Comparison of the seasonal small-scale spatial variability in alpine snowfall and snow accumulation

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Abstract

A mobile polarimetric X-band radar (MXPol) deployed in the area of Davos (Switzerland) collected valuable and continuous information on small-scale precipitation for the winter seasons of 2009/2010 and 2010/2011. These data were compared to local measurements of snow accumulation collected with Airborne Laser Scanning (ALS) at the Wannengrat area (Davos, Switzerland). This unique configuration makes the comparison of the variability in snowfall (as seen by the radar) and in snow accumulation (from laser scans) possible over the entire winter seasons.

The spatial variability, quantified by means of the variogram, is shown to be larger in snow accumulation than in snowfall. This indicates that other factors (like wind and turbulence taking place close to the ground) induced by small-scale topographic features govern the snow deposition and accumulation at the ground level in mountainous areas. In order to further investigate this question, the domain covered by the radar is divided in two sub-domains over which the altitude of the radar beam above the ground is either "small" or "large". The variability in snowfall appears consistently larger in the vicinity of the ridge than far from the ground, which confirms the influence of small-scale topography on snowfall. **The full work is currently under review (Scipión et al., 2012)**.

1 Introduction

Snowfall and resulting snow accumulation in mountainous terrain are crucial for studying and predicting natural hazards like floods and avalanches, as well as for water resources, hydroelectric power and tourism (e.g. ski resorts). At local scales, the spatial variability in both snowfall and snow accumulation is governed by the interaction between cloud microphysics, atmospheric dynamics, and topographic features (Lehning et al., 2008; Zängl et al., 2008; Schirmer et al., 2011). These processes make the distribution of snow accumulation a complex and dynamic process (Mott et al., 2011). The spatial variability of snow accumulation is important in order to estimate the timing of the snow melt (Grünewald et al., 2010), and to forecast avalanche danger (Schweizer et al., 2003). Lehning et al. (2008) have proposed the concept of preferential deposition, which has been studied and evaluated using measured snow deposition fields, simulated precipitation, and wind fields (Mott et al., 2010; Dadic et al., 2010), but no direct measured precipitation fields were available for verification.

In order to understand the contribution of snow precipitation on snow distribution variability, the main objective of this paper is to compare and analyze the respective spatial variability in snowfall and snow accumulation over the same area for a whole winter season. These comparisons and analyses are conducted by using snowfall observations collected by a Doppler dual-polarization X-band radar deployed in the eastern Swiss Alps during the winters 2009/10 and 2010/11 and snow accumulation measurements from laser scans (Mott et al., 2011). This unique combination of high-resolution data allows the analysis of small-scale variability, which is important in regions with complex topography. In addition, the influence of the topographically-induced flow pattern will also be investigated by considering sub-domains over which the radar beam is at distinct altitude ranges (close to the ridge and far from the ridge).

2 Experimental Setup

2.1 Data Set

The Wannengrat experimental site near Davos, Switzerland has provided useful data for snow cover and hydrology related research (i.e. Grünewald et al., 2010; Mott et al., 2010). The potential of the area for snowfall studies has been reinforced with the installation of a mobile X-band dual-polarization weather radar (MXPol) in the vicinity of Davos (see Figure 1).

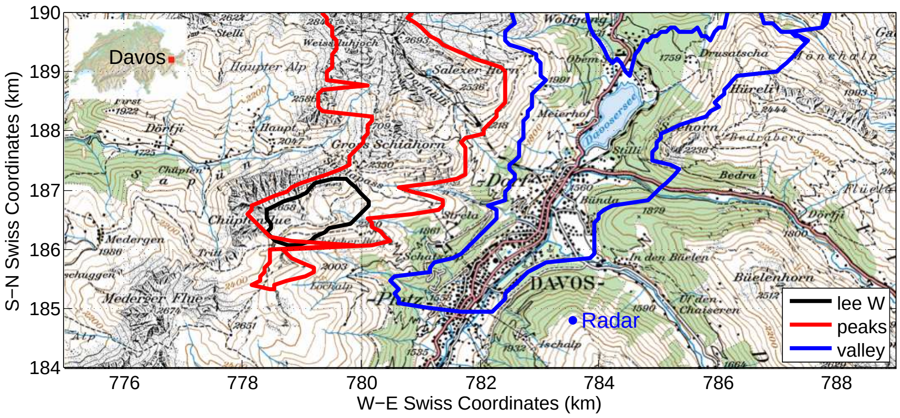

Figure 1: *Study site near Davos, Switzerland. The colored lines represent the different sub-domains of interest. The "lee-W" sub-domain is presented in black and corresponds to the leeward side of the Wannengrat. The other sub-domains are "peaks" and "valley" which can be found in red and blue, respectively. The location of the radar is marked with a blue dot.*

2.1.1 Snow Accumulation Measurements

Snow accumulation measurements for this study are obtained using Airborne Laser Scan (ALS) (see Figure 2). ALS measurements of snow accumulation were obtained at the time of the peak accumulation at the end of the accumulation for the winter seasons of 2007/08 and 2008/09 (Mott et al., 2010; Schirmer et al., 2011). Inter-annual consistency of snow accumulation measurements is assumed similarly to the Terrestrial Laser Scans in the Wannengrat area (Schirmer et al., 2011).

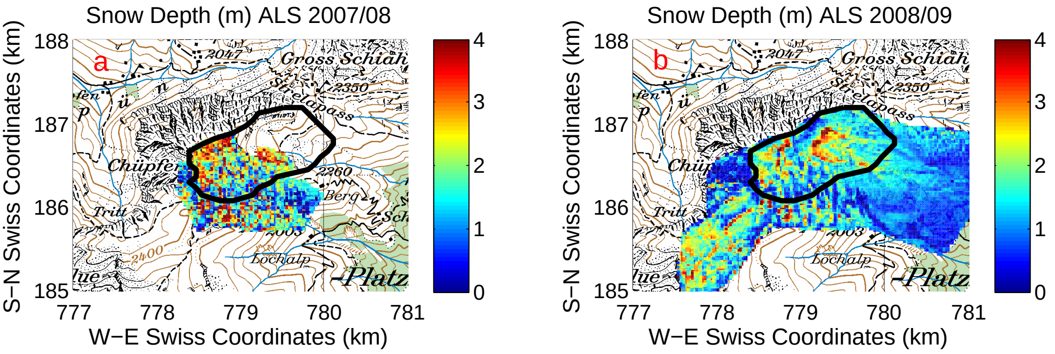

Figure 2: *Snow Accumulation measurements obtained from Airborne Laser Scans in the Wannengrat area. a: Measurements from the 2007/08 period. b: Measurements from the 2008/09 period. Additionally, the "lee-W" is highlighted in black.*

2.1.2 Radar Measurements

MXPol was deployed in the proximity of Davos, Switzerland (see Figure 1) at the beginning of the winter season of 2009. The first variable used in the present study is the radar reflectivity at horizontal polarization (Z_H), which is related to the amount and type of hydrometeors in the radar sampling volume. The differential reflectivity Z_{DR} defines the ratio between the radar reflectivity at horizontal and vertical polarization. Z_{DR} is independent of the hydrometeor concentration and, in this case, will work as an aid for quantifying the variability of snow particle types. Finally, the Doppler spectral width σ_v is related to shear or turbulence within the resolution volume (Doviak and Zrnić, 1984). The variations in the measured spectral width are assumed to be only due to turbulence. There is a significant uncertainty associated with radar estimation of snowfall rate. To avoid adding this uncertainty in the analysis of the spatial variability of snowfall conducted in this study, the variability in snow reflectivity directly measured by the radar is assumed to be representative of the variability in snowfall rate, similarly to Germann and Joss (2001) and Berne et al. (2004) for rain rate.

2.2 Domains of Analysis

2.2.1 Wannengrat Area

The leeward area of the Wannengrat ("lee-W", presented in Figure 1) has been selected due to local snow accumulation measurements, radar coverage, and the predominant NW wind observed in the area (Mott et al., 2010; Schirmer et al., 2011). The area of the sub-domain corresponds to 1.5 km^2. Snow deposition on the leeward area of the Wannengrat is directly affected by the NW winds, and it was already demonstrated by Mott et al. (2010) that small-scale precipitation patterns drive snow deposition here. Additionally, the laser scan measurements are located predominantly in this area (see Figure 2).

2.2.2 Peaks and Valley domains

Another subset of sub-domains was selected to investigate the effects of the topographically-induced wind processes on snowfall. Two disjoint areas have been chosen based on the difference in altitudes between the DEM (Swiss digital elevation model) and the radar beam elevation at 9°: the first sub-domain ("peaks") corresponds to a difference in elevations lower than 500 m and is mainly located over the the Wannengrat area and close to the ridge. The second sub-domain ("valley") corresponds to differences in elevations that ranges between 700 - 1200 m. This domain is located predominantly over the Davos valley and far from the ridge. Both sub-domains are presented in Figure 1, the "peaks" sub-domain with an area of 9.5 km^2 and the "valley" sub-domain with an area of 13.2 km^2.

2.3 Methodology

Radar data at 9° elevation are selected for the winters of 2009/10 and 2010/11 when only pure snow events were identified. Additionally, no attenuation in the snowfall is considered because the maximum distance under analysis is 10 km from the radar location and specific attenuation is limited in dry snow (Battan, 1973). After the events were selected, the radar data were censored using a Signal-to-Noise ratio (SNR) threshold of 5 dB.

Radar data were resampled and transformed from Polar coordinates to the Swiss Cartesian coordinates with a 75 m resolution in both North-South and East-West directions. The number of days of snowfall for the 2009/10 and 2010/11 winter periods are 49 and 10, respectively. The number of days is lower in 2010/11 than in 2009/10 because of maintenance work on the radar, but fortunately, the main snow events of the season were captured.

Snow accumulation values from ALS were obtained at the end of the winters of 2007/08 and 2008/09. Unfortunately, the snow accumulation periods do not coincide with the radar measurements from 2009/10 and 2010/11. However, inter-annual consistency in the Wannengrat area has been observed and documented (see Section 2.1). This quantitative inter-annual consistency was generalized for all winter events in the area (Schirmer and Lehning, 2011).

The spatial variability analysis of snow accumulation measured on the ground and of snowfall estimated by the radar is based on spatial (semi-)variograms. The variogram is a key tool used in geostatistics because it quantifies the spatial structure of a random function (i.e. Goovaerts, 1997). The variogram $\gamma(\mathbf{h})$ measures the dissimilarities of the random function $z(\mathbf{x})$ data separated by a vector $\mathbf{h}$. For better comparison between the variograms obtained from snowfall detected by the radar and the snow accumulation measured at the ground, normalized (or climatological) variograms are considered (Bastin et al., 1984). The normalization of the variograms is made by dividing the estimator by the variance of the data under consideration. The normalized variogram is dimensionless and has values ranging from zero to one.

Snow accumulation measurements were mainly collected in the "lee-W" sub-domain (See Figure 2). Normalized variograms of reflectivity and differential reflectivity are computed at each scan time (approximately every five minutes) for each of the sub-domains. In order to compute the seasonal variability, the normalized variograms were averaged over all time steps that correspond to the period of analysis. Finally, the variograms do not exhibit a large dependence on direction, so only the isotropic variogram is computed.

3 Results

3.1 Variability of snow accumulation and radar reflectivity

Variograms from snow accumulation in the "lee-W" sub-domain are presented in Figure 3a. At short distance lags (h<150 m) snow accumulation appears smoother in 2008/09 than in 2007/08 as indicated by the lower values of the variogram. The discrepancies between the two might be attributed to more noisy snow accumulation measurements observed in the 2007/08 period (see Figure 2). For large distance lags, the two variograms are very similar, which indicates similar variability. These results confirm the inter-annual consistency results Schirmer and Lehning (2011) and Deems et al. (2008). The variograms presented in this study complement those provided by Mott et al. (2011) by providing variogram values for larger distance lags (h >150 m).

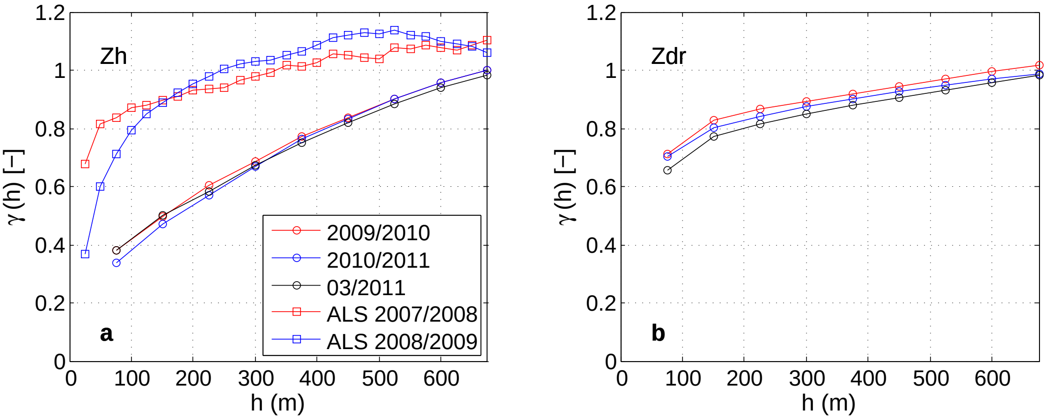

Figure 3: *Variograms obtained from the "lee-W" sub-domain for different seasonal periods. a: Variograms from snow accumulation (ASL) from the winters of 2007/2008 and 2008/209 are compared with the "reflectivity" field variograms from different seasonal periods. b: Variograms obtained from "differential reflectivity" field.*

The almost perfect agreement between the normalized variograms of radar reflectivity for the two winter periods of 2009/10 and 2010/11 shows that the average spatial variability in snowfall is consistent from one winter to the next (over the considered domain, at least), despite the possible differences in the number of snow events and in the quantity of snow they deposit on the ground. This suggests that the precipitating systems leading to (significant) snowfall are similar from one year to the next.

The difference in altitude between the actual terrain and the radar beam at 9° ranges between 300-600 m. The difference in the spatial structure between snowfall and snow accumulation are interpreted as the signature of the fact that the main processes governing snow accumulation take place close to or at the surface.

An important contribution of the present paper is to show that by considering spatially distributed snowfall, the small-scale variability of snow depth on the ground cannot be explained by the snowfall variability because additional wind-induced processes control snow distribution on the ground. This is a useful complement to the results from Mott et al. (2011).

In addition to the variograms of radar reflectivity, the variograms of differential reflectivity have also been studied (see Figure 3b). Contrary to the radar reflectivity, the differential reflectivity does not depend on the concentration of snow particles. So in this case, the spatial variability of radar differential reflectivity is driven by changes in the shape and density of snowflakes.

3.2 Close and far from the ridge

The "peaks" sub-domain corresponds to a radar beam altitude close to the terrain (95 - 500 m). This area is expected to be strongly affected by the wind and turbulence caused by its proximity to the terrain and the small-scale topographic features (ridge). The other sub-domain "valley" corresponds to distances far from the ground (700 - 1200 m), and it is supposed to be much less affected by turbulence and/or drifts (air-flows) generated by the terrain.

For both Z_H and Z_{DR}, the variograms of the "valley" domain from 2009/10 and 2010/11 are very similar, which shows the very good consistency from one winter to the other when the variability of snowfall (in intensity and in shape/density) is analyzed 700 m or higher above the ground. The variability in Z_{DR}, i.e. in snowflake shape/density, is smooth and limited relatively to the measurement errors. On the contrary, the variograms corresponding to the "peaks" domain are less similar in both Z_H and Z_{DR}. The season 2009/10 exhibits larger variability than 2010/11 in Z_H and Z_{DR} up to distance lags of about 1.5 km.

The (normalized) variograms in the "peaks" sub-domain indicates the following: a larger variability in snowfall intensity (through Z_H); a larger variability in snowfall shape and density distribution (through Z_{DR}) in the atmosphere close to the ridge. These large variabilities confirm the influence of the processes occurring close to the surface. Furthermore, the discrepancies between the variograms for the two winters in the "peaks" sub-domain can be related to small-scale processes because the agreement between the variograms of Z_H and Z_{DR} is excellent in the "valley" sub-domain for the two winters. If processes occurring at larger scales would govern this variability, the variograms in the "valley" sub-domain should also be different (as the "peaks" and "valley" sub-domains are close to each other).

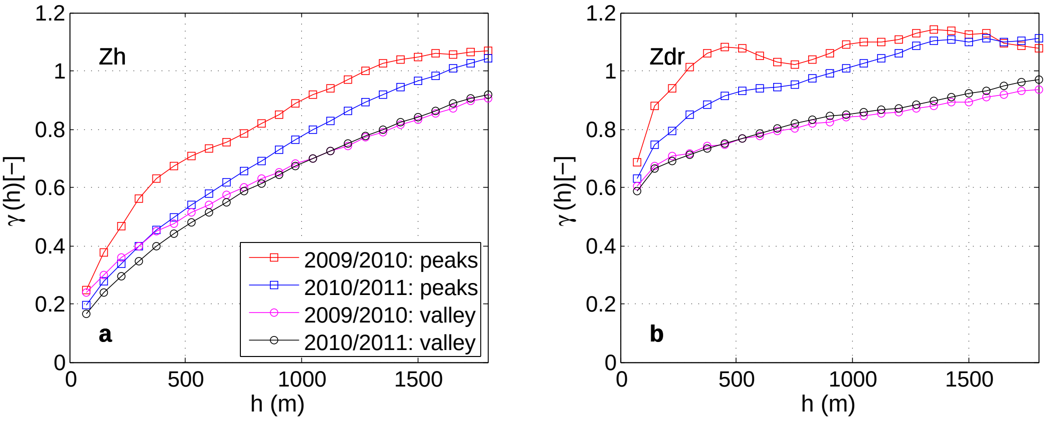

Figure 4: *Variograms obtained from the "peaks" and "valley" sub-domains for the different seasons. a: Variograms of "reflectivity" fields. b: Variograms of "differential reflectivity" fields.*

To verify these hypotheses, the distribution of the Doppler spectral width for both domains and seasons is calculated and presented in Figure 5. Both distributions of spectral width from the "peaks" sub-domain present larger mean values than the "valley" sub-domain. These findings quantitatively confirm that turbulence is stronger close to the surface where winds are in direct contact with the terrain.

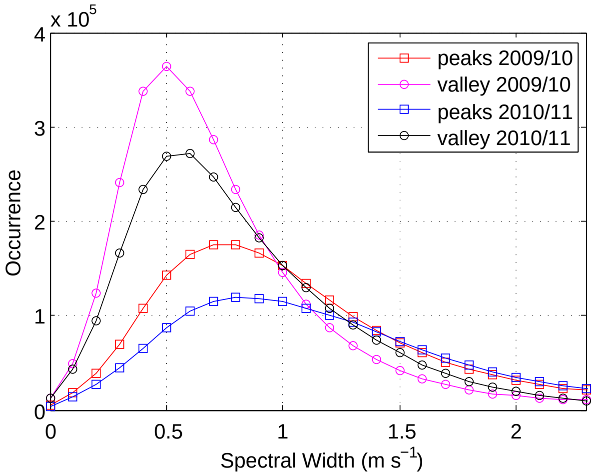

Figure 5: *Histograms of the Doppler spectral width obtained from the "peaks" and "valley" sub-domains for the different winter seasons. Histograms from the "peaks" sub-domain are presented with squares, and the "valley" are presented with circles.*

4 Summary and Conclusions

The main objective of the present study is to investigate the importance of the spatial variability of snowfall to explain the spatial variability of snow accumulation at the winter-season scale. As expected, the comparison of the variograms of snowfall and of snow accumulation shows that the variability is much smoother in snowfall than in snow deposition. Because the radar beam is between 300 - 600 m above the ground in the study area, this difference in spatial variability is due to small-scale processes occurring close to the surface. To investigate the influence of the topographically-induced wind patterns on snow accumulation, the spatial variability of Z_H and Z_{DR} is analyzed in two sub-domains defined by the relative altitude of the radar beam with respect to the terrain. The variograms in Z_H and Z_{DR} are almost identical in the "valley" sub-domain for the two winter seasons, whereas they are different in the "peaks" sub-domain. Additionally, in the "peaks" sub-domain Z_H and Z_{DR} present larger variability. This confirms the influence of the small-scale processes, and we assume mainly topographically-induced wind, on snowfall variability (in both intensity and snowflake shape/density). These assumptions were confirmed through the analysis of the distribution of the spectral width, related to turbulence, in both sub-domains. The "peaks" sub-domain exhibits higher values than the "valley" sub-domain, which indicates stronger turbulence caused by the strong interaction between wind and terrain.

These analyses presented in this article show that snowfall variability is not the driving factor of snow depth variability at small scales (below a few km), as the latter is additionally affected by snow redistribution processes and (indirectly) shows that topographically-induced wind patterns have a dominant influence on snow accumulation. Wind has also strong effect on the snow variability as seen for the different areas ("peaks" and "valley"). These results obtained from observations complement and confirm previous studies based on simulations.

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