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Interactive comment on "Projected changes of snow conditions and avalanche activity in a warming climate: a case study in the French Alps over the 2020–2050 and 2070–2100 periods" *by* H. Castebrunet et al.

H. Castebrunet et al.

helene.castebrunet@insa-lyon.fr

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Thanks very much for your interest and comments. Concerning technical corrections, we took them all into account directly in the revised text. We'll just here detail the discussion points. Please find our answers for each of your points :

(a) "[The authors used] an approach based on lot of assumptions and the diversity of the applied methods accumulates to a combined uncertainty which is hard to quantify. Therefore, it is very important to clearly mention that the projections are based on one

GCM-RCM model chain only. In regard to this fact, please also discuss the projections of this model chain compared to other model chain (e.g. ensemble mean and standard deviation).

===> This work has been realized in the frame of a project founded by French ministries, in collaboration between 2 institutes: Météo-France and IRSTEA. One of its goals was to combine both institutes' databases (avalanche counts from IRSTEA, and snow and weather parameters from Météo-France snow and weather models).

Therefore, discussing different snow and weather models merits and demerits, as forecasting tools comparisons is somewhat beyond the scope of the project and the paper. Some existing studies may better respond to your request: for example, Piazza et al. (2014: Projected 21st century snowfall changes over the French, Climatic Change, 122, 583–594, doi: 1007/s10584-013-1017-8) used a very large number of high spatial resolution climate projections over the French Alps based on different downscaling approaches for investigating the robustness of the projected snowfall changes in the French Alps to various sources of uncertainty. Also, Lafaysse et al. (2014, Internal variability and model uncertainty components in future hydrometeorological projections: The Alpine Durance basin, Water Resources Research, 50, doi:10.1002/2013WR014897) quantified uncertainties related to General Circulation Models (GCMs), Statistical Downscaling Models (SDMs) and the internal variability of each GCM/SDM simulation chain, basing on an ensemble of hydrological simulations covering the 1860–2099 period for the Upper Durance River basin (French Alps).

The advantage of the SAFRAN-Crocus MEPRA model chain is to give distributed information for each massif and for different levels of elevations and slopes, which allows describing the spatial and temporal variability of the snowpack at large scale, through the integration of numerous snow and weather observations in SAFRAN assimilation.

We added:

- p. 3 l. 9-11: "More detailed future simulations of the snow cover using climate change scenarios as input have emerged recently (e.g. Lopez Moreno et al. 2009; 2011; Bavay et al. 2009, 2013, Lafaysse et al., 2014, Piazza et al., 2014), allowing better quantification of the projected changes." - p. 3 l. 15-19: "Among these, the main obstacle in many impact studies pertains to the robustness of the downscaling and debiasing of large scale atmospheric variables from global or regional climate models (GCM) to the mountain environment featuring complex topography, and, in particular, a wider altitude range than in the topography resolved in GCMs (Rousselot et al., 2012; Bavay et al., 2011; 2013; Lafaysse et al.; 2014, Steger et al., 2013)." - Some perspectives p. 21 l. 9-21: "From these multiple new scenarios, future work should expand the results obtained here using a single GCM/RCM combination (one realization for each) to a wider range of large and regional scale climate scenarios. This would enlarge our confidence on the future predictions we make given that using few climate scenarios and a single GCM-RCM chain does not allow encompassing the entire range of uncertainty that downscaled climate projections carry (e.g., Lafaysse et al., 2014, Steger et al., 2013). We chose not to carry out this analysis in this paper since we focused on the methodological developments required to assess future changes in snow and avalanche variables and on the outcomes for our region of interest. Furthermore, handling new IPCC AR5 large scale climate scenarios and adapting to the topography of the French Alps represents significant work which has not been carried out yet. Note, however, that Piazza et al. (2014) has already studied the robustness of the projected snowfall changes in the French Alps to a very large number of high spatial resolution climate projections over the French Alps based on different downscaling approaches, but neither with the new SRES scenarios, nor within the SAFRAN representation of topography."

(b) Due to the importance of the uncertainties for the interpretation of the results I suggest to place them more prominently, e.g. in an own sub-chapter.

==> In our point of view, the part concerning uncertainties (p. 21 l. 22 to p.22 l. 2) is in a good place. After discussing snow and weather parameters, this part permits

to introduce the discussion about the avalanche activity indicators. However, in some parts of the papers, you can find references to the discussion part. See for example p. 7 l. 21; p. 9 l. 20. Having this discussion earlier would somewhat break the paper flow.

(c) How is "recent" defined [thickness of surface recent dry snow]? " How many days?

==> We answered in the paper. See p. 5 l. 33 to p. 6 l. 4: "The thickness of the surface recent dry snow is defined as the vertical distance between the snowpack surface and the deepest snow layer characterized by a dendricity greater than 0.25. The threshold expressed in terms of dendricity (Brun et al., 1992) ensures that the considered snow layer still features characteristics of precipitation particles or decomposed fragments (Fierz et al., 2009), and accounts for the impact of snow metamorphism on snow layers in a more consistent way than relying only on snow age, because the rate of transformation of snow properties strongly depends on temperature, temperature gradient and the occurrence of wet snow conditions, which is explicitly considered in Crocus and thus captured in our definition of surface recent dry snow."

(d) p. 590 l. 9-10: How are heavy multi day snowfalls considered, if "relatively long periods" are averaged?

==> Indeed, our approach loses the information related to the succession of short term meteorological situations (e.g. multi day intense snowfall). We clarified and added p. 7 l. 13-21 : "It appeared that the explanation may be that averaging over large areas and relatively long periods smoothes the signal, switching from meteorological and snowpack control at the daily scale to seasonal characteristics of the latter, making it possible to capture the predominant factors for the long-term interannual evolution in a more climatological sense with simple statistical regression models. On the other hand, the approach loses the information related to the succession of short term meteorological situations (e.g. multi day intense snowfall) interacting with a few massifs, except from the perspective of their contribution to the annual/seasonal mean. Hence, the approach is adapted to investigate seasons of high/low avalanche activity over large areas, but not for more localized 1-7 day episodes of highest activity." Also, the last paragraph of the discussion points out now more clearly the necessity of pushing forward in the future the approach on much shorter 1-7 days time scales.

(e) p. 592 l. 21-22 Why are more variables required in the North.

==> It is probably due to the fact that the northern massifs are more heterogeneous than the southern ones. In terms of altitudes, all French massifs have a maximum mean altitude between 2800 and 3800 m. However, contrary to the Southern massifs, three massifs of the Northern Alps (Bauge, Chartreuse and Vercors) cover a thinner range of altitude with a maximum mean altitude under 2500 m., which modify the response to meteorological conditions in terms of avalanche activity.

We detailed p. 8 l. 18-21: "This difference in variable numbers necessary to explain the year to year variability of avalanche activity may be linked to the larger extension of the Northern French Alps which include three massifs characterizing by low altitude (under 2500 m) making the triggering contexts to be considered less homogenous."

(f) p. 592 l. 24-27 Is there explanation why the northern french Alps (for whole year & winter) show the lowest prediction success rate?

==> The explanation may be the same that previously. We added p. 8 l. 15-18: "Again, the slightly lower prediction rates for the Northern French Alps (full year and winter) may be linked to their large extension, and hence, heterogeneity. However, this may also be fortuitous, since the differences between prediction rates between zones/periods are quite small."

(g) p. 594 l.11 : 12 km? This makes how many grid points per massif?

==> As massifs are about 500 km^2, there are 9-10 points per massifs.

(h) p.594 l.23-24: What is the resolution of the DEM used?

==> 12 km. See p. 9 l. 25-29.

(i) p. 600 l.9 "It can only be noted that differences in mean standardized anomalies are always negative, with maximal amplitude of around -15% for the Southern French Alps towards the end-21st century". The negative sign is in contrast to other model chains! See general comment.

==> Please find our explanation p. 14 l. 8-15: "This negative sign may be seen as surprising with regards to the results obtained by many authors with various GCMs/RCMs projections, often showing slightly increasing precipitation in the future. In our opinion, rather than a specificity of our RCM, a possible explanation of our negative sign may be the way we compute differences with regards to the reference period, slightly different to the one generally considered in the literature. Also, the specificity of the 1960-90 reference period in the mountain region we consider (rather cold, see Sect. 4 for discussion) may be an issue, so that other reference period choices may lead slightly different results in terms of relative changes. However, the main thing about our precipitation results is that the changes we highlight are almost always statistically insignificant, so that the null hypothesis of no change should rather be considered in potential practical outlooks of our study."

(j) p.608 l.15-18: Why unexpected? They are influenced by the same weather patterns!

==> We modified and clarified the sentence p.19 l.33 to p.10 l.2: "In first approximation, latitude effects are generally of little importance with regards to interannual variability. Hence, at constant altitude, the Southern French Alps are not significantly more affected than the Northern French Alps in terms of snow depth decrease. This is somewhat unexpected, since it is generally postulated that the stronger solar radiation input received in southern location would make the snowpack more sensitive to warming at a given altitude. Our results suggest that, at the scale of the north-south extension of the French Alps, this does not appear to be true."

(k) p.609 l.23: Are these villages high enough to support the hypothesis ?

==> Yes, that was showed by Lavigne et al. (2013). We clarified p.20 l. 28-30 : "This picture seems in good agreement with the results of Lavigne et al. (2013) suggesting that increased avalanche activity has already taken place around the villages situated in the highest massifs of the French Alps."

(l) p. 611 l.28: How "extreme avalanche cycles" defined in contrast to the "strongest avalanche activity"?

==> Extreme avalanche episodes are defined as clusters of events occurring at short spatio-temporal scales such 1-7 days in one or a couple of massifs. See p. 22 l. 24-25.

(m) Define "short time scale"

==> Between 1 to 7 days. See p. 22 l. 25 and 31.

Interactive comment on The Cryosphere Discuss., 8, 581, 2014.