PRECIPITATION IN THE SVARFAÐARDALUR REGION, NORTH-ICELAND

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ABSTRACT: During the summer of 2006, precipitation was measured with a network of 40 rain gauges in the region of Svarfaðardalur valley in N-Iceland. The precipitation distribution is investigated for different wind conditions and the intensity spectrum is explored. A large observed precipitation gradient (400% increase over a distance of 9 km) indicates that the orographic enhancement of precipitation may be very sensitive to the shape of the mountains and the exact aspect of the slopes. The distribution functions of precipitation intensities have similar forms for most locations, except at sea level below high mountains where low precipitation intensities are relatively infrequent while high precipitation intensities are frequent. The precipitation data are compared to information on avalanches that is retrieved from written sources and interviews. The highest values of precipitation coincide with very frequent avalanches, but there are other areas with only few avalanches but much precipitation.

KEYWORDS: Precipitation, complex terrain, Iceland, Svarfaðardalur, avalanches, precipitation intensity, orography.

1. INTRODUCTION

Several authors have attempted to describe and understand the distribution of precipitation in complex terrain. These attempts range from purely statistical methods to dynamic methods with full-scale numerical models based on the primitive equations with sophisticated parameterization of precipitation processes (e.g. Schmidli et al., 2001; Rögnvaldsson et al., 2004; Crochet, 2007). Some models can be considered as a mixture of tatistical and dynamical approaches; the cost-effectiveness of most statistical models is retained in a method that includes direct or indirect information on the dynamics of the orographic flows (Steinacker et al., 2006; Barstad & Smith, 2005). Somewhat less, but increasing effort has been invested in extensive fine scale precipitation observations to validate the models. Substantial amount of valuable precipitation and microphysical data has been collected in field programmes such as MAP (Richard et al., 2007), IMPROVE (Stoelinga et al., 2003), COPS and STOPEX (Reuder et al., 2007).

The Svarfaðardalur valley is oriented NNE-SSW. It carves into the Tröllaskagi peninsula from the fjord of Eyjafjörður in N-Iceland. At about 12 km away from the coast, the valley splits into two valleys. The land is formed by many valley glaciers and the terrain is therefore quite complex. The mountain heights vary from about 700 to 1445 m a.s.l. and there are still small glaciers in most of the subvalleys. The mean annual precipitation 1991-2000 was 546 mm at Tjörn, some 5 km inland in Svarfaðardalur but 919 mm at Kálfsárkot 8 km inland in Ólafsfjörður (Fig.1).

In order to investigate the variability of precipitation in the complex terrain of the region of Svarfaðardalur valley, 40 automatic rain gauges were installed in the summer of 2006. The rain

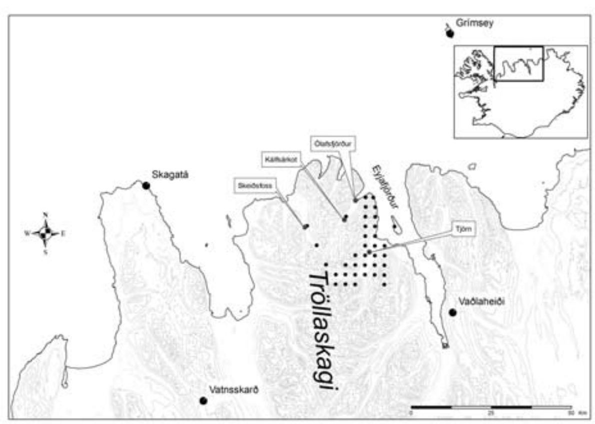

Figure 1: A map of North-Iceland showing the position of the rain gauges and the weather stations used in this study.

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gauges where placed in a regular grid with 3 km between gridpoints. Three rain gauges were installed next to manned precipitation stations from Veðurstofa Íslands (The Icelandic Meteorological Office) which are in operation in all seasons and have provided time series for several years. Most of the rain gauges were placed in mountains far away from roads.

Avalanches have caused many fatal accidents in Iceland. They also threaten many public roads and have caused heavy damage of structures. Hazard mapping and studies of weather prior to avalanches have already been done in coastal towns in Iceland (Haraldsdóttir et al., 2006) and currently, avalanche hazard evaluation in rural areas is starting. Svarfaðardalur valley in N-Iceland has been chosen as a pilot project in this context (Brynjólfsson et al., 2006). Precipitation is perhaps the most important factor contributing to avalanche hazard, and mapping of the precipitation in the region may not only be useful for meteorological and climatological purposes, but it is also a step towards an evaluation of the avalanche hazard.

In the remainder of this paper, the key features of the precipitation observations from the summer of 2006 will be presented. The results of the avalanche mapping will then be presented briefly. The results of the precipitation observations will be discussed in section 4, including a short comparison of the precipitation fields and the distribution of historical avalanches.

2. RESULTS FROM THE HIGH-RESOLUTION NETWORK OF PRECIPITATION OBSERVATIONS

Automatic data logging rain gauges with a tipping bucket were used for this study (HOBO RG3-M). One tip of the bucket occurs for each 0.2 mm of rain. The loggers were installed between 21 May and 16 June and most of them were down before 27 October. There were some periods with snow, and consequently no observations as the instruments only measure liquid precipitation. The buckets were placed at ground level in order to minimize the wind-loss of precipitation. Since we only measure liquid precipitation, errors of this kind can be considered to be small compared to the spatial variability of the precipitation and no attempt has been made to correct for undercatchment of any kind.

The accumulated precipitation observed during the summer of 2006, together with the frequency of wind directions during precipitation in the region is shown in Fig. 2. The figure reveals a very large precipitation gradient in the Svarfaðardalur region; the location of the minimum precipitation (83 mm) is only 9 km away from the maximum of 410 mm. In general, the accumulated precipitation in the mountains is between 200 and 350 mm, a little more than 100 mm in the valley and close to 400 mm in the northernmost mountains. The proportion of the number of hours with precipitation to the number of dry hours during the experiment is shown in Fig. 3. While there is precipitation during only 4% of hours at the valley´s mouth, the corresponding number for the mountains in the south and in the east is about 12-15%. This agrees with the pattern of the total accumulated precipitation (Fig. 2). However, in the northernmost mountains, there is slightly greater accumulated precipitation than in the south, but fewer wet hours. This is

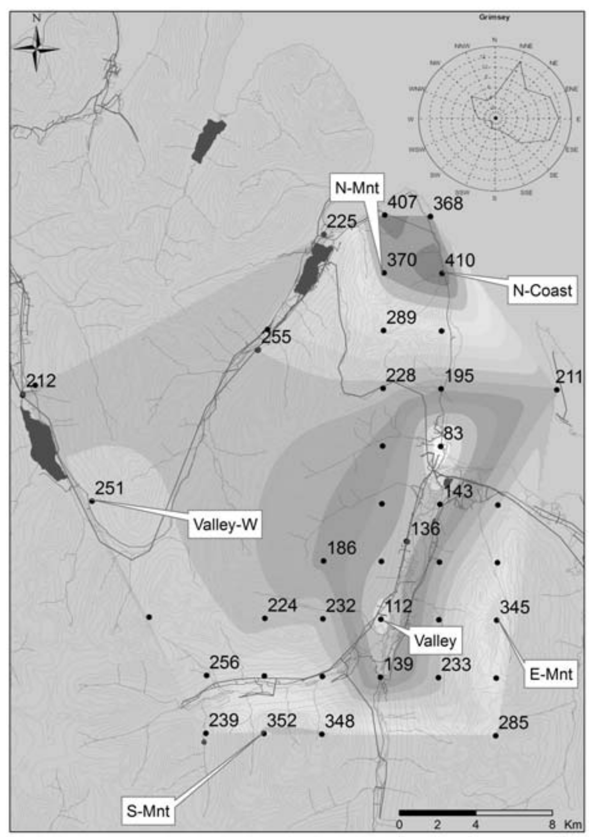

Figure 2: Accumulated precipitation (mm) during the period 16.6.2006 17 UTC to 10.10.2006 14 UTC. Frequency of wind directions observed in the Grímsey island (Fig. 1) at the time of non-zero precipitation in Tröllaskagi during the same period is also shown.

particularly clear for the northernmost coastal stations with only 8-10% of hours being wet, but more accumulated precipitation than anywhere in the south. There must consequently be a relatively greater frequency of small amounts of precipitation in the southern and the eastern mountains than in the north and this can indeed be seen in Fig. 4. The figure shows that the N-Mnt station (Fig. 1) has lower values of accumulated precipitation than the other mountain stations at hourly values less than about 2 mm, but similar or greater accumulated precipitation at higher precipitation intensities. Overall, the frequency curves are however quite alike for all stations, except the N-Coast, which is exceptionally flat, i.e. with relatively high number of hours of intense rain, but relatively few hours of weak rain.

Through the continuity of mass, a natural first approximation of the updrafts at the mountains is

$$W = V \bullet \Delta H \tag{1}$$

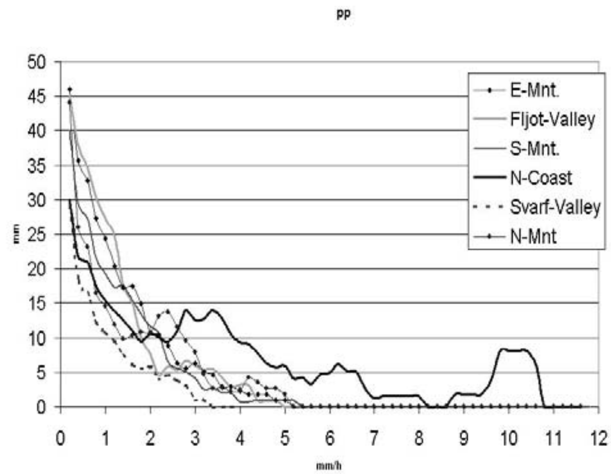

Figure 4: Frequency distribution of hourly precipitation intensities during the same period as in Fig. 2.

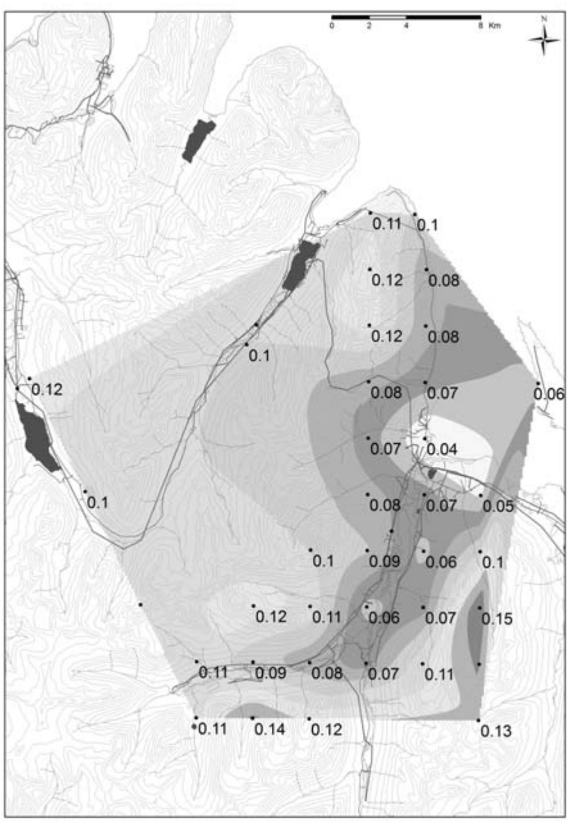

Figure 3: Proportion of the number of hours with precipitation to the number of dry hours during the same period as in Fig. 2.

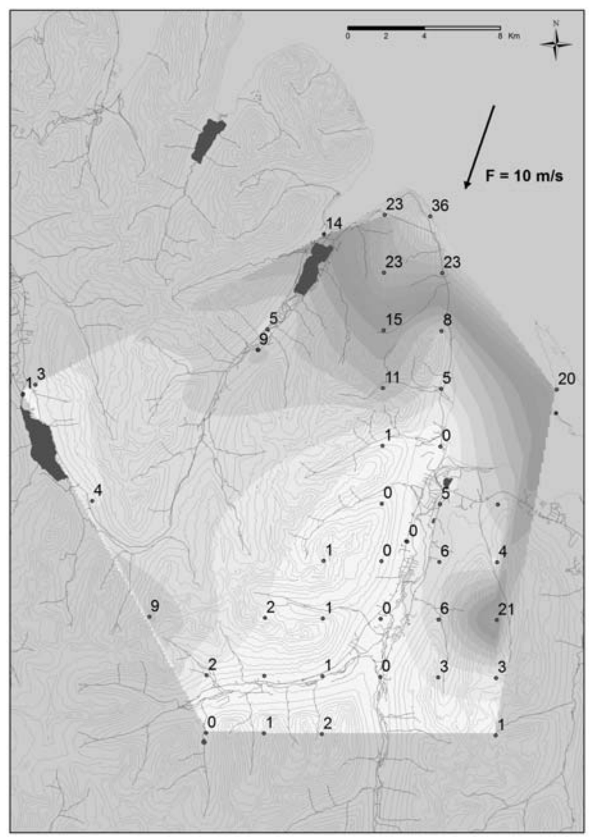

Figure 5: Accumulated precipitation (mm) from 14.8.2006 13 UTC to 14.8.2006 22 UTC. Winds: NNE 10 m/s.

where W is the vertical wind speed, V is the horizontal wind and H is the height of the terrain. In order to illustrate the precipitation distribution in different wind conditions we show three periods with wind direction and wind speed roughly constant. The winds are retrieved from Grímsey, Skagatá (northerly winds), Vaðlaheiði and Vatnsskarð (southerly winds). All these stations are in relatively open areas, away from the mountains in Tröllaskagi (Fig. 1) and can be expected to represent the winds impinging on the mountains in question.

In the case of northeasterly winds (Fig. 5), maximum accumulation of precipitation is found in

the northernmost mountains and in the mountains on the eastern border of the area. This is where the strongest ascending motion can be expected. The precipitation decreases as we move away from the coast into the western part of the valley and it is mostly dry along the valley floor and in the mountains on the south and the west side of the valley. There is a very strong gradient along the eastern edge of the northernmost mountains, yet, the rain gauges are all close to sea level and the orientation of the mountain range is roughly the same everywhere.

Figures 6 and 7 show the precipitation pattern in cases of southerly winds. In the SW storm (Fig. 6), there is some accumulation of precipitation in the southernmost mountains as well as in the mountains to the west of Svarfaðardalur valley, but further north and to the east there is hardly any precipitation. In the SE storm (Fig. 7), the precipitation distribution is quite uniform. The maximum precipitation intensity was 1.8 mm/hour for the SW storm but 1 mm/hour during the weak SE wind.

The maximum frequency of avalanches is observed in the northernmost mountains (Fig. 8). It is therefore of interest to assess the connection between the winds and the ratio of precipitation in these mountains to precipitation at the weather station Ólafsfjörður. To do this, all cases have

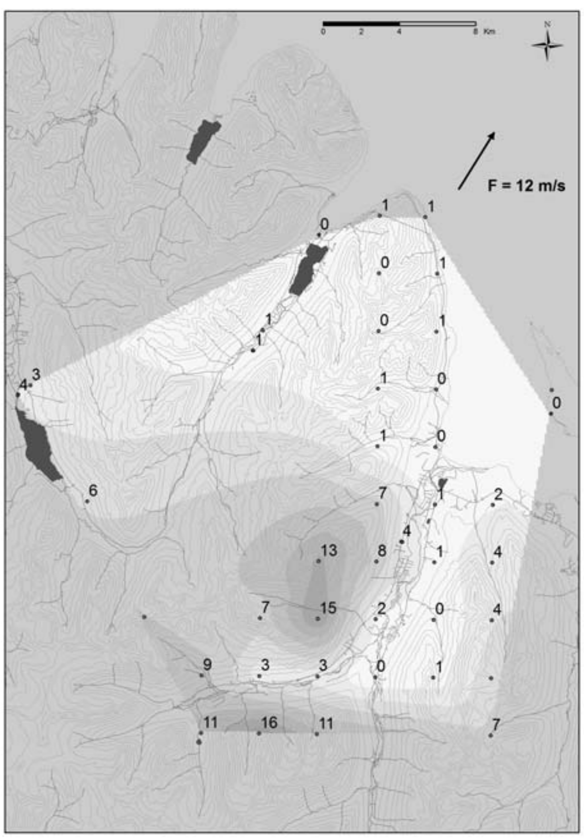

Figure 6: Accumulated precipitation (mm) from 16.6.2006 14 UTC to 16.6.2006 23 UTC. Winds: SW 12 m/s.

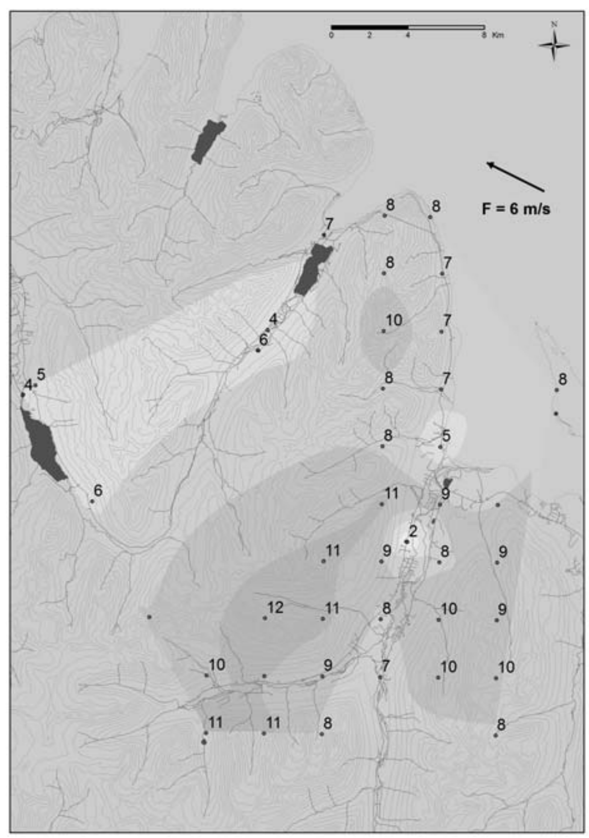

Figure 7: Accumulated precipitation (mm) from 8.8.2006 4 UTC to 8.8.2006 16 UTC. Winds: SE 6 m/s.

Table 1: Ratio of the mean precipitation of the two northernmost rain gauges and the N-Coast rain gauge (Fig. 2) to precipitation at Ólafsfjörður for different wind speeds and wind directions. Values are only shown where the total number of wet hours exceeds 10 and the total precipitation in the three rain gauges exceeds 20 mm.

	280 ≤ d < 320	**320 ≤ d < 360**	**0 ≤ d < 40**	**40 ≤ d < 80**	**d ≥ 80**
f ≥ 8m/s	x	x	2,4	2,2	x
4m/s < 8m/s	x	x	x	1,0	1,1
f ≤ 4m/s	1,3	1,3	1,0	x	1,1

been grouped according to wind speed and wind direction and the results are shown in Table 1. The table reveals that the orographic enhancement of precipitation does indeed increase with increasing winds and that this is quite independent of wind direction, to the extent that the data allows for such a comparison.

3. AVALANCHE MAPPING IN THE SVARFAÐARDALUR REGION

The northern part of Tröllaskagi including the Svarfaðardalur region has more snow accumulation than most other regions in Iceland. Avalanches are quite common and some of them have been fatal and damaging for buildings and structures. Thus, a pilot project in avalanche hazard mapping in rural areas in Iceland was started the summer of 2005 in Svarfaðardalur (Brynjólfsson et al., 2006). Information about avalanches was collected by interviews with local people and from written sources. Avalanches close to farms, roads and other structures are most likely to be remembered and mentioned in the written sources, while avalanches away from farms and man-made structures tend to be forgotten. Svarfaðardalur is somewhat less densely populated in its southernmost and easternmost parts, than elsewhere. The roads in the valley are also of a lower category than the main road along to coast to Ólafsfjörður. Consequently, we suspect that the number of avalanches entering the records may be biased and that avalanches in the western part of the valley and along the coast towards Ólafsfjörður are more likely to be recorded than avalanches elsewhere. In Fig. 8, the region has been divided into 9 areas and the number of recorded avalanches in each area is shown in the figure. Recorded avalanches are far more frequent in the northernmost part of the area than further south. The difference in frequency between the southernmost parts of the valley and the northernmost part is in fact 1-2 orders of magnitude. Yet, the terrain in the south is at many locations quite favourable for avalanches.

4. DISCUSSION

The overall pattern of the observed precipitation reveals very strong orographic influences. Comparing the average precipitation in all our buckets with accumulated precipitation at nearby locations not dominated

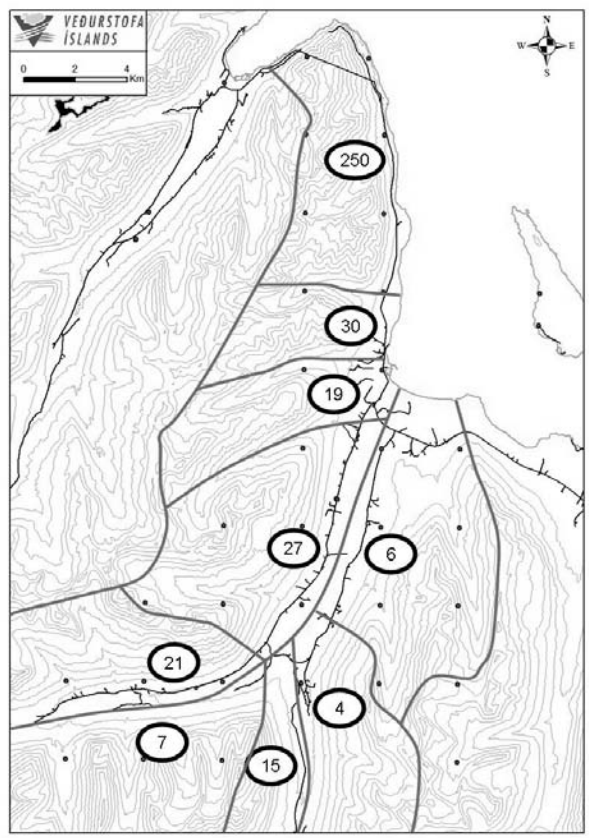

Figure 8: Number of recorded avalanches in different areas in the Svarfaðardalur region.

by orographic enhancement or sheltering we find that the region of Svarfaðardalur valley as a whole receives about 60% more precipitation than if the region had no mountains. This figure may be compared to a corresponding 40% increase in total precipitation in Iceland because of mountains (Rögnvaldsson et al., 2007a). The difference between maximum and minimum accumulated precipitation during the whole summer is of a factor 5. This is quite similar to what was observed in the Reykjanes peninsula in SW-Iceland (Rögnvaldsson et al., 2007b), although the mountains are typically higher than in Reykjanes.

In view of the high mountains, large precipitation gradients in the complex terrain of N-Iceland are of no surprise. However, a precipitation difference of 400% at sea level over a distance of only 9 km is more than expected, particularly in view of the fact that the aspect of the wettest and the driest stations to the nearby mountains is roughly the same. A comparable pattern has indeed not been recorded in the recent campaigns in Reykjanes (Rögnvaldsson et al., 2007b) and in Stord (Reuder et al., 2007). Some of the explanation for this gradient may be different sheltering by mountains east of Eyjafjörður fjord (about 15 km away), but local elements of the flow are most likely the dominating factor. The mountains in the north are somewhat steeper and oriented slightly more perpendicular to winds from the NE than the mountains west of the driest point (Dalvík). It is attempting to conclude that the precipitation is extremely sensitive to the shape of the mountains, and/or the exact aspect of the slopes.

High precipitation in the southernmost mountains in the SW case indicates that lack of precipitation in northerly winds in this region is compensated by precipitation in southerly flow. This may be a surprise, because the southerly flow has travelled across several mountain ranges before reaching the Svarfaðardalur valley and coastal weather stations in this region usually remain dry in winds from the south. However, this agrees with the experience of local farmers. These observations indicate that glaciers in the southern part of Tröllaskagi may be largely fed by precipitation in southerly winds, while glaciers in the northern part may receive most of their precipitation in northerly winds. If that is correct, their development may be different in a future climate where winter precipitation associated with northerly winds is expected to increase, while winter precipitation associated with southerly winds is expected to decrease. (Rögnvaldsson & Ólafsson, 2005).

The uniform precipitation field in the SE case (Fig. 7) is presumably related to stagnation in the low level airflow. When the winds are weak and perpendicular to the mountain ranges, the inverse Froude number (N/hU, where N is the Brunt-Väisälä frequency, h is mountain height and U is the speed of the wind impinging the mountain) is high and the airmass inside the valley is presumable “dead”, as well as the airmass upstream of the area. Consequently, the mountains do not contribute to substantial ascending (or descending) motion. This is to some extent reminiscent of the lack of vertical motion downstream in the Alps described by Zängl (2005).

The pattern of relatively high frequency of high-intensity precipitation and low frequency of low-intensity precipitation events at the foot of the mountain, compared to the mountain itself is a feature that has not been observed elsewhere to

the knowledge of the authors of this paper. The

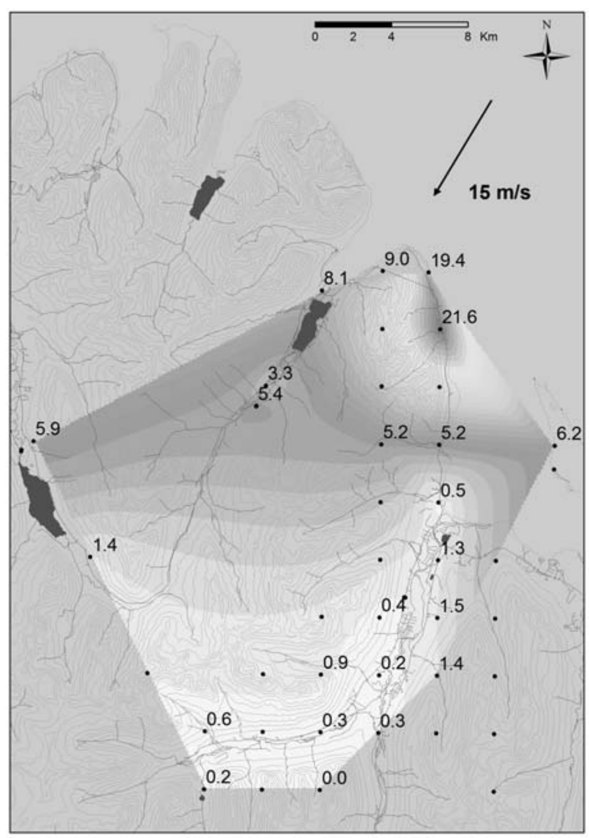

Figure 9: Accumulated precipitation (mm) during the period 28.8.2006 19 UTC to 28.8.2006 22 UTC. Winds: NNE 15 m/s.

general validity of this result is indeed unclear, but of some interest as this is a part of the precipitation climatology and knowledge of the distribution of precipitation intensities may be helpful in the interpretation and validation of numerical simulations. A possible physical explanation of the low number of low-intensity precipitation events at the coast may be associated with evaporation of light rain (even from the rain gauge itself), which does not take place in the cloud-embedded mountain tops. Some of the precipitation in the mountain may also be characterized as in-cloud drizzle, not being present below cloud level.

A positive correlation can be detected between wind speed and the orographic enhancement of the precipitation in the the northernmost mountains (Table 1), but it should be kept in mind that the Ólafsfjörður precipitation is not a very good representative of the “background” precipitation. However, a better representative is not available, as precipitation is not observed in Grímsey. Although sparse on information, Table 1 may be helpful in estimating the precipitation in the mountains from observations in Ólafsfjörður.

Comparing the avalanche frequency (Fig. 8) and the observed accumulated precipitation (Fig. 2) indicates that the high frequency of avalanches in the northernmost mountains is indeed associated with locally heavy precipitation. In the southernmost mountains and in the mountains in the east part of the valley there is however surprisingly heavy precipitation in view of the fact that there are only few recorded avalanches. As the terrain is in many places favourable for avalanches it may be considered likely that many avalanches are missing from the records in the south and in the southeast. This agrees with the previously explained impact of less dense population and road classification on avalanche recording in these areas. There are however major considerations that have to be made before drawing conclusions on avalanches from the present precipitation observations. Avalanches occur in the winter and they are a complex function of several meteorological elements, not only precipitation. Avalanche events are associated with lower temperatures and winds that are stronger than observed during most of the present experiment. Both may have an impact on the precipitation distribution, particularly the winds (cf. Eq(1)). The greatest impact of low temperatures may be through advection of precipitation particles due to different fall speeds of snow and rain. The event with the strongest northerly winds observed during the experiment (Fig. 9) does however show a similar pattern as in the more moderate winds (Fig. 5), but with greater orographic enhancement of the precipitation. Overall, a wintertime precipitation map is likely to have greater differences between the areas of low precipitation and the areas of high precipitation.

5. SUMMARY AND FUTURE WORK

Observations indicate very strong gradients of precipitation in the region of Svarfaðardalur valley, N-Iceland and that the precipitation is very sensitive to the form or the aspect of the mountains. When compared to observations in the mountains, a station at the foot of the mountains receives a relatively large part of its precipitation in the form of intense rain and a corresponding low proportion of events of weak rain. On an hourly basis, precipitation in the mountains is as much as four times as frequent as in the driest part of the valley, yet the valley is only about 5 km wide.

An extensive collection of records reveal that avalanches occur in almost all parts of Svarfaðardalur valley and that they are extremely frequent in the northern part of the region. The observed precipitation pattern in Svarfaðardalur valley agrees largely with the frequency of recorded avalanches, but indicates that avalanche events in the mountains to the south and east of Svarfaðardalur valley may be missing from records.

The primary value of the present dataset may be to validate future high-resolution numerical simulations that in turn can be expected to be helpful in predicting extreme snow accumulations in the mountains for avalanche forecasting and risk assessment

Acknowledgements: Thanks to Brynjólfur Sveinsson and Skafti Brynjólfsson for their help on installing the rain gauge network, to Tómas Jóhannesson and Þórður Arason for assisting with the data processing and to Maria Wastl for comments on the manuscript. This project received support from Ofanflóðasjóður (The Avalanche Fund), the research project RÁV and RANNÍS (The Icelandic Research Fund).

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