Climate change and planning for snow avalanches in transportation corridors in western Canada

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ABSTRACT
In the mountains of western Canada, good records of snowpack and avalanching over the last 30 to 50 years are available from transportation corridors through seven mountain passes. From the TransCanada Highway through Rogers Pass, no trend in avalanche activity could be detected, likely due to changes in explosive control over the decades. Using only avalanche paths at 6 other passes in which at least 75% of the avalanches were not triggered by explosives, weak trends suggest less frequent avalanches threatening highways. Given the weak or insignificant trends, we looked at snow cover records and models forced with climate change scenarios. Neither the historical trends nor the projections suggest a substantial increase in avalanches reaching transportation corridors within the current planning timeframe.

RÉSUMÉ
Dans les montagnes de l'ouest du Canada, de bons passages de neige et des avalanches au cours des 30 à 50 dernières années sont disponibles dans les couloirs de transport à travers sept cols de montagne. De l'autoroute TransCanada à travers le col de Rogers, aucune tendance à l'activité d'avalanche n'a pu être détectée, probablement en raison de changements de contrôle explosif au fil des décennies. En utilisant seulement des chemins d'avalanche à 6 autres passes dans lesquelles au moins 75% des avalanches n'ont pas été déclenchées par des explosifs, les tendances faibles suggèrent des avalanches moins fréquentes qui menacent les autoroutes. Compte tenu des tendances faibles ou insignifiantes, nous avons examiné les enregistrements de couverture de neige et les modèles forcés avec des scénarios de changements climatiques. Ni les tendances historiques ni les projections ne suggèrent une augmentation substantielle des avalanches atteignant les couloirs de transport dans le calendrier de planification actuel.

1 INTRODUCTION

Should those who plan transportation corridors in western Canada expect larger, or more frequent, snow avalanches reaching the elevations of the corridors in the next few decades?

This paper reviews the literature on past and expected changes in avalanching, as well as past and future changes in snow climate at elevations relevant to snow avalanches in western Canada. Studies from Switzerland and France are briefly summarized. In addition, we used the RCP 4.5 climate scenario to project air temperature and snowfall for 2025 and 2055 for the elevation of avalanche start zones above seven highway passes in British Columbia.

2 HISTORIC TRENDS

2.1 Switzerland and France

Using 70 years of avalanche occurrence records from the French Alps, Eckert et al. (2010a, 2010b, 2013) found an upslope retreat of the run-out distance for mostly natural avalanches with a 10-year return period, as well as a decrease in the frequency of powder avalanches.

Castebrunet et al. (2012) analysed an index of observed, mostly natural, avalanches and an instability index from a snow cover model from 1959 to 2009 in France. A time series analysis of the index shows a peak in activity during a cold snowy period around 1980 and subsequently exhibit a gradual increase that correlated with warming, notably at 3000 m. Over the entire period, no general trend in the avalanche activity index related to climate was found.

Based on 41 winters of records, Teich et al. (2012) found a significant decrease in potential avalanche days in forested areas of the Swiss Alps.

Laternser and Schneebeli (2002) found a long-term increase in precipitation but did not find an increase in long-term avalanche activity over 50 years at 54 avalanche operations in Switzerland. They noted uncertainty arising from the quality of the avalanche occurrence records.

Schneebeli et al. (1997) analyzed relations between climate and avalanche release from 1947 to 1993 and extreme snowfall events from 1896 to 1993. They found an increase in air temperature but no significant trends in snow depth or extreme snowfall events. They found no increase in days when snow depth and 3-day storm snow height exceeded 75 cm, notably in the Davos area where records were good. Based on the link between extreme weather and avalanche situations, they assumed that climatic causes for extreme avalanche periods have remained stable and did not show signs of change.

Marty and Blanchet (2011) 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 elevations and a decrease in extreme snowfall for the low and high elevations. Snowfall trends for the mid-elevations were not significant.

Summing up, snowfall, including 3-day maxima, and snow depth trends at start zone elevations in Switzerland and France are either decreasing or do not show significant trends. Although Castbrunet et al. (2012) found short term increases in avalanche activity, long term trends, most over five decades, are either decreasing or show little change.

2.2 An early study for the Canadian Pacific Railway in British Columbia

Fitzharris and Schaerer (1980) analyzed avalanches affecting the Canadian Pacific Railway from 1909 to 1979. They found a weak increase in the number of avalanches but did not consider the trend reflective of a climatic trend because of increased use of explosives in the latter years. For the period 1918 to 1979, they found the annual cumulative mass of avalanches reaching the railway decreased but this could be attributed to an increase in explosive triggered avalanches which are intended to reduce the frequency of avalanches, especially natural avalanches, reaching the railway.

2.3 Two recent studies at highway passes for British Columbia

Although not the only avalanche programs for highways in BC, seven highway passes with good historical records of avalanches are shown in Figure 1. Their coordinates as well as the elevation band for most of the start zones at each of the passes are shown in Table 1. In consultation with most of the avalanche forecasters for the highway passes, we selected a representative elevation for the avalanches start zones that most threaten each of the current highways (rightmost column in Table 1). These elevations are used for snow climate projections in Section 2.3.2.

Trends in the occurrence of avalanches reaching highways in recent decades exist but their relevance to future projections of natural avalanche activity is limited by the use of explosives, specifically

- the method of delivering explosives to start zones, which has changed over recent decades in most passes,
- the frequency of explosive use, which has increased with the increasing traffic volume, likely increases after an avalanche reaches a highway when it was open, and may vary with the preference of the avalanche forecaster at the time.

Snowfall within single storms, notably the 3-day maximum, is better correlated with the occurrence of large avalanches than snowfall averaged over periods ranging from a month to a winter (Schweizer et al. 2009). Nevertheless, the longer snowfall averages are used in this paper and others like it because these averages are more available, especially in climate projections.

Figure 1. Map of British Columbia showing the locations (dots) of the seven highway passes in this study. Rogers Pass (red dot) has been analyzed separately. Base map data © 2017 Google.

2.3.1 Glacier National Park, BC

Two snow study stations in Glacier National Park, BC, namely Rogers Pass at 1315 m and Mt Fidelity at 1905 m, have records dating back to 1965. For the analysis of long-term trends, Bellaire et al. (2016) divided the winter into three periods: early winter (September through November), mid-winter (December through February), and spring (March through May). In their analysis of weather and snowpack variables at these sites, only the following trends were found to be significant:

- Increases in air temperature were observed in mid-winter at both stations (1315 and 1905 m) but not for early winter or spring.
- The average 24-hour snowfall decreased significantly for all three winter periods at the lower station (1315 m) and for mid-winter at the upper station (1905 m). The annual maximum snowfall decreased significantly at both stations in mid-winter.
- The lower station showed a significant decrease in the maximum snow depth in mid-winter and spring. At the upper weather station, the number of early winter melt-freeze crusts increased. In some winters, such crusts contribute to hard-to-forecast avalanches throughout much of the following winter.

Table 1: Coordinates and elevations for seven highway passes

Mountain pass	Lat. (°)	Long. (°)	Pass elev. (m)	Start zone range Min. (m)	Start zone range Max. (m)	Rep. start zone elev. (m)
Rogers	51.2	-117.7	1330	950	2900	2100
Kootenay	49.1	-117.0	1770	1600	2150	1950
Ningunsaw	56.5	-129.5	650	600	1750	1400
Bear	56.1	-129.7	460	500	2050	1300
Duffey Lake	50.4	-122.5	1280	1300	2400	2150
Coquihalla	49.5	-121.1	1240	800	1900	1600
Kaslo-New Denver	50.0	-117.2	1080	1700	2200	2000

No significant trends were found for the ratio of solid to total precipitation at either station for any of the winter periods.

At the Rogers Pass station (1315 m), seven of the fifteen possible correlations analyzed by Bellaire et al. (2016) showed significant change. At the Mt. Fidelity station (1905 m), four of the 16 possible correlations were significant. This suggests more changes in snow climate are occurring at lower elevations than at higher elevations.

Bellaire et al. (2016) analyzed 27,330 avalanches observed at 140 avalanche paths in Glacier National Park between 1965 and 2014. About two thirds of these avalanches released naturally and one third were triggered by explosives. This study only found two significant trends for natural avalanches:

- An unexpected decrease in wet natural avalanches in mid-winter and spring.
- A decrease in natural avalanches in mid-winter.

Bellaire et al. (2016) caution that changes in the use of explosives may have affected the observed trends in natural avalanches. Hence, the observed trends should be considered “absence of evidence” of trends in climate-related avalanching.

2.3.2 Six other highway passes in British Columbia

Sinickas et al. (2016) analyzed historic trends in avalanches for the six of the seven highway passes in Figure 1. The avalanche programs for these six highway passes (black dots in Figure 1) are managed by the BC Ministry of Transportation and Infrastructure. Avalanching at Rogers Pass, which is managed by Parks Canada and analyzed by Bellaire et al. (2016), was excluded.

Sinickas et al. (2016) analyzed approximately 18,000 avalanches from 1981 to 2010 that occurred in about 300 avalanche paths. About 2200 avalanches reached or crossed the highways. Sinickas et al. (2016) used a Bayesian Hierarchical Model (Figure 2), which assumed the underlying probability distributions at the six passes would be similar, although the parameters at each pass were unconstrained.

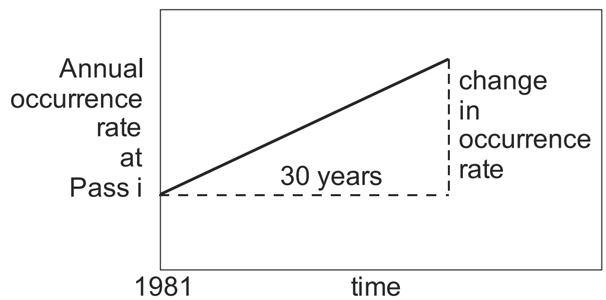

Figure 2. Annual occurrence rate over time for an individual highway pass. After Sinickas et al. (2016).

When analyzing all recorded avalanches over 30 years, changes at four of the six passes were minimal. However, Kootenay Pass showed a trend toward 31 fewer avalanches per year by 2010. Bear Pass showed a trend toward 9 fewer avalanches per year by 2010.

Since many avalanches were triggered by explosives, which can affect the occurrence of natural avalanches in the same path, Sinickas et al. (2016) reanalyzed the occurrence data using only paths in which at least 75% of the avalanches were natural (Figure 3). Kootenay Pass and Bear Pass showed a trend toward about 14 and 13 fewer avalanches per year, respectively.

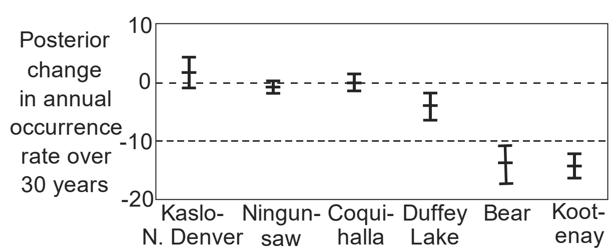

Figure 3. Change in annual occurrence rate over 30 years for avalanche paths with at least 75% natural avalanches at six highway passes in BC. The whiskers represent the 95% confidence interval. After Sinickas et al. (2016).

Sinickas et al. (2016) also used the same method to assess the change in wet and dry avalanche occurrences. Again, the significant changes were at Kootenay Pass and Bear Pass, where the decrease in dry avalanches was greater than the decrease in wet avalanches.

Limitations of the study include: assuming the occurrence rate follows a Poisson distribution; and 30 years may not be adequate to assess trends associated with climate change.

However, if there was a trend towards increasing avalanches, this method would have detected the increase. Hence, a reasonable conclusion is that there is no evidence of an increase in avalanching from 1981 to 2010 at the six highway passes.

3 FUTURE TRENDS BASED ON CLIMATE SCENARIOS

3.1 Climate scenarios and snowpack modelling, and coupling of climate, snowpack and avalanche formation models.

Projecting snow climate into the future requires assumptions about atmospheric model and future concentration of greenhouse gasses, notably carbon dioxide, in the atmosphere.

Assuming a doubling of atmospheric carbon dioxide concentration, Glazovskaya (1998) projected that snow depth, the number of days with snowfall > 10 mm, and the duration of the avalanche-prone period would all decrease in western North America.

Assuming high emissions of greenhouse gasses, O'Gorman (2014) predicts the annual mean precipitation will decrease in most areas but may increase where the surface temperature is low. Decreases in extreme daily snowfall are expected to be much smaller than in the annual mean snowfall.

To reduce uncertainty about atmospheric models, the next section uses an ensemble of 15 Global Circulation Models (GCMs) (Wang et al. 2012). For the concentration of greenhouse gasses, we chose Representative Concentration Pathway 4.5 in which emissions peak in 2040 and projected global warming increases by 1.4°C (likely range 0.9 to 2.0°C) by the period from 2045 to 2065 (Table SPM-2 in IPCC 2013).

Projected variables from the GCMs include monthly values of near surface air temperature, precipitation and precipitation-as-snow. These are sufficient for the assumption that more snowfall leads to more avalanches.

3.2 Climate trends at start zone elevations for seven highway passes in British Columbia

This section compares average values of three variables (air temperature, precipitation, and precipitation-as-snow) for three 3-month periods (September to November, December to February, March to May) for three time steps: the 1981-2010 climate normal, as well as 2025 and 2055 based on Representative Concentration Pathway 4.5 and an ensemble of 15 GCMs (Wang et al. 2012). All values are spatially interpolated for the coordinates of the seven passes in Table 1 and adjusted for the representative start zone elevation of the avalanche paths near the pass (Wang et al. 2012). All involve uncertainty due to the spatial interpolation and elevation adjustment. The 2025 and 2055 values also involve additional uncertainty due to climate modelling.

Snow climate trends in early winter (September through November in this paper), mid-winter (December through February) and spring (March through May) can differ in important ways (Bellaire et al. 2016). Figure 4 shows the climatic trends in average air temperature for these three 3-month periods. While all three periods show warming, the early winter and spring air temperatures are near the melting point whereas the average mid-winter temperatures are well below freezing. Thus, the mid-winter trends may see little shift towards more rain at start zone elevations, whereas more rain is likely in the early winter and spring.

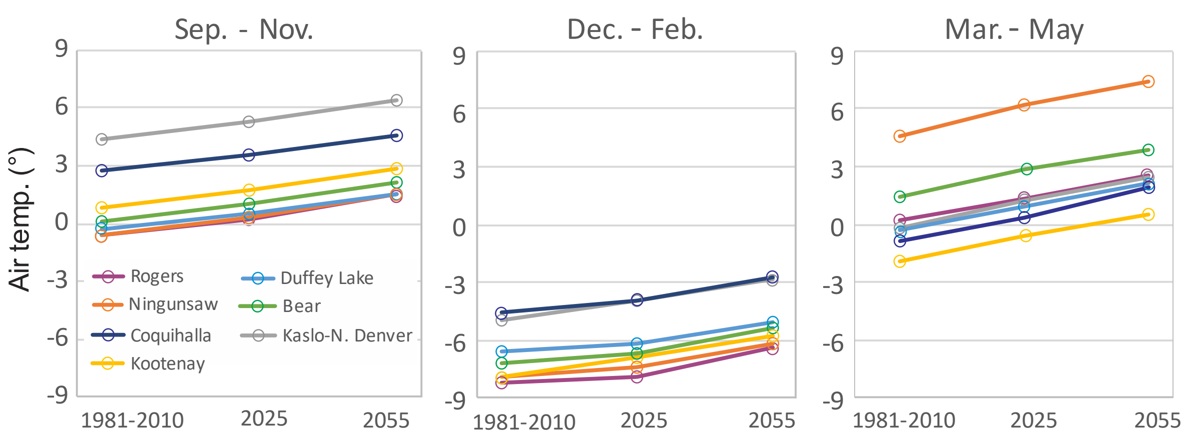

Figure 4. Average air temperature for September through November, December through February, and March through May for the seven mountain passes in Table 1. The three time steps are 1981-2010 (climate normal), as well as 2025 and 2055 based on RCP 4.5 and an ensemble of 15 GCMs.

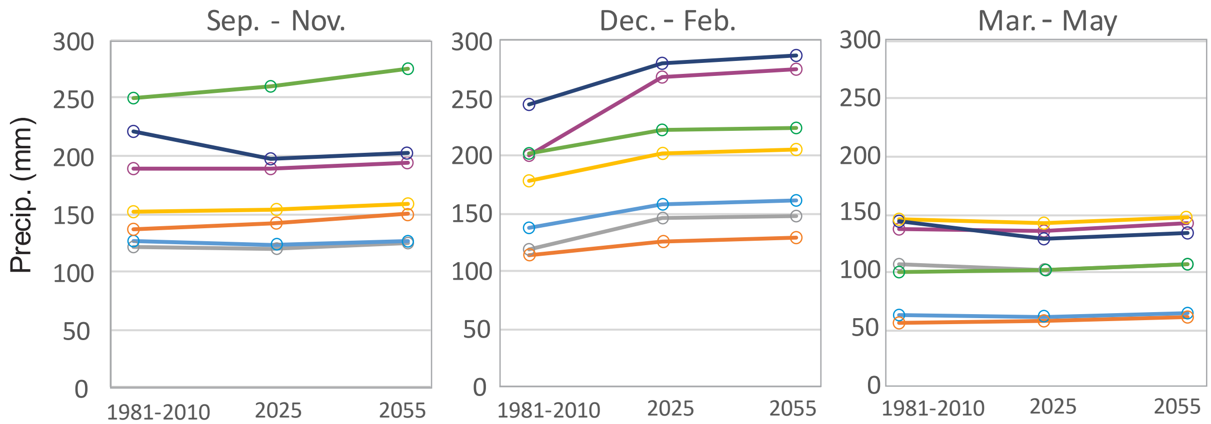

Figure 5. Average water equivalent of precipitation for the three 3-month periods at the seven mountain passes in Table 1. Line colours for the highway passes are as shown in Figure 4.

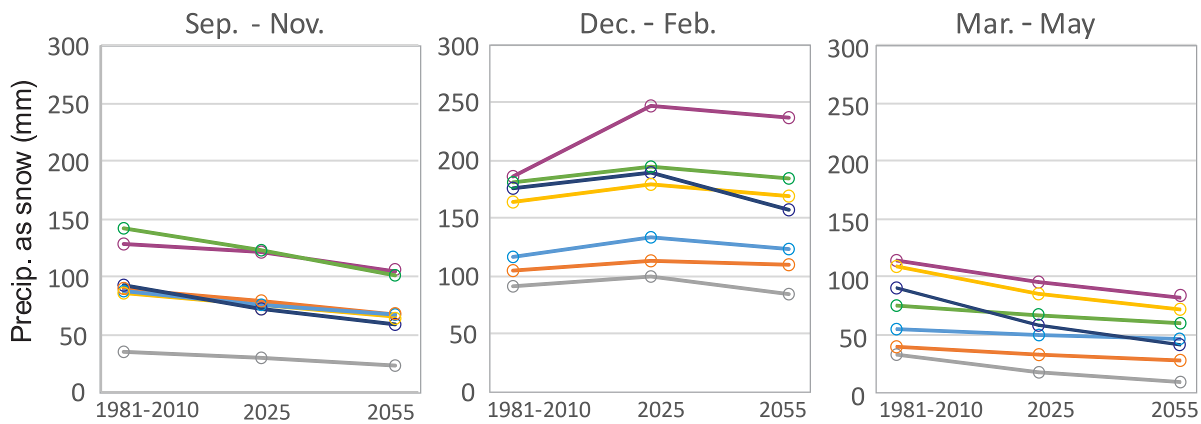

Figure 6. Average water equivalent of precipitation as snow for the three 3-month periods and seven mountain passes in Table 1. Line colours for the highway passes are as shown in Figure 4.

The climatic trends in the water equivalent of precipitation, averaged for each of the 3-month periods, are shown in Figure 5. For early winter (September through November), five passes show a weak increase, Coquihalla Pass shows a distinct decline by 2025, whereas the lowest elevation pass (Bear Pass on the Coast range) shows a distinct increase. In mid-winter, all seven passes show an increase in precipitation with Coquihalla and Rogers Passes showing the strongest increase by 2025.

All seven passes show a weak increase from 2025 to 2055. In the spring, all passes show less precipitation and only weak trends by 2025 and 2055.

Figure 6 shows the climatic trends in the water equivalent of snow-as-precipitation, averaged within each of the three 3-month periods. In early winter, all seven passes show a decrease in snow-as-precipitation, which is consistent with the air temperature being near the melting point and increasing (Figure 4).

Except for Rogers Pass, the other six passes show a weak increase in precipitation-as-snow (9 to 16 mm, average 13 mm; 7% to 13%, average 9%) in mid-winter (December through February) by 2025, followed by a decrease. In mid-winter, Rogers Pass shows a 62 mm (29%) increase by 2025, followed by a decrease. The increases by 2025 at the seven passes is consistent with the increase in precipitation in Figure 6 and the sub-freezing temperatures in the start zones (Figure 4).

Consistent with the warming temperatures near the melting point and weak trends in precipitation, all seven passes show a decrease in precipitation-as-snow through 2025 and 2055.

3.3 Coupling of an atmospheric model with snowpack and avalanche formation models

By coupling an atmospheric model with snowpack evolution models and avalanche formation models, it is possible to model snowpack layers and project slab avalanche formation. Martin et al. (2001) used this approach for the Alps in France and found that with a 10% increase in precipitation and a temperature rise of 1.8°C, the natural avalanche hazard may decrease slightly in winter (mainly in February) and decrease more in May and June. Under the same change in temperature and precipitation, natural wet snow avalanches were projected to increase.

When run for the next 35 to 85 years for the French Alps, climate models suggest little change in winter precipitation and an increase in temperature (Castebrunet et al. 2014). When coupled with snowpack models, a shortening of the dry snow season and an increase in the wet snow season projected. The changes are expected to be weaker in mid-winter and stronger in the spring. For avalanche activity, the coupled models indicate a 20 to 30% decrease in mean and inter-annual variability of avalanche activity. The decrease is expected to be strongest in the spring and at low elevations.

Using various climate change scenarios for 2030 and 2100 and global circulation models for a US ski area, Lazar and Williams (2008) found that the first days with air temperature above freezing would occur earlier in the latter part of winter, leading to earlier wet avalanches.

4 DISCUSSION

To a first approximation, more snowfall or precipitation-as-snow over one or more months suggests more avalanches of a given magnitude/runout, i.e. a decrease in the return period of avalanches reaching a specified point in the runout zone, such as a transportation corridor. However, there are at least three other factors that influence the return period of large avalanches in runout zones:

- The occurrence of large avalanches correlates better with heavy snowfall over several days than with increased snowfall over one or more months.
- Schweizer et al. (2009) found that the amount of snowfall associated with a 10-year runout occurred every 2 to 5 years. The reduction in runout frequency due to a threshold level of multi-day snowfall is likely due to the inconsistent presence of favourable snowpack properties such as a potential failure layer in the snowpack.
- With less snowfall in early winter, the runout zones will be rougher (less smoothing by early winter avalanches), providing more friction and reducing runout in mid-winter.

5 CONCLUSIONS

5.1 Trends in snow climate at relevant elevations in recent decades

Studies of snow climate over recent decades in western Canada for typical elevations of avalanche start zones show warming and snow stations in Glacier National Park show a decrease in snow depth and daily snowfall (Bellaire et al. 2016). None of the analyzed sites show an increase in snow depth or daily snowfall. For similar elevations in the French and Swiss Alps, there are comparable historic trends plus a decrease in 3-day snowfall. However, western Canada may not be experiencing comparable trends in snow climate as the Alps.

5.2 Snow climate projections

At the elevations of seven highway passes in British Columbia, warming is projected for early winter, mid-winter and spring. Precipitation-as-snow is projected to decrease in the early winter and spring. However, in mid-winter, six of the seven passes show a small increase in snowfall by 2025 followed by a decrease to 2055. At the other pass, Rogers, the increase by 2025 is greater, followed by a comparable decrease to 2055. The possible increase in avalanches starting in mid-winter may not result in more avalanches reaching highways because of decreased snowfall at lower elevations and decreased early winter avalanches, both of which will contribute to greater roughness in the runout zones where most avalanche-prone highways are located.

5.3 Trends in avalanching

Limited historic studies of avalanching in western Canada do not show an increase in natural avalanches (Fitzharris and Schaerer 1980, Sinickas et al. 2016). Uncertainty in the data and/or analytical methods prevent conclusions regarding a decrease in natural avalanches. For similar elevations in France and Switzerland, long-term trends in avalanche activity are either decreasing or insignificant. However, western Canada may not be experiencing comparable trends in snow climate and hence in avalanching.

5.4 Future projections in avalanche activity

For the French Alps, Martin et al. (2001) and Castebrunet et al. (2014) predict a decrease in dry natural avalanches but a potential increase in wet avalanches. In the Colorado Mountains, Lazar and Williams (2008) suggest wet avalanches may start earlier in the winter.

5.5 Some limitations

The long-term trends identified in this paper may not reflect a change in inter-annual variability associated with climate change, i.e. are infrequent winters with many large avalanches more likely? (Fitzharris and Schaerer 1980, Castebrunet et al. 2012, Eckert et al. 2013).

A few studies suggest wet avalanches may increase in the coming decades (e.g. Martin et al. 2001). In most paths, large wet avalanches do not run as far as large dry avalanches. However, when avalanches runout in gullies, wet avalanches may run farther than dry avalanches and potentially present an increase in the hazard to transportation corridors in gullied avalanche paths.

5.6 Summary

Most studies do not suggest an increase in avalanche activity at the elevations at which transportation corridors cross mountain passes in western Canada or western Europe. However, there is too much uncertainty to plan for a decrease in avalanche activity in western Canada. Sources of uncertainty include the analytical methods, climate projections, whether inter-annual variability will change, whether snow storms will become more severe, assuming climate change in western Canada will be similar to western Europe, and/or a possible increase in long-running wet avalanches, notably in gullies.

5.7 Future research

As data sets become longer and data quality improves – especially for avalanche occurrence data – there is merit in further analysis of avalanche trends and correlations with snow climate variables.

Projections in snow climate for relevant elevations are sure to improve. However, the correlation between snowfall and avalanching will not improve substantially unless extreme snowfall for multi-day storms can be extracted from the climate models. Coupling of climate models with snowpack evolution models and avalanche formation models will involve substantial model uncertainty but is nevertheless promising.

6 ACKNOWLEDGEMENTS

Our thanks to Steve Brushey, John Buffery, Kevin Maloney, Mark Talbot and Doug Tuck from the BC Ministry of Transportation and Infrastructure for advice on relevant elevations of avalanche start zones above highway passes in BC.

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