==

Interactive comment on "How much can we save? Impact of different emission scenarios on future snow cover in the Alps" by Christoph Marty et al.

Anonymous Referee #2

Received and published: 4 December 2016

Recommendation: minor revisions

GENERAL COMMENTS

This paper represents a detailed study of possible future snow pack changes in two mountainous regions in Switzerland. The authors use a very high-resolution (200 m) surface process model (Alpine3D) specifically designed for simulation of snow conditions in complicated mountain topography. They (i) first force this model for the 1999-2012 baseline with an AWS-observation-based analysis of hourly surface weather conditions and (ii) then modify these input data using a height-sensitive Bayesian kriging analysis of RCM-simulated seasonal mean temperature and precipitation changes. By using climate changes derived from RCM simulations for three different emission scenarios and lower and upper estimates of change derived from the variation of the RCM results, they assess the sensitive of their findings to the forcing scenario and climate modelling uncertainty.

The paper fits very well in the scope of the journal. Although there are several earlier studies on future changes in snow conditions in the European Alps and some of them use a similar methodology, this paper adds to the field (i) by providing a more comprehensive uncertainty assessment of the future changes and their sensitivity to the emission scenario, and (ii) by including a range of impact-oriented statistics, tailored to inform (e.g.) the winter tourism industry.

The paper is clearly structured and written in generally good English. However, some parts of the methodology are not very clearly described. Furthermore, the analysis of the changes in interannual variability might not be very informative because the delta change method only takes into account changes in long-term seasonal mean temperature and precipitation. Some of the figures also need improvement, particularly in the supplementary material. On the whole, however, the paper only appears to require relatively small revisions.

COMMENTS ON SCIENCE

1. Beginning of section 2.4. The method in which the climate change scenarios were obtained should be described in some more detail. From the description that is available now, the casual reader gets the impression that the RCM-simulated temperature and precipitation changes were used nearly as such. However, Zubler et al. (2014) reveals that they were based on a rather complicated Bayesian methodology. In particular, the "upper and lower bounds of this dataset" are not the minima and maxima of the 20 RCM simulations, but are based on the Bayesian model of Buser et al. (2009). An important and debatable feature of this Bayesian model is that it in some cases contracts the uncertainty range from that derived directly from the variation of the original RCM simulations (see Figs. 1 and 2 in the supplementary material of Zubler et al. (2014)). Therefore, the uncertainty ranges derived in this paper should also be seen as indicative only.

We thank the reviewer for this valuable comment. We changed to corresponging section accordingly: "The focus of this work is related to the (ensemble) mean median estimate of these 20 different combinations, which were derived by Bayesian methodology. The upper and lower bounds estimates (extremes) of this dataset, which contains the 97.5 %, respectively 2.5 % quantile of the 20 member ensembles are also considered for some analyses calculated for some analysis in order to get information about the range of the uncertainties of the temperature *and precipitation change. Hereof, it is important to know that this Bayesian methodology contracts in some cases the uncertainty range directly derived from the variation of the original RCM simulations. Therefore, the uncertainty range in this paper should also be seen as indicative only. A simple delta change approach was used to compile meteorological time series of future Alpine climate. This means that the time series of the reference period were modified with the provided gridded daily change values of the air temperature (ΔT) and precipitation (ΔP). More information about the calculation of these delta values and about the downscaling and can be found in Zubler et al. (2014)."*

2. The simple delta change method with constant absolute changes in temperature and constant relative changes in precipitation neglects changes in climate variability on both sub-seasonal and inter-annual time scales. However, it is a common feature in climate model simulations that temperature variability in midlatitudes decreases in winter but increases in summer (e.g. Holmes et al. 2016). Such changes in climate variability almost certainly affect the change in interannual variability of snow conditions (Section 3.3). They might also have some effects on the average change in snow conditions, because the phase of precipitation and snowmelt both depend nonlinearly on temperature.

We thank the reviewer for this comment and the corresponding reference. However, we are not convinced that the decrease of winter temperature variability in midlatitudes is a common feature in climate model simulations. Moreover, the evolution of the winter precipitation variability seems to be even less clear. We tried to explain that in few extra sentences and additionally emphasized the we cannot analyze the inter-annual variability as simulated by the RCM's with the applied method: "Since the applied Delta change method with scenario and time period dependent constant changes in temperature and precipitation neglects changes in future climate variability, the shown inter-annual snow variability cannot mirror the simulated inter-annual variability of the RCMs. According to climate model projections there are no clear signs how future temperature and precipitation variability will evolve in winter in midlatitudes (Deser et al., 2012), although a recent study demonstrates a slight decrease of winter temperature variability (Holmes et al., 2016). The analyzed inter-annual variability in this study is therefore first of all determined by the inter-annual variability of the underlying temperature and precipitation conditions in the reference period. For the future scenario periods the shown inter-annual snow variability is additionally influenced by the non-linear dependence of snow on temperature, which changes the variability dependent on the size of the ΔT values."

3. P12L23-24. Is this because the amount of snowfall is more sensitive to temperature when the precipitation is larger?

We don't know, but that could be a possible explanation, since larger precipitation events often happen at relatively warm temperatures.

4. P14L2-3. Is this just common knowledge or can you support the statement with a reference?

At least for "snow" people it is common knowledge, nevertheless we added the following references for those less familiar with this issue:

- *Norrman, J., Eriksson, M., and Lindqvist, S.: Relationships between road slipperiness, traffic accident risk and winter road maintenance activity, Climate Research, 15, 185-193, 2000.*

- *Hess, M., Saska, M., and Schilling, K.: Application of coordinated multi-vehicle formations for snow shoveling on airports, Intelligent Service Robotics, 2, 205, 10.1007/s11370-009-0048-5, 2009.*
- *Schmidlin, T. W.: Impacts of Severe Winter Weather during December 1989 in the Lake Erie Snowbelt, Journal of Climate, 6, 759-767, 10.1175/1520-0442(1993)006<0759:ioswwd>2.0.co;2, 1993.*

COMMENTS ON PRESENTATION

1. P2L28-30. Why are most of the results only shown for the Aare region? This should be mentioned and motivated in the text.

We forgot to mention this in the original manuscript. We therefore included the following sentence at the beginning of the Results chapter: "We often show results for both Alpine regions, but sometimes we focus on the Aare region only since the results are quite similar and its area below 500 m is larger and more homogeneous than the corresponding elevation zone in the Grisons region." Moreover, the results for the Grisons region were also added to Figure 2.

2. P3L1: eastern Atlantic? (western Atlantic = east coast of North America)

We agree and changed the sentence to: "The precipitation amount in this region is mainly controlled by large scale weather patterns coming from the northern Atlantic."

3. P4L19-22. Instead of describing the socioeconomic pathways, please indicate the end-of-century CO_2 concentrations which give a much more tangible idea of the magnitude of climate forcing.

We added the end of century CO_2 concentrations and changed the sentences to: "The A1B scenario is characterized by a rapid economic growth with a mixture of fossil and non-fossil energy sources.The maximum population will peak around 2050 and the CO2 concentration is roughly 720 ppm at end of the century. In the A2 scenario a continuously increasing population and a low economic rate of growth is assumed and the CO2 concentration reaches roughly 860 ppm (Nakicenovic and Swart, 2000)."

4. P6L7-8. "the uncertainty of model set up" should rather be "model fidelity".

corrected

5. P6L15. observed or simulated snow depth above 0.01 m?

The observed snow depth. The sentence reads now: "The RMSE was calculated for each of the 13 years of the reference period for the observed snow depth above 0.01 m (Table S1)."

6. P6L26 and 29. Replace "uncertainty" with (e.g.) "error" or "discrepancy"

corrected

7. P7L21-23. Would it not be simpler to directly compare the interannual variability (characterized e.g. by the coefficient of variation of snow depth or by the relative difference between the maximum and the minimum) in the baseline and future climates?

Yes, that would be another possibility, but this approach would not be able to provide the valuable information how the future inter-annual variability changes due to non-linear dependence of snow on temperature.

8. P8L9. What is the height range covered by the 500 m elevation zone?

The height range is a 100 m band, i.e. between 450 and 550 m for the 500 m elevation zone. We indicated this by changing the sentence to: "At the 500 m (450-550m) elevation zone..."

9. P8L14. "The decrease of the affected years with elevation ... is caused by the lower inter-annual variability" does not make sense. The results show that the overlap between the baseline and future distributions is larger at higher elevations, most likely because the colder baseline climate make snow conditions at higher elevations less sensitive to warming.

We agree and changed the sentence to: "At these higher elevations more winters remain with maximum snow depths higher than the current minimal snow depth. This is caused by the fact that the colder baseline climate makes snow conditions at higher elevations less sensitive to warming."

10. P8L30. Always snow-covered in winter?

We agree and changed the sentence to: "The absolute decrease is largest between 1500 and 2500 m asl, since this elevation band is nowadays always snow covered during the winter months and heavily affected by warmer temperatures."

11. P8L32. winter months

corrected

12. P9L1. the fact that

corrected

13. P9L4. How do you define the beginning and end of the snow season if the first continuous snow melts away or individual days with continuous snow occur after the main snow season?

The beginning and end of the snow season was defined as the longest snow covered period in each season. We there changed the sentence to: "The date of the first continuous snow (snow depth at least 1 cm) and the end of the snow season was calculated based on the longest snow covered period for each of the 13 years for all time periods."

14. P9L6-7. As Figure 7 shows, the time shifts depend on elevation. What elevation do you refer to in this text?

The former text refered to the elevation zone between 1000 and 2000 m. We realized and that the differences within this zone are large. Therefore we refer now to 1500 m and changed the text accordingly: "At 1500 m, for example, the snow season starts on average about 2 (2035) to 5 (2085) weeks later and ends 2 (2035) to 12 (2085) weeks earlier."

15. P9L12 and 13. "months" in plural.

corrected

16. P9L20-22. This complication could have been avoided by using the baseline period glacier mask for all periods.

Yes, you're right, that would have been another possibility.

17. P10L6. Note that the ...

corrected

18. P10L10-11. Please specify the emission scenario to which this result applies.

We added this information, which changed the sentence to: "During the middle of the century and the A2 emission scenario, the same probability can be found at 850 m asl."

19. P11L8. Note that this is ...

corrected

20. P11L14. snow cover or snow water equivalent?

corrected to snow water equivalent

21. P13L8-9. expected snow volume reduction ... in which season?

We added the information and changed the sentence accordingly: "Both regions show a similar clear reduction in the future snow volume (Jan-Mar)…"

22. P13L32. "summer months" in plural.

corrected

23. P14L9. “which might have worse consequences than the same amount of snow today”? While the preparedness will be most likely reduced, it is not obvious why the future preparedness for future’s snow extremes should be worse than today’s prepared- ness for today’s more severe snow extremes.

We see a clear difference in this respect. Today, we can also handle extreme snow amounts, , because we have the tools and some experience from “normal” snow events. In future, we will be much less prepared for snow abundant winters, because we don’t have the experience and infrastructure anymore, since we are used to winters without snow. An analogue of such situations can be seen in the rare cases, when there is abundant snow in such places as the Mediterranean or Florida. Nevertheless, we rephrased the corresponding paragraph: “Due to fact that precipitation towards the end of the century is projected to slightly increase, it is therefore probable, that also in future (then) unusual winters may experience short periods of abundant snow, which might have worse consequences than today since society probably would be less prepared for such rare events”

24. Table 2. Please mention the emission scenario in the caption.

We added the information and changed the caption accordingly: “Number of days with more than 30 cm/50 cm of snow depth at 3000 m asl in the Aare region for the reference period and the three future scenario periods based on the A2 emission scenario.”

25. Figure 2. It would be simple to include the results for the Grisons region by adding a parallel set of bars with a different colour.

We agree and added the results for the Grisons region.

26. Figure 3. The headings “Aare” and “Grisons” could be inserted above the figure panels for easier reference.

Is not necessary since the figure has been redesigned anyway and the two regions have been included in the legend.

27. Figure 4. How wide are the elevation zones in terms of their height ranges?

We added the following sentence to figure caption: “The elevation zones are 100 m wide, i.e. the 1500 m zone, contains all pixels between 1450 and 1550 m.”

28. Figure 4. The dashed lines are too faint.

corrected

29. Figure 6. Please specify the emission scenario in the caption and increase the size of the labels.

The size of the labels has been increased and the caption reads now: "Total volume of snow (Jan-Mar) in the Aare region for the today (solid line) and the end of the century (dotted line) based on the A2 emission scenario."

30. Figure 8. Please increase the size of the figure panels and the size of their labels, and reduce the unnecessary empty space between them. It would also be helpful to describe the interpretation of the box plots in the caption.

Corrected and the following description of the box plots has been added to the figure caption: "The little square in the box plots represents the mean value and the whiskers show the 2.5 % and 97.5 % quantile value of the different model simulations."

31. Caption of Table S1. The values suggest that this is not a "relative error" (which would be expected to be large at stations with little snow" but rather the absolute root mean square error. In addition, please spell out the station acronyms.

Yes, you're absolutely right. We therefore changed the table caption accordingly and also replaced the stations acronyms with their names.

32. Figure S1. Please use colours and increase the size of the headings and the labels. Also, as this figure is in the supplementary material, there is no need to squeeze the three panels on the same row.

corrected

33. Figure S2. This figure is difficult to understand. If the purpose is to illustrate the change in interannual variability, scatter plots with the yearly values of the baseline snow depth on the X axis and the corresponding future yearly values of snow depth on the Y axis would be more informative. Besides, the figure is too small.

We produced a scatter plot figure as suggested, but we cannot see the scientific gain of such an approach. The original figure has therefore been enlarged but we agree is still not easy to understand. However, we believe the figure provides a good approach to demonstrate how the distribution of snow abundant and snow scare winters changes dependent on the time and emission scenario due to non-linear dependence of snow on temperature.

34. Figure S4. Better in colour and with larger X and Y labels

corrected

35. Figure S6. The lines are far too faint and the labels (as well as the figure panels) far too small. Use colours for a better separation of the lines.

corrected