Answer to Reviewer #3:

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

by F. Hüsler et al.

We would like to thank Reviewer #3 for his thoughtful comments, which are much appreciated and led to valuable changes in the manuscript. We reply to these comments below, point by point:

→ **Bold: Comment of the reviewer**
→ Regular: Answer of the authors
→ *Italics: Changes to the initial manuscript*

Specific Comments:
1. It would be interesting to get an overview about the different NOAA-satellites and according AVHRR generations (1/2/3) that were processed and analysed during the study. Figure 2 could be improved by including such information. Since AVHRR/1 only comes with four channels, detection of cirrus clouds is often a problem for these observations. Even though you state an overall accuracy of 90% for your snow cover classification I doubt that this quality is possible for AVHRR/1 data.

Thank you for this important comment. Indeed AVHRR/1 only comes with four channels making the detection of thin cirrus clouds very difficult. This, in turn, has a large influence on the snow detection accuracy. The record at hand, however, does only include data derived from 5-channel instruments AVHRR/2 and AVHRR/3. The 90% accuracy mentioned refers to these two instruments only. The performance of the algorithm using AVHRR/1 has never been assessed. To clarify this, we added a sentence to the "Data" section explaining the instrument configurations involved in the record. For further details on the instruments, their lifetimes and representation in the University of Bern archive, we refer to Hüsler et al. 2011.

The following sentence was added:
"In this study, the used data is restricted to the five-channel instruments AVHRR/2 and AVHRR/3 to ease the discrimination of thin cirrus clouds. (…) Included platforms are NOAA-09, 11, and 14 equipped with AVHRR/2 and NOAA-16, 17, 18, and 19 carrying an AVHRR/3 instrument onboard."

2. Cloud removal: As already stated in an earlier comment, in –depth validation using station data also outside of Switzerland would contribute to the quality of the manuscript. The problem is that especially in the mountainous regions of the Alps, only very few stations may exist for the observation period (you may check ECA&D data for that purpose). However: I suggest that if no real in situ data is available, you may try to simulate "artificial clouds" by recoding cloud-free pixels within your

snow maps. After processing these scenes with your temporal gap-filling technique you may estimate the accuracy of this technique more precisely.

We totally agree with the reviewer and thank for the ideas and inputs on the product validation. In response to this comment, we extended the validation of the gap-filling product to assess the seasonal performance and validate longer time periods. We used the comparatively dense ground-station network which is available for Switzerland and complemented with the ECA&D snow measuring stations within the Alpine Region as a reference. The description of the method and the results were included in the validation section in the manuscript.
More specific, the following paragraphs and figures were added to the manuscript:

Station locations were included in Figure 1:

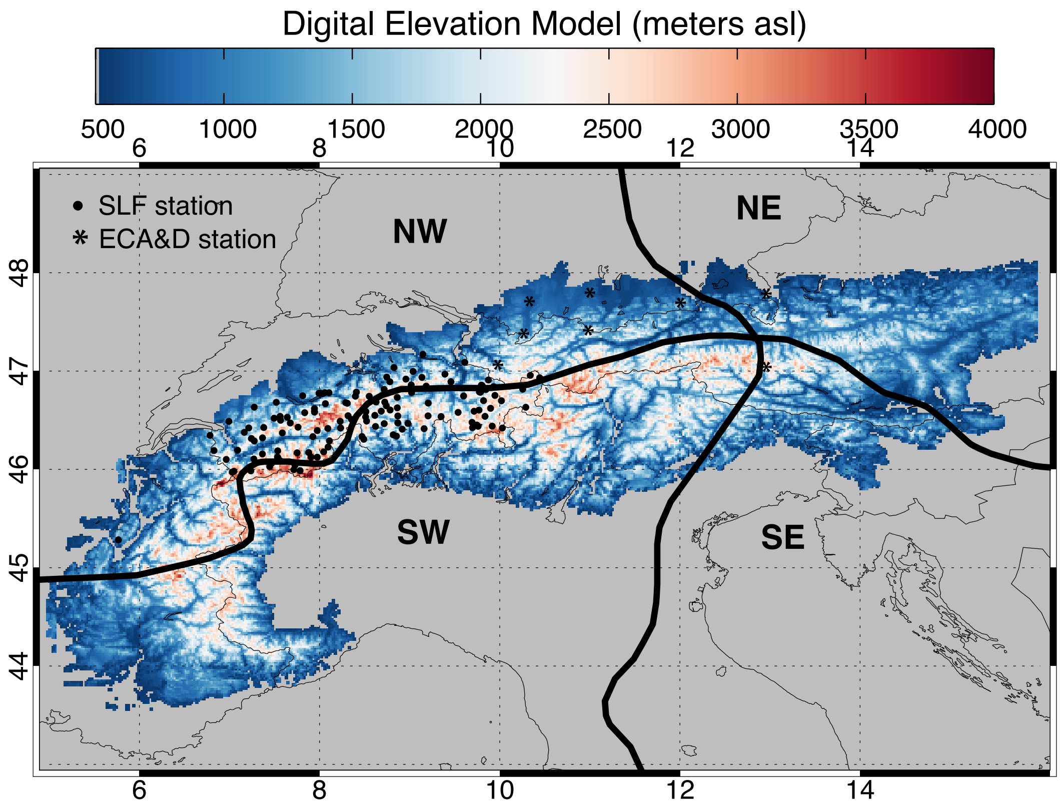


Figure 1: Digital elevation model of the Alpine region. Black dots (SLF station) and stars (ECA&D station) represent station locations used for the validation of the product. Bold lines indicate the subdivision into the four subregions (north-west, north-east, south-east and south-west) according to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

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

3.2 Gridded station dataset and snow-depth measurements

(…)
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.

A new section was added to the Methods section:

4.2 Snow gap-filling accuracy assessment

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.
(…)
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.
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. 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.

Results section (Gap-filled product) was expanded with the results from the station validation:

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 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 partic- ularly 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.

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

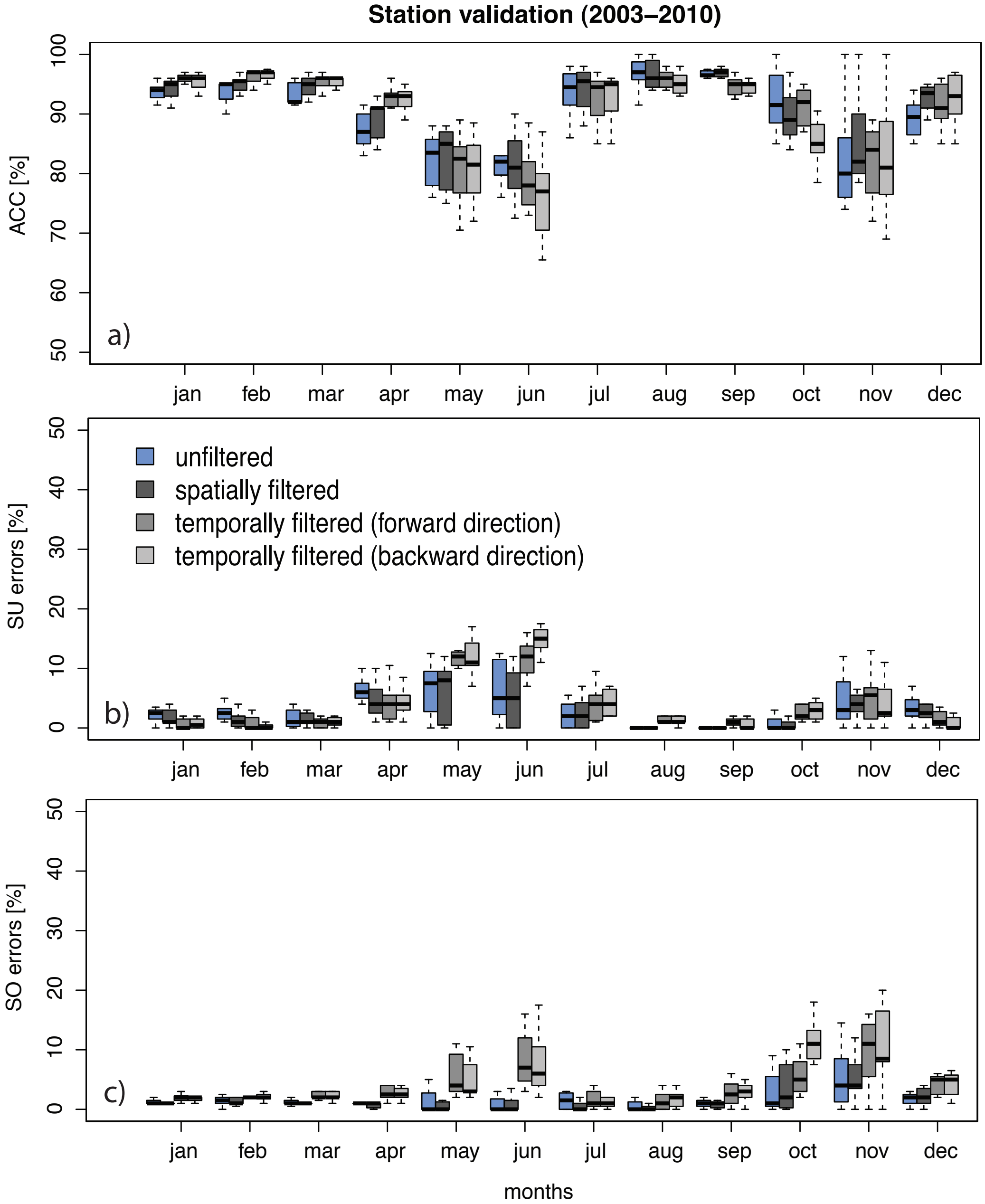


Figure 4: Monthly median and Inter Quartile Range (IQR) of (a) ACC, (b) SU error, and (c) SO error as from station validation for the period 2003-2010. Different colors refer to different types of filtering procedures (see legend).

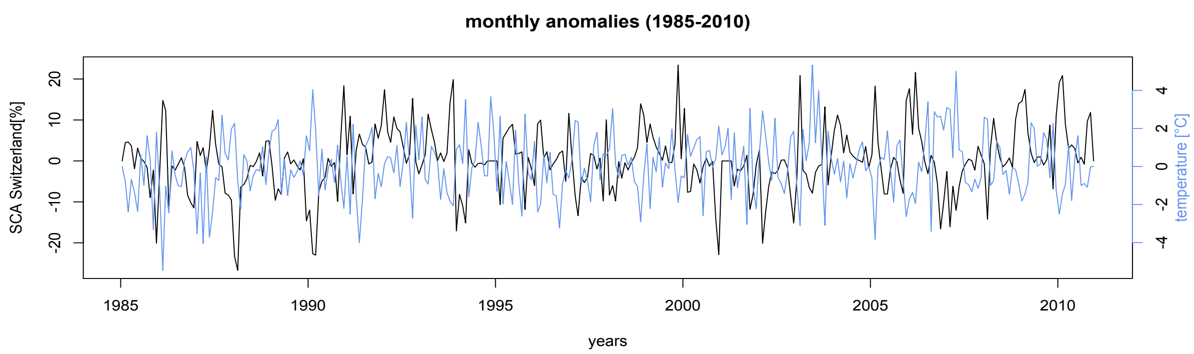
3. In the general discussion section it is stated that 1km spatial resolution is a minimum requirement for complex terrain snow cover products. However, within the GCOS “Systematic Observation Requirements For Satellite-Based Data Products for Climate” (2011 update) 100 m is given as target requirement. Therefore, this sentence should be modified/removed from the manuscript.

Thank you very much for this important comment. We removed the “minimum requirement” – statement from the text.

4. Figures like Fig. 7, or 9 to 11 would benefit from adding additional information like annual departures from mean temperature (Fig. 7) or standard deviation of surface temperature (Fig. 11). As temperature is the dominant factor in prolonging or shortening of snow cover duration, such information would add to the overall quality of the manuscript and help to understand the mechanisms and dynamics of climate change in Alpine environments. However, it is clear that such data may not be available for the whole area and in sufficient quality for the complete time series.

We agree with the reviewer that the investigation of such additional information (like temperature) would be very interesting. However, as also stated by the reviewer himself, such data is - to our knowledge - not available in sufficient quality/resolution comprehensively for the complete record. Furthermore, to properly attribute the snow variations found, also precipitation needs to be taken into account since the snow 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). It is therefore considered a highly complex issue to understand the mechanisms and dynamics of climate change in the Alpine environments and its influence on snow cover extent. Hence, we think that this subject would be beyond the scope of this study, which is dedicated to data preparation and trend detection, rather than attribution. Efforts are ongoing to properly attribute the trends found and to compile decent temperature and precipitation data of sufficient quality for the complete record.

However, to respond to the reviewer’s suggestion, here we exemplarily add a timeseries of the quality-checked mean monthly gridded temperature anomalies in Switzerland (Begert et al. 2005) as compared to the monthly SCA anomalies in Switzerland. The plot below shows that temperature seems to have a strong influence on the SCA as almost all the prominent positive (negative) temperature anomalies are opposed by negative (positive) SCA anomalies. Therefore, a follow-up study aims at further investigating the influence of temperature and precipitation on the Alpine snow cover extent.



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