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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 #2

1. **Overall comments –**

In section 2.2 the descriptions of the models used in the study did not provide sufficient details. A table with a brief description would suffice (ALADIN, ERA40, SAFRAN).
The ALADIN RCM model is described in section 2.1 with historical and scientific details. Concerning the description of ERA40 and Safran, the problem is probably more a formulation problem than a lack of details. The text of section 2.2 has been largely modified and more details about the models have been provided (see modified text of section 2.2 below).

The CROCUS model is introduced and is a major component of the study, but there is minimal description of it in the paper.
The methods used in the statistical downscaling (section 2.2) hard to understand as presented in the methods section. However in the discussion section, the methods were described quite clearly.
More details about the downscaling method and the CROCUS snow model have been introduced in section 2.2 (see modified text of section 2.2 below).

The overall presentation of your work could be greatly improved with better maps and figures. Consistent graph sizes, label sizes and y-axis are much easier to interpret. Similarly the maps really do not represent the quality work that was completed.
Most of the figures have been improved, as suggested by the reviewer. For information, we plan to publish second paper focused on the snow results, presenting in more details maps of snow cover evolution.

More needs to be said about the importance of snowpack to people and ecosystems. Not sure if hydropower is a factor, but if so it should be mentioned.
According to the reviewer's comments, the introduction has been modified as follows p.1, col. 2:

"Mountains are a key component of the global ecosystem and biodiversity, presenting major sources of water, as well as minerals, forests, and agricultural products. They also represent areas of interest for the detection of climate change and the assessment of climate-related impacts (Beniston, 2003). In the Alps, snow is a natural water storage component, an important hydropower factor and a major source of income for the tourist industry. Thus, now 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."

2. **Specific comments –**

Page 173, line 8 -9: "Simultaneously, temperature has largely increased, at a rate often much faster than on the global scale" Provide rough estimates of both rates.
According to this comment, the text has been modified as follows, p. 2 col. 2:

"Simultaneously, temperature has largely increased, up to 2°C since 1900 at high elevations and at a rate often much faster (about 3 times) than on the global scale."

Page 174, line 18: 2km is not very fine resolution. Perhaps it should be changed to higher resolution.
We modified the sentence as follows, p. 3, col. 2, 2nd paragraph:

"RCMs can be run at fine resolution …."

Page 175, First paragraph could be restructured. Put the objective of the paragraph first, not in the middle.
The text has been modified as follows, p. 3, col. 2, paragraph 2:

"In an ongoing project, SCAMPEI (French ANR project, 2009-2011), regional climate models are run at 10 km resolution to specifically study mountain climate and its impacts on the evolution of snow cover and debris flows in France. 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. To this aim, we adopted a combined statistical-dynamical approach, in which some of these simulations were statistically associated with analysis of real observed meteorological situations in the French Alps. For the specific snow application of the study, we also ran a physical snow model."

Page 177, The Mahalanobis distance is an obscure value and warrants a 1-sentence explanation of what it represents.
Section 2.2 has been largely reformulated and now includes more details on the Mahalanobis distance (see modified text of section 2.2 below).

Page 177, This page described a bulk of the methods, but it was not very clear to me. Perhaps an improved version of Fig 2 and text revisions would help.
Section 2.2 has been largely reformulated (see modified text of section 2.2 below), p.4-5.

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

- ALADIN atmospheric fields of air temperature at 2 m above ground (T2m) and 500 hPa 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 ~125 km (1.125°) and ~50 km resolution respectively, were

adapted by D09a with scale appropriate procedures on a grid of ~35 km 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 12 km-ALADIN fields were interpolated 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 at 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 900-3600 m 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.

The statistical distance, or analogue criterion, is built as follows. For each field X, unbiased seasonal anomalies X and seasonal standard deviation s 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. Seasonal means and variances used to statistically center ERA40 variables are steady during the research and correspond to the ALADIN field season. A Mahalanobis distance *d* (Mahalanobis, 1936) is then computed over the whole domain every 6 h following

$$d = \sqrt{\sum_{i=1}^{N} \frac{\left[\widetilde{X}_{\text{ala}}(i) - \widetilde{X}_{\text{era}}(i)\right]^2}{\sigma_{\text{ala}}(i)\sigma_{\text{era}}(i)}}, \qquad (1)$$

where the subscripts ala and era refer to ALADIN and ERA40 fields, respectively, and *N* is the number of grid points. 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 Xera(i).

Daily distances (from 06:00UTC to 06:00UTC the next day) are calculated on the near surface field T2m and the following upper-air fields: Z500, Z500 horizontal gradient (defined by its zonal and meridional components) and Z500 second spatial derivative. The analogue is determined by minimizing the sum of these distances. To account for the different topographies underlying the ALADIN and ERA40 fields, guarantee temporal coherence in the seasonal insolation and thus reproduce the main features of the current climate as well as possible, the analogue fields are corrected a posteriori by a quantile-quantile method (Déqué, 2007; see also Section 3) and appropriate factors.

Finally, these SAFRAN fields are used to force the CROCUS snow model (Brun et al., 1989, 1992), which computes profiles of temperature, density, liquid-water content and crystal types within the snowpack for the same elevations and orientations as those in SAFRAN and for three slopes (flat, 20_ and 40_). These runs thus describe the snowpack evolution on the French alpine massifs (Fig. 1). This approach is similar to that of Durand et al. (2009b) (referred to as D09b hereafter), where a snow climatology is derived for 1958–2002 using D09a SAFRAN data in the forcing of CROCUS, the difference being that climate series derived from ALADIN, instead of ERA 40, are treated here."

Page 179, Excellent approach to include weather patterns!
We thank the reviewer!

Page 180, Were other elevations evaluated? If so which ones? If not why not?
All elevations by step of 300 m were evaluated on the 23 massifs, as suggested by Figures 9, 11 and 13. For the sake of clarity, we chose to present our results either focusing on the elevation of 1800 m a.s.l. or on clusters of massifs (Northern, Central, Southern and Extreme Southern Alps).

Page 181, lines 5 -20: I had a hard time with this paragraph. It was not totally clear to me.
We agree that it is not very clear, probably because the axis of Figure 4 have been mixed up. This has now been corrected. Moreover, the text has been modified as follows:

p.8, beginning of col. 2 :
"Such q-q plots provide synthetic comparisons of statistical distributions in plotting a set of paired samples of same probability. These figures are thus useful to validate the regional and seasonal patterns of the downscaled climatology."

Page 181 and 182, You all discuss mean SWE. Is this for the watershed? What does this represent. It is unclear as no description of CROCUS was given.
The SWE is a good integrator parameter for the snow pack taking into account the thickness, density and liquid water content (LWC) of all the snowpack layers.

Also please define the winter months.
Winter Months are January, February and March as indicated in Figure 6.

Page 183, line 13 -15: The differences in the A1B, B1, and A2 are significant, and merits more discussion both here and in section 4.3.
The characteristics of each scenario A1B, B1 and A2 are presented in section 2.3. At the global scale, the most emissive the scenario (A1B, B1 and A2 in the increasing order of emission concentrations), the largest the temperature increase. We thus modified the sentence p. 11, col. 1, first paragraph as follows:
"In agreement with trends expected at the global scale, the spread of the annual mean temperature change as a function of the emission scenario increases at the end of the century,..."

However, at the global scale, trends in precipitation are not obvious over large regions, and sometimes display large discrepancies between models. For these reasons that we also mention in the paper, we do not wish to further comment on speculative reasons that could explain our results.

Page 184, lines 15 – 16: "despite likely more frequent anticyclonic situations." is awkward and should be rephrased.
This as been rewritten p.12, end of col.1:
"despite anticyclonic situations that are likely to get more frequent in the future."

Page 185, Section 4.4: How much less SWE? A summary table with quantities and values would help.
These information is presented in Figure 12, which has been improved and is now more readable.

Page 186, Section 4.4: No mention of shifts in timing of SWE accumulation or melt.
This is discussed page 188 in the Discussion section .

Page 186, Discussion section, first paragraph: A much better way to explain the downscaling! Move to the methods.
As mentioned above, the method section has been rewritten.

Page 187, lines 10 -15: This is a great point but is in the middle of a paragraph. Move to earlier in a paragraph.
This assumption is common to most of the downscaling studied. We made a new paragraph concerning the limitations of the q-q correction.

Page 189, lines 5 – 8: This concept is important and should be developed in greater detail.
We agree that this is an important concept. We thus discuss it more in details at the end of section 4.4, 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 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. 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."

Figures:

Figure 1: This map is hard to interpret. All I can see are the grid lines. I would suggest making these much lighter. Also if you provide a hillshade underneath the elevation model it will the Alps stand out.
Figure 2: Important conceptual diagram. Perhaps provide spatial and temporal resolutions of data sets.
Figure 3: Keep the scales on the y-axis the same. All the grid lines are distracting.
Figures 4 and 5: These figures are too small and hard to interpret. Make bigger and there will be no need for insets.
Figure 6: You can use one scale bar and it would simplify things immensely. Also a sequential color scheme is cartographically correct (www.colorbrewer.org).
Figure 7: Use the same y-axis and provide the weather type reference table from fig 2.
Figure 8 -11: Much to small to read.
Figure 11 is important, make sure that this is highlighted.
Figure 12: Use a sequential color map with one legend.

Figure 13: The graphs are fine, but the error bars are too small.

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