

Answer to Reviewer #1:

As interactive comment on: „A satellite-based snow cover climatology (1985–2011) for the European Alps derived from AVHRR data“

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by F. Hüsler et al.

We would like to thank the first reviewer, Juraj Parajka, for the constructive comments, which helped to substantially improve the manuscript. Below we will address each concern in a point-by-point answer:

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→ **Bold: Comment of the reviewer**

→ Regular: Answer of the authors

→ *Italics: Changes to the initial manuscript*

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1) to extend the validation of gap-filling method. Presenting just comparison for short January-April period is rather short and does not allow to infer robust interpretations. I would expect that forward and backward variants might have some distinct features/ differences in the spatial and temporal (i.e. snow onset/melt and snow poor/rich periods) distribution. I understand that the gridded snow dataset is available only for the Switzerland, but analyzing longer records and maybe splitting the Switzerland into two climate regions (i.e.NW,SW) would allow to draw more general conclusions about the seasonal performance of the filtering method.

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Thank you for raising this concern. Indeed, a proper validation is a prerequisite for all derived results. The validation with the gridded data set was only carried out until the month of April as its compilation is limited to this time frame (originally developed for avalanche prediction). However – and also the other reviewers commented on this - we extended the validation of the gap-filling product to assess the seasonal performance and validate longer time periods as suggested by the reviewer. For this we used the comparatively dense ground-station network in Switzerland and the available ECA&D snow measuring stations within the Alpine Region as a reference. The description of the data, method, and the results were included in the manuscript. In more detail, the following paragraphs and figures were added/changed in the manuscript:

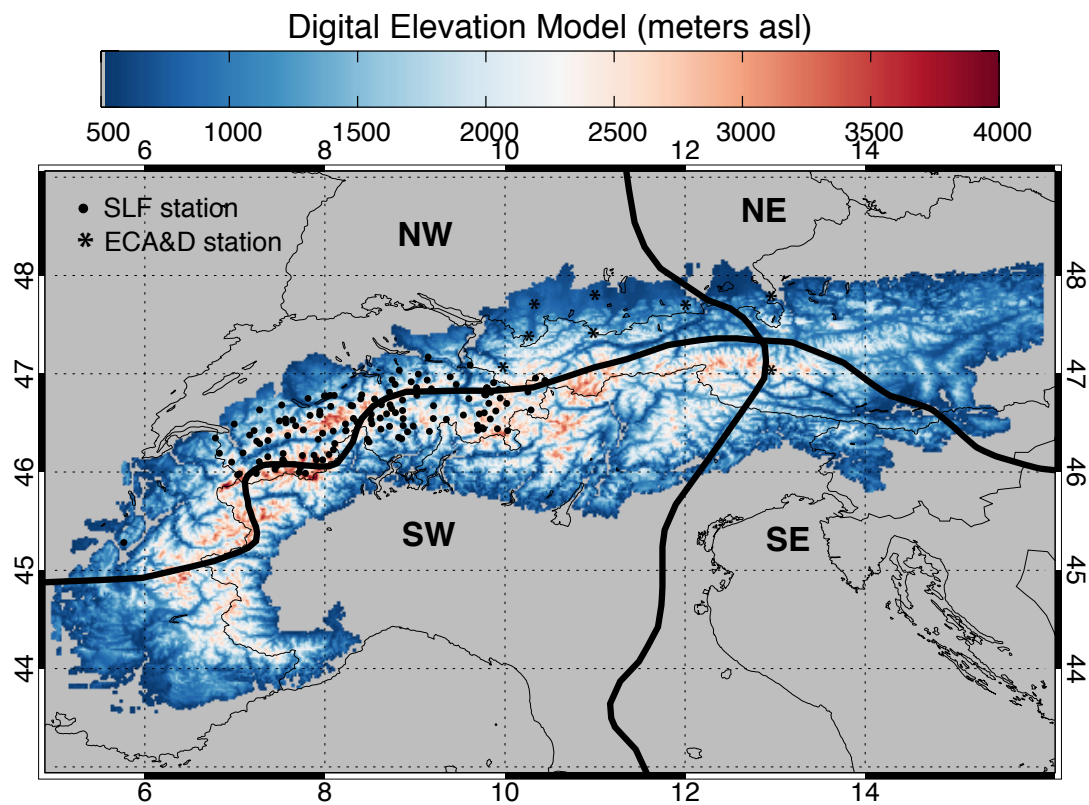
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Station locations were included in Figure 1:



5 *Figure 1: Digital elevation model of the Alpine region. Black dots (SLF station) and stars (ECA&D station) represent station locations used for the validation of the product. Bold lines indicate the subdivision into the four subregions (north-west, north-east, south-east and south-west) according to Auer et al. (2007). Data for the extra-alpine areas is not displayed.*

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A description of the dataset was added to the data section:

3.2 Gridded station dataset and snow-depth measurements

15 (...)

In addition, in situ snow depth information from 48 automatic stations over the time period 2003 - 2010 were used to validate the gap-filling procedure to include longer time periods, to assess the seasonal performance, and to ensure that the gap-filling does not significantly lower the initial accuracy. The stations are distributed all over Switzerland covering different elevation ranges and the data are provided by the WSL Institute for Snow and Avalanche Research (SLF). Snow-depth data is recorded automatically and available daily. To expand the validation beyond Switzerland, the 8 European Climate Assessment&Data stations (Klok 2005) lying within the Alpine Region (mainly Germany and Austria) were additionally included in the reference data set. The locations of all stations are illustrated in Fig. 1 and they are positioned at elevations between 480 and 3100 meters asl.

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A new section was added to the Methods section:

4.2 Snow gap-filling accuracy assessment

5 *To assess the accuracy and consistency of the gap-filled product, two types of reference data sets were used: gridded snow-depth data and in-situ snow-depth data.*

(...)

10 *For the point-wise validation the automated snow stations were considered as ground truth and were compared to the pixel closest to each station. As for the SLF stations, the snow depth is measured from above with an ultrasonic snow depth sensor (Lehning 1999). During the snow-free season, the same sensor measures vegetation height, which requested a pre-processing of the station data. For this purpose, a robust automated correction algorithm was implemented to find the first and the last occurrence of a location specific minimum value to determine the snow melt-out and onset timing. Values in between were set to zero as these are assumed to correspond to vegetation height rather than to snow depth. Quality checking indicated a good performance of the correction although short-term snow events after complete melt-out and before permanent snow onset might not be represented in the reference data.*

20 *Methodologically, the validation was carried out by means of investigating the accuracy index (ACC), defined as the sum of correctly classified pixels divided by the total number of compared (i.e. cloudfree) pixels. As above, the station was classified to be snow covered when the measured snow-depth was equal or higher to 5 cm.*

25 *Furthermore, the missclassified pixels were evaluated in terms of snow over- (SO) and underestimation (SU), both relating the sum of incorrectly classified pixels to the total number of compared (i.e. cloudfree) pixels as suggested by Parajka et al. (2010). For this type of validation it must be kept in mind, that, in mountainous regions, steep elevation gradients are common and one single AVHRR pixel may include both valleys and mountain peaks with elevation differences up to 1200 m at alpine sites. As a consequence, differences may be observed when a grid cell value is compared to an in-situ point observation in complex terrain.*

35 *The results section (“Gap-filled product”) was expanded with the results from the station validation:*

40 *The results of the station validation to assess the seasonal and filtered accuracy of the snow product are shown in Fig. 4 and consist of three boxplots. The topmost plot (a) illustrates the ACC for the four products (unfiltered, spatially filtered, forward and backward filtered) for all months while (b) and (c) show the SU and SO errors, respectively. The mean annual accuracy for the whole year ranges from 90% (for unfiltered and spatially filtered) up to 91% (for the temporally filtered products). As expected, the ACC is high for the full snow season (Dec–Mar) and the summer season with values constantly over 90%, whereas it decreases to 82%–89% in the transition season. The mixed pixels including patchy snow cover, different land cover types such as forest, combined with strong elevation differences are suggested to be the reason for this. Also the IQR increases for the transition season, however the general pattern*

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is quite consistent throughout all the years expressed in the comparatively small IQR values. Except for the month of June and October, the temporally filtered product does not decrease in ACC through the filtering process. On the contrary, it even slightly increases the performance of the snow mapping. This is assumed to be caused by the reduction of miss-classified cloudy as snowy pixels (or vice versa). Concerning the errors, they show constantly very low values close to 0%. The reduction of ACC in the transition season is attributed to a slight underestimation of the snow cover in spring (SU error of 6% (May) and 7.5% (June) for the unfiltered product). As stated above, this is most probably caused by mixed pixels (i.e. snow lying under trees or snow patches and therefore not being detectable by means of remote sensing). The temporally filtered products show a comparatively higher SU error (up to 12%–15% in June). As daily values are compared, this kind of validation is particularly sensitive to the uncertainty of ± 10 days inherent in the composite product. During the snow onset season (Oct, Nov), however, there is a tendency towards snow overestimation by the temporally filtered products. This is more pronounced for the backward filtered product (SO error of 11%) and is probably explained by the filling of pixels with clear-sky information from a couple of days (maximum 10) ahead of the actual day. Especially at lower elevations, the snow-onset process is characterized by several snow-onset events interrupted by melting events. Likewise, it needs to be considered that the correction of the station data described in Section 4.2 also leads to some uncertainties in the snow melt-out and onset timing as derived from the station. Particularly short-term spring or summer snowfall events after complete melt-out and minor snowfall events before permanent snow onset are not represented in the station measurements.

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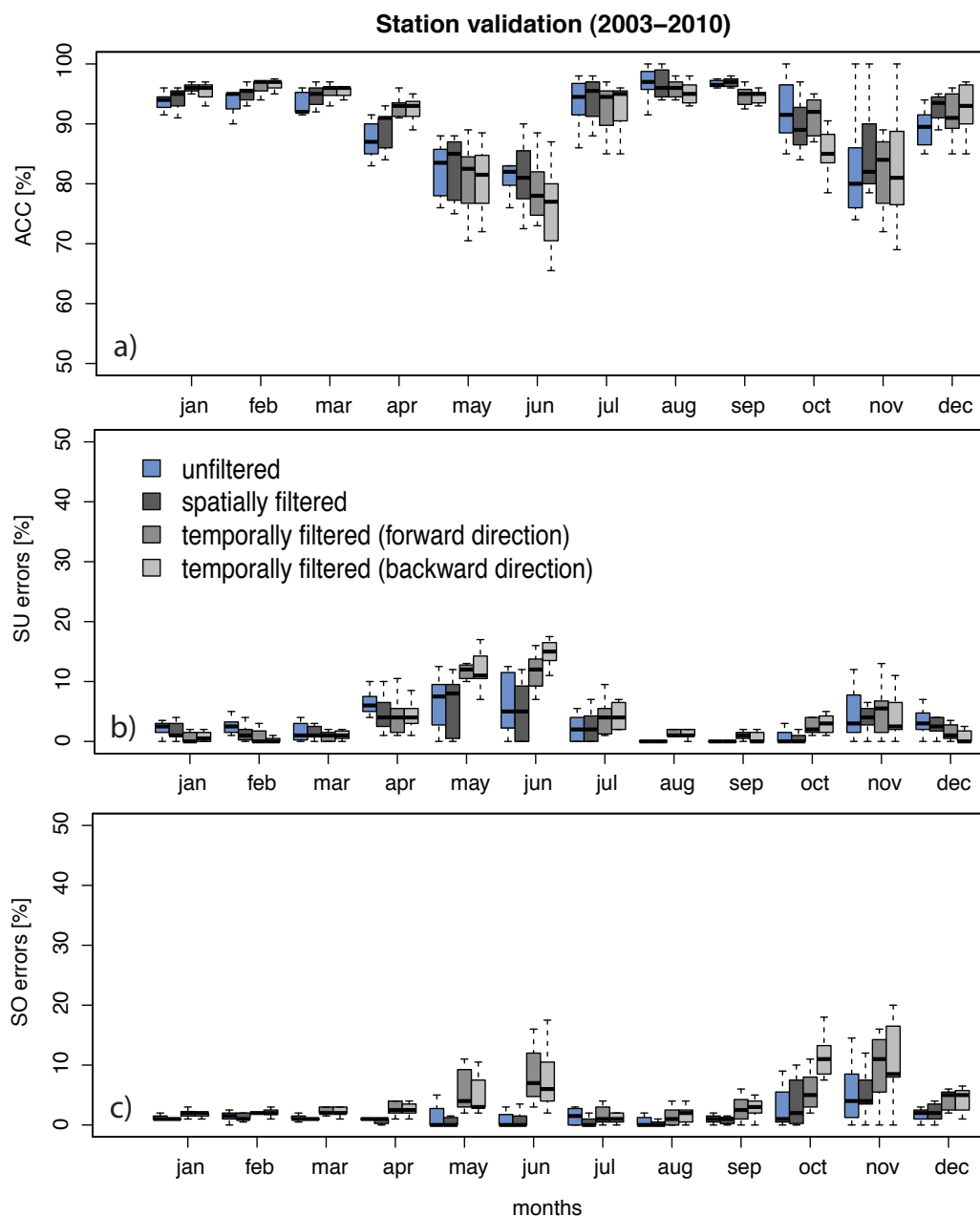
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A new figure (Fig. 4) was added to the “Gap-filled product”-Section in the results:



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Figure 4: Monthly median and Inter Quartile Range (IQR) of (a) ACC, (b) SU error, and (c) SO error as from station validation for the period 2003-2010. Different colors refer to different types of filtering procedures (see legend).

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2) to consider adding some quantitative assessment of some results (e.g. correlation between altitude and some snow cover characteristics in different regions) and attribution of trends found. What are the main controls affecting shorter snow cover duration in some regions in recent years? Is it increased air temperature (in winter, spring), less precipitation or more rain-on-snow events?

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In order to consider some quantitative assessment, we added Figure 5 to the manuscript showing the SCD as a function of altitude for the Alps and the four different climatic regions. In addition, we included a new paragraph describing and discussing the graph and related regional differences.

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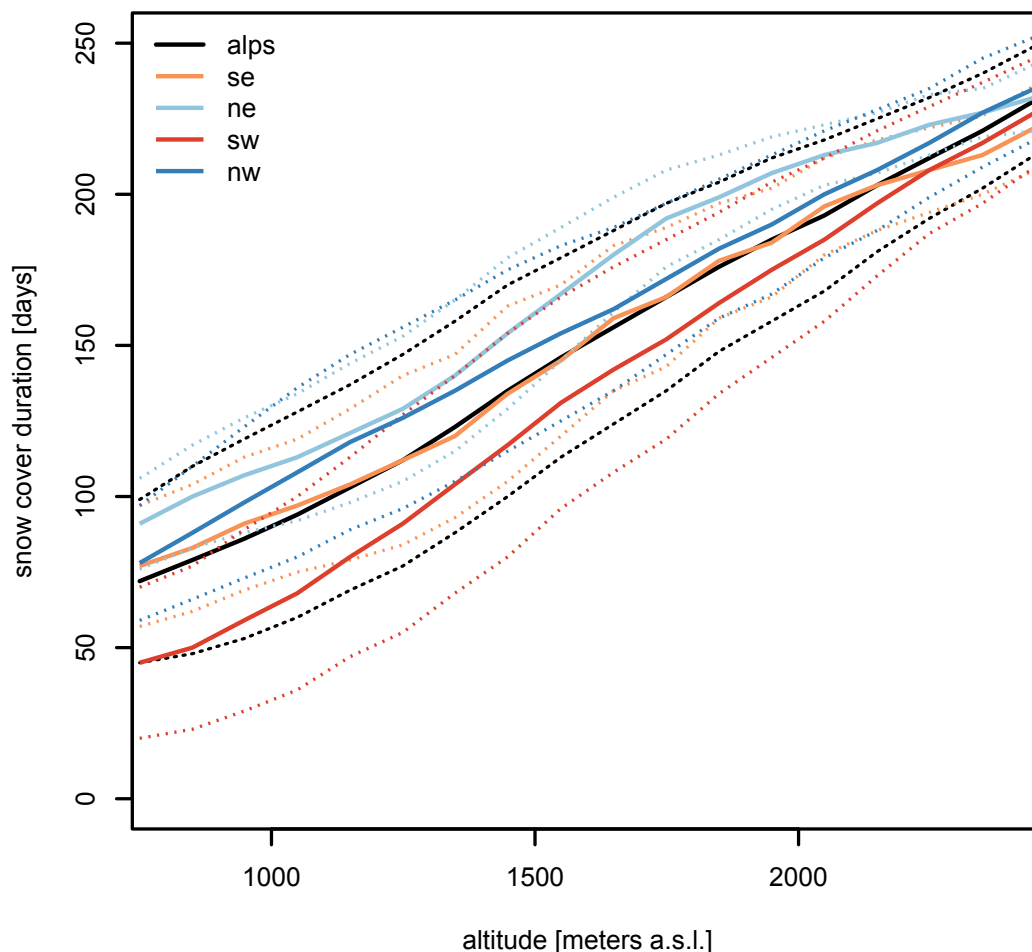


Figure 5: SCD as a function of altitude for the Alps and the four regions separately. Bold lines represent the altitude mean SCD while the dotted lines indicate the standard deviation. The analysis was done at steps of 100m.

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The new paragraph reads: "Figure 5 displays the SCD as a function of altitude and was calculated from all the pixel information available per 100m altitude in the respective region. As expected, a clear positive relation between altitude and SCD is found with an increase of approx. 10 days per 100 meters asl with a standard deviation of 25 days. This relation, however, seems to depend on the climatic region. While in the southern regions exhibit constantly lower SCD at elevations up to 2200, the northern regions show above-average SCD at the same altitudes. It is also remarkable that the regional differences are more pronounced at lower elevations and tend to disappear towards the high elevations. The same behavior is also found

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in the standard deviations. This may imply a higher sensitivity of SCD on temperature at lower regions and a stronger dependency of SCD on precipitation at the higher elevations."

5 We agree with the reviewer that it would be very interesting to attribute the trends to changes in climatic parameters or increased rain-on-snow events. However, particularly in such a pronounced topography with many regional peculiarities and high interannual variability of precipitation amounts such an attribution is a very complex issue (Durand et al. 2009; Marty 2008; Scherrer 2004; Schöner et al. 2009).
10 Due to the effect of potentially large variations in total precipitation (itself depending on location and altitude) the exact impact of changing temperatures is very difficult to separate and to quantify (Hantel et al. 2012).

15 From an optical remote sensing perspective only the snow extent can be estimated, not the snow depth. Even though a prolonged SCD might be a proxy for increased snow depth, high spring temperatures may also cause the SCD to be shorter because of faster melt out. Hence, a quantitative analysis on SCD is limited and can only be used as an estimator for snow depth combined with information on precipitation amount and temperature profiles.

20 Unlike glaciers, the snow cover extent is very sensitive to interannual fluctuations caused by both, more/less solid precipitation (i.e. depending on availability of humidity in the atmosphere and winter air temperature) or variations in spring temperature causing faster snow melting (i.e. Jacobi et al. 2012, Cohen 2012).
25 Furthermore, also light-absorbing impurities on snow can cause an earlier melt out by increased radiative forcing (Painter et al. 2012). Therefore, we think that this complex subject would be beyond the scope of this study, which is dedicated to data preparation and trend detection, rather than thorough analysis of the responsible mechanisms behind. Another scientific paper to properly attribute the trends will
30 follow.

Specific comments

1) Abstract (last paragraph): It is too general. Please consider to delete or to be more specific.

35 We changed the last paragraph of the abstract to be more specific. It now reads:
"Overall, this study recommends the complementary use of remote sensing data for long-term snow applications. Such data can provide spatially and temporally homogeneous snow information for comprehensive use in related research fields (i.e. hydrologic and economic applications) or can serve as a reference for climate
40 models."

2) Section 3.1 (p.3008, l.27): "the best results". Please consider to be more specific, why 10 days filter performs the best. In terms of what?

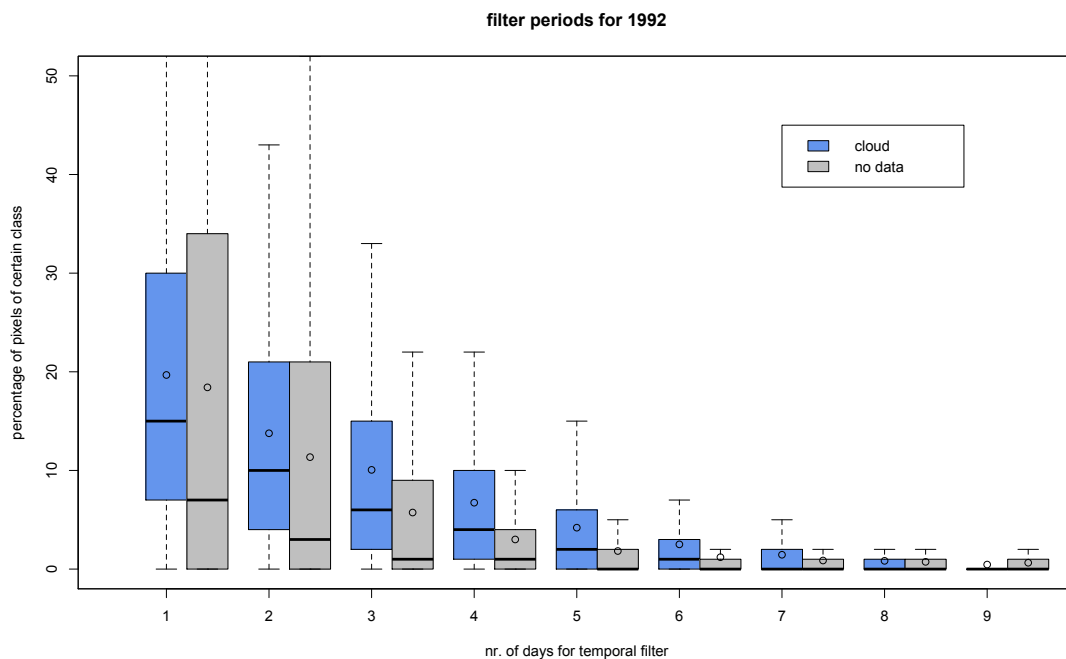
45 The following figures exemplarily illustrate the reduction of cloud and no-data values depending on the number of days used for the filtering (backward in this case) for

the year 1992 (representative for earlier years with limited data availability) and 2010 (representative for later years with high data availability). With each additional day, the amount of clouds and nodata is remarkably reduced, reaching almost zero after 9 filtering days (=10 day filter period). Especially for the earlier years, when less data is available (i.e. 1992), a period of minimum 10 days is required to get a cloudfree image and reach complete coverage. It needs to be kept in mind, however, that the closest clear-sky observation is used for the composite, which means that 10 days is the maximum amount of days to search for clear-sky observations and only applies to a small amount of pixels.

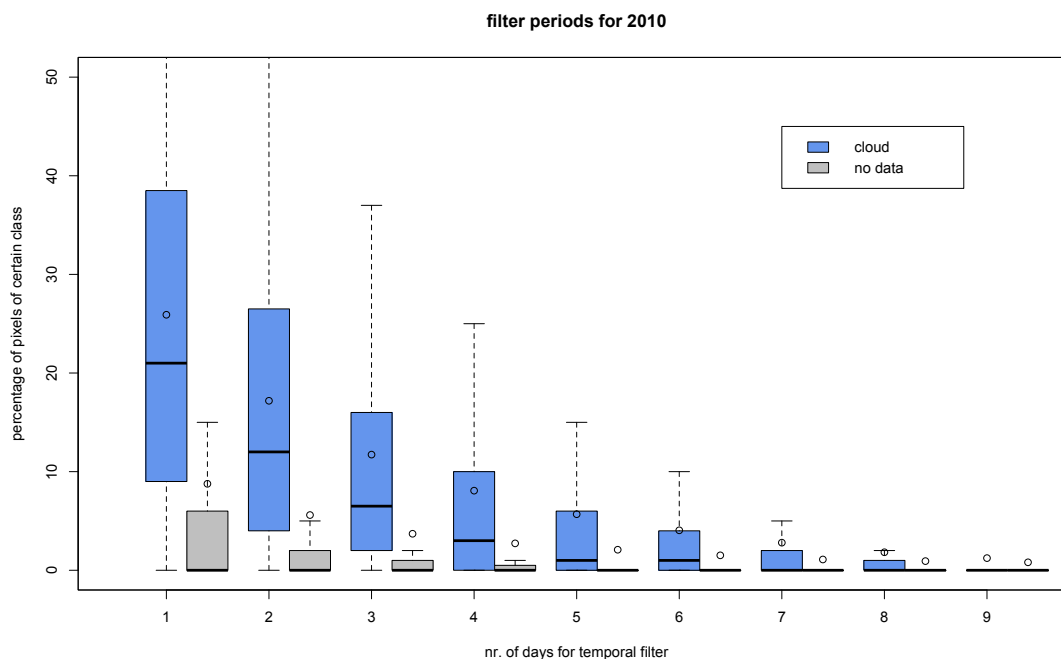
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To make it more clear in the manuscript we adapted the paragraph (in Section 4.1.) which now reads: *“Generally, the time period for filtering needs to be as short as possible but long enough to get cloudfree composites, especially during winter when cloud cover is frequent. Hence, it is a trade-off between remaining clouds and the “blurring” of snow information. Analyses of the amount of cloud and nodata value reduction showed that a minimum of 10 days is required to render cloudfree images. Even though this period might be slightly shorter for later years with abundant data, the number of days for the filtering is determined by the results for earlier years with limited data availability. It needs to be kept in mind, however, that always the closest clear-sky observation is used for the composite, which means that 10 days is the maximum amount of days to search for clear-sky observations and only applies to a small amount of pixels.”*

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5 **3) Section 3.2: It is not clear how is the X (Eq.1) derived? Please be also more specific how the SCA is estimated. Is it a ratio of snow covered pixels to all pixels or to the sum of land and snow pixels?**

Concerning X: For better explanation we added “*X is the single monthly mean value, calculated as the mean of all daily values available for a specific month.*”

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Concerning SCA: We slightly changed and expanded the sentences to be more specific on the SCA description. It now reads “*It is defined as the percentage area of a certain reference area (i.e., the Alpine region) covered by snow. More specific, it represents the ratio of snow covered pixels to all pixels at a specific point in time.*”

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4) Methodology: Please consider to add a section describing how is the AVHRR compared to snow gridded climatology.

Thank you for pointing out this shortcoming. In response, we added a full new section (Section 4.2: Snow gap-filling accuracy assessment) to describe the validation procedure of the gap-filled product, where also the station validation is included. The new section called “Snow gap-filling accuracy assessment” reads as follows (only gridded dataset paragraph):

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25 *To assess the accuracy and consistency of the gap-filled product, two types of reference data sets were used: gridded snow-depth data and point snow-depth data. For the comparison of the gridded dataset to the satellite gap-filled product, the SCA over Switzerland was calculated for both products for each day as described in Section 4.3. Different thresholds are suggested in literature to infer snow coverage from measured snow depth, which is assumed to approximately represent a 50% fractional snow cover in complex alpine terrain at 1 km resolution. These commonly*

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range from 1 cm (Parajka and Bloeschl, 2006; Foppa and Seiz, 2012) over 4 cm (Wang et al., 2009) to 5 cm (Romanov et al., 2002). Here, a threshold of 5 cm was used to calculate snow cover percentage to avoid shallow snow depth or patchy snow cover not detectable by satellite. Slopes steeper than 20° were excluded from the analyses as they are not considered being well represented in the two data sets. (...) “

5) Section 4.3: It is not clear how is the monthly statistics derived.

The monthly statistics in Section 4.3 is derived as the median SCA of all daily values for a respective month over the whole timeseries record (1985 – 2011). For clarity, we added a sentence to the section explaining this.

6) Figure 1: Please add the Swiss border to the map.

The borders of Switzerland are already displayed in Figure 1 – so we left it as it is. Furthermore the station locations were added to the figure (see Figure 1 in answer to the reviewers comment 1) in this document).

References:

Cohen, J. L., Furtado, J. C., Barlow, M. A., Alexeev, V. A. and Cherry, J. E.: Arctic warming, increasing snow cover and widespread boreal winter cooling, *Environ. Res. Lett.* 7 014007, doi:10.1088/1748-9326/7/1/014007, 2012.

Durand, Y., et al.: Reanalysis of 47 years of climate in the French Alps (1958-2005): Climatology and trends for snow cover, *J. Appl. Meteorol. Climatol.* 48 (12), 2487-2512, doi:10.1175/2009JAMC1810.1, 2009.

Hantel, M., Maurer, C. and Mayer, D.: The snowline climate of the Alps 1961-2010, *Theoretical and Applied Climatology*, 110 (4), 517-537, doi: 10.1007/s00704-012-0688-9, 2012.

Jacobi, H.-W.: Snow: a reliable indicator for global warming in the future?, *Environ. Res. Lett.* 7 011004, doi:10.1088/1748-9326/7/1/011004, 2012.

Klok, E.J. and Klein Tank A.M.G.: Updated and extended European dataset of daily climate observations. *Int. J. Climatol.*, 29, 1182, doi:10.1002/joc.1779, 2009.

Lehning, M., Bartelt, P., Brown, B., Russi, T., Stöckli, U. and Zimmerli, M.: SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations. *Cold Regions Science and Technology*, 30:145-157, 1999.

Marty, C.: Regime shift of snow days in Switzerland, *Geophys. Res. Lett.*, 35 , L12501, doi:10.1029/2008GL033998, 2008.

Painter, T. H., Bryant, A. C., Skiles S. M.: Radiative forcing by light absorbing impurities in snow from MODIS surface reflectance data, *Geophys. Res. Lett.*, 39, L17502, doi: 10.1029/2012GL052457, 2012.

5 Parajka, J., Pepe, M., Rampini, A., Rossi, S., and Blöschl, G.: A regional snow-line method for estimating snow cover from MODIS during cloud cover, *Journal of Hydrology*, 381, 203–212, doi:10.1016/j.jhydrol.2009.11.042, 2010.

10 Scherrer, S. C., Appenzeller, C. and Laternser M.: Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability, *Geophys. Res. Lett.* , 31 , L13215, doi:10.1029/2004GL020255, 2004.

15 Schöner, W. et al.: Long term trend of snow depth at Sonnblick (Austrian Alps) and its relation to climate change, *Hydrol. Processes* , 23 (7), 1052 – 1063, doi:10.1002/hyp.7209, 2009.