Snow Cover Duration in Lowland Regions of Switzerland :

Comparison of Three Methods

Master's Thesis

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Abstract

The study and understanding of snow climatology are of importance for many different environmental or economic purposes. In fact, it is involved in flood assessment, water reservoir assessment, avalanche studies, and it is an indicator of the number of skiing days, for example. Then, the study of snow variable implies getting valuable information on snow data. The first idea relates to, automatic stations. This idea seems to be the best source of that type of information. This belief is true for middle and high altitude. Studying snow in lower regions is quite more challenging. Thus, this master's thesis aims at studying snow cover duration (here as the number of days with snow for an entire period) in lowland regions using three different sources of snow data: man-made observations, the snow accumulation model and remote sensing satellite data. In a first step the snow cover duration is studied separately with different methodologies. A step-like decrease in snow cover duration at the end of the 1980's is observed. In a second step, a comparison between methods is made. Man-made observations show a good match with the modelled estimated data. Both methods give similar tendencies for snow cover duration. On other hands, satellite data suffer from issues, which are related to the difficulty to make the distinction between clouds and snow, and also suffer also from missing values and instrument failures. Thus, the remote sensing data does not match both other methods well.

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1. Introduction

1.1 Interest of the Topic

The knowledge of snow climatology is of great interest from different environmental and economical perspectives. Snow has to be taken into account as a variable for flood assessment, hydro-power production, water reservoir management, or avalanche prevention. For example, days with a snowpack are relevant for winter tourism and skiing days, which could affect the economy of mountainous regions. The Swiss Alps are closely concerned with snow climatology. It is estimated that around 90% of Alpine locations economically depend on winter tourism (Abegg, Agrawala, Crick and de Montfalcon, 2007). Thus, snow climatology impacts winter tourism and water management. Being aware of those issues, it can easily be understood that snow monitoring needs a good measurement network to get the best data possible. This is true regarding mid and high altitude areas. SLF, which is in charge of snow measurement, has automatic stations mainly located above 1700 meters above sea level. This would be enough in order to provide data for avalanche research, hydrology issues, winter tourism or water reservoir assessment. Some stations of MeteoSwiss get measurements for snow, but they suffer from their few numbers which retrieve snow data. Thus, what about low locations where most people live? We realize that snow measurements, and by the way, research about lowland snow assessment are underestimated. However, problems associated with snow apparition in lowland regions do exist: traffic accidents, disturbances of the railway network or agriculture troubles. It is possible to obtain information on lowland snow measurements: satellite data, model-derived data, and hand made in situ observations. The interest is now to assess those different methods to investigate which one is suitable for the study of lowland snow. Moreover, one question is to see if hand made observations constitute a reliable source of information.

1.2 Research Question

The aim of this project is to evaluate the different snow data retrieved for low altitudes. The purpose was to find out if there are any matches between the three different snow data available over the past 30 years: Ground observations of the BernClim observations network, remote sensing observations and a temperature based snow line model. In order to assess these methods, the investigation of snow cover duration (SCD) will be the theme of the analysis. Here, SCD means the number of days with snow for a given period, and not consecutive days with snowpack presence. This work will focus on the lowland regions of Switzerland, because of the lesser amount of research concerning low elevated sites as compared to mid and high altitude. To assess the snow climatology, available data could be provided by three different methodologies: ground-based monitoring networks, modelling approaches and satellite remote sensing. Each of these different ways to assess snow variables has its advantages. Then, it is obvious that depending on the research question, one or the other approach is more relevant to use. But it is interesting to know if the three different approaches give similar results or not.

Thus, the subject of this work is to compare three different methods to assess SCD in the low regions of Switzerland and to check if the different retrievals can be matched. Another challenging intention of the work is to determine if man-made observations are of interest and if they could be a solid source of snow data. At this point, and as a first assumption, studying SCD on low altitudes is possible using satellite retrievals or model-oriented methods. Then the main research question would be to see if man-made observations give similar results for the study of SCD as the results with other methods. For this purpose, the environmental research question will concern the assessment of SCD ,and according to Scherrer, Appenzeller and Laternser (2004), this duration must have been changed for decades: "*In the late 20th century, Swiss midwinter Alpine snow cover showed a pronounced decrease at low altitude stations.*" This thesis will confirm if it is the case.

1.3 Procedure

In order to assess and to find any matches between those methodologies, it is first necessary to describe them and to foresee their advantages and disadvantages. This task begins with the description of the data; that implies describing the quantity and the quality of the data: number of stations, number of measurements and resolution. It is then necessary to evaluate the method of measurement itself. For this, the description of the three methodologies is required. After this, the description of our available data set has to be evaluated. The first step will consist in delimiting the study area, mainly depending on the availability of data. BernClim data does not have a homogeneous spatial coverage over Switzerland. Therefore, defining the study area will be the first constrain. The aim is to define an area in which we will find the best homogeneous measurement network according to the different retrieval techniques. After that, the period of study has to be determined. It will cover the last 30 years. In a second step, when data from the three approaches have been described, the construction of a SCD indicator according to each approach is needed. With this indicator, it will be possible to reconstruct the SCD over the past 30 years. An evaluation of the SCD could be undertaken, analysing its variability and its behaviour over the considered period. This operation has to be done separately for each methodology. Finally, the comparison with the three retrieval methods will be undertaken. The idea is then to check if handmade measurements give similar results as other retrieval techniques.

1.4 Previous Studies

Numerous papers have discussed snow cover depth and duration in the Alps. Most of them refer to mid and high altitude. Some of them focus on low regions. Beniston (1997) says that based on historical records, no one has ever observed such conditions except the ones experienced in the 1980s for the last 700 years. In fact, Baumgartner and Apfl (1994) added that: "*Alpine snow cover reached its smallest extent during the 1980s".* In addition, Föhn (1991) affirms that this unusual phenomenon was most marked in low to medium elevated sites. Then, concerning Switzerland more particularly, Marty's (2008) paper can be cited and used as main reference for further comparison. This paper depicts a clear snow regime shift in the snow days anomalies in the late 1980s. Then, the analysis of SCD using our three data sets should lead to a decrease in number of days with snowpack in the 1980s. Most studies that deal with snow variables use different sources of data: historical data, modelled estimate data, automatic-station data, or satellite data. Then, each researcher prefers one or the other method to make their analysis. Sometimes a method is used to complete or validate results. But the comparison of different methods is not usually undertaken. This is one of the motivations for this work.

2. Data Set Description

2.1 BernClim Network

2.1.1 Description of the Project

The BernClim topo-climatic project started in the early 1970. The project was designed to collect data provided by individual contributors among citizens. The main concept was to retrieve data corresponding to those that the Swiss Meteorological Institute provided. These data represent plant phenology and climatic observations (Jeanneret and Rutishauser, 2011). Among the latter are data about snow cover which is the subject of our interest. The first question is to check how those observations are made and what the quality of the man-made work is. Is there a procedure to follow by those involved in the project? Is there any control of the selected sites? Did the project leaders verify the collected data? Here are some basic questions to answer before using the data set. But, there is confidence that the creator of the BernClim project was aware of those questions.

Then, if we look at BernClim snow data, the aim was to observe snow for each station at different specific sites (Jeanneret and Rutishauser, 2011). For this purpose, a site was selected in the bottom of a valley and on both flanks during winter. This contrasts with the traditional ground measurements. BernClim was more focused on spatial density than on time resolution (Jeanneret and Rutishauser, 2011). Observers were asked to collect the snow data between 7am and 8am. For flat terrain, the snow depth was retrieved. On slopes, it was only asked to observe the snow cover. The location was first made by the postal code, to which a decimal was added to allocate different sites within the same locality. This strategy caused some bias. First, for the big localities with more than one observer, there could have been some mismatches. Second, the change of postal code over the time makes this classification inadequate. Then, the use of coordinates was imposed as the best solution. The reference system is CH1903 LV03. Instructions addressed to observers are available. As far as snow observations are concerned, instructions were similar to the standard of the Swiss Institute of Meteorology MeteoSwiss for their stations. There is confidence about the quality of the instructions given by this serious state office. Finally, the main bias will come from the observers themselves. And it will be the goal of this study to analyse if the observations they made were reliable or not. Each observer gets a form to complete depending on the variables they retrieve. On the winter form, a schedule for snow and one for fog is found. The one for snow contains three columns for the three locations expositions per day. Each day, a symbol informs about the presence of the snow cover. For snow height, the reel hour was noticed. At the top of the sheet, topographic information was described. Then, errors can occur depending on the way the observer makes the observations and the way they enter the data.

2.1.2 The Data Set

The data set used for this study was a digitized version of the basic forms from the observers. It includes the postal code, the Swiss coordinates, the name and the region for the location of the sites. The altitude, the exposition and the slopes inclination of the locations provide topographic information. Then, for each year, one finds the number of days with snow cover per month and the total amount for the year. Finally, a column with remarks about the digitisation is available, that clarifies the indication about the location as well as the date and about the instructions. For this study, the use of snow cover presence is sufficient. The density of the BernClim project was represented by about 200 stations at the beginning of the project and, unfortunately around ten nowadays. They covered mainly the canton of Bern as the name of the project tells. Nevertheless, the investigator of the project got a better view of the objectives. It has been decided to create a transect trough Switzerland from the Jura Mountains, trough the canton of Bern up to Tessin. This represents most of the different environments of Switzerland, from 400 up to 1400 meters above sea level. The selection of the time period and the study area explain the fact that the BernClim data set is limited both spatially and temporally. It will be the limiting factor for data selection. This data set is not homogeneous. But it is certain that some good series of data will be found.

2.2 Snow Accumulation Model

The second data set consists of a constructed snow cover index. The data is constructed considering the snow accumulation model based on degree-day method (Auchmann and Brönnimann, 2012; Singh and Singh, 2001). In this model, three data sets are involved: daily maximum temperatures, daily minimum temperatures and daily precipitation. In the model, the temperature is used as an index for snow melt. Then, it was necessary to find these three data inputs. They will be provided by the MeteoSwiss grid-data. It consists of a matrix of 0.02 degree resolution that is a combination of all available ground measurements.

2.2.1 Daily Precipitation

The daily precipitation, RhiresD, from MeteoSwiss Grid-data products are given in millimeters (equivalent to square meters). It gives the rainfall or snowfall water equivalent account for 24 hours from 6 am of day 1. "*RhiresD is a spatial analysis of daily precipitation covering the entire territory of Switzerland and extending over a multi-decadal period (1961-present). It provides detailed spatial information and high accuracy by exploiting all available automatic and manual non-real time measurements*." (Documentation of MeteoSwiss Grid-Data Products, 2013). The measurements are quite reliable in time, with a good homogenization. The number of stations have increased then decreased since 1960 (between 420 and 520 stations). The distribution of stations below 1200 meters is well balanced, whereas it is not the case above this threshold. For purpose of this study, this will not be a problem to consider. All the rain-gauges are of similar design and then the measurement technique is homogeneous since 1960. The method of analysis of the daily precipitation is made in 4 steps. This procedure is described in detail in the product description from MeteoSwiss (Documentation of MeteoSwiss Grid-Data Products, 2013), but it mainly consists in spatial interpolation and anomalies calculation over selected reference periods. The use of an algorithm is required and trusted as of good quality in this work. The accuracy depends on many factors within the data set. The accuracy mainly depends on the instrumental measurements (rain-gauge) and the interpolation scheme. MeteoSwiss estimated that RhiresD underestimates daily precipitation. Unfortunately, this error is expected to be more important during snowfall periods as for wind exposed sites. This underestimation has to be kept in mind for subsequent comparison of methods. As mentioned above, the grid resolution is 2km. Nevertheless, the effective resolution stands between 15 and 20 km, that corresponds to the mean distance between two stations. Thus, the local (1 pixel) analysis is not expected to be representative. These remarks will be considered in the snow model accumulation. As it will be described later, the use of 9 pixels will be prevalent. Thus, the product provided by MeteoSwiss is of good quality for the running of the snow model. But it has to be remembered that for the purpose of snow information retrieval, underestimation could occur.

2.2.2 Daily Minimum and Daily Maximum Temperature

Temperature also comes from the grid-data analysis of MeteoSwiss (Documentation of MeteoSwiss Grid-Data Products, 2013). TminD and TmaxD are 2 meters above ground measurements of minimum and maximum daily temperatures in degrees Celsius. The minimum and maximum temperatures are those between 00h00 and 24h00. They have a km-resolution, and use about 90 homogeneous long-time station series, with the reference period from 1970 to the present. MeteoSwiss ensures a high quality of stations long-time series: "*To ensure a high degree of long-term consistency in the analyses, the primary data source is a set of high-quality records that have been rectified (homogenized) for the effect of instrument changes and stations relocations*." (Begert, Seiz, Schlegel, Musa, Baudraz and Moesch, 2003; Begert, Schlegel and Kirchhofer, 2005). Moreover, since 1980, the automatisation of stations supplies a great amount of data. Since then, daily temperatures are given as means of measurements which are made each ten minutes. The accuracy looks quite similar to the precipitation data set. Thus, the terrain elevation may vary a lot within a 2-km pixel resolution. Then for precise locations, the error could be quite important. In addition, two other small-scale effects are not included within the analyses: influence of local topography and land cover effects, such as urban heat islands. As it is the case for precipitation, the use of TminD and TmaxD to grid-point analysis could bring up considerable errors. For the same reason, it was decided to use an average of 9 pixel to compute the snow model in this work.

2.3 Satellite Data

The last data set consists of remote sensing data derived from Advanced Very High Resolution Radiometer (AVHRR) satellites, provided by the National Oceanic and Atmospheric Administration (NOAA). The product is a binary information that informs about daily maximum scene snow cover extent (Hüsler, 2015). This version was performed with a better cloud masking scheme (use of cloud probability mask). The available binary values offer 5 possibilities for each grid cells: 0 for snow free land, 100 for snow presence, 200 for water area, 250 for cloud cover and 255 for no data. Each grid cell is georeferenced with longitude and latitude at its upper left corner. The pre-processing is complex and well described in the papers from Hüsler, Jonas, Wunderle and Albrecht (2012) to Hüsler, Jonas, Riffler, Musial and Wunderle (2014). It is roughly composed of a radiometric calibration, a geolocation and orthorectification, and a cloud masking scheme. The exact description of the data retrieval will not be explained in details here because of the complexity and the amount of processing included. Nevertheless, issues concerning satellite data have to be clarified. It has to deal mainly with the change in instrumentation and in interference. First, some overflights are affected by scan motor failures (Hüsler et al, 2012; Hüsler et al, 2014). In addition, NOAA is composed of several satellites launched at different periods, and they are not all of the same quality. For this data set, it is recommended not to use NOAA-12 and NOAA-15. The reason is that there are not any quality checks. In fact, a change in the overpass-time earlier in the morning makes the shadowing higher and thus the analysis for snow extent is more difficult. Another issue concerns the NOAA-14 after year 2000 that seems to be of bad quality. Also, the discrimination between snow and cloud is still a major unresolved problem. In addition, the accuracy to detect snow in forested areas is still a problem in late winter because of the interference of the canopy. These issues will certainly affect the use of SCD analyses. Moreover, because the aim of the work is to analyse low altitude snow cover over the Swiss plateau, clouds will be a major issue. Indeed, the stratus will certainly be a problem in the data set. The retrieval of the sum of days with snow during winter period will be affected by cloud retrieval information. This data set seems at first glimpse the less usable for the purpose of snow cover analysis throughout time. Nevertheless, the use of remote sensing data to make spatial comparison with other methods could get some interesting results.

3. Method

3.1 Basic Idea and Software

Data processing consists in obtaining the SCD for the considered winter period defined from September of the current year up to April of the following year. SCD is simply considered here as the number of days with the presence of snowpack within the winter period. Thus, the first step of the method is to extract this indicator from the three different data sets. It appears that it was the most time-consuming phase of the work. BernClim data were quite easy to process, because the digitalized data gives the location and the SCD for each month. This is the reason why the extraction of the indicator from the BernClim data set will not be discussed in detail.
The extraction of the data is decided to be handled with the R-CRAN project statistics software. This choice was motivated by the fact that R-software was a free open source software. Additionally, R is known to have a great and wide users' community that develops and shares R-code. The second motivation was to compute the three methods with the same software, and not using different devices. It was challenging to use this software, while more powerful software exists. The next section will explain the main steps to obtain the SCD from the snow model and from the remote sensing satellite data. For each method, two paragraphs will explain with more details the treatment of the time-pattern analysis as well as the extraction of subset for the space-pattern, that demands slight adjustments from the first extraction. Before this explanation, one looks into time period and area of study more precisely.

3.2 Time Period, Area of Study and Data Selection

The choice of the study area as well as the period was mainly restricted by the BernClim data set. The number of BernClim stations has constantly decreased since its start. It decreased from 250 stations at the beginning of the project in the 1970s to 10 stations in 2010 (Jeanneret and Rutishauser, 2011). This decrease in the number of stations and the human-dependent aspect of man-made observations makes it difficult to find good quality time series. Besides, the focus of the research is on lowland regions defined here as areas located below 1000 meters a.s.l. And finally, the BernClim stations are mainly located within the canton of Bern, even if the set provides a transect through Switzerland. The choice of a first data subset is then selected as follows, using the BernClim data set. First, all the stations above 1000 meters were removed from the set. Then, only stations from the Mittelland region were considered. A specific attention to the exposition of the stations is also taken into account. Indeed, northern, southern and flat terrain expositions were chosen. This choice was decided a priori and then confirmed with the data set. The number and the quality of other expositions provided poor time series. From this step, the selection of the remaining data becomes more complicated and will depend on their quality check. It is necessary to investigate the quality of the data manually. The aim was to find good time series with as few year gaps as possible. The final selection of the sites is fully dependent on a personal, non statistical decision. At the end, the number of stations is 10. These 10 time series have to be carefully manually verified once again. All potential errors were either removed or corrected if possible. Because one of the main goals is to assess the different methods and compare them, the winter season is not defined from the hydrological point of view. The BernClim data set for snow is retrieved from September up to April. Then it is decided to use the maximum of the available information. For this research, a winter season is defined from September to April of the next year. Then, the winter year 1999-2000 includes all months from September to December of 1999 and all months from January to April of 2000. We will use the first year (in our example 1999) to name the winter season in the following lines.

A second subset was created. The purpose of the first subset was to obtain time series to evaluate the SCD trough time, as well as the evaluation of the method compared to others over the time. The purpose of the second subset is to study the SCD in space for one year only. The second subset was chosen taking into account the following: the stations above 1000 meters were removed and only Swiss Plateau areas were considered. For this subset, the whole range of expositions was used; the fact that we do not look for time series is not a limiting factor any more. Then, a year in the 1970s was selected, the one which has the highest number of observations. While the time period decided from the first subset starts in 1975, the selected year for space analysis is 1975 as well. With this choice we account for 148 stations for the second subset. At first glimpse, this data subset will be better than the first one for the assessment and comparison between methods. Two supplement years were selected: 1985 and 1989. Both correspond to the year with the higher SCD relating to the year with the lowest SCD. This duration was calculated from the whole BernClim data set for all the stations, as the mean of the total number of days with snow per year. To easily understand what will follow, a distinction will be made between the two subsets naming them time-pattern and space-pattern respectively.

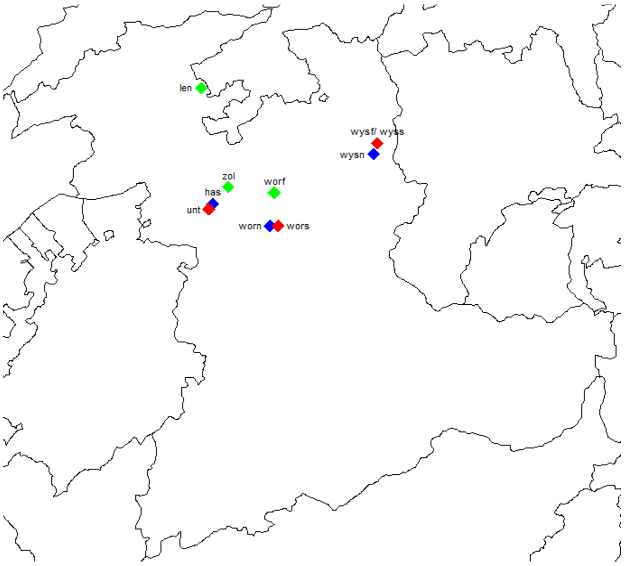
As it can be seen, the BernClim data are the limiting factor for the choice of the study period and the covered area. The inhomogeneity of the data set restricts the number of sites of study. Nevertheless, this little number of stations will be enough to make any comparisons between different methods. The other methods will be adapted to the BernClim subsets according to the study area. The snow model based on temperatures and precipitation is available for the entire Switzerland, as do the remote sensing data. Concerning time period, the snow model could fit the BernClim subsets. It is not the case for the remote sensing data that begins around the 1990s. It means that neither the remote sensing data nor the time series subset, nor the specific year subset fixed before 1990 will fit well. This is the first evidence that these methods could perfectly be complementary, but hard to compare.

3.3 Snow Cover Duration from BernClim

3.3.1 Time-Pattern Subset

As said before, the BernClim data set directly gives information, for a georeferenced location, the total number of days with snow for each month taken separately. It was then easy to obtain the SCD indicator. Nevertheless, the data have been verified and examined manually, to get good series with continuous record. The selection of the stations of interest is decided according to this BernClim data set. It was already explained that the sites were chosen depending on the quantity of data available. More precisely, the purpose was to select locations with the highest number of years with complete observations. It has to be kept in mind that the locations were also selected according to an altitude under 1000 meters a.s.l. and situated over the Swiss Plateau. Then, the arbitrary choice of the threshold, for the number of years needed, was made in a way to obtain the more stations possible with a good time-pattern. The 10 selected stations are shown on map 1. Out of these 10 sites, there are two stations that are represented by the three expositions. Actually, the sites of Worb and Wyssachen are 3 times used within the subset 1. Complementarily, both south and north expositions are completed by Unterdettigen and Hasli respectively, whereas Zollikofen (Bern) and Lengnau (Bern) complete the flat terrain sites. Table 1 describes the 10 stations that are selected for the time-pattern analysis with more details.

Long Time-Series Stations



Map 1 - Location of the 10 stations from the BernClim data set, which are used as time-series for the time-pattern analysis. Coloured points represent the flat (green), northern (blue) and southern (red) exposition. The 10 stations are located within the canton of Bern.

Table 1 - Description of the 10 stations used for the time-pattern analysis.

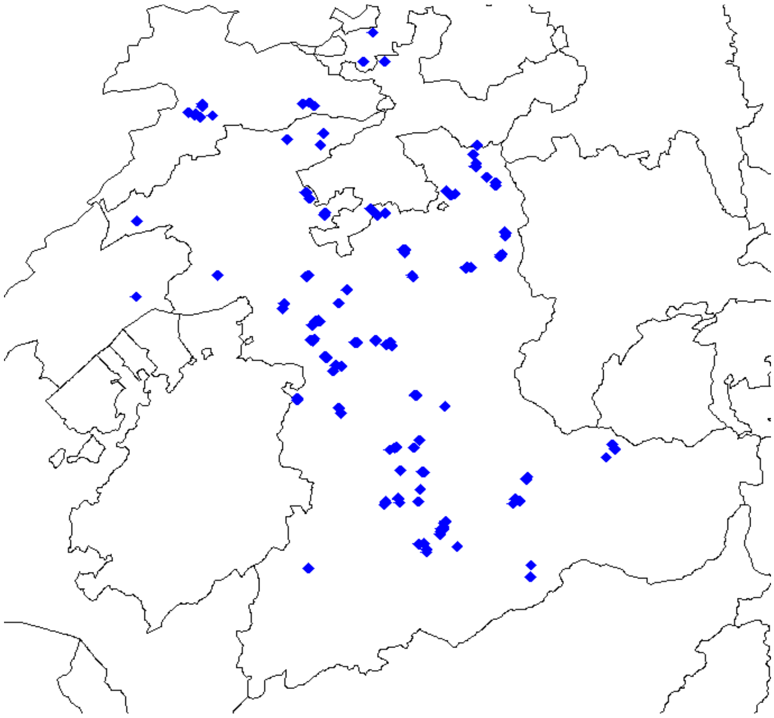
Code	Station	Exposition	Swiss Coordinates	Altitude
worf	Worb Kirche	flat	609600/197700	590 m
worn	Worb Wislenboden	north	608925/197400	600 m
wors	Worb Widen	south	610050/197500	620 m
wysf	Wyssachen Koronten	flat	629600/214375	710 m
wysn	Wyssachen Alpmettlen	north	629370/211810	920 m
wyss	Wyssachen Ofe	south	629875/214475	770 m
len	Lengnau (Bern)	flat	594860/225037	440 m
unt	Unterdettigen	south	596550/202050	520 m
zol	Zollikofen Landgarben	flat	600250/205200	570 m
has	Hasli	north	596800/201750	490 m

If one looks at the time series, Wyssachen provides two good time series with one year missing for both south exposition and flat terrain. Only Worb at its northern exposition is close with two missing years of SCD retrieval. The weakest time series are Wyssachen for northern exposition and Unterdettigen, that counts 12 and 13 missing values (years). Furthermore, those two time series begin around 1985. It makes them shorter, but they are almost continuous. This will unfortunately impact the analysis of site to site comparison. Each station has a different gap in the time series, which is uncomfortable for valuable comparison. This issue will be compensated with average subset of different stations that will be part of other subsets. One of them consists of the average of the 10 stations. This is relevant because of the selection of the 10 sites that have quite similar characteristics in terms of altitude and location. It can be argued that exposition does not permit to make this assumption. That's why another subset was created as the average of SCD relative to their exposition. These two last subsets provide complete time series with no year gap. They will be good for the comparison with other methods.

3.3.2 Space-Pattern Subset

It was easier to select the space-pattern subset. In fact, the set was filtered by year and, as the highest number of stations was found at the beginning of the BernClim project, year 1975 was selected to construct the first subset for the space-pattern analysis. With this, we obtain 148 stations (map 2). The two other years, previously described as the year with the highest and the year with the lowest SCD were extracted as year 1985 and year 1989 respectively. For the highest SCD year, 29 stations were available, 26 for the lower SCD year. The two last subsets were effectively weak for a spatial analysis of the SCD. Nevertheless, it will be interesting to investigate how the different methods behave for extreme years. Note that the extraction for the BernClim data set only consists in selecting the locations and then summing up of the number of days with snowpack in the considered years.

BernClim Stations for Year 1975



Map 2 - Location of the 148 stations used for the space-pattern analysis for 1975.

3.4 Snow Cover Duration from the Snow Model

3.4.1 Time-Pattern Subset

The snow model based on degree day factor takes into account the daily temperature and the daily precipitation. Then, the inputs of the model are minimum temperature (Tmin), maximum temperature (Tmax) and precipitation. The model contains two parameters: the temperature threshold that differentiates snow from rain, and the melting rate of snow.

3.4.1.1 The Model

The snow model is a simple snow accumulation model. In fact, the algorithm works as follow. First, the degree day factor is calculated with the minimum and the maximum temperature. Here it is decided to define the degree day factor (DDF) such as a weighted average of minimum and maximum temperature:

$$DDF = (2*Tmax+Tmin)/3$$

Other determinations of the DDF are possible. The choice was the one provided by Singh and Singh (2001), and, Auchmann and Brönnimann (2012). The critical mean temperature which corresponds to the threshold at which precipitation falls either as snow or rain is fixed. Here, there is a basic assumption that below 0°C, the precipitation falls as snow. It is not a realistic assumption, but for the purpose of this study it helps to model SCD for 8 months, the bias will not be too important. Then, the method is simple. The daily precipitation is considered. If the mean temperature of Tmin and Tmax is below the critical mean temperature, the amount of precipitation is transformed into the water equivalent of newly fallen snow. It will accumulate for all the period. But within the process, the melting of snow is considered. If the DDF is exceeding the value 1, the snow is melting at a rate defined at 1.74 [mm/°C/day]. This melting rate is the subject of many studies and literature reveals a broad range of values from 1 up to 9 depending on the author. Here the one similar to Basel is chosen. It was found by the US Army Corp of Engineers (U.S. Army Corp of Engineers, 1956). The end results are the daily accumulation rate and thus the daily snowpack height. Following are some more details about the process depending on the data set form.

3.4.1.2 Algorithm and Process

Temperature and precipitation are on a Netcdf format, which is a common format for georeferenced climatic variables. This format is relevant and widely used. Thus, it would be obvious to use this format directly. But, as it was decided to use R-software, the data set has to be manipulated and extracted into an array of 4 dimensions (longitude, latitude, day, and year). For the time-pattern subset, we only need to run the model for the selected locations. The pixel that must contain the location is chosen as the nearest coordinates within the grid. Then it has been decided to extract the inputs around the location taking the 8 pixels surrounding the pixel that includes the location. The model runs for one location at a time. The model converts the Swiss coordinates into lon/lat coordinates that are used within the MeteoSwiss data. The code was uploaded from the Swisstopo website (Federal Office of Topography Swisstopo, 2014). At this stage, the data for 9 pixels around a specific location are stored within an array. Thus the process consists in running the snow model as it was explained earlier. We compute the model in a loop for each day during the period from 1975-2010. Thus one gets the precipitation into snow water equivalent. This amount is accounted as snow if the mean temperature (here as the mean of Tmin and Tmax), is below 0°C. If the DDF is above 1, thus we account for the melting of the snowpack. We end with a snowpack's height for each day. Then the value of the day d is used to set the model for d+1. Once we get the snow height for each day, it is simple to get the presence of snowpack. The next step simply consists in creating the winter year as the months of September to December of the current year adding the months of January to April of the next year. Finally, we are interested in the number of days with snowpack, a binary indicator is created and shows the absence or presence of snow. Finally, the sum of the number of days with the presence of snowpack permits to obtain the SCD for one location. We get a value for the 9 pixels that we store in an array. The centered pixel is used for some analyses, but globally the average of the 9 pixels is calculated to have a better estimation of the SCD. The model is running for the other sites and the data is stored in one matrix which contains the SCD indicators for the 10 sites for each year.

3.4.2 Space-Pattern Subset

To get the same indicator but for the space analysis, the same model framework was used. The main algorithm difference is that the model is run for the entire Switzerland. Then when the binary information about the presence or absence of snowpack is available, the SCD for the selected sites are summed up. Nevertheless, we get the information of SCD for each pixel which covers the whole Switzerland.

3.5 Snow Cover Duration from Satellite Data

Satellite data are similar in many points to the MeteoSwiss data. In fact, it consists of a georeferenced grid. But, the grid points do not exactly correspond to this in the MeteoSwiss. Furthermore, a direct product of daily maximum snow extent is used. The data set consists of encoded information about the presence or absence of snow, or of other features described in the section of data set description. Thus, the process to get the number of days with snow is rather simple.

3.5.1 Time-Pattern

To extract SCD for the 10 stations, we run the process for one location at time, which is later stored in a single matrix. As for the model, the 8 pixels surrounding the pixel that includes the site are extracted. The data from the AVHRR product is in a GeoTIFF format, which is also a georeferenced format. This time, for the extraction of the data on R-software, we obtain not an array but a vector of length 92000 that contains the grid of Switzerland. It is inconvenient to find the right location within a vector instead of a matrix. The next steps are similar to these with the snow model. It is necessary to sum the days with snow in the 9 pixels that the satellite records. Then the winter year is constructed. Finally the procedure is repeated for each location. As for the model, the 9 pixels values are stored. And in addition, the average of the area that is representative of the locations is calculated. Here, a function to transform the GeoTIFF data into a raster form is used. Then, using this method, the format is converted into an ASCII scheme. It is more usable with the R-software. The inconvenience in treating data in this manner is that the encoded information is then stored in a vector; finding the position is not as simple as if it was a matrix. The vector is made as if each longitude were scanned by latitude. Thus, binding each vector of latitude together. Then, it is just necessary to count the number of days with snowpack retrieved by the satellite. As mentioned before, the data set contains some missing values and cloud values. The daily maximum snow extent final product has to deal with some unresolved issues. Particularly, it is not always possible to distinguish between snow and cloud. It is not the purpose of this thesis to work on the basic data set, in order to obtain the type of algorithm that solves the problem. Here, the product of AVHRR is used and the method evaluated.

3.5.2 Space-Pattern

As we have selected the year for the space-pattern analysis according to the BernClim data set, the data for the satellite space-pattern is not possible to obtain. Indeed, as a reminder, the three selected years were 1975, 1985 and 1989. Unfortunately, the satellite data time period begins in 1990. It means that the space-pattern for remote sensing retrieval will not exist for our comparison. It will be possible to select a year after 1990 to assess the method. But we miss data from the BernClim data set, and the purpose of the comparison of a high number of stations will not be fulfilled, which was the aim with the space-pattern subset. It would be interesting to compare the satellite data to the snow model for the entire altitudes below 1000 meters of the

Swiss Plateau. Even if the spatial resolution is not the same, both methods cover the entire country. But, because one of the main goals is to assess the relevance of man-made observations, it has been decided not to investigate this case of study in this way. Nevertheless, a comparison between the model and the satellite data will be undertaken.

3.6 Analysis Procedure

In the previous section, the data was described and the procedure to get subsets to assess the SCD was explained. This will support the analysis of the comparison of the three retrieval techniques. In a first step, a brief analysis of the SCD for individual methods will be undertaken. It will provide three analyses for evaluating the behaviour of SCD during the last decades. A general situation of this behaviour will be discussed. Subsequently, these results will be the support for the comparative analysis. As already motivated, the assessment of the different methods will be the main interest. It is then necessary to use appropriate statistical methods to make this comparison. De facto, the data available is three times the same variable for the same period and location with three different methods. Thus, if all methods perfectly retrieve the snow cover, the result will be three identical SCD indicators. It is not the case. But they are expected to be the closest possible. The first basic idea is to represent the indicator in a very simple way. The different subsets will be plotted according to some characteristics. As far as possible, the three different methods will be plotted together to get a good overview of the results. In a second part, the use of statistics will be used to evaluate the similarity between the data sets. Basics statistics will be applied in this case.

3.6.1 Visual Representation

The different plots and maps that are going to be displayed will attempt to represent different things, depending either on the location characteristics or on average features. The distinction between the time-pattern and the space-pattern for SCD will form the two sections of the plotting part. As far as time-pattern scheme is concerned, the 10 stations are first plotted independently for the three methods. Because the stations have different locations, it would be wise to plot average SCD by exposition of the site in a second step. Consecutively, it seems obvious to plot the average SCD of the all 10 stations. Concerning space-pattern, plots will not represent time-series. The idea here is to plot the three selected years in a relevant and informative way. For each year, the BernClim SCD indicator will be sorted from its lowest to highest value. In a second step, the same idea will be applied, but this time BernClim SCD indicator will be sorted by locations altitude. At first glimpse, the year 1975 is the most valuable subset, because of its number of stations, which reach 148. However, the year 1985 and 1989 will be displayed as well even if the total number of stations is less than 30 sites. In addition, a map will be presented to express the spatial aspect of the SCD. Moreover, snow model or satellite methods make the cover of Switzerland in its entirety possible.

3.6.2 Statistical Analysis

Simple statistical techniques will be applied to the SCD indicator, in order to study the similarity between data sets from the three methods. The main difficulty is to choose a reference. Making a comparison between methods would normally suggest that a reference acts as the reality. A dilemma appears at this point. Man-made observations are very close to the reality if and only if the observers made the job properly. For snow cover observations, it seems evident to have quality data as it is just a task to record the presence or absence of snow. In the other way, one purpose of this work is to assess if these records are of good quality. Thus, making the comparative analysis between the methods entails just checking how close they are (or how far). In a first step, the statistics applied in this case consist in the comparison of the mean. Thus, a comparison of the three means observed from the three independent samples (type of data set) whenever it is possible and relevant. Then, because one computes anomalies, the mean will be close to zero and the comparison of the mean becomes inappropriate. Then, the next step is to compare the pattern of the different methods, and to see if they are similar. Coefficients of correlation and associated test will easily be used in order to do that.

3.6.3 The Comparison and Assessment of the Methods

Plots and statistical analysis permit to assess the retrieval methods one against the others. Then, it is known that methods could be used together to complete any purpose. Thus, in a final step, a synthetic analysis of the different methods will be achieved. Relevant advantages and disadvantages will be discussed. This will help to make an appreciation of the different methods and to analyse how they could be used together. A particular questioning will address data complementarities and gap filling. This phase will end with a proposition on how to proceed to obtain any good-quality snow cover data for low altitude in the absence of automatic stations. It will make a final overview of the different methods to provide snow cover information. This work is based on the fact that automatic stations act as a kind of solid standard for climatic variables. This is not completely true, because we use temperature and precipitation from the MeteoSwiss automatic stations as inputs for the snow model. Nevertheless, it can be affirmed that both climatic variables are the two most common variables that are often retrieved from ground automatic stations. Then, if we consider the snow variable for low altitude, this work does not use these automatic processes. In a sense, the aim is to provide a catalogue of snow retrieval techniques, which specifies advantages, quality and specific characteristics.

4. Results

4.1 Snow Cover Duration: Time-Pattern Analysis

This part focuses on the representation of SCD for the three different methods. It takes the form of plots which represent the SCD for each year with a different point of view. It has been decided to mainly analyse the anomalies. This choice is motivated by the difference between the stations and the methods. Actually, the goal is to make the data comparable. Even if the same stations are analysed with different methods, there will certainly be some divergence between the methods. Then, the results will differ as well. Thus, it has been decided to get focused on the trend of SCD through anomalies, which will make the results, a priori, closer between methods.

4.1.1 BernClim Stations

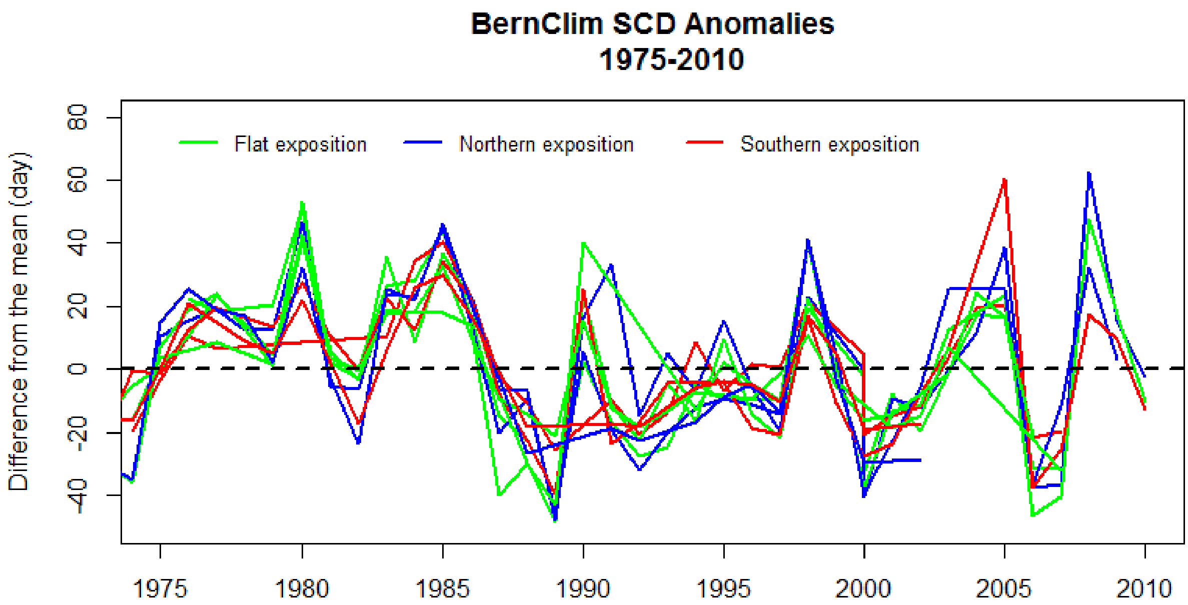


Figure 1 - Anomalies of snowpack duration for the period 1975-2010 according to 10 time-series BernClim stations. Anomalies are calculated as the simple difference from the mean for the entire considered time-period. The sites expositions are represented using green (flat), blue (north) and red (south) colours.

The BernClim SCD anomalies are displayed on figure 1. The plot shows each station, with distinctive expositions (colours). The difference from the mean has been plotted in order to suppress the extreme stations with high or low amount of snow. It rules for having values around zero. At first glimpse, a decrease in the SCD since the late 1980s can be estimated. In fact, more negative anomalies have been observed since this period. However, it can be argued that the period before 1990 has not been long enough to affirm it. But, it is reasonable to say that the number of days with snow per year is decreasing on average. Another interesting fact is the highest positive anomaly that appears in 2008 for Worb at northern exposition and for Wyssachen at southern exposition in 2005, which means recently. The highest negative anomaly stands between those two years. Thus, within our data set it is observed that there are extreme values during the last decades. It is a bit ambitious to affirm that it corresponds to global climate change and the related change in the magnitude and frequency of extreme events. Globally, the stations show a similar pattern. We are not able at this stage to distinguish well between the different expositions, and we cannot evaluate any clear distinction between one and the others. A last tricky observation concerns the divergence between the stations. It seems that in the middle of 1970s the stations show closer SCD, whereas it seems not to be as true after 1990.

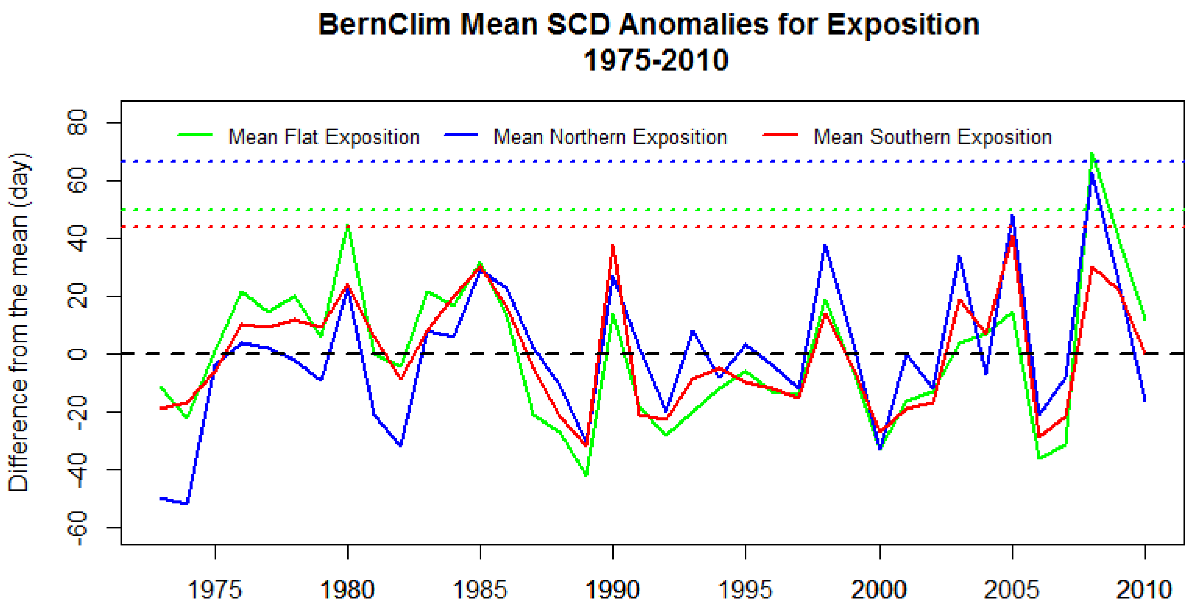


Figure 2 - Anomalies for the snowpack duration according to exposition (green, blue and red colours for flat, north and south expositions respectively) average using BernClim stations for the time period 1975-2010. Anomalies are calculated as the difference for the mean of the time period considered. Mean SCD is represented with the dotted lines.

It is interesting to differentiate the stations by exposition and average then get a more consistent and reduced information. Figure 2 shows SCD anomalies for the flat (green colour), north (blue colour) and south (red colour) expositions. In addition, the mean value for SCD is drawn with dotted lines and associated colours. It is less obvious here that a step-like decrease in the SCD occurs after 1990. The trend is not as pronounced as it was the case for each individual station. Firstly, it brings to light that the mean SCD for northern exposition is higher than the one for southern exposition. It is trivial in a way, but it allows assessing consistency with BernClim data. In fact, the mean SCD for northern exposition is around 67 days. The mean for flat exposition is 50 days and for southern exposition it is 44 days. More generally, the different expositions tend to have the same pattern and behaviour. It is partly due to the fact that we used the same location within the BernClim data set, with different expositions. For example, stations of Worb and Wyssachen have both the three expositions represented in the data set. Then, there is no clear decrease or increase for the SCD anomalies. Nevertheless, it is observed that there is a change in the frequency of high SCD around 2000 up to nowadays.

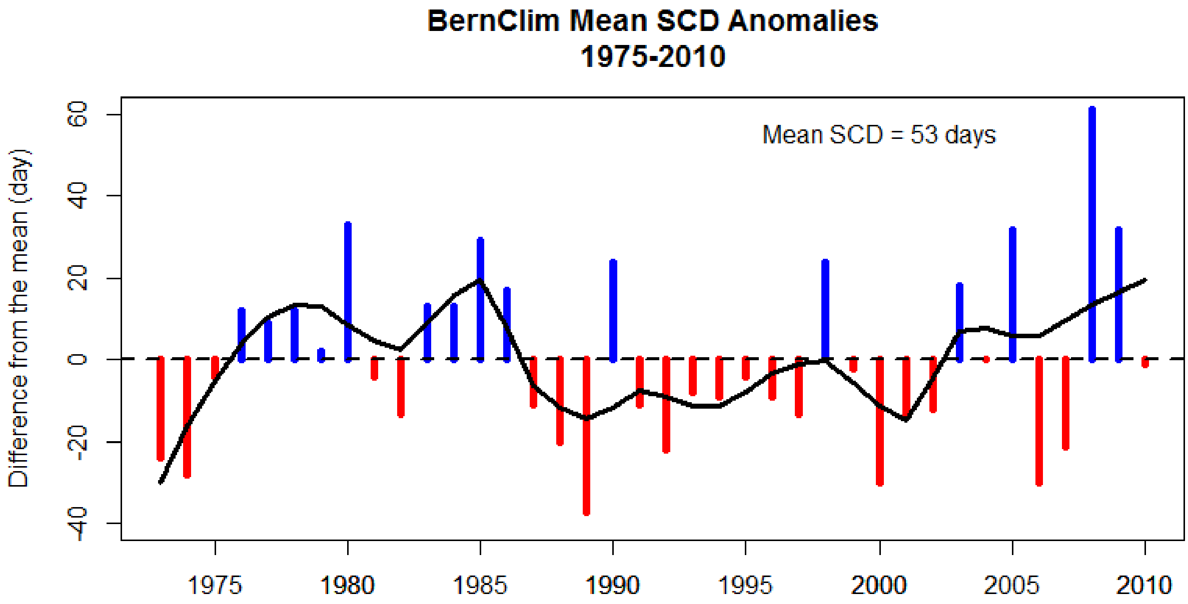


Figure 3 - Anomalies of the snowpack duration according to the 10 BernClim stations for the period 1975-2010. Blue vertical bars represent positive anomalies and red one negative anomalies. The black line represents the smoothed values using a polynomial regression fitting process.

Figure 3 represents the mean SCD anomalies for all the selected locations. One obtains a mean SCD of 53 days for the entire period. More negative SCD anomalies are observed since the middle of the 1980s. We observe here a step-like decrease in SCD anomalies. In addition, the highest positive anomaly appears in 2008 as it can also be noticed with individual plotting of stations. The uncertainties, calculated as standard deviation, are a bit higher between 1990 and 2003 (appendix 1). Even if the uncertainty range is considered, the increase of SCD negative anomalies tends to be higher since the early 1990s. A smoothing method has been added to get a better approximation of the SCD anomalies. The decrease around the 1990s is better seen. A contrario, an increase after year 2000 is evident, and the anomalies seem not to fall below zero.

4.1.2 Snow Model

SCD anomalies processed with the accumulation snow model are displayed on figure 4 for individual stations.

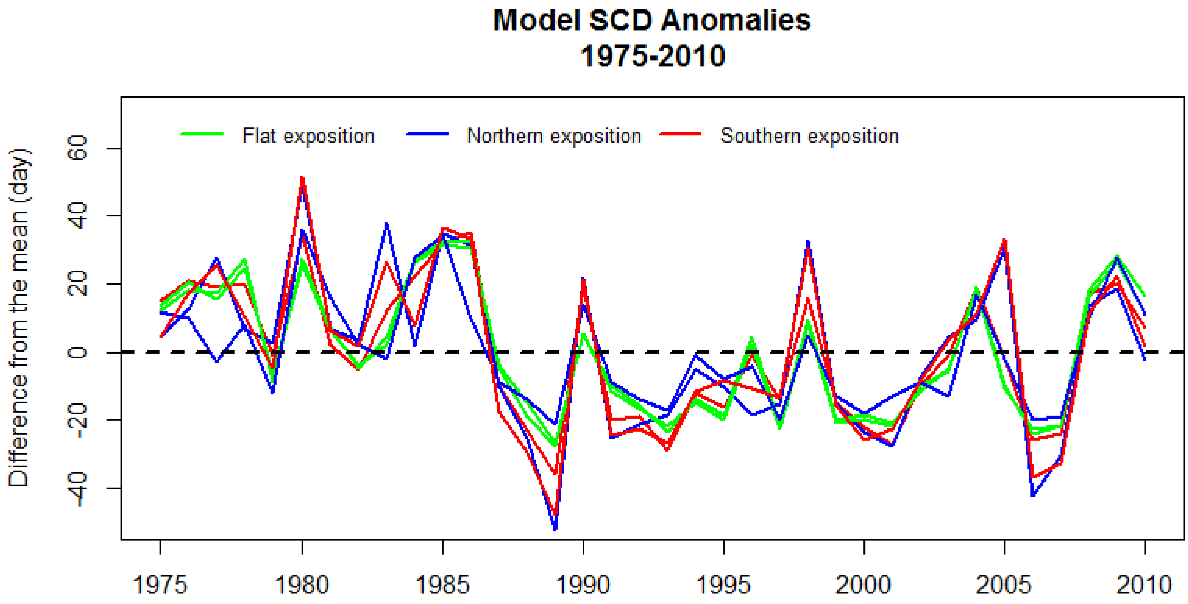


Figure 4 - Anomalies of snowpack duration for the period 1975-2010 according to 10 locations (same as BernClim) computed with the snow model. Anomalies are calculated as the simple difference from the mean for the entire considered time-period. The sites expositions are represented using green (flat), blue (north) and red (south) colours.

Interestingly, the dispersion between the stations is less important with the numerical model than with BernClim. It is more evident here that more negative anomalies occur around 1990. No site is far apart from another. The pixel resolution would be an appropriate explanation for this. In fact, with the BernClim data, in situ measurements come into play, whereas snow model involves km-pixel. Furthermore, values are interpolated. It loses information and precision. It is not possible to distinguish between the different expositions. Because all the 10 stations are relatively close one to the others, it is appropriate here to average the stations, especially due to the resolution and the proximity of some locations. Some sites that were differentiated in the BernClim data set stand in the same pixel within the gridded data.

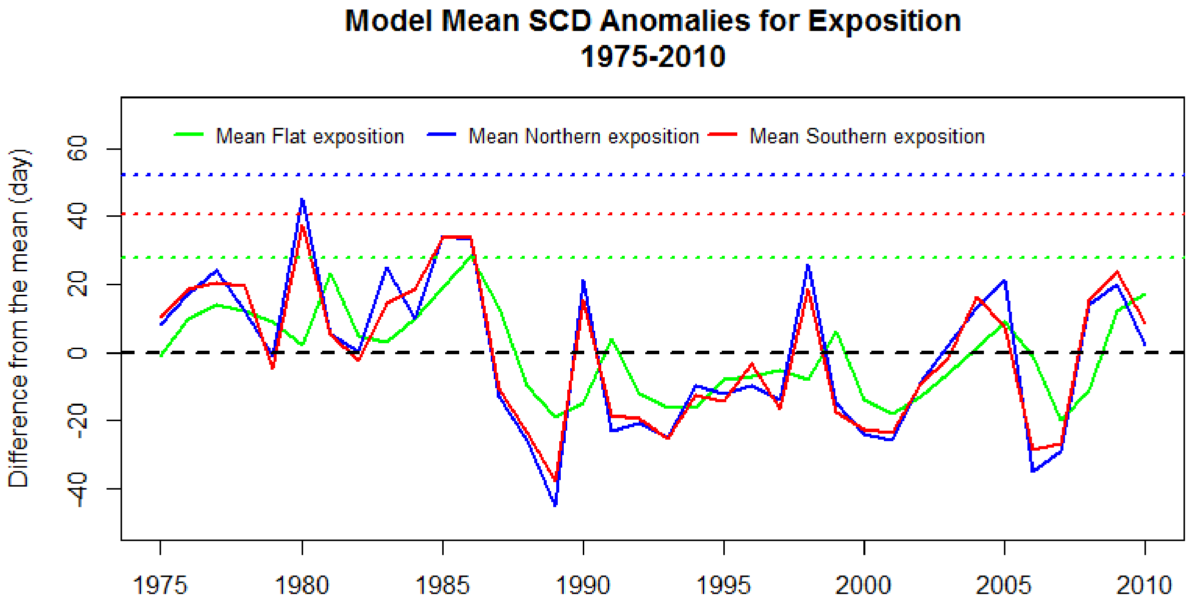


Figure 5 - Anomalies of the snowpack duration according to exposition (green,blue and red colours for flat, north and south exposition respectively) average using sites calculated with snow model for the time period 1975-2010. Anomalies are calculated as the difference for the mean of the time period considered. Dotted coloured lines are the mean SCD.

The mean SCD by exposition (Figure 5) looks close to the plot of individual stations. Nevertheless, it brings more clarity. As for the previous plot, there is an increase of negative anomalies since the late 1980s. High positive or negative anomalies are not much. And the three different expositions follow quite a similar variation. It is true according to northern and southern expositions, which are almost superposed. Then, both match very well. However, their SCD means are different. The mean SCD (dotted coloured lines) shows that flat terrain is lower than south exposed terrain. It would be more realistic if either show quite equal value or that flat terrain has slightly higher values than southern exposition. Nevertheless, the northern exposition gets the highest value. Mean SCD is 52 days for the northern terrain, 40 days for the southern ones and around 28 for flat terrains. As the exposition average is quite close, the SCD mean using all locations gives a good representation of the situation for lowland regions. In addition, the uncertainty range is relatively small. It therefore gives a solid indication of the snow cover. But, it has to be kept in mind that the model has a resolution which implies that for different locations, the same pixel is used to evaluate the SCD. For example, the three stations for Worb are represented by the same nine pixels to compute the model. Then, Worb is used three times in each exposition with almost same pixels.

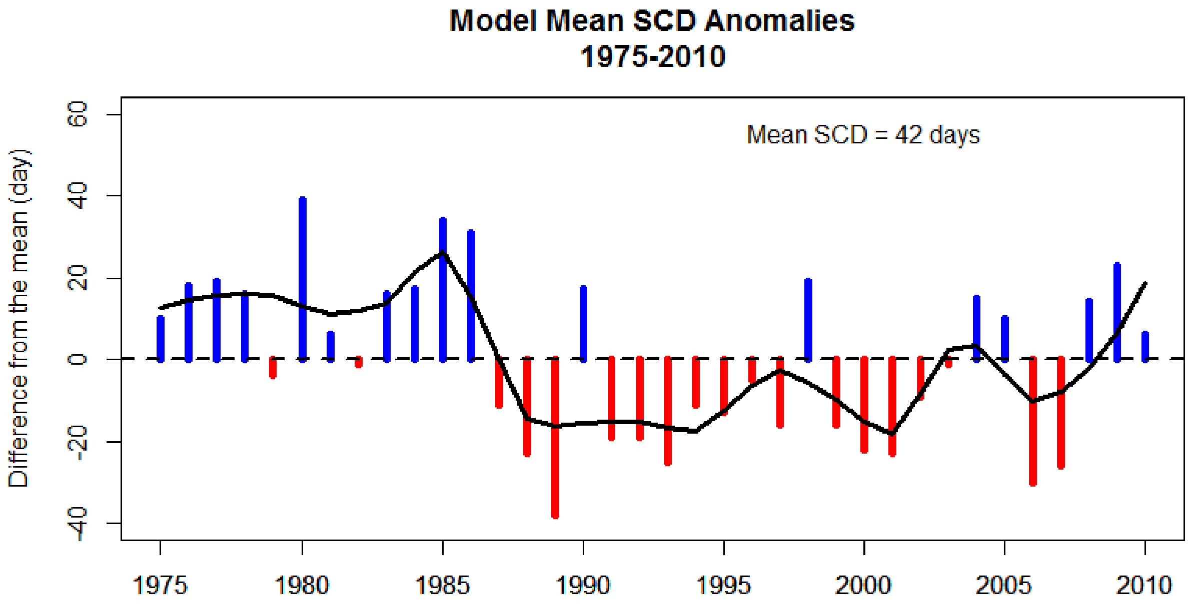


Figure 6 - Anomalies of the snowpack duration according to the 10 snow model locations for the period 1975-2010. Blue vertical bars represent positive anomalies and red ones, negative anomalies. Black line represents the smoothed values using a polynomial regression fitting process.

Looking at the figure 6, it is observed that there is an increase of negative anomalies for the average of the 10 stations as viewed previously. But, in this case the magnitude is not as strong. There is not any important peak of SCD, it is even less for the year 2008. The frequency seems not to be irregular any more, as it was the case with the BernClim data. The relevant observation here is the quasi absence of negative anomalies before 1987. Thus, according to our stations and the method, a change in the SCD in the lowland region of Switzerland is observed. If the mean of SCD for the period going from 1975 to 1986 is calculated, the result is 59 days. If the mean of SCD for the period going from 1987 to 2010 is calculated, the result is 34 days. A clear drop in the SCD in lowland regions appears here. Applying the smoothing Gaussian method, the black bold line is obtained. Anomalies are plotted, with smoothing lines. Thus with these fitted lines, mainly negative anomalies are observed between 1987 and 2007. As already said, some stations, more precisely their corresponding pixels, are used more than once for the averaging (different expositions for the same station). Thus, in the model some locations are weighted by a factor of 3. It diminishes the uncertainty range (appendix 2) and makes the results biased.

4.1.3 NOAA-AVHRR

The satellite data set is unusable considering the way we analyse the data. As explained in the data set description, many issues about satellite snow retrieval are still occurring. Moreover, the time period is small with only 20 years of data. Thus, adding those two parameters, no results close to reality are expected a priori.

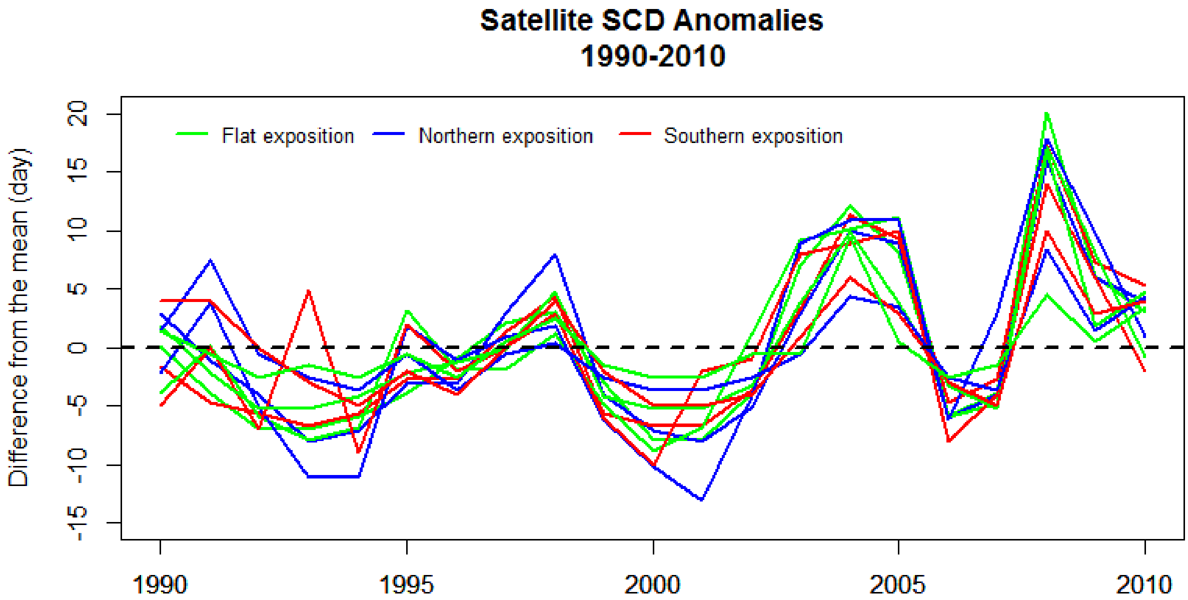


Figure 7 - Anomalies of snowpack duration for the period 1975-2010 according to 10 locations (same as BernClim) retrieved from satellite data. Anomalies are calculated as the simple difference from the mean for the entire time-period considered. Site expositions are represented using green (flat), blue (north) and red (south) colours.

Figure 7 represents SCD anomalies for individual stations using the NOAA-AVHRR satellite data. At first glimpse, the 10 stations show similar tendency. The fact that within the data set differentiating between the cloud and the snow is unsolved makes the trend more constant because of clouds that are more constantly present. This figure for individual stations gives no clear information. It will be good to plot the mean of exposition in order to hope for a better understanding of satellite data.

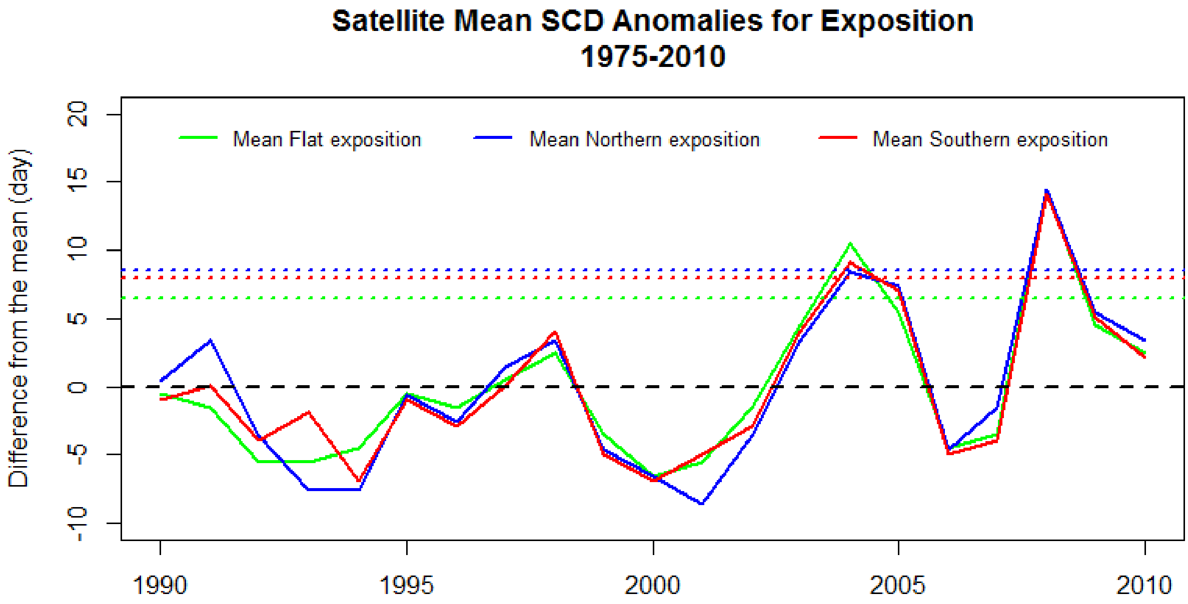


Figure 8 - Anomalies for the snowpack duration according to exposition (green, blue and red colours for flat, north and south expositions respectively) average using sites retrieved from the satellite data for the time period 1975-2010. Anomalies are calculated as the difference for the mean of the time period considered. Dotted lines are the SCD mean for expositions.

The SCD anomalies plotted according to the different expositions (Figure 8) show quite the same results. The result for a mean duration of snow cover from the highest to the lowest value is 9 days for the northern exposition, 8 days for the southern exposition and 7 days for the flat exposition. There are relative extreme positive anomalies around the year 2000 and 2008. Otherwise, the anomalies are quite close to zero with mainly negative values. Northern exposition has a higher mean SCD than southern and flat expositions. As for previous methods, the occurrence of negative anomalies is high. Nevertheless, we observe here a slight increase of SCD anomalies. Because of the time period, obvious trends such as the drop in SCD are not seen. The short period of time of the last two decades is poor regarding time resolution.

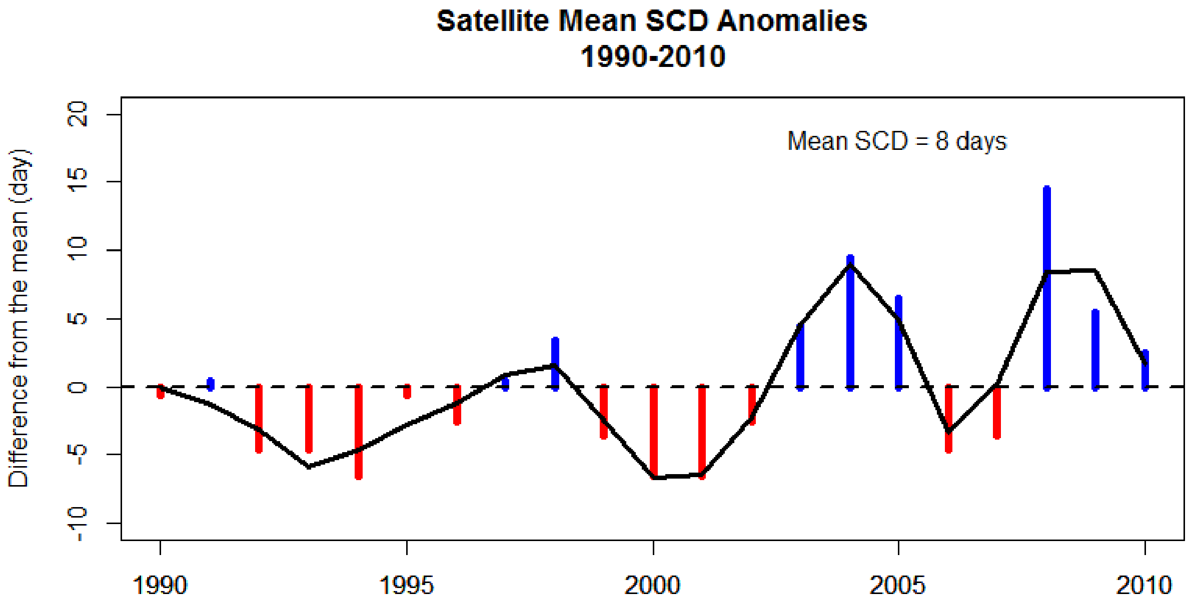


Figure 9 - Anomalies of snowpack duration according to the satellite data set for the period 1975-2010. Mean is calculated with 10 locations. Blue vertical bars represent positive anomalies and red ones, negative anomalies. The black line represents the smoothed values using a polynomial regression fitting process.

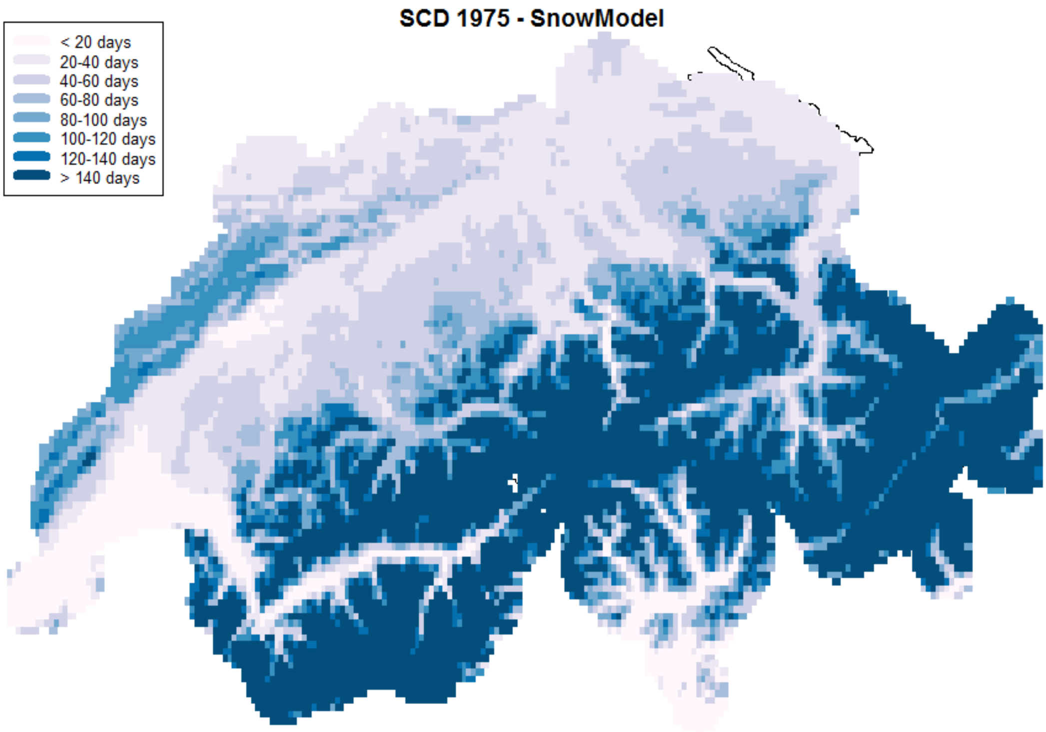
There is a low mean SCD with a value of 8 days (Figure 9). In fact, the set represents only the two last decades and SCD tends to slightly increase last 10 years, but the value seems to be low. Thus, the first conclusion is that the satellite data seem not to fit the reality in term of quantity but could be true in term of tendency. There is a change in SCD anomalies since 2003. Actually, positive anomalies appear in the last year of the time period. At this stage, just the plot is considered and those conclusions are judgemental. The issues relating to this data set do not permit to undertake any assumption for SCD.

4.2 Snow Cover Duration: Space-Pattern Analysis

4.2.1 Prelude

The analysis of the space-pattern includes only BernClim and snow model data set. The selected years 1975, 1985 and 1989, are not included within the remote sensing time period. Then, the comparison is reduced. It would be possible to select another year in order to use the satellite data. But first, the quality of the NOAA-AVHRR data makes the analysis not of our interest. Secondly, the underlying aim of studying the man-made observations means that interest is focused on BernClim data set. The analysis of one year, to get space-pattern results, seems not relevant to SCD analysis. This pattern is mainly useful for the method comparison, as partly explain in the introduction of this work. It will be displayed with satellite data and compare with the model, hoping to get some informative results.

4.2.2 Year 1975



Map 3 – Snow cover duration computed with the snow-accumulation model for the year 1975.

Map 3 represents the number of days with snow for the year 1975 using the model. The map shows a usual representation of the different climatic zone of Switzerland, and it highlights the mountainous terrain and the intra alpine valleys as well. It should be kept in mind that the model uses precipitation and temperatures, and for the considered year it sets up a snowpack of 0 cm. The model does not consider the present snowpack at the starting date. Because the focus is on lowland regions, this remark is not a major problem. It can be assumed that at these altitudes, an important snowpack or even a small one can be found. On lowlands regions, a gradient of SCD is observed, depending on the distance from the mountain range. There is a zone parallel to the Alps and the Jura chains.

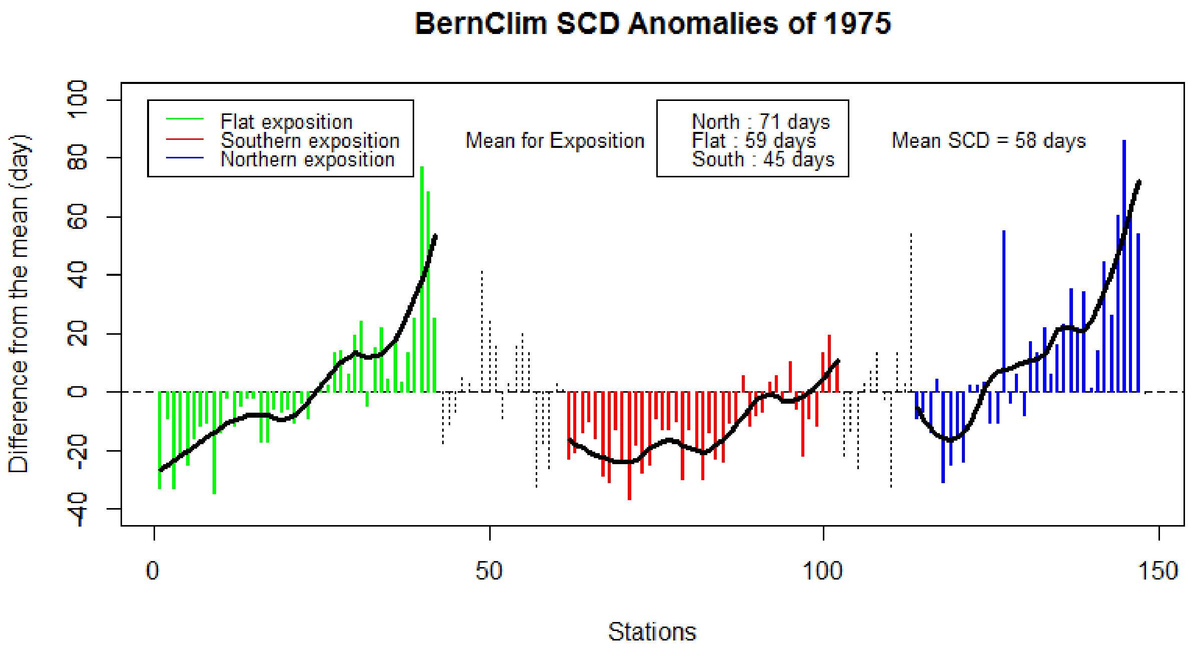


Figure 10 – Anomalies of snowpack duration for year 1975 using BernClim stations. Anomalies are calculated as the difference from the time-period mean. Stations are sorted by exposition and then by altitude. Flat (green), north (blue) and south (red) exposition are highlighted. Dotted anomalies represent the other intermediate expositions. The black line represents smoothed values using a polynomial regression fitting method.

Figure 10 shows the SCD anomalies for 148 stations selected for the year 1975 within the BernClim data set. The stations were plotted according to their expositions (colours) and then by altitude (from left to right). The exposition begins with the flat exposition and after it goes clockwise from the North-East up to the North. To facilitate the visualization, the colours of considered expositions have been drawn. The dotted line represents the other stations' expositions. The altitude effect for each exposition is obvious. There is an increasing trend with some variations. The southern exposition show less pronounced trend, at least within the altitude range below 1000 meters. Here, northern exposition has a higher mean of SCD. Flat exposition follows and, last southern exposition has the lowest value for mean SCD, which is consistent with the physical reality of insolation. This is expanded by the higher positive anomalies for northern exposition and lower values for south. This is coherent with natural behaviour.

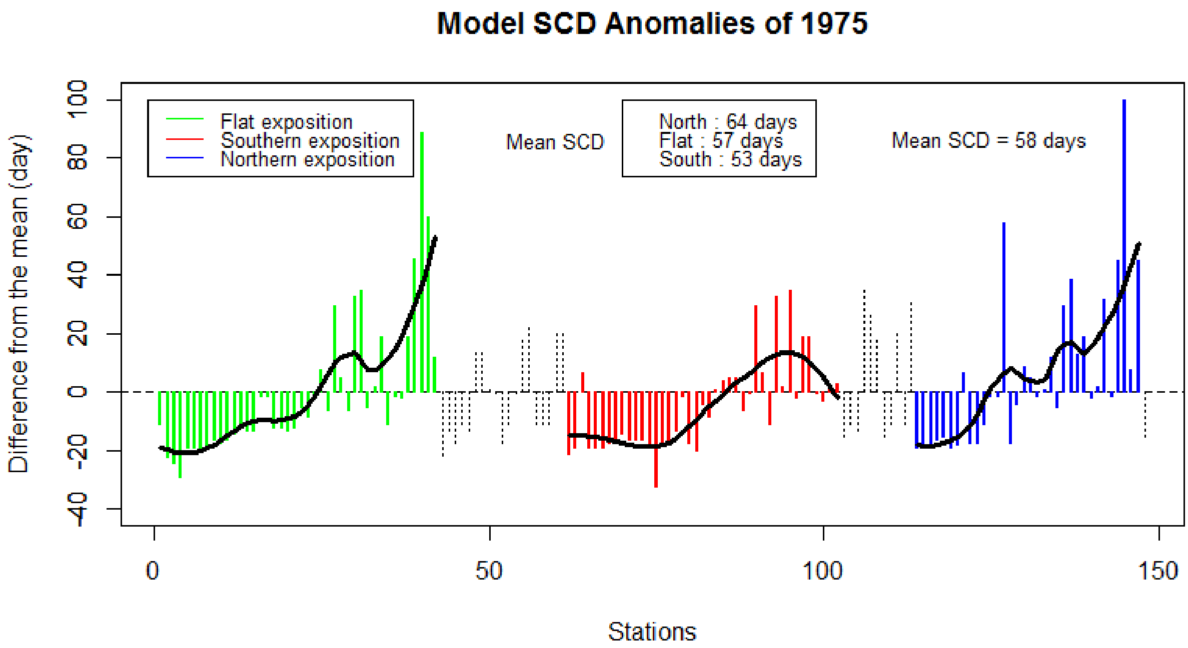
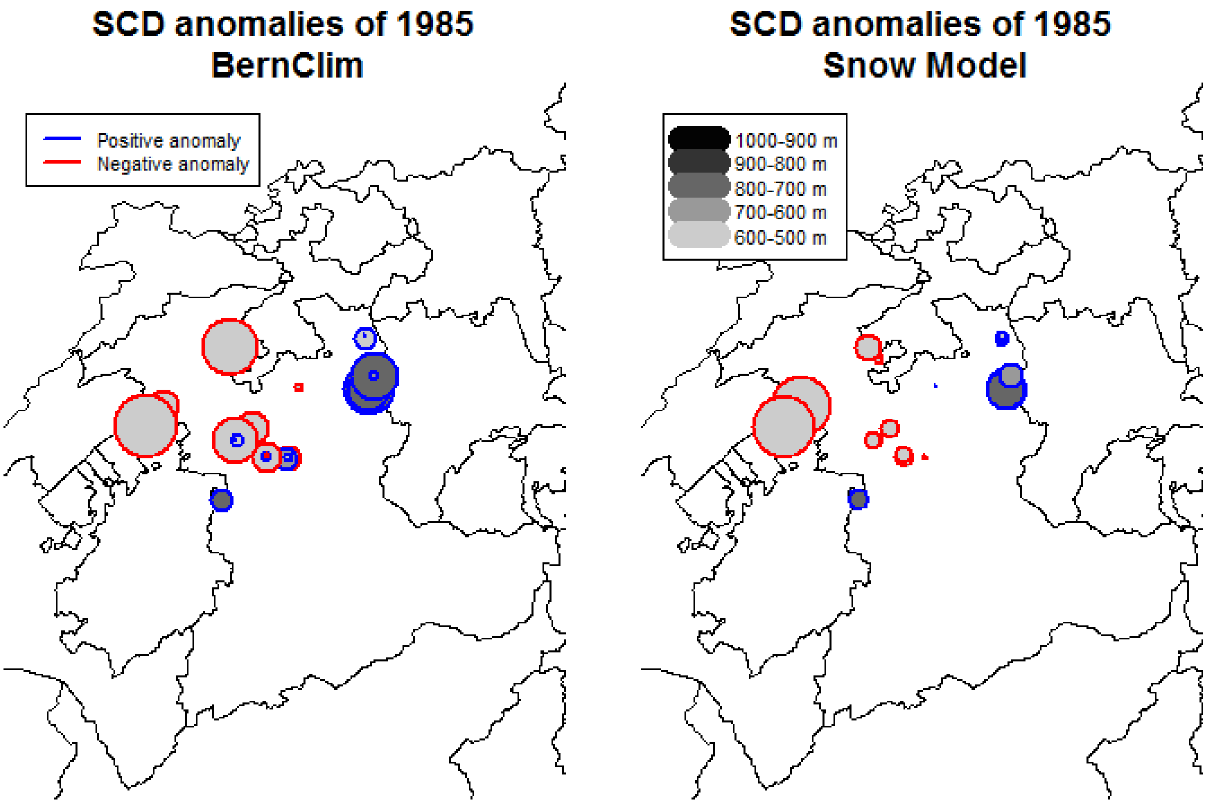


Figure 11 - Anomalies of snowpack duration for year 1975 using the snow model. Anomalies are calculated as the difference from the time-period mean. Stations are sorted by exposition and then by altitude. Flat (green), north (blue) and south (red) exposition are highlighted. Dotted anomalies represent the other intermediate expositions. The black line represents smoothed values using a polynomial regression fitting method.

Figure 11 is the same plots as the previous one but computed with the snow model. Similar trend relating to altitude is perceptible. Nevertheless, there is a higher number of big positive anomalies. High oscillations also appear. Of course, all of this depends on the location of the stations, which could be more propitious to receive snow. Once again, northern exposition has a higher mean SCD and southern exposition gets the lowest value, which makes sense. The mean SCD is of 58 days – the same as the one found with the BernClim method. It shows that for big number of stations, the two methods for one year give a similar mean for SCD. It will be great if the same similarity could be found for another year with less number of stations.

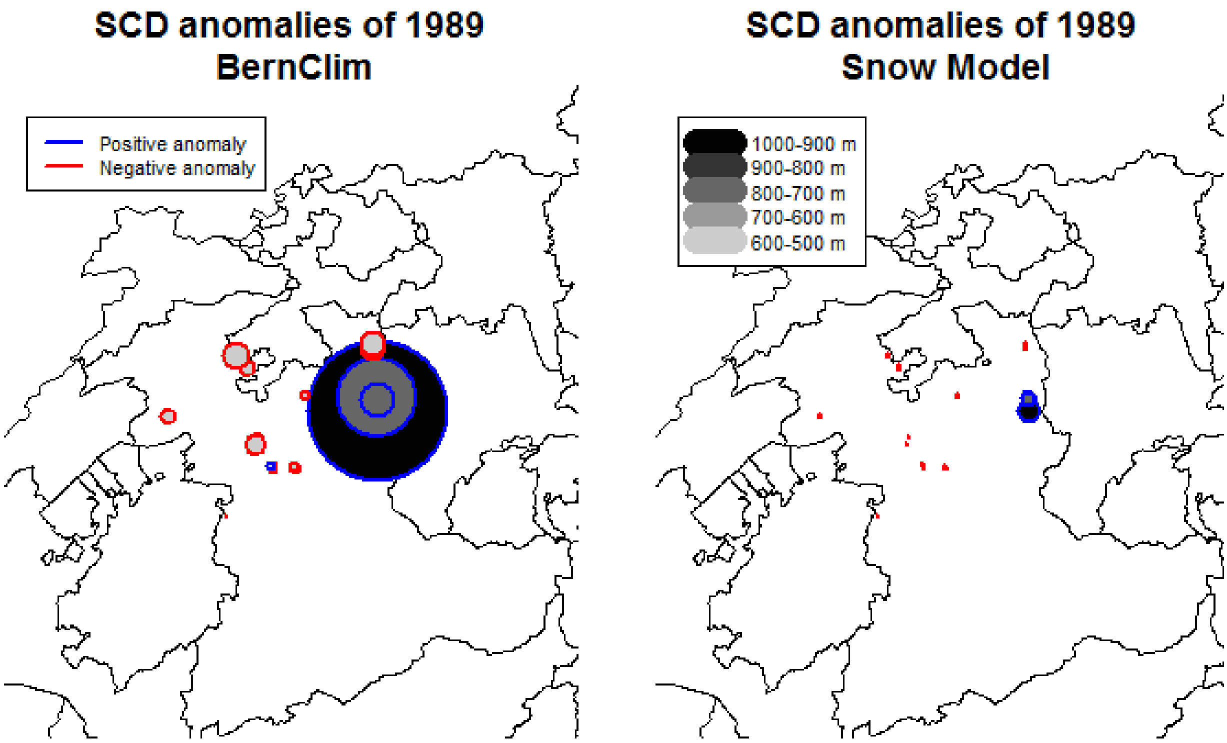
Let's see now at which altitude the anomaly becomes positive. When the BernClim method is used, this change appears at 570 meters for the northern exposition and at 800 meters for southern exposition. Following the snow model, this threshold stands at 575 meters for the northern exposition and 670 meters for the southern one. For both methods, the flat exposition shows a threshold of change in anomalies sign at 630 meters. If we calculate this critical altitude for the entire 148 stations (considering all the expositions), the result shows 640 meters with BernClim method and 620 meters with the snow model. Here there is comparative information between the two methods: for the southern exposition, the threshold between both methods differs by 130 meters, which is quite important. Nevertheless the 20 meters of difference for the entire data set is a good result.

4.2.3 Extreme Years: 1985 and 1989



Map 4 - Anomalies of the snowpack duration for year 1985 according to BernClim (left) and the snow model (right). Anomalies are calculated as the difference from the time-period mean. Positive (negative) anomalies are plotted with a blue (red) circle. The size of the circle gives the relative value of the anomalies.

The space-pattern analysis for 1985 and 1989 is quite complicated. The number of stations reaches 29 respectively 26. Thus, to look at exposition or altitude, this number is much lower and gives little information, as shown on map 4 (and appendix 3). Nevertheless, there is a positive trend according to altitude. In fact, a gradient from the North West up to the South East is observed. Expositions were not plotted because no relevant information was found. It is not possible to make any strong assumption since there are not enough values.



Map 5 - Anomalies of the snowpack duration for year 1989 according to BernClim (left) and the snow model (right). Anomalies are calculated as the difference from the time-period mean. Positive (negative) anomalies are plotted with a blue (red) circle. The size of the circle gives the relative value of the anomalies.

It is also the case for the year 1989 (map 5 & appendix 4), which corresponds to the year with the lowest mean amount of snow relative to the BernClim data set. There are increasing anomalies in the altitude dependence. But the exposition seems not to have any influence, which is understandable with the very low amount of snow. This is the reason why the different expositions were not indicated on this map. The model returns very low anomalies. Mean SCD is of 7 days. The BernClim data show much higher anomalies for the highest stations. This shows the difference between the measurement point and the interpolation over a grid. To sum up, with a poor number of stations and a year with low snowpack duration, it is clearly difficult to make any assumption. More relevant results are expected with the comparative analysis between the methods.

4.3 Comparison Between Methods

This part investigates the level at which the three methods provide similar results. This evaluation will be made in three parts. First, a simple plot review will give us a first insight into the comparison. Secondly, a statistical analysis will be performed to compare mainly the mean and then, the pattern relation between the methods will be analysed. And finally, a list of advantages and disadvantages will be provided for the three methods as a summary.

4.3.1 Time-Pattern Comparison

For the time-pattern comparison, the 10 stations from year 1975 to 2010 are concerned. The two ideas were basically either to compare each station using the different methods, or to compare an average of stations. As already used, it is possible to analyse the mean SCD according to the exposition of all the stations. Nevertheless in a first step, the mean of the entire stations is considered and the SCD for the three methods is plotted before looking at SCD anomalies. The result appears on figure 12.

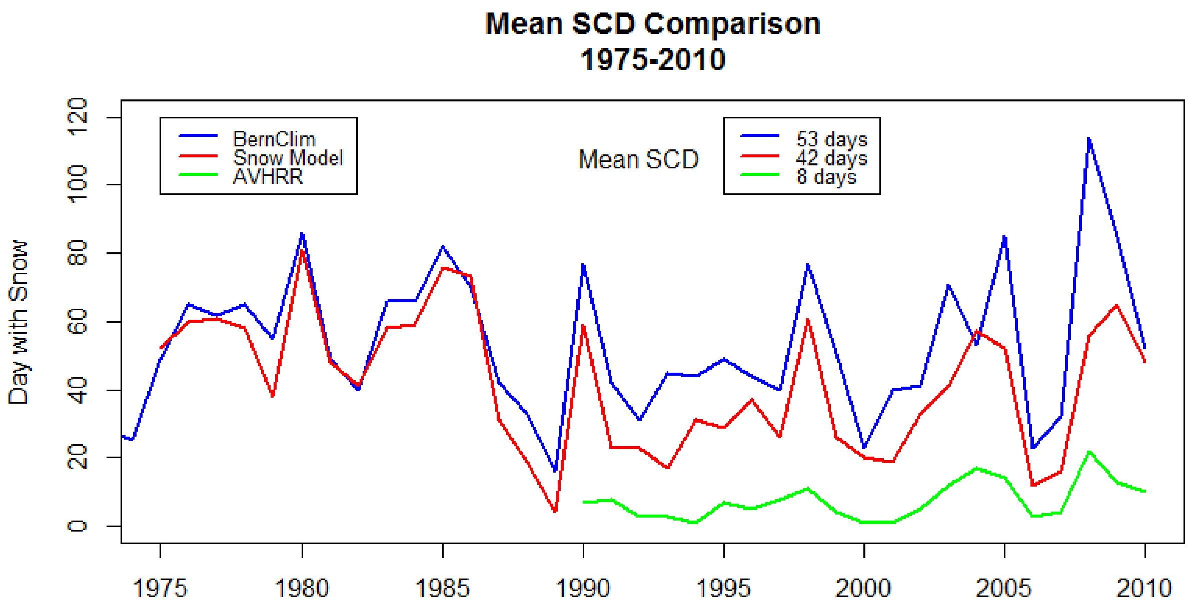


Figure 12 - Comparison between BernClim (blue), snow model (red) and satellite (green) methods for mean snow cover duration in days for the period 1975-2010.

The first observation, which appears clearly, is the mismatch from the satellite data. Even if the time period is not the same, the mean SCD is far lower than for the two other methods. The satellite data has many issues discussed in the data description. It may explain this underestimation of SCD. Secondly, the snow model gives lower values, and BernClim data show higher extreme values. It is coherent with the mean SCD of 53 days for man-made observations and 42 days with the model. Another interesting observation is that both methods seem to give closer values of duration before 1987 and then show quite bigger differences. The calculation of the mean for the period going from 1975 to 1986 shows 63 and 59 days of snow for the BernClim and the snow model data set respectively. For the period going from 1987 to 2010, the mean is 51 days for BernClim and 34 days for the model.

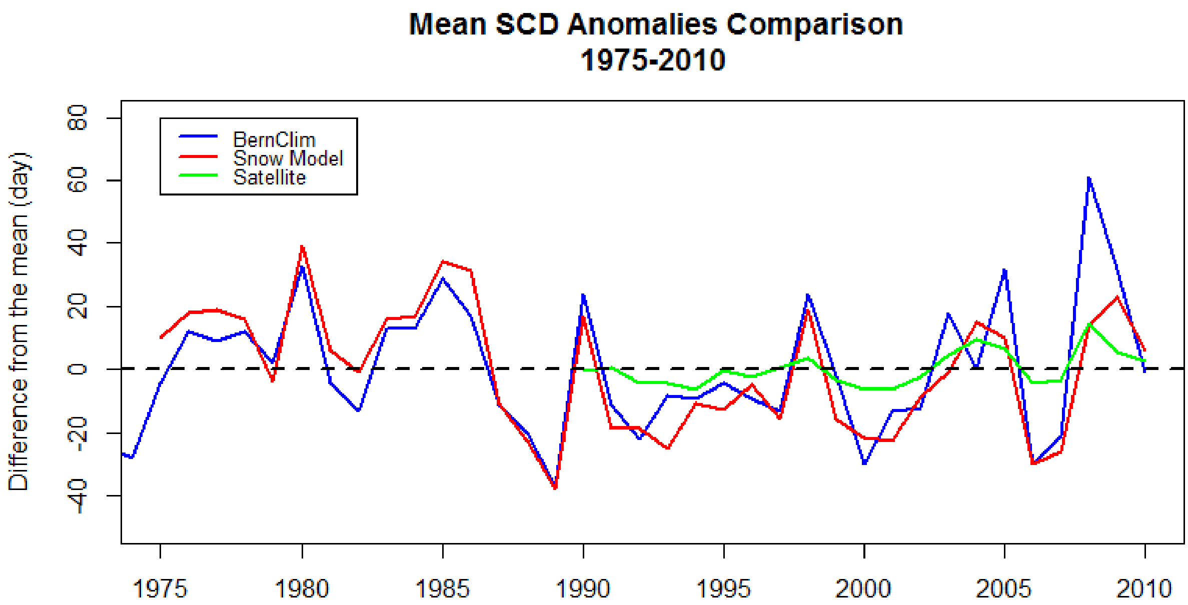


Figure 13 - Comparison between BernClim (blue), snow model (red) and satellite (green) methods for mean snow cover duration anomalies in days for the period 1975-2010.

Looking at the anomalies (Figure 13), the satellite data is less pronounced than the two other methods. It swings around zero most of the time. Nevertheless, the satellite data shows the same tendency since 2003 and it returns the same signs of the anomalies. Positive and negative anomalies match very well. As far as the two other methods are concerned, a good fit globally appears, at least for the tendency (increase and decrease). It is judicious to look into both methods comparing the SCD anomalies, to see if it gives more consistent results.

There is a good match between both man-made observations and modelled SCD anomalies. There is only one mismatch in the year 2008 where the BernClim which gives an anomaly of 60 days and the model only 14 days. It gives 46 days of difference, whenever the lowest difference between the anomalies is lower than 1 day. The mean difference between the two methods for the

SCD anomalies is 8.8 days. Then, both methods give similar result for SCD anomalies. A Student's test gives the following results: the t-test gives statistics equal to 0.72. If we consider a confidence level of 5%, it means that we do not reject the hypothesis that the mean SCD anomalies of both methods are equal. If we proceed with the same test for the SCD we obtain a t-test value a bit higher than 6. Thus the means are different, because the value is out of the]-2.03,2.03[interval. Then it confirms that the BernClim data set and the model gives mean SCD anomalies that are close, but dissimilar mean SCD.

The next step is to compare the methods considering the different expositions. As reminder, the strength of the man-made observations stands in the specific features of the terrain, such as exposition consideration.

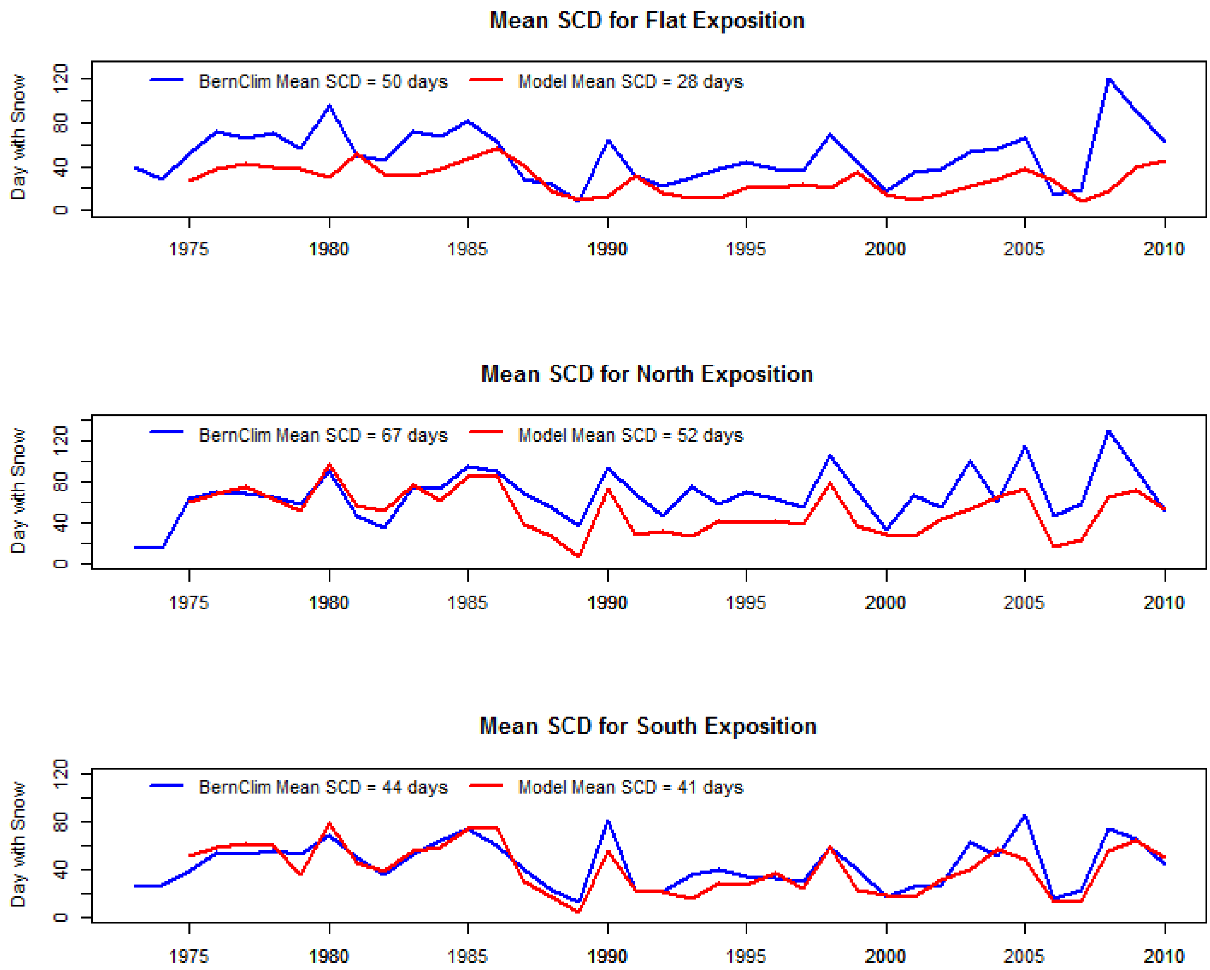


Figure 14 - Comparison between BernClim (blue) and snow model (red) data for mean duration in days of the snowpack depending exposition for the period 1975-2010. Flat (up), north (middle) and south (down) expositions are displayed.

Figure 14 shows the mean SCD for the three expositions. It appears that the southern exposition displayed the best similarities between both methods. For the flat and the northern expositions, the snow model is under-evaluating the SCD comparing to the BernClim data. On the contrary, this difference is of only 3 days for the southern exposition. However, if a Student's test is run, it results in a t-value of 2.26 which is out of the interval of critical value]-2.03,2.03[. This means that the hypothesis that the mean difference is equal to 0 is rejected. As before, it may be more relevant to look at anomalies in order to investigate anomalies more than the strict SCD.

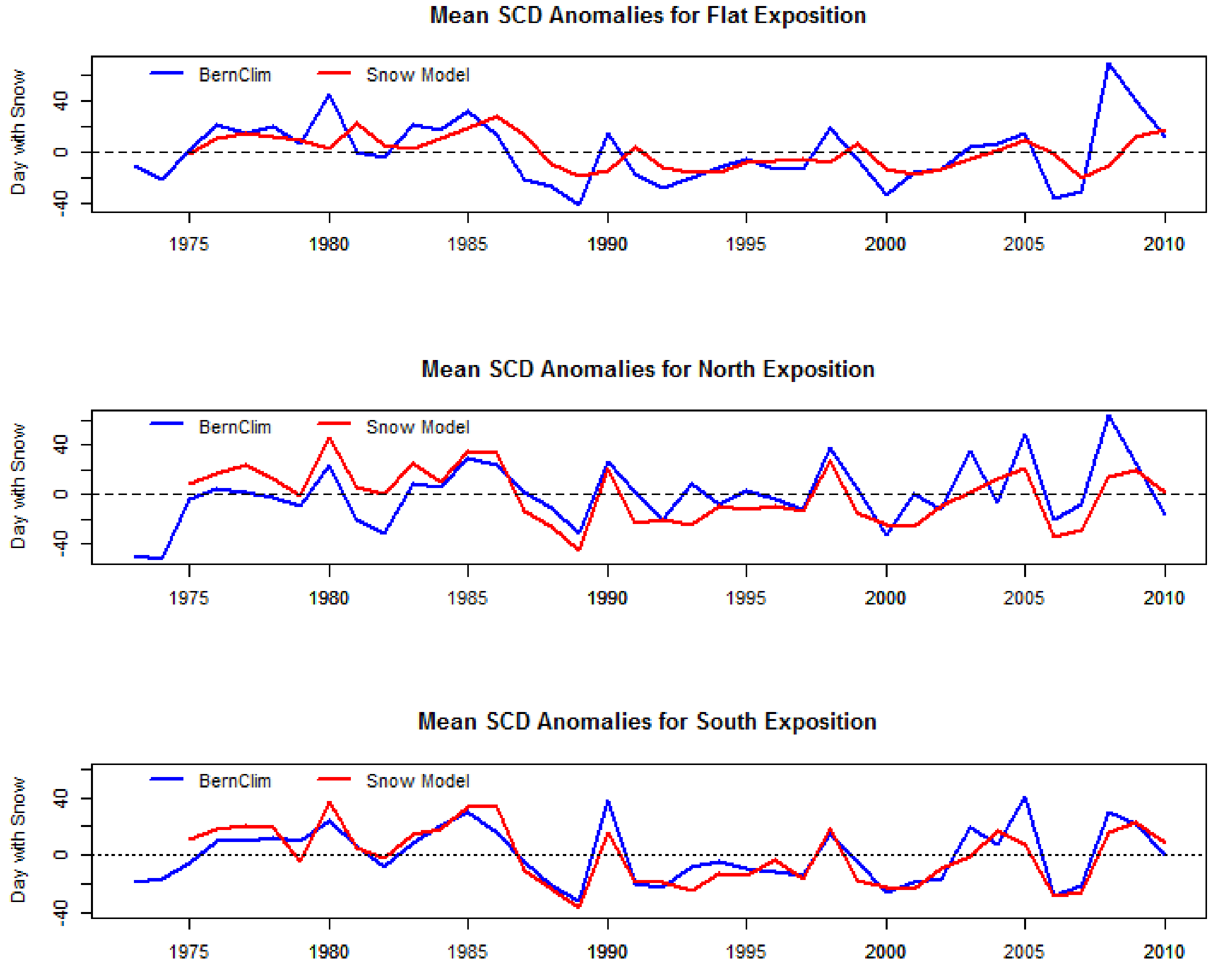


Figure 15 - Comparison between BernClim (blue) and snow model (red) data for mean duration anomalies of the snowpack depending exposition for the period 1975-2010. Flat (up), north (middle) and south (down) expositions are displayed. Anomalies are calculated as the difference from the time-period mean.

On figure 15, there is a good match between both methods for the southern exposition. It is quite the same thing for the northern exposition; the anomalies follow the same tendency. The interesting fact here is that the snow model shows higher anomalies roughly before 1988 and lower anomalies after. In general for the three expositions, the snow model gives mainly negative anomalies after the mid 1980s, whereas the BernClim gets some high positive anomalies. The snow model seems less variable in magnitude than the other methods. It could be due to the higher pixel resolution. The average difference between both methods for southern exposition is 9 days. The median value is 7 days. Concerning the flat exposition in the snow model approach, the anomalies do not diverge a lot around the mean. In other words, the snow model shows constancy and does not reflect the extreme value from the BernClim data set.

Looking again at mean SCD anomalies, the idea is now to capture important pattern within the data. If a simple smoothing method is applied for the mean SCD anomalies, figure 16 is obtained.

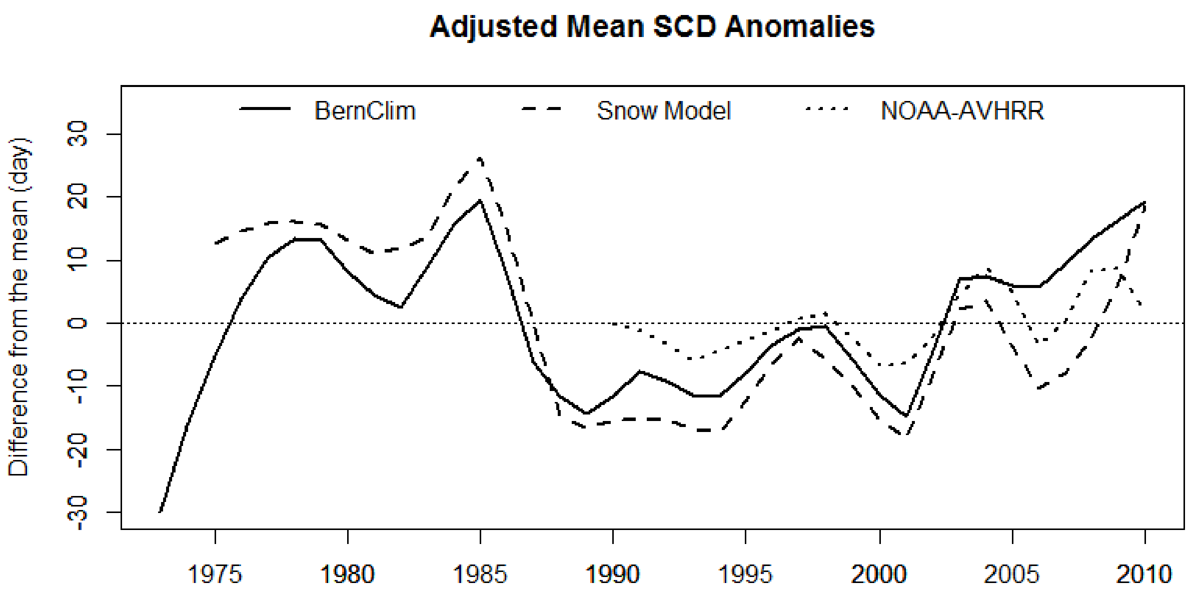


Figure 16 - Anomalies of the duration of the snowpack for the period 1975-2010 with the BernClim (black line),the snow model (dashed line) and the satellite-based (dotted line) methods using a polynomial regression fitting process.

Figure 16 better shows the similar tendency of mean SCD anomalies. Here, a polynomial regression fitting is processed using R-function “loess”. Negative anomalies for the period going from 1987 to 2003 are mainly observed. Then, it can be stated that a step-like decrease in the SCD anomalies happens in the 1990s, which begins later in the 1980s and finishes in the early last decade. BernClim and model methods show the same tendency and it is one of the good points for the purpose of this study. The two different methods agree to reach the same result.

The values are not always close to one another for both methods, but the tendencies (increase or decrease of anomalies) are similar. The anomalies are added here using the satellite method. It is observed that the tendency is globally the same as for others methods. Nevertheless, the values are closer to zero, especially before year 2000. After this year, the data seems closer to the values from the BernClim and the snow model. It could be representative of a better control of the remote sensing data. Additionally, we observes a slight increase after 2000 for all the methods.

To sum up the time-pattern comparative analysis, it can be said that satellite data has too much bias to be used for the comparison, even if similarities with other methods occur. Firstly, the data set has a poor time-period, which does not allow getting relevant trend information. Secondly, the different issues that affect satellite data are too numerous, and make the data useless. Concerning the two other methods, it is observed that the SCD anomaly tendencies are similar. Both methods do not provide the same duration of snowpack in winter, it is due to station features that are not the same. But even if the station is separated according to major features such as exposition, BernClim or snow model data returns different values. In general, the snow model is more “moderate” than man-made observations. It does not give such extreme values as does the BernClim data set. It is certainly due to the fundamental difference between in situ measurements and interpolated data. Nevertheless, when it is used as anomalies, these data are valuable to get information about the trend of snowpack duration.

As said before, satellite data underestimate the SCD because of the difficulties to differentiate snow from clouds, and because of other issues. Thus, one idea is to adjust the model to the satellite method (Figure 17) .

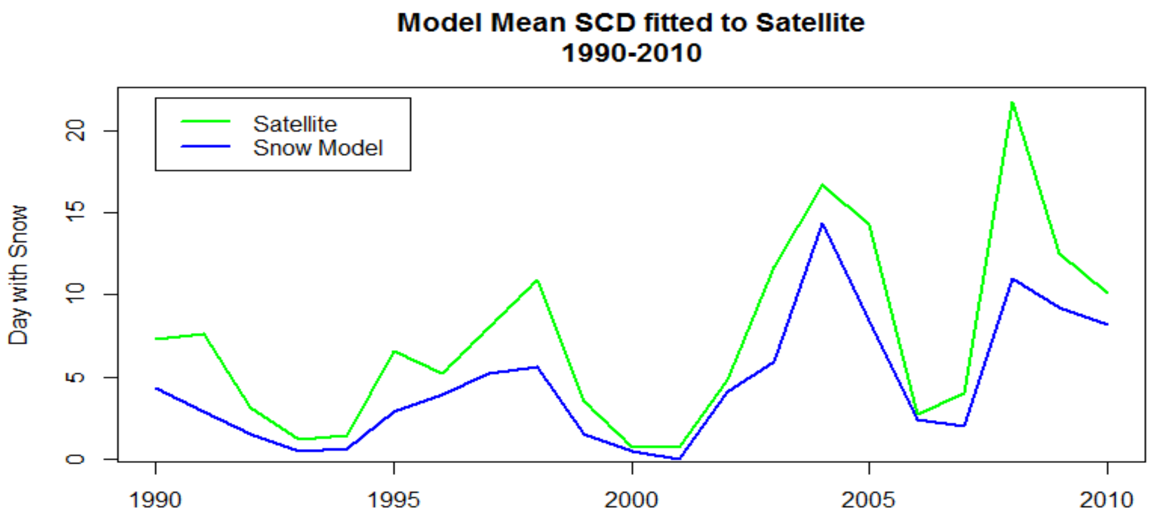


Figure 17 - Mean SCD in days for the period 1990/2010, using satellite data as reference. The snow model is adjusted to the satellite data, meaning that only days the satellite retrieves snow are used.

Then a check should be made to see if the model returns a day with snow when satellite retrieves a day with the presence of snow. To do this, the 10 stations for the period going from 1990 up to 2010 are considered. The mean SCD is plotted using satellite data and, then the SCD is plotted with the model, considering only the days the satellite retrieved the snow presence. It appears that the model does not return always a day with snow when the satellite gives one. Even if the model does not agree 100% of the time with the satellite data, the tendency is the same. The coefficient of correlation is of 0.93 with an associated p-value equal to 1.067E-09 between both methods. It does not resolve the issues posed by the satellite method, and it is always difficult to study SCD for a year with this method. Figure 17 mainly shows that both methods mismatch together. If it is considered that the satellite data are fully reliable when retrieving snow, thus the model underestimates the SCD. Here, either the satellite retrieved clouds and model returns no snow, or the snow model gives no snow while there should be some.

4.3.2 Space-Pattern Comparison

In this section the same procedure used previously applies. To do this, it has been decided to use the BernClim data set as a reference. The idea is to plot the SCD anomalies according to these features: the altitude, and the duration of the snowpack. Of course, the distinction between the expositions is still available. With these features, it is hoped that the behaviour of the different methods will be determined. As already mentioned, the satellite data will be difficult to integrate in this comparison. First, the selected years are out of the time-resolution of NOAA-AVHRR. Secondly, the few amounts of available values for the remote sensing data do not abet us to investigate in this way. It has been decided to study the 3 selected years in three separate ways. Each year was selected according to a criterion that could be studied separately. Year 1975 possesses a higher number of stations and, thus gives the best evaluation of the space-pattern analysis. Then year 1985 and 1989, which respectively represent the year with the highest and the lowest mean SCD, will be helpful to determine the behaviour of the different techniques according to the extreme year-events. Unfortunately, these two years are represented with less than 30 stations. In addition, year 2000 will also be used to compare the satellite-based SCD with the snow model. The BernClim data for this date is put away because the number of stations is too small to make a good comparison. Furthermore, these methods could cover the entire Switzerland and it will be interesting to investigate the comparison for the entire country.

4.3.2.1 Year 1975: High Number of Stations

Year 1975 is represented by 148 stations, which are located below 1000 meters in the Mittelland region. Then, for this year, the number of stations is satisfactory for a good comparison. The idea is to first look at the altitude effect on SCD anomalies with both man-made observations and the model.

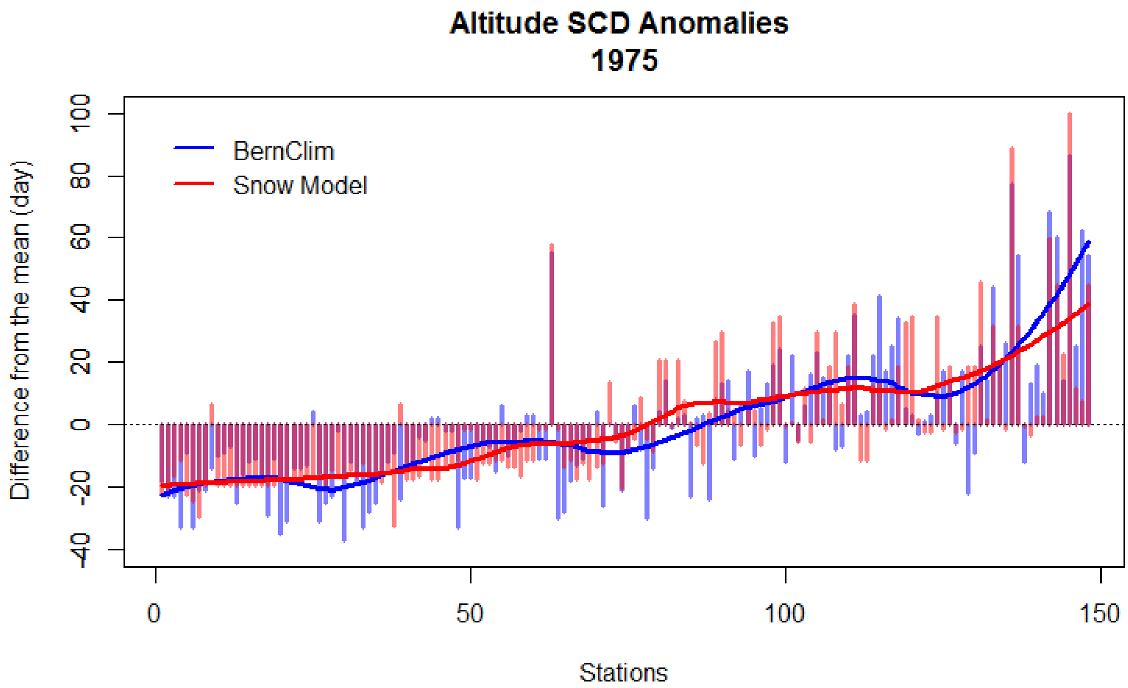


Figure 18 – Anomalies of the snowpack duration for year 1975. The 148 stations are displayed from the lowest to the highest altitude for the BenClim (blue). The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

On figure 18, we have the SCD anomalies for year 1975. It is observed that both methods give quite close values. If a polynomial regression fitting, plotted with the solid blue and red lines, is applied, the increasing trend related to altitude appears. An extreme and singular high value is observed for station 63, which is displayed by the both methods. This station (Birkental, Alpen) is situated at an altitude of 576 meters and gets a high SCD. The surprising thing here is that it is a high value for such an altitude, and the fact that both methods show this same result entails good-quality for both techniques. The mean difference of SCD anomalies between the methods is 12 days. It is high. But, as already claimed, the tendency is similar. Now, it is interesting to find out if this is also the case when differentiating the expositions. The results are plotted on figure 19.

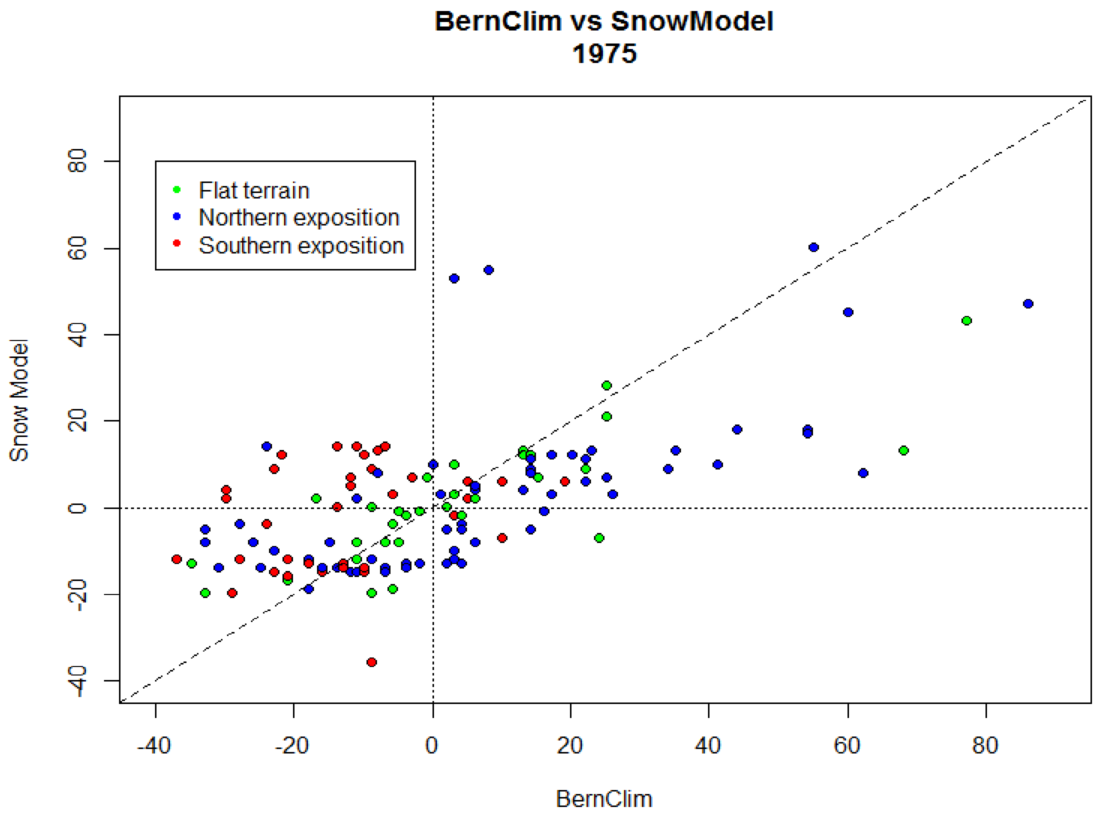


Figure 19 – Scatter plot. BernClim (X-axis) against snow model (Y-axis) SCD anomalies. The expositions are represented with the different colours: green for the flat terrain, blue for the northern expositions and red for the southern expositions.

The flat exposition (green dots) shows the best match, whenever the south shows important discrepancies, in particular for elevated stations. BernClim data display negative anomalies when the model displays positive anomalies (see appendix 5). It is observed from the scatter plot that for southern exposition, the snow model returns higher values than BernClim. In fact, the red dots stand mainly over the dashed line (which represents the perfect fit between the methods). It seems that the opposite happens for the northern exposition. For extreme values especially, the blue dots are mainly situated under the dashed line. The flat terrain shows the best closeness between methods. The mean difference between both methods for the flat exposition is 9 days; the median is 8 days, which is quite reasonable. For the southern exposition, the mean difference and the median are respectively 14 and 12 days. For north exposition, it is quite the same results with 14 and 13 days. Thus, it is bit presumptuous to affirm that the methods are similar, but they provide some identical information, such as the increase and the decrease of the SCD anomalies. The flat exposition gives however quite close results.

Now, we are interested in the comparison between the methods depending on the total number of SCD. In fact, for the next comparison, the BernClim SCD information will be plotted from the lowest value to the highest value. After that, it will be compared with the snow model in order to investigate if there are differences depending on duration values.

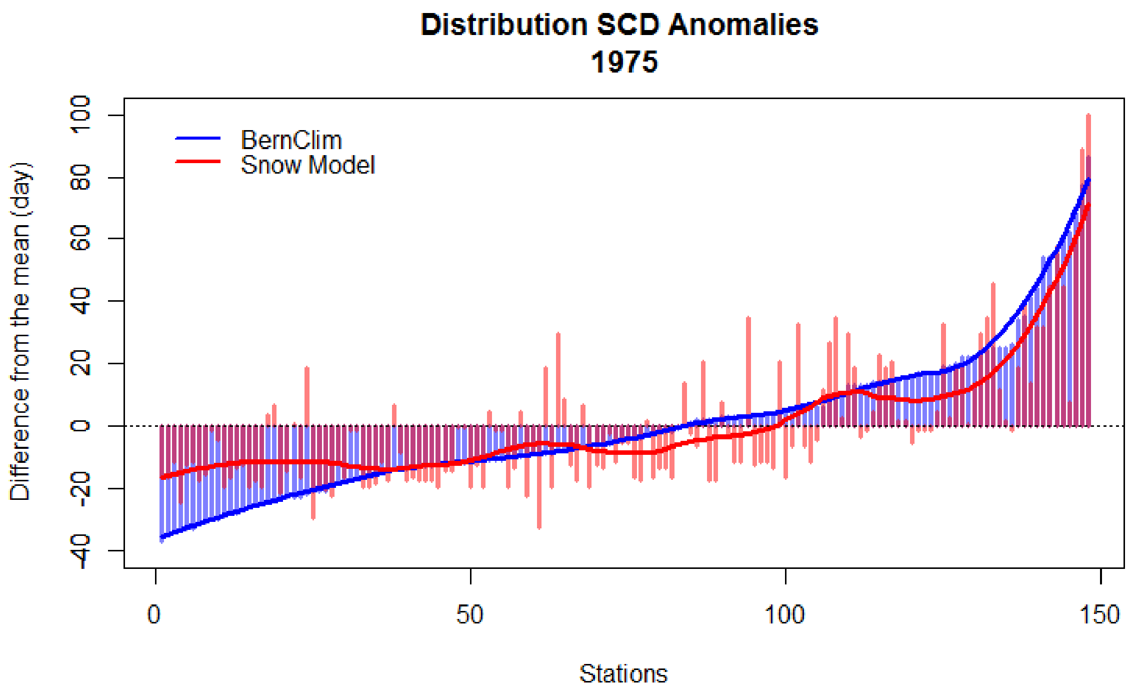


Figure 20 – Anomalies of the snowpack duration for year 1975. The 148 stations are displayed from the lowest to the highest duration of the snowpack according to the BernClim (blue) method. The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

Then, on the figure 20, the BernClim SCD anomalies are plotted from the lowest to the highest value. Snow model is overplotted. Thus, the polynomial regression fitting matches the vertical lines very well. The mean difference between both fitting lines is 6 days and the median is 5 days. Thus, the results are good in this way. Looking at the plot, it is observed that for SCD anomalies retrieved from the BernClim data set, the model tends to underestimate the SCD provided by BernClim. As first explanation, that could be attributed to the higher pixel resolution and the averaging, as well as the interpolation of the input data of the model. One question that arises from this remark is, whether it will return better results if we use the pixel the station belongs to, instead of making the average of nine pixels around it. Then figure 21 represents the same content as the previous one, but suppressing the pixel averaging for the model.

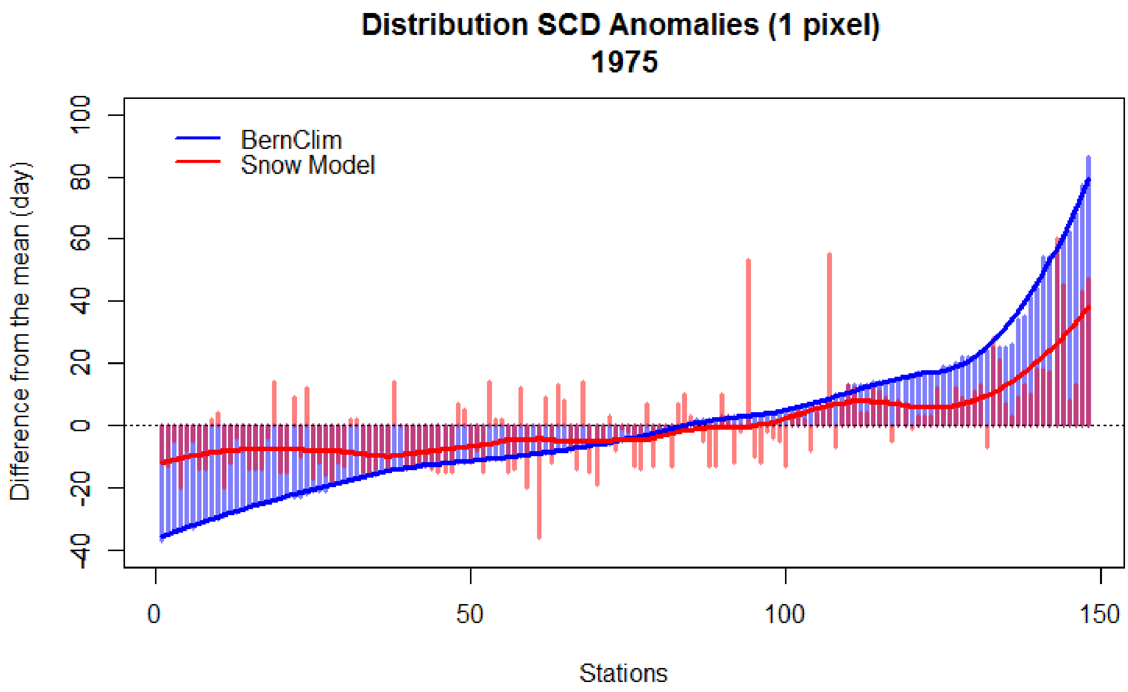


Figure 21 – Anomalies of the snowpack duration for year 1975. The model was computed using only one pixel. The 148 stations are displayed from the lowest to the highest duration for the BernClim (blue) method. The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

It is surprising to see that the divergence from the fitting lines is bigger at both extreme of low and high values. Furthermore, the mean SCD anomalies difference rises to 10 days; the median remains at 5 days. Thus, it is concluded that the average of 9 pixels for the model gives better matches with BernClim method. If one pushes the procedure further and uses 25, 49 or 81 pixels for averaging, we obtain a mean SCD roughly equal to 6 days, and the plots look very similar to the one with 9 pixels averaging.

4.3.2.2 Year 1985: A Winter With High Precipitation

Year 1985 represents the winter that counts the highest mean SCD according to the BernClim data set. Then, it has been decided to investigate how the methods behave with high extreme values of SCD. The weakness attributed to this year is the little number of stations (29 stations) which will not be representative for global SCD. Nevertheless, for the comparison between the methods, this number seems large enough.

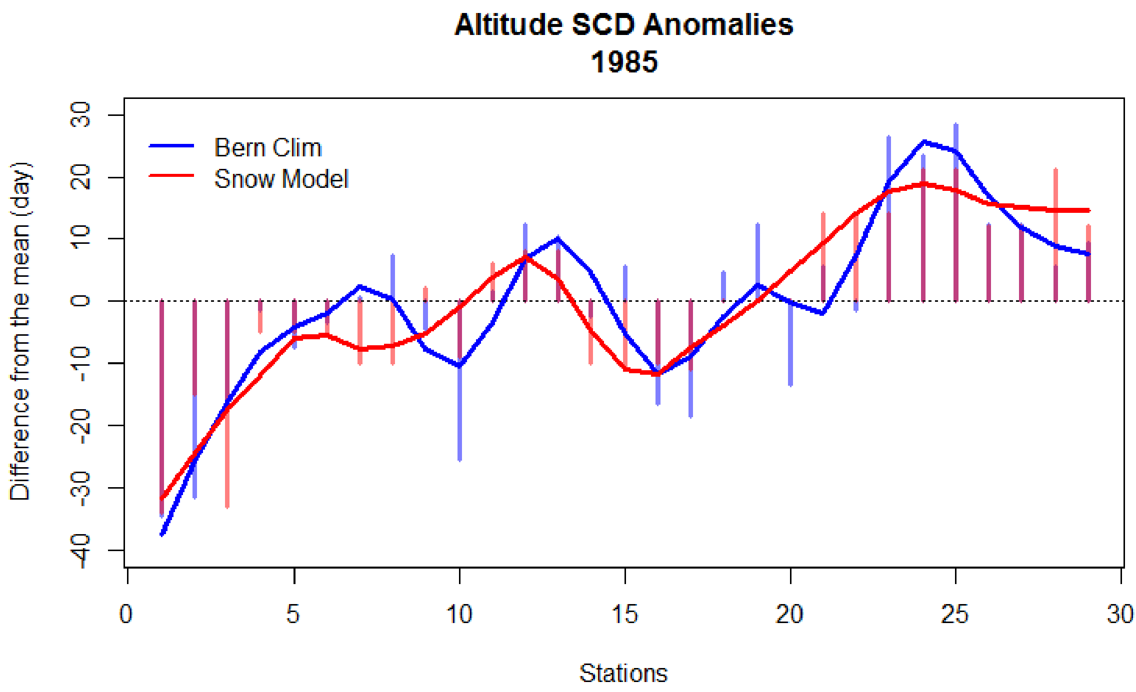


Figure 22 - Anomalies of the snowpack duration for year 1985. The 29 stations are displayed from the lowest to the highest altitude for the BernClim (blue). The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

Figure 22 plots the stations depending on their altitudes. Here, the altitude effect is not as evident as before. Anomalies swing around zero. It is explained by the little range of altitude that goes from 437 meters to 780. The variability is then more dependent on other locations effects than on altitude. Nevertheless, both methods have good trend matches. There are only five stations where the anomalies are opposite between the model and the BernClim method. The mean SCD anomalies difference between the fitting lines is however of 8 days; the median is 7 days. The differentiation between the different expositions will suffer from the little number of stations too. In fact, the result respectively shows 11, 8 and 7 stations for the flat, south and north expositions. The scatter plot of SCD anomalies is given on figure 23.

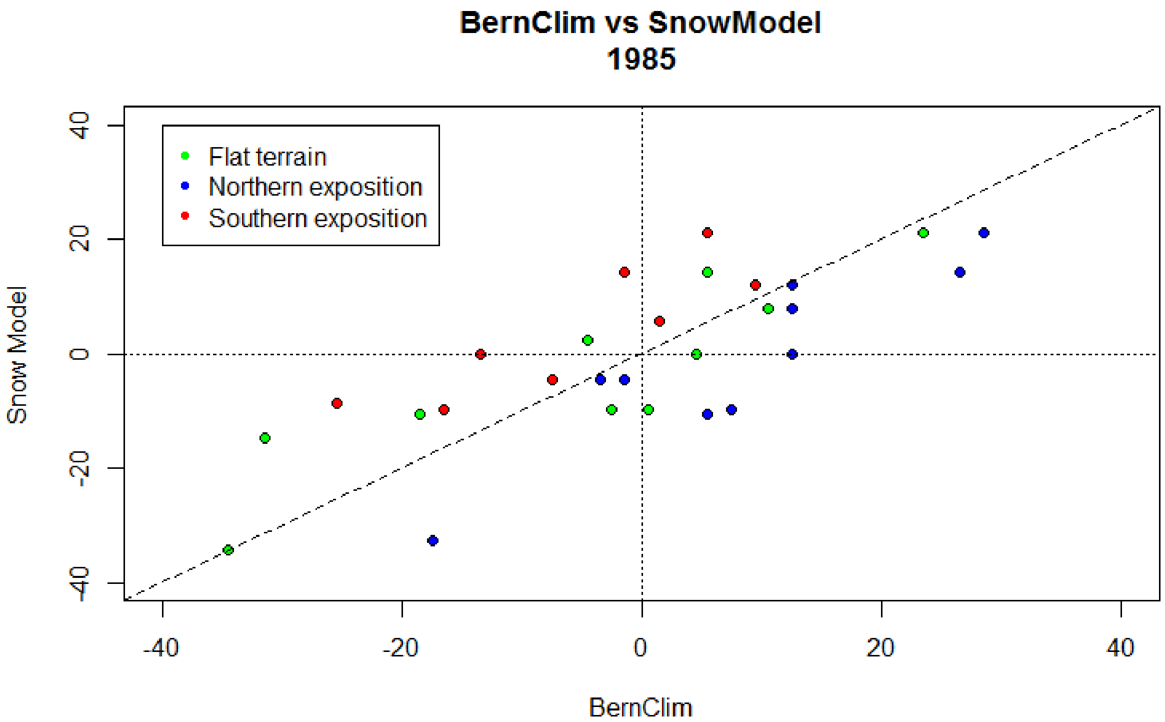


Figure 23 – Scatter plot. BernClim (X-axis) against snow model (Y-axis) SCD anomalies. The expositions are represented with the different colours: green for the flat terrain, blue for the northern expositions and red for the southern expositions.

Firstly, it is observed that the model overestimates the SCD anomalies for southern exposition and underestimates it for the northern exposition. We found the same result for the year 1975. Here, this is valid for all the stations. Thus, it biases results especially for north exposition. Indeed, BernClim model gives a positive anomaly for the seventh northern exposed stations. The snow model gives a negative anomaly for three stations. The mean SCD anomalies difference is 10 days and the median is 12 days. For south exposition, the mean and the median are 10 days. Better results are obtained for the flat exposition with a mean SCD anomalies difference of 6 days and 7 days for the median. Once more, the trend of the fitting lines (appendix 6) is the same for both methods. Thus, in term of increase or decrease in SCD anomalies between the stations, both methods reach the same results. The next question is to see how the different methods behave depending on the duration of the snowpack.

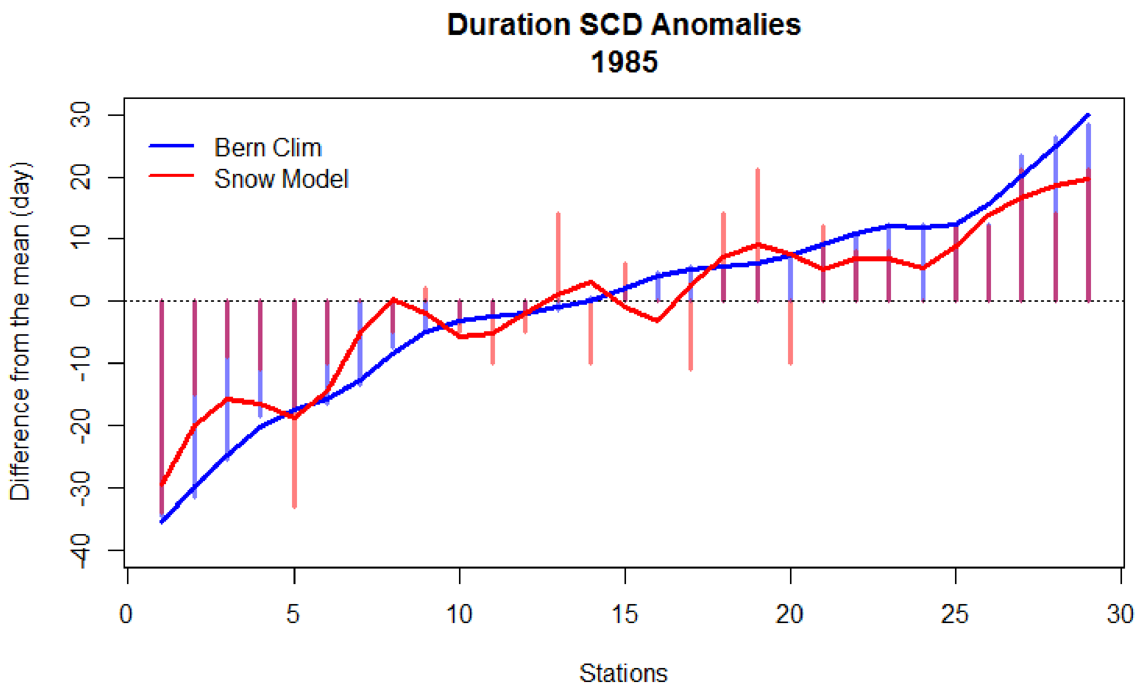


Figure 24 – Anomalies of the snowpack duration for year 1985. The 29 stations are displayed from the lowest to the highest duration of snowpack according to the BernClim (blue) method. The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

Figure 24 gives the BernClim SCD anomalies sorted out on the basis of the duration from the lowest to the highest value. The SCD anomalies with the snow model are overplotted. The trend remains the same. Then, the snow model fitted line swings with a mean of 4 days (median is 3.5) around the BernClim fitted line; with a maximum of 10 days. The snow model sometimes gets extreme values that do not match with man-made observations. This explains the divergence between both fitted lines. The question once again is to know if the averaging of pixel get an influence on the results. Then, one runs the model to get the SCD anomaly processes with the pixel that contains the stations from the BernClim data set. Surprisingly, the difference is imperceptible. The mean difference between the fitted lines is not only 4 days (same as median) but a maximum of 13 days. These are the same result as with the 9 pixels average. If we consecutively use 25, 49 and 81 pixels for the average, the following means, median and maximum are obtained: 4, 5 and 11 days for 25 pixels; 5, 6 and 14 for the 49 pixels; 6, 5, and 15 days for the 81 pixels. Thus, there is little increase of divergence between methods when increasing the number of pixels used for averaging. Then 1 or 9 pixels are sufficient to study the trend at least. When an 81 pixels average is used, the model underestimates the BernClim values. It is certainly due to the averaging and the interpolation that affects the model which tends to be less pronounced than the in situ measurements. Then, it is concluded that it is not necessary to use too many pixels to get a good average of SCD.

4.3.2.3 Year 1989: A Winter With Low Precipitation

The year 1989 represents the winter with the lowest SCD according to BernClim data set. The procedure is similar to the two last years already shown. For this year, only 26 stations are concerned, and the values are small. Thus, it will not be comfortable to distinguish any differences between the methods a priori.

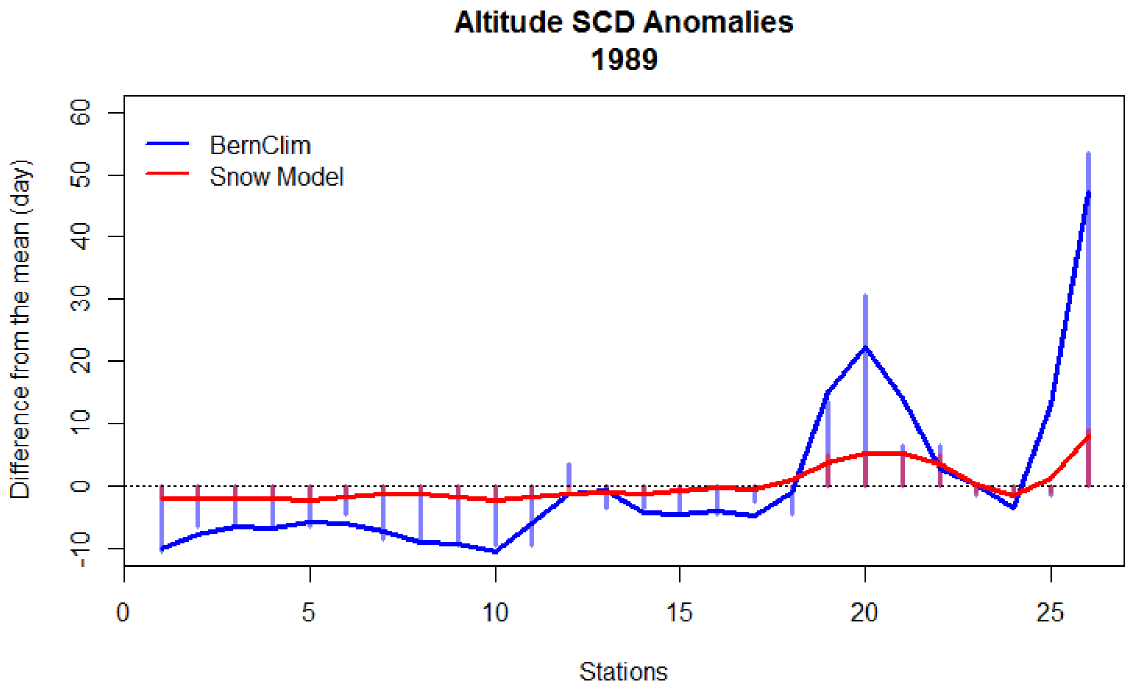


Figure 25 - Anomalies of the snowpack duration for year 1989. The 26 stations are displayed from the lowest to the highest altitude for the BernClim (blue). The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

There are 8 stations that are located on flat exposition and 5 stations each for both other expositions. Before plotting the anomalies, a look should is given to the SCD result from the snow model. Results show a mean SCD of 2.4 days, a median SCD of 1 days and a maximum SCD for one station of 11 days. Comparing the BernClim data set gives 11 days as the mean, 6 as the median and 64 days for the maximum SCD observed manually. These differences are quite tremendous. Let's see now how the anomalies behave. On figure 25, there are these differences through the anomalies as well. The model stays quite constant and gets little values, whereas the BernClim data shows very strong anomalies for some elevated stations. This shows the particularity and the features of some in situ measurements. However, the signs of the anomalies are the same for each station according to both methods except for one station, although, it is difficult to say anything about the tendency.

The plot of the SCD anomalies depending on the exposition will not be displayed. With 8, 5, and 4 stations for each exposition, one is not usable to make any assumptions. Nevertheless, one positive observation from the data is that the anomalies for the three expositions are always of the same sign for both methods, even if the size of the anomalies is diverging a lot for positive anomalies. Let's look now at the behaviour of the methods depending on the duration of the snow cover. The results are on figure 26.

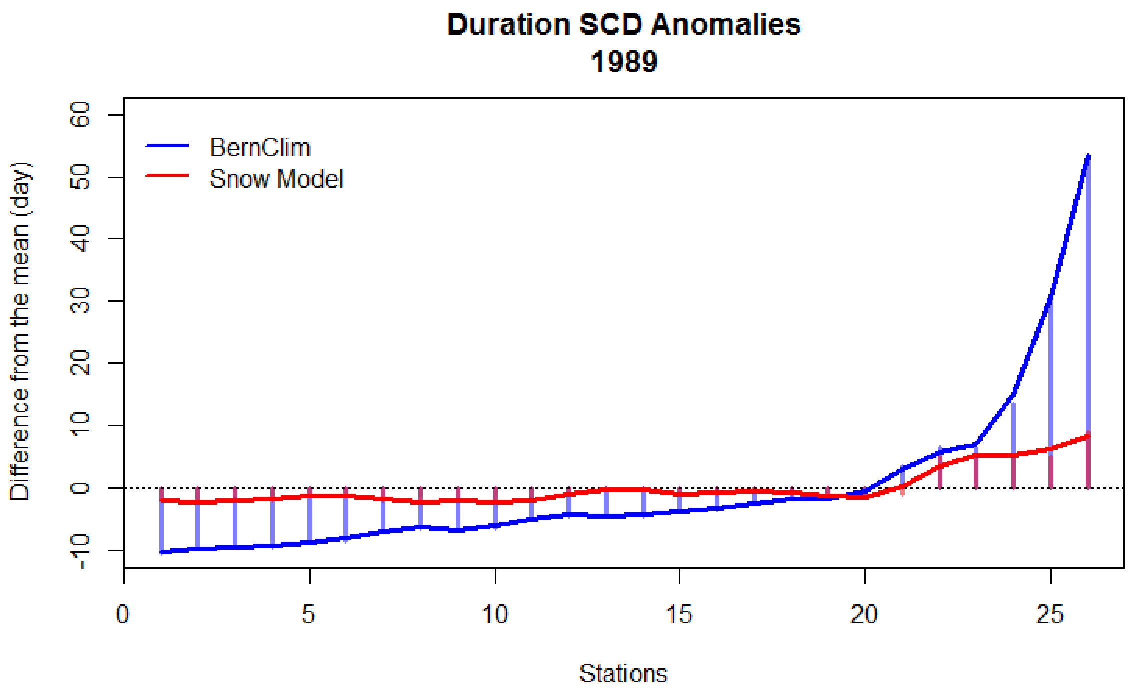


Figure 26 – Anomalies of the snowpack duration for year 1989. The 26 stations are displayed from the lowest to the highest duration of snowpack according to the BernClim (blue) method. The snow model (red) is overplotted. Anomalies are calculated as the difference from the mean of all stations. Solid lines represent the smoothed values using a polynomial regression fitting process.

Once again, the snow model underestimates man-made observations. This underestimation is important. In fact, the maximum difference between the highest positive anomalies from the BernClim data set with the model is of 45 days. Here, it is accepted that there is strong mismatch. This maximum difference is observed for the highest station located at 920 meters.

Then, it could be thought that this divergence is due once again to the pixel resolution of the snow model. If the model is run using one pixel, the problem remains the same; the maximum difference is of 44 days. And if we use 5 times 5 pixels resolution, we obtain a maximum difference of 46 days. Thus, there is a little increase of a few days. Whatever the pixel resolution up to 9 times 9 pixels, there is a mean difference of 6 or 7 days and a median of 4 days. As first impression, it is a good result, but it has to be reminded that we dealt here with a year with little duration. The conclusion is that there is no good result for a winter year with little precipitation.

4.3.2.4 Year 2000: Comparison for Entire Switzerland

In order to use the satellite data and compare it with other methods, another year is chosen for comparison. Thus, the year 2000 was chosen. The comparison will be different for this section. In fact, the number of BernClim stations for this year being too small, only the snow model will be compared to the remote sensing data. But, for this comparison, the entire Switzerland will be plotted. Then, figure 27 and 28 displays the SCD according to the snow model and the satellite methods respectively.

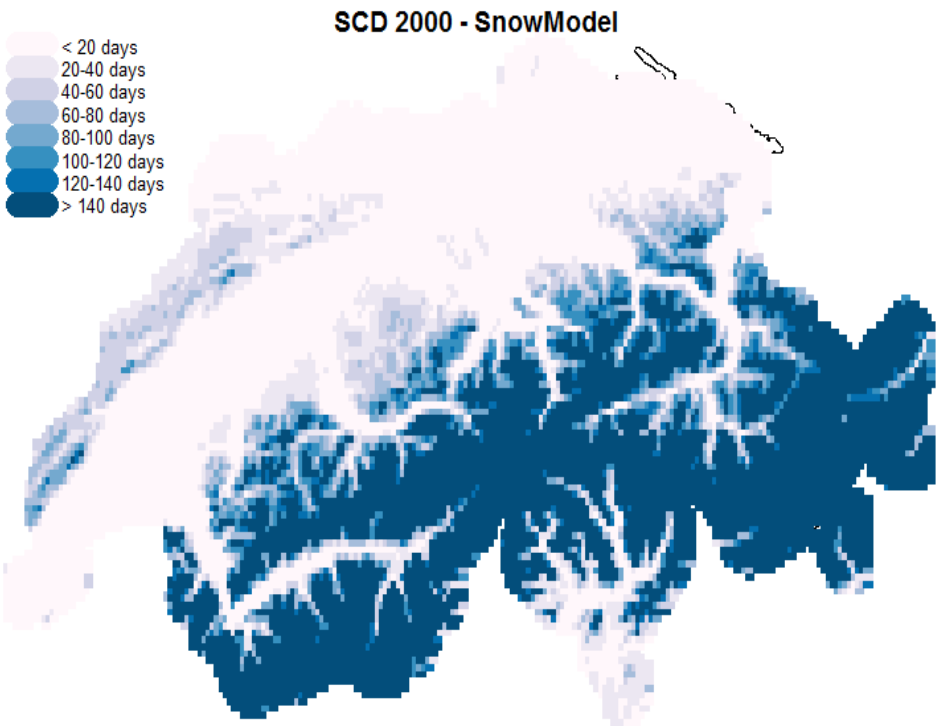


Figure 27 - SCD for the year 2000 using data from the snow-accumulation model.

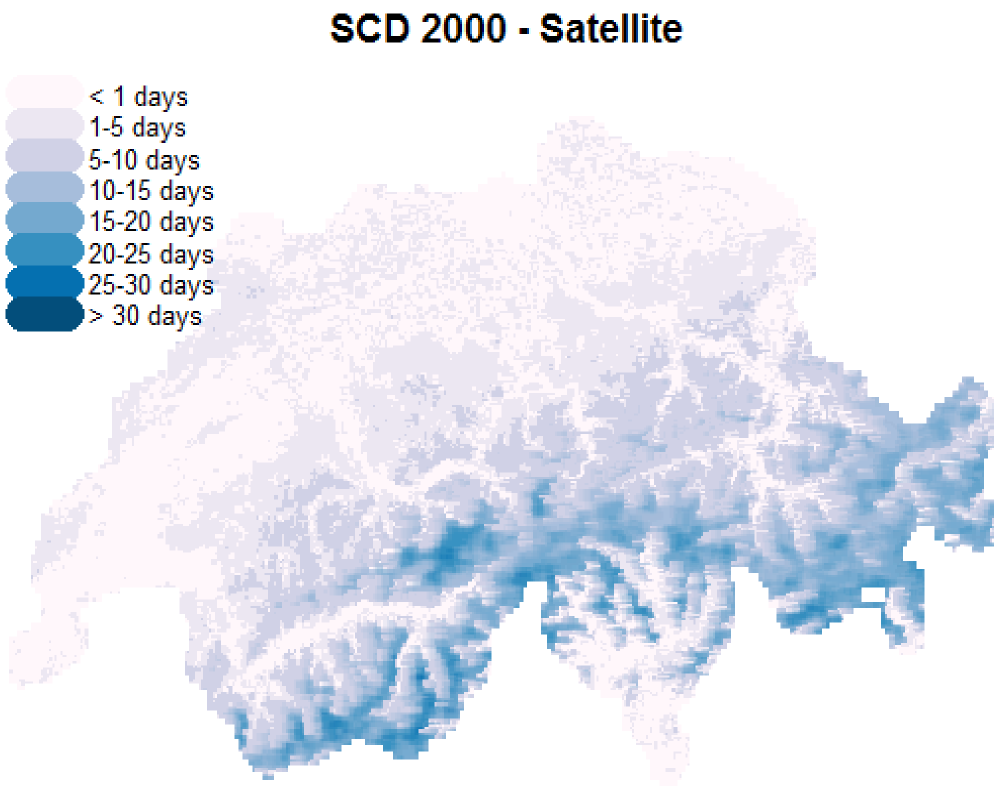


Figure 28 - SCD for the year 2000 using data from the NOAA-AVHRR satellite.

The satellite-based map displays lower value for SCD than with the snow model. In fact, a high number of missing values affect the data set and clouds is still a major problem. Around half of the values for low elevated site, are either missing values or clouds. It is then difficult to obtain similar results with the model. Thus, we could ask if the results should be closer to computing anomalies. Thus, the SCD anomalies for the period going from 1990 up to 2000 is plotted, with the two methods for whole Switzerland (figure 31 and 32). The anomalies are calculated here as the difference from the period-mean for each pixel separately.

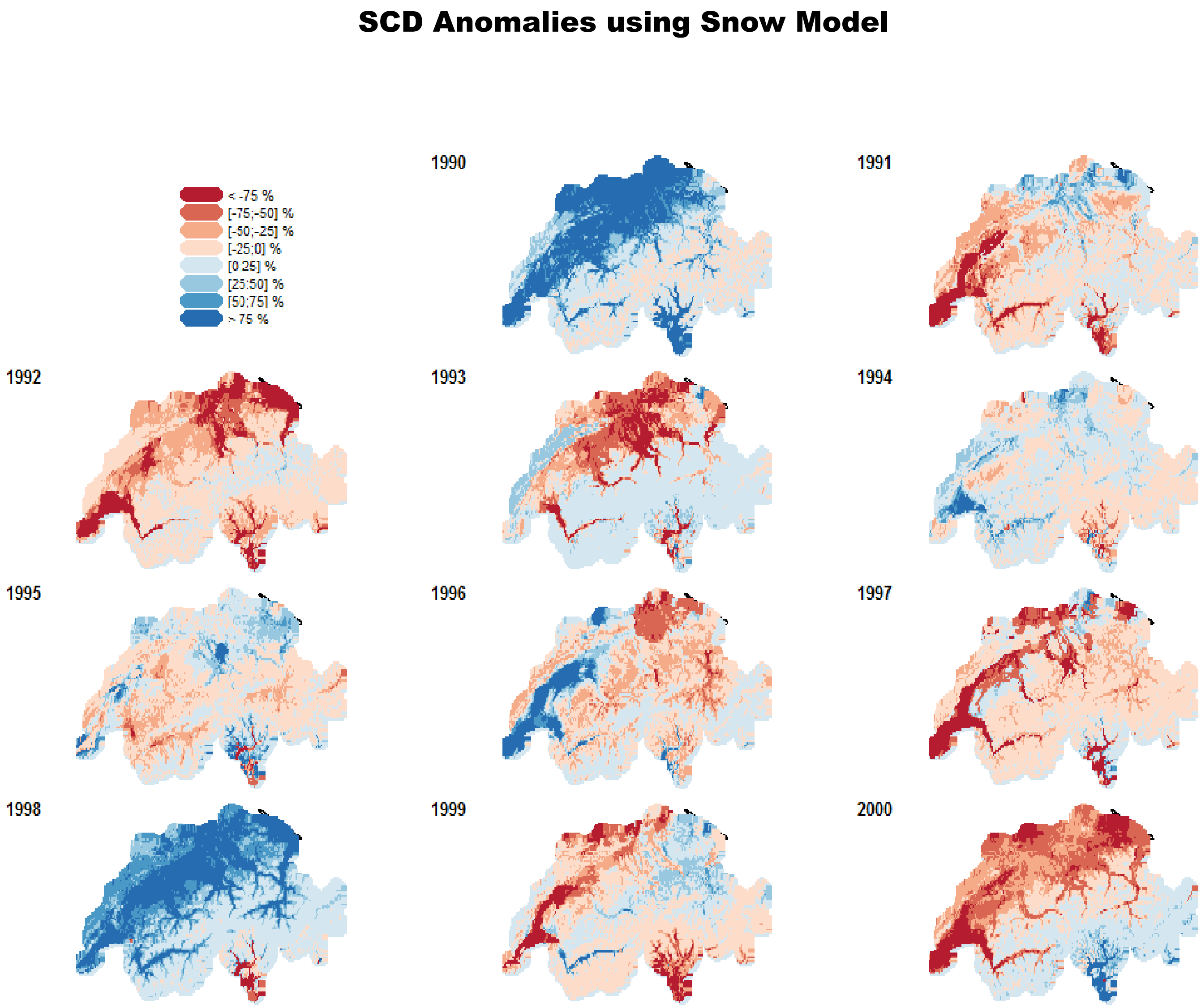


Figure 29 - Snow cover duration anomalies for the period 1990-2000 using the snow-accumulation model. The anomalies are calculated as the percentage of difference for the time-period mean for each grid cell.

Figure 29 shows that year 1990 and 1998 are the years that account the highest number of positive anomalies. This is particularly true for the Swiss Plateau. Year 1998 especially shows a year with higher SCD, except for the Tessin region. The altitude gradient for year 1993 and 2000, where lowland regions show negative anomalies is observed. Thus, there is not any clear tendency here for one or the other regions. Let see now what results return the satellite data.

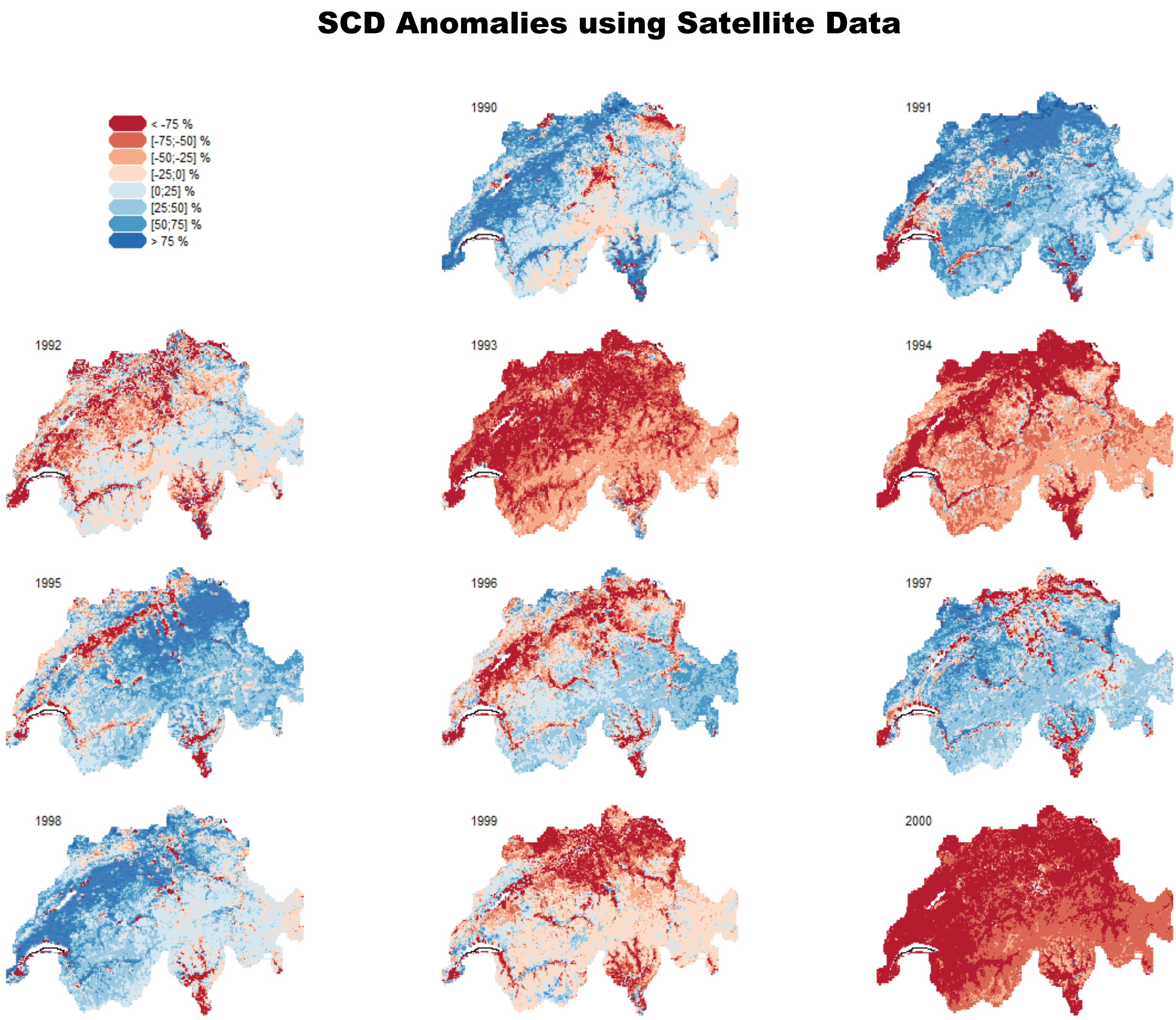


Figure 30 Snow cover duration anomalies for the period 1990-2000 using the satellite data. The anomalies are calculated as the percentage of difference for the time-period mean for each grid cell.

The first observation on figure 30 concerns years 1993, 1994 and 2000 that gives negative anomalies, almost for the entire country. This was not found with the model. Thus, this could be due to less retrieve of snow information, or another satellite-related issue. Here, the altitude gradient for the year 1996 is well observed. Then, at first glimpse, it seems that both methods do not return the same results. And it is the case. A simple statistical analysis shows that the best coefficient of correlation between the methods for the entire territory is 0.28 for the year 1998. All p-value are close to zero which means that we reject the hypothesis that the correlation is equal to zero. Nevertheless, both methods do not return similar results. The satellite data certainly causes this mismatch.

4.3.3 Similarities: Statistical Tests

Thus, what are the conclusions of the comparison between the methods? Throughout the comparison section, some statistical comparisons have mentioned for the different methods to get an idea of the similarity between the methods. Thus, it would be interesting to get statistical values for the different methods and the different representation of the SCD variables. The following section will provide systematic statistical values for the methods and the different representation of the SCD. In order to do that, simple statistical tests and values are going to be applied. Student's test for the SCD and Pearson's correlation test and coefficient of correlation for the SCD anomalies is used. Time-pattern and space-pattern will be studied separately. For the comparison of the mean (Student's test), the value of the test is indicated on the right-hand side of the plot's diagonal and the p-value on the left-hand side. For the correlation, the coefficient of correlation is indicated on the right-hand side of the plot's diagonal and the p-value of the Pearson's correlation test on the left-hand side. Finally, a 5% both sided level of significance (= 2.5% at each side) is chosen. The test and the value that involve the satellite data are calculated for the 1990-2010 period.

4.3.3.1 Time-Pattern SCD

Table 2 - Values of the Student's test (upper right of the diagonal) and associated p-value (bottom left of the diagonal) for the mean of snowpack duration for period 1975-2010. Red (green) colour means a rejection (non-rejection) of the null hypothesis H0: SCD means are equal.

p-value \ t.test	BernClim	Snow Model	Satellite
BernClim	-	6.238	11.075
Snow Model	3.70E-007	-	9.857
Satellite	5.53E-010	4.03E-009	-

Table 2 shows that SCD means are not similar at all between any methods. In fact, all the p-values are largely smaller than 0.025, meaning that we rejected the hypothesis that the means are equal. This is not surprising, because the mean SCD of the data sets are 53.1 (BernClim), 41.9 (snow model) and 7.6 (satellite) days. Then, for SCD the methods do not give similar results. This can be explained by many factors. First, the low values of satellite data, added to the important cloud cover during winter period over the Swiss plateau leads to an underestimation from the remote sensing data. On this side, man-made observations are in situ and there is no threshold determining the presence of snow, where one is found in the snow model. A fixed 2mm of snow equivalent is there to admit the presence of snowpack in the accumulation model. It could explain the high SCD for BernClim data. Furthermore, the snow model is biased by the interpolation and the pixel resolution that involves averaging. Then, the question is to know if the same results should be expected depending on the exposition.

Table 3 - Values of the Student's test (upper right of the diagonal) and associated p-value (bottom left of the diagonal) for the mean of snowpack duration depending exposition for period 1975-2010. Red (green) colour means a rejection (non-rejection) of the null hypothesis H0: SCD means are equal.

Flat Exposition

p-value \ t.test	BernClim	Snow Model	Satellite
BernClim	-	6.218	5.97
Snow Model	3.90E-007	-	7.4
Satellite	7.70E-006	3.87E-007	-

Northern Exposition

p-value \ t.test	BernClim	Snow Model	Satellite
BernClim	-	5.602	10.56
Snow Model	3.90E-007	-	11.12
Satellite	1.30E-009	5.13E-010	-

Southern Exposition

p-value \ t.test	BernClim	Snow Model	Satellite
BernClim	-	5.6	5.8
Snow Model	2.60E-006	-	8.9
Satellite	1.16E-005	1.90E-008	-

Once again, there are no significant similarities between the methods for SCD (table 3), even if the means are respectively 22.2 and 19.3 days for the period 1990-2010 between the model and the satellite data. These two means are lower than the one from man-made observation, which reaches 46.9 for the same period, and 50 for the extended period. In fact, the different means SCD for north exposition are 66.9, 51.8 and 17.7 days; for southern exposition they are 43.8, 40.5 and 15.3. The spread is important. Then it can be concluded that the methods give very different results for SCD and those results do not match.

4.3.3.2 Time-Pattern SCD Anomalies

Even if the strict SCD is not similar between the methods, the SCD anomalies could have similar patterns. For this, a coefficient of correlation and a Pearson's test will be used. This time, the p-value must be lower than 0.025. In practice, the hypothesis that the correlation is equal to zero might be rejected in this case.

Table 4 - Values of the coefficient of correlation (upper right of the diagonal) and associated p-value (bottom left of the diagonal) for the mean of snowpack duration anomalies for period 1975-2010. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

p-value \ coeff. correlation	BernClim	Snow Model	Satellite
BernClim	-	0.827	0.819
Snow Model	4.90E-010	-	0.774
Satellite	5.70E-006	3.87E-005	-

For the general case (table 4), there is a high coefficient of correlation between all methods for the mean SCD anomalies, which is supported by the tests. The latter show that the correlation is not equal to zero for all the case. The best fit stands between the BernCLim and the model. Then, as it has been observed with the plot depending on exposition, both methods give quite similar patterns, and this is reinforced by statistics (table 5).

Table 5 - Values of the coefficient of correlation (upper right of the diagonal) and associated p-value (bottom left of the diagonal) for the mean of snowpack duration anomalies depending exposition for period 1975-2010. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

Flat Exposition

p-value \ coeff. correlation	BernClim	Snow Model	Satellite
BernClim	-	0.446	-0.214
Snow Model	6.00E-003	-	0.393
Satellite	0.378	0.077	-

Northern Exposition

p-value \ coeff. correlation	BernClim	Snow Model	Satellite
BernClim	-	0.627	-0.325
Snow Model	4.27E-005	-	0.721
Satellite	0.174	2.20E-004	-

Southern Exposition

p-value \ coeff. correlation	BernClim	Snow Model	Satellite
BernClim	-	0.839	-0.197
Snow Model	1.57E-010	-	0.772
Satellite	0.418	4.10E-005	-

Effectively, we have a p-value lower than 0.025 for all the exposition between the BernClim and the model (table 5) as between the model and the satellite methods. However, the coefficient of correlation is satisfactory only for the southern and northern exposition. This coefficient is higher than the one for the average regarding the BernClim and the model. The coefficients for flat terrain are low to affirm that they are well correlated. It is good to see that the SCD anomalies from remote sensing data are similar to those of the model, considering the mismatch of their SCD. Now, it is interesting to look at the correlation between the polynomial fitted values that was plotted before. Only these values between BernClim and the snow model were calculated on table 6.

Table 6 – Values of the coefficient of correlation (down) and associated p-value (up) for the mean of smoothed snowpack duration anomalies for period 1975-2010. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	Average	Flat	North	South
p-value	6.00E-010	3.30E-011	0.08	3.40E-014
coeff. correlation	0.825	0.854	0.295	0.905

Thus, only northern exposition is not well correlated and we cannot reject the hypothesis that the correlation is equal to zero. The other p-values are very close to zero, and the coefficients of correlation are good. To sum up, the BernClim and the model method show in general similar SCD anomalies pattern at a significant 5% level.

4.3.3.3 Space-Pattern

Year 1975

The comparison for the space-pattern analysis is only made between the snow model and the BernClim data. For the average of all the stations, we see the behaviour of the correlation when we change the number of pixels used for the average. Thus, the table contains the statistics for 1, 9 and 81 pixels averaging. These pixel calculations are not made for the expositions.

Table 7 – Values of the coefficient of correlation and associated p-value for the mean of snowpack duration anomalies (up) and the smoothed values (down), for the year 1975. Three values are calculated depending on the different pixel resolution for the snow model. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	1 pixel	9 pixels	81 pixels
p-value	2.20E-016	2.20E-016	2.20E-016
coeff. correlation	0.645	0.765	0.676
Polynomial Regression Fitting			
p-value	2.20E-016	2.20E-016	2.20E-016
coeff. correlation	0.853	0.966	0.952

The remark on table 7 is that all the p-values are very close to zero. The R-software does not calculate p-value below 2.2e-16. Thus, all the tests performed give a very significant rejection of the hypothesis that the correlation is equal to zero. Nevertheless, the coefficient of correlation is satisfactory for the 9 pixels averaging. The polynomial regression fitting gives better statistics. Therefore using 9 pixels remains the best averaging in order to have the best coefficient of correlation.

Table 8 – Values of the coefficient of correlation and associated p-value for the mean of snowpack duration anomalies (up) and the smoothed values (down), for the year 1975. Three values are calculated depending on the different exposition. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	Flat	North	South
p-value	2.67E-015	1.00E-009	5.60E-003
coeff. correlation	0.891	0.833	0.425
Polynomial Regression Fitting			
p-value	2.20E-016	2.20E-016	1.37E-007
coeff. correlation	0.968	0.964	0.717

Once again depending the exposition, all the p-value permits to reject the assumption that the correlation is equal to zero (table 8). Then, only the coefficient of correlation for the southern exposition is weak. But in general, both methods show similar pattern for year 1975.

Year 1985

Table 9 - Values of the coefficient of correlation and associated p-value for the mean of snowpack duration anomalies (up) and the smoothed values (down), for the year 1985. Three values are calculated depending on the different pixel resolution for the snow model. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	1 pixel	9 pixels	81 pixels
p-value	3.88E-007	5.81E-007	5.60E-006
coeff. correlation	0.788	0.781	0.734
Polynomial Regression Fitting			
p-value	2.20E-016	2.20E-016	1.75E-015
coeff. correlation	0.961	0.965	0.953

All the p-value for year 1985 is very low (table 9). In addition, the coefficients of correlation are all satisfactory; they exceed 0.750. Once again, the best pixel choice is 9; it returns the best statistics among the others.

Table 10 - Values of the coefficient of correlation and associated p-value for the mean of snowpack duration anomalies for the year 1985. Three values are calculated depending on the different exposition. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	Flat	North	South
p-value	1.60E-004	0.006	0.047
coeff. correlation	0.900	0.761	0.860

The table 10 shows a non-rejection of the assumption that the correlation is equal to zero for the southern exposition. It is frustrating, because the coefficient of correlation is 0.860, which is good. Both other expositions are significantly correlated. Here, the fitting values are not displayed because they are quite the same. The number of stations, which is very low, does not favour the processing of a relevant polynomial regression fitting.

Year 1989

Table 11 - Values of the coefficient of correlation and associated p-value for the mean of snowpack duration anomalies (up) and the smoothed values (down), for the year 1989. Three values are calculated depending on the different pixel resolution for the snow model. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	1 pixel	9 pixels	81 pixels
p-value	1.18E-008	1.14E-009	4.30E-005
coeff. correlation	0.865	0.890	0.713
Polynomial Regression Fitting			
p-value	2.20E-016	2.20E-016	6.63E-008
coeff. correlation	0.973	0.978	0.843

Year 1989 gives similar pattern with both methods. In fact, the whole p-value is lower than the 2.5% threshold, which means that the assumption that the correlation is equal to zero is rejected. Then, except for the 81 pixels for the averaged station, all the coefficients of correlation are satisfactory to accept that the SCD anomalies have similar pattern. In more details, we notice that using 9 pixels as resolution returns the best statistics. Reversely, the 81 pixels resolution returns the lowest statistics. Then, the conclusion for these remarks is that it is not necessary to consider too many pixels, and on the contrary, 1 pixel is not sufficient to get good matches between the methods.

Table 12 - Values of the coefficient of correlation and associated p-value for the mean of snowpack duration anomalies for the year 1989. Three values are calculated depending on the different exposition. Green (red) colour means a rejection (non-rejection) of the null hypothesis H0: correlation is equal to zero.

BernClim vs Snow Model	Flat	North	South
p-value	4.10E-004	0.005	0.007
coeff. correlation	0.945	0.995	0.965

Looking at the exposition (table 12), it is noticed that the correlation are greater than for average. And the p-value gives positive results. This provides very interesting results. However, the very low number of stations for each exposition does not permit to affirm that the methods match quite perfectly. These good matches could be as well explained because the year 1989 is a year with low precipitation. Then the SCD values tend, for both methods, to be close to zero in lowland regions. Thus, we cannot dare to affirm that this is the best results among the others.

5. Discussion

5.1 Synthesis

The analysis of the duration of the snowpack revealed that a step-like decrease in SCD anomalies appears few years before 1990. This decrease is perceptible with BernClim and the snow model after the winter 1986/1987. The mean SCD with BernClim from 1975 to 1986 is 63 days; from 1987 to 2010 the SCD mean is 51. With the model the mean from 1975 to 1986 is 59 days; from 1987 to 2010 the SCD mean is 34 days. The decrease appears clearly in the model. Moreover, there are almost no negative anomalies before 1987. Nevertheless, man-made observations show an increase after 2003 that is perceptible with the model as well. Because of the shorter time period of the satellite data, this step-like decrease could not be confirmed. Here stands the second main result of the SCD analysis. The NOAA-AVHRR data set is not relevant in the form we get it. The important underestimation and incoherence with both other methods makes the data set not useful for the work. Thus, the satellite data do not match our other data sets.
Now, we will compare some of our results with those of Marty (2008). In his paper, Marty uses different class of altitude to evaluate the regime shift of snow days. Actually, one station he used for northern situation in low altitude is Bern. For the same climatic environment, he also gets Basel, Sion, Zürich, Neuchatel, Visp and Landquart. For these stations, he found that the regime shift appears in 1988. It is close to our result, which was estimated at the end of the 1980s. Another altitude range near ours was used by Marty. This range includes Lauterbrunnen, Küblis, Einsideln, La Chaux de Fond, Engelberg and Klosters. This range of altitude goes from 805 up to 1195 meters. It is a bit higher than our threshold, but it is interesting to compare the results. The regime shift happened in 1988 as well. Thus, the mean difference stands in the SCD mean that Marty found for those two different altitude ranges. For the low altitudes, the mean he found was 27 days; for the mid altitude, he found 54 days. The fact that Marty uses different threshold for his snow index makes the comparison with our results biased. Furthermore his time period is

larger than ours. Nevertheless, we found a mean SCD of 53 with the BernClim data set, 42 days with the model and only 18 days with the satellite data. But the BernClim data is close to the middle altitude range that Marty defined. This is however complicated to compare to our result because of the different class each of us made, and the time-period we get.

The comparison of methods for SCD is not relevant. There is no good quality match between the three techniques. Only the rejection of the hypothesis that the SCD means are equal for all methods is obvious. It was evident when looking at the plot. The BernClim give higher values; the satellite data give lower values and the model stands in between. Then, in this way the three methods do not match at all in order to obtain snowpack duration values. These mismatches make us consider tendencies and anomalies, which return better results. Even if the SCD is not similar with the different methods, its behaviour appears to be close. Unfortunately, the comparison mainly considers the BernClim data and the snow model. The satellite data were put aside because of their lowest values. In this way, quite good result and good matches between the in situ observations and the model are obtained. According to the time-pattern analysis, the p-values tell us that in the general cases such as the three different expositions, the correlation is not equal to zero between the model and the BernClim data. The coefficient of correlation is good for the average of the 10 stations, and for the southern exposition, which exceed 0.8. This is not the case for both other expositions; even if 0.63 for the northern exposition could be accepted as satisfying. Applying the polynomial regression fitting, it is surprising that for north exposition, there is no rejection of the assumption that the correlation is equal to zero (p-value = 0.08). Using this smoothed method, we get similar result for the average of 10 stations: we reject the assumption that the correlation is equal to zero and the coefficient of correlation is the same. However, the south and flat expositions have better coefficients with the polynomial fitting. In fact, they exceed 0.8.

The space-pattern returns only rejections of the hypothesis that correlation is equal to zero between the model and the BernClim data except for the southern exposition in 1985. Year 1985 and year 1989 return information that has to be considered with circumspection. Actually, the very low number of stations makes the results weaker than those of the year 1975, especially for the exposition distinction. Year 1975 with 148 stations is a great source of information. Thus, the test tells us that we strongly reject that the correlations are equal to zero. Then, both methods match very well and show similar pattern. The use of a polynomial regression fitting method provides a better match between the methods. Besides, flat and north exposition get a coefficient of correlation higher than 0.9 and the south exposition rises to 0.72 (better than with no smoothing). For the average case of the 148 stations, we get a coefficient of correlation over 0.9 using the smoothing method, whenever this coefficient stands below 0.8. Other consideration concerns the pixel resolution. Actually, it is observed that using 9 pixels to make the average results in a better correlation between the methods than with one 1 or 81 pixels. This is also true for years 1985 and 1989. Then, the best pixel resolution is 3 times 3. Satellite data show significant similarities with the snow model for northern and southern exposition. Indeed, with a coefficient of correlation higher than 0.7 and a very low p-value, it shows that the tendency that we depicted with the plot effectively exists.

To conclude, the BernClim, man-made observations and the snow model match together when we display the SCD anomalies. They both show a decrease in the duration after winter 1986-1987. However, the snow model shows less variability than BernClim data. This is trivial, because the model computes an average of pixel that poorly takes into account the specific features that the in situ measurements used (topography). Moreover, the inputs consist of interpolated data. Concerning the satellite data, the too numerous issues that affect the data set makes this information not usable for this work. Satellite and model methods show similar anomaly tendencies, even if the strict SCD is really different. It was one of the main purposes to evaluate the BernClim data set. Then, man-made observations are of very good quality. Obviously, we find the same tendency and pattern as with the model, which has made its proof before. Furthermore, the in situ measurements provide better terrain specific features. Thus, the spatiality is effectively a major aspect of the set, as announced by Jeanneret and Rutishauser (2011). The values for the duration of snow cover are higher than those from the model. This denotes the issue of the parameterisation of the model. More discussion will take place in the next chapter. No further details will be given on this method.

5.2 Evaluation of the Three Methods

It was noticed that the evaluation of the SCD slightly differs depending on the method used. This section is devoted to the description of the advantages and disadvantages of each method.

Table 13 – Comparison of the three methods regarding time, space and pixel resolution.

Method	Time Resolution	Space Resolution	Pixel Resolution
BernClim	**1971-2010** * Daily measurements	*1971: 254 stations *2010: 15 stations	"in situ"
Snow Model	**1961-2015** * Daily T and P	Interpolation of T and P For Switzerland	Lon/lat 0.02°
Satellite	**1990-2015** * Daily Snow max Extent	Switzerland	Lon/lat 0.02°

Table 13 gives an overview of the three methods evaluated in this thesis. This will summarise some characteristics mentioned through the previous sections. It has been noticed that the remote sensing method takes little place in the analysis. The many issues related to the satellite method are the reason for that. It is nevertheless one of the major disadvantages of these techniques, obviously for the purpose of this study. Nevertheless, a satellite has many advantages. It covers huge territory, with high resolution. It is possible to obtain more than one scene per day. Moreover, satellite data provide homogeneous data, even over areas that are hardly accessible for ground measurements. Unfortunately, satellite data do not permit to get long time series, because of the youthfulness of the method. Then, this technique is used for present and near present purposes. In addition, issues already mentioned such as instrumental defaults, natural interferences and change in satellite compel to use the method with particular caution and satellite data need careful validation.

The snow model, which uses ground automatic measurements as inputs, is less homogeneous than satellite data in the sense that a process of interpolation is computed to get the gridded data. Then, the interpolation process leads to bias and estimated reality. However, it permits to obtain values that cover the entire country too. Moreover, the time period is as long as the one from ground stations could provide. Thus, the model provides a homogeneous space resolution with good time-series. Then, the model could be evaluated better than satellite data. But, the simplification and the parameterisation of the model cause a loss of trueness. Indeed, the simple model that was used is clearly an oversimplification of the reality. Then, if the purpose was to retrieve snow height, it can be argued that the model is weak. But, the purpose which is to analyse the presence of snow and to study the trend, favour the idea that the model could be considered good. Both methods cover the entire area of study. Satellite data provide specific information for each pixel, whereas the model gives an estimate for each pixel using interpolation. This is where the BernClim data gets its specificity. In fact, the in situ man-made observations give value for a site that has been selected for special reasons. It was seen through this work that the exposition is an interesting feature that shows mismatches between methods. The other interesting feature is to have different observations for the same location but with different expositions. The weakness of the man-made observations method comes from the space homogeneity. As we already know, in situ ground measurements are used for validation of data product. MeteoSwiss has observers for the validation. BernClim could be used as one, but the strength of this method is quite different here. Jeanneret and Rutishauser (2011) judiciously named their paper in this way: "BernClim - seasonality monitoring". BernClim retrieve a bunch of climatic and phenological data to get informed on how the seasonality actually behaves, using different information. Thus, the inhomogeneity of sites monitoring is not an issue for the purpose of the project. Then, using the snow information was ambitious to study SCD as done here. Nevertheless, the fact that we find matches with modelling techniques and similarities with Marty (2008) results comfort us in the quality of the BernClim data. Then, we only could deplore the decreased number of the stations in the last years.

6. Conclusion

To sum up, it is evident that each of the three methods used in this work get biased and has disadvantages in order to investigate the SCD. Then, the comparison between the three methods suffers from these issues and differences. Nevertheless, the same tendencies have been observed between the methods regarding SCD anomalies and, in this way, it is satisfactory. It should be possible to go further in the analysis. Indeed, it would be possible to try to find a similar step-like decrease with phenological record in the 1980s. It should not be forgotten that BernClim provides this kind of data. Another aspect to study in detail was the monthly variation of the

SCD. In fact, there is access to SCD values for each month separately. And it would be interesting to look at this variability, especially with satellite data. The cloud cover could vary from a month to another. Then, these questions are still open.

A more precise analysis of the satellite data, using a new algorithm or using gap filling would be interesting to look at. But, the aim of this study was not to work on the data products themselves, but to see what results they give individually and then to compare them. It is now obvious that we could use the three methods together in order to study SCD. This was not the intention here.

To conclude, man-made observations are a source of good-quality data. Indeed, in terms of the presence of snow, this data set is valuable. And the data set is precious because it provides specific topographic features, which we do not find with other methods that return gridded values. It would be great that this kind of ground measurements still exist.

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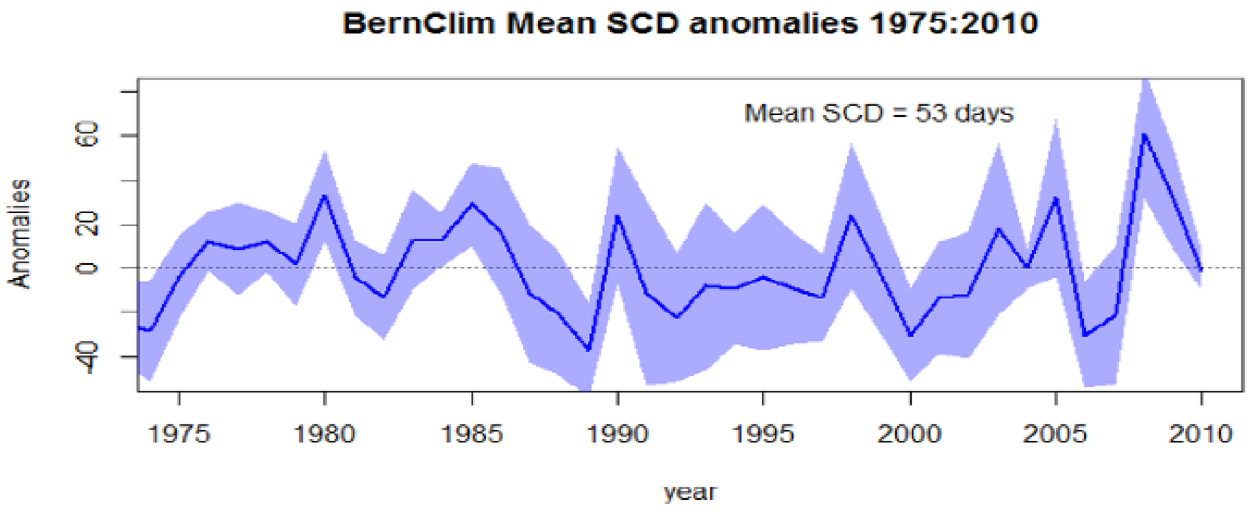
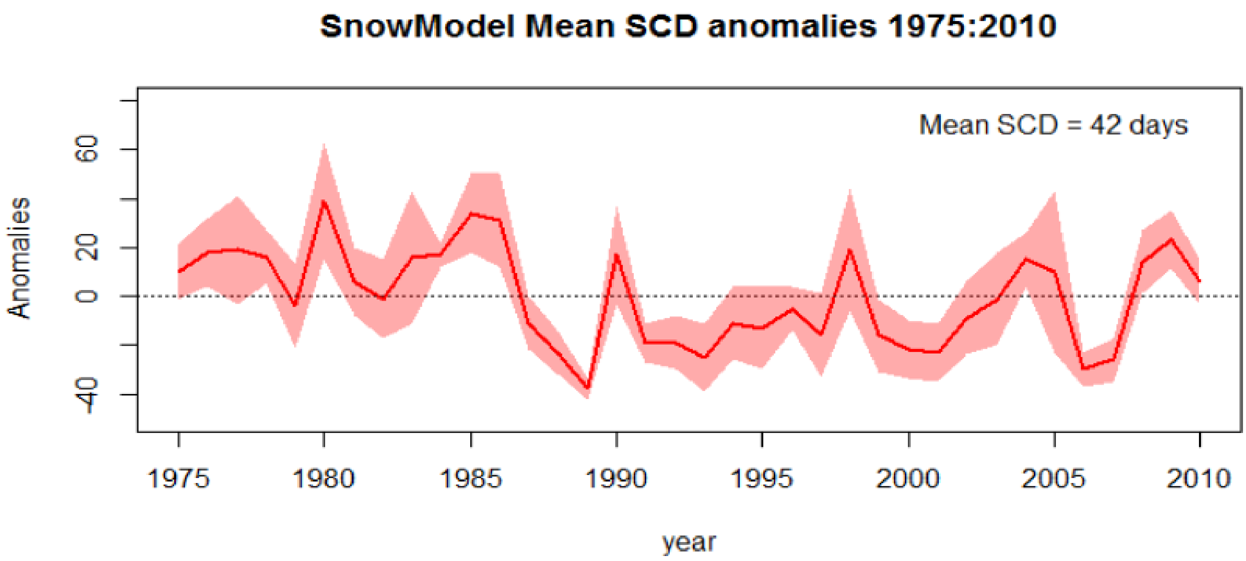
Appendix

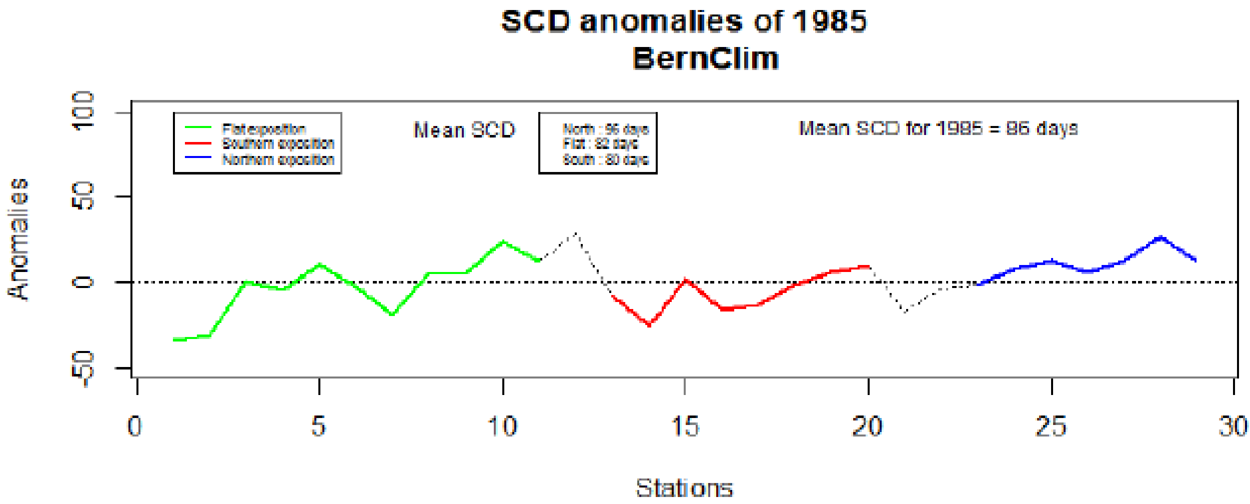
Appendix 1 Anomalies of snowpack duration according to the BernClim data set for the period 1975-2010. Mean is calculated with 10 stations. The uncertainty range is based on the standard deviation and anomalies is equal to the difference from the mean of the entire selected time-period.

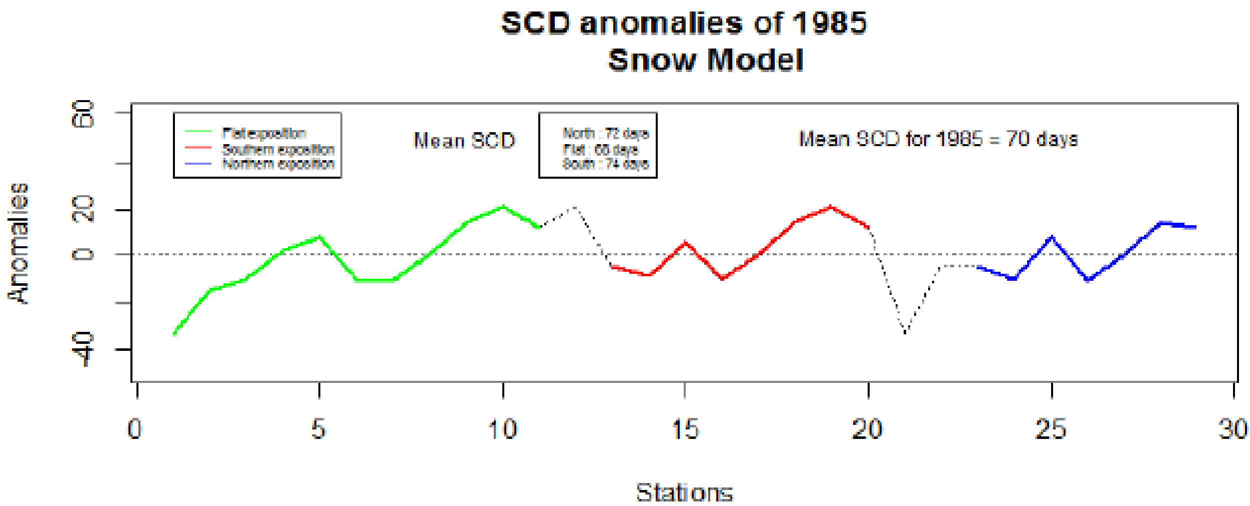


Appendix 2 Anomalies of snowpack duration according to the snow model data set for the period 1975-2010. Mean is calculated with 10 locations. The uncertainty range is based on the standard deviation and anomalies is equal to the difference from the mean of the entire selected time-period.

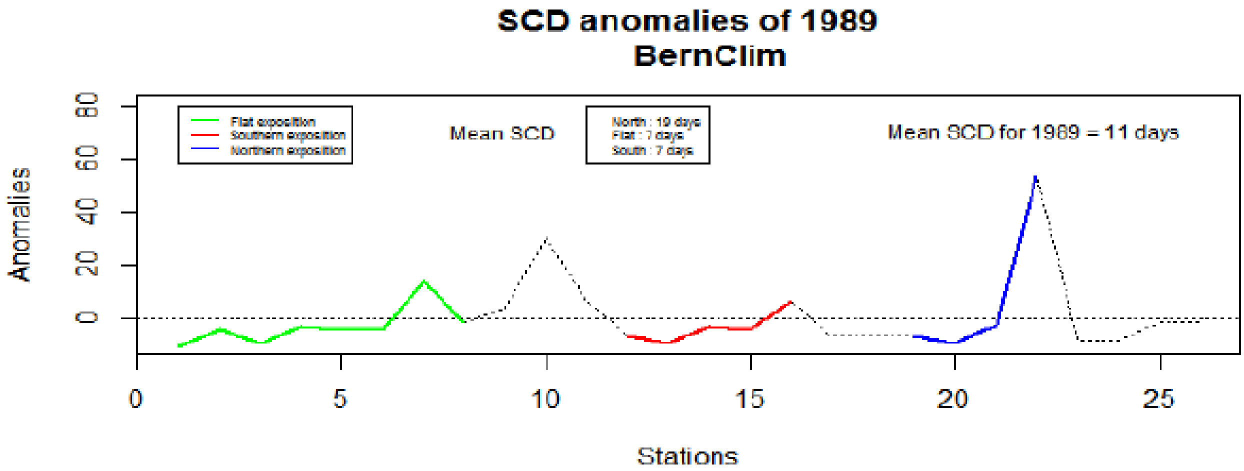


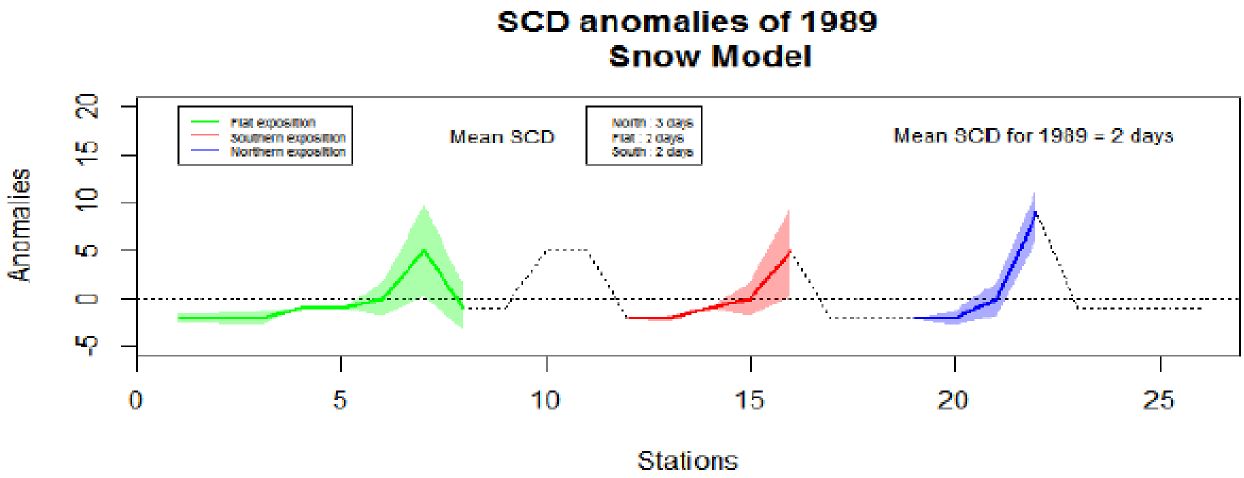
Appendix 3 Anomalies of the snowpack duration for year 1985 according to BernClim (up) and the snow model (down). Anomalies are calculated as the difference from the time-period mean. Stations are sorted by exposition and then by altitude. Flat (green), north (blue) and south (red) exposition are highlighted. Dotted anomalies represents the other intermediate expositions.



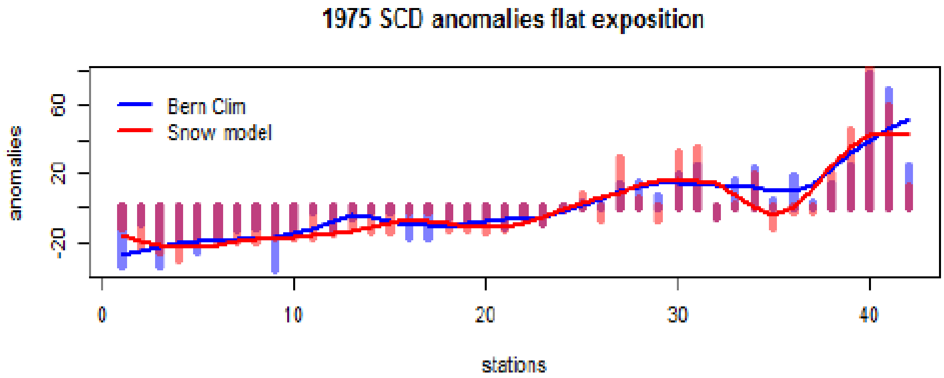


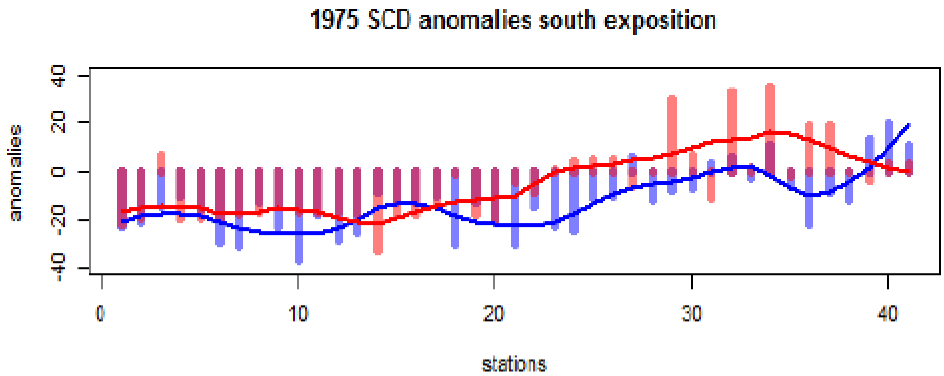
Appendix 4 Anomalies of the snowpack duration for year 1989 according to BernClim (up) and the snow model (down). Anomalies are calculated as the difference from the time-period mean. Stations are sorted by exposition and then by altitude. Flat (green), north (blue) and south (red) exposition are highlighted. Dotted anomalies represents the other intermediate expositions.

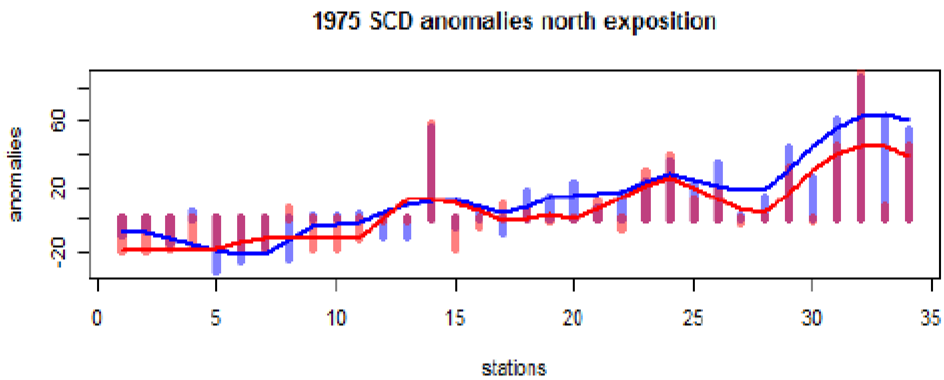




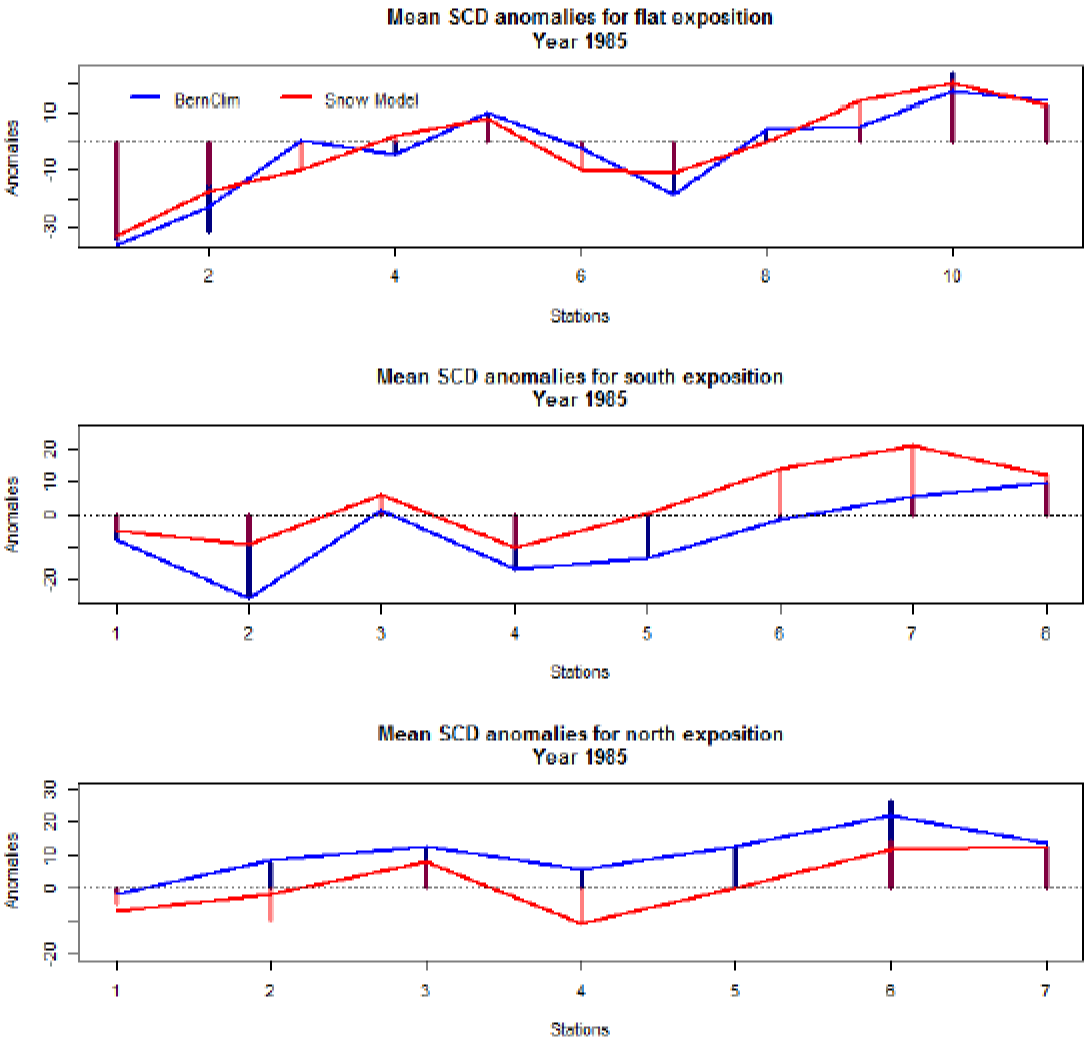
Appendix 5 Anomalies of the snowpack duration for year 1975. The stations are displayed depending their exposition: flat (up),south (middle) and north (down) for the BenClim (blue) and the snow model (red). Anomalies are calculated as the difference from the mean of all stations. Solid lines represents the smoothed values using a polynomial regression fitting process.







Appendix 6 Anomalies of the snowpack duration for year 1985. The stations are displayed depending their exposition: flat(up),south (middle) and north (down) for the BenClim (blue) and the snow model (red). Anomalies are calculated as the difference from the mean of all stations. Solid lines represents the smoothed values using a polynomial regression fitting process.



Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Mayor Benjamin

Matriculation number: 09 - 802 - 471

Programme: M. Sc. Climate Science

Bachelor ☐ Master ☒ Dissertation ☐

Thesis title: Snow Cover Duration in Lowland Regions of Switzerland : Comparison of Three Methods

Thesis supervisor: Pr. Stefan Brönnimann

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise. I grant inspection of my thesis.

Troistorrents, the 6th of October

Place, date

M. Benj

Signature