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SPATIAL VARIABILITY OF SNOW ACCUMULATION ON VERNAGTFERNER, AUSTRIAN ALPS, IN WINTER 2003/2004

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With 7 figures

ABSTRACT

In this paper the pattern of snow accumulation on Vernagtferner (46° 52′ N, 10° 49′ E) is analyzed. The measurements of snow depth and snow density were carried out at the end of the glaciological winter period 2003/2004. The values of snow depth are particularly reliable because the summer of 2003 with its high ablation rates left a dense surface layer that was easy to detect with snow sondes even in the upper firn area. The snow accumulation pattern is statistically analyzed regarding its relationship with topography and wind regime. A generalized-least-squares regression is applied using geomorphometric attributes representing measures of local wind sheltering. The main wind direction for winter 2003/2004 is derived from data of two meteorological stations in the catchment and used for directional parameters. It was shown that elevation is the predominant factor influencing the amount of snow accumulation in the lower areas between 2750 and 3050 m. Above 3050 m, redistribution by wind is the decisive factor both regarding snow erosion and accumulation. The results are applied in a regionalization procedure with universal kriging.

DIE RÄUMLICHE VERTEILUNG DER SCHNEEAKKUMULATION AUF DEM VERNAGTFERNER, ÖSTERREICHISCHE ALPEN, IM WINTER 2003/2004

ZUSAMMENFASSUNG

In dieser Arbeit soll eine Auswertung der räumlichen Verteilung der Schneeakkumulation am Vernagtferner (46° 52′ N, 10° 49′ E) vorgestellt werden. Die Messungen von Schneetiefe und Schneedichte erfolgten zum Ende des glaziologischen Winterhalbjahres 2003/2004. Die besonders günstigen Bedingungen für getreue Messwerte der Schneetiefe entstanden aufgrund der hohen Schmelzraten im vorangegangenen Sommer 2003. In Folge dessen war der Vorjahreshorizont, durch seine hohe Dichte, bei der Messung mit Schneesonden auch in den höheren Firnlagen gut zu erkennen.

Das Schneeakkumulationsmuster wird statistisch ausgewertet und in Beziehung zu verschiedenen Einflussfaktoren, wie Topographie und Wind gesetzt. Dabei wird eine Regression mit geomorphometrischen Eigenschaften verwendet, die ein Maß für lokale Exposition zum Wind darstellen. Die vorherrschende Windrichtung für das Winterhalbjahr 2003/2004 wird anhand von Daten zweier meteorologischer Stationen im Einzugsgebiet bestimmt und als gerichteter Parameter angewendet. In den unteren Höhenlagen zwischen 2750 und 3050 m ist die Höhe selbst der wesentliche Einflussfaktor für die Schneeakkumulation. Oberhalb von 3050 m dominiert der Einfluss aus Windverdriftungen, mit Schneeerosion und Schneeablagerung. Die Ergebnisse der Analyse finden in einer Regionalisierung mittels universellem Kriging Anwendung.

INTRODUCTION

Since 1964/65 the Commission for Glaciology at the Bavarian Academy of Sciences has been determining the distributed glacier mass balance of Vernagtferner, resulting in measurements of winter and summer mass balance (Escher-Vetter et al., 2004). The photogrammetric and hydrological method are used complementarily for this purpose (Moser, 1986). The combination of these methods allows cross-checking the results, which is especially important as the measurement of winter precipitation and its interpolation is still problematic in the high alpine region.

Snow accumulation in the field is determined from measurements of snow density and snow depth. The assessment of winter snow accumulation on a glacier by snow depth measurements using sondes often implies inaccuracies resulting from the vague identification of the previous summer horizon.

The summer 2003 with its extremely high ablation rates left a dense surface even in the upper firn basins of Vernagtferner. Thus at the end of the accumulation period in winter 2003/04, snow depth measurements profited from a well-defined base layer. Detailed measurements were taken during a field survey at the end of April 2004 in order to obtain a data base of snow accumulation at Vernagtferner.

In the past 40 years, measurements of specific mass balance used to be distributed over the entire glacier as a polynomic function of elevation (Moser et al., 1986). This method assumes a strong correlation between specific mass balance and elevation but in fact correlation is low in most cases. In the present work, the spatial distribution of detailed measurements of specific mass balance and process-related terrain parameters is computed from a digital elevation model. The analyses are intended to obtain insight into snow redistribution patterns on Vernagtferner, and to optimize sampling and estimation procedures for future work.

STUDY AREA

Vernagtferner is located in the Ötztal Alps in Austria at 46° 52′ N and 10° 49′ E. In 2003 the glacier covered 8.36 km^2, extending from 2780 to 3628 m. The main aspect of the slopes is to the south, but the glacier can be divided into three parts facing different directions (Fig. 1): Schwarzwand area facing northeast to southeast, the Taschach area exposed to southeast to southwest and the Brochkogel area with an aspect ranging from south to west (Reinwarth and Escher-Vetter, 1999). These areas have different altitudinal extent and size. Schwarzwand area and Brochkogel area both comprise about 2 km^2, whereas Taschach area extends over about 4.5 km^2 and has two accumulation areas that merge into one glacier tongue.

The Vernagt basin extends over an area of 11.4 km^2 down to the gauging station at 2635 m a.s.l. Based on the calculation of water balance components of the Vernagt basin, the mean precipitation of 1974–2002/03 was determined to be 1381 mm, with a winter precipitation of 892 mm (Escher-Vetter et al., 2004). All winter precipitation in the catchment is in the form of snow. In terms of mass balance, winter precipitation varies very little between the years compared to summer ablation (Escher-Vetter et al., 2004).

METHODOLOGY

FIELD MEASUREMENTS

The direct glaciological method is applied using a fixed date system. During the field work from 29 April to 2 May 2004, 480 measurements of snow depth serving 165 sample sites were taken at Vernagtferner, covering most of the glacier's slopes (Fig. 1, Table 1). At each site, three snow depth measurements were taken randomly within 10 m of horizontal

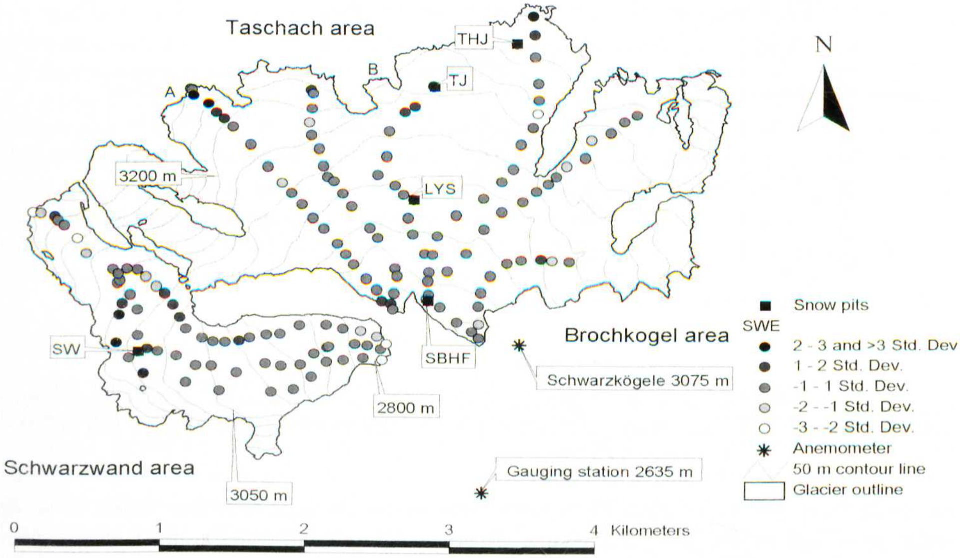

Fig. 1: Vernagtferner (46° 52′ N, 10° 49′): Location of the 5 snow pits and 165 snow depth sample sites during field work from 29 April to 2 May 2004, and location of two anemometers in the catchment. A = Sexegertenjoch, B = Taschachjoch

distance; these triple measurements were averaged. The sample sites are located along nine vertical profiles. The distance between the sample sites varied usually from 50 to 300 m within the same profile. Snow density was measured gravimetrically at five snow pits located between 2940 and 3260 m (Fig. 1). The coordinates of all sample sites were recorded by GPS.

Table 1: Summary of the data used in the regression model based on 480 measurements.

Variable	Mean ± Std. dev.	Range
SWE [mm]	881 ± 164	510–1395
Elevation [m a.s.l.]	3068 ± 138	2791–3399
Slope [°]	6.9 ± 2.3	2.7–14.5
Distance from ridge in NW [m]	989 ± 735	0–2787
Shelter index	0.15 ± 0.10	−0.20–0.42
Curvature	−0.44 ± 3.44	−10–10
Southeast-exposure	0.45 ± 0.41	−1.10–0.85

Field experience of past years shows that the spatial variability of snow depths is greater than that of snow density which corresponds to findings elsewhere (Elder et al., 1989). A comparison of densities measured at five GPS-referenced sites between 2001 and 2004 shows that there is no clear altitudinal trend, while inter-annual variation amounts to 5–10 % of average snow densities (Fig. 2). Due to the lack of a distinctive altitudinal pattern,

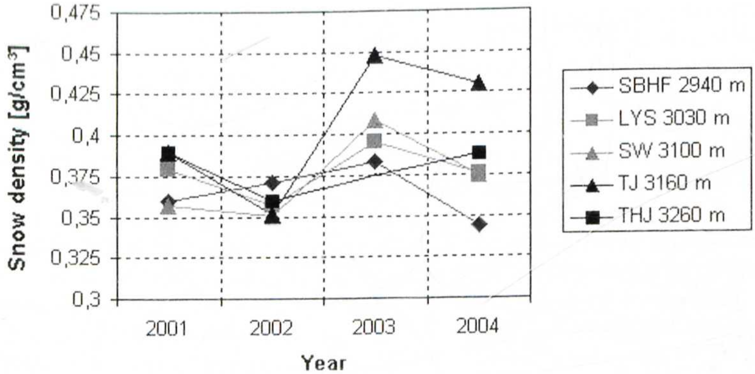

Fig. 2: Snow density at the snow pits measured at the end of the accumulation period in the years 2001–2004. Location of the pits can be seen in Figure 1. Note: No measurement was taken at pit THJ in 2003.

the mean snow density of 2004 (0.38 g/cm^3) was uniformly used to derive values of snow water equivalent for the 165 sample sites. Thus snow depth and water equivalent are taken to be directly proportional.

Since snow redistribution by wind plays a major role for the spatial pattern of specific mass balance (Kuhn, 2003), wind direction and speed were analyzed from data of two stations in the glacier's catchment, 1 October 2003 to 30 April 2004, on an hourly basis, using Thiess anemometers. One of these stations is located at a gauging station below the glacier at 2635 m a.s.l., the other one at 3075 m a.s.l. at Schwarzkögele, located on the eastern side of Vernagtferner (Fig. 1). Average and maximum wind speeds were calculated for 12 classes of wind direction, and directional wind frequencies were summarized for these classes at both stations. A detailed account of field work and analysis is given by Plattner (2004).

TERRAIN PARAMETERS

For the analysis of the statistical relation between snow distribution, topography and main wind direction, morphometric terrain parameters were derived from a digital elevation model (DEM) using the software ArcView 3.2, its extension DEMAT, the terrain analysis software SAGA. Version 1.1 (http://www.saga-gis.uni-goettingen.de), and own code for computing wind sheltering indices written in the data analysis environment R (R Development Core Team 2004). The digital elevation model with a resolution of 10 m was obtained from stereoscopic analysis of aerial photographs taken in summer 2003 within the OMEGA project (Development of Operational Monitoring System for European Glacial Areas).

In addition to the locally defined terrain parameters elevation, aspect, slope and curvature, process-related morphometric site characteristics were used. These include the horizontal distance from the ridge in windward direction (northwest), a measure of topographic wind sheltering as defined below, and potential incoming solar radiation for the months of June and December. In the case of the aspect variable, cosine transforms *cos(aspect – offset)* were used in order to obtain an interval-scaled variable from a spherical one.

Similar to a definition by Winstral et al. (2002), we use the maximum gradient within a given radius in upwind direction as a measure of topographic wind sheltering:

Shelter index $(S) = \arctan(\max\{(z(\boldsymbol{x}_0) - z(\boldsymbol{x})) / |\boldsymbol{x}_0 - \boldsymbol{x}| : \boldsymbol{x} \in S\})$

where $S = S(\boldsymbol{x}_0, a, \Delta a, d)$ is the set of grid nodes within a distance $\leq d$ in the range of directions $a \pm \Delta a$ from $\boldsymbol{x}_0$. In contrast to the original definition of Winstral et al. (2002), whose shelter index is an average of the present one for $\Delta a'$ near 0 and a' varying between our $a - \Delta a$ and $a + \Delta a$, the present definition does not depend on a specific choice of $\Delta a'$ in the implementation. Optimal azimuth and tolerance parameters were estimated by numerically minimizing the residual standard error in the presence of the other relevant model parameters.

GEOSTATISTICAL ANALYSIS

The statistical relation between snow water equivalent and terrain parameters was analyzed using a generalized-least-squares linear regression model in conjunction with an exponential model of spatial autocorrelation. The generalized least-squares approach was chosen since ordinary least-squares models are not able to account for the autocorrelation structure that is inherent to spatial data. Ordinary regression would therefore yield biased variance estimates and invalid p-values in the presence of autocorrelation. Model variables were selected manually based on the reduction of residual standard error and a significance level of 0.05 for variables to be included.

The prediction method corresponding to generalized-least-squares regression is called universal kriging, which is performed with the R package *spatial*. The kriging result was compared to the sum of the standard interpolation of snow water equivalent as a polynomial function of elevation, as used by the Commission for Glaciology (Moser et al., 1986).

A variant of universal kriging was earlier applied to spatial snowpack prediction by Erickson et al. (2005) in the Rocky Mountains of Colorado. An alternative method, namely an additive model was used by López-Moreno (2005) in a regional-scale model for snow depth in the Spanish Pyrenees. This model class adds non-linear flexibility to regression, while running the risk of over-fitting the data (Venables and Ripley, 2002). This especially applies to rather small datasets in complex terrain as the one studied in the present work, and in the presence of spatial autocorrelation, which cannot be represented by the currently available software for additive models (Hastie and Tibshirani, 1990; Wood, 2001). Similar observations can be made for tree-based methods (Breiman, 1984; Balk and Elder, 2000; Erickson et al. 2005), which in addition are not continuous functions of the explanatory variables and therefore yield non-smooth prediction maps.

The spatial variability and dependence structure of snow water equivalent was analyzed using empirical correlograms of the model residuals. Correlograms represent the change (usually decrease) of correlation between pairs of measurements as the distance between the points increases (Cressie, 1993; Goovaerts 1997). Directional and omnidirectional correlograms were used to check for anisotropies. The correlation structure of the regression model was initially estimated from preliminary ordinary regression residuals, and later adjusted to the residuals of the selected model in order to fit a valid final model.

Statistical analyses were performed within the open-source data analysis environment R using its *spatial* and *nlme* packages (Venables and Ripley, 2002; Pinheiro et al. 2004).

RESULTS

WIND DISTRIBUTION

At the gauging station, the main wind direction during winter is from northwest to southeast, with a slightly minor frequency in the opposite direction (Fig. 3). Since the station is located below the glacier, an influence of catabatic winds passing through the former glacier bed can be expected. The general atmospheric circulation coincides with the northwest direction of the winds at this station and therefore plays an additional role (Fig. 3). Valley wind in the opposite direction is less frequent, but reaches similar wind speeds.

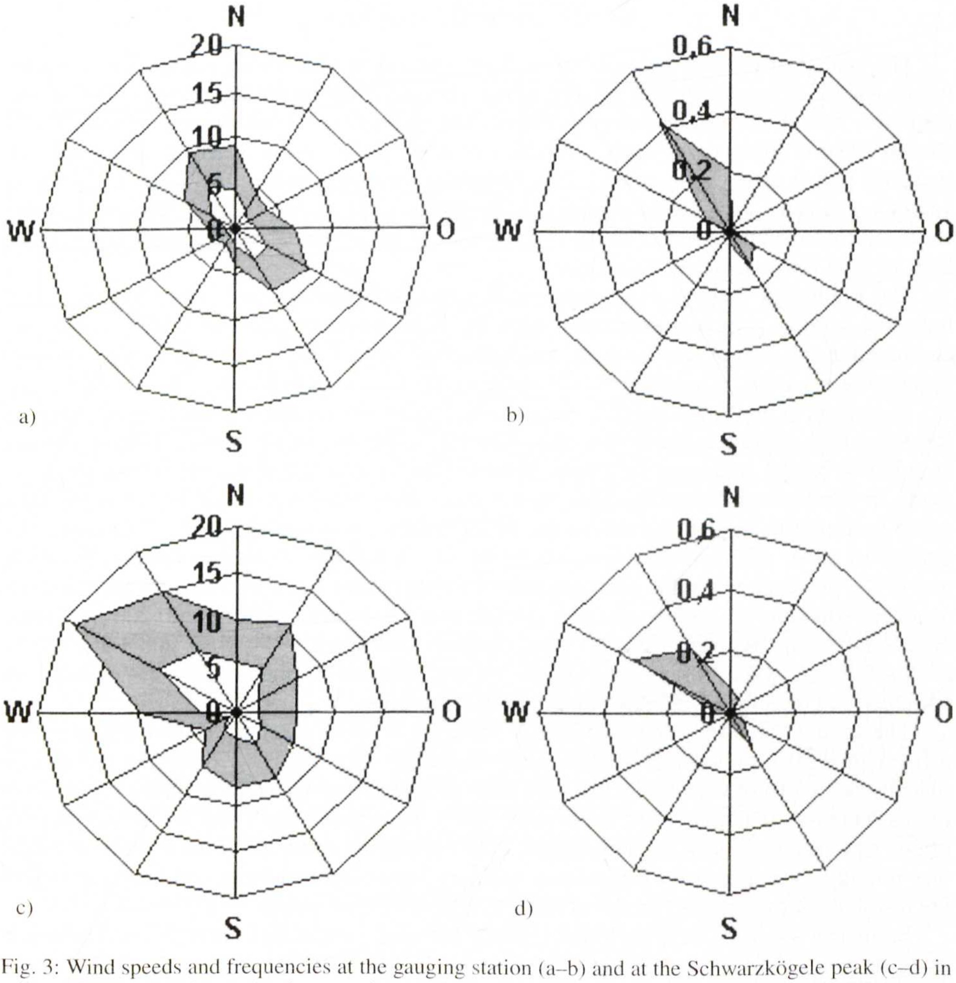

Fig. 3: Wind speeds and frequencies at the gauging station (a–b) and at the Schwarzkögele peak (c–d) in winter 2003/04. Panels a and c show maximum (dark gray) and averaged (white) wind speeds [km/h] in 12 wind directions. Panels c and d display the frequency distribution of wind direction for wind speed > 10 km/h. The location of the measurement sites is shown in Fig. 1.

Because of its high elevation and exposure the wind system found at Schwarzkögele reflects the air flow near mountain ridges. Average and maximum wind speeds at Schwarzkögele are greatest for wind coming from the northwest sector, which contrasts with the more balanced speeds at the gauging station (Fig. 3).

In summary, northwesterly wind is dominant in the upper area of Vernagtferner, whereas at lower elevations catabatic and valley wind become more important. Ridges running in southwest-northeast direction may cause differences between windward and leeward sides.

REGRESSION ANALYSIS

The exploratory analysis of the relation between snow water equivalent and elevation shows a nonlinear behavior, with increasing SWE up to 3050 m a.s.l. and a reverse trend above this elevation, if effects of other covariables are considered (Fig. 4). In order to represent this relation in the regression model, elevation was centered at 3050 m, and an indicator variable for elevation being greater than 3050 m was introduced to model the different slopes using an interaction term.

The altitudinal trend in the three parts of Vernagtferner may be further differentiated. While there is only a weak trend in the Brochkogel area, in the opposite Schwarzwand area snow water equivalent appears to decrease above 3150 m, but these data are strongly scattered. In the central part of Vernagtferner, the Taschach area, in contrast, snow water equivalent is less scattered and strongly increases in the upper parts of the profiles. This phenomenon can best be seen and modeled in relation to the distance to the ridge that extends in windward direction above the Taschach area (Fig. 4).

Apart from these general trends within the study area, local-scale topographic effects in terms of curvature and wind-drift related parameters were analyzed. The curvature variable was transformed since its distribution presented large tails on both sides, and since the relation to snow water equivalent is not linear. The latter reflects the assumption that for almost straight (near-zero) curvature, small differences will have a great influence on snow water equivalent, while in strongly convex or strongly concave areas, the same difference in curvature will have little effect on snow water equivalent . The proposed transformation first cuts down the computed curvature to the interval from -10 to $+10$ to eliminate artifacts, and then takes a cubic root while preserving the sign.

The residual standard errors of a regression model using the wind shelter index in combination with the other significant variables display two areas of local optimality in the index' two-dimensional parameter space (Fig. 5). Wind direction was taken to be northwest, and maximum distance and directional tolerance were allowed to range between 30 and 600 m and between 5° and 45°, respectively.

The global optimum is obtained for a distance parameter of 60 m and a tolerance of 15°, corresponding to rather local effects. A secondary local optimum is achieved for a distance parameter of 250 m and a tolerance of 10°, corresponding to wind transport over greater distances.

Multiple regression analysis showed that an interaction of transformed curvature with elevation is present. Specifically, the higher the elevation, the greater is the effect of curvature on snow water equivalent, while at low elevations, there is almost no effect. The combined effect of curvature and its interaction with elevation is displayed in Figure 4b.

As a consequence of the overall topography, measurement distribution is unbalanced with respect to slope orientation. Exploratory analysis suggests that SWE is higher in south-

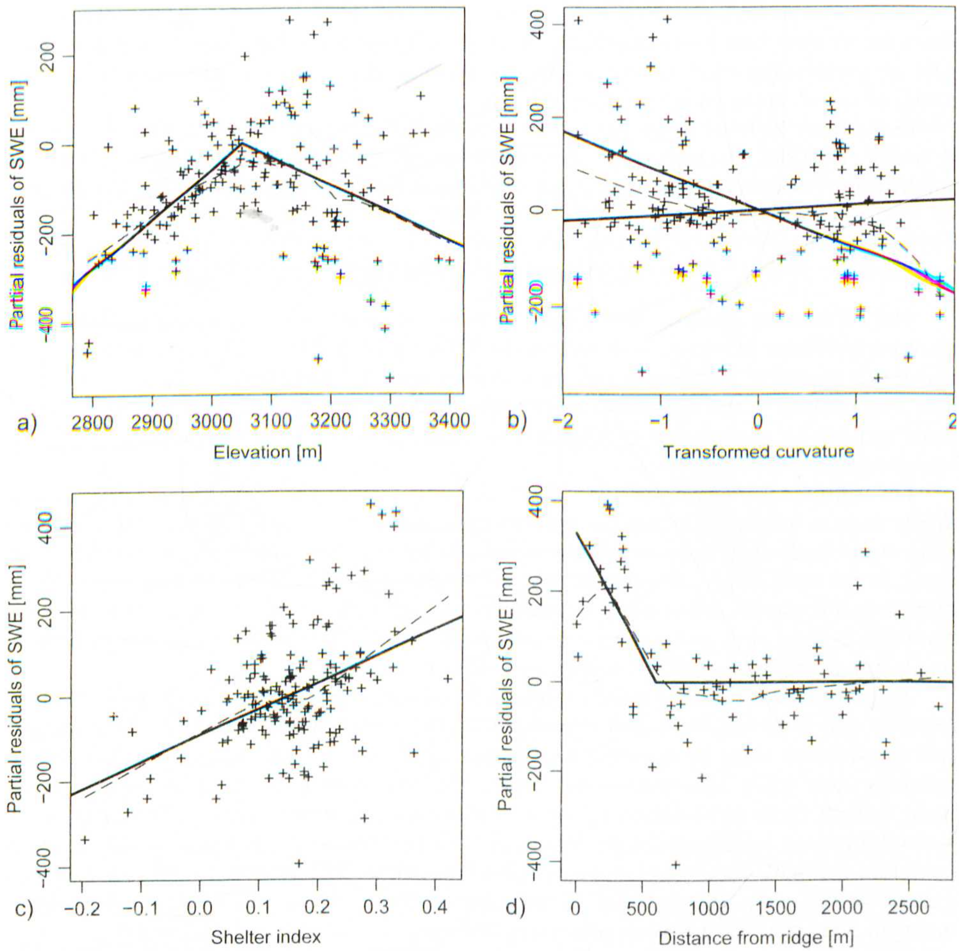

Fig. 4: Scatter plots of partial SWE residuals versus explanatory model variables. The dashed lines represent univariate non-parametric smoothers, the solid lines are sections of the linear regression prediction surface. In panel b, representing curvature and its interaction with elevation, the descending line represents high-elevation areas, and the slightly ascending one low elevations. Partial residuals corresponding to selected explanatory variables refer to the part of SWE that is not explained by a model in which the corresponding coefficients are set to zero. Panel d displays only data from the Taschach area.

erly and easterly-exposed areas than in the opposite directions. A minimization of residual error with respect to cosine transformations *cos(aspect – offset)* with varying offset directions as mentioned above showed that the best fit is reached for the measure of 'southeast-exposure', *cos(aspect-135)*.

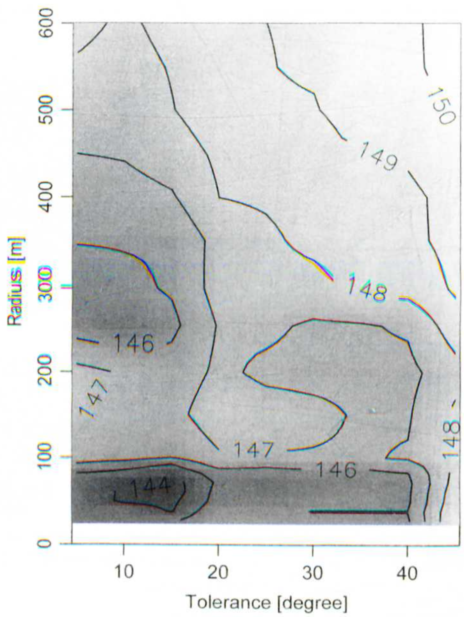

Fig. 5: Residual standard errors of the model for the parameter space of the maximum distance and directional tolerance parameters of the wind shelter index. Wind direction was taken to be northwest. The parameter space is discretized in 5° steps in the tolerance dimension and in 10 m (up to 100 m distance) and 50 m steps (> 100 m distance) in the case of the distance parameter.

SPATIAL VARIABILITY OF THE SNOW COVER

The omnidirectional residual correlogram (Fig. 6) shows an exponential decrease of spatial autocorrelation with distance. Autocorrelation approaches zero at a distance of ~ 250 m, the effective range of autocorrelation of the residual random field.

The directional empirical correlograms display a heterogeneous and irregular pattern of spatial variability. In particular, there are no clear signs of a geometric anisotropy in the main wind direction. Preference was therefore given to an isotropic correlogram.

REGRESSION MODEL

The regression model was selected by manually combining the mentioned transformed and untransformed variables as well as meaningful interactions between pairs of variables. The final model contains elevation, the (short-distance) wind shelter index, transformed curvature and their interaction, the interaction of elevation with the elevation threshold of 3050 m, and a variable representing the distance to the ridge in the Taschach area. The parameter estimates of the final generalized least-squares regression are displayed in Table 2. An exemplary representation of the regression surface is shown in Figure 5.

While the optimal (short-distance) shelter index resulted in a significant contribution to the model fit, longer-distance versions did not add significant information in presence of the

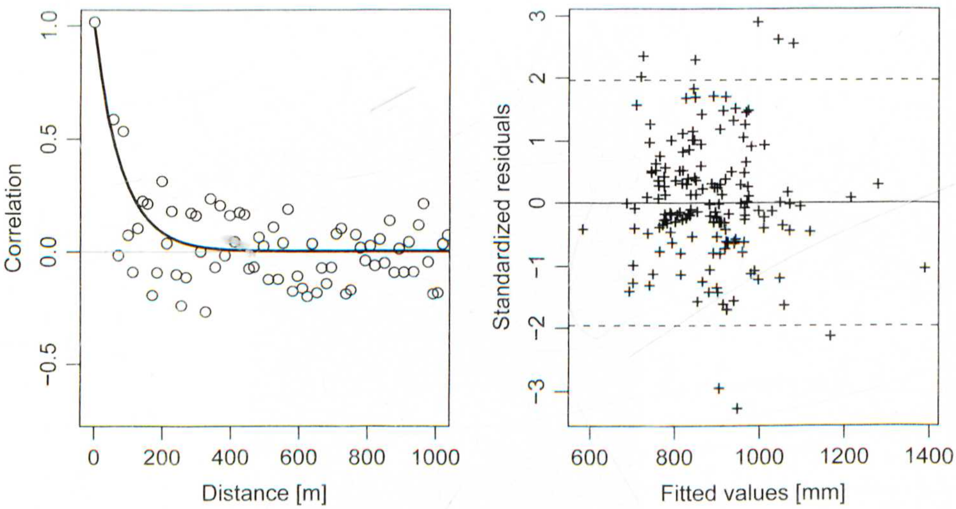

Fig. 6: Left: Omnidirectional empirical correlogram of linear regression residuals and the fitted isotropic exponential correlogram model. The effective range of autocorrelation is of 250 m. Right: Plot of standardized model residuals.

former. The 'southeast-exposure' parameter and local slope inclination are not significant variables and were therefore dropped.

Table 2: Estimated model parameters of the linear regression using generalized least squares and an exponential correlogram. The elevation was centered by resting 3050 m.

Variable	Coefficient	P value
Intercept	859	0.000
Elevation	−0.627	0.008
Transformed curvature	−27.0	0.024
Transformed distance	0.555	0.000
Shelter index	621	0.000
Elevation * Transf. Curvature	−0.191	0.007
Elevation * (Elevation > 3050 m)	1.75	0.000
Effective range of autocorrelation [m]	250	–
Winder shelter range parameter [m]	60	–

LOCAL DISTRIBUTION

Universal kriging was performed based on the regression model and autocorrelation structure as fitted and described above, yielding a prediction map of snow water equivalent on Vernagtferner (Fig. 7). The predicted mean is 923 mm snow water equivalent and therefore 3.4 % higher than the 891 mm snow water equivalent derived by the interpolation of snow water equivalent as a polynomial function of elevation. The estimated total amount of winter precipitation on Vernagtferner is $7.80 \cdot 10^9$ m^3 in the case of universal kriging, and $7.54 \cdot 10^9$ m^3 for the method introduced by the Commission for Glaciology (Moser et al.,

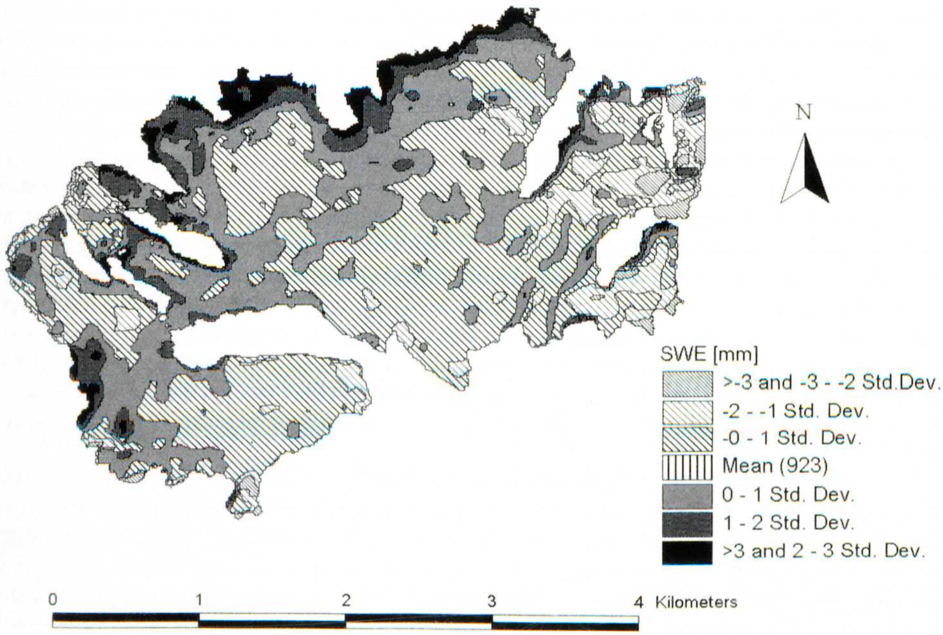

Fig. 7: Snow water equivalent (SWE) [mm] at Vernagtferner (46° 52′ N, 10° 49′) derived from universal kriging.

1986). Note that for both methods the grid extent is greater than the polygon area of Vernagtferner.

DISCUSSION

The observed relationship between snow water equivalent and elevation, with a plateau in snow water equivalent at higher elevations, is in accordance with findings of earlier investigations on this glacier (Moser et al., 1986) and on nearby Hintereisferner (Kuhn et al., 1999). This indicates a greater influence of wind redistribution at and especially deflation from these altitudes. A zone of maximum winter precipitation is not to be expected at these altitudes (Richter, 1996).

Since the effect of curvature on snow depth is essentially related to wind redistribution from convex to concave areas, the parameter estimates of curvature itself and of its interaction with elevation suggest that wind redistribution has little effect at low and great effect at high elevation. In the upper parts of Vernagtferner, the snow water equivalent at concave sites is on average ~ 200 mm higher than in strongly convex areas at the same altitude. This corresponds to ~ 50 cm of difference in snow depth.

In the Taschach area, the predominant southeastward winds transport snow from the neighbouring Gepatschferner situated northwest of the ridge to the leeside into the upper part of this glacier. This redistribution contributes to the snow accumulation at distances of up to 600 m from the ridge. It is favoured by a rather low and open geometry of the divide, running perpendicular to the main wind direction. The mountain ridge rises about 50–100 m above the glacier, with the Sexegertenjoch and the Taschachjoch as passes in the Taschach area. Braun (1985) found highest snow accumulation on south-facing slopes leeward of mountain crests. The leeward deposited snow starts to melt at the surface and forms a crust when it freezes again. Therefore the snow is not likely to be removed by wind, even if the wind direction changes.

In the Schwarzwand and Brochkogel areas, in contrast, more complex wind flow is expected, as both the mountain ridge and the glacier slopes follow downwind directions that differ from the observed main wind direction. Thus no relation of SWE with distance to ridge in northwest-southest direction can be found there. Regions with great snow accumulation eastwards of the mountain ridge in the Schwarzwand area at an elevation of about 3100 m suggest a greater influence of westerly winds there. At higher altitudes, areas with low net snow accumulation were detected. This contradicts the simplified division into leeward southeast-facing and windward northwest-facing slopes as applied in the Taschach area. Physical models of air flow may help explain the pattern of acceleration and deceleration in these areas and the corresponding deposition patterns (Bernhardt et al., 2005).

The estimated range of autocorrelation of the SWE residuals of ~250 m suggests that snow redistribution on the glacier's surface is generally restricted to this distance. The local optima of the distance parameter of the wind shelter index at 60 and 250 m, which reflect the maximum length of areas of snow deposition, are compatible with this interpretation. The ridge distance of up to 600 m at which leeward snow accumulation takes place in the upper part of Vernagtferner, indicates that redistribution in exposed areas by strong winds may exceed the above-mentioned distances. This correlates well with results from Liston and Sturm (1998) who found that 95 % of the transported snow is deposited within 500 m of distance.

Using a denser sampling design in almost glacier-free terrain, Erickson et al. (2005) found much smaller (effective) ranges of autocorrelation annually varying between 30 and 200 m. The range parameter of the Vernagtferner at the upper end of this interval data may be due to the smoother local topography of the glacier.

A nugget effect could not be safely determined from the data due to the rather great average distances between neighbouring sampling points. Since snowfall and snow redistribution processes are continuous in space, a nugget effect should be absent if measurement error is negligible. This was assumed in the present analysis. However, due to the small range, residual variability at distances below the DEM resolution of 10 m is considerable and is an equivalent of a nugget effect at the given scale.

Regarding the overall model fit, though R^2 is not an appropriate measure of the fit in the case of correlated data, it shall be used for illustration. In an ordinary regression model with the same variables as mentioned above, an R^2 of 0.414 is achieved. This portion of explained variance reflects the great variability of snow distribution and the complex relation with environmental variables, especially the spatio-temporal wind pattern.

Slope does not play a decisive role for snow accumulation at Vernagtferner due to its small variability in the study area and in the dataset used (Table 1). Slope inclination rarely exceeds 40°. Avalanches are therefore not an important factor for snow redistribution in the study area (Witmer, 1984).

Universal kriging predicts a complex pattern of snow distribution on Vernagtferner. If only its integral, i.e. the winter mass balance, is considered, the difference to an estimate obtained using polynomial functions of elevation without process parameterization is small.

The reason for this lies in the local oscillations of curvature and shelter index, which cancel out if integrated over the entire glacier, but represent important local effects in the regression model.

If the observed snow distribution pattern and model structure are representative for other years, the present analyses allow for an optimization of the sampling design for future field measurements. In order to obtain independent measurements of snow depth, a minimum distance of > 250 m between sampling sites would be desirable. More detailed studies in the upper parts of the basin may furthermore be beneficial in order to better differentiate patterns of wind deposition in these areas with a strong contribution to snow water equivalent. Additional measurements of snow density will also improve the estimation of winter mass balance, as shown by Matzi (2004) for Hintereisferner.

CONCLUSIONS

The statistical analysis of snow water equivalent revealed topographic parameters having a significant effect for snow distribution on Vernagtferner in winter 2003/2004. These parameters are related to the distribution of snowfall and its redistribution by wind. The analytical results help improve future field surveys, and provide a distribution model that represents the present process knowledge.

For future research it is recommended that the snow accumulation data of previous years is compared with the regionalized snow accumulation pattern of 2004 in order to detect spatio-temporal variations of snow distribution. Based on these comparisons, the distribution model may be calibrated for the estimation of winter mass balances of other years.

The estimation of the winter mass balance, however, does not yet consider the spatial variability of snow density. In order to derive a spatial distribution pattern of snow density, investigations on the spatial variability in the test site could be conducted by use of the snow micro-penetrometer (Kronholm, 2004). Thus further field research will be necessary to expand the knowledge about the distribution of both snow depth and snow density. As redistribution of snow plays a major role at Vernagtferner, further measurements of wind regime or the reconstruction of air circulation would be beneficial in order to model redistribution of snow in the catchment (Bernhardt et al., 2005).

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