hypotheses that could be used to explain the lower cold bias observed. Kotlarski et al. (2014); Vautard et al. (2013)
381 invoked the persistence of a too extended snow cover in the RCMs, which would lead to a cooling during the winter
382 months due to the interaction of snow-covered soils and the atmosphere. They also pointed out potential issues in
383 the parameterization of the surface scheme leading to insufficiently strong ablation processes (melt, etc.) of the snow
384 cover. A too persistent snow cover is also invoked in Kevin et al. (2017) which investigated the effects of snow
385 albedo feedback on the temperature at 2 m, although in this study the ALADIN model was the only model appearing
386 to be insensitive to the snow albedo feedback.

387 Keller et al. (2016) and Ban et al. (2014) stated that a better representation of clouds linked to the explicit resolution of
388 deep convection, modifying the surface radiation balance, could provide more realistic temperature diurnal extrema.

389 Other hypotheses are discussed in the following section.

390 | **AROME vs. S2M and ADAMONT**

391 Despite the lower cold bias of AROME compared to ALADIN, AROME output provides lower temperature than in the
392 S2M reanalysis or ADAMONT adjusted projections, especially in winter and spring at high elevations in past or future
393 climate. Although part of the cold bias could be inherited from ALADIN, this does not seem to explain it entirely, since
394 it is also found in NWP applications of AROME as highlighted by Vionnet et al. (2016), who compared the operational
395 AROME NWP surface atmospheric fields with the S2M reanalysis over 4 winters (2011 to 2014). According to Vionnet
396 et al. (2016) and Quéno et al. (2020), this cold bias could be due to the underestimation of downward infrared radiation
397 (ILW), and the overestimation of incident solar radiation (ISW) in AROME, related to an underestimation of the cloud
398 cover.

399 The snow cover model and its interaction with the atmosphere in AROME may also play a role. Indeed, the single-
400 layer scheme describing the evolution of the snow cover in AROME (D95, Douville et al. (1995)) does not simulate
401 liquid water retention in the snow cover, and the influence of freezing/thawing on surface latent fluxes. According to
402 Vionnet et al. (2016), this absence can lead to an underestimation of the surface temperature, by omitting the surface
403 refreezing processes releasing latent heat by phase change. This process is particularly active during melting periods,
404 and may explain the stronger deviation from December to May. Finally, Rontu et al. (2016) have also suggested that
405 the turbulence scheme in AROME may misrepresent stable boundary layer dynamics, leading to an underestimation
406 of mixing, and thus to a too frequent decoupling of the surface and the atmosphere. The decoupling leading to lower
407 near surface temperatures and snow surface temperatures is also an hypothesis put forward by Lapo et al. (2015),
408 who compared the response of two snow models of different complexity to irradiance errors.

409 By gathering together literatures, some hypotheses can be retained to partly explain the cold biases over the Alps,
410 whether they come from RCMs or CPRCMs :

- 411 • A too thick and persistent snow cover in the RCM and possibly the CP-RCM combined with a too coarse represen-
412 tation of the topography.
- 413 • Problems related to the parameterizations, impacting the representation of turbulent fluxes and the too simple
414 snow cover scheme in AROME.
- 415 • Incorrect representation of the cloud cover, leading to a biased radiation balance.

416 Further studies are needed to investigate these issues through sensitivity studies, focusing on the parameterizations
417 mentioned above, in similar configurations in order to apportion the contribution to the total bias due to each of the
418 parameterizations, and the part inherited from the driving models.

419 Overall, these hypotheses help to better understand the observed cold bias between AROME and the S2M reanalysis.
420 They may also be invoked to explain part of the cold bias of the ALADIN RCM, and help understanding the processes
421 behind the unrealistic snow accumulation shown in Figures 4-d-h.

422 | **Spurious snow accumulation**

423 As shown in Figure 4.d-h 6.h-p and described in section 3, snow accumulates unrealistically at some grid points, for
424 AROME driven by ERAi above 2100 m, from 1500 m when driven by CNRM-CM5, and above 2400 m for ALADIN
425 driven by ERAi, 2100 m when driven by CNRM-CM5.

426 Above 2500 m, it is expected for snow to accumulate from one year to the next, since this elevation corresponds to the
427 lower limit of the equilibrium elevation line of the Alpine glaciers, on average around 3000 m (Rabatel et al., 2013). The
428 S2M reanalysis, which focuses on seasonal snow, is designed to partly reset the snow cover state on August 1st each
429 year in order to limit multiannual snow accumulation (Vernay et al., 2021). However, below 2500 m, it is unrealistic
430 for snow to accumulate from one year to the next, and reflects an erroneous behaviour of the corresponding model.

431 We note that snow accumulates more and at lower elevations when driven by the CNRM-CM GCM than by ERAi in
432 ALADIN and AROME. This behavior is similar to what was identified in the studies investigating the results of the
433 EURO-CORDEX RCMs by Terzago et al. (2017), focusing on the snow water equivalent (SWE) and Matiu et al. (2020)
434 focusing on the snow cover fraction and snow depth. In these two studies, the authors attribute the differences
435 in accumulation to atmospheric forcings (as a "legacy" of GCM biases), inducing a thicker snowpack (due to higher
436 snowfall and lower temperatures). This hypothesis is consistent with our results, as snowfall (total precipitation and
437 fraction of solid precipitation) for AROME and ALADIN (and air temperature for AROME) are significantly higher when
438 driven by a GCM than driven by ERAi (see table 1) and could therefore explain differences between ERAi and GCM
439 driven simulations.

440 However, as snowfall amount and air temperature at 2 meters values are respectively higher and lower in ALADIN
441 outputs, neither the atmospheric forcings (from the GCM), nor the atmospheric conditions within ALADIN or AROME
442 can explain the highest snow accumulation found in AROME outputs, in past or future climate.

443 Some further explanations for this behaviour are hypothesized and listed below :

- 444 • The different degrees of complexity of the snowpack scheme used in each model probably participate to the dif-
445 ference in snow accumulation. AROME uses D95 model which is a single-layer snowpack scheme coupled within

446 AROME, while ALADIN uses the multi-layer ISBA-ES model, taking into account more processes than D95 such as
 447 the liquid water retention, heat transfer, compaction, and thawing/freezing latent fluxes.

448 • The differences in the radiation balance as well as the turbulence parameterizations affect near surface conditions.
 449 • The daily/hourly characteristics of wet events as well as differences in temperatures diurnal cycles (intensities,
 450 durations and frequencies) may affect the responses of the snowpack scheme and explain part of the more or less
 451 pronounced snow accumulation between models, configurations and between grid points for a given model and con-
 452 figurations.

453 • According to Terzagó et al. (2017), more finely resolved topography allows areas of snow accumulation to be better
 454 isolated, and thus produce stronger maxima, corresponding to mountain peaks.

455 In summary, spurious snow accumulation below 2500 m might be explained by the atmospheric conditions (higher
 456 snowfall, cold biases, daily/hourly characteristics of wet events, and diurnal cycle of temperatures), weaknesses of
 457 the snowpack schemes (and their different levels of complexity) and the surface-atmosphere coupling (snow albedo
 458 feedback, radiation/turbulence parameterizations). All of these factors vary among configurations and models, explain-
 459 ing differences in snow accumulation between models simulations.

460 Addressing the causes for spurious snow accumulation would require further studies to apportion the contribution of
 461 the different factors involved and improve the models accordingly.

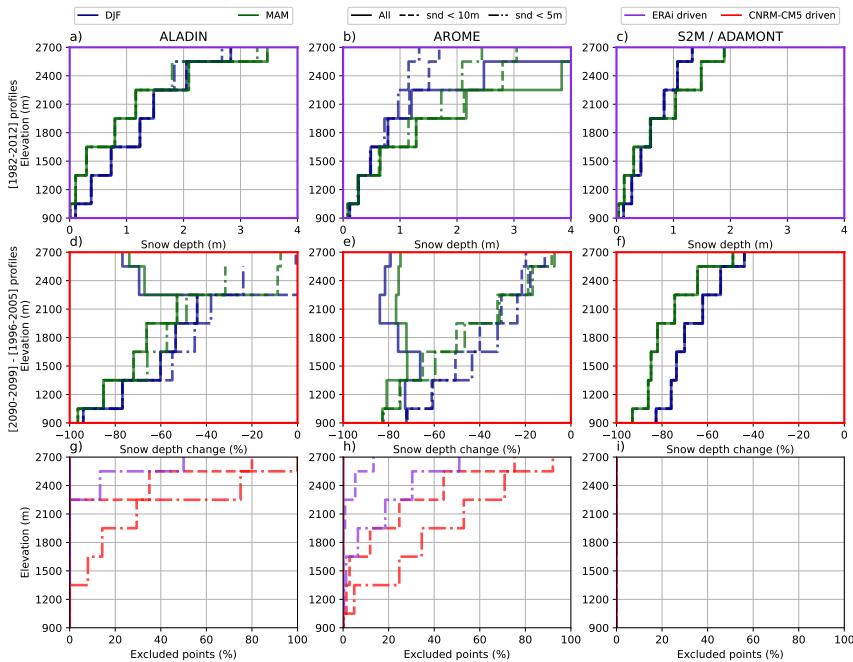


FIGURE 8 Altitudinal profiles of mean snow depth (snd) values averaged over the 1982-2012 period for DJF and MAM seasons for ALADIN (a), AROME (b) and S2M (c), with different threshold values applied to exclude grid points exceeding the threshold values from the profiles (no threshold - solid line, 10 meters - dashed line, 5 meters - dotted line). The second line shows the difference of mean snow depth values for DJF and MAM seasons, between the averages of the end-of-century (2090-2099) and beginning-of-century (1996-2005) period for ALADIN (d), AROME (e), ADAMONT (f) with same thresholds applied than for panels a), b) and c). The third line shows the proportion of points excluded according to each threshold (dashed line - 10 meters, dotted line - 5 meters), respectively for panels a), b) and c) in violet, and for panels d), e) and f) in red.

462 Figures 5 and 7 (and Figures A2 and A4) show that snow accumulation only concerns some grid points for AROME and
463 ALADIN, with high values bringing the spatial averages to exceptionally high values at high elevations (see Figures
464 4.d-h and 6.h-p).

465 Figure 8 shows the altitudinal profiles of mean snow depth values for DJF and MAM seasons, similar to Figure 4.d (for
466 ALADIN, AROME and S2M) and Figure 6.d-l (for ALADIN, AROME and ADAMONT), but excluding some grid points
467 from the computation according to different snow depth thresholds. Thresholds are applied to seasonal means, in
468 such a way that if a seasonal value at a given grid point (or S2M elevation band) exceeds the threshold for at least
469 one year for one season, the grid point is entirely removed from the computation of the spatial average for a given
470 elevation band.

471 Figure 8.a-b shows that using a 5 m threshold reduces the deviation above 2400 m between ALADIN and S2M, and
472 between AROME and S2M above 2100 m. The number of excluded points is larger for AROME than for ALADIN in
473 Figure 8.g-h, because the spurious snow accumulation pattern concerns more grid points in AROME simulations (30%
474 at 2400 m for the 5 m threshold) than in ALADIN outputs (only 15% at 2400 m for the 5 m threshold), whereas no
475 elevation bands are removed from S2M simulations (see Figure 8.i). Figure 8.a-b also shows that despite the lower
476 deviation above 2100 m for AROME and ALADIN with a 5 m threshold, both are still showing higher snow depth values
477 than S2M for both seasons and all elevation bands. These results are consistent with the hypotheses provided above
478 to explain snow accumulation, due to too high snowfall values, and underestimated snowmelt, leading to generally
479 overestimating snow depth values in AROME and ALADIN.

480 Figure 8.g-h also confirms that snow accumulation is larger and more extended geographically in simulations driven
481 by CNRM-CM5 than by ERAi, with more than twice the number of excluded points for AROME regardless of the
482 elevations considered, and more than 3 times in ALADIN at 2400 m for the 5 m threshold.

483 Figure 8.d-e shows that applying a 5 m threshold considerably modifies the shape of the elevation profile for both
484 seasons, and better matches the relative decrease with elevation of the snowdepth decrease of the ADAMONT data
485 results across the 21st century. Nevertheless, for both AROME and ALADIN, results above 2100 m when driven
486 with CNRM-CM5 are obtained using less than 40% of the grid points, that are not removed, thereby questioning the
487 representativeness of this result.

488 Overall, even if snow depth values as they stand are difficult to exploit at high elevation for AROME and ALADIN
489 and can affect the overall simulation results due to snow cover feedbacks, removing the grid points concerned by
490 exceptional snow accumulation may enable a restricted use of the snow depth fields. We note that these problems
491 are not systematically encountered for all CP-RCMs (Lüthi et al., 2019).

492 | **Difference in future climate change between dynamic and statistical downscaling**

493 By design, ADAMONT cannot represent elevation-dependent warming, because for each massif only one grid point
494 from the driving RCM is used (Verfaillie et al., 2017; Pepin et al., 2015), in contrast to AROME which intrinsically
495 represents the topography at 2.5 km horizontal resolution. The vertical distribution of summer and autumn warming
496 rates could be interpreted as indicating an elevation-dependent warming signal, but an investigation of the distribution
497 of grid points for AROME at different elevations (see Figures A3 and A4) partly dismisses this hypothesis at least at the
498 scale of the French Alps. Indeed, the distribution of grid points at high elevations are not well distributed among the
499 French Alps, but concentrated in inner Alps in contrast to low elevations with more points concentrated in exterior

500 Alps. Therefore, regionally aggregated elevation dependent warming could actually reflect spatial variations of the
501 warming rate. The temperature change in the AROME and ALADIN outputs show a rather smooth spatial pattern,
502 while ADAMONT shows a larger inter-massif variability, potentially inherited from S2M heterogeneities used for the
503 adjustment process. A stronger warming signal than AROME are also found in ADAMONT for the summer and
504 spring seasons at all elevations and the autumn below 1800 m.

505 Similar geographical variations of the 21st century change in the amount of seasonal precipitation in the French Alps
506 can be seen in all three datasets : general increase in winter and autumn in the northern part at all elevations, and a
507 decrease in the southern part at all elevation, whereas a general drying dominates in spring and summer in the entire
508 domain. Investigations were conducted by Ménégoz et al. (2020) addressing 20th century changes in the French Alps
509 using the MAR model driven by a reanalysis, where wetter trends were explained by more intense wet days and
510 longer albeit less-frequent wet spells, and drying trends with less frequent wet days. Further extensive research at
511 finer spatio-temporal scale would provide further information on these changes. Despite close geographical variation,
512 the AROME simulations almost systematically show either a larger relative increase or a smaller relative decrease of
513 accumulated precipitations compared to the ADAMONT adjusted projections.

514 For the fraction of solid precipitation in winter and the snow depth values at the different elevation investigated, the
515 same analysis as for the accumulated precipitations can be made, with close geographical differences, but a smaller
516 change in AROME and ALADIN compared to ADAMONT, consistent with comparatively lower temperature change.

517 For all variables considered, the spatial pattern of the changes are generally similar for AROME and ADAMONT.
518 This also holds true for ALADIN although its low horizontal resolution does not allow to represent the finest spatial
519 variations. Differences in the changes remain difficult to interpret, due to the multitude of limitations induced by the
520 two types of downscaling, which can alter the changes, and the difficulty in quantifying the impact of each. Our study
521 shows that both the AROME and ALADIN simulations exhibit large cold deviations compared to ADAMONT outputs,
522 that can reasonably be considered as biases in the evaluation period.

523 Concerning the ADAMONT statistical adjustment, Verfaillie et al. (2017) recall that the quality of the method when
524 applied outside its learning period depends strongly on the quality and temporal homogeneity of the observations
525 used to carry out the adjustment. However, the SAFRAN S2M reanalysis has spatial and temporal heterogeneities
526 over mountain regions and make the assumption of intra-massif homogeneity which is not systematically verified.
527 Furthermore, Verfaillie et al. (2017) suggest that spatial heterogeneity in the quality of the adjustments may be induced
528 by the method of selecting the points to be used due to a lack of points at high elevation with ALADIN compared to
529 S2M. An additional source of uncertainty for its application in future climate concerns the assumption of temporal
530 invariance of regional climate model errors as well as a modification of the climate change trends due to quantile
531 mapping adjustment (Maraun, 2016).

532 | On the added value of using CP-RCMs to model past and future climate

533 Despite all the limitations discussed in the previous sections, the use of CP-RCMs and specifically AROME in this study
534 shows clear added-values compared to raw ALADIN outputs, but also with respect to using the statistical downscaling
535 and adjustment method ADAMONT using S2M as a reference.

536 Compared to ALADIN outputs, temperature differences between S2M and ADAMONT are lower in AROME simula-
537 tions, regardless of the seasons and elevation. The hypotheses invoked to explain these lower values are discussed in

538 section 4. accumulated precipitation values for a given elevation are almost systematically lower in AROME compared
539 to ALADIN, and closer to S2M values used as a reference. Due to the parameterisation of deep convection, the trig-
540 gering of the convective pattern during orographic uplift may be too frequent and too intense in ALADIN simulations.
541 Prein et al. (2013) showed that most RCMs that do not explicitly resolve deep convection produce convective systems
542 that evolve too slowly, leading to an overestimation of their intensity, net heat transport, and precipitation. Moreover,
543 the ALADIN mesh represents the Alps as a long north-western slope, which flattens the pre-Alpine massifs to the
544 north, and does not allow for an accurate account of the barrier effects leading to low accumulated precipitations in
545 the inner massifs. This largely explains the high accumulations at 1800 m elevation simulated in ALADIN (see Table
546 1).

547 On the other hand, the seasonal accumulations values produced by AROME (see Figures 4b-f), showing a strong
548 altitudinal increase, and maxima in winter and spring, are very different from those in S2M in past climate or ADA-
549 MONT in future climate for which the altitudinal gradient is lower, with maxima in autumn. These results were also
550 found with MAR simulations compared to S2M reanalyses and other observation datasets Ménégoz et al. (2020), as
551 well as similar geographical seasonal variations of accumulated precipitations. Similarly to the results of Vionnet et al.
552 (2016), we find that total snowfall values are larger for AROME above 1800 m, with a difference increasing with el-
553 evation, despite a strong spatial variability relative to the orography. According to Vionnet et al. (2019), the quality
554 of the SAFRAN precipitation reanalysis is limited at high elevations due to the lack of observation stations used in
555 the analysis, and by limitations of precipitation measurements for snowfall due to wind-induced undercatch. These
556 discrepancies over mountain regions between observing systems and CP-RCMs have already been shown with the
557 WRF atmospheric model and the PRISM observation dataset in the USA by Hughes et al. (2020), who also noted
558 that models systematically overestimate precipitations on the windward side of mountains, and underestimate them
559 on the lee side. Although these investigations only concern snow precipitation, they make it possible to explain, on
560 the one hand, the increase in the difference in accumulations with elevation and, on the other hand, the difference
561 between AROME and S2M in terms of the seasonal maximum accumulations, in autumn for S2M and the November
562 to April period for AROME.

563 Despite the difficulty of drawing conclusions due to the absence of fully reliable observation sources at high elevations,
564 it is possible that the accumulations simulated by AROME in the high mountains are closer to reality than those of
565 S2M, and by design, those of ADAMONT.

566 Overall, assessments using several sets of observations, as performed by (Ménégoz et al., 2020) at finer spatio-
567 temporal scales, on daily or subdaily indicators, as well as on extremes events, are worth exploring in the future
568 in order to assess another dimension for which CP-RCMs are designed to provide further added value.

569 5 | CONCLUSION

570 Simulations of the CP-RCM AROME, driven by the RCM ALADIN under past and future climate conditions, are an-
571 alyzed in the French Alps, and compared to its driving RCM as well as a statistical downscaling method ADAMONT
572 applied to the same driving RCM. We demonstrated the added value of AROME compared to its driving RCM AL-
573 ADIN, with temperature and precipitation fields closer to the reference values from the S2M reanalysis. Also, the use
574 of AROME leads to a better representation of the geographical patterns of the variables based on 10 years averages
575 for the historical simulations, as well as on 30 years average. As multiple studies have suggested for high resolution
576 models (Lundquist et al., 2019), AROME could also provides a better estimate of accumulated precipitation at high

577 elevation than the S2M reanalysis and consequently the ADAMONT projections, which are based on the reanalysis,
578 although this added value remains difficult to assess due to the lack of reliable observations at high elevation. Future
579 projections with AROME show more realistic spatial patterns, for a given elevation, than ADAMONT results, which in-
580 herit and potentially amplify, in future projections, spatial heterogeneities from the S2M reanalysis used as a reference
581 dataset. This study corroborates the advantages in the use of CP-RCMs over mountain regions, as Prein et al. (2013)
582 did in their study by showing the systematic added value of CP-RCMs in summer rainfall that we extend here with the
583 other seasonal rainfall, the representation of near-surface temperature fields showing added-value here compared to
584 ALADIN with a smaller negative temperature deviation. The added-values listed above having cascading effects on
585 the estimation of the rain-snow limit elevation, snow precipitation, and snow depth values.

586 Nevertheless, there are still some obstacles to using AROME to fully exploit all of its output variables. Indeed, strongly
587 negative temperature differences between AROME the simulations and S2M-based simulations at intermediate and
588 high elevations in both past and future climate conditions are remaining, appearing as a recurrent feature of AROME
589 simulations. Preliminary investigations suggest that it is linked to its representation of surface radiative fluxes, to the
590 coupling with its surface model, and thus to its capacity to correctly represent the surface-atmosphere interactions,
591 in particular concerning the evolution of the snow cover. Unrealistic accumulation of snow is also found at elevation
592 above 1800 m, and is most probably the result of several factors, that we expect some to be partly linked with the
593 cold bias, and that affect only some grid points at a problematic amplitude. These need to be extensively studied
594 and addressed, but provided that grid points characterized by spurious snow cover accumulation in AROME and
595 ALADIN simulations are removed from the analysis, snow depth fields from these simulations are consistent with
596 S2M/ADAMONT simulations, with differences requiring further investigations.

597 Some characteristics at finer spatial and temporal scales of the CP-RCMs outputs remain to be studied in mountain
598 areas and constitute promising perspectives to be explored. Indeed Prein et al. (2020) highlighted the benefits of CP-
599 RCMs by their capacity to quantify and represent extreme events. Matiu et al. (2020) expected that the finer resolution
600 would increase precision of the temperature fields and orography, also improving the representation of the hydrolog-
601 ical phenomena and the snow cover fields. These potentialities (not addressed here) open up a wide field of research
602 applications in a large number of areas related to the impacts of climate change on mountain social-ecological systems.
603 The use of the AROME CP-RCM to study climate over mountain regions demonstrate clear added-value compared to
604 its coarser-scale driving RCM ALADIN, whether it concerns the representation of accumulated precipitations or finer
605 and less biased temperatures fields, both in all seasons. Further benefits are expected concerning the representation
606 of snow conditions (Terzago et al., 2017; Matiu et al., 2020), even if critical issues were identified in AROME.

607 Besides these improvements, the differences between a dynamic and statistical downscaling of climate change projec-
608 tions remain difficult to assess in detail as both feature limitations, although our study provides a consistent analytical
609 framework for evaluating CP-RCMs outputs in a systematic way. It is therefore necessary, and possible, to complement
610 this study with extensive developments on statistical adjustments, applicable for CP-RCMs, and with multi-model ap-
611 proaches to better quantify the model uncertainties. Nevertheless, the increasing use of CP-RCMs in the assessment
612 of climate change impacts through various European and international projects (e.g. CORDEX Flagship Pilot Study -
613 Convection (Coppola et al., 2020; Ban et al., 2021; Pichelli et al., 2021)) as well as the particular attention given to
614 mountain regions (TEAMx, Rotach et al. (2020)) are encouraging perspectives for future research in this field.

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786 A | APPENDIX

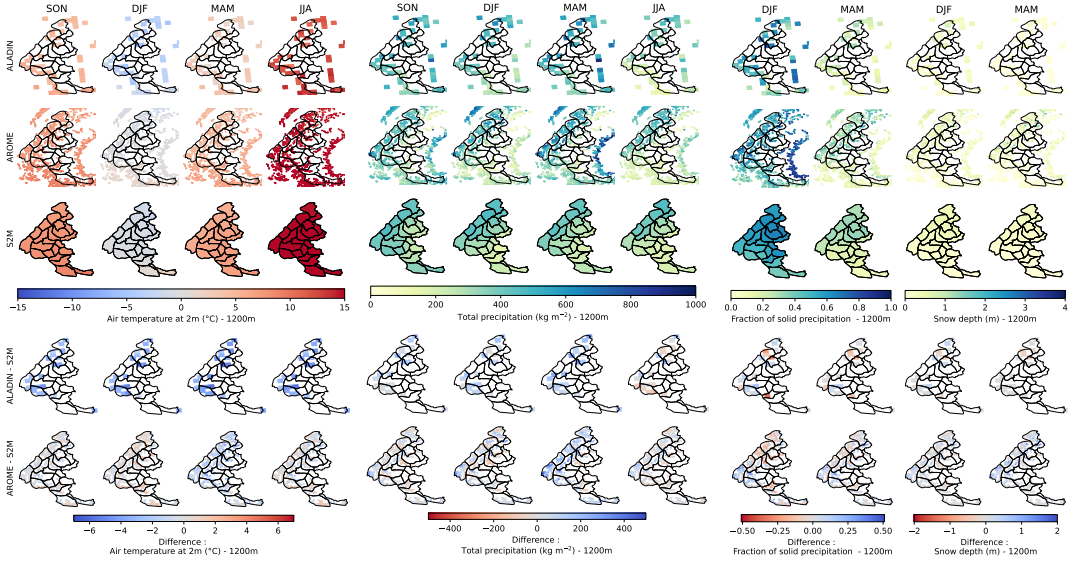


FIGURE A1 Same as Figure 5 but for 1200m elevation band.

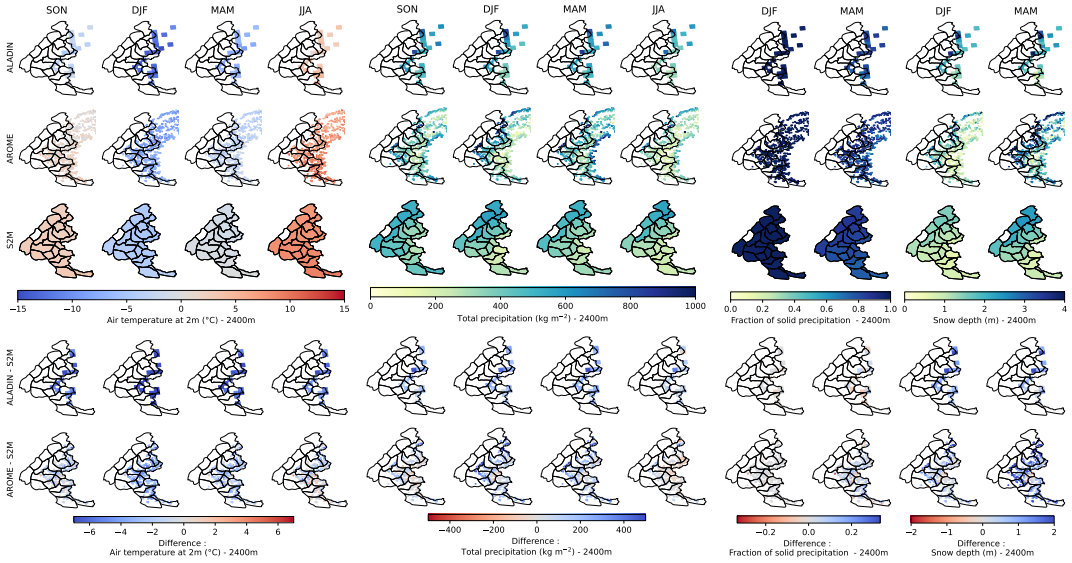


FIGURE A2 Same as Figure 5 but for 2400m elevation band.

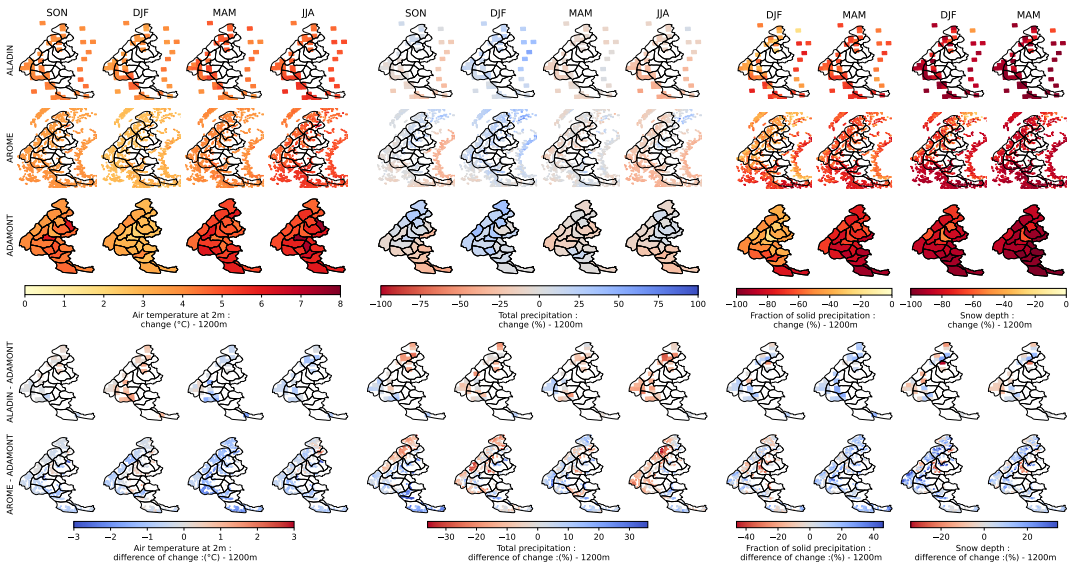


FIGURE A3 Same as Figure 7 but for 1200m elevation band.

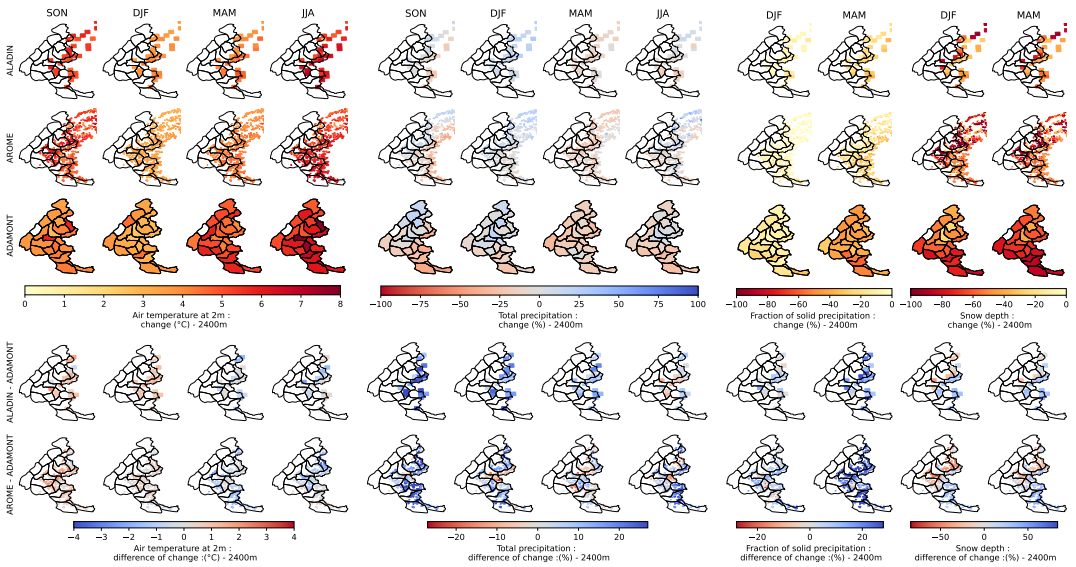


FIGURE A4 Same as Figure 7 but for 2400m elevation band.