The avalanche climate of Glacier National Park, B.C., Canada during 1965-2011

Sascha Bellaire1,2*, Bruce Jamieson1, Grant Statham3
1Institute of Meteorology and Geophysics, University of Innsbruck, Tyrol, Austria
2Dept. of Civil Engineering, University of Calgary, AB, Canada
3Parks Canada Agency, Banff, AB, Canada

ABSTRACT: Climate change is evident and long-term changes of the climate system have been observed. It has been shown that changing atmospheric conditions influence the formation and evolution of the seasonal mountain snow cover and therefore determine the avalanche hazard. For this study we analyzed long-term weather data as well as snow and avalanche data from Glacier National Park, British Columbia, Canada. Weather and snow cover data was measured at two experimental sites Rogers Pass and Mt. Fidelity at 1340 m and 1905 m a.s.l., respectively. The avalanche data were observed along the section of the Trans Canada Highway located within Glacier National Park. The mean annual air temperature at both stations showed similar increases for the last decades as already found for the Northern Hemisphere. The largest increase of the monthly mean air temperature was found for the early winter months from November to January. A significant decrease of the solid precipitation, i.e. proportionally more rain, was found for Mt. Fidelity station in November. This trend might have favoured the formation of early season rain crusts, which were found in manual snow cover profiles more often during the last two decades. These crusts favour more weaknesses deep in the snowpack and potentially more deep slab avalanches. The frequency of natural avalanches within Glacier National Park did not increase during recent decades, but a trend towards more avalanches in January and March was found. However, these trends might be influenced by avalanche control work conducted at Glacier National Park and might therefore be unrelated to climate change.

KEYWORDS: climate change, avalanche formation, avalanche activity, solid precipitation rate, crust formation

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 2007) has stated that the warming of the climate system is unequivocal, as is now evident from observations of increases in global average air temperature and ocean temperatures, widespread melting of snow and ice, and rising global average sea levels. It has also been found that the frequency of heavy precipitation events has increased over land areas, which is consistent with the warming and observed increase of atmospheric water vapour.

Avalanche formation is clearly related to atmospheric conditions including precipitation rate, duration and type as well as wind, air temperature and radiation. Therefore, avalanche activity should also be affected by changing atmospheric conditions in a changing global climate.

Very few studies have discussed the impact of climate change on avalanche activity (e.g. Fitzharris, 1987; Foehn, 1992, Schneebelei et al., 1997, Laternser and Schneebelei, 2002) and most of them showed inconclusive results. This shows the difficulty of relating climate change to avalanche activity, which is partly due to the fact that avalanche cycles are caused by short-term weather systems (days) rather than long-term climate trends (decades). However, the snow cover structure as the main driving agent of avalanche formation might have been influenced by climate change. For example, increasing air temperature might stabilize the snow cover, on the other hand warm air can hold more moisture, which might increase the amount of new snow. Marty and Blanchet (2011) showed that the latter might not be the case. They applied extreme value statistics to long-term time series of snow depth and snowfall for 25 Swiss stations between 200 m and 2500 m. They found decreasing trends of extreme snow depth for all altitudes and a decrease in extreme snowfall for the low and high altitudes. Snowfall trends for the mid-altitudes were not significant.

Increasing air temperature also increases the probability of rain events, which can have a stabilizing effect or could contribute to the formation of melt-freeze crusts. These

Corresponding author address:
Sascha Bellaire, Institute of Meteorology and Geophysics, University of Innsbruck, Innrain 52, Innsbruck, Austria
email: Sascha.Bellaire@uibk.ac.at
crusts can favor the formation of facets - a typical weak layer (Jamieson, 2006).

Marty and Meister (2012) found that the annual mean air temperature at six high-alpine weather stations in Europe increased by 0.8 °C during the last three decades. On the other hand, they found no significant changes for long-term snow measurements for the mid-winter season, but found decreasing trends for the solid precipitation ratio, snow fall and snow depth for the melt season.

In western Canada, Fitzharris and Schaerer (1980) analyzed a 70-year record of avalanches affecting the Canadian Pacific Railway at Rogers Pass, British Columbia. The data set contains avalanche frequency, mass and run-out as well as the winter snowfall and air temperatures. They found that the size of the avalanches decreased during the decades leading to 1979.

On the other hand, practitioners state that in recent years avalanches ran farther and occurred with higher frequency; hence more explosive control was required. In addition, avalanche practitioners observed that the formation of early season rain crusts increased during the last decade, i.e. were less frequently observed two or three decades ago. Such early season rain crusts can cause deep instabilities resulting in large, difficult to forecast and highly destructive avalanches (e.g. Jamieson et al., 2001). These partly subjective assessments are
often related to climate change, but have neither been quantified nor analyzed yet.

The aim of this initial study is to investigate the potential relation between a changing climate and avalanche activity. Therefore we analysed long-term weather and avalanche data from Glacier National Park, British Columbia, Canada in order to a) show the degree of climate change for key parameters known to influence avalanche activity and b) relate apparent changes of these key parameters to avalanche activity, with a special focus on early season rain crust formation.

2 DATA AND METHODS

2.1 Meteorological data

For this study we used meteorological data from two weather stations located within Glacier National Park, British Columbia, Canada. The first station, Rogers Pass, is located at 1340 m a.s.l. and the second station, Mt. Fidelity, is located at 1905 m a.s.l. Meteorological data from these stations are available from 1966 to 2011 for Mt. Fidelity and from 1908 to 2011 for Rogers Pass. Precipitation was measured at both stations with a precipitation gauge. In the event of precipitation falling as snow, the snow water equivalent (SWE) was calculated based on measured snow density.

The solid precipitation ratio, i.e. the fraction of the solid precipitation in the total precipitation was then calculated for each year and month between 1965 and 2011. However, for some years the solid precipitation ratio could not be calculated due to missing monthly precipitation measurements.

Note that air temperature as well as precipitation measured at Rogers Pass was homogenized (Mekis et al., 2011; Vincent et al., 2012). Air temperature and precipitation measured at Mt. Fidelity was non-homogenized data.

2.2 Avalanche data

The Avalanche Control Section at Glacier National Park systematically recorded avalanche observations since 1965 along the Trans Canada Highway within the park. Avalanches were observed roughly between Mt. Fidelity station and 10 km east of the Rogers Pass station a distance of about 30 kilometers from east to west. For this study we used all avalanches with a qualitative size of medium and large. The qualitative size (small, medium, large) is not a standard observation and was introduced by the Avalanche Control Section at Rogers Pass. It represents the size of an avalanche in relation to maximum avalanche that can occur in the particular path where the avalanche was observed. A medium qualitative size avalanche at Rogers Pass can be classified as an avalanche with a destructive size (CAA, 2007) of about 2 to 3 depending on the size of the avalanche path. Avalanche classified as large might reach a destructive size of 3 to 4 also depending on the size of the avalanche path (Goodrich, personal communication, 2013).

In addition to the size selection we only used avalanches triggered naturally or by explosives (artillery). This leaves a total number of 22,553 avalanches observed between 1965 and 2012 for the analysis, whereas 16,306 were classified as natural released avalanches (72%) and 6247 as avalanches triggered by explosives (28%).

![Figure 3: Change of the solid precipitation ratio per month for Rogers Pass (orange) and Mt. Fidelity (blue) between 1974 and 2003. Positive values indicate an increase and negative values a decrease of the monthly solid precipitation ratio. Trends were calculated based on a 10-year moving average.](image-url)
2.3 Manual snow cover observations

Manual snow cover profiles recorded at Mt. Fidelity at a flat experimental site were used to assess whether or not early season rain crusts formed more often in recent years. Therefore manual profiles recorded in early December between 1959 and 2012 were searched for the presence and absence of crusts. For this study we define a crust as a distinct layer of smaller than 10 cm consisting of ice or melt-forms with a hardness of larger than 1 finger or a ram resistance of 400 N and higher (Fierz et al., 2009).

3 RESULTS

3.1 Air temperature

The mean annual air temperature measured between 1908 and 2011 at Rogers Pass and measured between 1966 and 2011 at Mt. Fidelity is shown in Figure 1. During the last three decades (1982 to 2011) Rogers Pass and Mt. Fidelity show a similar linear increase of +0.7 °C and +0.5 °C, respectively. Trends for Rogers Pass and Mt. Fidelity were found to be not significant (Rogers Pass p-value = 0.12; Mt. Fidelity p-value = 0.29), but are comparable to the corresponding temperature increase for the Northern Hemisphere (Brohan et al., 2006; HadCRUT3, +0.44 °C for 2011). The absolute temperature differences can be explained by elevation differences of the two stations, i.e. Rogers Pass 1340 m and Mt. Fidelity 1905 m, respectively.

Monthly temperature trends for the period between 1982 and 2011 for each month

![Figure 4: Maximum snow depth per year measured at Rogers Pass and Mt. Fidelity between 1969 and 2012. Dashed line shows the linear trend. The numbers indicate the trends over time between 1969 and 2012.](image)

![Figure 5: Linear trends per month (October to May) of the mean snow depth for Rogers Pass (orange) and Mt. Fidelity (blue). Trends were calculated using a 10-year moving average over 44 years between 1969 and 2011.](image)
(October to September) for the stations Rogers Pass and Mt. Fidelity are shown in Figure 2. Both stations show similar trends, i.e. increasing trends for all months except for October and March at both stations. In addition, both stations show the strongest increase during the early winter month from November to January. These trends differ from the findings from the Alps where the largest warming was found from April to June. Trends were found to be significant (p-value < 0.05) for most months except from March to May at both stations and October at Rogers Pass.

3.2 Precipitation

Monthly trends (1974-2003) of the solid precipitation rate, i.e. the fraction of the solid precipitation of the total precipitation are shown in Figure 3. Note that a 10-year moving window was applied to the solid precipitation rate before the linear trends were calculated. Significant decreasing trends where found in November at Mt. Fidelity as well as for the month of March to May at both stations and tend to be stronger for Rogers Pass. Significant increasing trends of the solid precipitation ratio were found in October for both stations. Except for a slightly increasing trend in December at Mt. Fidelity all other trends either increasing or decreasing for both stations were found to be not significant (p-value > 0.05).

3.3 Snow cover

The maximum snow depth measured between 1969 and 2012 at Mt. Fidelity and Rogers Pass is shown in Figure 4. For the given period, there was a decrease of the maximum snow depth of 12.1 cm for Mt. Fidelity and 32.5 cm for Rogers Pass. Both linear trends were found to be not significant (Rogers Pass, p-value = 0.67; Mt. Fidelity, p-value = 0.07). However, the trends found are consistent with the observation that higher elevations are less affected by climate change compared to lower elevations.

It is further consistent with the trends found for the monthly mean snow depth over the last four decades (Figure 5). Although most trends of the monthly mean snow depth found for Mt. Fidelity were not significant the monthly mean snow depth at Mt. Fidelity showed less change compared to the lower elevation station of Rogers Pass. Decreasing significant trends between 20 cm and 30 cm were found for this station. Both stations showed a significant increase of the mean snow depth in November.

3.4 Avalanches

The frequency of natural avalanches with a qualitative size (Avalanche Control Section - Rogers Pass) of medium and large tended to decrease between 1966 and 2012, whereas the frequency of explosive controlled avalanches increased during the same period (Figure 6). When both trigger types are combined there is a slightly decreasing but non-significant trend. Trends for natural and explosive controlled avalanches were found to be significant (p-value = 0.04).

A significant increase of naturally triggered avalanches was found for the winter months of January and March as well as a significant decrease of natural avalanche activity in February (Figure 7).

Figure 6: Number of avalanches with a qualitative size of medium and large separated by natural avalanches (blue) and explosive triggered avalanches (orange) as well as both combined (All, black) per year. Smoothed lines are based on a 5-year moving average. Dashed line shows the linear trend. The numbers indicate the linear decrease or increase over time between 1966 and 2012, respectively.
4. DISCUSSION

Increasing temperature trends were found for both stations and were found to be comparable with trends already found for the Northern Hemisphere (Brohan et al., 2006: HadCRUT3, +0.44 °C for 2011). However, trends were found to be not significant, which is likely related to strong inter annual variations. Homogenized data were only available for the Rogers Pass station. However, the calculated trends were found to be the same when non-homogenized data were used.

A significant negative trend, i.e. more rain, was found for Mt. Fidelity in November. This likely explains the observation of practitioners who state that in recent years, the formation of early season rain crusts has increased. The analysis of manual snow profiles observed between 1959 and 2012 showed that early season rain crusts formed more often during the last two decades (Figure 8). A segmented linear regression showed a significant breakpoint in 1993. However, this finding might have an observation bias because practitioners realized these crusts as a problem and are therefore specifically looking for them. Significant increasing trends in October, i.e. more snow, does not conflict with the formation of these early season rain crusts since a homogeneous snow cover which covers the ground roughness is a prerequisite for the formation of a distinct early season rain crust.

Mt. Fidelity showed no significant trends of the monthly mean snow depth between December and May, whereas Rogers Pass clearly showed decreasing trends for the same period. However, an increasing trend of the monthly mean snow depth was found for both stations for November. This might be related to the fact that warmer air can hold more moisture and hence intense early season storms could occur. However, this does not conflict with the formation of early season rain crust, since an early season rain crust requires snow on the ground prior to the rain event as stated above.

Trends found for the avalanche activity seem to be inconclusive. This might be related to the avalanche control work done at Rogers Pass, which likely biased the data set. That means the found decreasing trend of natural avalanches might be a result of effective control work conducted at Rogers Pass, i.e. avalanches were triggered by explosives prior to a natural avalanche release. Tracz and Jamieson (2010) showed that deep slab avalanches (natural and artificially triggered) peak in January. In the present study we found significant increasing trends of avalanche activity in January and March. This might be related to the formation of early season rain crust, i.e. deep instabilities.

5 CONCLUSIONS

An increase of the mean annual air temperature over the last three decades was found for the stations at Rogers Pass and Mt. Fidelity +0.5 °C or +0.7 °C, respectively. These trends are comparable to the increasing trends for the Northern Hemisphere. A significant decreasing trend of the solid precipitation rate, i.e. more rain, was found for Mt. Fidelity in November. The monthly mean snow depth showed significant decreasing trends for Rogers Pass especially for the late winter season. Mt. Fidelity showed no trends of the monthly mean snow depth, which is consistent with the fact

Figure 7: Linear trends (on 10-year average) for the number of natural avalanches per month (medium and large qualitative size, blue) as well as the monthly mean for the period between 1983 and 2012. Negative values (blue) indicate a decreasing trend, positive numbers an increasing trend of the frequency of natural avalanches.
that higher elevations are less affected by climate change.

The warming and the trend towards more rain events during the early season likely favours the formation of early season rain crusts, which in turn are favouring more weaknesses deep in the snowpack and potentially more deep slab avalanches.

Significant trends of avalanche activity for Glacier National Park (Rogers Pass), BC, Canada could not be found. This could be related to avalanche control work, which could have biased the analysed data, i.e. start zones were released by explosives before they released naturally. However, a trend towards more avalanches in January and March was found. If this increasing trend is related to the formation of early season rain crusts remains unknown at this point.

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