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Inter-annual variations of snow days over Switzerland from 2000–2010 derived from MODIS satellite data

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Abstract

Snow cover plays a vital role in the Swiss Alps and therefore it is of major interest to determine and understand its variability on different spatiotemporal scales. Within the activities of the National Climate Observing System (GCOS Switzerland) inter-annual variations of snow days over Switzerland were derived from 2000 to 2010 based on data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite. To minimize the impact of cloud cover on the MODIS snow product MOD10C1, we implemented a post-processing technique based on a forward and backward gap-filling approach. Using the proposed methodology it was possible to determine the total number of annual snow days over Switzerland from 2000 to 2010 (SCD_{MODIS}). The accuracy of the calculated snow days per year were quantitatively evaluated against three in situ snow observation sites representing different climatological regimes (SCD_{in_situ}). The correlation (c) between annual SCD_{MODIS} and SCD_{in_situ} is highest for the lowland regions by ($c = 0.90$) with a slightly lower correlation for the Central Alps of 0.82 and a mean absolute difference of -6 to -7 days ($SCD_{in_situ} - SCD_{MODIS}$). Differences were further analysed on a monthly and daily resolution over the entire period. The overall agreement between SCD_{MODIS} and SCD_{in_situ} on a daily basis over 10 yr is 88 % to 94 %, depending on the regional characteristics of each validation site. Differences between SCD_{MODIS} and SCD_{in_situ} vary with higher mean absolute differences during the snow accumulation period in autumn and smaller differences after spring, in particularly for the Central Alps. These findings are in agreement with other studies.

1 Introduction

Snow cover represents a significant geophysical variable for the climate system through a range of complex interactions and feedback mechanism related to its physical properties (IPCC, 2007). High priority is therefore accorded in the Implementation Plan of

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the Global Climate Observing System (GCOS) to strengthen and maintain snow cover observations, ideally supplemented with other observing systems (WMO, 2006, 2010).

The estimation of snow parameters such as snow extent, snow depth, and snow water equivalent plays a vital role in the Swiss Alps for winter tourism as well as for the management of water resources (e.g. Elsasser and Messerli, 2001; Abegg et al., 2007; Uhlmann et al., 2009). Therefore, ground-based monitoring of the snow cover has a long tradition in Switzerland and a number of studies have been published over the last years, focusing on its temporal variability and long-term trend (Beniston, 1997; Laternser and Schneebeli, 2003; Scherrer et al., 2004; Scherrer and Appenzeller, 2006; Marty, 2008). Overall, these results describe a decrease of the alpine snow pack since the mid 1980s especially at lower altitudes which is linked to an increase of local winter temperatures (Scherrer et al., 2011). Most of these studies focused on the spatiotemporal variability of days with snow cover. Beside snow measurements (e.g. new snow depth), the number of snow days is an important climatological indicator serving applications in tourism, transportation, construction, or agriculture. In general, a snow day is defined as a day with a snow depth larger than a certain threshold (WMO, 2009). Different thresholds are published to derive the number of snow days for climatological applications (e.g. Eckel, 1938; Hantel et al., 2000; Laternser and Schneebeli, 2003; Scherrer and Appenzeller, 2006; Marty, 2008).

Compared to ground-based observations with the limitation of being sparse, satellite data give an area-wide and spatially consistent information of the ground or atmosphere. For more than three decades, satellite remote sensing has been used to measure snow properties from drainage-basin to continental scales (Hall and Martinec, 1985). With the continuity of Earth Observation programs of climate relevant sensors, satellite data series will be further extended and the development of new satellite systems will provide the retrieval of critical measurements. Concerning satellite-based snow cover monitoring, climatological studies on a decadal and hemispherical to regional scale were carried out (e.g. Robinson and Frei, 2000; Armstrong and Brodzik, 2001; Bales et al., 2008; Foster et al., 2009; Boi, 2010). For Switzerland, polar-orbiting

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NOAA AVHRR data (Foppa et al., 2004, 2006) and geostationary Meteosat SEVIRI data (De Ruyter de Wildt et al., 2007) were used for the near-realtime retrieval of the snow cover extent and thereof derived climatological pilotstudies (Seiz et al., 2007; Foppa et al., 2008).

5 In this study, we focus on the inter-annual variations of snow cover days (SCD) from October 2000 to September 2010 based on data from the Moderate Resolution Imaging Spectrometer (MODIS) on board the Terra platform. The purpose is to examine the spatiotemporal variation of the snow conditions on a yearly basis over Switzerland. A simple cloud gap-filling technique is implemented by post-processing the MOD10C1
10 product to derive the number of days with snow cover. The multi-year time series of SCD on an annual basis are compared with selected in situ snow observations and further discussed on a monthly and daily resolution to demonstrate the potential of our SCD product. The study reported here is placed in the broader context of the satellite activities within the National Climate Observing System of Switzerland (GCOS
15 Switzerland) (Seiz and Foppa, 2007, 2011; Seiz et al., 2011).

2 Data

2.1 MODIS satellite data

Within this study the MODIS/Terra Snow Cover Daily L3 Global 0.05 degree Climate Modeling Grid (CMG) Version 5 (MOD10C1) product was used, obtained from the Na-
20 tional Snow and Ice Data Center (NSIDC). The data set spans the period from the 1 October 2000 to 30 September 2010. Version 5 (V005), also known as Collection 5, is the most current version of data available from NSIDC. In the MOD10C1 product, a binning algorithm maps MOD10A1 daily snow cover data at 500m resolution into a grid of a 0.05 degree (CMG) and calculates snow and cloud percentages, Quality
25 Assessment (QA), and a confidence index based on the mapping results. The algorithm generates these parameters based on the total number of observations of a class

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(snow, cloud, land, and others) and the total number of land observations mapped into a grid cell of the CMG (Riggs et al., 2006). The MODIS snow cover retrieval is based on the Normalized Difference Snow Index (NDSI) and further criteria tests (Hall et al., 2002; Hall and Riggs, 2007). A number of studies have assessed the accuracy of the MODIS snow cover algorithm and its derived products on a regional scale (e.g. Klein and Barnett, 2003; Tekeli et al., 2005; Parajka and Blöschl, 2006). A comprehensive overview of the MODIS-based snow products and validation studies is given by Parajka and Blöschl (2012).

2.2 In situ snow observations

In Switzerland, snow variables such as total snow depth and new snow depth are measured mainly by the Federal Office of Meteorology and Climatology MeteoSwiss and the Swiss Federal Institute for Snow and Avalanche Research SLF. The observations consist of either manually or automatically recording stations. The amount of new snow depth and total snow depth at conventional stations is measured twice daily (morning and evening) by an observer on a representative plot in horizontal terrain (Bezzola, 2004). This network of conventional observations covers the entire region of Switzerland. The advantage of manual observations is the longer time series of up to more than 50 yr providing valuable information for climatological studies. Over the past few years, efforts have been made to identify, digitize and explore snow measurements from historical data sources dating back to the second half of the 19th century (Wüthrich, 2008). A recently published report by MeteoSwiss (Wüthrich et al., 2010) defined a potential basic climatological network for snow, based on the analysis of 160 historical snow measurement series. In our study, three stations have been selected from this so-called National Basic Climatological Network for Snow (NBCN-S) representing main climatological regimes in Switzerland and varying altitudes (Table 1). All in situ observation data have been well quality controlled and verified through various standard quality processing steps (Bezzola, 2004). In our study, we defined snow days with a snow depth of at least 1 cm (SCD_{in_situ}) as used at MeteoSwiss.

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3 Method for satellite-derived snow days

A weakness of optical satellite sensors is that they are not able to see the ground in cloudy conditions in contrast to in situ observations. The spectral specifications of the MODIS sensor do not allow for observations of the Earth's surface under cloudy conditions, which is a major limitation for studies of snow cover. This particularly applies to areas with frequent cloud cover, e.g. mountain regions such as the Alps. The MOD10C1 snow cover product uses the ancillary MODIS cloud mask (i.e. MOD35 product) based on cloud-detection tests indicating a level of confidence that MODIS observes clear skies (Ackerman et al., 1998; Platnick et al., 2003).

Several techniques have been developed to reduce the cloud cover pixels from MODIS products. They include one or a combination of different approaches, such as spatial filtering (Parajka and Blöschl, 2008; Gafurov and Bárdossy, 2009; Xie et al., 2009), temporal filtering, temporal composites of maximum snow cover extent, prior cloud-persistence and combining Terra and Aqua MODIS data (Parajka and Blöschl, 2008; Gafurov and Bárdossy, 2009; Wang et al., 2009; Hall et al., 2010).

To produce a consistent daily MODIS snow cover map at 0.05 degree resolution, we applied a post-processing technique to fill data gaps in the MOD10C1 product caused by clouds. The methodology uses a combination of thresholds in the post-processing of the MODIS product and a subsequent two step gap-filling approach as described below.

In a first step, we re-classified the pixels as follows: if cloud percentage of a CMG cell is >95 % the pixel is re-classified as cloud covered; if snow percentage of a CMG cell is >4 % and cloud percentage \leq 95 %, the pixel value is then normalized, resulting in a snow fraction related to the cloud free land observed (confidence index). If the CMG snow cover is less than 4 % and the CMG cloud observation is less than 95 %, the grid cell is defined as snow free. In a second step, a cloudy pixel is replaced by the cloud free (snow fraction or snow free) observed pixel information from the previous day. Even though the number of consecutive days with cloud cover could accumulate over

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time, the gaps are filled with the same value provided from the latest cloud-free grid cell. In accordance to this so-called forward gap-filling approach, we applied the same procedure in reverse direction, e.g. 30 September 2001 to 1 October 2000. We assume that through the exactly opposite gap-filling of forward and backward technique, the over- or underestimation in one of the directions is minimized. As we focus on a yearly temporal resolution, we calculate the mean of the total number of snow days derived from the forward and backward gap-filling procedure. Data gaps were treated as cloudy conditions. Furthermore, information from the last or first day of the neighbouring year was not taken into account if the first or last day of the year was cloud covered. The MODIS derived snow cover days (SCD_{MODIS}) are calculated for the hydrological year starting 1 October of any given year and end on 30 September of the subsequent year. It should be noted that this procedure is usable for data re-processing only, comparable to nowcast (forward gap-filling) and hindcast (backward gap-filling) modeling. It is the intention to derive the total number of snow days on a yearly time resolution.

4 Results

4.1 10-yr snow cover climatology based on SCD

Figure 1 shows the SCD_{MODIS} maps binned into 15 classes on a 25-days interval basis. The SCD_{MODIS} maps highlight the number of snow days for the period of 1 October to 30 September for the years 2000–2010, representing different snow conditions. It is clearly visible that the SCD_{MODIS} product reflects the topography of Switzerland with larger number of snow days in higher altitudes and less days with snow cover in the Swiss midlands and in Southern Switzerland. Regions with less than 25 days of snow cover per year are mostly found in the Rhein Valley, in France and in the plain of the Po River in Northern Italy. The inter-annual spatial variations are most apparent on the Swiss Plateau whereas in the Central Alps the year to year variability is marginal. The years 2001/2002 and 2006/2007 are outstanding with a relatively small number

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of days with snow particularly in the Swiss lowlands. In contrary, the years 2004/2005 and 2008/2009 demonstrate years with a relatively large number of days with snow in the Swiss lowlands.

Figure 2 shows the temporal evolution and variability of the total number of snow days for each year from 2000 to 2010 for the three selected stations based on MODIS (SCD_{MODIS}) and in situ (SCD_{in_situ}) data. The highest located station Samedan has at least 130 days with snow per year with up to more than 200 for 2008/2009. At the stations Basel and Lugano, some years without snow occurred. The year with a larger number of snow days for Lugano (2008/2009) is reflected in the corresponding maps in Fig. 1 for the region of northern Italy. The year 2006/2007 is characterized with the minimum number of snow days over the 10 yr, except for Basel and Samedan. In general, the inter-annual variability of snow days derived from in situ observations over the 10 yr is captured very well by our post-processed MOD10C1 product. The annual total number of snow days derived from MODIS is higher compared to the in situ defined number of snow days for 7 out of the 10 yr in Basel and for 9 out of the 10 yr in Lugano, respectively. Only at Samedan the in situ based number of snow days is in 6 out of the 10 yr higher than the satellite-derived number of snow days. However, the absolute differences between the SCD_{in_situ} and SCD_{MODIS} vary significantly between the three stations with a maximum discrepancy of 33 days (18 %) for Samedan in 2002/2003. At Basel (2002/2003) and Lugano (2008/2009), largest differences of 16 days (34 %) and 18 days (50 %) are found, respectively.

The MODIS derived snow cover days (SCD_{MODIS}) versus the in situ based calculated snow days (SCD_{in_situ}) for the three stations and over the 10 yr is summarized in Table 2. The mean difference d , the standard deviation of the difference s and the correlation coefficient c is indicated for each station (Table 2). Additionally the annual mean of the total number of snow days derived from in situ measurements is indicated (SCD_{in_situ}) as well as annual mean of the cloud cover based on the MOD10C1 cloud obscuration. The 10 yr average of SCD_{in_situ} and cloud cover refers to the regional characteristics of each of the three sites. Although the statistical evidence is based on a small sample,

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a certain tendency of the discrepancy is obvious. Overall, the satellite based total number of days with snow agrees well ($c > 0.8$) with a slight overestimation of up to 7 days. However, the standard deviation of the difference is twice as high for Samedan as for Basel or Lugano ($s = 14.46$).

4.2 Analysis of monthly SCD

Table 3 summarizes the results of the comparison of SCD_{MODIS} and SCD_{in_situ} at monthly resolution for each of the three sites. Additionally, the monthly average of the snow days defined by in situ measurements and of the cloud coverage based on the MOD10C1 cloud mask is indicated. The total number of snow days based on MODIS differs from the in situ observations for most of the month. Outstanding is the month February (Basel and Lugano) and the period January to April at Samedan with a positive bias. Largest negative deviations are found at the beginning of the snow season (October, November), when ephemeral snow fall is frequently observed, especially at high elevation sites such as Samedan. In the Southern Alps at Lugano, highest biases are noted later in winter (December, January). As the snow season advances, the agreement increases quite constantly. Inter-monthly variations of the cloud cover are clearly visible for each station with different cloud cover maxima and minima for each site and region.

Figure 3 shows the month to month variations and differences from October 2000 to September 2010, exemplified for Samedan. Overall, the monthly variations from MODIS and in situ correspond quite well. Periods with complete snow cover (December, January, February, March) are generally captured by SCD_{MODIS} in every year. A somewhat lower agreement is found during the transition periods in fall (October, November) and spring (April, May). Differences of more than 5 days per month are registered in November (e.g. 2002), December (15 days in 2001), April (19 days in 2002) and May (2003).

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4.3 Analysis of daily SCD

Daily data were analyzed to further examine the discrepancies between both data sets. The results are reported in Fig. 4 for Samedan for the 2002/2003 season. A total of 185 snow days were extracted from the MODIS post-processed product, as opposed to 152 days determined from in situ observations (i.e. a difference of 33 days). Figure 4a illustrates the snow cover fraction (blue) and the frequency and duration of cloud coverage from the daily MOD10C1 product (light brown) and the defined snow free days (green). The longest period of cloud cover occurs at the end of December (8 days) and a maximum cloud free period of up to 20 days in February. Figure 4b and c explains the forward and backward gap-filling approach by artificial adding of additional days with snow and days with no snow, respectively. The complimentary effect of these opposite processes is explained in Fig. 4d: contrary gap-filling results are detected between the middle of October and beginning of November. While the forward approach substitutes cloud cover with snow free land, the backward approach does fill the cloud obscured days with snow. The months of October (+7 days), November (+6 days), and extensively April (+19 days), are causing a larger total number days with snow per year compared to the in situ observations (Fig. 4e).

A confusion matrix (e.g. Pu et al., 2007) was constructed to better assess the overall accuracy of the gap-filling technique. Table 4 presents three confusion matrices for Basel (a), Samedan (b) and Lugano (c), based on a daily comparison between SCD_{in_situ} and SCD_{MODIS} from 1 October 2000 to 30 September 2010. The results of the forward (SCD_F) and backward (SCD_B) gap-filling approach are combined for snow covered (e.g. SCD_{F_snow}) and snow free days (e.g. $SCD_{B_snowfree}$). The overall agreement describes the number of cases where both gap-filling approaches indicate snow days (SCD_{F_snow} and SCD_{B_snow}) and agree with the in situ derived snow days ($SCD_{in_situ_snow}$) on snow covered and snow free conditions to the total number of days (Klein and Barnett, 2003). For Basel and Samedan the overall agreement is quite similar and high at 88.4 % and 88.7 %, respectively. At the site Lugano the agreement

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is higher at 93.7 %. Both satellite-based gap-filling approaches incorrectly substitute cloudy pixels as snow covered in 1.2 % and 2.0 % of all days (commission errors) for Basel and Lugano, respectively. At Samedan around 3.7 % of all days are incorrectly defined as snow covered by the post-processed MOD10C1 product instead of snow free. In contrary, a wrongly replacement of cloud coverage with snow free observations occurs in about 1 % of all days for all three sites (omission errors). The fraction of inconsistent gap-filling results (e.g. SCD_{F_snow} and $SCD_{B_snowfree}$) on the total number of days varies between 3.8 % for Lugano, 6.1 % for Samedan and a maximum of 9.3 % for Basel.

5 Discussion

The derivation of the yearly number of snow days from the MOD10C1 product is adequate for describing the inter-annual variability of the snow cover over Switzerland. For example, the relatively small number of snow days particularly in the Swiss lowlands is in agreement with monthly temperatures above average for several months between September and June in the years 2001/2002 and 2006/2007 (MeteoSwiss, 2001, 2007). In contrary, completely snow covered Swiss lowlands were observed in the years of 2004/2005 and 2008/2009 due to early snow fall events and winter conditions (MeteoSwiss, 2005, 2009). Although the spatial resolution of the MOD10C1 is moderate (0.05°) topographic features such as the main alpine valleys are clearly apparent in the satellite-based product. As such, SCD_{MODIS} provides valuable information to complement the sparsely distributed point observations on the ground.

Analyses at both annual and monthly levels showed that the number of snow days is overestimated by our post-processed MOD10C1 product. For the lowland stations in the northern (Basel) and southern (Lugano) part of Switzerland, the absolute deviations are smaller compared to Samedan on a yearly basis from 2000–2010. However, for the alpine site Samedan, the relative error ($SCD_{in_situ} - SCD_{MODIS}$) averaged over the 10 yr is significantly smaller (7 %) than for Basel (45 %) or Lugano (41 %).

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The overestimation is also shown by a higher commission error rate of SCD_{MODIS} (e.g. 3.7 % for Samedan) than the error rate of omission (e.g. 1.5 % for Samedan). Thus, the post-processed MOD10C1 product appears to have a tendency to retrieve too many snow days compared to SCD_{in_situ} . A small percentage of about 4 % (for Lugano) to 9 % (for Basel) of all days with contradictory results from the forward and backward gap-filling approach (e.g. SCD_{F_snow} and $SCD_{B_snowfree}$) compared to SCD_{in_situ} (e.g. $SCD_{in_situ_snow}$) was registered.

The overall positive bias could not be related directly to the amount of cloudy pixels over the whole period (cloud cover Basel: 50.6 %, Lugano: 38.8 %, Samedan: 42.3 %), introducing uncertainty in filling the gaps with either snow or no-snow. The frequency of cloud occurrence and its temporal continuity has probably a higher impact on the accuracy of the number of snow days compared to in situ results. This could be explained by the increase of the uncertainty when the number of consecutive days of cloud obscuration increases. An isolated snow event followed by a period of continuous cloud coverage could lead to a certain overestimation of snow days, which mainly would happen during the transition period in autumn and spring. In contrary, an underestimation might occur when snow falls after a snow free period and cloud coverage remains stable over a region.

The difference between monthly SCD_{in_situ} and SCD_{MODIS} shows a seasonal variation with largest differences between October and April. In contrast, differences are smaller during the months with little or no snow (June to September). Parajka and Blöschl (2006) related their seasonal performance pattern of the MODIS analysis to the overall snow coverage of Austria, and explained above average errors with above average snow coverage. This was not confirmed in our study, given the better agreement for January at Basel ($d = -0.30$ days) even though snow coverage was relatively high (9.2 days). Only in the Southern Alps in Lugano, the largest discrepancy in December ($d = -2.10$ days) and January ($d = -3.60$) might be related to the larger number of 4.8 and 5.2 snow days, respectively.

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Several previous studies described larger MODIS product (e.g. MOD10A2) errors in autumn and smaller errors in spring (Vikhamar and Solberg, 2003; Simic et al., 2004; Parajka and Blöschl, 2006), which is also supported by our results. These studies linked the larger winter errors to the MODIS snow algorithm and pointed out the need to correct for tree and surface shading effects in winter when solar zenith angles are sub-optimal. Other studies such as Gao et al. (2010) and Klein and Barnett (2003) found the lowest accuracies in the transitional months and refer to more changeable and patchy snow distribution, detected by the ground station but not necessarily classified in the corresponding image pixel (i.e. sub-pixel effect). This is apparent for Samedan in the Central Alps, where a positive bias is correlated with months of almost total snow cover (December to March) at this altitude. In contrary, distinct deviations occur during the snow accumulation and ablation phase. In mountainous regions, steep elevation gradients are common and one single MOD10C1 grid cell of 0.05 degree resolution may include both valleys and mountain peaks with e.g. elevation differences up to 1200 m such as around Samedan. As a consequence, differences are expected when a MOD10C1 grid cell is compared to in situ point observations in complex topography, which could explain the lower agreement at Samedan ($c = 0.82$) compared to Basel ($c = 0.90$) and Lugano ($c = 0.93$). This overestimation is also underlined by the percentage of MODIS grid cells defined by the forward and backward gap-filling approach as snow covered (3.7 % of all days) instead of snow free. Furthermore, single snow events, which occur mostly during the transition periods at this altitude, are likely to propagate errors in the final gap-filled product due to the gap-filling technique. This particularly applies to periods with a large number of consecutive overcast days. On a daily basis, the good overall agreement of around 88 % (Samedan) to 94 % (Lugano) between SCD_{in_situ} and SCD_{MODIS} is comparable with results from North America based on the MOD10A1 snow product which was compared with in situ measurements from the automated Snowpack Telemetry (SNOTEL) network (Klein and Barnett, 2003).

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6 Conclusions and outlook

This study presented inter-annual variations of snow cover days (SCD) over Switzerland for the period 2000 to 2010 based on the MOD10C1 snow product (SCD_{MODIS}). The total annual SCD were retrieved by applying a gap-filling approach to reduce cloud cover obscuration. The gap-filling methodology proposed substitutes cloud covered pixels accounting for around 30 % (Lugano) to 50 % (Samedan) of all pixels over the whole period. Through the presented method, annual snow day maps were derived from 2000 to 2010 over Switzerland. The MOD10C1 product with a moderate grid resolution of 0.05 degree was shown to be adequate to describe the temporal and spatial variation of snow days over Switzerland on a yearly basis.

An accuracy assessment based on three in situ observation sites representing different climatological regimes in Switzerland (Basel, Samedan and Lugano) demonstrated the potential of the SCD_{MODIS} . The correlation between the satellite-derived annual number of snow days and those calculated from in situ observations (SCD_{in_situ}) is high (0.88) with a mean absolute difference of -6.6 days for the three stations combined. To better understand the annual differences in detail, investigations of SCD_{MODIS} on the monthly and daily resolution have been conducted. On a monthly basis, the discrepancies between SCD_{in_situ} and SCD_{MODIS} vary with higher mean absolute differences during the snow accumulation period in autumn and smaller differences after spring. These findings are in line with other studies and are clearly apparent for the alpine site of Samedan.

The impact of the gap-filling approach was visualized on a daily basis for all three stations over the entire period from 2000 to 2010. The day to day comparison of both forward and backward gap-filling against SCD_{in_situ} indicates an overall agreement of 94 % and 88 % for the Southern Alps and the Central Alps, respectively. In 1.2 % of all days the MODIS gap-filling approach has erroneously classified snow free days as snow covered for the Swiss Plateau and in 3.7 % of all days for the Central Alps, respectively.

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For further discussing the spatiotemporal variability of snow days on a regional to local scale, other higher spatial resolution products from MODIS or other sensors might be used. The longer record of satellite data such as from NOAA AVHRR might provide more significant long term information on the change and variability of snow days over Switzerland although other challenges would arise. Additionally, the use of high temporal resolution data such as from geostationary satellites (e.g. Meteosat) could be of interest for the development of a combined gap-filling approach.

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Table 1. Location of the selected in situ snow stations.

Station	Region	Latitude	Longitude	Altitude [m a.s.l.]
Basel	Swiss Plateau	47.54	7.58	316
Samedan	Central Alps	46.53	9.87	1708
Lugano	Southern Alps	46.01	8.96	370

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Table 2. SCD_{MODIS} versus SCD_{in_situ} on a yearly basis (d = mean difference of $SCD_{in_situ} - SCD_{MODIS}$, s = standard deviation, c = coefficient of correlation). SCD_{in_situ} indicates the averaged number of days with snow over the 10 yr and CC is the averaged annual cloud cover in percent derived from the MOD10C1 product.

	Basel: Swiss Plateau	Samedan: Central Alps	Lugano: Southern Alps
d	−6.30	−6.30	−7.30
s	6.48	14.46	6.55
c	0.90	0.82	0.93
SCD_{in_situ}	24	160	14
CC [%]	50.59	42.26	38.84

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Table 3. Mean difference of $SCD_{in_situ} - SCD_{MODIS}$ (d) and standard deviation of the difference (s) as well as number of snow days (SCD_{in_situ}) and cloud cover in percent (CC) averaged over each month for the 10 yr and each station site.

(a) Basel												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
d	−1.50	−1.30	−1.70	−0.30	0.50	−1.00	−0.40	−0.30	0.00	−0.10	0.00	−0.20
s	2.07	1.77	4.27	3.95	2.01	4.27	1.51	0.95	0.00	0.32	0.00	0.42
SCD_{in_situ}	0.2	0.7	4.0	9.2	6.2	2.9	0.3	0.0	0.0	0.0	0.0	0.0
CC [%]	53.2	62.0	70.6	61.9	62.1	54.8	46.3	45.8	37.0	36.5	40.3	36.6
(b) Samedan												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
d	−2.90	−2.20	−0.40	1.10	0.50	0.10	0.10	−1.60	−0.30	−0.20	−0.30	−0.20
s	2.64	3.71	5.58	2.13	0.71	1.52	7.96	3.03	1.42	0.79	0.67	1.87
SCD_{in_situ}	3.8	17.6	28.7	30.7	27.7	30.1	17.9	2.3	0.3	0.1	0.0	0.7
CC [%]	37.4	41.0	40.3	42.3	43.6	52.3	55.7	56.5	40.0	30.6	37.4	30.0
(c) Lugano												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
d	−0.70	−0.20	−2.10	−3.60	0.70	−0.10	−0.20	0.00	−0.40	−0.10	−0.32	−0.30
s	1.64	0.79	3.90	5.10	2.41	0.57	0.63	0.00	0.97	0.32	0.95	0.67
SCD_{in_situ}	0.0	0.4	4.8	5.2	3.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
CC [%]	48.1	50.0	45.8	46.1	44.3	41.6	45.0	37.4	30.7	21.6	25.5	30.0

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Table 4. Confusion matrix for SCD_{MODIS} compared with in situ derived snow days (SCD_{in_situ}) from 1 October 2000 to 30 September 2010 on a daily basis for all three validation sites.

(a) Basel		SCD _{MODIS}			
		SCD _{F_snow} SCD _{B_snow}	SCD _{F_snow} SCD _{B_snowfree}	SCD _{F_snowfree} SCD _{B_snow}	SCD _{F_snowfree} SCD _{B_snowfree}
SCD _{in_situ}	SCD _{in_situ_snow}	2.6 [%]	1.4 [%]	1.4 [%]	1.1 [%]
	SCD _{in_situ_snowfree}	1.2 [%]	2.9 [%]	3.5 [%]	85.8 [%]
Agreement		88.4 [%]			

(b) Samedan		SCD _{MODIS}			
		SCD _{F_snow} SCD _{B_snow}	SCD _{F_snow} SCD _{B_snowfree}	SCD _{F_snowfree} SCD _{B_snow}	SCD _{F_snowfree} SCD _{B_snowfree}
SCD _{in_situ}	SCD _{in_situ_snow}	39.5 [%]	1.0 [%]	2.0 [%]	1.5 [%]
	SCD _{in_situ_snowfree}	3.7 [%]	1.3 [%]	1.7 [%]	49.2 [%]
Agreement		88.7 [%]			

(c) Lugano		SCD _{MODIS}			
		SCD _{F_snow} SCD _{B_snow}	SCD _{F_snow} SCD _{B_snowfree}	SCD _{F_snowfree} SCD _{B_snow}	SCD _{F_snowfree} SCD _{B_snowfree}
SCD _{in_situ}	SCD _{in_situ_snow}	2.4 [%]	0.2 [%]	0.8 [%]	0.6 [%]
	SCD _{in_situ_snowfree}	2.0 [%]	1.2 [%]	1.5 [%]	91.3 [%]
Agreement		93.7 [%]			

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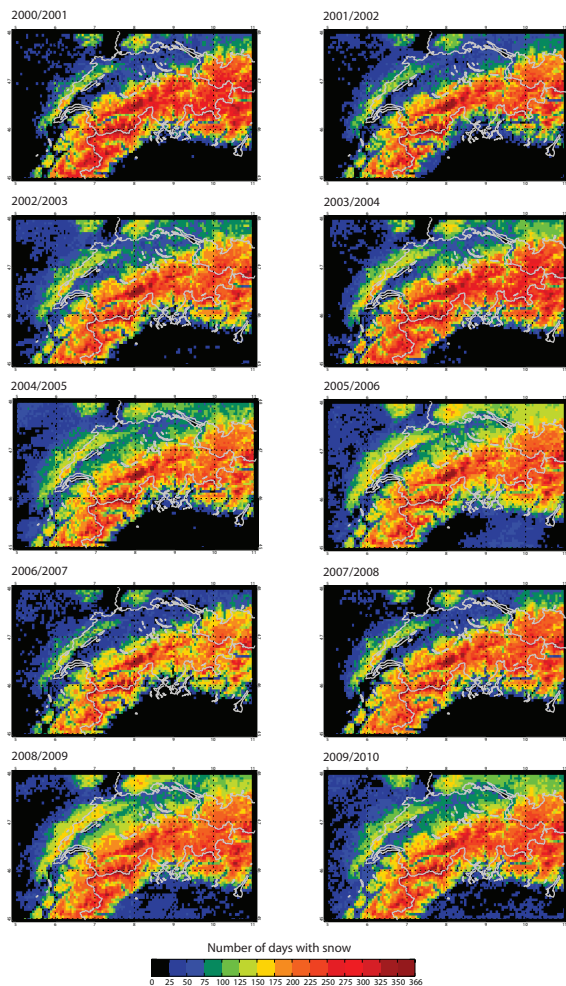


Fig. 1. Satellite-derived number of days with snow per year over Switzerland from 2000 to 2010.

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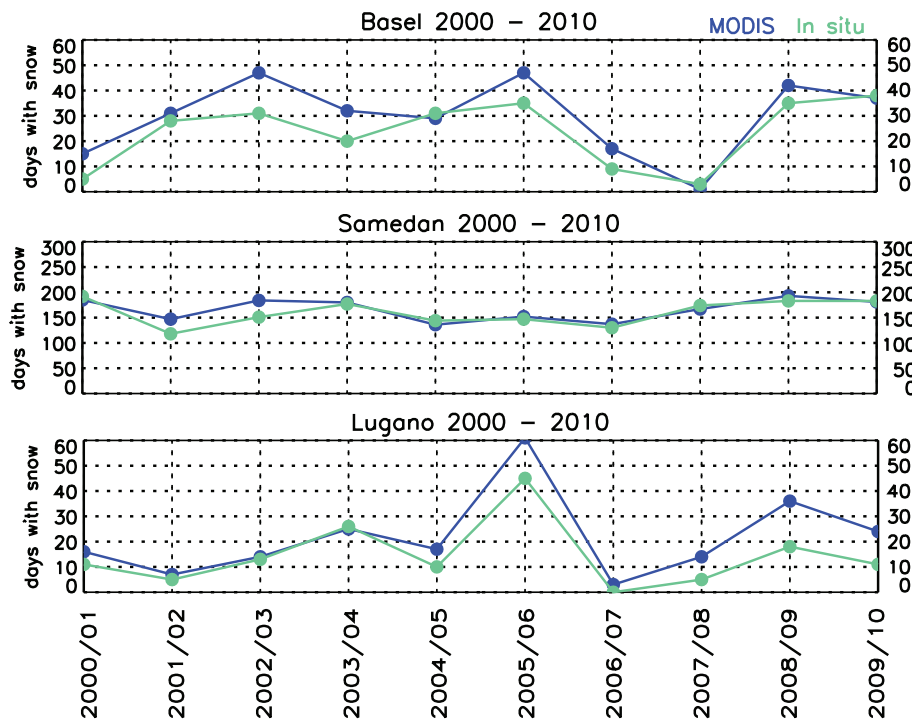


Fig. 2. Temporal variability of the total yearly number of snow days from 2000–2010 for Basel (Swiss Plateau), Samedan (Central Alps) and Lugano (Southern Alps) in Switzerland.

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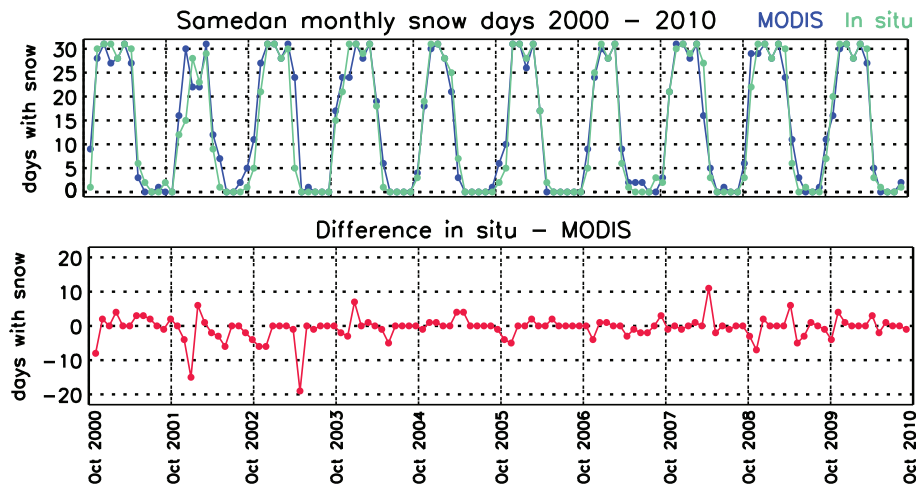


Fig. 3. Temporal variability of the total yearly number of days with snow from 2000–2010 for Samedan.

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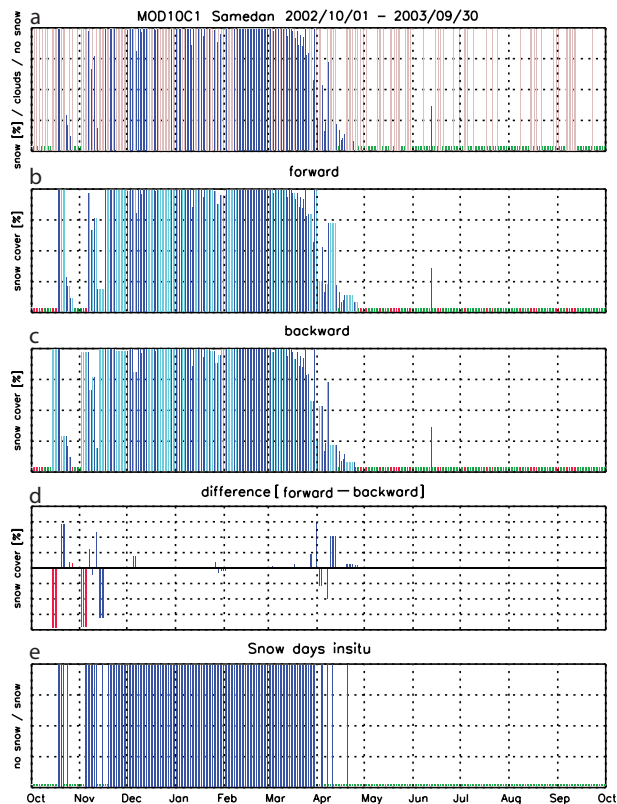


Fig. 4. Processing steps to derive the yearly number of snow days based on the MOD10C1 product **(a)** by including a forward **(b)** and backward **(c)** gap-filling approach. Artificially added snow days (light blue) and days with no snow (light red) are indicated. The differences resulting from the cloud removable technique are visualized **(d)** with red bars showing a contrary gap-filling and with blue bars showing a consistent gap-filling (i.e. forward **(b)** and backward **(c)** indicate snow). The temporal variability of snow days calculated from in situ observations is demonstrated **(e)**. The period from 1 October 2002 to 30 September 2003 is presented.

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