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EXPEDITIONARY MEASUREMENTS OF SNOW IN EXTENSIVELY FORESTED CARPATHIAN MOUNTAINS: EVALUATING PARAMETERS VARIABILITY

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Abstract: Snow cover parameters are studied in the basin of the Šance water reservoir in the Moravian-Silesian Beskids (Czech Republic). The location is overlaid with a regular 2x2 km square grid along the axes of a coordinate system of a single trigonometric cadastral network. In each of the total of 52 squares at least one sample plot is established comprising of two types of subplots: open plots and plots under adjacent forest. The studied parameters include snowpack depth, snow density and snow water equivalent. Depth is measured directly on the plots and the two other characteristics are calculated additionally using the directly measured parameters (depth and weight of the snow samples taken). Snowpack depth is measured 20 times on each plot with precision to 1 cm. For calculating snow density and snow water equivalent 2–5 samples of snow are taken and their corresponding values are determined on the basis of sample depth with precision to 1 cm, calibration volume of the sampling cylinder (precision to 0.05 l), and weight (to 0.01 kg). The purpose of this article is to evaluate the accuracy of the measuring of snow cover using jittering method on forest as well as unforested plots to get accurate data for evaluation of snow damage to forests.

The analysis demonstrated local variability of snowpack depth on the order of centimeters. Only exceptionally does the SD value exceed 10 cm. The coefficient of variation reaches high values only at the lowest values of snowpack depth, where the standard deviation is no more than a few centimeters. A procedure for eliminating maximum and minimum measured values reduces the variability significantly but has practically negligible influence on the mean snowpack depth. The estimated variability of water equivalent depends on the precision of determining the inputs for mean snow depth and density and usually ranges up to 10 mm. Nearly all indicators of snow depth variability correlate with the mean snowpack depth. While standard deviation increases only slightly with mean snowpack depth cover and may be characterized by linear regression, the coefficient of variation is inversely proportional to the mean snowpack depth.

Key words: snow, depth, water equivalent, density, precision, variability

1. INTRODUCTION

Snow is a characteristic seasonal phenomenon of the Earth's temperate to sub-polar zones. Changes in its distribution and amount are among the interesting indicators of climate changes (Thompson et al., 2002; Cook et al., 2002; Gillet & Thompson, 2003; Doran et al., 2002). Snow cover is important in the hydrologic cycle as water storage, and especially in mountain areas where it constitutes a significant proportion of annual precipitation (Doesken & Robinson, 2009). Evaluation and prediction of snow cover in mountain headwaters is vital for allometric derivation of snow thawing, its diversity in different habitats, as well as its runoff and retention in the soil. Measuring of snow cover parameters is thus a valuable research component not only in the fields of meteorology, climatology and hydrology but also geography, ecology, forestry and agriculture.

Forest stands are a dominant vegetation formation of the temperate zone. As true of all vegetation, they influence the hydrologic cycle, including snow cover parameters, directly by influencing snow interception, evapotranspiration and infiltration, and indirectly through their impact on climate (Holko et al., 2009). Interception by woody species manifests itself as decreased snow cover depth and snow water equivalent. Different rate of snow thawing is caused by the "shading" effect of the forest, particularly at the end of the winter period (Holko et al., 2009; Kantor & Šach, 1988; Kantor, 2005). The overall variability in snow cover characteristics in forest and open areas depends on many factors, such as terrain relief, climate, vegetation characteristics, woody species present and forest area (Gelfan et al., 2004).

The amount of snow captured in tree crowns creates a mechanical load, which will lead to damage of individual tree species and entire stands if the limits of the wood's strength are exceeded.

Studying the effect of snow in damaging forest vegetation lies in obtaining detailed data on the snow cover and resulting damage. Measuring depth of snow cover is a regular part of weather station (climate and precipitation) operations in the Czech Republic (Anonymous, 2008). The data is not useful, however, for determining the effect of snow on specific forest stands and creating useful models. It is necessary, therefore, to obtain a certain amount of detailed data directly from the forest stands since even the use of satellite images for hydrologic purposes is limited (Němec, 2006a). Snowpack depth (*d*) and snow water equivalent (SWE) cannot be remotely sensed in large heterogeneous landscapes (Cline et al., 1998; Mote et al., 2003). The snowpack depth (*d*) and SWE parameters are determined rather by mathematical estimates. The use of active microwave systems appears to be promising (Brodský, 2008), and algorithms for evaluating snow cover parameters are being developed. Those methods' wider use has been limited today mainly due to their availability and the price of data with the necessary accuracy, resolution and coverage (Urbaňcová, 2008). SWE can be derived from the snowpack depth (d) if the relevant density of the snow is known (Němec, 2006b).

To obtain detailed data from a forested landscape, it is necessary to conduct individual measurement expeditions whereby detailed data from a large territory are obtained during a short period. The data must characterize specific parameters of snow as a result of which the forest vegetation is damaged. To ensure the quality, accuracy and mutual comparability of the data obtained from regular as well as expeditionary measurements it is crucial to follow standardized procedures. For measuring snow depth, mobile or fixed snow rods or poles are used, and possibly specially calibrated probe rods (Doesken & Robinson, 2009). To determine SWE, devices for measuring snow weight are used in the case of irregular expeditionary measurements (Němec, 2006b). They have the form of hollow cylinders with serrated or otherwise sharp edge so that they can easily penetrate through the snow cover to the soil surface in order to sample the snow column and subsequently weigh it (Doesken & Robinson, 2009).

The purpose of this article is to evaluate the accuracy of the measuring of snow cover on forest as well as unforested plots to get accurate data for evaluation of snow damage to (see Appendix).

2. MATERIAL AND METHODS

2.1. Methodology for measuring snow cover

Snow cover parameters are studied in the basin of the Šance water reservoir in the Moravian-Silesian Beskids (Czech Republic). The Moravian-Silesian Beskids are characterized by extensive forest coverage (75%) with a prevalence of Norway spruce (*Picea abies* (L.) Karst.) tree species with low resistant to mechanical load. Mountain locations prevail here, and potential beech-fir (*Fageto-Abietinum*) forests would cover 80% of the area (Holuša, 2004). This area has one of the highest rainfall totals within the Czech Republic, and it has a thick snow cover in winter (Tolasz et al., 2007). For these reasons, we can expect frequent and intensive snow damage to forest vegetation in the region of the Moravian-Silesian Beskids (Holuša et al., 2010).

The purpose of the research is to determine spatial distribution of snow cover parameters in a representative sample by means of controlled regular spatial selection according to availability in a square grid.

The location is covered by a regular 2x2 km square grid along the axes of the coordinate system of a single trigonometric cadastral network. In each of the total 52 squares at least one sample plot is located comprising two types of plots: open plots and plots under adjacent forest. The time of measurement is chosen according to the course and character of the winter period, ideally when the snow cover culminates at the end of winter and the snow avalanches are significant with the potential for causing damage to forests.

In each square within the research location, one sample plot must be measured. If a plot suitable for measurement cannot be found in squares where the research location (the basin) reaches only marginally, a sample plot outside the research location may be measured provided the conditions (gradient, exposure, height above sea level, snowpack depth) correspond at least approximately to those in the relevant section of the research location. In exceptional cases when a suitable plot in marginal squares cannot be found, such squares may be skipped.

A sample plot is comprised of two parallel measurements:

Subplot 1. The first measurement must always be conducted on an open area in the minimum distance of one-half the height of the adjacent vegetation in such direction that disturbance by the neighboring vegetation is minimized – it is necessary to exclude places shaded by adjacent vegetation, places downwind and to which snow is blown or, vice versa, places upwind from which snow is blown. Ideally, measurements shall be conducted on a meadow or, possibly, a clear-cut area. Plots should not be established on paths or waste sites where we cannot exclude the possibility that snow has been removed or, vice versa, piled up or that snow from other places has been stored there during winter, and we also should exclude ski slopes.

Subplot 2. A control plot shall be established in an adjacent (nearest) stand at a distance of between ca one-half the height and 1x the height from the edge of the stand.

The studied parameters include snowpack depth, snow density and water equivalent. Depth is measured directly on the plot and the two other characteristics are calculated using the directly measured parameters (depth and weight of the snow sample taken). Snowpack depth is measured by inserting a ranging pole perpendicularly down to the soil surface 20 times in total. The minimum distance between any two measurement points is 1 m. When measuring, it is necessary to avoid substantial irregularities of snow cover which may indicate terrain irregularity (tree stumps, ravines, knolls, anthills, etc.), snowdrifts, snow banks, wind-swept places, places near windfalls where snow has melted, boulders, rocks, warm springs, and the like, as well as places with apparent disturbance of snow cover (animal dwellings). Average snowpack depth on the plot is determined as an arithmetic mean from 16 measurements – the 2 highest and 2 lowest values from the 20 measurements are not included in the calculation (they are crossed out). Snowpack depth is measured with precision to 1 cm.

The measurement to calculate snow density and water equivalent is performed by taking a sample of an integrated profile of snow, preferably from the entire profile of snow cover or at least from its largest part (depending on the practical sampling possibilities). The snow is collected with a sampling cylinder and the volume is determined according to the depth to which it is pressed. The same rules apply for selecting places for snow sampling as for measuring snowpack depth, i.e. we avoid places with an altered or disturbed snow surface. Sampling and measuring can be repeated in up to five places. When taking samples on plots with very low or disjointed snow cover, it is necessary always to take at least a 3-centimeter layer of snow per sample. The collected snow sample is weighed, and the snow density is calculated as a ratio of the weight and volume of snow. The volume of the collected snow sample is calculated by multiplying the calibration volume of the sampling cylinder and median depth of the snow sample. In weighing the snow we work with precision to 0.01 kg, while in determining volume we calculate with precision of the sample depth to 1 cm and precision of the cylinder's calibrating volume to 0.05 l.

Volume of collected snow:

$$V = \frac{V_k \cdot d_{Sn}}{100},$$

where V = volume of snow sample taken [l]; V_k = calibration volume of the cylinder indicated on the wall of the cylinder [l]; d_{Sn} = mean depth of snow cover at the spot of sinking the sampling cylinder [cm].

Snow density:

$$\rho = \frac{m}{V} \cdot 1000 = \frac{m}{V_k \cdot d_{Sn}} \cdot 10^5$$

where: ρ = density [kg.m^{-3}], m = weight of snow collected [kg]

Snow water equivalent:

$$SWE = \frac{\overline{d} \cdot m}{V} \cdot 10 = \frac{\overline{d} \cdot m}{V_k \cdot d_{Sn}} \cdot 1000$$

where: SWE = snow water equivalent [mm], $\overline{d}$ = (average) snowpack depth [cm]

Weights and volumes of taken samples are summed.

The same measurements are conducted on both subplots – the open plot and the control plot under adjacent vegetation. Measured values are recorded in a working diary (using a prepared form).

The snow parameters were measured two or four times in 2006-2009 (Table 3).

For repeated measurement we select always the same sample plots. Only in a case that it is not possible to conduct measurement on the same plot – as in the final measurement for reasons described in conditions for selecting a sample plot – a new sample plot shall be established according to the rules described above.

Table 1. Directly measured parameters of snow cover

Symbol	Parameter	Unit of measurement used	Number of values for one measurement on a sample plot	Smallest unit of measuring device	Comments
d	Depth of snow cover	cm	20	1 cm	
V	Volume of snow sample	l	2 – 5	0,5 l	2006 only
d_{Sn}	Depth of snow sample	cm	2 – 5	1 cm	since 2007
m	Weight of snow sample	kg	2 – 5	0,01 kg	
V_k	Calibration volume of the cylinder	l	1	0,05 l	constant, since 2007

Table. 2 Calculated parameters from measuring snow cover

Symbol	Parameter	Unit of measurement used	Formula	Comments
$\bar{d}$	Snowpack depth	cm	$\frac{\sum_{i=1}^{n} d_i - d_{max1} - d_{max2} - d_{min1} - d_{min2}}{(n-4)}$	n = 20
ρ	Snow density	kg.m^{-3}	$\frac{\sum_{i=1}^{n} m_i}{\sum_{i=1}^{n} V_i} \cdot 1000$	n ∈ <2;5>
V	Volume of snow sample taken	l	$\frac{V_k \cdot d_{Sn}}{100}$	Height of the sampling cylinder = 100 cm
SWE	Snow water equivalent	mm	$\frac{\bar{d} \cdot \sum_{i=1}^{n} m_i}{\sum_{i=1}^{n} V_i} \cdot 10$	

2.2. Variability indicators

From each measurement on an individual subplot, a set of 20 snowpack depth values was created (*d*). Standard variability indicators were calculated for this set: range of variation, standard deviation (SD) and coefficient of variation (CV). By means of the methodological procedure, all indicators were further calculated using only the 16 central values, i.e. excluding the two highest and two lowest measured snow depths for each measurement on an individual subplot.

The practical usefulness of this procedure in making the result more precise was evaluated by comparing the mean values of sets of calculated means and variability indicators for 20 measured values and for 16 central values using a two-sample t-test.

Moreover, a record of weights (*m*) and volumes (*V*) of samples taken is available from each measurement. These data were compiled as summary statistics for each measurement on individual subplots and indicators of local variability cannot be established for them.

For the calculated parameter of snow density (*ρ*) only the theoretical maximum error (Δmax) was calculated according to the declared precision of the measuring devices. For the parameter of snow water equivalent (*SWE*), the estimated variability indicator was calculated on the basis of the variance in snowpack depth (*d*) and determined snow density (*ρ*), as well as the theoretical maximum error according to the declared accuracy of the measuring devices. By multiplying the measured snow depths by density, we obtain a set of *SWE* estimates whose variance parameters shall be calculated similarly as for snowpack depth (*d*). The set of these statistics from all cases of measurement on all plots was subsequently analyzed according to the values for the mean snowpack depth ($\bar{d}$), individual measurement periods, and for forested versus unforested areas.

2.3. Statistical analyses

To compare the variability between individual measurement periods and between the forested and unforested areas, two-factor ANOVA was used, and, in consideration of the non-normal distribution of the statistical sets *d,* the Kruskal-Wallis test was also used. All of this was processed using Statistica 8.0. Otherwise data from one plot has normal distribution, data from the whole study area are of non-normal distribution.

Regression analysis was used to determine the dependence of the standard deviation (SD) of snowpack depth (*d*), of the standard deviation (SD) of water equivalent (SWE), and the coefficient of variation (CV) for snow depth. In constructing the regression model, it was assumed that the data set includes a considerable number of influential points, on both the y- and x-axis. The number of influential points is evidenced by the example of the dependence of a standard deviation of water equivalent – SD(*SWE*) – for unforested areas on snow depth (Fig. 1 – Williams plot) (Meloun & Militký, 2004). In view of the fact that not all these points could have been excluded from the analysis, we used a method which permits limiting the significance of influential points on both axes. That is to say, we used bounded influence regression (or BIR), which is regression with limited influence. The BIR method was used for linear regression for SD(*d*) and SD(*SWE*) dependencies for forested and unforested areas, and the calculations were carried out in QC-Expert 2.7 (Trilobyte, 2007).

For comparing the quality of the model, the ordinary least squares (OLS) method was used as well. In the case of dependence of the coefficient of variation on the snow depth, nonlinear regression in GraphPad Prism 5 was used (Motulsky, 2007). For the CV dependence for forested areas, the model Y=(A - P)*exp(-B*X) + P was used where A, P and B are the parameters (Motulsky, 2009).

An exponential model was also used for the dependence of CV for unforested habitat. In this case, however, it was a model comprised of two parts: the part of the model with rapidly decreasing values, expressed by the parameters AF and BF; and the part of the model with more slowly decreasing values, expressed by the parameters AS and BS (modified according to Motulsky, 2009).

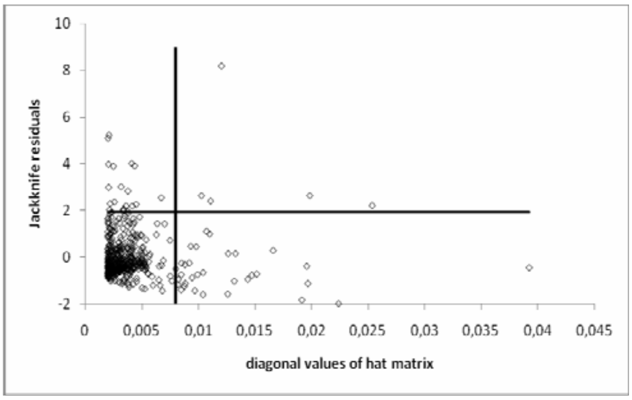

Figure 1. Williams graph (details in Meloun, Militký 2004) of outlying values for the standard deviation (SD) of snow cover, unforested habitat. Influential points of the response are above a horizontal line, influential points of x-values are right of a vertical line.

This model was used because there is an extreme drop in snow depth values in a range from 1 to 15 cm and subsequently these values level off substantially. The previous model was not able adequately to model this sharp break: Y=P + AF*exp(-BF*X) + AS*exp(-BS*X), where P, AF, BF, AS and BS are the parameters of the model. Here the method suggested by Motulsky and Brown (2006) was used to exclude influential points and was implemented into the program GraphPad Prism. This method is based on a new type of robust nonlinear regression combined with rejection of outliers. It is an adaptive method that gradually becomes more robust as the method proceeds. The authors state that their method identifies outliers not fitting the nonlinear curve with reasonable power and few (less than 1%) false positives.

3. RESULTS

The procedure that excludes borderline values of snow depth has a negligible influence on the calculation of average snow coverage. Only in 2% of cases does the difference of the mean snowpack depth ($\bar{d}$) calculated from a set of 16 central values compared to the mean of all 20 measured values exceed 1 cm, the maximum difference is 2.4 m (Table 3). The two-sample t-test confirmed agreement between the two sets for α = 0.01 (t = 3.185; P = 0.0015). This procedure logically has the greatest influence on the range of variation.

Table 3. Mean values (median) of statistics for local variability of parameters for snow cover according to period of measurement and habitat

Habitat	Indicator	20061	20062	20071	20072	20082	20083	20091	20092	20093	20098
Nonforest	*d* (20 values) (cm)	119.7	36.0	20.0	23.9	0.0	12.5	26.9	94.4	73.6	60.0
	range	16.0	18.0	7.50	6.0	0.0	5.5	7.0	11.0	13.5	9.0
	SD	4.2	5.2	2.1	1.5	0.0	1.5	1.7	2.9	3.5	2.6
	CV	3.4%	13.5%	10.3%	6.4%	0.0%	12.3%	6.8%	3.3%	4.2%	5.0%
	d (16 values) (cm)	119.7	36.3	20.1	23.9	0.0	12.4	26.9	94.4	74.3	60.4
	range	9.0	12.0	5.0	3.0	0.0	3.5	4.0	7.0	8.0	6.0
	SD	2.8	3.8	1.4	1.1	0.0	1.2	1.1	2.0	2.4	1.8
	CV	2.4%	10.2%	6.4%	4.4%	0.0%	8.3%	4.6%	2.2%	2.9%	3.4%
	ρ (kg/m^{-3})	320.4	464.2	374.0	194.2	352.1	166.7	230.3	178.2	328.0	184.5
	Δmax	2.7	9.5	14.2	6.8	11.2	9.2	7.1	2.1	3.9	3.0
	SWE (mm)	380.0	172.5	80.5	44.0	58.0	20.0	63.0	165.0	260.0	99.0
	SD	8.8.1	17.7	5.6	2.2	6.7	2.0	3.0	3.5	7.5	3.1
	CV	2.4%	11.3%	7.7%	4.4	12.%	8.8%	4.6%	2.2%	2.9%	2.4%
	Δmax	5.2	6.1	4.6	2.6	3.9	2.1	3.4	2.9	4.5	2.5
Forest	*d* (20 values)	93.7	32.5	3.0	15.9	0.0	10.1	12.4	68.6	59.2	43.4
	range	20.0	20.0	5.0	7.5	0.0	4.0	6.0	18.0	14.0	12.0
	SD	5.8	5.3	1.4	2.1	0.0	1.2	1.6	4.6	3.5	3.1
	CV	6.6%	14.4%	12.6%	13.3%	0.0%	14.6%	12,9%	6.4%	6.5%	8.2%
	d (16 values)	93.2	32.6	2.53	15.8	0.0	10.1	12.2	68.8	59.1	43.2
	range	14.0	12.0	3.0	5.0	0.0	3.0	4.0	10.0	8.0	7.0
	SD	4.1	3.7	1.0	1.5	0.0	0.9	1.2	3.1	2.5	2.1
	CV	4.7%	10.4%	8.7%	9.2%	0.0%	11.1%	9.4%	4.4%	4.2%	5.8%
	ρ (kg/m^{-3})	320.7	426.7	377.5	192.5	359.3	127.9	254.5	175.5	307.78	181.9
	Δmax	3.3	10.0	21.9	9.7	12.4	10.6	16.3	2.6	4.6	3.9
	SWE (mm)	299.5	140.0	8.5	32.0	89.0	13.0	37.0	126.5	182.0	74.0
	SD	13.7	16.6	6.0	2.9	13.2	1.4	3.4	5.3	7.7	4.2
	CV	4.8%	10.5%	13.8%	9.2%	14.4%	10.2%	9.5%	4.4%	4.2%	5.9%
	Δmax	4.7	5.3	4.9	2.6	3.8	2.1	3.6	2.6	4.3	2.5

Period of measurements: 20061 = 6. – 9. 3. 2006, 20062 = 13. – 14. 4. 2006, 20071 = 5. – 7. 3. 2007, 20072 = 22. – 24. 3. 2007, 20082 = 3. – 4. 3. 2008, 20083 = 25. – 26. 3. 2008, 20091 = 20. – 22. 1. 2009, 20092 = 24. 2. – 2. 3. 2009, 20093 = 24. – 27. 3. 2009, 20098 = 16. – 20. 10. 2009 (*SWE* – snow water equivalent, *d* – snowpack depth, ρ – snow density, SD – standard deviation, CV – coefficient of variation)

The mean value of the range of variation decreased from 14.2 for 20 values to 8.8 for 16 values. By excluding the extreme values, the variability of snowpack depth (*d*) data is reduced. SD decreases by 1.1 on average (Table 3). Almost all indicators of snowpack depth (*d*) variability correlate with mean snowpack depth ($\bar{d}$) (Table 4). Meanwhile, SD increases only slightly with mean snowpack depth ($\bar{d}$) (Figs. 2–3, 6–7) and can be characterized by linear regression, and CV is in inverse proportion to the mean snowpack depth ($\bar{d}$) (Figs. 4–5).

Comparison of OLS and BIR regression models for SD(*d*) and SD(*SWE*) dependencies on the snow depth suggests that the influential points significantly influence the shape of the regression model. The quality of both models was compared using Akaike information criterion (AIC) and in all cases it was found that the BIR model is better (Table 4). In the case of the BIR model, no statistically significant dependency was established for the model forest SD(*SWE*), where even the dependency manifested by the OLS method is very weak ($R^2 = 0.03$) (Table 4) and this dependence is evidently "caused" only by the influential points.

Finding a model for dependence of the coefficient of variation on the snow depth was rather difficult, as the CV values vary considerably for low values of snow depth (approximately up to 20 cm) and after that the values are already leveling out. The graphs suggest (Figs. 2–7) that exclusion of the influential points is significant only for low levels of snow depth (ca 5–15 cm) while the further courses of the models are virtually identical (Table 5, Figs. 2–7).

Analysis of local variability of snowpack depth (*d*) showed that local variability differs between individual years and measurement periods and between forested and unforested localities (Fig. 8).

For the analysis we used the data from 41 duplexes where measurements were taken in all evaluated years and measurement periods.Local variability of snowpack depth (*d*) is significantly higher in forested areas compared with unforested areas (Table 6). This influence of forest environment is particularly significant in measurements after snowfall (periods 20071, 20082, 20091, 20093). During a longer period without snowfall in which the snowpack depth (*d*) is reduced, differences in local variability between forested and unforested areas gradually disappear (periods 20071, 20082, 20091, 20093) (Table 7).

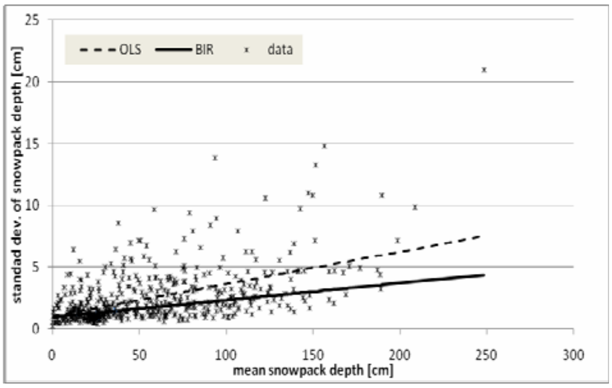

Figure 2. Dependence of standard deviation of snow depth on mean snowpack depth (unforested habitat, all measurements)

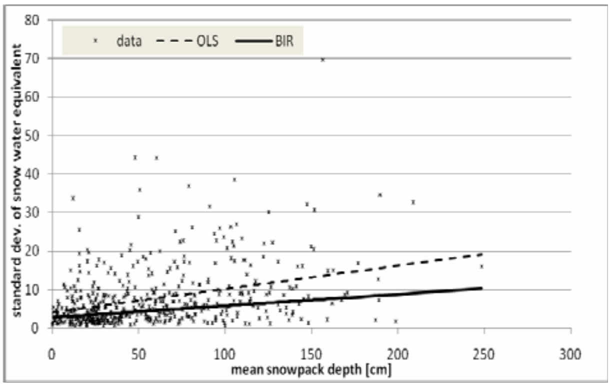

Figure 3. Dependence of standard deviation of snow depth on mean snowpack depth (forested habitat, all measurements)

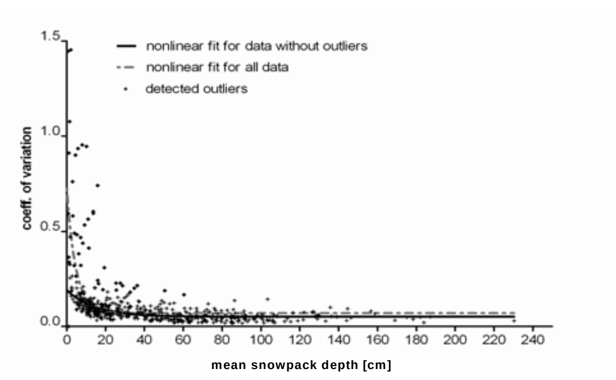

Figure 4. Dependence of the coefficient of variation on mean snowpack depth (unforested habitat, all measurements)

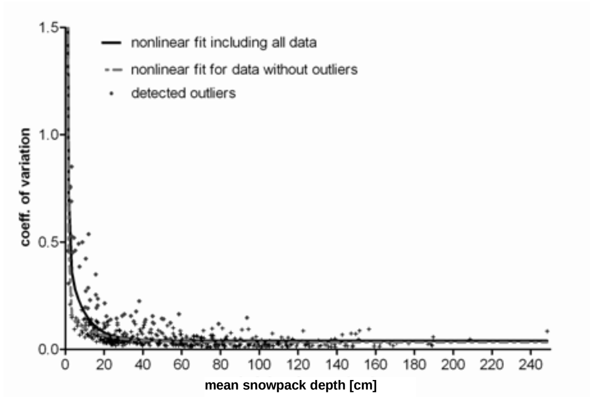

Figure 5. Correlation of the coefficient of variation with snowpack depth (forested habitat, all measurements)

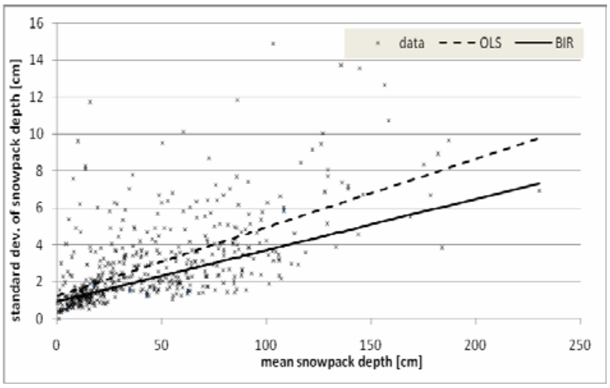

Figure 6. Dependence of standard deviation of snow water equivalent on mean snowpack depth (unforested habitat, all measurements)

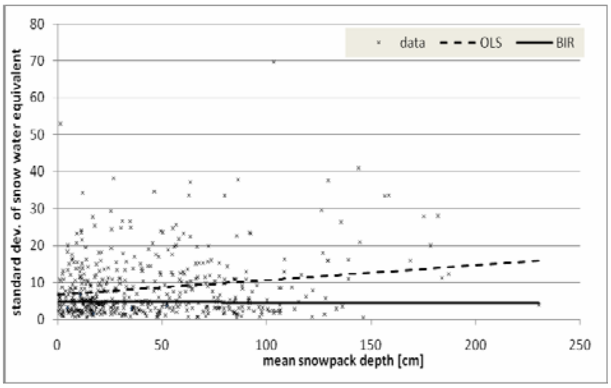

Figure 7. Dependence of standard deviation of snow water equivalent on mean snowpack depth (forested habitat, all measurements)

Table 4. Values of parameters for linear models of dependence of standard deviation of snow depth SD(*d*) and snow water equivalent SD(*SWE*) on mean snow depth (OLS – ordinary least squares; BIR – bounded influence regression)

Model	Method	Coefficients		Lower 95 % CI		Upper 95 % CI		R	R^2	RSS	AIC	p
		a	b	a	b	a	b					
forest SD(d)	OLS	1,2320	0,0371	0,9968	0,0331	1,4686	0,0411	0,6235	0,3888	1 664,82	609,26	s.
forest SD(d)	BIR	0,9288	0,0278	0,8496	0,0262	1,0081	0,0294	0,9549	0,9119	240,06	- 399,69	s.
forest SD(SWE)	OLS	6,7300	0,0397	5,6496	0,0214	7,8104	0,0580	0,1862	0,0347	33 220,08	2 127,66	s.
forest SD(SWE)	BIR	4,7570	-0,0012	4,3650	-0,0085	5,1491	0,0061					n.s.
nonforest SD(d)	OLS	1,0258	0,0261	0,7506	0,0223	1,3011	0,0299	0,5155	0,2657	1 853,21	660,26	s.
nonforest SD(d)	BIR	0,9467	0,0138	0,8541	0,0123	1,0393	0,0152	0,9483	0,8993	254,17	- 341,03	s.
nonforest SD(SWE)	OLS	4,0685	0,0608	3,0142	0,0463	5,1228	0,0754	0,3452	0,1192	26 825,59	1 995,25	s.
nonforest SD(SWE)	BIR	2,7871	0,0298	2,4481	0,0246	3,1261	0,0351	0,9416	0,8867	3 450,87	969,89	s.

CI – confidence interval, s. – significant model, n.s. – non-significant model, R – correlation coef. , R2- coef. of determination, RSS – residual sum of squares, AIC – Akaike information criterium

Table 5. Values of parameters for nonlinear models of dependence of the coefficient of variation on mean snow depth (Y=P + AF*exp(-BF*X) + AS*exp(-BS*X), where P, AF, BF, AS and BS are parameters of the model). Here the method suggested by Motulsky and Brown (2006) was used to exclude influential points.

Parameter	Coefficient of variation - forest						Coefficient of variation - nonforest					
	for all data			without outliers			for all data			without outliers		
	parameter	95% LL	95% UL	parameter	95% LL	95% UL	parameter	95% LL	95% UL	parameter	95% LL	95% UL
A	0,7229	0,6182	0,8275	0,1920	0,1737	0,2103						
B	0,2141	0,1659	0,2622	0,0691	0,0555	0,0829						
P	0,0704	0,0550	0,0858	0,0515	0,0470	0,0561	0,0401	0,0311	0,0492	0,0339	0,0305	0,0372
AF							3,7038	3,4839	3,9288	4,2256	4,0595	4,3068
BF							1,4670	1,3230	1,6110	1,5170	1,4500	1,5830
AS							0,4341	0,3561	0,5050	0,1316	0,1100	0,1490
BS							0,1200	0,0932	0,1468	0,0701	0,0561	0,0842
R2	0,3490			0,5090			0,9250			0,9871		
R	0,5908			0,7134			0,9618			0,9935		

95% LL - lower limit of confidence interval, 95% UL - upper limit of confidence interval

Table 6. Analysis of variability of standard deviations of snowpack depth measurements

Source of variability	SS	Difference	MS	F	P	F crit
Habitat	17,23891	1	17,23891	7,076714	0,007966	3,853103
Period	1061,833	9	117,9815	48,43235	8,26E-70	1,891568
Interaction	64,17028	9	7,130031	2,926936	0,002019	1,891568
Together	1948,804	800	2,436006			
Total	3092,047	819				

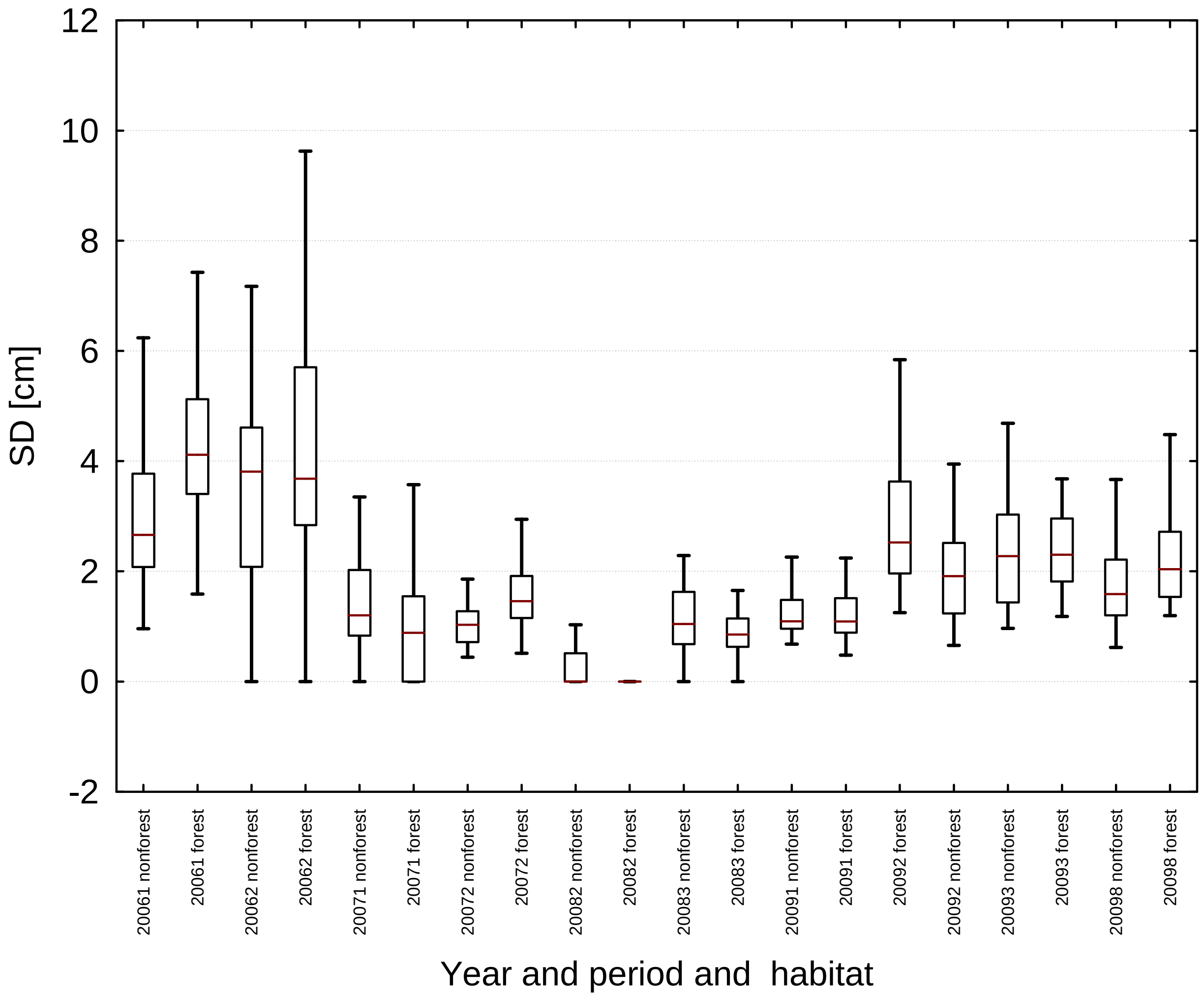

Figure 8. Local variability (standard deviations from 16 medium values of each locality) of snowpack depth (*d*) inside and outside the forest in all periods of study (periods see Table 3) (line…median, box…25-75% of values; barrs…minimum and maximum of nonoutleiers).

4. DISCUSSION

The purpose of expeditionary snow measurement is to determine snow cover parameters at given points (localities) and subsequently to construct a model for the distribution of these parameters throughout the basin. Information as to the accuracy of data attainable from expeditionary measurements is important for creating the model. Local variability in measured or, as the case may be, calculated values on a sample plot (measuring point) comprises a set of several factors: (i) declared accuracy (or inaccuracy) of measurement devices, (ii) actual accuracy of the measurement devices in given (e.g. weather) conditions, (iii) unknown error of a measuring device (human error), (iv) natural variability of snow cover parameters within an individual place of the sample plot (ca 20 m^2), and (v) other undefined random factors.

While on the basis of the declared accuracy of measuring devices we can estimate the theoretical maximum error of measurement and gross errors of measuring devices can be generally captured through data control – already during field measurements using computer-aided data collection (e.g. control of unlikely or impossible – more than 900 kg.m^{-3} – values of snow density (ρ)), other factors usually blend and combine variously and the difficulty to decipher their proportions exceeds the gains from refining the results if the overall variability is within acceptable limits.

The analysis demonstrated local variability of snowpack depth (*d*) on the order of centimeters. Only exceptionally does the value exceed the SD of 10 cm. The coefficient of variation reaches high values only at the lowest values of the snowpack depth (*d*), where the standard deviation (SD) is no more than a few centimeters.

Table 7. Multiple comparison of standard deviation values according to the measurement periods and habitat (Kruskal-Wallis test: H(19; 820)=428.34;p<0.0001) (*p< 0.05;**p<0.01;***p<0.001)

	20061 nonforest R:592,61	20061 forest R:704,15	20062 nonforest R:609,54	20062 forest R:661,39	20071 nonforest R:334,99	20071 forest R:241,37	20072 nonforest R:273,99	20072 forest R:386,07	20082 nonforest R:154,35	20082 forest R:82,049
20061 nonforest		2,13209	0,32357	1,31478	4,92461***	6,71426***	6,09067***	3,94808*	8,37755***	9,75970***
20061 forest	2,132094		1,80853	0,81731	7,05671***	8,84635***	8,22276***	6,08018***	10,50964***	11,89180***
20062 nonforest	0,323567	1,80853		0,99122	5,24818***	7,03782***	6,41423***	4,27165**	8,70112***	10,08327***
20062 forest	1,314784	0,81731	0,99122		6,23939***	8,02904***	7,40545***	5,26287***	9,69233***	11,07449***
20071 nonforest	4,92461***	7,05671***	5,24818***	6,23939***		1,789644	1,166055	0,97653	3,45294	4,83509***
20071 forest	6,71426***	8,84635***	7,03782***	8,02904***	1,789644		0,62359	2,766174	1,66329	3,04545
20072 nonforest	6,09067***	8,22276***	6,41423***	7,40545***	1,166055	0,62359		2,142585	2,28688	3,66904*
20072 forest	3,94808*	6,08018***	4,27165**	5,26286***	0,97653	2,766174	2,142585		4,42947**	5,81162***
20082 nonforest	8,37755***	10,50964***	8,70112***	9,69233***	3,452939	1,663295	2,286884	4,42947**		1,38215
20082 forest	9,75970***	11,89180***	10,08327***	11,07449***	4,83509***	3,045449	3,66904*	5,81162***	1,38215	
20083 nonforest	5,68061***	7,81271***	6,00418***	6,99540***	0,756001	1,033644	0,410054	1,732531	2,69694	4,07909**
20083 forest	6,84340***	8,97550***	7,16697***	8,15819***	1,918792	0,129147	0,752737	2,895321	1,53415	2,9163
20091 nonforest	5,37942***	7,51152***	5,70299***	6,69421***	0,454813	1,334832	0,711242	1,431343	2,99813	4,38028**
20091 forest	5,58752***	7,70642***	5,90909***	6,89417***	0,693407	1,085156	0,465428	1,66389	2,73815	4,11175**
20092 forest	0,242034	2,38693	0,56754	1,56471	4,71216***	6,51255***	5,88521***	3,72976*	8,18583***	9,57629***
20092 nonforest	2,523965	4,65606***	2,84753	3,83875*	2,400646	4,19029**	3,5667	1,424116	5,85358***	7,23574***
20093 nonforest	1,586366	3,71846*	1,90993	2,90115	3,338245	5,12789***	4,50430**	2,361715	6,79118***	8,17334***
20093 forest	0,783742	2,91584	1,10731	2,09853	4,14087**	5,93051***	5,30692***	3,164339	7,59381***	8,97596***
20098 nonforest	3,293953	5,42605***	3,61752	4,60874***	1,630658	3,420302	2,796713	0,654128	5,08360***	6,46575***
20098 forest	1,755376	3,88747*	2,07894	3,07016	3,169235	4,95888***	4,33529**	2,192705	6,62217***	8,00433***

	20083 nonforest R:295,44	20083 forest R:234,61	20091 nonforest R:311,20	20091 forest R:298,49	20092 forest R:580,02	20092 nonforest R:460,57	20093 nonforest R:509,62	20093 forest R:551,61	20098 nonforest R:420,29	20098 forest R:500,78
20061 nonforest	5,68061***	6,84340***	5,37942***	5,58752***	0,242034	2,523965	1,586366	0,783742	3,293953	1,755376
20061 forest	7,81271***	8,97550***	7,51152***	7,70642***	2,386933	4,65606***	3,71846*	2,915836	5,42605***	3,88747*
20062 nonforest	6,00418***	7,16697***	5,70299***	5,90909***	0,567544	2,847532	1,909933	1,107309	3,61752	2,078943
20062 forest	6,99540***	8,15819***	6,69421***	6,89417***	1,564714	3,83875*	2,901149	2,098525	4,60874***	3,07016
20071 nonforest	0,756001	1,918792	0,454813	0,693407	4,71216***	2,400646	3,338245	4,14087**	1,630658	3,169235
20071 forest	1,033644	0,129147	1,334832	1,085156	6,51255***	4,19029**	5,12789***	5,93051***	3,420302	4,95888***
20072 nonforest	0,410054	0,752737	0,711242	0,465428	5,88521***	3,5667	4,50430**	5,30692***	2,796713	4,33529**
20072 forest	1,732531	2,895321	1,431343	1,66389	3,72976*	1,424116	2,361715	3,164339	0,654128	2,192705
20082 nonforest	2,696938	1,534147	2,998126	2,738152	8,18583***	5,85359***	6,79118***	7,59381***	5,08360***	6,62217***
20082 forest	4,07909**	2,916302	4,38028**	4,11175**	9,57629***	7,23574***	8,17334***	8,97596***	6,46575***	8,00433***
20083 nonforest		1,162791	0,301188	0,057913	5,47270***	3,156646	4,09425**	4,89687***	2,386659	3,92524*
20083 forest	1,162791		1,463979	1,213504	6,64247***	4,31944**	5,25704***	6,05966***	3,54945	5,08803***
20091 nonforest	0,301188	1,463979		0,24141	5,16970***	2,855458	3,79306*	4,59568***	2,085471	3,624047
20091 forest	0,057913	1,213504	0,24141		5,38015***	3,079188	4,01098*	4,80864***	2,313968	3,84302*
20092 forest	5,47270***	6,64247***	5,16970***	5,38015***		2,297091	1,35386	0,546415	3,071703	1,523885
20092 nonforest	3,156646	4,31944**	2,855458	3,079188	2,297091		0,937599	1,740223	0,769988	0,768589
20093 nonforest	4,09425**	5,25704***	3,79306*	4,01098*	1,35386	0,937599		0,802624	1,707587	0,16901
20093 forest	4,89687***	6,05966***	4,59568***	4,80864***	0,546415	1,740223	0,802624		2,510211	0,971634
20098 nonforest	2,386659	3,54945	2,085471	2,313968	3,071703	0,769988	1,707587	2,510211		1,538577
20098 forest	3,92524*	5,08803***	3,624047	3,84302*	1,523885	0,768589	0,16901	0,971634	1,538577	

The procedure for eliminating maximum and minimum measured values reduces the variability significantly but has a practically negligible influence on the mean value. The estimated variability of *SWE* depends on the precision of determining the inputs mean snowpack depth (*d*) and snow density (*ρ*) and usually ranges up to 10 mm. It appears to be problematic to establish snow density (*ρ*) in limiting low snowpack depth (*d*) where due to a small volume of samples taken extremely high errors in determining snow density (*ρ*) may occur. Therefore, snow density (*ρ*) and snow water equivalent are determined for samples $d \geq 3$ cm ($V \geq$ 0.26 l). For other analyses, increasing this lower limit (the methodology of the Czech Hydrometeorological Institute allows for determining SWE from $d \geq 4$ cm, while Němec (2006b) works with a smaller cylinder diameter) or assigning the calculated values of snow density (*ρ*) with weights according to mean snowpack depth ($\bar{d}$) may prove effective.

Fragmentation of the landscape with surface-limited unforested areas (1–5 ha) in the distance of ca 1 km was the reason for using accessibility sampling for selecting plots in jittered squares. The key issue for fixing the site is the location of a suitable unforested area. These unforested areas must be of a representative size so as to avoid interference by the surrounding vegetation. Sample plots were established in the distance of at least one-half the height from the edge of the stand. In other periods, we performed repeated measurements on the very same plots.

Use of a stratified nested design is an alternative (Watson et al., 2006), a condition for which, however, is an a priori assumption of factors influencing snow cover parameters. We used stratifications according to the date of measurement and vegetation, not according to the solar radiation and height above sea level. The difference is that for our purposes we primarily focused on unforested habitats while plots beneath the forest vegetation served us in identifying differences compared to unforested areas. We do not regard stratification according to the height above sea level as suitable for the continuous variable of height above sea level with direct influence on snow cover parameters. It is better to introduce this stratification to the model subsequently, on the basis of a regression analysis (e.g. in the case of a multi-peak distribution).

The design for snow cover measurement and other snow parameters was very similar to those used when studying snow cover parameters in forested areas. This involves a line of 10, or even 25, points with a spacing of 5 m where the snow density (*ρ*) was measured at every fifth place (Pomeroy et al., 1998b). As the measurements are time-consuming and must be performed in as short a time as possible in order not to influence the quality of snow by thawing, sublimation and drifting away (Pomeroy and Gray, 1995), we chose shorter spacing, i.e. 1 m. The distances between measuring points have been tested (Faria, 1999 in Pomeroy et al., 1998a, b) and the sample lengths are sufficient for estimating the SWE. Finer resolution of the grid (by 1 m) shows similar statistical properties.

The analysis demonstrated that there are differences of local variability statistics between individual years and measurement periods (depending on the course of the weather) and also between forested and unforested areas. The snowpack depth variability (*d*) is significantly higher in the forest, especially in a period soon after snowfall (Křístek et al., 2008). This difference disappears during a period without snowfall and the opposite phenomenon can occur as well (i.e. the snowpack depth (*d*) variability is lower in the forest than in the open plot). This confirms the assumption that forest environment has a significant effect on the variability of snow cover parameters (Golding and Swanson, 1986; McKay & Gray, 1981; Kuz'min, 1960; Hedstrom & Pomeroy, 1998; Pomeroy & Grey, 1995; Pomeroy et al., 2002), and in spatial interpolations it will be necessary to evaluate the data from open plots and the data from the forests separately.

Determination of snow density (*ρ*) is very difficult at low values of snowpack depth (*d*) (i.e. in the case of small-volume samples). Δmax decreases exponentially depending on mean snowpack depth ($\bar{d}$), which is caused especially by there being several small samples of snow taken at the lower limits of snow cover. If we substitute values of half of the declared accuracy of the hanging weight and sampling cylinder into the formula for calculating snow density (*ρ*), we obtain a fractional function

$$\rho = \frac{\sum_{i=1}^{n} m_i + 0.005n}{(1-0.0029)\cdot\sum_{i=1}^{n} V_i - 0.04375n}\cdot 1000,$$

ρ = snow density [$kg.m^{-3}$], *m* = weight of snow sample, *V* = volume of snow sample, *n* = number of symplex

which implies that in taking small samples of snow the declared error of measuring devices can cause very high theoretical error in determining snow density (*ρ*) (up to the order of hundreds of percent). The methodology permits the depth of snow sampled to be no less than 3 cm.

Δmax for *SWE* normally does not exceed 10 mm under usual conditions. The exception includes places with very low snowpack depth (*d*) and thus limited by small snow samples where large measurement errors may occur as a result of large errors in determining snow density (*ρ*). Estimation of SD(*SWE*) is 8 mm on average. In 7% of cases it exceeds 20 mm and in extreme cases it reaches several tens of millimeters. In more than 70% of cases it exceeds the theoretical maximum measurement error.

The assumption of constant snow density (*ρ*) on a sample plot is, however, fictive. In fact, a relationship wherein $SWE = \rho \cdot d$ is valid between the water equivalent, depth and density of snow (*ρ*), where *SWE* is the most balanced quantity out of these three parameters (Křístek et al., 2008; Juroš, 2008). It seems that a change in the snowpack depth (*d*) in a given locality is (partially) compensated by a change in density (and vice versa), i.e. due to snow subsidence and compaction.

In view of the fact that all measured variables are real, the outliers are very important to us. Therefore, the use of bounded influence regression is very advantageous. BIR is robust both with regard to the diverging values of a dependent variable and regarding the strongly influential outlying data values for an independent variable. In that last-stated property, the BIR method differs from other robust methods. An advantage of this method lies also in the fact that it excludes none of the points on an a priori basis, but it only weights them such that the more influential the point is the less weight it gets (Meloun & Militký, 2004). This is clearly the reason why the BIR method is more suitable for processing the studied data: it gives much lower Akaike's information criterion (AIC) values, better correlation coefficients, and narrower confidence intervals for the model. That leads also to a more reliable model of dependence.

5. CONCLUSION

Measurements of snowpack depth 20 times on each plot with precision to 1 cm in studied plots placed in the extensively forested landscape on forest as well as unforested plots give precise results. The analysis demonstrated local variability of snowpack depth on the order of centimeters. Only exceptionally does the standard deviation (SD) value exceed 10 cm. The coefficient of variation reaches high values only at the lowest values of snowpack depth, where the standard deviation is no more than a few centimeters. A procedure for eliminating maximum and minimum measured values reduces the variability significantly but has practically negligible influence on the mean snowpack depth.
For calculating snow density and snow water equivalent 2–5 samples of snow are taken and their corresponding values are determined on the basis of sample depth with precision to 1 cm, calibration volume of the sampling cylinder (precision to 0.05 l), and weight (to 0.01 kg). The estimated variability of water equivalent depends on the precision of determining the inputs for mean snow depth and density and usually ranges up to 10 mm. Nearly all indicators of snowpack depth variability correlate with the mean snowpack depth. But the methodology permits the depth of snow sampled to be no less than 3 cm (volume of 0.26 l)."

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REFERENCES

Anonymous, 2008. *CHMI Climate and Precipitation Station Network.* CHMI, Climatology Section (online) [last update 8. 1. 2008]. Available at: http://old.chmi.cz/meteo/ok/mapyste.html.

Brodský, L., 2008. *FLOREO. Demonstration of ESA environments in support to Flood Risk Earth Observation monitoring.* GISAT, PřF UK Praha, 31. 10. 2008, 26.

Cline, D. W., Bales, R. C. & Dozier, J., 1998. *Estimating the spatial distribution of snow in mountain basins using remote sensing and energy balance modeling*. Water Resources Research 34, 1275–1285.

Cook, E. R., D'Arrigo, R. D. & Mann, M. E., 2002. *A Well-Verified, Multiproxy Reconstruction of the Winter North Atlantic Oscillation Index since A.D. 1400*. Journal of Climate, 15, 1754-1764.

Doesken, N. J. & Robinson, D. A., 2009. *The Challenge of Snow Measurements*. Historical Climate Variability and Impacts in North America, 978-90-481-2828-0, Part 4, 251-273.

Doran P. T., Priscu J. C., Lyons W. B., Walsh J. E., Fountain A. G., McKnight D. M., Moorhead D. L., Virginia R. A., Wall D. H., Clow G. D., Fristen C., H., McKay C. P. & Parson A. N., 2002. *Antarctic climate cooling and terrestrial ecosystems response*. Nature 415, 517–520.

Fox, J., 2002. *Robust Regression*. Web appendix to An R and S-Plus Companion to Applied Regression. Sage, Thousand Oaks, CA. http://socserv.socsci.mcmaster.ca/jfox/Books/Companion/appendix-robust-regression.pdf

Gelfan, A. N., Pomeroy, J. W. & Kuchment, L. S., 2004. *Modeling Forest Cover Influences on Snow Accumulation, Sublimation, and Melt*. Journal of Hydrometeorology, 5, issue 5, 785-803.

Gillet, N. P. & Thompson, D. W. J., 2003. *Simulation of Recent Southern Hemisphere Climate Change*. Science, 302, 273-275.

Golding, D. L. & Swanson, R. H., 1986. *Snow distribution patterns in clearings and adjacent forest*. Water Resources Research, **22** (13), 1931-1940.

Hedstrom, N. & Pomeroy, J. W., 1998. *Intercepted snow in the boreal forest: measurement and modelling*. Hydrological Processes, 12, 1611-1625.

Holko, L., Škvarenina, J., Kostka, Z., Frič, M. & Staroň, J., 2009. *Impact of spruce forest on rainfall interception and seasonal snow cover in the Western Tatra Mountains, Slovakia*. Biologia, 64/3, 594-599, Section Botany.

Holuša, J., 2004. *Health condition of Norway spruce Picea abies (L.) Karst stands in the Beskid Mts.* Dendrobiology, 51 (Suppl.), 11-17.

Holuša, J. , Křístek, Š. & Trombik, J., 2010. *Stability of spruce forests in the Beskids: an analysis of wind, snow and drought damages*. In: Beskydy, 1/2010, MZLU v Brně, ISSN 1803-2451.

Holuša, J. (ed.), 2000. *Regional Plan of Forest Development (RPFD). NFR 40 Moravskoslezské Beskydy*. (in Czech) ÚHÚL Brandýs nad Labem, pobočka Frýdek-Místek, 225.

Huber, P. J., 1964. *Robust Estimation of a Location Parameter*. Annals of Mathematical Statistics, 35, 73-101.

Juroš, J., 2008. *Distribution o the snow cover in the catchment of the Sance dam*. Diploma thesis. HGF VŠB-TU Ostrava, 103.

Kantor, P., 2005. *Water management potential of mountain forests at extreme precipitation*. (in Czech) In: Kulhavý, J., Skoupý, A., Kantor, P., Simon, J. (eds.). Sustainable forest and landscape management: From the concept to reality. MZLU v Brně, 225-230.

Kantor, P. & Šach, F., 1988. *Hydrolic efficiency of young substitute stands of Picea omorika and Betula verrucosa*. (in Czech) Lesnictví, 34, 1017-1040.

Kilpeläinen, A., Gregow, H., Strandman, H., Kellomäki, S., Venäläinen, A. & Peltola, H., 2009. *Impacts of climate change on the risk of snow-induced forest damage in Finland*. Climatic Change, 1573-1480.

Křístek, Š., Samec, P., Rychtecká, P. & Holuša, J. ml., 2008. *Numerical analysis of temporal and spatial snow cover distribution in the Ostravice catchment (Moravian-Silezian Beskids, Czech Republic) during the winters 2005/2006 and 2006/2007*. (in Czech) Meteorologický časopis (Meteorological Journal), 2008/11, č. 3. Slovenský hydrometeorologický ústav, Bratislava, ISSN 1335-339X, 107-117.

Kuz'min, P. P., 1960. *Structure of Snow Cover and Methods of Snow Reserves Measurements*. Gidrometeoizdat: Leningrad. (in Russian), (Published 1963 as *Snow Cover and Snow Reserves*. [English Translation by Israel Program for Scientific Translation, Jerusalem]. National Science Foundation, Washington, DC).

McKay, G. A. & Gray, D. M., 1981. *The distribution of snowcover*. In: Gray, D. M., Male D. H. (eds.). Handbook of Snow: Principles, Processes, Management and Use. Pergamon Press, Toronto, 153-190.

Meloun, M. & Militký, J., 2004. *Statistical analysis of experimental data*. (in Czech) 2. vyd. Academia, Praha, 953 pp.

Mote, T. L., Grundstein, A. J., Leathers, D. J. & Robinson, D. A., 2003. *A comparison of modeled, remotely sensed, and measured snow water equivalent in the northern Great Plains*. Water Resources Research 39, 1209.

Motulsky, H. J., 2007. *GraphPad Prism, Version 5.0, Regression Guide*. GraphPad Software, Inc., San Diego, 294.

Motulsky, H. J., 2009. *GraphPad Prism 5.0, Learning Guide*. Available at: http://graphpad.com/help/prism5/prism5help.html?usingnonlinear_regression_step_by_s.htm

Motulsky, H. J. & Brown, R. E., 2006. *Detecting outliers when fitting data with nonlinear regression – a new method based on robust nonlinear regression and the false discovery rate*. BMC bioinformatics, 7, 123. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16526949.

Němec, L., 2006a. *Evaluation of reliability and efficiency of the measurement of snow depth and snow water equivalent.* (in Czech language) In: Sandev M. (ed.). Meteorological and hydrological evaluation of the 2006 spring floods in the Czech Republic. ČHMÚ, Praha, A35-53.

Němec, L., 2006b. *Snow water equivalent*. Lecture Czech Meteorological Society, Ostrava, 9. 1. 2006, 17.

Plíva K., 1991. *Functionally integrated forest management. 1st Natural conditions in the forest management planning*. (in Czech) Ústav pro hospodářskou úpravu lesů Brandýs nad Labem, 257.

Pomeroy, J. W. & Gray, D. M., 1995. *Snowcover accumulation, relocation and management*. National Hydrology Research Institute, Science report No. 7, Saskatoon, Environment Canada, 144.

Pomeroy, J. W., Gray, D. M., Hedstrom, N. R. & Janowicz, J. R., 2002. *Prediction of seasonal snow accumulation in cold climate forests*. Hydrological Processes, 16, 3543-3558.

Pomeroy, J. W., Gray, D. M., Shook, K. R., Toth, B., Essery, R. L. H., Pietroniro, A. & Hedstrom, N., 1998a. *An evaluation of snow accumulation and ablation processes for land surface modelling*. Hydrological Processes, 12, 2339-2367.

Pomeroy, J. W., Parviainen, J., Hedstrom N. & Gray D. M., 1998b. *Coupled modelling of forest snow interception and sublimation*. Hydrological Processes, 12, 2317-2337.

Rychtecká, P. & Urbaňcová, N., 2008. *Natural disturbances in forest 1996-2006 - Part 1 Abiotic and anthropogenic factors*. (in Czech) Lesnická práce, Časopis pro lesnickou vědu a praxi, 2008, sv. 6, ISSN 0322-9254, 14-15.

Savill, P. S., 1983. *Silviculture in windy climate*. For Abs, 44, 473-488.

Slodičák, M., 1995. *Thinning regime in stands of Norway spruce subjected to snow and wind damage*. In: Coutts, M.P., Grace, J. (eds.). Wind and Trees. Cambridge University Press, 436–447.

Škvarenina J., Tomlain J. & Križová, E., 2002. *Climatic water balance of vegetation altitudinal zones – stages in Slovakia*. (in Czech) Meteorologické zprávy 55, 103–109.

Taylor, C. M., Harding, R. J., Pielke, R. A. Sr., Vidale, P. L., Walko, R. L. & Pomeroy, J. W., 1998. *Snow breezes in the boreal forest*. Journal of geophysical research, 103, 23087-23101.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Henderson, K. A., Brecher, H. H., Zagorodov, V. S., Mashiotta, T. A., Lin, P. N., Mikhalenko, V. N., Hardy, D. R. & Beer, J., 2002. *Kilimandjaro Ice Core Records: Evidence of Holocene Climate Change in Tropical Africa*. Science, 298, 589-593.

Tolasz, R., Brázdil, R., Bulíř, O., Dobrovolný, P., Dubrovský, M., Hájková, L., Halásová, O., Hostýnek, J., Janouch, M., Kohut, M., Krška, K., Křivancová, S., Květoň, V., Lepka, Z., Lipina, P., Macková, J., Metelka, L., Míková, T., Mrkvica, Z., Možný, M., Nekovář, J., Němec, L., Pokorný, J., Reitschläger, J. D., Richterová, D., Rožnovský, J., Řepka, M., Semerádová, D., Sosna, V., Stříž, M., Šercl, P., Škáchová, H., Štěpánek, P., Štěpánková, P., Trnka, M., Valeriánová, A., Valter, J., Vaníček, K., Vavruška, F., Voženílek, V., Vrablík, T., Vysoudil, M., Zahradníček, J., Zusková, I., Žák, M. & Žalud, Z., 2007. *Climate Atlas of Czechia (in Czech)*. 1. vydání. Český hydrometeorologický ústav, Universita Palackého, Praha, Olomouc, 256, ISBN 978-80-86690-26-1.

Trilobyte 2007: *QC-Expert 2.7 User Guide*. Trilobyte, Ltd., Pardubice, 199 pp.

Urbaňcová, N., 2008. *Possibilities of remote sensing technology*. (in Czech) Interní zpráva projektu NAZV č. QH81334 Geoprostorové modelování potenciálního ohrožení lesních porostů. ÚHÚL Frýdek-Místek, 17.

Watson, F. G. R., Anderson, T. N., Newman, W. B., Alexander, S. E. & Garrott, R. A., 2006. *Optimal sampling schemes for estimating mean snow water equivalents in stratified heterogeneous landscapes*. Journal of Hydrology, 328, 432-452.

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