SNOW LINE ANALYSIS IN THE SWISS ALPS BASED ON NOAA-AVHRR SATELLITE DATA

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ABSTRACT

A method to derive the snow line elevation using NOAA-AVHRR satellite data in combination with a digital elevation model is presented. The AVHRR sensor enables the frequent observation of the snow cover with a sufficiently high temporal resolution. The definition of the snow line and the impact of geo-coding errors, as well as errors due to misclassification, are discussed. A comparison of the NOAA-AVHRR data with higher resolution data from IRS-WiFS indicates that even at spatial resolution of 1.1km, a quantitative analysis of the snow line elevation is possible. Satellite data from 1992, 1996, 1998 and 1999 are analysed and used to define regions within Switzerland with similar behaviour concerning the snowline elevation development.

INTRODUCTION

The snow cover is an important feature of mountainous regions like the Alps. For several months a year, the higher elevations are completely covered by snow. The high surface albedo of snow has a great influence on the local climate, decreasing the surface net radiation and thus the energy transfer. In addition, the snow cover is a relevant factor not only for the development of ecosystems, but also for human activities like hydropower generation or ski tourism. The snow line is an important indicator of the snow coverage. Viewed over a large area, the elevation shift of the snow line indicates certain climate behaviour, either towards cold and maybe wet conditions or towards a warmer climate.

For many years, satellite data have been widely used in snow hydrology on a regional to continental scales (BAUMGARTNER et al. 1991, CARROLL 1990, EHRLER & SCHAPER 1997, KLEINDIENST et al. 1999). However, only few publications deal with the use of satellite data for assessing the snow line elevation (e.g. SEIDEL et al. 1997). To the authors' knowledge, NOAA-AVHRR (National Oceanographic and Atmospheric Administration – Advanced Very High Resolution Radiometer) data have never been used in this context. The major advantages of NOAA-AVHRR are that it provides a sufficiently high repetition rate and covers an area as large as the Alps. The aim of this paper, therefore, is to show the applicability of NOAA-AVHRR data for the purpose of analysing the snow line elevation at an alpine scale. Once the method is established, it can be applied to a long time series of AVHRR data.

SNOW LINE DERIVATION USING SATELLITE DATA

Definition of the snow line in satellite images

Snow maps derived from satellite data are a pixel-based representation of a snow-covered area. With spatial resolution of a few hundred metres up to one kilometre, a pixel, either classified as 'snow' or 'no-snow', often consists of snow-covered and snow-free parts. In theory, the snow line defines the line separating snow-covered from snow-free areas. However, because of the patchiness of the edge of the snow cover, no distinct line can be drawn. Instead, a more or less narrow belt has to be defined as the snow line, which represents a zone of approximately 50% snow coverage (WMO – World Meteorological Organisation – in SEIDEL et al. 1997). The application of satellite data supports this definition due to its mixed pixel aspect.

Assuming that a pixel is classified as 'snow' if equal or more than 50% of its area is covered by snow, those pixels representing the edge of the snow-covered area would define the snow line belt (white edge). Figure 1 displays a situation on a slope, indicating the pixels, which would be selected as snow line pixels.

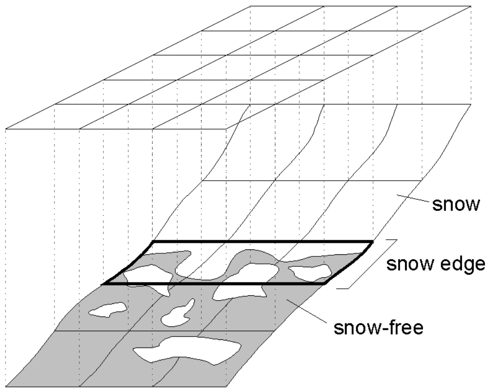

Figure 1: Schematic view of a slope with snow line. The grid represents the satellite data pixels. The pixels marked with a thick line are defined as snow edge pixels.

As an alternative, the pixels representing the edge of the snow-free area can be selected as snow line pixels (green edge), in which case the elevation of the snow line would obviously be lower. The choice whether to work with the white edge or the green edge depends on the snow classification algorithm. Applying a more conservative algorithm, which tends to overestimate the snow-covered area, suggests the use of the white edge, since even pixels with less than 50% snow coverage might be classified as 'snow' pixels. An algorithm generally underestimating the snow coverage, on the other hand, supports the use of the green edge. Figure 1 shows the distribution of the snow line elevation based on the white edge and the green edge, resulting from an overlay of a NOAA-AVHRR derived snow map over the digital elevation model. It is based on all snow edge pixels for the whole of Switzerland, which explains the large range of the distribution.

A comparison of both the white-edge and the green-edge distribution of the snow line elevation, using satellite data with higher spatial resolution (IRS-WiFS – Indian Remote Sensing Satellite, Wide Field Sensor: 180m) suggests using the white edge as snow line reference. However, further analysis have to be carried out, including the application of satellite data with even better spatial resolution such as Landsat TM (Thematic Mapper) (30m).

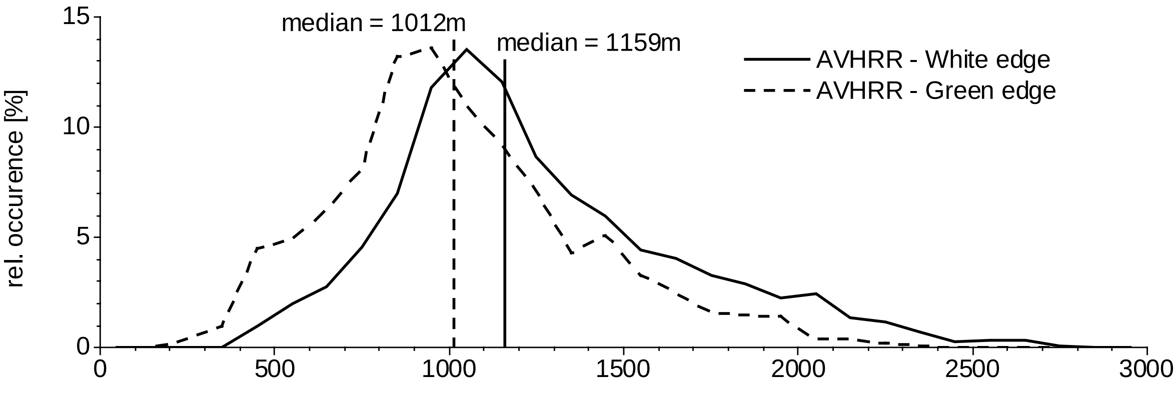

Figure 2: Comparison of the snow line elevation distribution based on the "white edge" and "green edge" of a NOAA-AVHRR snow map (24 March 1999). The statistical distribution covers the whole of Switzerland and is based on classes of 100m intervals.

Influence of errors in geo-coding

In order to use satellite data in combination with other data sets, for example a digital elevation model, the satellite data have to be transferred into a common geographical reference system. However, this process called geo-coding inherits a certain error, preventing the determination of the exact position of a specific pixel. In general, an accuracy of about 0.5 – 1 pixel can be achieved, which means an uncertainty of roughly 500m in the case of NOAA-AVHRR, having a 1.1km resolution.

Assessing the snow line elevation of a specific slope, for example with an incline of 45°, a horizontal displacement as large as 500m would lead to the same vertical error. However, as displayed in figure 3 the average snow line elevation in the case of two similar slopes facing each other would remain about constant. As a consequence, no aspect-dependent analysis of the snow line elevation is possible, with the errors inherent in the underlying satellite data. Only if the snow line elevation of complementary aspects is averaged, the error caused by inaccurate geo-coding is levelled out.

Using hydrological basins as a basis for averaging the elevation data takes advantage of this behaviour, since it can be assumed that within a hydrological basin, usually no aspect dominates. However, the size of the applied basins has to be large enough in order to ensure that a sufficient number of snow edge pixels can be used for statistical analysis. It has also to be taken into account that an ideal situation as displayed in figure 3 is not very likely to occur.

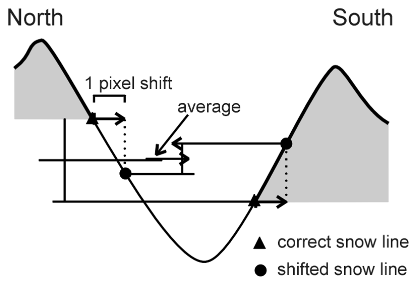

Figure 3: Effect of a one-pixel north shift of the snow line on the average of the snow line elevation in the case of two slopes facing each other, with similar inclination.

For testing the effect of geo-coding problems, the satellite data building the basis for the snow line definition is shifted northwards by one pixel, introducing an artificial error. Figure 4 shows that the effect of this manipulation on the distribution of the snow line elevation is minimal. However, if the northeast- and southwest-facing slopes are averaged separately, the median elevations are 1045m and 1382m, respectively. The north-shift makes these values change to 1143m and 1233m, reducing the difference from 337m to only 90m.

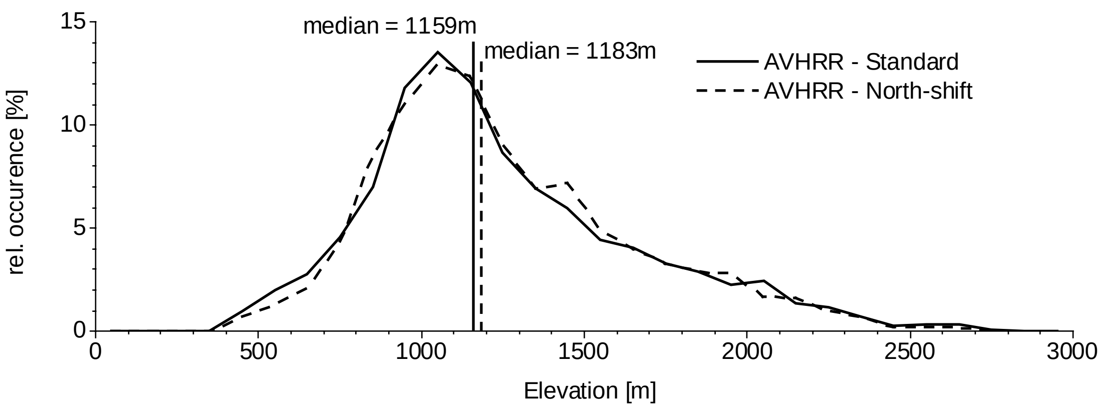

Figure 4: Effect of a one-pixel north-shift of the snow line on the elevation distribution of the snow line for the whole of Switzerland (based on NOAA-AVHRR data, 24th March 1999).

Problems due to wrong classification

The original satellite data consist only of digital numbers, indicating the radiation energy received at the sensor. Using publicly available calibration information, these numbers can be transformed into values with physical meaning, like albedo or brightness temperature. Classification procedures turn these values or numbers into thematic information, making use of the fact that certain surface types such as vegetation, water, snow or clouds have specific spectral properties and, therefore, distinct relations between channels with different wavelength sensitivity.

Two major difficulties have to be taken into account concerning the classification procedure. In the case of mixed pixels, which contain two or more surface classes, the assignment of such pixels to a specific class is sometimes not well defined, especially close to the edge of the snow cover. Many factors influence the appearance of the pixels, like the state of the atmosphere, the solar angle or shadow effects.

The second problem results from complete misclassification of a pixel, for example if two objects show a similar spectral behaviour. Specifically snow and clouds are difficult to separate, especially if low water clouds are involved. Such misclassification can lead to apparently snow covered areas at strange elevations. Figure 5 visualises the problems, which can occur due to classification errors.

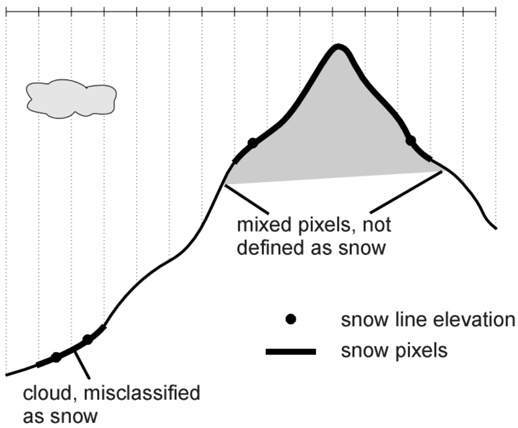

Figure 5: Problems concerning the definition of the snow line elevation, arising due to classification errors. The vertical lines represent the pixel structure of the satellite data.

Derivation of the snow line elevation

Once all pixels representing the snow line are marked, the elevation of each can be determined based on a digital elevation model. However, as shown above, the uncertainty of the single pixel's location as well as the problems concerning snow classification require a certain number of pixels to allow reliable snow line definition as an average of these pixels.

In order to fulfil these requirements, river basins can be used as reference areas. Using watersheds for this purpose has the great advantage, that usually all aspect classes are represented within the basin areas, leading to more reliable averages of the snow line elevation, as shown in Figure 3. The elevation distribution of all snow edge pixels within one such basin can be plotted as in Figure 2 and Figure 4. In order to compare the elevation distributions of different dates or regions, statistical values representing the snow line elevations have to be defined. Having the WMO definition in mind (SEIDEL et al. 1997), saying the elevation with approximately 50% snow coverage can be defined as snow line, the median of the distribution is the obvious choice. One half of the snow edge pixels is above this median elevation, the other half shows lower elevations.

It is important to note that the reference areas have to be large enough to contain a sufficient number of snow edge pixels for sound statistical analysis. As a test, NOAA-AVHRR data with a spatial resolution of 1.1km are plotted against IRS-WiFS data with 180m resolution, both data representing the situation on 24th March 1999. Thereby, two different sets of reference areas are applied, with an average size of 145km^2 and 2340km^2, respectively (Figure 6). The first plot, comparing both sensors using the small basins, indicates that the size of the first set of reference areas is too small. Applied the larger regions, an improved agreement between AVHRR and WiFS data can be achieved, as shown in the second plot of Figure 6. The average difference of AVHRR and WiFS based snow line elevation is reduced from 141m to 69m. The maximum deviation improves to 183m for the large basins, compared to 669m in the case of the small ones.

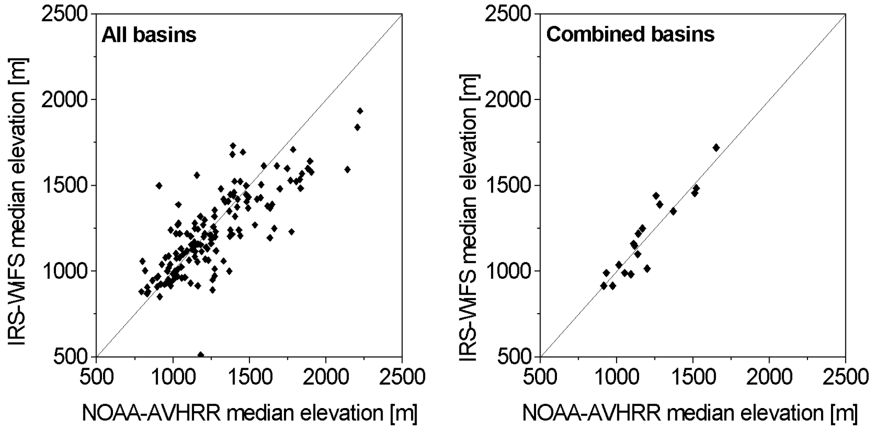

Figure 6: Comparison of the basin's median snow line elevation based on NOAA-AVHRR and IRS-WiFS (24 March 1999). The left plot shows the result for small basins with an average size of 145km^2. The right plot shows the same data for basins combined to an average of 2340km^2.

Methodological restrictions

The accuracy limitations of geo-coding, classification and spatial distribution of satellite based snow maps as described above have to be taken into account when further conclusions are drawn from the results. It is certainly not possible to assess the behaviour of a small area represented only by very few pixels, especially if only one day is investigated. The data resulting from the current processing show too much noise to allow such analysis. However, if a larger area or a number of days is averaged, the noise is reduced. In the exemplary application documented below, either a complete ablation period or whole area of Switzerland is summarised.

APPLIED REMOTE SENSING AND GIS DATA

Satellite data

The NOAA-AVHRR sensor is well suited for snow cover monitoring. Its repetition cycle of less than one day allows to map the change of snow cover extent with a sufficiently high temporal resolution. With channels in the visible, near-infrared and thermal infrared part of the electromagnetic spectrum, this sensor allows semi-automatic discrimination of snow, cloud and snow-free areas. RANGO et al. (1983) state that the spatial resolution of 1.1km is sufficient if large areas of more then 200-500km^2 are targeted, however, an area of 500-1000km^2 and more seems to provide a more sound statistical data basis.

In order to assess the applicability of the NOAA-AVHRR data for snow line analysis as presented here, additional data from the Indian sensor IRS-WiFS are used. This sensor has a spatial resolution of 180m with a repetition cycle of three to four days. However, its spectral setting does not allow differentiation of snow and clouds, which limits the compatibility of the two data sets.

Snow map generation

Only the early afternoon passes of NOAA-AHVRR are used for derivation of snow maps, showing the least shading effects caused by the rough terrain. The image processing of the satellite data includes several steps, namely geo-coding, calibration and classification.

The geo-coding transfers the satellite data to a common geographical reference system, which is done interactively via ground control points (GCP's). With an average of approximately 30 GCP's, the remaining error is usually less then one pixel, which is important if the data are used together with other spatial data sets like a digital elevation model. After calibration and terrain normalisation, the pixel values of the satellite data are transformed into top-of-the-atmosphere reflectance (RAO & CHEN 1995) and brightness temperature. These values are used for snow and cloud classification, applying a 6-step threshold scheme, which works as a negative test, eliminating all pixels containing other information than snow.

The basic idea of this approach is to find reflectivity and temperature thresholds defining boundary conditions for snow influenced AVHRR pixels. A combination of several thresholds proved to be adequate for this purpose, and a pixel is assumed to be snow influenced, only if all threshold tests pass. Table lists the different tests and defines default values for each specific test. These threshold values are adapted manually to improve the snow classification for each scene (VOIGT et al. 1999).

Table 1: Typical threshold values are a recommendation for a scene in the Alps early in the year. The suggested values cannot be generally applied. BT (brightness temperature), NDVI (normalised difference vegetation index), R1/R3 (reflective part of channel 1 and 3 of NOAA-AVHRR).

No.	Name	Definition	Typical value (winter/summer)
1.	Warm brightness temperature	$BT_4 <$ max BT_4(snow)	0°C / 20 °C
2.	Cold brightness temperature	$BT_4 >$ min BT_4(snow)	-30°C / -10°C
3.	Cirrus	$BT_4 - BT_5 < \Delta BT_{45}$ (cirrus)	2.5°K
4.	Vegetation	NDVI < min (vegetation)	0.2
5.	Water Cloud	$R_3 <$ max R_3(snow)	8%
6.	Albedo	$R_1 >$ min R_1(snow):	20 %

For the IRS-WiFS data, an unsupervised classification is carried out, assigning the values 'snow' and 'no-snow' interactively to the resulting classes. The spectral setting of this sensor does not allow the application of the threshold scheme.

Digital elevation model and reference areas

As a basis for deriving the elevation of the snow line, a digital elevation model is required. The RIMINI model (BUNDESAMT FÜR LANDESTOPOGRAPHIE 1960-70) covers the whole of Switzerland with a spatial resolution of 250m. The vertical error can be as high as 50m, however, having the elevation range within a 1km pixel in mind the influence of this error is relatively small. Nevertheless, due to the development history of the RIMINI model a systematic overestimation might occur.

For aggregation of the snow line elevation data, water balance areas are used. The average size of the original areas counts 145km^2. These basins were aggregated into 18 regions with an average size of 2340km^2, in order to get a better basis for statistical analysis.

FIRST APPLICATIONS AND RESULTS

Data from four years with different snow-cover conditions are available to analyse the behaviour of the snow line during the ablation periods. Whereas the winters 1991/92 and 1997/98 are average in terms of snow amount and snow cover duration, 1995/96 represents mild conditions with little snow and early ablation. 1998/99 on the other hand, is dominated by heavy snowfall in February and partly in April, causing an extended period of snow coverage even at lower elevations. Table lists the number of available satellite scenes per month for these four years.

Table 2: Number of available snow maps per month for the four test years.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1992	0	5	3	5	1	2	1	1	0
1996	2	6	2	2	5	1	3	0	0
1998	0	0	3	1	2	2	0	2	1
1999	3	2	8	3	8	5	3	0	0

Time series analysis

The first analysis is carried out for the area of Switzerland as a whole, thus minimising the difficulties concerning the size of the reference areas. During the extreme years 1996 and 1999, the average snow line elevation was calculated as statistical median for the elevation distribution for each day of observation. Figure 7 compares the resulting temporal development for both years.

As mentioned above, the selected years represent special situations, with little snow and early ablation in 1996 and heavy snowfalls in 1999. As can be seen in Figure 7, major differences occur during the months of April and May. During these two months, the snow line was approximately 500m higher in 1996 than in 1999. Comparing corresponding elevation rather then corresponding time it can be seen that snow ablation occurred earlier in 1996 than 1999. Especially at elevations between 1500m and 2500m, snow ablation in 1999 took place approximately one month later.

These numbers are rough figures because detailed error estimates have not yet been carried out. Additional analysis is currently ongoing to allow specific quality estimates.

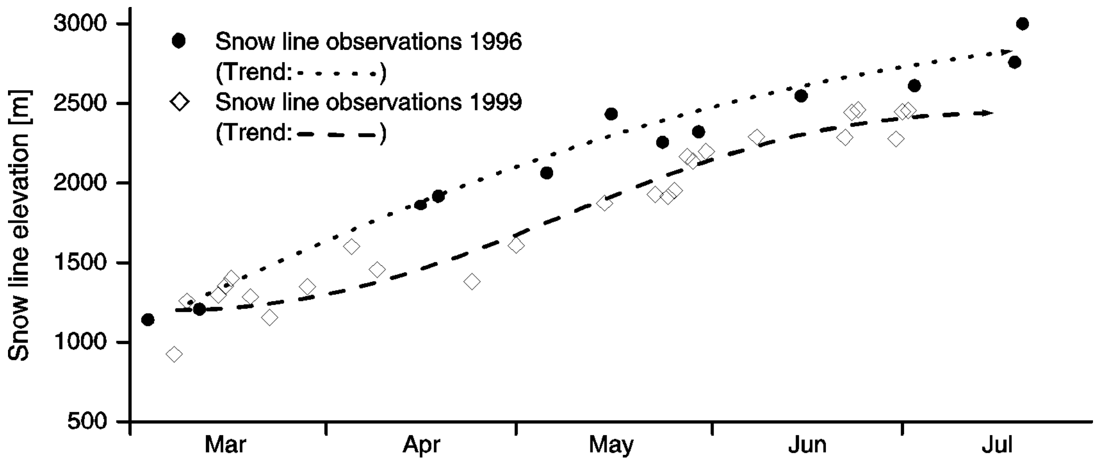

Figure 7: Increase of the snow line elevation in Switzerland during the years 1996 and 1999. In order to compare the data, a manually estimated trend is included for both years.

Spatial patterns of snow line behaviour

The second application aims at deriving spatial patterns based on the temporal snow line development. Considering precipitation, wind and solar radiation as well as cloudiness and temperature, Switzerland can be subdivided into seven homogeneous climate regions, four to the north and three to the south of the main Alpine ridge (SCHUEPP et al. 1978, Figure 8).

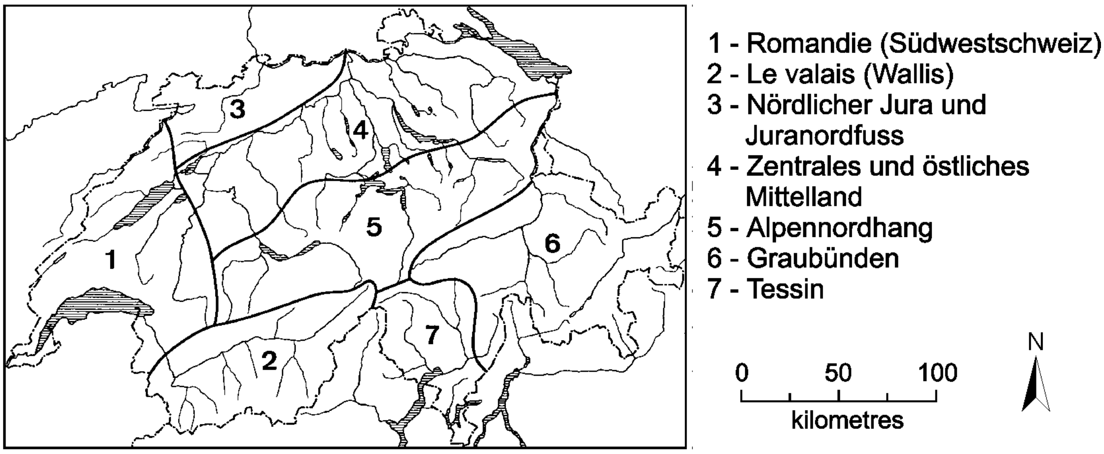

Figure 8: Definition of seven climate regions in Switzerland after Schuepp et al. (1978), based on precipitation, wind, sunshine, cloudiness and temperature data.

The snow cover and also the snow line are strongly influenced by all the different climate parameters. A similar pattern as shown in Figure 8 is, therefore, expected to appear in the spatial distribution of the snow line elevation. However, individual situations might be influenced by single snowfall events and thus do not necessarily represent general behaviour. Figure summarises the snow line analysis of the four test years.

As a first approach, the average snow line elevation of each region as defined in section 3.3 is compared to the Switzerland-wide average for each day recorded by satellite. The elevation differences between the two scales are then averaged using data from all available observations during the four test years. The resulting spatial pattern of elevation differences is shown in the central part of Figure 9. However, the normalisation based on the Switzerland-wide average is not absolutely reliable. Partial cloud cover over Switzerland can cause a bias, for example if clouds obscure a region with an extraordinarily high snow line elevation. This method can, therefore, only be an approximate way to define similar regions.

For further comparison of different regions, the temporal development of the snow line elevation can be used. Such temporal behaviour can be addressed as temporal signatures of snow line elevation. Four regions are instancing selected in Figure 9. Regions 4 and 9 as well as regions 6 and 13 show the same snow line deviation relative to the overall median, respectively. As a reference for comparison, the temporal signature of Switzerland as a whole is included in each region's graph.

Regions 4 and 9 both show tendencies towards snow line elevations above the Switzerland-wide average. However, the slope of the elevation increase gradient is less steep in region 9, with the snow line elevation starting high and reaching the Swiss average only in July. Region 13 represents the central part of Switzerland. The course of the temporal snow line signature is similar to the Switzerland wide average, however, the elevation is slightly lower. The exceptional behaviour of the Tessin (region 6) is partly caused by misclassification of cloud as snow.

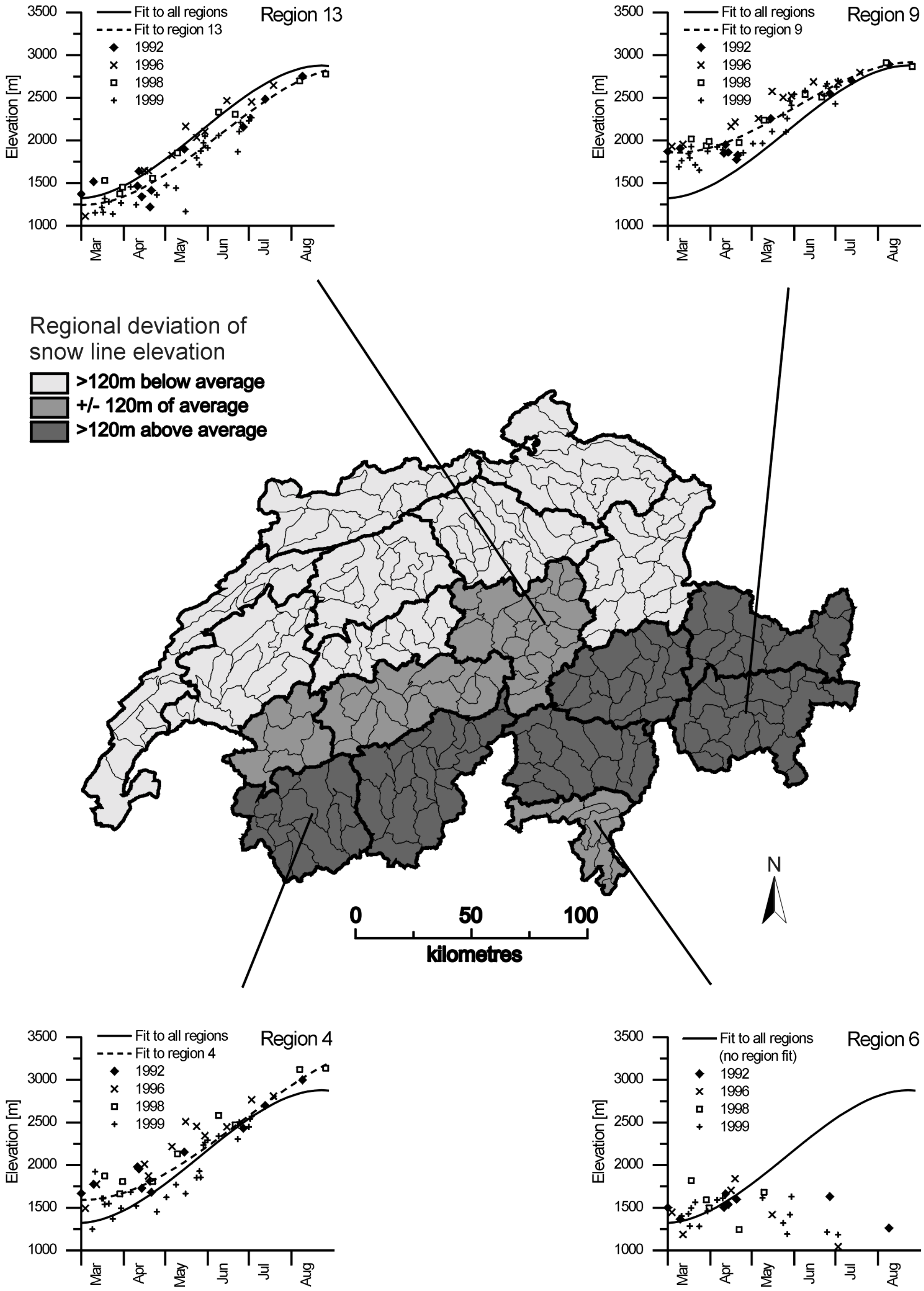

Figure 9: Temporal behaviour of the snow line for four different regions using NOAA-AVHRR data from all four years. The classification of the regions is based on the average tendency of the snow line elevation compared to the Switzerland-wide statistical median of the elevation distribution.

Discussion and outlook

The application of satellite data for assessing snow line elevation as demonstrated here indicates a high potential for this method. Figure shows that the temporal snow line signature can be used to identify regions with different snow line behaviour. This study can, therefore, be understood as a first approach towards a snow climatology, which would, however, require an extended data basis, including several more years with snow line data.

Before further and more detailed analysis can be carried out, some problems addressed above have to be solved first. As can be seen in the Tessin (region 6 in Figure 9), the misclassification of clouds and snow can still be a problem, even with NOAA-AVHRR, which has a certain capability to discriminate between snow and cloud. It has to be tested whether statistical methods or GIS approaches can be applied to mask out the resulting exceptional elevations. As a second issue, the relevance of the spatial distribution of the applied satellite data has to be investigated further. In addition to IRS-WiFS also Landsat TM data can be used, having a spatial resolution of 30m. Finally, if improved geo-coding can be applied, for example based on ortho-rectification using ditigal elevation data, the number of pixels required for statistical analysis can be reduced, allowing smaller basins to be applied as reference areas.

SUMMARY

A method to derive the snow line elevation using NOAA-AVHRR satellite data in combination with a digital elevation model is presented. The AVHRR sensor enables frequent observation of the snow cover with a sufficiently high temporal resolution.

The definition of the snow line and the impact of errors in geo-coding as well as errors due to misclassification are discussed. A comparison of the NOAA-AVHRR data with higher resolution data from IRS-WiFS indicates that even a spatial resolution of 1.1km enables a quantitative analysis of the snow line elevation.

Satellite data of the years 1992, 1996, 1998 and 1999 show the influence of different wintry conditions in Switzerland on the elevation of the snow line. As a first result, the spatial pattern of the average snow line elevation is presented. In addition, the snow line signature, characterising the increase of snow line elevation with time, is derived for four regions and compared with the Switzerland-wide snow line signature.

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REFERENCES

Baumgartner, M.F., Schönenberger, A. & Stalder, U. (1991): Snow cover variations in the Alps using NOAA-AVHRR data. In: Bergmann. H, Lang, H., Frey, W. Issler, D. & Salm, B. (eds): Snow, Hydrology and Forests in High Alpine Areas. International Association of Hydrological Sciences Publication 205: 41-50.

Carroll, T.R. (1990): Operational Airborne and Satellite Snow Cover Products of the National Operational Hydrologic Remote Sensing Center. In: Proceedings of the Forty-Seventh Annual Eastern Snow Conference, Bangor, Maine: 87-98.

Ehrler, C. & Schaper, J. (1997): Analyse von Ausaperungsmustern der saisonalen Schneedecke mit Fernerkundungsmethoden. *Geographica Helvetica*, 52, 1: 11-20.

Kleindienst, H., Pfister, M. & Baumgartner, M.F., (1999) Pre-operational snowmelt forecasting based on an integration of ground measurements, meteorological forecasts and satellite data. In: Tranter, M., Armstrong, R., Brun, E., Jones, B., Sharp, M. & Williams, M., editor: Interactions Between the Cryosphere, Climate and Greenhouse Gases. In: IAHS Publ. 256: 81-89.

Bundesamt Für Landestopographie (1960-1970): RIMINI. Bern

Rango, A., Martinec, J., Foster, J. & Marks, D. (1983): Resolution in operational remote sensing of snow cover. IAHS Publ.145: 371-381

Rao, C. R. N. & Chen, J. (1995): Inter-satellite calibration linkages for the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA-7, -9 and -11 spacecraft. *International Journal of Remote Sensing* 16: 1931-1942.

Schuepp, M., Bouët, M., Bider, M., Urfer, Ch. (1978): Klimatologie der Schweiz, Band II: Regionale Klimabeschreibungen, 1.Teil. Beiheft zu den Annalen der Schweizerischen Meteorologischen Anstalt, Zürich.

Seidel, K., Ehrler, C., Martinec, J. & Turpin, O. (1997): Derivation of statistical snow line from high-resolution snow cover mapping. In: Wunderle, S. (ed.): Remote Sensing of Land Ice and Snow. Proceedings of the EARSeL Workshop, 31-36, Freiburg.

Voigt, S., Koch, M., Baumgartner, M. F. (1999): A multichannel threshold technique for NOAA AVHRR data to monitor the extent of snow cover in the Swiss Alps. In: Tranter, M., Armstrong, R., Brun, E., Jones, B., Sharp, M. & Williams, M. (eds): Interactions Between the Cryosphere, Climate and Greenhouse Gases, IAHS Publ. 256: 81-89.