17 The Use of Terrain Analysis in the Evaluation of Snow Cover Over an Alpine Glacier

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ABSTRACT

The terrain parameters of elevation, slope angle, aspect, profile curvature and planform curvature were calculated from a digital elevation model of Haut Glacier d’Arolla, Switzerland. Principal components and cluster analysis were used to divide the glacier into similar zones based on these terrain parameters. Snow water equivalent (SWE) measurements made at two-week intervals during the summer melt season indicate that elevation is the primary control on variations in SWE. Regression of SWE with elevation provides the best estimates of SWE, although terrain zonation also produces an effective partitioning of the glacier into areas of similar SWE. Improved evaluation of snowpack conditions may therefore be possible by combining terrain zonation with elevation-based regression predictions. Determination of terrain curvature may also help in accounting for the redistribution of snow by processes such as wind drift and avalanching. This should improve the areal extrapolation of point measurements of SWE, and stratification of terrain before sampling should increase the accuracy and decrease the labour requirements of snow surveys.

INTRODUCTION

Increased demand for water in mountain regions due to population growth, coupled with resource development, has made accurate assessment of snow cover distributions essential for resource managers. Most runoff in alpine areas is from the seasonal snowpack (Elder et al., 1991), and more water may be produced per unit area than in non-alpine regions (Alford, 1980). Knowledge of snow cover distribution is also required for glacier energy and mass balance models (Arnold et al., 1996; Willis et al., Chapter 15). In addition, there is a need to improve the calibration and testing of snowmelt models as the use of runoff data alone provides little information about the spatial distribution of melt (Blöschl et al., 1991).

To meet the need for snow cover data, traditional methods of evaluation have been based on areal extrapolation of the product of point measures of snow depth.
and density to provide estimates of snow water equivalence (SWE). An important question is the optimum number of measurements needed to effectively characterise the SWE of a snowpack. Given the wide range of factors (e.g. elevation, slope angle, aspect, curvature, energy availability) that interact to determine the final snow cover distribution, linear extrapolation of point values is not always effective. These distribution factors are exaggerated in high relief basins because of the rapidly varying topography, resulting in a heterogeneous snowpack that changes markedly over space and time (Elder et al., 1991).

Past work has provided a relatively good understanding of snowpack variation within regions of mild relief (e.g. Steppuhn and Dyck, 1974; Adams, 1976; Rawls et al., 1980). Direct extrapolation of snowpack distribution relationships from low relief areas to high relief alpine regions is problematic, however, owing to the complexity of the terrain. Rychetnik (1987) related the date of disappearance of snow cover to snow depths, elevations, slope angles and aspects. Elder et al. (1989, 1991) classified snow distribution as a function of solar radiation, slope angle and elevation. Blöschl and Kirnbauer (1992) used aerial photographs to detect snow presence, but ignored SWE and only considered elevation and slope angle. A major limitation in these and other studies has been the effective determination of snow redistribution by processes such as wind drift and avalanching. Redistribution does not change the total SWE in a watershed, but can be hydrologically important because it causes rapid variations in SWE over short distances. For example, Woo et al. (1983) found SWE to vary from 30% on hilltops to 300% in gullies as compared to flat areas in the Canadian Arctic, and Golding (1974) reported mean water equivalents of 70% on ridge tops and 170% at valley bottoms for an Alaskan basin.

The aim of the study reported here was to investigate the relationship between snow cover and terrain in an alpine area. Cluster analysis was used to determine whether terrain-based stratification of a glacier can improve estimation of the snow cover distribution. This involved dividing the study area into similar terrain zones based on elevation, slope angle, aspect, profile (downslope) curvature and planform (across-slope) curvature. Field measurements of SWE were used to indicate whether this zoning provided an effective partitioning of the snow cover over the study area. SWE predictions based on terrain zonation of the study area were also compared with SWE predictions based on regression of elevation with SWE.

**STUDY SITE**

Haut Glacier d’Arolla is a temperate valley glacier located in Valais, Switzerland, at 45°58’N, 7°32’E (Figure 17.1). The glacier covers an area of 6.3 km², within a basin of 11.7 km². The glacier is located above the tree line, and vegetation is virtually non-existent in the surrounding area. The glacier ranges in elevation from 2550 to almost 3500 m, with a mean of 2952 m, while the entire basin ranges from 2460 to 3838 m. The glacier has a mean surface slope angle of 15.8°, faces predominantly north, and is surrounded by steep cliffs.
Figure 17.1 Map of Haut Glacier d’Arolla, Switzerland. Black dots show the location of the main sample point network. A, B, C and D are the locations of the snow density pits

METHODOLOGY

Terrain Analysis

Before field sampling, a DEM of Haut Glacier d’Arolla with a nodal spacing of 20 m was constructed from a combination of field survey and data capture from published maps (Figure 17.2). Using equations given in Zevenbergen and Thorne (1987), a
computer program was written to calculate the terrain parameters of slope angle, aspect, profile curvature, and planform curvature at each node from a regular $3 \times 3$ sub-matrix as it passed over the digital elevation model (DEM). To make the results more easily interpretable in statistical calculations, a modification was made to the aspect data. This is because two slopes with aspects of $3^\circ$ and $357^\circ$ are physically very similar, yet mathematically near the extremes of a continuum from $0$ to $360^\circ$. To resolve this problem, a north–south scalar determined by the cosine of the aspect, and an east–west scalar determined by the sine of the aspect, were used. For the north–south scalar, $0^\circ$ is represented by a value of $1$, and $180^\circ$ is represented by $-1$; for the east–west scalar, $90^\circ$ is represented by $1$, and $270^\circ$ is represented by $-1$.

It was anticipated that terrain parameters would control the snow cover distribution because: (i) elevation relates to increases in precipitation with altitude, and processes controlled by air temperature such as the transition from rain to snow; (ii) slope angle relates to variations in snow depth induced by wind drift and
avalanching, as well as differences in direct beam and diffuse radiation; (iii) aspect relates to variations in snow cover caused by variations in solar radiation and prevailing wind direction, and also defines the slope direction and hence the direction of flow; and (iv) curvature relates to snow redistribution. This is due to the relatively low SWE in convex areas where flow (e.g. from wind or avalanching) accelerates and diverges, and the relatively high SWE in concave areas where flow decelerates and converges. Concave areas are also shadowed for longer than convex areas.

In data analysis, a routine was included to remove the problem of erroneous results at the edge of the study site, by ignoring a point if it, or any of the surrounding eight points, had a missing value. This resulted in the loss of a 20 m wide strip of values around the edge of the study area, although this was not significant because field sampling was undertaken away from the glacier margin. Side slopes were not included because this study was only concerned with the distribution of snow over the glacier. The position in map coordinates of each node was also calculated to allow location of points in the field. The final computer program produced a data set with the coordinates, elevation, slope angle, north–south scalar aspect, east–west scalar aspect, profile curvature and planform curvature evaluated at every 20 m interval over the surface of Haut Glacier d’Arolla (Figures 17.3 to 17.7).

**Terrain Clustering**

Correlation of the terrain parameters showed collinearity between some factors. For example, elevation was positively correlated with slope angle because higher parts of the glacier tend to have steeper slopes. In order to remove such statistical problems, principal components analysis (PCA) was performed on the terrain values. PCA involves rewriting a data set such that the new variables are weighted representations of the original values and uncorrelated with one another (Johnston, 1980). The correlation matrix was used for the PCA process so that the component scores were calculated from standardised variables. The correlation between each variable and component (the loadings matrix) is given in Table 17.1. A component was deemed significant if the eigenvalue was greater than 1, because this represents the variance of the original variables. The first three components are significant in Table 17.1, accounting for 66.54% of the total variance. Table 17.2 shows that the significant components represent the original data set quite well, except for east–west scalar aspect. This is likely to be of minimal significance, however, as the greatest contrast in radiation receipts is between north- and south-facing slopes. In general, component 1 is an elevation/slope angle factor, component 2 is a curvature factor, and component 3 is a north–south scalar aspect factor.

The three significant, standardised components identified by PCA were then clustered using nearest centroid sorting. In this sorting routine a site is assigned to the cluster for which the value between the site and the cluster centre is smallest. Cluster analysis involves the placing of objects into more or less homogeneous groups, although formal tests of significance do not yet exist (Norusis, 1990).
Zoning with six to 16 clusters was completed, with semi-qualitative assessment indicating which zonation best represented the division of the glacier. This assessment involved visual analysis of maps of the clusters, and of the distribution of points between zones. In general, a few zones tended to contain a high proportion of the data, while many zones contained a few points. Clustering with 10 zones was chosen as this provided a reasonably even spread of points between zones, and also divided the terrain into regions that match quite well with personal knowledge of the glacier (Table 17.3; Figure 17.8). When Tables 17.2 and 17.3 are viewed together it is apparent which terrain features were important in defining the different zones. For example, zone 1 was generally defined by just below average slope angles and elevations (component $1 = 0.482$), minimal curvature (component $2 = 0.028$), and was predominantly north-facing (component $3 = 0.626$). Zone 6 was defined by slightly lower slope angles and elevations (component $1 = 0.122$), greater curvature (component $2 = 0.224$), and was more south-facing (component $3 = -0.753$).
Field Methods

Following terrain analysis, an intensive field programme was completed at Haut Glacier d’Arolla between 19 June and 2 August 1993. SWE was recorded every two weeks at a network of 87 points (marked with wooden poles) over the glacier surface. As one of the aims was to test the validity of terrain clustering, measurement sites were not selected on the basis of the cluster zones. Classifying the sample network before data collection would have implied pre-existing knowledge of the snow distribution and may have biased the results. Figure 17.1 shows that the sample points were grouped into three zones due to the logistical need to complete the first two surveys over three days. Some melting probably occurred during survey periods, although the time taken to complete each survey was relatively short in comparison to the time between surveys.
Snow depth was recorded with a 3 m long metal avalanche probe. To minimise local irregularities, the depth at each sample point represented the mean of measurements at the central point and 2 m away to the north and south. The initial survey used the mean of five measurements at each location, but was unnecessarily time-consuming with little increase in accuracy. Sample locations were determined by electronic theodolite, and converted to map coordinates to enable direct correlation of the SWE measurements with the computed terrain parameters and zones identified by cluster analysis.

Snow density was recorded at four pits identified as A, B, C and D (Figure 17.1). It was assumed that pit A represented the glacier snout, pit B the lower glacier, pit C the glacier centre, and pit D the upper glacier. At each 20 cm increment in the vertical pit wall, 1000 cm³ of snow was removed by a stainless steel cutter and weighed with a hand-held spring balance. Density was recorded at only a few
locations as density measurements are time-consuming and snow depth varies far more than density in alpine areas (Logan, 1973).

In addition to the glacier-wide surveys, a rapid snow depth survey was completed at 101 locations on 14 July 1993 after a major new snowfall. The rapid survey sample points were located in nine transects across the glacier between approximately 2700 m and 2850 m elevation. The rapid snow depth survey allowed analysis of the relation between terrain and snow cover on the small scale after a single accumulation event. Density measurements could not be made during this survey owing to time and safety constraints.

**RESULTS**

The computed terrain parameters matched well with field observations of terrain, indicating that the equations described by Zevenbergen and Thorne (1987) provide
an effective way of calculating slope angle, aspect and curvature from a DEM. Parametric tests were performed to relate the point SWE values to the terrain parameters. Steppuhn and Dyck (1974) noted that the distributions of snow cover data are often non-symmetric, although this was not deemed a problem as the means tend towards a normal distribution when there are a large number of samples (Goodison et al., 1981). The problem of a high number of zero SWE values skewing the data in later surveys was overcome by removing from analysis any locations at which bare ice was present in the previous survey. The information provided by the SWE initially falling to zero was therefore included, but the lack of change after this was excluded. Pearson’s correlation coefficient was used to determine the relation between the point SWE values and terrain parameters for each survey (Table 17.4). An optimising stepwise regression method was then used for the multiple situation to remove problems associated with collinearity (Johnston,
Table 17.1 Loadings matrix from principal components analysis on the terrain parameters. The percentage of the total variance explained by each component, and the eigenvalue of each component, are also provided

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>-0.741</td>
<td>-0.081</td>
<td>-0.385</td>
<td>0.340</td>
<td>0.163</td>
<td>-0.392</td>
</tr>
<tr>
<td>Slope angle</td>
<td>-0.805</td>
<td>-0.341</td>
<td>0.021</td>
<td>0.146</td>
<td>-0.037</td>
<td>0.462</td>
</tr>
<tr>
<td>N–S scalar aspect</td>
<td>-0.027</td>
<td>-0.214</td>
<td>0.878</td>
<td>0.393</td>
<td>0.094</td>
<td>-0.137</td>
</tr>
<tr>
<td>E–W scalar aspect</td>
<td>-0.448</td>
<td>-0.343</td>
<td>0.255</td>
<td>-0.765</td>
<td>0.012</td>
<td>-0.176</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>-0.283</td>
<td>0.751</td>
<td>0.167</td>
<td>-0.138</td>
<td>0.545</td>
<td>0.105</td>
</tr>
<tr>
<td>Planform curvature</td>
<td>0.430</td>
<td>-0.654</td>
<td>-0.193</td>
<td>-0.004</td>
<td>0.589</td>
<td>0.066</td>
</tr>
<tr>
<td>Explained variance (%)</td>
<td>27.74</td>
<td>21.30</td>
<td>17.50</td>
<td>14.93</td>
<td>11.34</td>
<td>7.20</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>1.664</td>
<td>1.278</td>
<td>1.050</td>
<td>0.896</td>
<td>0.680</td>
<td>0.432</td>
</tr>
</tbody>
</table>

Table 17.2 Explained variance (%) and communality values (%) for significant components in principal components analysis (+/- indicates whether relation between terrain parameter and component is positive or negative)

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Communality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>-54.97</td>
<td>-0.66</td>
<td>-14.80</td>
<td>70.43</td>
</tr>
<tr>
<td>Slope angle</td>
<td>-64.75</td>
<td>-11.62</td>
<td>+0.05</td>
<td>76.42</td>
</tr>
<tr>
<td>N–S scalar aspect</td>
<td>-0.07</td>
<td>-4.57</td>
<td>+77.16</td>
<td>81.80</td>
</tr>
<tr>
<td>E–W scalar aspect</td>
<td>-20.11</td>
<td>-11.76</td>
<td>+6.49</td>
<td>38.36</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>-8.03</td>
<td>+56.47</td>
<td>+2.78</td>
<td>67.28</td>
</tr>
<tr>
<td>Planform curvature</td>
<td>+18.47</td>
<td>-42.74</td>
<td>-3.71</td>
<td>64.92</td>
</tr>
</tbody>
</table>

Table 17.3 Cluster centres and data distribution within zones for 10 clusters. The centre of each zone is defined by its scores on the three components

<table>
<thead>
<tr>
<th>Zone</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
<th>No. cases</th>
<th>Overall %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.482</td>
<td>0.028</td>
<td>0.626</td>
<td>5830</td>
<td>49.61</td>
</tr>
<tr>
<td>2</td>
<td>-0.124</td>
<td>-0.676</td>
<td>-1.347</td>
<td>36</td>
<td>0.31</td>
</tr>
<tr>
<td>3</td>
<td>0.252</td>
<td>0.717</td>
<td>-2.381</td>
<td>780</td>
<td>6.64</td>
</tr>
<tr>
<td>4</td>
<td>-1.623</td>
<td>0.107</td>
<td>0.267</td>
<td>1204</td>
<td>10.25</td>
</tr>
<tr>
<td>5</td>
<td>-5.920</td>
<td>8.706</td>
<td>2.799</td>
<td>15</td>
<td>0.13</td>
</tr>
<tr>
<td>6</td>
<td>0.122</td>
<td>0.224</td>
<td>-0.753</td>
<td>2733</td>
<td>23.26</td>
</tr>
<tr>
<td>7</td>
<td>2.385</td>
<td>-5.144</td>
<td>-2.936</td>
<td>13</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>1.683</td>
<td>11.841</td>
<td>-2.972</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td>9</td>
<td>-3.156</td>
<td>2.819</td>
<td>0.923</td>
<td>132</td>
<td>1.12</td>
</tr>
<tr>
<td>10</td>
<td>-0.907</td>
<td>-1.636</td>
<td>-0.125</td>
<td>1005</td>
<td>8.55</td>
</tr>
</tbody>
</table>
Figure 17.8  Division of Haut Glacier d’Arolla into 10 cluster zones based on terrain

Table 17.4  Pearson correlation coefficients for SWE versus terrain parameters for all surveys. Starred values are statistically significant at the 95% level

<table>
<thead>
<tr>
<th></th>
<th>Survey 1</th>
<th>Survey 2</th>
<th>Survey 3</th>
<th>Survey 4</th>
<th>Rapid survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>0.727*</td>
<td>0.761*</td>
<td>0.646*</td>
<td>0.553*</td>
<td>0.197</td>
</tr>
<tr>
<td>Slope angle</td>
<td>-0.025</td>
<td>-0.034</td>
<td>0.162</td>
<td>0.303*</td>
<td>0.097</td>
</tr>
<tr>
<td>N–S scalar aspect</td>
<td>-0.233*</td>
<td>-0.256*</td>
<td>-0.355*</td>
<td>-0.266*</td>
<td>-0.322*</td>
</tr>
<tr>
<td>E–W scalar aspect</td>
<td>0.208</td>
<td>0.211</td>
<td>0.065</td>
<td>0.244</td>
<td>-0.232*</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>-0.155</td>
<td>-0.161</td>
<td>-0.157</td>
<td>-0.085</td>
<td>-0.107</td>
</tr>
<tr>
<td>Planform curvature</td>
<td>-0.237*</td>
<td>-0.178</td>
<td>0.026</td>
<td>0.110</td>
<td>-0.124</td>
</tr>
</tbody>
</table>
1980). A significance level of 95% was chosen to provide a way of limiting discussion to the most important variables.

**Survey 1 (20–22 June)**

Snow covered the entire glacier during this survey, with a mean SWE of 0.856 m. Snow density varied little, with a mean of 0.527 g cm\(^{-3}\), and standard deviation of ±0.031 g cm\(^{-3}\). Correlation of SWE with terrain identified elevation, north-south scalar aspect and profile curvature as significant (Table 17.4). Stepwise regression identified elevation as the most important variable in the multiple situation, accounting for 52.9% of the SWE variance. Profile and planform curvature were also significant in stepwise regression, accounting for 3.1% and 2.9% of the variance respectively, with SWE increasing as the glacier surface became more concave.

**Survey 2 (3–5 July)**

There was some melt since survey 1, with a survey 2 mean SWE of 0.513 m. The snow had melted from some areas towards the glacier terminus by survey 2, meaning that density could no longer be recorded at pit A. The mean snow density at the remaining three pits remained similar at 0.533 g cm\(^{-3}\), with a standard deviation of ±0.016 g cm\(^{-3}\), varying much less than depth. Correlation again identified elevation and north-south scalar aspect as significant influences on SWE (Table 17.4). Stepwise regression identified elevation as the only significant variable, explaining 57.9% of the variance. This value was lower than for survey 1, although the proportion of variance explained by elevation alone was slightly higher. North-south scalar aspect was not highlighted owing to collinearity with elevation.

**Survey 3 (17–18 July)**

Once again there was melt since the previous survey, with a mean SWE of 0.426 m for this survey. The melt was less than between surveys 1 and 2 owing to new snowfall and freezing temperatures between 11 and 13 July. Snow density had also increased slightly since survey 3 to 0.551 g cm\(^{-3}\), with a standard deviation of 0.059 g cm\(^{-3}\), although it remained virtually constant over the glacier. To meet the normality assumption, the locations at which SWE was zero in survey 2 were excluded from analysis, leaving a data set with 69 values. Elevation was still the most important factor in the linear case, with north-south scalar aspect also significant (Table 17.4). Collinearity remained important as stepwise regression identified elevation as the only significant influence on survey 3 SWE, accounting for 41.7% of the variance.

**Survey 4 (1–2 August)**

Significant melt had occurred since survey 3, with a mean SWE loss of 0.242 m. Bare ice was now exposed over the lower part of the glacier, meaning that snow density could only be recorded at pits C and D. Mean snow density had increased
slightly again to 0.554 g cm⁻³, with a standard deviation of 0.014 g cm⁻³. The
locations at which SWE was zero in previous surveys were again removed from
analysis, leaving a data set with 59 values. Correlation with SWE showed that
elevation, slope angle and north–south scalar aspect were significant (Table 17.4).
Although several variables were influential in the linear case, stepwise analysis
identified elevation as the only significant factor in the multiple situation, accounting
for 30.6% of the variance.

Rapid Survey (14 July 1993)

Correlation identified north–south and east–west scalar aspect as significant influ-
ences on snow depth (Table 17.4). Stepwise analysis identified north–south scalar
aspect (10.4%) and elevation (4.9%) as significant in the multiple situation, together
accounting for 15.3% of snow depth variance. This value is relatively small in
comparison to the other surveys, and shows the heterogeneous nature of the snow
cover on the small scale.

Terrain Clustering

The majority of sample locations (62) were in zone 1, while there was one point in
zone 3, two points in zone 4, 21 points in zone 6 and one point in zone 10. Only
those points located in zones 1 or 6 were analysed further as the other zones
contained too little data for effective interpretation. The non-parametric Mann-
Whitney U test was used to compare the SWE in different zones because the
number of points in each class differed greatly, and no assumptions need to be
made about the data distribution characteristics. The Mann-Whitney U test was
more than 99.9% significant for all four surveys, showing that the mean SWE was
significantly different between zones 1 and 6. Terrain-based zonation of the glacier
therefore provided an effective division of the snow cover between zones 1 and 6,
although the use of data from only two zones means that this is a preliminary test
rather than a comprehensive assessment.

Comparison between the effectiveness of terrain-based zoning in predicting SWE,
and SWE predictions from regression of elevation with SWE are given in Table
17.5. For terrain zoning, the predicted SWE at each sample point consists of the
mean SWE for the zone in which the particular sample point was located. For
regression, the predicted SWE at each sample location was determined from a line
of best fit to the SWE measurements. Table 17.5 shows that regression with
elevation provides the best predictions of SWE for the main surveys, although the
predictions based on terrain zonation become relatively better in the later surveys.

DISCUSSION

Depth and Density

Field measurements consistently showed that snow density varied much less than
snow depth, with only a small increase in density from one survey to the next. The
mean snow density of 0.541 g cm\(^{-3}\), and standard deviation of 0.030 g cm\(^{-3}\), compares well with Elder et al. (1991), who found a mean of 0.520 g cm\(^{-3}\) and standard deviation of 0.044 g cm\(^{-3}\) for an alpine basin in California. This is in contrast to the mean snow depth of 1.624 m, and standard deviation of 0.760 m, for the first survey. These results support claims that more snow depth than density measurements are necessary to characterise the areal SWE variability over an alpine basin (Logan, 1973; Adams, 1976; Goodison et al., 1981; Elder et al., 1991). Given that depth has a strongly predictive value for SWE when the density deviation is small, accurate results can be obtained by combining many depth readings with a few density measurements. Gruzinov (1990) actually recommends abandoning density measurements altogether to increase efficiency in snow surveys.

**Relation Between Snow Cover and Terrain**

**Elevation**

The correlation coefficients consistently highlighted elevation as the single most important factor, accounting for more than 50% of SWE variation for the first two surveys, and over 30% for the last two. The rapid survey results indicated that elevation was significant, but of less importance, on the smaller scale. Elevation has been widely recognised as an important influence on variations in snow cover (McKay and Gray, 1981). The increase of SWE with elevation could be due to several factors, including the decrease in air temperature, and increase in precipitation with altitude. For the main surveys, air temperature is likely to have been of prime importance as meteorological measurements on the glacier showed a consistent decrease of at least 4\(^\circ\)C between 2547 m and 2872 m.

The poor relationship between elevation and snow depth on the smaller scale can be explained by winds of over 8 m s\(^{-1}\) during the storm prior to the rapid survey. These wind speeds are likely to have caused redistribution, so reducing the influence of elevation on the small scale. Debris cover may also have been important as moraine was virtually free of snow due to wind scour and the higher thermal conductivity and lower albedo of rock debris compared to ice.
Aspect and Slope Angle

North–south scalar aspect was significantly negatively correlated with SWE for surveys 2, 3 and 4. This was unexpected because the lower solar radiation receipts of more northerly facing areas would suggest a positive relationship. One explanation could relate to the collinearity between north–south scalar aspect and elevation. Alternatively, the strong negative correlation between north–south scalar aspect and slope angle for the rapid survey results suggests that snow accumulation occurs against slopes that face the wind. This is because wind speeds were high and blowing in an up-glacier (southerly) direction during the rapid survey. Cline (1992) also found that slope angle had an influence on the redistribution of snow by wind.

Curvature

Profile and planform curvature were significant parameters in stepwise analysis for survey 1, accounting for 3.1 and 2.9% of the variance respectively. These values are low, but important, as determination of terrain curvature appears to help in accounting for redistribution. The higher SWE in concave areas probably relates to wind deceleration and convergence (i.e. deposition), whereas the lower SWE in convex areas probably relates to wind acceleration and divergence (i.e. erosion). The effects of avalanching could not be quantified owing to safety considerations, although observations suggest that initiation occurs in convex areas with high slope angles, and runout occurs at the base of slopes with a marked concavity. Only theoretical considerations of the relationship between terrain curvature and snow cover have been made before (Adams, 1976; Elder et al., 1989, 1991; Blöschl and Kirnbauer, 1992).

Longer Term Processes

The data presented here indicate a general decline in the proportion of variance attributable to the terrain as the melt season progresses. This pattern is similar to that reported by Rychetnik (1987), where only a small proportion of the spatial variations in the time of disappearance of the snow cover could be explained by terrain. Rainfall and melt have the effect of reducing spatial contrasts in SWE, while phenomena such as redistribution are more complex. Wind is of greatest influence during accumulation and early in the melt season, when density is low and snow can be entrained from the glacier surface. This is suggested by the rapid survey results and the significance of curvature for survey 1 only.

Radiation is important in defining the spatial distribution of melt. It was hoped that the determination of aspect would account for much of the variation in radiation receipts, although it was not significant in any multiple regression calculations. This probably relates partly to shading from surrounding topography, and partly to collinearity between the terrain parameters. Collinearity becomes increasingly evident in later surveys as the sample points are restricted to the tributary glacier, which is at a higher elevation and noticeably steeper and less northerly facing than lower areas.
Overall, the results support attempts at delineating SWE according to terrain. Although the importance of the terrain declines over the melt season, multiple regression is able to account for a higher proportion of SWE variability than previous similar investigations. For an alpine basin in California, Elder et al. (1991) found no discernible relationship between SWE and radiation, slope and elevation for the 1986 water year, a relation of 40% in 1987, and a relation of 27% in 1988. The higher values from Arolla may be due to the sample point distribution, although the significance of several factors in linear regression, and curvature in multiple regression for survey 1, suggests that the objective evaluation of a wider range of terrain parameters may improve snow cover evaluation.

**Terrain Clustering**

Division of the glacier surface into 10 cluster zones according to terrain appears to have been successful, as the mean SWE was consistently higher in zone 6 than zone 1 (> 99.9% significant for all surveys). The use of only two zones in statistical analysis is limiting, although data from the other zones and visual analysis of the snow cover support clustering as a means of delineating spatial variations in SWE. Regression of elevation with SWE provided better estimates of SWE than terrain zonation, although linear interpolation does not account for the small-scale variability observed in rugged terrain (Elder and Dozier, 1990). A combination of terrain zonation and regression-based approaches may therefore provide the best estimates of SWE in alpine basins. This has important implications for snow cover monitoring as the effective division of SWE according to physically based parameters allows improved extrapolation of point values over space.

Using the predictions from terrain zonation, the volume of water held in the snowpack was estimated for each survey by adding the product of the mean SWE, grid size and number of points within each zone (Table 17.6). While this is a “rough-and-ready” calculation, it is useful as a basis against which other results can be compared. Comparison with melt model results from 1992 suggests that the general patterns are correct (Sharp et al., 1993). The change in water volume between survey dates was clearly influenced by climate, with the smallest decrease between surveys 2 and 3 related to freezing temperatures and new snowfall. The importance of individual zones varies through the melt season as, for example, zone 1 dominates surveys 1 and 2, while zone 6 dominates surveys 3 and 4. This is probably because zone 6 is generally higher in the basin, meaning that terrain zonation has captured some of the influence of elevation.

**CONCLUSIONS**

The computer program written for this study has enabled the quantitative determination of slope angle, aspect, profile curvature and planform curvature for an entire glacier, and is applicable to any DEM with regular spacing between grid points. Using these terrain parameters, elevation has been consistently highlighted as the most important variable, accounting for 30.6% to 57.9% of the variance in
Table 17.6 Total volume of water held in the snowpack for the four main surveys (S1, S2, S3, S4) using predictions based on terrain zonation. The predicted SWE depth for each zone consists of the mean of all measurements made in that zone. The overall mean SWE was used for the zones that did not contain any sample points (zones 2, 5, 7, 8, 9)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Points</th>
<th>S1 SWE (m)</th>
<th>S1 Total (m³)</th>
<th>S2 SWE (m)</th>
<th>S2 Total (m³)</th>
<th>S3 SWE (m)</th>
<th>S3 Total (m³)</th>
<th>S4 SWE (m)</th>
<th>S4 Total (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5830</td>
<td>0.757</td>
<td>1765 324</td>
<td>0.409</td>
<td>953 788</td>
<td>0.328</td>
<td>764 896</td>
<td>0.140</td>
<td>326 480</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>0.856</td>
<td>12 326</td>
<td>0.513</td>
<td>737 426</td>
<td>0.292</td>
<td>613 184</td>
<td>0.184</td>
<td>2650</td>
</tr>
<tr>
<td>3</td>
<td>780</td>
<td>0.924</td>
<td>288 288</td>
<td>0.542</td>
<td>169 164</td>
<td>0.292</td>
<td>91 104</td>
<td>0.000</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1204</td>
<td>0.991</td>
<td>477 266</td>
<td>0.719</td>
<td>346 270</td>
<td>0.526</td>
<td>253 322</td>
<td>0.231</td>
<td>111 250</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>0.856</td>
<td>513 613</td>
<td>0.513</td>
<td>307 426</td>
<td>0.292</td>
<td>256 184</td>
<td>0.184</td>
<td>1104</td>
</tr>
<tr>
<td>6</td>
<td>2733</td>
<td>1.102</td>
<td>1204 706</td>
<td>0.759</td>
<td>829 739</td>
<td>0.625</td>
<td>683 250</td>
<td>0.264</td>
<td>288 604</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td>0.856</td>
<td>445 130</td>
<td>0.513</td>
<td>268 426</td>
<td>0.292</td>
<td>221 184</td>
<td>0.184</td>
<td>957</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>0.856</td>
<td>1027 313</td>
<td>0.513</td>
<td>616 426</td>
<td>0.292</td>
<td>511 184</td>
<td>0.184</td>
<td>221</td>
</tr>
<tr>
<td>9</td>
<td>132</td>
<td>0.856</td>
<td>45 197</td>
<td>0.513</td>
<td>27 086</td>
<td>0.426</td>
<td>22 493</td>
<td>0.184</td>
<td>9715</td>
</tr>
<tr>
<td>10</td>
<td>1005</td>
<td>1.593</td>
<td>640 386</td>
<td>1.366</td>
<td>549 132</td>
<td>1.100</td>
<td>442 200</td>
<td>0.479</td>
<td>192 558</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4444 107</td>
<td>2888 868</td>
<td>2268 681</td>
<td>933 539</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SWE. There is an overall decline in the differentiation of snow cover as the melt season progresses owing to the homogenising effects of melt and rainfall.

Division of the glacier into areas of similar terrain may resolve some of the problems associated with collinearity, as cluster analysis allows the simultaneous evaluation of many terrain parameters. This more clearly represents the real physical processes as the artificial separation of variables in regression does little to account for their interaction in the field. Zonation has been attempted for one basin before (Elder et al., 1989, 1991), but the problems with collinearity were ignored, and clustering was limited to radiation, elevation and slope angle. Although the conclusions from this study are preliminary owing to the statistical comparison of only two zones, it appears that cluster analysis provides an effective method of partitioning the SWE within alpine basins. The method could possibly be improved by using a multiplier to weight the importance of elevation in the clustering process.

Snow cover evaluation may be improved in the future by using pattern recognition methods such as upslope drainage area to identify groups of cells with an assemblage of characteristics favourable for avalanching and/or wind drift. The determination of slope curvature is particularly valuable because improved avalanche predictions should result. For example, cells with profile concavity which lie downslope of cells with high slope angles and downslope convexity are likely to provide a focus for deposition. This may be an important research area, as most studies (e.g. McClung and Tweedy, 1993) have focused on when, rather than where, avalanching occurs.

The results suggest that the volume of water held in the seasonal snowpack may be rapidly evaluated by taking a few depth measurements in each of the major zones identified by cluster analysis. Only one density profile for the whole study
area would be necessary if the density variability is small. Stratification before sampling should increase accuracy and lower the number of samples, while also giving confidence to the areal extrapolation of point measurements for use in the calibration and testing of snowmelt models.

ACKNOWLEDGEMENTS

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REFERENCES

Gruzinov, A. V., 1990. O ratsionalizatsii rabot po opredeleniyu vodnosti snega v basseynе ledn. Abramova (On rationalising work on determining water content of snow in the basin


