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Seasonal snow accumulation in the mid-latitude forested catchment

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Abstract: The study deals with the snow cover characteristics (snow depth – SD and snow water equivalent – SWE) concerning the mid-latitude forested catchment. Namely, the influence of the forest canopy (*Picea abies* (L.) Karst. and *Fagus sylvatica* L.) and altitude (ranging from 835 m a.s.l. to 1118 m a.s.l.) was investigated. Forest cover was proved to have a significant influence on the snow cover accumulation, reducing SWE by 50 % on average, compared to open sites. The elevation gradient concerning SWE ranged from 30 to 40 mm and from 5 to 20 mm per 100 m in open and forested sites, respectively. Its magnitude was found to be temporarily variable and positively related to the total seasonal snowfall amount. The SWE/SD variability among measurement sites (with different altitude) was higher in open sites compared to forested ones. The catchment SWE/SD variability increases significantly in the snowmelt period (March–April) both in open and forested locations. The differences among snow interception losses, concerning various elevations and the forest canopy, were not statistically significant.

Key words: forested catchment; snow depth; snow water equivalent

Introduction

Snow accumulation and snowmelt dominate the hydrology of most inland catchments in mountain and boreal forest environments. Hydrological importance of seasonal snow cover consists of detaining significant amount of water during the accumulation period followed by its fast release during the melt period. The processes that control snow accumulation and melt in open areas (not influenced by the forest canopy) are well described for a wide range of climates (Storck et al. 2002).

At the catchment-scale, the variability of snow accumulation and snowmelt is influenced by topography, with elevation and aspect as the dominant controls (Anderton et al. 2004; Pomeroy et al. 1998). Wind redistribution (Luce et al. 1998), micro topography, and vegetation are causes of a high plot-scale variability of snow pack properties. It is well accepted that, at mesoscales and microscales, snow accumulation differs substantially between forested and open environments because of processes of interception, sublimation and wind redistribution (Pomeroy et al. 1998). The forest canopy also influences snow characteristics by altering the snowpack energy balance (Faria et al. 2000; Storck et al. 2002), which results in lower average snow accumulation and lower average melt rates under the forest canopy in comparison to clearcuts and other non-forested landscapes.

The estimation of snow characteristics in forested mountainous regions contributes significantly to the efficiency of the spring flood forecasting in the Czech Republic. Considering larger areas, field measurements of snowpack characteristics is time demanding and costly (Erxleben et al. 2002). Hence, in order to obtain spatial snow distribution, interpolation techniques based on quantified regularities are utilized. The estimation of the snowpack under the forest canopy in different altitudes belongs to these regularities. In the central European region, the influence of the forest cover on snowpack characteristics was studied e.g. by Stehlík & Bubeníčková (2002), Holko et al. (2009), Hríbik et al. (2012). Holko & Kostka (2008) focused on the SWE elevation gradient and stressed that the increase of SD and SWE with altitude is not linear. On top of that, Kutláková & Jeníček (2012) focused on the modelling of the snow processes in Krušné Hory Mts. Attempts were also made to estimate snow water equivalent in a mountain catchment using a distributed model of snow accumulation and melt (Holko et al. 2003). But the seasonal changes in the SWE elevation gradient and the influence of altitude on differences between open and forested areas remain vaguely described. Thorough review of the articles devoted to snow hydrology in central Europe is presented in Holko et al. (2011).

Norway spruce (*Picea abies* (L.) Karst.) is planted in central Europe for centuries and has become the most important commercial forest tree species in the region (Nadezhdina et al. 2013). Thus, the main aim of this study is to contribute to the quantification of

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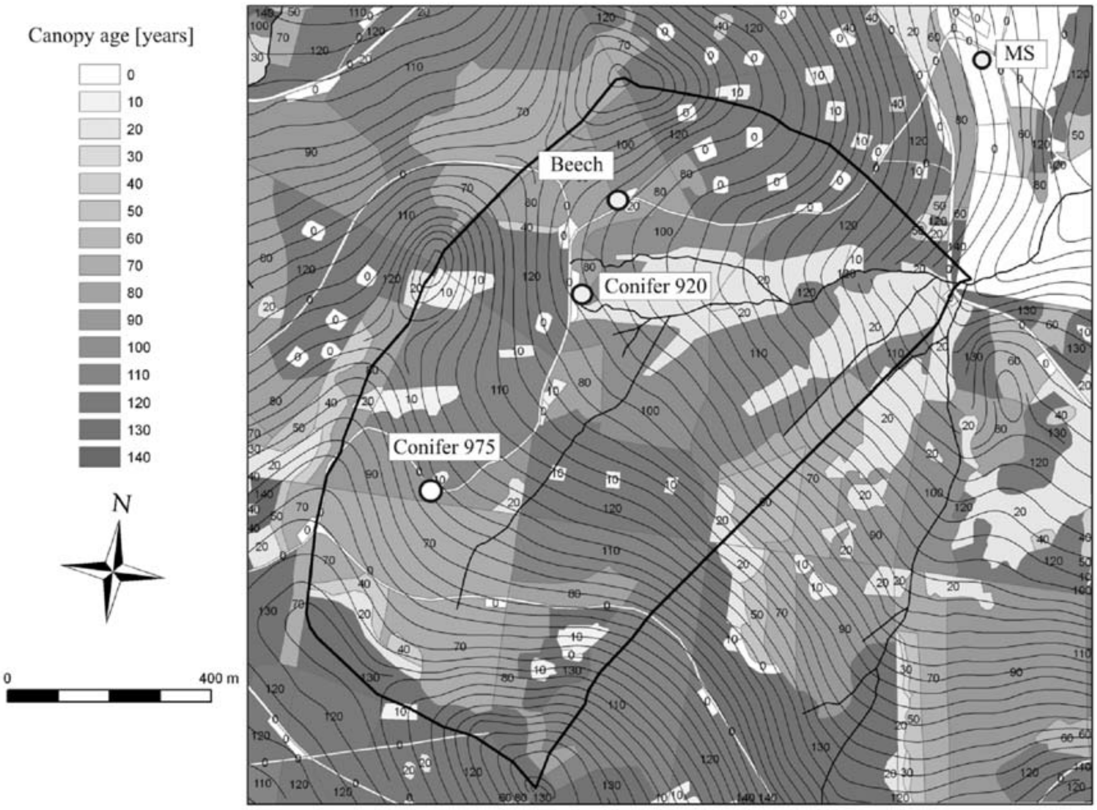


Fig. 1. Snow measuring sites in the Liz experimental basin.

the differences in the snowpack accumulation in open and forested sites (covered mainly with Norway spruce (*Picea abies* (L.) Karst.). The attention is also paid on the annual snowpack evolution. The seasonal variability of the SWE elevation gradient is explored and the canopy interception amount (concerning snowfall) is determined.

Data and methods

The study area is located in the mountainous and forested part of the Bohemian Forest Protected Landscape Area, in South Bohemia, Czech Republic (13°41′ E, 49°04′ N). The total catchment area attains 99.7 ha. The altitude in the catchment ranges from 826.62 m a.s.l. (zero point of the outlet) to 1074 m a.s.l. (surrounding peaks) and the average altitude of the basin is 941 m a.s.l. The catchment faces east and north-east in direction, with an average slope angle of around 16 %. Climate and vegetation are characteristic for the mild climate zone with the mean monthly temperature varying from –3.4 °C in January to 13.6 °C in July and the mean annual temperature is 6.6 °C. The mean annual precipitation is 863 mm, the mean annual runoff depth 345 mm (values were determined for hydrological years 1976–2013). The mean number of days with snow cover is 92.The entire catchment is covered by mixed forest, with prevailing Norway spruce (*Picea abies* (L.) Karst.) of various ages (up to 140 years). The overview of the catchment and location of measurement sites are displayed in Fig. 1.

The meteorological data were obtained from the meteorological station located next to the experimental catchment (430 m from the outlet and 1000 m from the centre of the catchment) at the altitude of 829 m a.s.l. The snow cover characteristics were measured from the winter 2002/2003 to the winter 2012/2013. Two fundamental variables of snow cover, snow depth (SD) and snow water equivalent (SWE) were measured. SWE was determined by a mass method, using a gauging tube with a digital balance. The snow tube Metra (with an area of 50 cm^2) was used until January 2007. Since then, the snow tube with an area of 30 cm^2 was used. The snow cover was measured at four different sites (see Fig. 1): Meteorological station (MS) (835 m a.s.l.), Conifer 920 and Beech (920 m a.s.l.), and Conifer 975 (975 m a.s.l.). Conifer 920 and Conifer 975 depicts the locations in the Norway spruce (*Picea abies* (L.) Karst.), which differ only in altitude. The last measurement is taken from the nearby (4 km from the experimental plot border) meteorological station at Churáňov hill (1118 m a.s.l.). Four sites differ primarily in altitude and one (Beech) is located in the beech canopy (*Fagus sylvatica* L.) in the same altitude as the Conifer 920 site. Besides the Churáňov hill, snow measurements were always conducted in the forest canopy and in the nearby open site, in order to observe the influence of the forest canopy on snow accumulation and melting processes. All the measuring sites in the forest canopy were placed in the forest of a similar age.

Results

The influence of two determining factors was studied using the snow depth and the snow water equivalent characteristics. In the first place, the differences between forested and open sites were quantified. Second, the influence of the altitude on both snow characteristics was studied.

Tab. 1. Annual average SWE in all experimental sites [mm]

	Meteostation		Conifer 920		Beech		Conifer 975		Churáňov
	open	forest	open	forest	open	forest	open	forest	open
2002/2003	28.95	11.22	46.43	25.23	37.96	19.00	69.60	29.26	91.23
2003/2004	44.75	20.74	68.40	33.81	51.15	26.13	83.63	37.19	124.61
2004/2005	39.50	17.85	55.28	42.24	59.52	32.28	100.77	44.35	167.44
2005/2006	89.89	44.99	122.36	96.90	115.13	73.28	164.68	109.90	220.87
2007/2008	15.21	5.40	24.56	9.08	19.73	7.91	49.71	13.80	94.88
2008/2009	46.82	25.92	83.23	41.45	71.84	23.56	113.09	60.93	148.77
2009/2010	36.94	29.14	61.42	38.15	50.06	27.73	77.24	40.28	87.81
2010/2011	21.97	15.87	55.67	17.47	34.54	11.68	78.81	20.29	88.17
2011/2012	39.80	24.03	77.52	33.37	61.14	23.63	113.92	42.00	149.24
2012/2013	23.79	15.77	60.36	32.42	50.50	18.19	77.40	33.14	93.03
Average	38.76	21.09	65.52	37.01	55.16	26.34	92.89	43.11	126.61

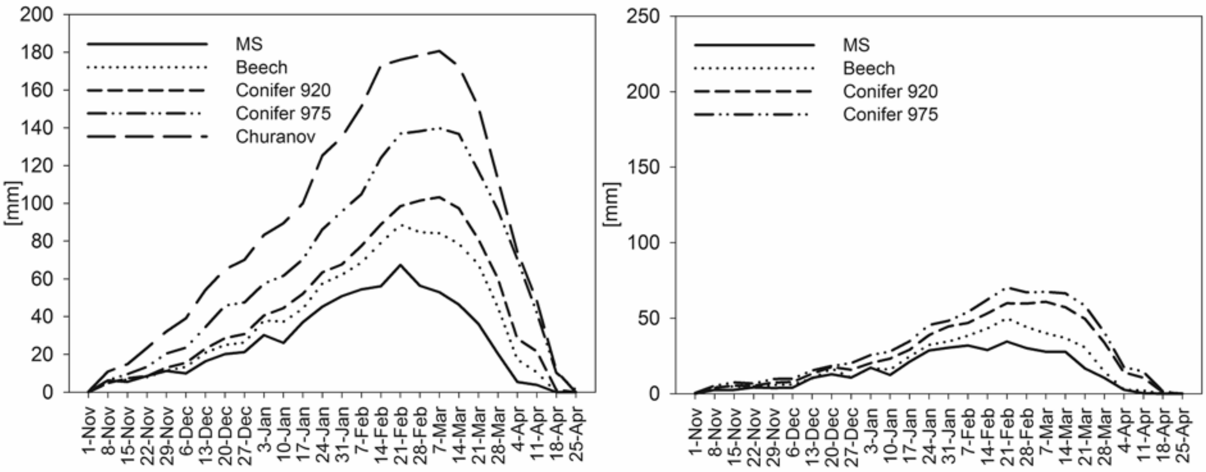


Fig. 2. The average annual course of SWE in open (left panel) and forested site (right panel).

Annual course of snow cover in open and forested sites
The importance of the hydrological conditions in the forest, in the context of intense drought periods, was highlighted by Střelcová et al. (2013).The main processes influencing SD and SWE at various sites are represented by: snowfall, snowmelt, interception, sublimation, and wind redistribution. In this study, four paired site measurements were established in order to investigate the differences among open and forested areas concerning the snow cover characteristics. Similar approach was adopted e.g. by Stehlík & Bubeníčková (2002) or Winkler et al. (2005).

The average seasonal course of SWE is depicted in Fig. 2. Particular values were constructed as weekly averages of SWE over the studied period (2002/2003–2012/2013). Although, the annual courses are very similar in forested and open sites, the picture demonstrates the most significant difference among them, which is represented by the total amount of snow water accumulated. SWE is generally higher concerning open areas in all years studied (Table 1). The ratio of forested to open site SWE ranges from 26% to 79%. On average, SWE in forested site equals to 50% of SWE in the open site. The value of the ratio might be related to the total snowfall amount. The higher the snowfall is, the smaller the difference between open and forested sites is. This relation is more pronounced with increasing altitude – the correlation coefficient ranging from 0.01 (MS) to 0.55 (Conifer 975).

SWE in the forested site might be related to the open site by a simple regression as the relationship seems to be linear (Fig. 3). Correlation coefficients between forested and open sites are higher than 0.90 (at the 95% significance level) for the entire study period. Hence, for the purpose of the hydrological forecasting it might be sufficient to measure the SWE in open area and then estimate the SWE in nearby forest. According to Fig. 2, the snow cover is present usually both in the forest and open site in the Liz experimental basin. As it was also shown in Fig. 2, the phenomenon of slower snowmelt in the canopy covered areas, identified e.g. by Hríbik et al. (2012) in Slovakia, was not observed. Only slight improvement of predicting relations was found when the winter was split into accumulation and snowmelt periods as performed by Stehlík & Bubeníčková (2002).

The trend analysis using a standard Mann-Kendall test was conducted. The average monthly and annual values of SWE and SD for all five locations represented the input data. Using the period of winters 2002/2003–

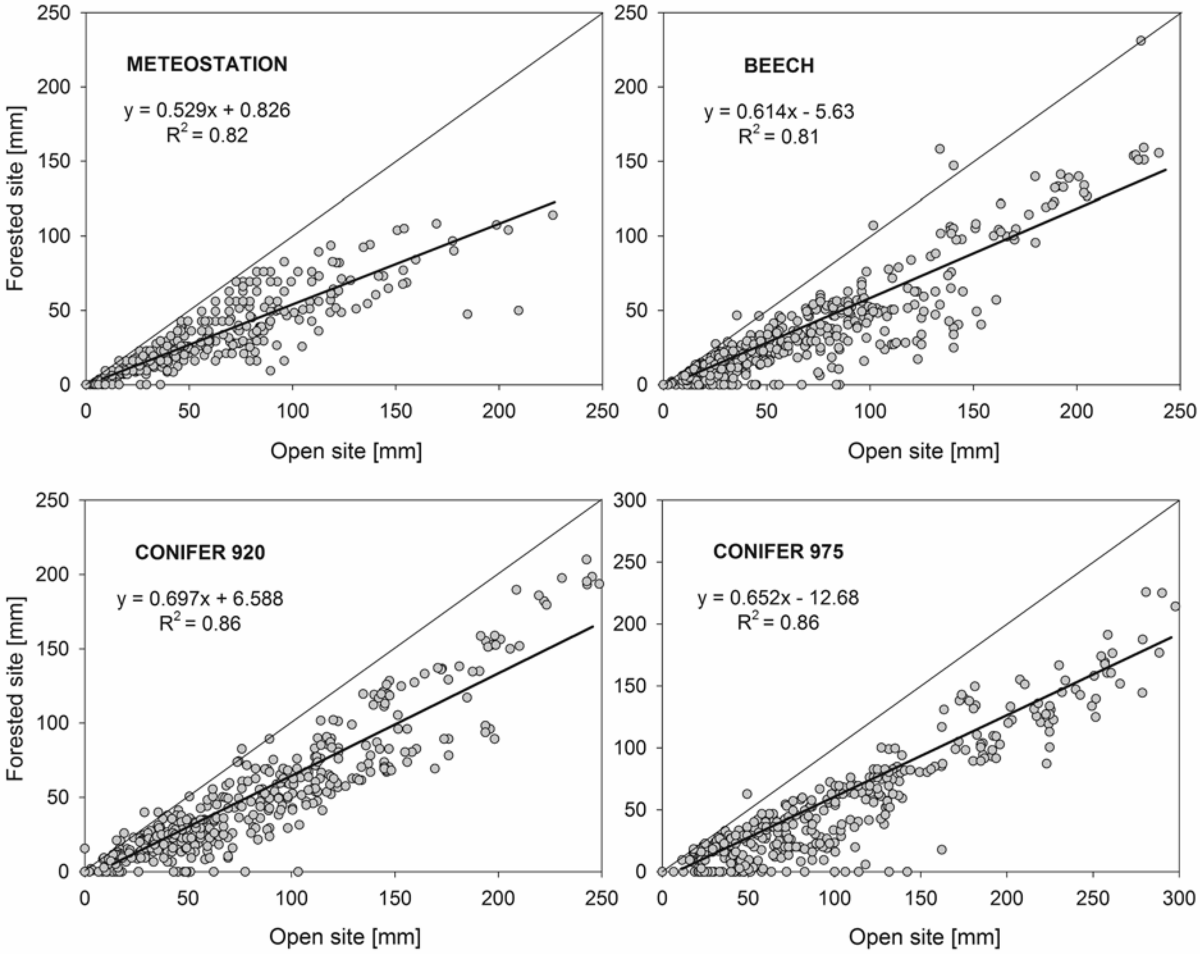


Fig. 3. Relations of open and forested SWE for all observed sites (2002/2003–2012/2013).

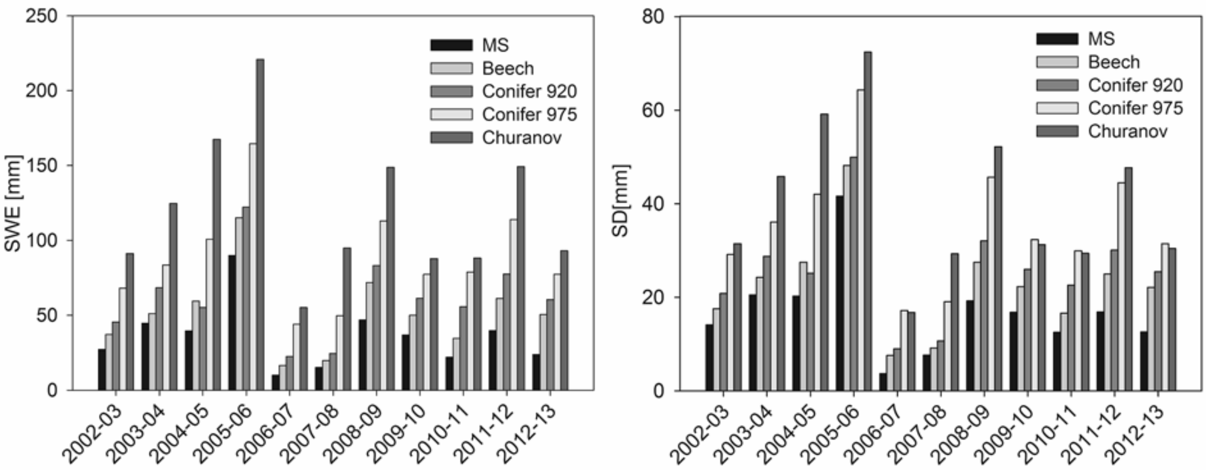


Fig. 4. The average annual SWE (left plot) and SD (right plot) for all open sites.

2012/2013 no statistically significant (given by 95 %percentile of the empirical probability distribution) trend was observed.

Influence of altitude

Altitude has a profound influence on the magnitude of snowfall events and snow processes (Varhola et al. 2010). In this study, the relations of SWE and SD to altitude were investigated. In all winter periods, SWE (as well as SD) increased with altitude both in forested and open sites. Fig. 4 depicts the annual averages of SWE and SD in open sites, representing various elevations above the sea level. The differences between sites are more pronounced in the case of the SWE, which might be attributed to the different snow melting dynamics at various elevations. The average coefficient of

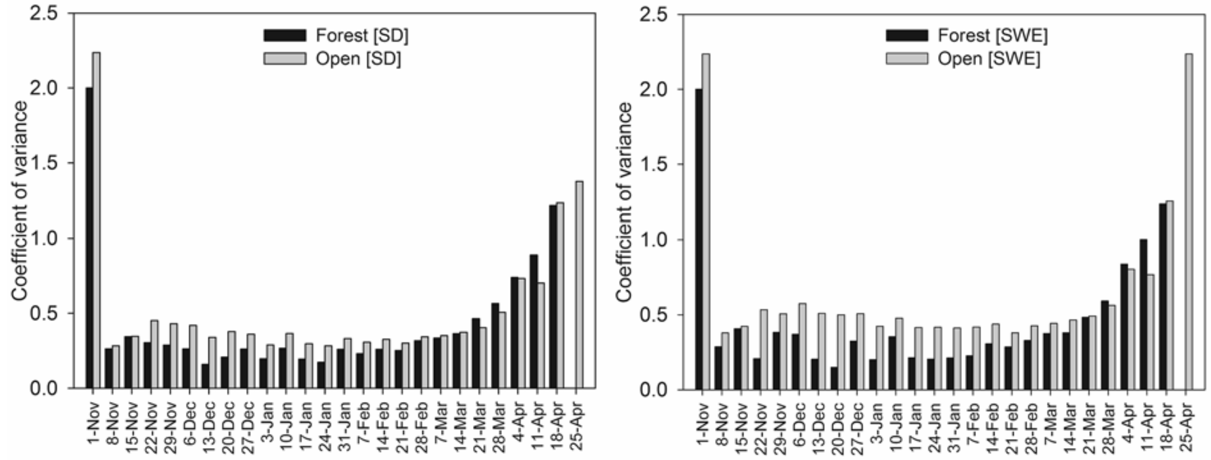


Fig. 5. An average course of the coefficient of variation for open sites and forested sites (2002–2013), SD (left plot) and SWE (right plot).

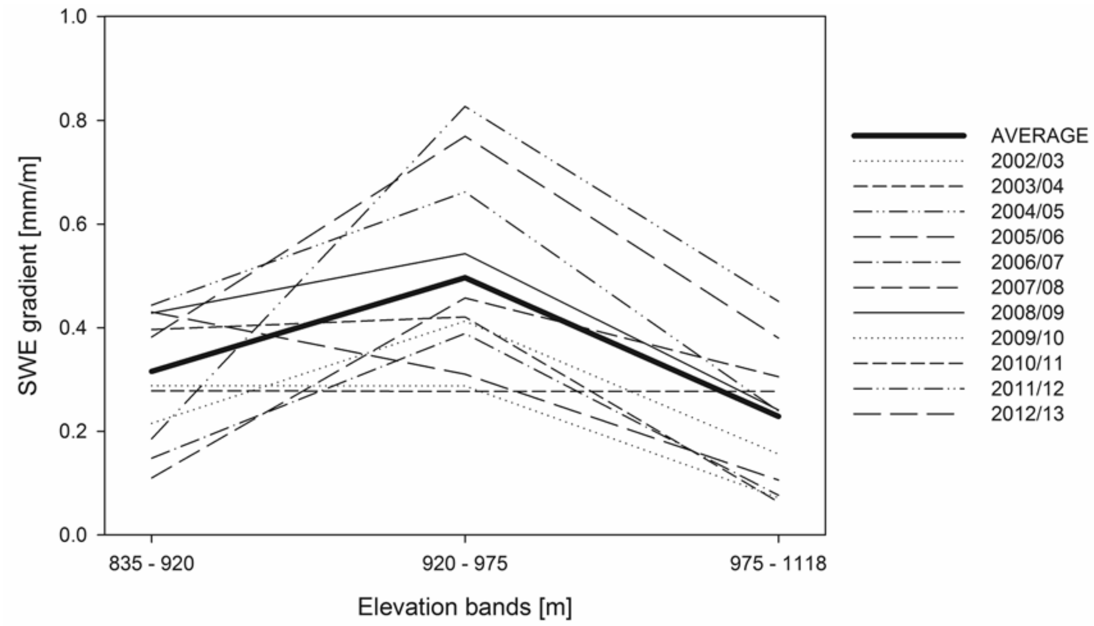
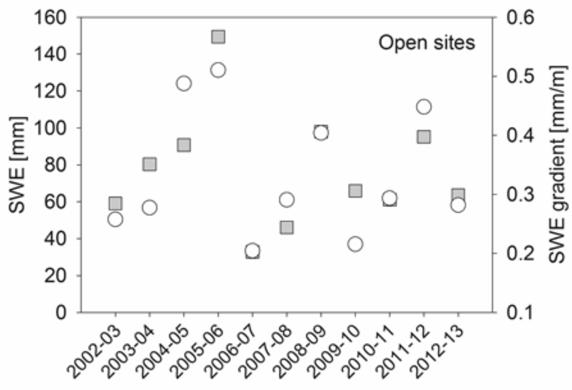


Fig. 6. Annual averages of SWE elevation gradient in among four different altitudes for open sites (2002–2013).

variation equals 0.50 concerning SWE data contrasting with 0.39 concerning SD.

Considering the elevation based snow cover variability, data from the forested sites are more homogenous with an average coefficient of variation attaining 0.2–0.3 during the accumulation period (November–February). In this period, the in situ variability for open sites ranges between 0.3–0.4. In both type of sites, the coefficient of variation increases from the end of February to the end of the melting period, reaching 1.2 on average both for the SCE and SWE values (see Fig. 5). Hence, the differences in altitude are more pronounced during the snowmelt period. The differences present at the very beginning and end of the snow cover period are determined by the gradual onset of the snow cover respecting the elevation.

Wike et al. (2013) pointed out the importance of particular variable gradients when handling large areas. Hence, the experimental determination of the SWE gradient in the small scale is essential. The gradient of SWE increase was obtained as the difference of the average SWE for specific places and years with respect to the elevation difference between them. The altitudinal gradient exhibits generally higher values between two intermediate sites (Conifer 920 and Conifer 975) and lower values in lower and upper parts of the area (documented in Fig. 6). This is contrasting with the findings of Holko et al. (2011), who reported nearly linear increase up to 1500–1600 m a.s.l. in the Western Carpatians. Nevertheless, the values from the Churáňov Hill might be more influenced by the wind redistribution (snow drift) than the rest of the locations. The gradient of snow increase varied significantly among particular years. However, it is significantly positively correlated (at the 95% percentile level) with the average winter SWE in the locations (Fig. 7). The correlation coeffi-



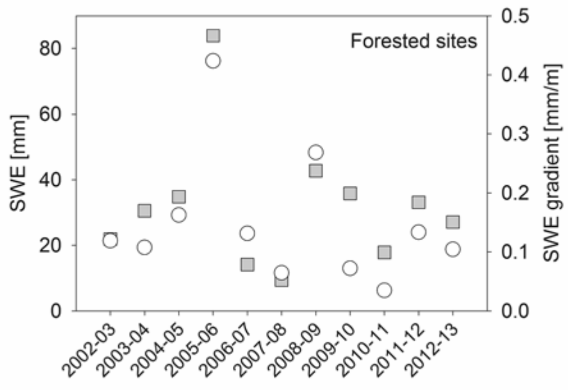


Fig. 7. Relations of the average SWE elevation gradient (white circles) over the entire studied area and average annual SWE (grey squares) for open and forested sites.

cients between average annual SWE and SWE elevation gradient are ranging between 0.60 and 0.94 in the entire period 2002–2013 (both for forested and open sites). The average correlation coefficient equals 0.85 and 0.90 for open and forested sites, respectively. These values are interpreted as a good relationship with the average annual SWE. Therefore the SWE gradient should not be considered only elevation dependent, as demonstrated by Holko & Kostka (2008), but also temporally variable with respect to a total snowfall amount. The average SWE was found to increase at rate of 30–40 mm per 100 m for open areas and 5–20 mm for forested areas, which is higher than the values 21–27 mm (open sites) and 11–15 (forested sites) presented by Toews & Gluns (1986) in British Columbia, Canada. However, the gradients are comparable to those obtained by Holko (2000) in Tatra Mts, Slovakia.

Interception

Snow interception by the mature canopy was inferred as the difference between the increase in SD in the open site and the increase in SD under the canopy assuming that the new snow density is the same. The differences in the SWE were not taken into account as they might be influenced by different melting and sublimation processes concerning open and forested sites. The periods when the snow depth increased significantly more in the forested site than in the open area were excluded from the analysis, as they probably represent the exceeded interception capacity of the forest canopy allowing accumulated snow to fall to the ground via canopy unloading (McKay & Gray 1981).

The interception was estimated at four different locations. Three representing spruce forest (*Picea abies* (L.) Karst.) at different altitude (MS, Conifer 920, and Conifer 975) and one located near Conifer 920, but covered with beech forest (*Fagus sylvatica* L.). Data for all sites are plotted in Fig. 8, which demonstrates that the character of intercepted snowfall amount is very similar considering all locations. It constitutes around 40 % of the total snowfall depth (in mm), which corresponds to values presented by Hedstrom & Pomeroy (1998) from British Columbia, Canada. Maximum interception capacity ranges from 6 to 9 mm of snow depth. According to the angle of the trendline, the interception is slightly increasing with altitude and is more efficient in spruce forest (*Picea abies* (L.) Karst.) compared to the beech covered site (*Fagus sylvatica* L.). However, the ANOVA analysis was conducted taking into account all 646 episodes and the null hypothesis that the site characteristic (elevation or canopy coverage) would influence the variance of intercepted snow depth was rejected at 5% confidence level. Hence, the snow interception might be considered elevation and canopy cover independent at our experimental location.

Conclusions

Snow cover characteristics were measured for eleven years at five distinct sites representing various altitude and canopy cover. Following conclusions might be drawn from the extensive research:

– SD and SWE in open sites are significantly higher than in forested sites and might be related with each other in a linear way. The difference is negatively correlated to total snowfall amount. The annual course of SD and SWE is similar in forested and open sites.

– No significant trend is observed considering monthly and annual averages of SD and SWE.

– SD and SWE are elevation dependent. The snow cover is more homogenous in the forested canopy in different elevations. The elevation variability increases in the snowmelt period in both types of sites.

– The average SWE elevation gradient equalled to 30–40 mm and 5–20 mm per 100 m in open and forested sites, respectively. The SWE elevation gradient is temporarily variable and positively correlated to total winter snowfall amount.

– Interception losses (concerning the SD) are similar in all sites regarding the canopy cover and altitude. The maximum interception threshold for SD ranged from 6 to 9 mm.

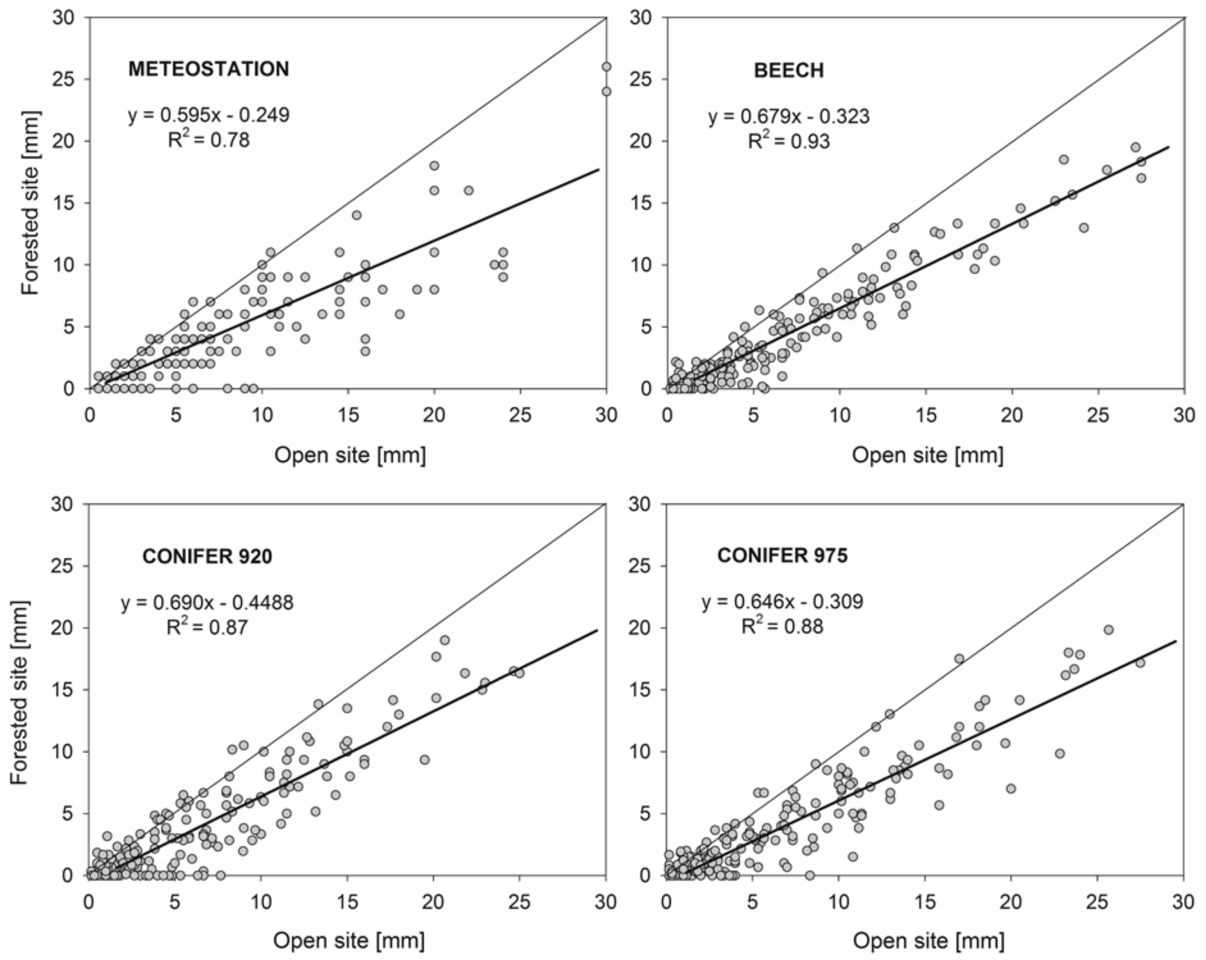


Fig. 8. The comparison of ΔSD in open area and under the canopy.

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