

## Spatial variability of snow water equivalent – the case study from the research site in Khibiny Mountains, Russia

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**Abstract:** The aim of the investigation was assessment of spatial variability of the characteristics of snowpack, including the snow water equivalent (SWE) as the main hydrological characteristic of a seasonal snow cover. The study was performed in Khibiny Mountains (Russia), where snow density and snow cover stratigraphy were documented with the help of the SnowMicropen measurements, allowing to determine the exact position of the snow layers' boundaries with accuracy of 0.1 cm. The study site was located at the geomorphologically and topographically uniform area with uniform vegetation cover. The measurement was conducted at maximum seasonal SWE on 27 March 2016. Twenty vertical profiles were measured along the 10 m long transect. Vertical resolution depended on the thickness of individual layers and was not less than 10 cm. The spatial variation of the measured snowpack characteristics was substantial even within such a homogeneous landscape. Bulk snow density variability was similar to the variability in snow height. The total variation of the snowpack SWE values along the transect was about 20%, which is more than the variability in snow height or snow density, and should be taken into account in analysis of the results of normally performed in operational hydrology snow course SWE estimations by snow tubes.

**Keywords:** Snow water equivalent; Snow height; Snow density; Accuracy of measurements.

### INTRODUCTION

The temporal and spatial variability of the measurable snow cover characteristics (snow cover height, density and stability) shows the possibility of 100% difference between a point-based estimate and a mean for a corresponding horizontal profile of tens meters length, with different variability in different climate conditions (Chernous et al., 2015). Analysis of variability of distinct layers constructing the snow cover based on their penetration resistance (being a representation of snow microstructure including snow density) shows different degrees of autocorrelation for the penetration resistance from 4 m to more than 20 m on a slope from layer to layer (Kronholm et al., 2004). Understanding such variability is of high importance for snow avalanche formation research (Brown and Armstrong, 2008; Fierz et al., 2009). However, in operational hydrology the major parameter of concern is the mean snow water equivalent (SWE) in a catchment, with the spatial SWE variability regulated by topography, wind regime and vegetation (Grünwald et al., 2013; Revuelto et al., 2014).

The usual approach is the estimation of a SWE by repeated measurements along a snow course at the distances of dozens or hundreds meters (Elder et al., 1998; Rasmus, 2013) or more detailed estimation of SWE in the areas with selected uniform landscape features (Fassnacht et al., 2010). It is usually accepted that the spatial variability in snow cover density is significantly smaller than the spatial variability in the snow cover height (Mizukami and Perica, 2008; Sturm et al., 2010). Thus, the snow cover height can be considered as the representation of the SWE at an area of hydrological investigations (i.e. Singh, 2016). This simplifies the task of the SWE estimation and allows incorporation of the results of the remote measurements of snow cover height to hydrological investigations (Deems et al., 2008; Trujillo et al., 2007), also required for validation of the distributed or lumped snow models based on measured snow cover characteristics (Holko et al., 2009).

Published results on estimation of the accuracy of snow density measurements by different techniques show up to 9% difference in reported value in dependence on the type of snow (Conger and McClung, 2009; Proksch et al., 2016). The snow density variability obtained by the same observer using the same method of measurement is considered as a correct quantification of the true variability.

Evidently, the combination of the snow cover height and the snow cover density, as presented in SWE, can be more variable from point to point than each of these parameters alone. Both should theoretically differ more between different landscapes than among several measurements in one topographically uniform area with uniform vegetation. However, the variability can be expected in the nature even in the latter case, and a quantified example of such variability is presented below.

### THE SITE AND METHODOLOGY

The study site was located at the Lomonosov Moscow State University meteorological station in Kirovsk (Murmansk Region), 67°38'14" N, 33°43'31" E. The site is a geomorphologically and topographically uniform area covered with natural grass. The climate conditions of the investigated region are characterized by long duration of winter period with high repeatability of blizzards, strong winds and low temperatures. Melting events are extremely rare during the winter seasons, although the ice layers may form on the snow surface in spring. The data analyzed in this work were measured on 27 March 16 (time of maximum seasonal SWE). Twenty consecutive measurements along the 10 m long transect with horizontal resolution of 50 cm at a geomorphologically and topographically uniform area were made. First, the SnowMicropen (SMP) (Schneebeli and Johnson, 1998) measurements were made along the transect. Then, the 10 m long snowpit along the transect was dug. Snow structure was described and snow layers were determined in accordance with Fierz et

al. (2009) taking into account also the SMP data. As a result, nine distinct snow layers were detected. The distance between the 20 resulting vertical snow profiles was set by the tape measure. The snow density in each vertical was measured by the standard “Swiss” “box cutter”. Vertical resolution of the measurements varied depending on the thickness of the layers (Proksch et al., 2016). For the layers thinner than 10 cm three density measurements were made at the same snow height in the middle of the layer and the mean value was calculated. For thicker layers, the set of “the same height” three measurements were made with no more than 10 cm vertical distance between the selected levels. The total number of measurements for each of the twenty snow density profiles was about 40.

Data analysis was carried out on the base of detailed description of snow microstructure visually determined in the snowpit and checked by the SMP profiles snow layers. Horizontal and vertical distributions of measured snow characteristics were constructed and the spatial variability was statistically processed. Detailed presentation of all data is out of the scope of this work. We focus on the SWE variability along the transect. SWE for each vertical profile was calculated from the density and thickness of the individual layers.

## RESULTS

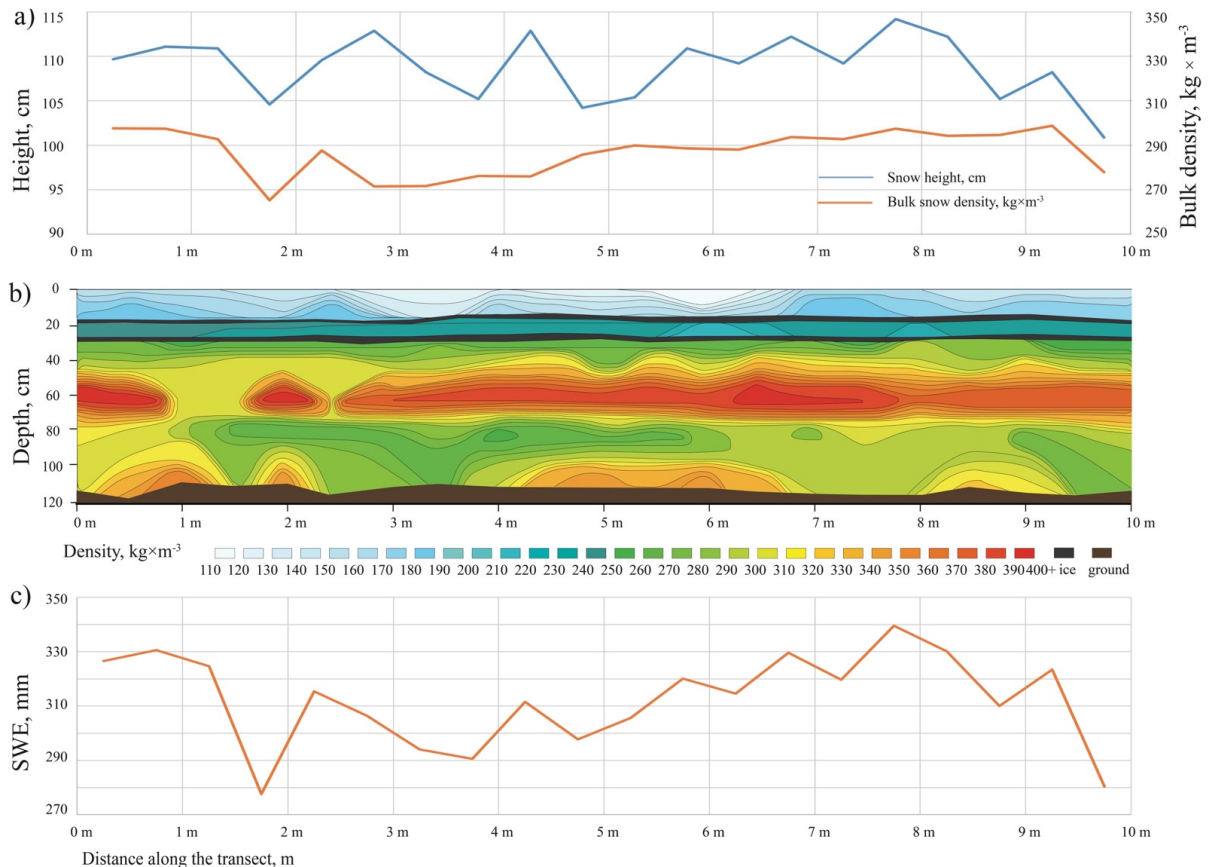
Snow height (20 points) along the transect varied from 101 to 114 cm, with the average value of 109 cm (Fig. 1a). Thus, the variation of this parameter along the transect was 12%. The variation of the thickness of individual snow layers along the transect was much higher which is documented in Fig 1b.

The snow density in individual snow layers (as represented by three measurements per layer in each vertical profile) varied from 118 to 341  $\text{kg}/\text{m}^3$  (Fig. 1b). The densities of ice layers were not measured in the field and were substituted by the theoretical value of 900  $\text{kg}/\text{m}^3$  for calculation of SWE of individual profiles. The bulk snow density was calculated as the ratio of the mean SWE and total snow height for each of the 20 profiles. It varied from 265 to 299  $\text{kg}/\text{m}^3$  (Fig. 1a), which represents the variation of 12%. The average value of the bulk density was 284  $\text{kg}/\text{m}^3$ .

The SWE of the snowpack calculated for each vertical profile varied from 280 to 340 mm, with the mean value of 312 mm for the transect in total (Fig. 1c). This gave the variation of 20% at the time of seasonal SWE maximum at the studied site.

## CONCLUSION

According to our results the variation of SWE at the date of maximal seasonal SWE in 20 profiles 50 cm apart along a 10 m transect at a geomorphologically and topographically uniform area with uniform vegetation cover can be 20% for the snow cover of about 1 m height. The variability in snow height and mean snow cover density, averaged per each profile, did not exceed 12%. This disagrees with common assumption that the spatial variability in snow cover density is significantly less than the spatial variability in the snow cover height. Our results showed that they can be the same which means that the spatial variability in snow cover height does not necessarily represent the spatial variability in SWE. Spatial variability of snow height



**Fig. 1.** a) Snow height and bulk snow density along the 10-m transect. b) Snow density variability along the 10-m transect. c) Snow water equivalent (SWE) along the 10-m transect.

may represent the spatial variability of SWE when comparing different landscapes or is focused on continental scale SWE and snow density variability (Bormann et al., 2013; Zhong et al., 2014) or the effect of terrain characteristics on the SWE (López-Moreno et al., 2013). However, it should be kept in mind that one single SWE measurement by snow tube per uniform area with the spatial resolution of 500 m (Hannula et al., 2016) can be significantly biased. SWE difference close to 20% was observed between the two verticals 1 m apart (Fig. 1c). Measurements made every 5–10 m which are considered as “accurate” enough (Fassnacht et al., 2010) each can have an accuracy of about  $\pm 10\%$ , and their averaging would not necessarily represent the actual mean value for the surrounding area. Snow height measurement alone cannot substitute the SWE assessment. Based on the presented SWE analysis and the snow microstructure data which are beyond the scope of this article we assume that the greatest spatial variability of the SWE values along the profile should be observed during winters characterized by long cold periods, rapid temperature changes (leading to the increase of temperature gradient and the vapor migration within the snowpack), as well as heavy blizzards with high wind velocities (leading to dense layers’ formation).

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