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The Cryosphere
Discussions

Interactive comment on "Statistical adaptation of ALADIN RCM outputs over the French alpine massifs – application to future climate and snow cover" by M. Rousselot et al.

Anonymous Referee #1

1. Major points

"Description of the analogue method in Section 2.2...same analysis grid".

We agree that a clearer description of the grids of each models and the interpolation grid is missing:

- As mentioned in the paper, ALADIN has been run on a domain covering France at 12 km resolution (p. 4, col. 2, l.2).
- It is not stated that the ARPEGE data used for the analogue search were produced on a ~20km grid.
- We did not mention that ERA40 reanalyses were produced at a 1,125°*1,125°, i.e. ~125km*125km resolution.
- To perform the analogue search, all datasets were interpolated on a common grid, shown on Figure 1 but not discussed in the text. This grid has 11 latitude bands with a spacing of 0,375°, and 9 longitude bands with a spacing of 0,5°; i.e. a resolution of about 35 km.

According to these comments, section 2.2 has been largely modified (see text below).

"The effect of the differing grid resolutions... should be discussed"

The latter 35 km grid is the one used to interpolate large-scale input simulations to produce analysis with SAFRAN (D09a; Durand et al., 1999). This resolution is representative of the scale (100-500km^2) of the massifs. This implies that if any atmospheric fields were available at a finer resolution, the lower part of their spectra would hardly be accounted for in the final snow modelling.

In this study, our final goal is to simulate snow cover at the scale of the massif and produce monthly or annual diagnostics. As mentioned above, the 35 km scale is representative of the massif. Moreover, it is not clear whether the fine-scale signal of ALADIN can be studied at a daily scale (Déqué et al., 2008), as ALADIN in its RCM version is a rather smooth model, even when results are produced on a 12 km computation grid. For these reasons, we interpolated the initial 12 km ALADIN fields at this coarser 35 km resolution.

Déqué, M. and Somot, S., 2008: Added value of high resolution for Aladin Regional Climate Model. Research Activities in Atmospheric and Oceanic Modelling 38, 5.2-5.2 .

Despite the different initial resolution of the data from ARPEGE and ERA40, we do not have any evidence that the analogue method selected preferentially one or the other source of information, the number of days from ARPEGE (2191) being much smaller than that of ERA40 (16071).

According to these reviews, the text p. 4-5 has been rewritten :

"A simple analogue method was applied on a domain centered on the French Alps and snow modelling was carried out on the alpine sub-domain (Fig. 1). Briefly, the modelling set-up, as shown in Figure 2, was as follows:

- ALADIN atmospheric fields of air temperature at 2m above ground (T2m) and 500hPa geopotential height (Z500), available with a 6-hour time step, were linked through a statistical distance to real, analogous large-scale reanalyses.
- The reanalyses were available from Durand et al. (2009a), referred to as D09a below, who used them to force SAFRAN and establish a fine-scale climatology on the French Alps. The reanalyses consisted of a combination of ERA-40 fields from 1958-2002 (ECMWF, 2004) and Météo-France's ARPEGE analysis from 2003-2008. These fields, initially produced at 125km (1,125°) and 50km resolution respectively, were interpolated by D09a on a grid of 35km resolution (Fig. 1). This grid corresponds roughly to the spatial scale of the massifs considered by Météo-France for snow modelling. In the present work, these atmospheric fields were used at the same resolution and referred to as "extended ERA40 fields".
- As our final goal is to simulate snow cover at the scale of the massif and produce monthly or annual diagnostics, the 12km-ALADIN fields were interpolated and thus on the same grid (Fig. 1). Thus, details at a scale finer than the scale representative of the snow modelling outputs were not considered. As a consequence, the analogues that were sought each day for all the alpine massifs were representative of the main features of the meteorological flow over the Alps t a spatial resolution compatible to the size of the massifs.
- The date series of these analogues was then used to retrieve finer real meteorological fields from the D09a climatology. This climatology consists of weather reanalyses for 1958-2008, defined at the massif-scale for elevations ranging from 900-3600m a.s.l. and considering various orientations and slopes. It provides hourly fields of air temperature, quantity and phase of precipitation, humidity, cloudiness, horizontal wind speed, and direct and indirect solar radiation (D09a).

Thus, in this method, raw, large-scale fields from the ERA40 database are not used explicitly for snow modelling."

Figure 1 has been modified and now displays a horizontal scale, the resolution of the interpolation grid and the four alpine sub-domains. Its caption has been modified as follows:

"**Fig. 1.** Map showing surface elevation of the ALADIN RCM sub-domain considered in this study. The analog research between the extended ERA-40 and ALADIN fields, interpolated on the analysis grid (black dots), was performed over the whole domain. Snow modelling was conducted on the 23 massifs of the French Alps as defined in SAFRAN (red line, see text for details). MB, GR, Qu and Ub designate the Mont-Blanc, Grandes Rousses, Queyras and Ubaye massifs respectively. The four alpine sub-domains, North, Central, Southern and extreme Southern Alps, are identified."

"A further open question is whether the analogue method is applied separately for different season/times of the year... but this point remains unclear"

The search for analogue days is carried out based on the entire year. We did so to allow the selection of analogues representative of hotter days in the future. In some cases, the couple of analogues do not belong to the same season. For example, the analogue research for the days in March 2100 provides 11 analogous dates in April, 11 stay in March and only 3 in February (Table R0). More generally, 6 analogous dates are in autumn, 11 are in spring (all in April) and none in summer.

"Future" date				"Analogous" date				Distance
Year	Month	Season	Day	Year	Month	Season	Day	
2100	3	1	1	1998	3	1	5	1,40
2100	3	1	2	1986	12	4	31	1,01
2100	3	1	3	1967	3	1	3	0,71
2100	3	1	4	1987	11	4	18	0,58
2100	3	1	5	1970	10	4	29	0,64
2100	3	1	6	1990	2	1	23	0,56
2100	3	1	7	1972	11	4	4	0,65
2100	3	1	8	1990	3	1	13	0,55
2100	3	1	9	1965	4	2	1	0,67
2100	3	1	10	1990	3	1	21	0,70
2100	3	1	11	1976	3	1	27	0,88
2100	3	1	12	1978	10	4	28	0,65
2100	3	1	13	1976	3	1	28	0,66
2100	3	1	14	1989	3	1	6	0,56
2100	3	1	15	1984	4	2	14	0,64
2100	3	1	16	1965	4	2	5	0,72
2100	3	1	17	1965	4	2	12	0,74
2100	3	1	18	1980	4	2	21	0,99
2100	3	1	19	1973	4	2	4	0,78
2100	3	1	20	1970	4	2	15	0,63
2100	3	1	21	1976	3	1	28	0,58
2100	3	1	22	1989	3	1	12	0,68
2100	3	1	23	1963	4	2	14	0,67
2100	3	1	24	1995	3	1	19	1,19
2100	3	1	25	2000	2	1	19	1,30
2100	3	1	26	1967	4	2	22	1,07
2100	3	1	27	1975	3	1	26	0,66
2100	3	1	28	1960	2	1	22	0,73
2100	3	1	29	1983	4	2	5	1,12
2100	3	1	30	1995	12	4	25	1,08
2100	3	1	31	1968	4	2	28	0,74

Table R0 : Example of analogous dates of the days of the March 2100 March and value of the statistical distance.

In practice, there are very few of these examples, as the analogues are generally selected in the same season. This can be explained by the fact that in the distance computation (Eq. 1), ALADIN and ERA40 fields are statistically centred by subtracting their mean seasonal value. Thus, for a research in a given season, days out of the season are automatically penalized as they result in larger ERA40 deviations.

Figure R1 shows the distribution of the differences in month between the days of March in ALADIN and the dates of their analogues in ERA40/ARPEGE, for the reference period (1961-1990) and the A1B scenario. It appears that in all cases, the analogue is selected either in the same month or in the neighboring month.

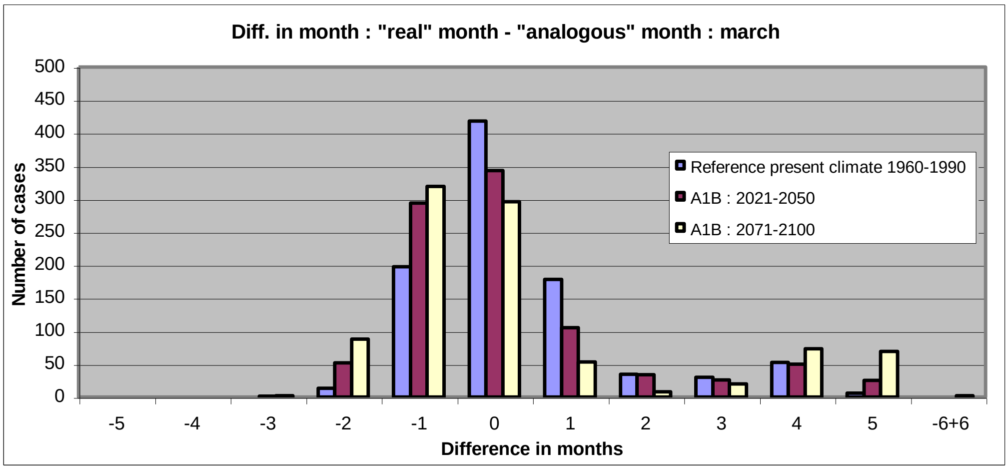


Figure R1: Difference in months between the days of March of the ALADIN run and the month of the corresponding analogues, for the reference period (1961-1990), and two periods of the scenario A1B (2021-2050 and 2071-2100).

According to these reviews, we added two sentences at the end of the first paragraph, p. 6:
"In this computation, there is no formal constraint in terms of date or season in the analogue research: for a given day of ALADIN, any extended ERA40 dates, from July 1958 to December 2008, can be selected. Nevertheless, in practice extended ERA40 days out of the season are penalized as they result in larger ERA40 deviations $X_{era}(i)$."

"page 177 lines 18-22: it is obvious that the different topographies of ERA40 and ALADIN … methodology"

We agree that there is a difference in the topography of ERA40 and ALADIN that needs to be corrected. Ideally, a time-dependent correction based on the atmospheric vertical profiles of both models would guarantee a consistent search for analogue meteorological conditions. However, only few data were available for our study, as only two levels (T2m and Z500) were archived during the ALADIN runs. Thus, in our opinion, such a dynamical correction would rely here on many speculative hypotheses, for example on the characteristics of the vertical atmospheric profiles, their extrapolation to near surface profiles and situations of temperature inversion.

For these reasons, we chose to conduct the analogue search between seasonal anomalies of ERA40 and ALADIN, i.e. values that are statistically centred for each season, in particular near surface temperature anomalies T2m – Mean(T2m). In this way, effects related to different topographies in the analogue search are smoothed out. This method is rather simple but does not guarantee good temporal consistency in the analogue search, as the difference of topographies is not treated daily but seasonally.

As a consequence of these limitations, we paid major attention on the validation of the method. The two CR and CT experiments conducted on the reference period (1961-1990) produce "raw" climatologies, which are not corrected by any q-q correction. In particular, as explained in the paper p.6 Section2.3,

- the CR experiment is an analogue search between two ERA40 datasets. It was carried out to assess the error introduced by the minimization of the distance d (Eq. 1) alone;
- the CT experiment is an analogue search between ERA40 and ALADIN. It was carried out to assess the total error resulting from the minimization of the distance and the different parameterization of both models (which may concern for example topography, physical processes, numerical schemes...).

However the reader may have been misled by a mistake in Figures 4 and 5, where the CT and CR axes are inverted. This has now been corrected.

As shown in Figures 4 and 5, the CR experiment indicates that the method leads to a statistical distribution of T2m in agreement with this of D09a, but tends to underestimate the precipitation. This dry bias has been corrected by a q-q correction. As shown in Figure 5 a-d, this correction is rather small, of less than 5mm.day-1 in winter and spring, the seasons which are most relevant for snowpack studies. A similar correction has been applied to the other meteorological inputs of the snow model. The impact of this correction on the meteorological variables in term of SWE at 1800m for the 23 massifs and the JFM season is illustrated in Figure R2.

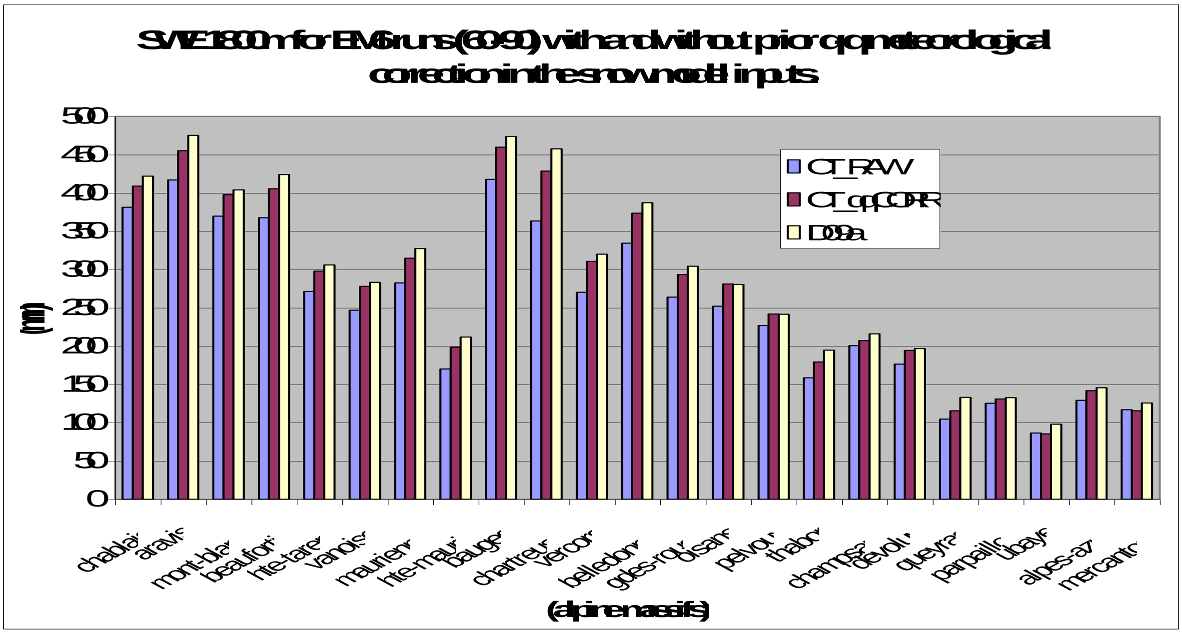
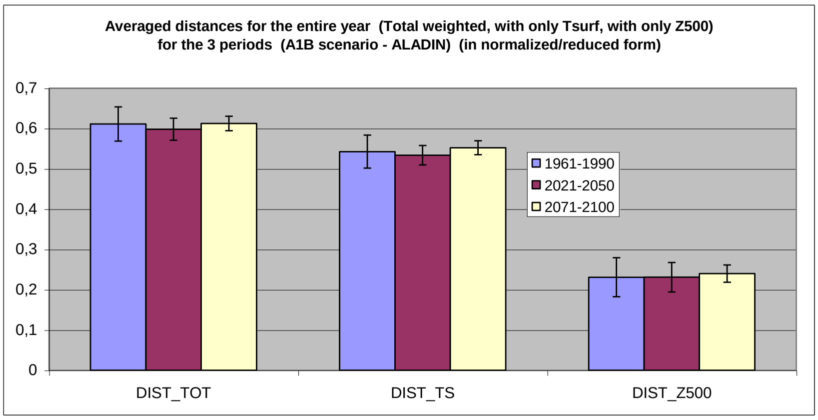


Figure R2: SWE at 1800m a.s.l. in the alpine massifs resulting from CROCUS simulation forced with the outputs of the CT experiment (blue), the CT experiments corrected by a q-q correction (red) and the D09a climatology (yellow).

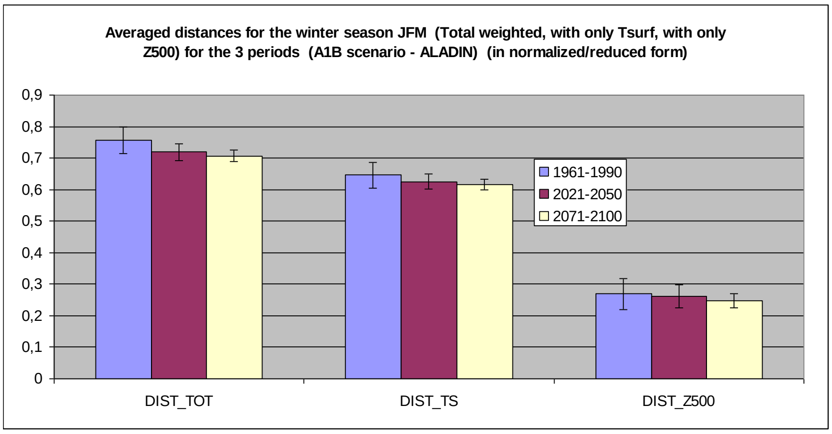
As shown in Figure R2, the mean correction over all massifs is about 9% in relative change of SWE, with a maximum value of 18 % in Chartreuse. The corrected values generally underestimate the analyzed climatology, by 4% in mean, with maximum values of 13% in the Queyras and Ubaye massifs.

“Search of analogue conditions in the scenario periods… on this issue”.

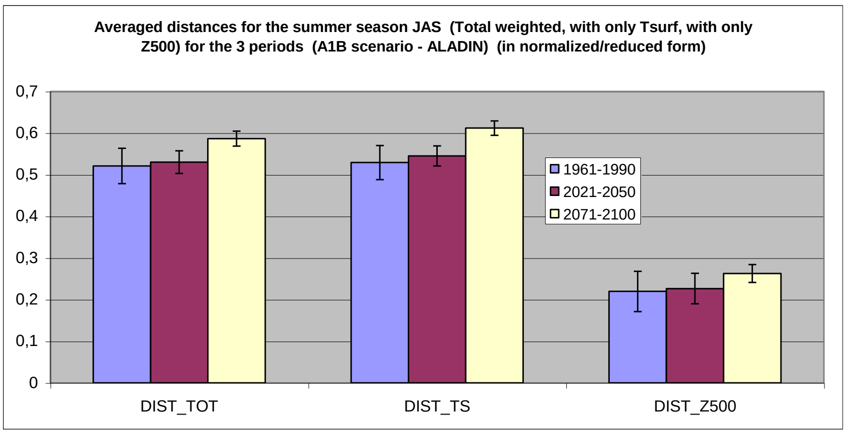
The reviewer is right, the fact that future meteorological conditions may not be found in the database relative to the current period is a well-known limitation of analogue methods. We investigated this issue by comparing the value of the mean distance for the different periods (1961-1990, 2021-2050 and 2071-2100), as suggested by the reviewer (Fig. 3R).



a)



b)



c)

Figure R3: Mean value of the distance computed in the analogue research on the T2m (dist-Ts) and Z500 fields (dist-Z500), and the weighted sum of it (dist-tot). The distance is averaged on (a) a full *year, (b) the winter season and (c) the summer season, for the A1B scenario and the periods 1961-1990, 2021-2050 and 2071-2100.*

Figure R3 shows the values of the distances computed in the analogue research for different periods and seasons. The mean value of the total distance is larger for future periods and the summer season. In contrast, the distance decreases in the future in winter. The distance, averaged over a year, is roughly constant for all periods. These features can be explained by climate warming over the Alps, where warmer analogues are selected in the future scenarios. In other words, current seasons tend to shift toward warmer seasons. When the method is applied to research future analogues in winter, the selection of days of the current period in spring or autumn partly compensate the lack of "warm" months in the research sample (1958-2008). The method seems therefore not well adapted for the warmest months (summer season), for which good analogues probably do not exist in the 1958-2008 dataset, as indicated by the large values of the distances computed in summer. We expect that this limitation does not significantly affect the snow modelling conducted in this study.

The text end of p. 15 and first paragraph p. 16 been modified as follows
"Nevertheless, an analysis of the mean value of the computed distance (Eq. 1) shows that it increases slightly for future periods and the summer and autumn seasons, i.e. that largely warmer analogues tend to be selected for these seasons in future scenario. Thus, our method does not seem to be well adapted for the warmest months of the future, for which close analogues probably do not exist in the 1958-2008 database, However, such features are not observed for the winter and spring seasons, so that we expect that this limitation does not significantly affects results of the snow modeling. Moreover, we have verified a posteriori that our method …."

"It might help... These two should roughly agree with each other."

We agree that such a comparison helps to validate the method. However, the main difficulty here is that the final results of the analogue method are available in the space of the massifs at different elevations, whereas ALADIN outputs are produced on a grid 11x9 (discussed above). We thus chose to make the comparison between changes simulated by the analogue method and these simulated by ALADIN using tables. Table R1 shows the annual temperature changes simulated by the analogue method at 3 elevations for the 23 massifs, the 2021-2050 and the 2071-2100 periods for the scenario A1B. Results show changes ranging roughly between 1.7-2.0°C for the 2021-2050 period and 3.3-3.9°C for the 2071-2100 period. Table R2 shows corresponding changes in temperature on the ALADIN computation grid shown in Figure 1 of the paper. Results related to the grid points close to or included in the massifs are printed in bold here. Comparison of Tables R1 and R2 indicates that temperature changes produced by the analogue method and ALADIN are in good agreement over the Alps. The variability of the ALADIN results tends to be slightly larger than this of the analog method.

We cannot conduct a similar comparison for precipitation, as only ALADIN Z500 and T2m fields are available. If we would have had ALADIN precipitation field, we would have used it in the definition of the distance and probably improve the analogues research.

A1B (21-50) - Present (61-90)	chablais	aravis	mont-blanc	beaufortin	hte-tarent	vanoise	maurienne	hte-maurie	bauges	chartreuse	vercors	belledonne	gdes-rouss	oisans	pelvoux	thabor	champsaur	devoluy	queyras	parpaillon	ubaye	alpes-azur	mercantour
1200m	1,7	1,8	1,7	1,8	1,8	1,8	1,9	1,8	1,9	1,9	1,8	1,9	1,9	1,8	1,8		1,8	1,7	1,8	1,8	1,7	1,7	1,7
1800m	1,9	1,9	1,8	1,9	1,8	1,8	1,9	1,8	2,0	2,0	2,0	1,9	1,9	1,9	1,8	1,8	1,8	1,9	1,8	1,7	1,7	1,8	1,7
2400m	1,9	1,9	1,8	1,9	1,8	1,8	1,9	1,7			1,9	1,9	1,9	1,8	1,7	1,8	1,7	1,8	1,7	1,7	1,7	1,7	1,7
A1B (71-2100) - Present (61-90)																							
1200m	3,4	3,5	3,3	3,5	3,5	3,6	3,7	3,6	3,6	3,7	3,7	3,7	3,6	3,6	3,6		3,5	3,5	3,6	3,5	3,4	3,5	3,5
1800m	3,7	3,8	3,7	3,7	3,6	3,7	3,8	3,6	3,9	3,9	3,9	3,8	3,8	3,7	3,6	3,7	3,6	3,7	3,6	3,6	3,6	3,6	3,5
2400m	3,8	3,8	3,7	3,8	3,7	3,7	3,8	3,6			3,9	3,8	3,7	3,7	3,6	3,7	3,6	3,7	3,6	3,5	3,5	3,6	3,5

Table R1: Annual mean changes in temperature (°C) at 1200, 1800, 2400m over the massifs and the 2021-2050 and 2071-2100 periods and the scenario A1B.

A1B (21-50) - Present (61-90)								
1,4	1,5	1,5	1,5	1,5	1,6	1,6	1,4	1,6
1,4	1,5	1,5	1,6	1,4	**1,7**	1,8	1,0	1,9
1,4	1,5	1,5	**1,6**	**1,7**	**1,8**	1,5	1,7	1,7
1,5	1,6	**1,6**	**1,6**	**1,8**	**1,9**	1,6	1,8	1,7
1,5	1,6	**1,6**	**1,7**	**1,9**	**1,9**	1,8	1,7	1,7
1,6	1,6	**1,6**	**1,8**	**2,0**	**1,8**	1,7	1,8	1,8
1,7	1,6	**1,6**	**1,7**	**1,8**	**1,9**	1,7	1,8	1,7
1,7	1,6	1,6	1,7	**1,7**	**1,8**	1,7	1,7	1,5
1,6	1,7	1,6	1,7	1,7	**1,6**	1,6	1,6	1,4
1,6	1,6	1,7	1,6	1,7	1,5	1,4	1,4	1,4
1,4	1,4	1,4	1,4	1,5	1,4	1,4	1,4	1,4

A1B (71-2100) - Present (61-90)								
3,0	3,1	3,1	3,1	3,0	3,2	3,2	3,2	3,3
3,0	3,1	3,1	3,2	2,8	**3,3**	3,5	3,4	3,6
3,0	3,2	3,2	**3,2**	**3,2**	**3,5**	3,0	3,7	3,3
3,1	3,3	**3,2**	**3,3**	**3,5**	**3,7**	3,1	3,6	3,4
3,2	3,3	**3,3**	**3,4**	**3,7**	**3,7**	3,5	3,5	3,6
3,2	3,3	**3,3**	**3,5**	**3,9**	**3,5**	3,6	3,7	3,7
3,3	3,3	**3,3**	**3,4**	**3,6**	**3,5**	3,6	3,6	3,4
3,3	3,3	3,4	3,4	**3,4**	**3,4**	3,4	3,5	3,1
3,3	3,3	3,4	3,5	3,3	**3,2**	3,2	3,2	2,8
3,1	3,2	3,4	3,4	3,4	2,9	2,8	2,8	2,8
2,8	2,9	2,9	2,9	2,9	2,8	2,8	2,8	2,8

Table R2: Annual mean changes in temperature (°C) simulated by ALADIN on the grid shown on Figure 1 of the paper, for the 2021-2050 and 2071-2100 period and the A1B scenario. The bold values correspond to grid points roughly located within the massifs.

"page 179 lines 13-14...Please clarify this point".

We agree that this sentence is incomplete. Our test integrates the errors coming from the analogue research as well as ALADIN errors. Thus, the sentence p.7, first paragraph of section 3.1, has been rewritten:

"Here, this classification is used to evaluate the ability of both ALADIN CT run and the downscaling method to correctly identify these large-scale circulation patterns."

"page 181 lines 13-17:... correct the figure or the text section and the table."

It is right, as mentioned above the axes in figure 4 have been mixed up. This has now been corrected.

"Snow cover validation in Section 3.3...The authors should think about it."

The cross-validation proposed by the reviewer would be a good way to validate our results if time series were available long enough, which is not the case here. From a climatic point of view, a 30 years is the minimum length of a period to be able to draw any conclusion on the period, including values of quantiles in a qq-correction. Moreover the 1958-2008 period is not homogeneous in terms of temperature increase over the alpine area, as shown in D09a, which gives evidence for a sharper increase starting in the 1980's.
We answer this comment by comparing the simulated SWE not corrected by any method, to both the SWE produced with corrected climatological data and the reference D09b snow climatology (Durand et al…, 2009B, J. of Appl. Meteo. and Clim.) This snow climatology has been extensively validated based on several ground observations. This comparison is shown in Figure R2, which has been discussed above.

"Analysis of surface temperature changes in Section 4.2... In principle, the same also applies for the analysis of precipitation changes in Section 4.3"

See Table R1 and R2 and comments above.

The text has been modified at the end of paragraph 4.2 page 11 :
"The annual temperature changes over the Alps provided by the analogue method were compared to these directly simulated by ALADIN on the grid points roughly located in the Alps (Fig. 1). These changes are in agreement with each other and range respectively from 1.7 to 2°C for the 2021-2050 period and 3.2 to 3.9°C for the 2071-2100 period for the A1B scenario."

"Analysis of temperature and precipitation changes in Sections 4.2 and 4.3... (agreement / disagreement with previous works?)."

PRUDENCE and ENSEMBLES experiments are mentioned in the paper with their respective references, but our study could probably benefit from being put into a broader context. Some sentences have been added in the validation paragraph, as well as in section 4.2 and 4.3.

p.11, end of 1st column and beginning of 2nd column:

"Changes obtained for the A1B scenario are in agreement with results obtained on the European Alps in the framework of the ENSEMBLES project. In this project, a rather uniform temperature increase of about 1.8- 2°C for the 2021-2050 period was simulated by a set of 16 weighted RCMs (van der Linden, 2009). In addition, Beniston (2011) suggested a warming of about 3-4 °C in winter and 6-7 °C in summer over the Swiss Alps for the 2071-2100 period and the A2 scenario, which is in agreement with the trends simulated in our study over the Northern Alps."

p. 12, end of 2nd column:

"Comparison of our results over the French Northern Alps with these obtained over the Swiss Alps (Beniston, 2011) for the end of the century reveals that the summer precipitation deficit is on the same order of magnitude in both countries, with a reduction of about 30-50 % in France and 20-40 % in Switzerland. However in winter, precipitations seem to increase by 15-35 % in the Swiss Alps, in contrast to the 0-10% increase suggested by our results in the Northern Alps. A possible reason for this discrepancy is the difference of parameterization and variability of the RCMs used in both studies."

End of p. 12 and beginning of p.13:

"As in other studies (van der Linden at al., 2009), projections of precipitation trends over the alpine areas for 2021-2050 are difficult to interpret, showing contrasted results according to scenarios, seasons and regions (Fig. 10 a-e)."

page 185 lines 6-9: I disagree with this statement. ...Please rethink this paragraph and reformulate.

The reviewer is right. The text has been rewritten p.13, 1st column, 2nd paragraph

"Figure 11 shows the altitudinal gradients of relative annual precipitation changes over the main alpine regions, for 2021–2050 and 2071–2100 and all scenarios. As for temperatures, the simulated precipitation anomalies do not seem to depend on the altitude. This suggests that the orographic gradient currently observed in the different regions of the Alps (Durand et al., 2009a) may be qualitatively the same in the future. "

"Analysis of snow changes in Section 4.4: It seems that a discussion of the reason for the strong elevation dependence of snow changes is missing. The temperature change signal is similar at all altitudes. The authors should discuss why, nevertheless, relative snow cover changes are stronger at low altitudes and in the southern parts (lower temperature level, shorter snow season, etc.)."

Temperature and precipitation are relevant parameters to describe snowpack evolution, but other complex snow-atmosphere interactions such as turbulent heat fluxes or snow drift also lead to snow cover change. These interactions result in non-linear and threshold effects in the energy and mass balance of the snow cover. As energy balance governs snow pack physical properties (snow temperature, liquid water content, density, grain size etc...), these properties also display some non-linear behavior. In our study, the adaptation of the snowpack parameters to the continuously changing meteorological conditions is simulated by the snow model Crocus, which calculates energy exchange at the snow surface, in-pack snow processes, melting and liquid water flow, heat conduction, and vapor diffusion. Thus, we need to consider a large range of complex physical processes to discuss snow pack evolution.

Snow studies conducted at mid-latitudes generally show that snow pack sensitivity to near-surface temperature is higher when the snow is close to its melting point: when the melting point is reached, the incoming energy is used for melting the surface layers, resulting in a decrease of the snow depth. This implies that in the Alps, at high elevations, snow cover is mainly governed by precipitation regimes whereas at lower elevations, all the terms of the energy balance are relevant to describe snow cover evolution. Thus, in our experiment, snow pack close to the melting point is more sensitive to small air temperature increase: this concerns snow cover located at low altitudes and in southern regions, characterized by generally higher temperature levels. These areas also show large relative SWE changes (Figs. 12 and 13) because of their initial low SWE values. A secondary effect that could explain the snow pack decrease in the southernmost areas is the decrease of precipitation, particularly in fall (Fig. 10).

The text has been rewritten; p**. 14:**

"Snow studies conducted at mid-latitudes generally show that snow pack sensitivity to near-surface temperature is higher when the snow is close to its melting point: when the melting point is reached, the incoming energy is used for melting the surface layers, resulting in a decrease of the snowdepth. This implies that in the Alps, at high elevations, snow cover is mainly governed by precipitation regimes whereas at lower elevations, all the terms of the energy balance are relevant to describe snow cover evolution.
In our experiment, snow pack close to the melting point is more sensitive to small air temperature increase: this concerns snow cover located at low altitudes and in southern regions, characterized by generally higher temperature levels. These areas also show large relative SWE changes (Figs. 12 and 13) because of their initial low SWE values. A secondary effect that could explain the snow pack decrease in the southernmost areas is the decrease of precipitation, particularly in fall (Fig. 10). These results are in agreement with a previous study (Martin et al., 1994) conducted on the same massifs but with climatic data of coarser resolution. "

"page 187 line 5-6: It is not clear a-priori that the bias correction by the q-q-method conserves inter-parameter consistency. Apparently, the method is applied separately for all driving parameters of the CROCUS snow model. If the authors want to claim that inter-parameter consistency is conserved by their approach, they need to show it."

We agree that the sentence is badly formulated. The q-q correction is indeed applied separately for all driving parameters of the snow CROCUS model. It is nevertheless applied on a set of initially consistent meteorological data issued from D09a. As the correction is small compared to the magnitude of the parameters (Figs. 4 and 5), we can argue that the corrected variables are not fully independent from each other, and present a given degree of consistency.

The text has been rewritten p. 15:

"The introduction of a statistical q-q correction provided a partial solution to this problem. This kind of correction has many advantages: it is simple, robust and appropriate to treat extreme events. Moreover, the correction, which is applied to a set of initially coherent meteorological data, is relatively small compared to the absolute value of the variables (Figs. 4 and 5), so that it guarantees a certain degree of consistency in the corrected driving parameters of the snow CROCUS model. In addition, the q-qmethod can account for the annual cycle as it is applied to individual seasons separately. In this study, this correction was applied to temperature, humidity, wind velocity, precipitation and cloudiness. A coherent correction was derived from these corrected variables for radiation using a radiation model. "

"page 187 lines 20-22: I might have missed it, but right now it is not clear to me where this has been shown. A comparison against the direct ALADIN outputs (as suggested above) has not been carried out. Please better clarify this point."

The reviewer is right, it has not been shown. As shown in Table R2, changes in ALADIN T2M fields (between present and future) are in agreement with changes obtained with our method on the alpine massifs. The text has been rewritten as mentioned above.

"page 187 lines 24-29: This statement is certainly true. However, the study presented does apparently not make use of the full 12 km resolution of the ALADIN RCM. The common grid on which the analogue method is carried out seems to be much coarser (see Figure 1). Please specify the grid resolution and consider reformulating this paragraph."

We agree with the reviewer. As discussed above, we use the 12 km resolution ALADIN outputs on a coarser grid of about 35 km. This grid is the one on which ERA40 fields were downscaled.

The text has been rewritten: **page 16, 1st column, 2nd paragraph:**

"Despite these limitations, the method presents several advantages. It enables the use of RCM scenarios at an intermediate resolution (35km), consistent with the size of the alpine massifs. At the same time, the finer initial resolution of the ALADIN outputs (12km) guarantees a fine representation of the different meteorological features. These fine-scale features, even if interpolated on a coarser 35km grid, improves the description of the temporal climate variability."

"Table 1: This table seems incomplete and doesn't correspond to the text section 2.3. Please specify the meaning of rows and columns and check the entries."

The reviewer is right; the two experiments have been inverted. Table 1 has been corrected.

"Figure 1: This figure definitely needs to be improved. It is not clear if this figure shows the ALADIN RCM domain or only a part thereof. Please specify. Furthermore, a horizontal scale is missing. Also the resolution of the analysis grid (black dots) should be specified either in the text or in the figure caption, ideally in both. The four sub-domains North, Central, Southern and extreme Southern Alps are referred to in the text but cannot be identified from Figure 1. I suggest to colour the individual massifs according to the sub-domain."

The figure has been improved. An error on the location of the Queyras massif (Qu) has also been corrected (see paper).

"Figure 3: A legend (meaning of the dark gray and light gray bars) should be added. In panel d) the light gray bars (CT experiment) do not add up to 100%. What's the reason for this? Are there unclassified days in the weather classification scheme? Please clarify."

The figure has been changed. The problem of CT in JAS is only graphical; its value for the type 7 is about 85% which could be represented with the previous y-axis scale. There is no unclassified day in the system.

"Figures 4 and 5: These figures are too small and hardly readable, their size should be increased. In general, I'm wondering how useful the correlation coefficient is as validation measure in a q-q-diagram. As quantiles are shown, the correlation will probably always be strongly positive. Does the literature present any other metric that is more useful? If so, please consider of switching to another metric. In Figure 5, the axis labels seem to be mixed up (see comment above)."

Q-Q plot are often used to compare two probability distributions, providing a graphical view of how properties such as location, scale, and skewness are similar or different in the two distributions. The use of Q-Q plots to compare two samples of data can be viewed as a non-parametric approach to comparing their underlying distributions. If the two distributions being compared are similar, the points in the Q-Q plot will approximately lie on the line y=x. If the distributions are linearly related, the points in the Q-Q plot will approximately lie on a line, but not necessarily on the line y=x. If the general trend of the Q-Q plot is flatter than the line y = x, the distribution plotted on the horizontal axis is more dispersed than the distribution plotted on the vertical axis. Conversely, if the general trend of the Q-Q plot is steeper than the line y = x, the distribution plotted on the vertical axis is more dispersed than the distribution plotted on the horizontal axis.

Thus, the closer the correlation coefficient between the paired sample quantiles is to one, the closer the distributions are to being shifted, scaled versions of each other. For these reasons, the use of q-q plot for validation purposes supposes to consider both the correlation coefficient and the graphical shape of the curve.

Other possible statistical tests are:

- A Khi2 test on the squared sum of the differences for each quantile (100 points) formulation of the pdf
- A Kolmogorov-Smirnov test, which quantifies the maximum deviation between two distributions and tests the shapes of the PDFs. If the variances of the two samples of population are very close (as it is the case here, see for instance the Figure R4 of this review), the result of this test in terms of correlation is similar to that of the Khi2 test.

We thus conducted a Kolmogorov-Smirnov and a Khi2 test between the two statistical distributions (CT and D09) at 1800 m a.s.l. in all massifs (Table R3). The two tests are always true for annual temperatures at the 5% level of significance. For annual precipitations, the KS test fails in 4 massifs (see below), whereas the Khi2 test is always true. Both tests are positive for seasonal temperatures, but the tests for seasonal precipitation exhibit a lot of discrepancies, especially in the Northern Alps in winter (KS test) and in most of the massifs in summer (both KS and Khi2 tests).

Massif	Period	Level	Variable	K-S Diagnostic	Significance	K-S Computed_value	KS-Threshold	Variable	K-S Diagnostic	Significance	K-S Computed_value	KS-Threshold	Khi2 Diagnostic	Significance	Khi2 Computed_value	Khi2-Threshold
chablais	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,08	0,14	ACCEPTE	5%	0,98	3,84
aravis	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,07	0,14	ACCEPTE	5%	0,89	3,84
mont_blanc	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,08	0,14	ACCEPTE	5%	0,96	3,84
beaufortin	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,08	0,14	ACCEPTE	5%	0,93	3,84
hte_tarent	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,12	0,14	ACCEPTE	5%	2,03	3,84
vanoise	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	**REFUSE**	5%	0,17	0,14	ACCEPTE	5%	2,37	3,84
maurienne	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	**REFUSE**	5%	0,17	0,14	ACCEPTE	5%	1,29	3,84
hte_maurie	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	**REFUSE**	5%	0,38	0,14	ACCEPTE	5%	2,06	3,84
bauges	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,11	0,14	ACCEPTE	5%	0,44	3,84
chartreuse	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,12	0,14	ACCEPTE	5%	2,42	3,84
vercors	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,08	0,14	ACCEPTE	5%	1,98	3,84
belledonne	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,09	0,14	ACCEPTE	5%	1,22	3,84
gdes_rouss	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	**REFUSE**	5%	0,21	0,14	ACCEPTE	5%	1,02	3,84
oisans	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,07	0,14	ACCEPTE	5%	0,44	3,84
pelvoux	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,06	0,14	ACCEPTE	5%	0,00	3,84
thabor	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,07	0,14	ACCEPTE	5%	0,65	3,84
champsaur	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,08	0,14	ACCEPTE	5%	0,26	3,84
devoluy	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,11	0,14	ACCEPTE	5%	0,19	3,84
queyras	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,06	0,14	ACCEPTE	5%	0,71	3,84
parpaillon	ANN	6	Temperature	ACCEPTE	5%	0,02	0,09	Precipitation	ACCEPTE	5%	0,06	0,14	ACCEPTE	5%	0,22	3,84
ubaye	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,06	0,14	ACCEPTE	5%	0,53	3,84
alpes_azur	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,06	0,14	ACCEPTE	5%	0,01	3,84
mercantour	ANN	6	Temperature	ACCEPTE	5%	0,03	0,09	Precipitation	ACCEPTE	5%	0,06	0,14	ACCEPTE	5%	0,01	3,84

Table R3 : Results of the Kolmogorov-Smirnoff and Khi2 test conducted on the two statistical distributions (CT and D09) at 1800 m a.s.l. in all massifs

The text has been rewritten page 180 lines 13-22:

"Results obtained for T2m suggest fairly good agreement between the D09a climatology and the ALADIN outputs treated in the CT experiment for all the selected massifs and seasons (Fig. 4a–d). As expected, this correlation is improved in the CR experiment (Fig. 4e–h), in which possible sources of errors related to the use of RCM predictors have been removed. In addition, a Kolmogorov-Smirnoff (KS) and a Khi2 test were conducted to compare the the D09 and CT temperature probability density functions (PDFs). Results of these tests at a 5% level of significance are positive for the annual and seasonal temperatures and all massifs.

For precipitation, the CT climatology seems to be drier than the D09a climatology, particularly in summer (Fig. 5a–d). As for temperatures, the seasonal correlation between simulated and reference precipitation distributions is generally improved in the CR experiment (Fig. 5e–h). However, in the CT experiment, precipitation intensities are still underestimated, particularly in summer and, to a lesser extent, in autumn. The KS and Khi2 tests also provide contrasted diagnostics. For annual precipitation, the Khi2 test is always true whereas the KS test is rejected for 4 massifs of the Central Alps. In addition, for seasonal precipitation, both tests provide negative results, especially in the Northern Alps in winter for the KS test and in most of the massifs in summer for both tests."

"Figures 8, 9, 10, 11, 12 and 13: The markers in these figures are too small and hardly recognizable. Their size should be increased. Furthermore, it is not clear how the standard deviations on which the error bars are based have been computed. Is it the standard deviation of the 30 individual annual climate change signals (individual years in the scenario period with respect to the 30-year mean in the control period?). Please specify this either in the method section or in the figure captions. In Figures 9, 11 and 13 a legend (indicating the meaning of the colors) would be helpful. In Figure 9, the panels have been mixed up in the caption (Northern Alps are for instance shown by panels a and e, not by panels a and b). Also in Figure 10, the caption has to be adjusted (the panels of the right row are missing in the description). The legends in Figure 12 are too small as well, and the rows (B1, A1B, A2 ?) and columns (change 2021-2050, SD 2021-2050, change 2071-2100, SD 2071-2100) need to be labeled for clarification. In all Figure captions "A1" needs to be replaced by "A1B"."

The figures have been modified according to the reviewer's comments.

2. MINOR POINTS

"*Page 171, title: I'd suggest to replace "French alpine massifs" by "French Alps", which is as informative but shorter and better suited for a paper title."*

This has been modified.

"Page 172 line 27 to page 173 line 1: With "local changes in climate" the authors probably mean potential feedbacks of snow cover changes on, for instance, temperature changes. If so, please make this point more clear (e.g. mention the snow-albedo feedback)."

The text has been modified: p. 1, 2nd column, l. 8:
"Snow cover reduction may have important environmental and socio-economic impacts on water resources, winter tourism, ecology and local changes in climate through potential feedbacks on, for instance, surface temperature and snow albedo"

"Page 173 line 3: "Long term climatology" should be replaced by "Long term snow cover climatologies" to make clear which parameter is referred to."

This has been corrected.

"Page 173 line 23: "150-300km" instead of "300-150km"."

This has been corrected.

"Page 174 line 20: "25-50km" instead of "50-25km"."

This has been corrected.

"Page 174 line 21: "van der Linden and Mitchell" instead of "linden and Mitchell"."

This has been corrected.

"page 174 line 24: The study of Haylock et al. is mainly concerned with the setup of a gridded observational dataset for RCM validation and not with RCM experiments themselves. The citation at this place is somewhat misleading."

The citation has been removed.

"page 175 lines 1-10: The objectives of the work should be better clarified and explicitly mentioned".

The text has been modified p.3, col.2 :
In this framework, our objective is to obtain climate scenarios adapted to detailed snow cover modelling, i.e. describing the physical evolution of the snow properties according to massif, altitude and exposure.*

"page 176 line 5: "output of several recent" instead of "output of the recent"."

This has been corrected.

"page 176 lines 5-12: It should be clarified on which domain the RCM ALADIN was run. It's probably not the entire European continent, and probably it's also not the domain shown in Figure 1."

The sentence has been completed p.4, col.2, 2 paragraph
"Here, in the framework of the SCAMPEI project, we use outputs of several recent 30$year ALADIN simulations run at a 12 km resolution over France."

"***page 177, line 9: In case of ALADIN, isn't the method also applied to the scenario periods 2021-2050 and 2071-2100?"***

yes, the sentence has been corrected p. 5, col.2, paragraph 3.

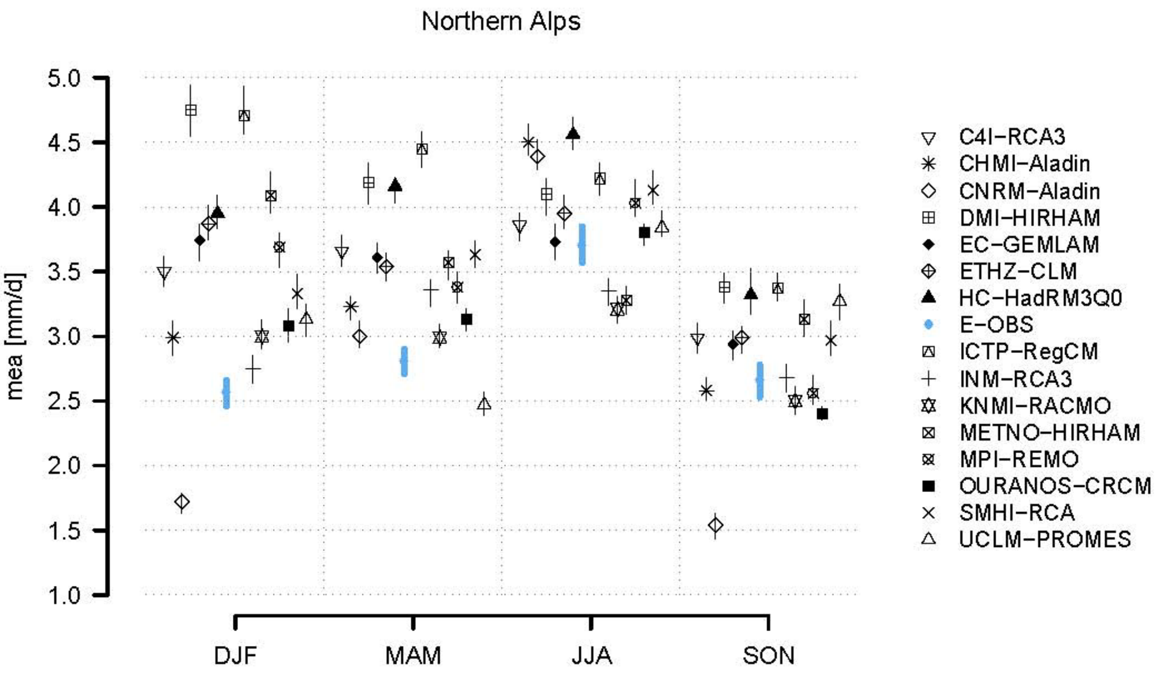
"For each field X, unbiased seasonal anomalies … are computed at each grid point i on the 1961-1990, 2021-2050 and 2071-2100 periods for the ALADIN dataset and on the 1958-2008 period for the extended ERA40 dataset."

"page 178 lines 3-4: This statement is not correct as also time series representing the current control climate (1961-1990) are treated."

The sentence has been modified p. 6, 2nd column, end of 1st paragrapg:
"… the difference being that climate series derived from ALADIN, instead of ERA 40, are treated here. "

“page 181 lines 10-12: In my opinion, the most likely reason is a bias already in the driving ARPEGE experiment (boundary conditions for ALADIN), which penetrates through the RCM. Could the authors comment on this?”

According to existing studies (Figure below) ALADIN seem to have a dry bias, also with ERA40 boundary conditions.



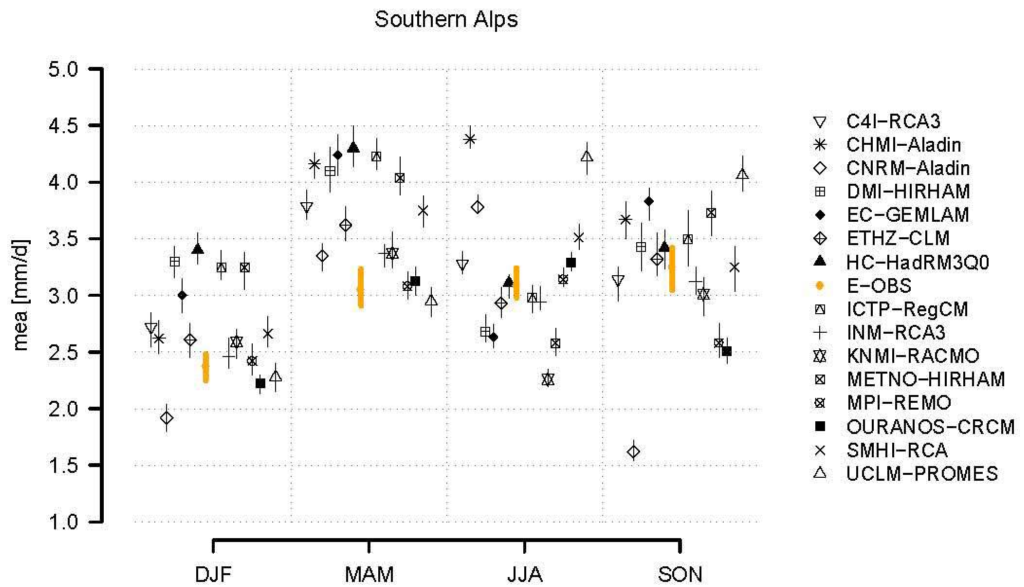


Figure 4R: *Domain mean values (symbols) and 90% bootstrap confidence intervals (vertical lines) of mean precipitation (mea, mm/d)for the Northern Alps (NA, Figure 5.1a) and Southern Alps (SA, Figure 5.1b) subregion. Results are depicted for ENSEMBLES regional climate models (black) and observations (blue (NA), orange (SA)).*

Julian Arnold, Pardeep Pall, Thomas Bosshard, Sven Kotlarski, Christoph Schär, 2009. Detailed study of heavy precipitation events in the Alpine region using ERA40 driven RCMs. Deliverable 5.32: Detailed study of heavy precipitation events in Alpine region using ERA40 driven RCMs, Project ENSEMBLES . GOCE-CT-2003-505539