MAPPING SNOW DEPTH IN THE ALPS

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ABSTRACT: The Swiss Federal Institute for Snow and Avalanche Research SLF publishes snow depth maps of Switzerland. These maps provide valuable input for avalanche warning, hydrological snowmelt runoff modelling, climatology, winter tourism and popular geovisualizations e.g. dynamic overlays for Google Earth. The snow depth maps are derived from snow station measurements using a spatial interpolation method based on the dependency of snow depth on altitude. On days with little cloud cover, an operational snow cover product obtained from the polar-orbiting NOAA AVHRR satellite is included in the GIS analysis. Through this process, an additional set of virtual snowfree stations is gained to increase the density of the imeasurements. The resulting snow depth maps are calculated at a spatial resolution of 1x1 km. In this study we transfer and adapt this approach to the neighbouring region of South Tyrol (northern Italy). In a case study we demonstrate the merging technique and evaluate its accuracy based on cross-validation analysis. The error estimates indicate that the introduction of virtual snowfree stations results in an improved spatial snow depth interpolation. Limiting factors are associated with the number of cloud free satellite images and the sub-optimal illumination conditions during mid-winter in the rough alpine terrain. For the future, an alpine-wide snow depth map would be of great interest. Also, an adaptation and application to other mountain regions in the world could be of great relevance.

KEYWORDS: snow cover, snow cover mapping, interpolation, NOAA AVHRR, GIS

1. INTRODUCTION

Monitoring snow depth, measured vertical on horizontal terrain, has a long tradition in the Alps. The first regular snow observations in Switzerland date back to 1892. In the meantime the network of snow and weather stations grew continually. These measurements provide a basis for avalanche forecasting, hydrological snowmelt runoff modelling, meteorology and climatology and serve as an increasingly important source of information for winter tourism. The Swiss Federal Institute for Snow and Avalanche Research SLF at Davos provides daily information about the avalanche situation and the snow conditions in the Swiss Alps. In addition to avalanche text bulletins, country-wide maps for avalanche danger, snow pack stability, new snow depth and snow depth are primary products of SLF's snow information (http://www.slf.ch). In Italy the avalanche warning is organised independently by the regions and provinces of the Alps. They also provide a range of avalanche text bulletins, various maps and graphics about the current avalanche situation.

The distribution of snow in a landscape is a result of microclimatic, topographic and vegetative effects on snow accumulation, redistribution and ablation. One of the most reliable methods for mapping the spatial distribution of snow is the collection of snow depth in situ and subsequent spatial interpolation. We are looking for a simple solution to interpolate the irregularly distributed and temporally changing point measurements to a grid of 1x1 km. Early work on interpolating snow depth in the European Alps was done by Witmer et al. (1986). Witmer developed a method to calculate an area wide snow depth value based on a linear dependency of snow depth and altitude for seven predefined climatological regions based on 20 years data from 1960/61 – 1979/80. Schwarb et al. (2001) published similar maps featuring the mean annual and seasonal precipitation throughout the European Alps 1971 – 1990, based on PRISM, a statistical-topographic model for mapping precipitation over mountainous terrain. To account for local conditions the observed station values

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are weighted by differences in altitude and exposition to the estimated grid point. For interpolating meteorological data over Swiss alpine catchments Verbunt et al. (2003) used several methods such as inverse distance weighting (e.g. for sunshine duration), altitude dependent regression (e.g. for incoming solar radiation) or a weighted combination of both methods (e.g. for precipitation). López-Moreno and Nogués-Bravo (2006) compared the most commonly used interpolation methods in snow studies over the Spanish Pyrenees. These include techniques as inverse distance weighting, kriging, regression-tree and generalized additive models.

In Switzerland snow depth is measured at about 250 snow and weather stations, mainly in the alpine region. These point measurements are the basis for the interpolation of the snow depth maps. Recently a new interpolation model has been developed at the SLF (Auer et al., 2004). An area-wide base value is determined and adjusted by a regional-to-local compensation value. The resulting snow depth map is calculated on a grid cell size of 1x1 km over Switzerland. This model performs best in regions with a dense network of snow stations. However, the number of operational snow stations varies during a winter season because in early winter and in spring the snow stations in lower altitudes are not in operation. Therefore an additional snow information source is included into the interpolation process by the use of real-time snow cover products derived from NOAA AVHRR satellite data.

The objective of the study is to apply the operational and real-time method to calculate snow depth maps developed in Switzerland to a dataset for the autonomous alpine province of South Tyrol (northern Italy).

2. STUDY AREA

The study site of this analysis covers the Province of South Tyrol in northern Italy. It consists of an area of approximately 7400 km² and is located from 46°10' N to 47°10' N and 10°20' E to 12°30' E. Three main topographical landscapes can be distinguished: the alpine ridge with the highest mountain ranges up to 3900 m a.s.l. in the north, the Etsch valley separating the country into a western and eastern part and containing the lowest point in South Tyrol at 200 m a.s.l. and the Dolomites, an alpine massive up to 3343 m a.s.l. in the south east. The mountain ridges act as a natural obstacle on which larger-scale weather systems, developing mainly over the Atlantic Ocean and the Mediterranean, can be deflected or modified. These landscape characteristics influence the spatial and temporal variability of the seasonal snow cover.

3. DATA

3.1 <u>In situ snow depth observations</u>

In South Tyrol snow depth is measured by the Hydrological Service in Bozen/Bolzano. It operates two different types of networks. The network for the avalanche service consists of conventional observation stations and automatic snow and weather stations. The manned 18 conventional stations are generally located at alpine villages and ski resorts. They survey a variety of snow, avalanche and weather parameters on a daily basis. Snow depth is measured manually on a representative plot in horizontal terrain. The 10 automatic snow and meteorological stations are situated at altitudes above 2000 m a.s.l.. They are close to avalanche starting zones and provide half hourly data. Snow depth is measured at these locations through an ultrasonic distance measurement sensor. In this study additional measurements from the hydrological network are included to densify the dataset. Figure 1 shows the locations of all 43 snow stations included in the analysis. The total number of snow measurements is dropping to about 50% in early winter and spring due to a shorter period of observation at the snow stations at lower altitudes.

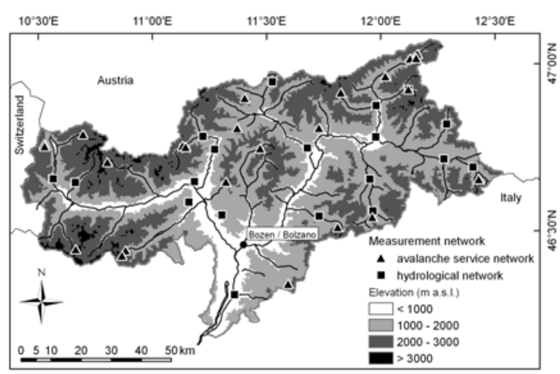


Figure 1: Topographical map of the province of South Tyrol (7400 km^2) and locations of the 43 snow stations included in the analysis.

Table 1: Overview of the specific NOAA AVHRR datasets of the selected days. Mean scan angle is calculated from the entire dataset pre-processed in real-time. All other parameters are determined for the area of South Tyrol.

Date of in situ measurements	Date NOAA-N17 Satellite scene (UTC)	Mean scan angle (degree)	Satellite zenith (angle)	Satellite azimuth (angle)	Solar zenith (angle)	Solar azimuth (angle)
18 Dec. 05	19 Dec. 05 10:11	20.65	7.10	283.70	71.20	167.40
28 Jan. 06	01 Feb. 06 10:54	22.65	5.00	10.20	66.20	159.90
21 Feb. 06	27 Feb. 06 11:01	21.45	1.10	322.0	57.50	158.30

The snow depth mapping process is analysed for three days during winter 2005/06 (Table 1). These dates mark the end of important snow fall periods and are chosen with respect of testing the interpolation approach not only for snow depth maps but also for new snow depth maps. The latter is beyond the scope of this study.

The digital elevation model with a resolution of 500 m cell size is provided together with the snow depth data by the Hydrological Service.

3.2 Satellite data

The operational polar orbiting satellites from the U.S. National Oceanic and Atmospheric Administration (NOAA) provide daily images from the AVHRR (Advanced Very High Resolution Radiometer) scanner with 1.1 km^2 spatial resolution at nadir. The AVHRR scanner has five spectral bands measuring reflected solar (visible and near-infrared) energy and emitted thermal energy from the earth's surface and the atmosphere. The Remote Sensing Research Group at the University of Bern, Switzerland, receives and archives NOAA AVHRR HRPT (High Resolution Picture Transmission) data covering the area of the whole European Alps from 40.5° N to 50° N and 0° E to 17° E. Since the beginning of 2002, an operational status to process the data in near real-time is in use (Foppa et al., 2004).

In this study, NOAA-17 morning passes are used due to the favourable illumination conditions in winter and the advantage of the purely reflective channel 3A (1.6 μm) for an improved snow/cloud discrimination. Additionally, we are dealing with channel 1 (0.6 μm) and 2 (0.9 μm). The pre-processing includes calibration according to the NOAA KLM User's Guide, georeferencing including a feature-matching algorithm to geocode the satellite data with sub-pixel accuracy and an atmospheric correction of the visible channels 1 and 2 (Foppa et al., 2004). Atmospheric correction is based on the SMAC algorithm (Simplified Method for Atmospheric Corrections) (Rahman and Dedieu, 1994). Atmospheric parameters are derived from the NCEP datasets (National Center for Environmental Prediction, http://www.ncep.noaa.gov) and from the Alpine Model (aLMo, http://www.meteo suisse.ch/web/en/weather/models/almo.html) of MeteoSwiss whereas the atmospherical aerosol content is extracted from the same AVHRR dataset processed. The datasets are orthorectified using the terrain model GTOPO30 (http://edc.usgs.gov). This is an essential step to take into consideration of the geometric distortions introduced by the complex terrain and the observation geometry. Cloud detection and masking is done using the Cloud and Surface Parameter Retrieval (CASPR) package (Key, 2002). The cloud cover observed on the study dates was not considered in advance. In Table 1 the selected dates for the analysis and additional information about the selected AVHRR scenes are listed. A selection of suitable AVHRR scenes for the study dates is impossible due to dense cloud cover or unfavourable illumination conditions. Therefore the satellite scenes are selected from subsequent days (Section 4.4).

4. METHODS

4.1 Snow depth interpolation

At the SLF a spatial interpolation method was developed, which is based on the dependency of snow depth on altitude above sea level. This general dependency is later adjusted through in situ snow depth observations to represent the local and regional characteristics of the snow distribution (Auer et. al., 2004).

The algorithm incorporates two steps. First, the area-wide base value is determined, which describes the correlation between the snow depth and altitude with a power function. This general description is an approximation explaining 50-70% of the total variance of the snow depth with the variable altitude. The base value is thereafter adjusted with a local to regional compensation factor in a second step. This results in the following general formula:

$$HS_j = G(h_j) + A_j \tag{1}$$

where HS is the snow depth, G the altitude dependent base value and A the compensation value for the grid cell j to be calculated.

The compensation value is added to the base value to adjust the snow depth value for each cell in the 1x1 km grid. This compensation value is calculated as mean value of the difference of the base value and the measured value for the three stations nearest to the grid cell. The neighbourhood function is including the horizontal and vertical distances. The vertical distance of the neighbouring stations to the predicted grid value is included into the distance function to favour neighbouring stations that lay in larger distance on the same elevation level over neighbouring stations that lay in smaller distance on a different elevation level.

Therefore the formula for the compensation value A applied to 3 neighbours is:

$$A_j = \sum_{i=1}^{3} (HS_i - G_i)/3 \tag{2}$$

where HS is the measured snow depth and G the calculated base value at observation station i located at minimum distance d to the grid cell j where

$$d_{j_i} = \left[(x_j - x_i)^2 + (y_j - y_i)^2 + p*(h_j - h_i)^2 \right]^{1/2} \tag{3}$$

where x and y are coordinates, h is altitude and p the weight applied to favour horizontal distance over vertical distance, p=1000.

4.2 *Snow cover product from satellite data*

The Remote Sensing Research Group at the University of Bern, Switzerland, produces daily snow cover maps of the whole European Alps using NOAA AVHRR data. This AVHRR snow product provides information on the snow cover extent at sub-pixel resolution. A snow fraction algorithm takes into account potentially mixed pixels covering different land cover types, which are common in the rugged relief of the Alps. The final snow product is generated using an automatical approach for operational and real-time applications. A detailed description of the algorithm and discussion on the separated processing steps is given by Foppa et al. (2004). The performance of the method is explored on high-spatial resolution ASTER data showing a mean absolute error of around 10% fraction of snow cover for three case studies (Foppa et al., 2006a).

4.3 *Merging of ground-based snow depth data with satellite data*

The spatial interpolation method described in Section 4.1 yields to area-wide snow depth maps with good accuracy in areas with a dense snow station network (Foppa et al. (2006b). However, the interpolation method tends to overestimate the snow cover extent into areas with no measurements. This is often the case in early winter or spring. The satellite derived snow cover product provides on the other hand important information on the extent of the snow-covered area. In fall and spring the quality of the satellite snow cover data is improved compared to mid-winter, due to the illumination condition of the northern hemisphere. The aim of merging in situ snow depth data with satellite data is to take advantage of these oppositional trends which should lead to an improved result of the snow depth interpolation, merely at the snow - no snow transition.

The process of combining measured snow depth data with data of the snow cover extent from satellite data to calculate an area-wide snow depth map is a complex process and little previous work is found in the literature (Hartman et al., 1996). A direct masking of the interpolation result with the snow cover extent was analysed but rejected due to the frequently observed cloud coverage in the daily AVHRR sub-pixel snow product and because by simple masking no smooth transition of the snow depth from snow to no snow is achievable. For this reason we focus on another approach where no snow pixels are used as sample observations with zero snow depth to constrain the interpolation. The definition of snowfree pixels from the AVHRR sub-pixel snow product is a crucial factor. Due to the constraints of the sub-pixel algorithm each pixel contains a certain amount of snow in the final AVHRR sub-pixel snow cover product. During the post-processing a threshold is set to define pixels which are snowfree (Foppa et al., 2004). This threshold is set at a snow cover fraction value of 15% as proposed in other studies by Foppa et al. (2006a; 2006b). The snowfree pixels are intersected with a point grid and thereafter entered as virtual snow stations with a zero snow depth value into the snow depth interpolation. All other grid points are not included in the calculation. In Switzerland an irregular grid pattern with a possible total of approximately 400 virtual stations is in operational use. Foppa et al. (2006b) identified minor oversampling effects due to the dense virtual station network. In this study this effect is rectified by using a coarser regular 10 km point grid of 74 possible virtual stations show in Figure 2.

4.4 *Accuracy estimators*

The interpolation results are evaluated using cross-validation methodology (López-Moreno and Nogués-Bravo 2006). The method is based on removing one data point at a time, performing the interpolation for the location of the removed point using the remaining samples (i.e., pretending that removed point does not exist), and calculating the difference (residual) between the predicted value of the removed data point and the actual value at this point. This scenario is repeated until every data point has been, in turn, removed. The overall error of the interpolation is computed both as the mean bias error (MBE), which indicates a bias in estimation when it is nonzero and the root mean square error (RMSE) to incorporate the spread of errors.

4.5 *Operation mode*

The snow depth mapping process described above is in operational use at the SLF since the winter 2004/05. These snow depth maps are published weekly, sometimes more often after relevant changes in the snow depth. The map production is done in an interactive GIS application. There are two main operation modes. On days with little cloud effects the final snow depth map is calculated with the merging process specified in Section 4.3. However on days with dense cloud cover or in mid-winter, when the illumination conditions for the satellite in the rugged alpine terrain are insufficient, the map is calculated based on the ground-measurements only as described in Section 4.1. A special operating mode is applied in periods with little changes in snow depth. Then the ground-measurements may be combined with a snow cover map of a subsequent cloud free day, thus improving the final snow depth map.

5. RESULTS

In this study we applied the method to calculate snow depth maps developed in Switzerland to a dataset of the province of South Tyrol (northern Italy).

The full analysis is exemplarily carried out with the ground-measurements for February 21, 2006 and the AVHRR snow product for February 27, 2006. Figure 2 shows the AVHRR snow product classified with a threshold of 15% snow fraction. The snow product is intersected with the point grid of 74 possible virtual stations. The thereby identified 18 virtual snowfree stations, the 42 ground-measurements and the digital elevation model are input into the interpolation method (Section 4.1).

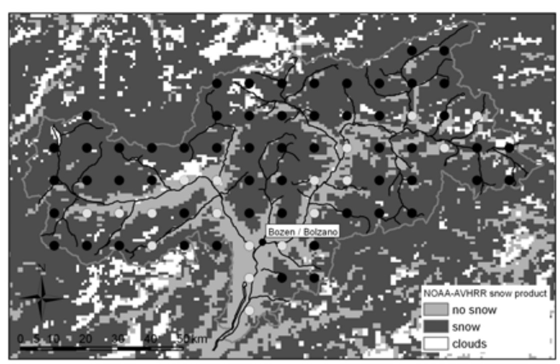


Figure 2: February 27, 2006 NOAA AVHRR snow product intersected with the virtual station point grid. The 18 light grey points are selected as virtual snowfree stations and therefore included in the interpolation.

The resulting snow depth map is presented in Figure 3. The snow depth distribution is dominated by the altitude gradient. The highest snow depth values are found in the northern part along the alpine ridge.

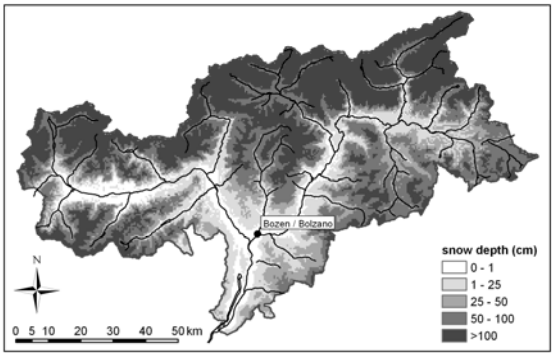


Figure 3: Snow depth map for 21 February 2006 interpolated with the combined data from 42 ground-measurements and 18 virtual snowfree stations.

The effect of the merging procedure is shown in Figure 4. The difference between the snow depth map interpolation calculated without using virtual snowfree stations and the snow depth interpolated using the 18 virtual snowfree stations identified from the NOAA AVHRR snow product is calculated. A decrease of the snow depth is mainly observed in the lower elevations, where the ground-measurements are sparse and snow depth is generally overestimated if no virtual snowfree stations are included in the interpolation process.

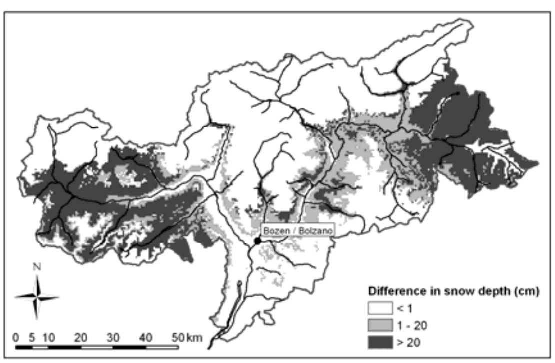


Figure 4: Snow depth difference map for 21 February 2006: difference between snow depth calculated without using virtual snowfree stations and snow depth interpolated using 18 virtual snowfree stations defined by the satellite snow cover product.

The compensation value shown in Figure 5 is added to the base value to adjust the overall interpolation to represent the local and regional characteristics of the snow distribution. Positive values (light grey areas) are found in the northern part of South Tyrol. These values indicate areas with higher snow depths compared to the base value. In contrary, negative values (dark grey areas) are found in the western, southern and eastern part of the region corresponding to the Southern Alps, the Etsch valley and the Dolomites.

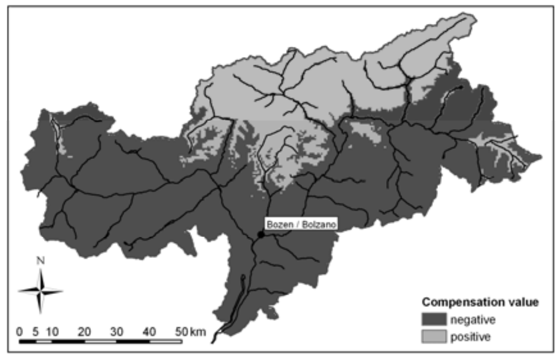


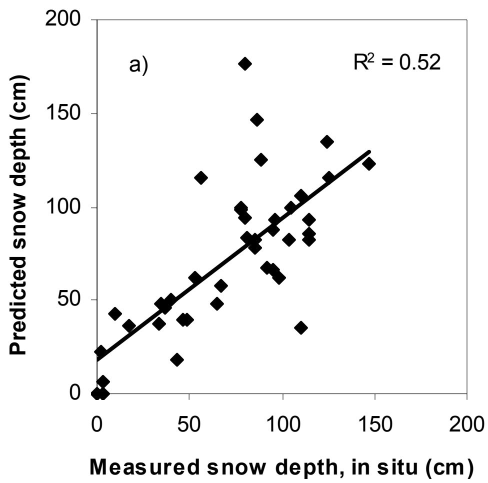
Figure 5: Compensation value for 21 February 2006. The compensation value is added to the base value to account for local to regional distinctions in the snow depth distribution.

Table 2 gives a summary of the cross-validation results. With the inclusion of the virtual stations the mean bias error MBE decreased for all dates, whereas the root mean square error RMSE shows a bigger spread of errors for December 18, 2005. This is explained with the poor illumination conditions and the partly cloud cover influencing the satellite snow cover product on that day. Best improvements through the merging process are achieved for the dataset of January 28, 2006, where the RMSE declined by 50%.

Table 2: Summary of the accuracy estimators MBE and RMSE for the selected dates. The calculations including virtual snowfree stations (merged) result in smaller error values, except for RMSE on December 18, 2005.

	in situ		merged	
Day	MBE (cm)	RMSE (cm)	MBE (cm)	RMSE (cm)
18 Dec. 05	1.07	14.60	-0.73	20.24
28 Jan. 06	-1.53	19.77	-0.97	9.86
21 Feb. 06	0.93	29.11	0.63	27.56

Figure 6 shows the correlation between the measured and predicted snow depth values for February 21, 2006. In the Figure 6a the cross-validation results for the interpolation without virtual snowfree stations is given, whereas in Figure 6b the results for the interpolation with 18 virtual snowfree stations is drawn. The increase of the R^2-Value in Figure 6b is indicating a slight improvement of the interpolation result through the merging procedure. Some virtual snowfree stations reach a high predicted snow depth (> 50 cm), what indicates a misclassification in the utilised snow cover product.



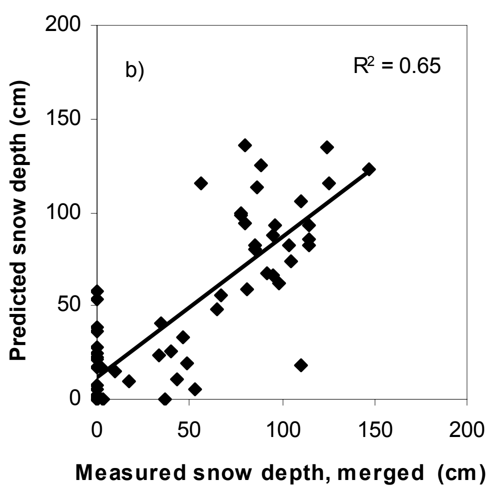


Figure 6: Correlations between measured and predicted snow depth for February 21, 2006. 6a shows the cross-validation results for the in situ interpolation only. 6b shows the cross-validation results for the merged calculation (in situ measurements and 18 virtual snowfree stations). The R^2-Value increases from 0.52 to 0.65, indicating an overall improved interpolation through the merging process.

6. CONCLUSION AND OUTLOOK

The study demonstrates how the newly developed snow depth interpolation method used at SLF in Switzerland is applied to a dataset of snow depth measurements of the province of South Tyrol. The adaptation and transfer of the approach is straightforward since the same interpolation method and merging procedure including an European-wide snow cover product derived from NOAA AVHRR data is used. The cross-validation shows that the introduction of virtual snowfree stations positively affects the overall interpolation performance up to 50%. This option is limited by the number of cloud free satellite imagery and the sub-optimal illumination conditions during mid-winter in the rough alpine terrain.

The interpretation of the interpolation results leads to a series of maps and graphs that allow further analysis. The compensation value may be of interest for climatology studies, a thorough analysis of the distribution of the cross-validation residuals could identify stations with misrepresentative values in the snow measurement network and the maps can easily be converted to popular geovisualisation products like Google Earth.

In future, an alpine-wide snow depth map would be of great interest. It could be realised based on ground-measurements from snow depth networks supported by other countries within the European Alps, the NOAA AVHRR data and the interpolation method we present here. An adaptation and further application to other mountain regions in the world could be of relevance.

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