DERIVING MEAN SNOW DEPTH IN COMPLEX TERRAIN FROM FLAT FIELD MEASUREMENTS

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ABSTRACT: Snow depth is an important parameter for various applications, including hydrological and avalanche forecasting. Various measurement networks were therefore developed throughout the world to measure snow depth and/or snow water equivalent. However, measurement stations are generally located in gentle terrain (flat field measurements) most often at lower or mid elevation. While measurements from these sites have provided a wealth of information, various studies have questioned the representativity of such flat field snow depth measurements for the surrounding topography, especially in alpine regions. In this study, we used highly resolved snow depth maps at peak of winter from two distinct climatic regions in eastern Switzerland and in the Spanish Pyrenees to develop a mean snow depth parameterization for large-scale model applications over complex topography based on flat field snow depth measurements and easy to derive topographical parameters. Removing the elevation dependent gradient in mean snow depth revealed remaining topographic correlations with the sky view factor. We performed a scale dependent analysis for domain sizes to specify error statistics inherent in large-scale grid cell sizes. Overall, our results show that correlations between subgrid terrain characteristics and mean snow depth increase with increasing domain size. As the parameterization is independent of a specific geographic region it could be used to assimilate flat field snow depth measurements into large-scale snow model frameworks.

KEYWORDS: mean snow depth; avalanche forecasting; meteorological models; subgrid parameterization.

1. INTRODUCTION

Information on the current state of the snow cover as well as future changes is of great relevance for avalanche forecasting. Indeed, when a large snowfall is forecasted, it is crucial to know if it will be deposited on the bare ground, on a well consolidated snow cover or on a snow cover containing critical weak layers. One important component in this evaluation is to estimate how much snow is currently lying in the mountains, often by extrapolating a single flat field measurement to relatively large geographic regions. Flat field snow depth measurements thus provide important information for avalanche forecasting and also for various other applications, including hydrological forecasting. Various measurement networks therefore exist throughout the world to measure snow depth and/or snow water equivalent. However, many studies have found that these index stations only poorly represent snow depths in the surrounding terrain (for a good literature overview see Grünewald and Lehning (2015)).

Recently, Grünewald and Lehning (2015) used high-resolution spatial snow depth data to show that measured snow depth at index stations is only marginally representative for means of the surrounding terrain at distances of up to 400 m. They also found large differences between snow depth at index stations and average snow depth of the corresponding 100 m elevation band in the entire region. However, Helbig et al. (2015) found that domain-averaged snow depth can roughly be approximated with high-resolution mean flat field snow depth within the same domain (Pearson r = 0.86), especially for domain sizes larger than 1500 m. These results suggest that depending on the scale, flat field snow depth measurements can be representative for the surrounding terrain.

In general, flat field snow depth has to be representative for a larger region as these are inherently related to large-scale precipitation patterns. On the other hand, small-scale terrain can induce

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large snow depth variations due to wind sheltering/exposure leading to spatially different deposition, terrain shading leading to spatially different snow melt/settling and removal of snow by avalanches.

It is well known that overall snow depth increases with elevation, which is attributed to precipitation gradients. Grünewald et al. (2014) reinvestigated this elevation trend by analyzing seven high resolution spatial snow depth data sets at peak of winter. They found that snow depth increases with elevation up to a certain altitude with a distinct decrease for higher elevations, which they attributed to redistribution of snow by wind and gravitational forces. In alpine regions meteorological parameters which influence the snow depth distribution, such as wind speed or radiation, also show elevation dependencies which might balance, attenuate or reinforce elevation dependencies of precipitation. To account for all these processes is clearly far from straightforward. However, some of the diverse or random complexities can be removed by averaging snow depth over larger domain sizes. A scale analysis for aggregated snow depth in varying domain sizes can reveal the lower limit to adequately describe the domain average of snow depth. Grünewald et al. (2013) found a lower limit of 400m but only investigated domain sizes up to 800m. Melvold and Skaugen (2013) and Helbig et al. (2015) also included larger domain sizes in their analysis and found a lower limit of about 1km.

In the research outlined in this paper, we investigate how flat field snow depth measurements can be corrected to describe domain-averaged snow depth (i.e. gridded snow depth) over complex, treeless topography. For this we used several spatial snow depth data sets from two large regions in the Eastern Swiss Alps and from one region in the Eastern Spanish Pyrenees. The highly resolved snow depth data from consecutive years were all acquired close to the peak of winter. A large number of snow depth subsets are obtained by randomly selecting domains of different sizes within each region. We related subgrid terrain parameters, i.e. unresolved summer terrain parameters, to domain-averaged snow depths in view of scaling flat field snow depth measurements to obtain domain-averaged snow depth.

2. DATA

2.1 Spatial snow depth data

Seven spatially continuous snow depth data sets from three alpine regions in two distant geographic locations were used to analyze snow depth as a function of terrain parameters. Two locations, called Wannengrat and Dischma, are located near Davos in the Eastern Swiss Alps covering about 30 km^2 (Wannengrat) and 120 km^2 (Dischma) (Fig. 1a). The third alpine region, Val de Núria, is located in the Eastern Spanish Pyrenees and covers about 28 km^2 (Fig. 1b). More details on the study regions can be found in Helbig et al. (2015).

Spatial snow depth data for the Swiss regions were obtained from summer and winter stereo images using an opto-electronic line scanner (Sensor ADS80 and ADS100 from Leica Geosystems) (Bühler et al. (2012); Bühler et al. (2015)). The snow depth maps have a horizontal resolution of 2 m and a Root-Mean-Square error (RMSE) of approx. 30 cm compared to simultaneously obtained ground measurements. We used snow depth maps around the peak of winter from three years (2012, 2013 and 2015). Spatial snow depth data for the region in Spain were gathered by airborne laser scanning (ALS) (Moreno Banos et al. (2009)). Grünewald et al. (2013) extracted spatial snow depth data at a horizontal resolution of 1m. The mean accuracy of this data set is also around 30 cm. One data set was acquired around the peak of winter in 2009.

2.2 Flat field snow depth measurements

Automatic weather stations (AWS) around the Wannengrat and Dischma regions were used to obtain flat field snow depth data (HS_{flat}). The stations are part of the Intercantonal Measurement and Information System (IMIS) operated by the WSL Institute of Snow and Avalanche Research SLF (Lehning et al. (1999)). Snow depth is measured automatically with ultrasound sensors. For both regions there were several AWS in the immediate vicinity. For each region we selected the one with the best combination of low terrain horizon, large sky view factor and low slope angle.

For the Val de Núria region there was no nearby AWS. We therefore used the Spanish data set exclusively for developing the parameterization, but not for validation.

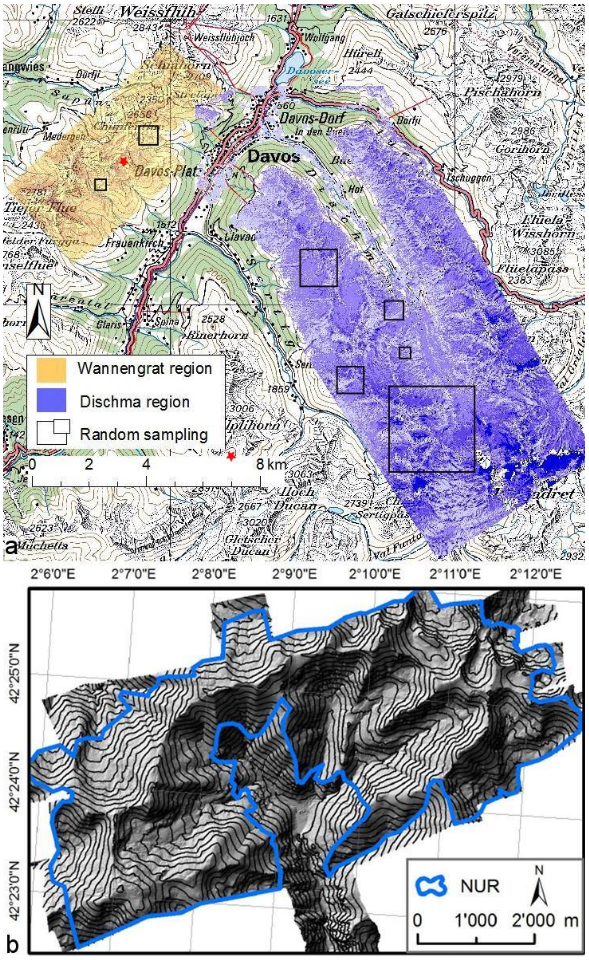

Fig. 1: Maps of (a) measured snow depths at Wannengrat and Dischma area in the eastern Swiss Alps and (b) hillshade at Val de Núria in the eastern part of the Spanish Pyrenees. The black squares illustrate examples of randomly selected domain sizes of varying size. The red stars show the location of the two AWS. The underlying pixelmap (1:200'0000) in (a) stems from swisstopo © 2008. Figure and caption are adapted from Helbig et al. (2015).

3. METHODS

3.1 Aggregating snow depth data

In order to perform a scale dependent analysis, snow depth data were averaged in squared domain sizes L of 50 m, 100 m, 200 m, 500 m, 1000 m, 1250 m, 1500 m, 1750 m, 2000 m, 2500 m and 3000 m. We assume that this broad range of domain sizes captures a range of spatial snow depth shaping processes. A domain size L can also be seen as a large-scale model grid cell Δx. By randomly selecting 50 realizations of each L within each region (allowing for overlap) and for each gathering day we created a total of 3600 snow depth grids for the two Swiss sites and 400 grids for the Spanish site, where we could only average snow depth data up to L = 1500 m. Note that each of our domain size L has to have at least 75 % valid snow depth values. The large number of gridded snow depth grids allows a systematic analysis accounting for a variety of terrain characteristics.

3.2 Terrain characteristics

To find the dominant terrain shaping characteristics for the gridded snow depth data sets we derived several terrain parameters from the corresponding summer digital surface model (DSM) for each region. Similar to Helbig et al. (2015) we made use of the fact that slope characteristics of real topographies can be reasonably well approximated by Gaussian statistics (Helbig and Löwe (2012)). Each summer DSM of size L x L can then be described by only two underlying characteristic length scales, namely a valley-to-peak elevation difference σ (typical height of topographic features), and a lateral extension ξ (typical width of topographic features) describing the correlation length of the summer DSM. Using these two length scales we derive a terrain parameter, related to mean-squared slope $\mu=\sqrt{2}\sigma/\xi$. It can be derived from first partial derivatives of terrain elevations in orthogonal directions using $2\mu^2=\overline{(\partial_x z)^2+(\partial_y z)^2}=4(\sigma/\xi)^2$ as outlined by Löwe and Helbig (2012). The correlation length of the summer DSM ξ can be derived via $\xi=\sqrt{2}\sigma_z/\mu$ using σ_z the standard deviation of the summer DSM. Furthermore, we use the L/ξ ratio, which roughly indicates how many topographic features are included in a domain size L. To minimize impacts of (subgrid) grid size Δx and L on domain-averaged parameters the condition $\Delta x \ll \xi \ll L$ must be met. This guarantees that enough terrain is included in a domain size L (cf. Helbig et al. (2009); Helbig and Löwe (2014)).

In order to derive the correct characteristic length scales for the corresponding domain size L, terrain parameters were extracted from linearly detrended DSM's, similar to Helbig et al. (2015). Using the above mentioned terrrain parameters allowed us to compute the domain-averaged sky view factor $F_{\mathrm{sky},L}$ by applying a recently presented subgrid parameterization $F_{\mathrm{sky}}=f(L/\xi,\mu)$ (Helbig and Löwe, 2014).

4. RESULTS AND DISCUSSION

4.1 Correlation between snow depth and topographical parameters

For all domain sizes L, by far the largest correlation was between domain-averaged snow depth HS_L and terrain elevations z_L (Pearson r = 0.36, p < 0.01). The second largest correlations was between HS_L and parameterized sky view factor $F_{\mathrm{sky},L}$ (Pearson r = -0.18, p < 0.01), i.e. HS_L decreased with increasing $F_{\mathrm{sky},L}$. However, since $F_{\mathrm{sky},L}$ also had a significant negative correlation with z_L (Pearson r = -0.29, p < 0.01) we assume that the true correlation between HS_L and $F_{\mathrm{sky},L}$ is masked by the correlation with elevation.

To uncover the true correlation between snow depth and sky view factor therefore required removing the masking elevation trend. To do so, we first normalized elevation z_L with the mean elevation for each region z_{reg}, allowing us to combine data from different geographical regions. Then, for each geographical region and acquisition day we determined the mean snow depth in 25 normalized elevation bands ($\Delta z_L/z_{reg}$), which we used to normalize snow depth measurements HS_L in the corresponding elevation band. Essentially, this corresponds to removing a moving mean trend, which we deemed appropriate since the real elevation trend is non-linear and unknown (e.g. Grünewald et al. (2014)).

When removing the elevation trend in this manner, we obtained a weak but significant positive correlation between the sky view factor and the normalized domain-averaged snow depth for all data (Pearson r = 0.12, p < 0.01; Fig. 2). Note that the correlation coefficient remained very similar when changing the number of elevation bands, except for a very low (< 5) or a very high (> 100) number of elevation bands. Thus, we now find the opposite trend, namely that domain-averaged snow depth increases with increasing domain-averaged sky view factor. Given that the sky view factor is not simply the opening area above a point, but is derived on an inclined surface, a larger domain-averaged sky view factor implies overall flatter terrain, which does not contain (or numerically resolve) a lot of steep ridges or mountain tops where less snow would accumulate due to wind, incident radiation or gravitational forces.

4.2 Parameterization of domain-averaged snow depth

The results above suggest that a parameterization of domain-averaged snow depth based on topographical parameters is possible. To derive a parameterization for snow depth data from different geographical regions, we normalized the data with the mean for that region and that gathering day. Since snow depth correlated best with elevation our first parameterization for HS_L uses a commonly applied linear elevation trend: $HS_L = HS_{\mathrm{flat}}\,(z_L/z_{flat})$. Our second parameterization is based on the fact that once the obvious elevation trend is removed there remains a positive correlation with the sky view factor. This second parameterization therefore combines two power law trends, one for elevation and one for sky view factor: $HS_L \sim HS_{\mathrm{flat}}\,(z_L/z_{flat})^{2.6}\,(F_{\mathrm{sky},L})^{0.5}$. Since $F_{\mathrm{sky},L}$ had a negative correlation with z_L, the power law relation with $F_{\mathrm{sky},L}$ in our parameterization reduces the increase of HS_L for larger elevations.

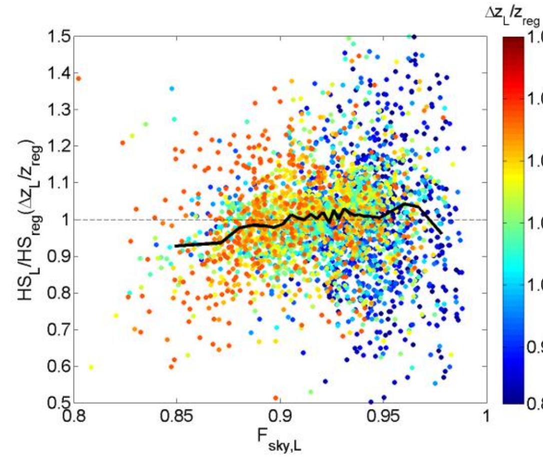

Fig. 2: Normalized domain-averaged snow depth $HS_L/HS_{reg}(\Delta z_L/z_{reg})$ as function of domain-averaged parameterized sky view factors $F_{\mathrm{sky},L}$. Snow depth was normalized with the mean in 25 normalized elevation bands. Colors show the domain-averaged normalized elevation band $\Delta z_L/z_{reg}$, with z_{reg} the mean elevation for each geographical region. The black line indicates the moving mean (window length of 100).

Overall, our second parameterization performed better than the first simple linear elevation trend (Fig. 3). Furthermore, the performance increased with increasing L (colors in Fig. 3a) and L/ξ ratios *[not shown]*. For larger L/ξ ratios more terrain is included in a domain, resulting in more reliable domain-averaged snow depth estimates. Applying the sky view factor parameterization of Helbig and Löwe (2014) to derive domain-averaged snow depth HS_L has the advantage that implicitely a scale dependent correction for finite grid cell sizes via the L/ξ ratio was introduced.

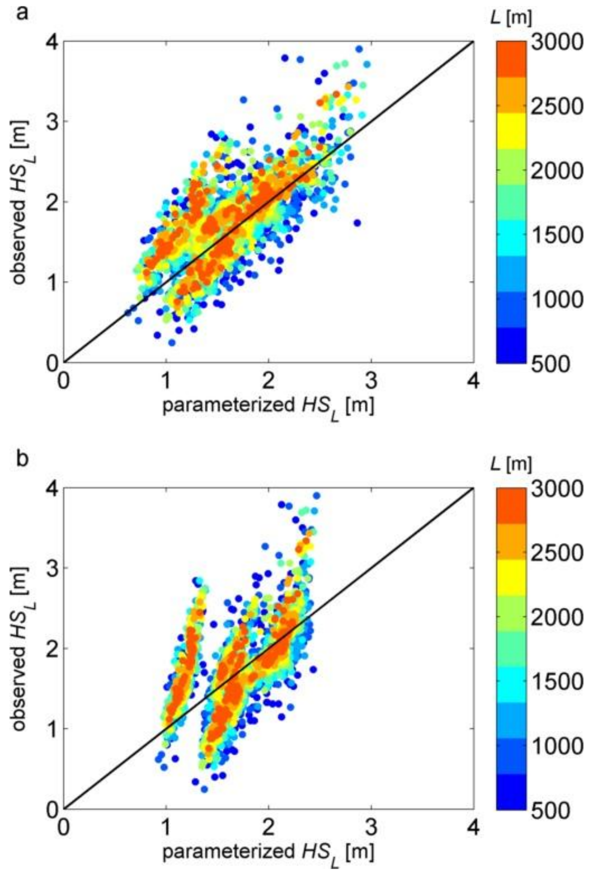

Fig. 3: Parameterized and measured domain-averaged snow depth HS_L for $L \geq 500$ m, without Val de Núria. Snow depth was parameterized using flat field station elevation and snow depth measurement in the vicinity. The parameterization consists of (a): two power law trends for elevation and $F_{\mathrm{sky},L}$ and (b) a linear trend with elevation.

Performance statistics improved for a variety of measures compared to the simple linear parameterization (Tbl. 1). Overall, the performance of our second parameterization was somewhat poorer as that reported in Helbig et al. (2015). However, we used a single flat field measurement in the vicinity of our measurement domain, while they used mean high-resolution flat field snow depth within each domain. With this in mind, the results presented here are very encouraging.

Note that the elevation trends were derived using all domain-averaged HS_L, i.e. over the entire range of L. For the parameterization with the sky view factor, on the other hand, we only used HS_L for $L \geq 500$ m to ensure that the condition $\xi \ll L$ was met (e.g. Helbig and Löwe, 2014). Excluding $L < 500$ m still allowed us to use 2700 snow depth data grids.

Table 1: Correlations (Pearson r), absolute errors (Mean-Absolute error (MAE), Normalized RMSE (NRMSE)) and probability distribution errors (NRMSE of Quantile-Quantile (Q-Q) plots for probabilities in [0,1]) for linear elevation trend (P1) and combined power law elevation and sky view factor trend parameterization (P2).

	r	MAE [cm]	NRMSE [%]	$\mathrm{NRMSE}_{\mathrm{Q\text{-}Q}}$ [%]
P1	0.58	30	8.6	6.1
P2	0.71	27	7.8	4.9

5. CONCLUSIONS AND OUTLOOK

In this study we presented a simple method to extrapolate a flat field snow depth measurement to surrounding terrain. We compared two parameterizations with varying complexity, namely a commonly applied simple linear lapse rate and a more complex parameterization based on a power law elevation trend scaled with sky view factors. Input parameters are easy to derive subgrid terrain parameters in combination with a nearby flat field snow depth measurement.

Our results show that the more complex parameterization is superior. We conclude that for domain-averaged mean snow depths in grid cells ≥ 500 m, it is possible to account for subgrid terrain impacts with increasing performances for increasing L. Including the sky view factor seems important for the larger elevations where we found overall smaller sky view factors. Nevertheless, the most important impact remains the precipitation trend with elevation, which can be approximated by a power law.

Given that the analysis was conducted using snow depth data from three different regions gathered in different years we believe that the parameterization is independent of a specific geographic region. Here, we only investigated snow depth distribution close to peak of winter. Future efforts will require including other periods during the accumulation and the ablation season to confirm or improve the results obtained here.

ACKNOWLEDGEMENTS

We would like to thank Yves Bühler and Thomas Grünewald for ADS and ALS data preparation, respectively.

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