Historic and Projected Climatology for the In-SHUCK-ch FSR

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Objective: Provide historic and projected weather and climate data to inform the PIEVC protocol to assess risks to the In-SHUCK-ch FSR resulting from a changing climate.

Report produced for Brian Chow, Engineering Branch, BC Min Forests Lands and Natural Resource Operations, Victoria.

14 May 2015

Acknowledgements

Stephen Sobie and Trevor Murdock of the Pacific Climatic Impacts Consortium (PCIC) produced historic and projected climate data for the area bounding the In-SHUCK-ch Forest Service Road. They also produced the graphics used in Figures 1, 2 and 3 and provided review comments on this report. PCIC supplied the data base for detailed analyses of changes and data for specific weather stations. Participants at a workshop provided guidance on selecting and defining the magnitude of thresholds for weather-induced risks to infrastructure. Jim Barnes and Dirk Nyland (BC Min Transportation and Infrastructure) provided guidance on the PIEVC protocol.

Executive Summary

Adapting infrastructure to a changing climate is critical to reduce risks to public safety. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol is a five step process used to assess the engineering vulnerability of infrastructure. An important component of this risk assessment procedure is identifying the magnitude of current and future weather and climate conditions that may affect the infrastructure.

The In-SHUCK-ch forest road was identified by Engineering Branch, MFLNRO, for a pilot project to apply the PIEVC protocol. This approximately 80 km long road runs by the Lillooet River from Harrison Lake to Lillooet and is surrounded by mountains over 2000m elevation. The road provides access for first nation communities, forest harvesting, recreation, and hydro power infrastructure.

Long-term weather stations adjacent to the area were used to describe historic climate, define thresholds and evaluate the downscaled spatial climate change data base. These data also enabled estimating the magnitude of projected future conditions rather than just changes in climate. The Pacific Climate Impacts Consortium's (PCIC) provided downscaled daily historic and projected maximum and minimum air temperature and precipitation grids at a resolution of about 10 km. PCIC produced climate summaries for an ensemble of 12 models and the RCP 4.8 and 8.5 emission scenarios for the In-SHUCK-ch area. Assessments for specific grids were made by the author using four models.

Two workshops with local Engineering Branch staff, MFLNRO, MoTI staff, a geological consultant and local road operators helped define appropriate weather/climate variables and their thresholds for the risk assessment. This information was combined with criteria used by MoTI in previous PIEVC assessments. An analysis was made of weather conditions during October 2003 and December 2014 storms that had negative impacts the road. The 1-day and 3-day totals of precipitation during these storms were within the 20 to 30 year return period. This suggests that the 20-year return period values were appropriate to use as thresholds to assess future risk to the road infrastructure.

Warming is projected to occur in all seasons with temperatures increasing by 2 to 4°C by 2050s (2041-2070 period) and 4 to 7°C by 2080s (range is a function of all models and the two RCPs). The current 20-year return extreme maximum temperature averages 34°C for the area. This is projected to increase to 38°C for RCP 4.5 and 41°C for RCP 8.5 by 2050s. Temperatures will be greater at the road level reaching the mid 40's by 2080s. Summers are projected to be drier and winters wetter. The 20-year return 1- and 3-day annual maximum precipitation are projected to increase by 20 to 50%. The projected increase in fall and winter precipitation will not be sufficient to offset the effect of warming on reducing the winter snowpack.

In conclusion, the most noticeable features of the projected changes in climate are the increase in summer heat (maximum temperatures indices) and a large reduction of the return period for what are currently 20-year 1- and 3-day precipitation totals. Increases in the winter temperature result in a decrease in weather events that influence road conditions, e.g., a reduction the number of freeze/thaw events, a reduction snow pack depth and fewer snow fall events.

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Introduction

Over the last 60 years average annual temperatures in south western BC have increased by about 1°C. Temperatures are projected to increase by a further 2 to 5°C over the next 80 years. July and August precipitation is projected to decrease by approximately 10% while in the rest of the year precipitation could increase by about 10% (Fettig et al., 2013, PCIC 2013). Changes in extreme conditions will likely accompany the changes in the mean and dry periods during the summer will likely become more intense (Sillmann et al. 2013). The warming climate could result in the increase in number and intensity of events such as "Pineapple Expresses" and "Atmospheric Rivers" that have already had major impacts on coastal BC. Such changes in climate will increase the risk of weather-related impacts to forest growth and composition, and the accompanying changes in the frequency of landslides, floods and debris flows could impact the infrastructure associated with access and use of the land base.

Adapting infrastructure to a changing climate is critical to reduce risks to public safety. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol is a five step process to assess the engineering vulnerability of infrastructure. The assessment is intended to assist with identifying measures to adapt to a changing climate that can be incorporated into the design, development and management of existing and planned infrastructure (Lapp 2011). An important component of this risk assessment procedure is identifying current and future weather events that may affect the infrastructure.

The In-SHUCK-ch forest road was identified by Engineering Branch, MFLNRO, for a pilot project to apply the PIEVC process. The experience of MoTI staff was used to guide the application of the process and local MFLNRO staff and operators of the road were involved in the accompanying workshops. The Pacific Climate Impacts Consortium (PCIC) were contracted to provide information on past and projected future climate conditions for the area and Dave Spittlehouse, Competitiveness and Innovation Branch, MFLNRO, was asked to synthesis these data, collate other weather and climate information as necessary and present the data in the workshops. This report presents the historic and projected climatology and combines it with information from the workshop on potential thresholds for risk of damage to infrastructure. This information is summarized in a PIEVC scoring table.

Methods

The In-SHUCK-ch forest road is about 80 km long paralleling the Lillooet River from Harrison Lake to Lillooet (Figure 1). It provides access for first nation communities, forest harvesting, recreation and hydro power infrastructure. For most of its route it is at 80 to 250 m elevation in an approximately 1 km wide valley with surrounding terrain rising to over 2000 m. Consequently, weather conditions at the road will be strongly influenced by the weather at higher elevations, e.g. orographic effects on precipitation, as the source of water for the streams that the road crosses and terrain stability issues. For this analysis an area about 10 km either side of the road (the In-SHUCK-ch boundary – Figure1) was defined by PCIC for the spatial climate summaries.

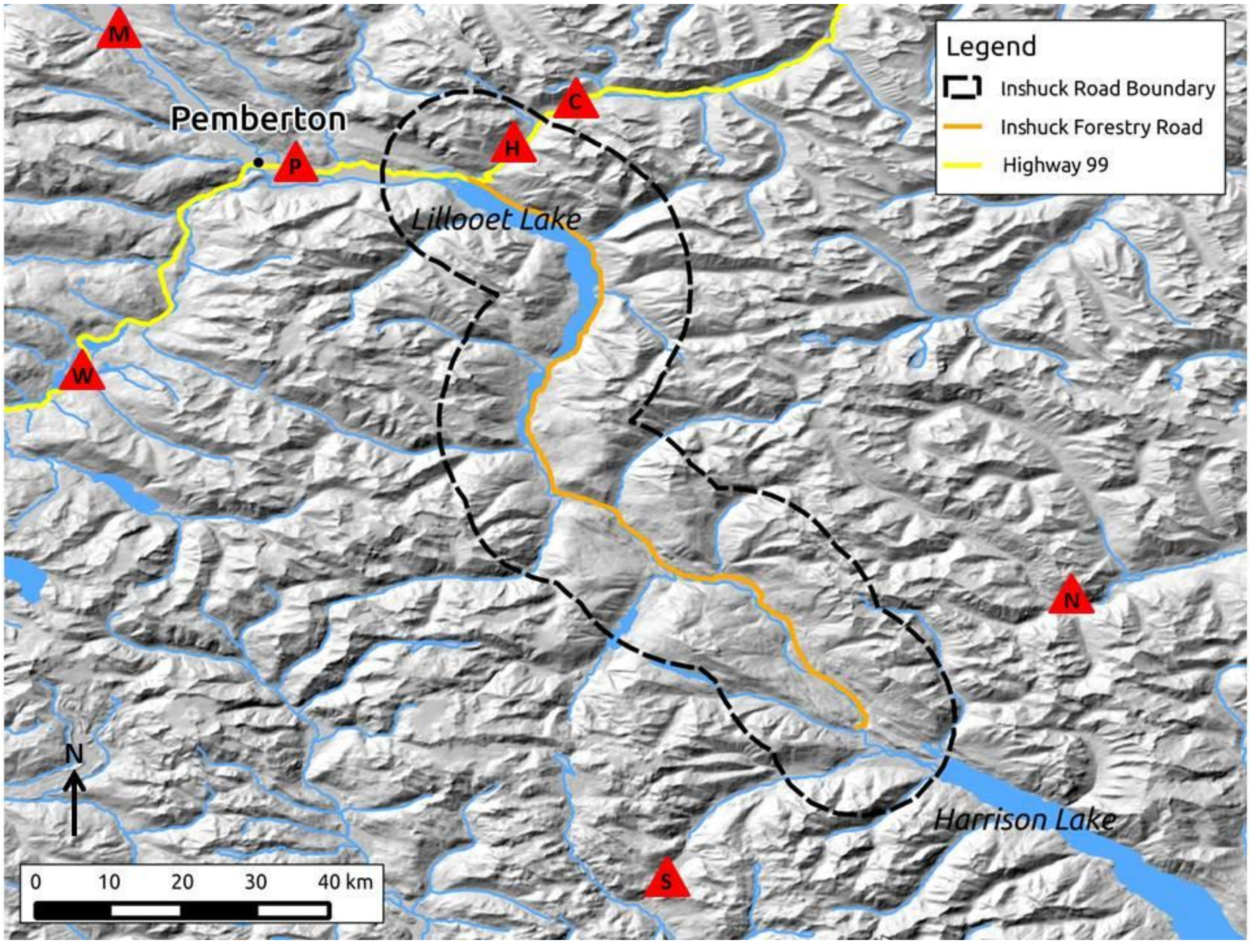


Figure 1: In-SHUCK-ch road (orange line), boundary area (dotted line) and adjacent weather stations (red triangles). M=Pemberton Meadows, P=Pemberton airport, H=Pemberton Hatchery, C=Cayoosh Summit, W=Whistler, N=Nahatlatch, S=Stave Upper. The Cheakamus Upper station is just off the map to the west of the Whistler station and Big Silver2 is southeast of Nahatlatch. Base map produced by Pacific Climate Impacts Consortium (2015).

Weather and Climate Data

Historic weather data: There are no long-term weather stations in the valley. However, there are stations of Environment Canada, BC Hydro, BC Min. TI and BC Min. FLNRO networks adjacent to the area. Data from these stations (Table 1) were used to describe historic extreme precipitation occurence, define thresholds, evaluate the downscaled spatial climate change data base and enable estimating the magnitude of projected future conditions. Weather conditions were determined for October 2003 and December 2014 storms where there was damage to infrastructure. Daily temperature and precipitation data were obtained from PCIC's BC Station Data portal (http://www.pacificclimate.org/data/bc-station-data) and supplemented with data from the various network web sites. Data were analysed in Excel.

Table 1: Weather stations adjacent to the In-SHUCK-ch boundary area. EC is Environment Canada, BCH is BC Hydro, MoTI is Min. Transportation and Infrastructure and FWS is Min. Forests, Lands and Natural Resource Operations fire weather network. Grid indicates midpoint and elevation of the BCCAQ grid (see text) that contains the weather station. Values are given where comparisons were made between stations and gridded data.

Station	Location	Grid	Period	Comments
Whistler - EC	50.13N, 122.915W, 658 m	50.125N, 122.958, 879 m	12/1967-12/2014	Missing data filled using Alta Lake, Alta2, Blackcomb
Stave Upper - BCH	49.6237N, 122.4021W, 930 m	49.625N, 122.375W, 1160 m	01/1960-12/2014	
Stave Lower - BCH	49.5561N, 122.3219W, 330 m		01/1960-12/2014	
Cheakamus Upper - BCH	50.122N, 123.133W, 880 m	50.125N, 123.125W, 998 m	01/1960-09/2014	
Cayoosh Summit auto - MoTI	50.380N, 122.474W, 1350 m	50.375N, 122.458W, 1717 m	09/1997-12/2014	October to April in early years
Cayoosh Summit manual - MoTI	50.376N, 122.471W, 1280 m		1978-1997 October to April	Added to auto record without adjustment
Nahatlatch - FWS	49.9018N, 122.021W, 1400 m		07/2001-12/2014	Cannot measure precip as snow
Big Silver 2 - FWS	49.691N, 121.86W, 561 m		07/2009-12/2014	Missing data. Cannot measure precip as snow
Pemberton Hatchery - EC	50.333N, 122.5W, 256 m		04/1908-09/1936	
Pemberton Meadows - EC	50.45N, 122.933W, 223 m		08/1912-01/1967	Missing data in 1960s
Pemberton A - EC	50.31N, 122.73W, 204 m		01/1984-12/2014	Missing data. Unreliable snow measurements

Monthly normals for the 1971-2000 period were obtained using ClimateBC v5.1 (Wang et al. 2006, 2012). A 1 km grid of latitude, longitude and elevation (generated by Adrian Walton, MFLNRO) for an area 10 km either side of the In-SHUCK-ch road was used as input to ClimateBC v5.1. Data were output as csv files and imported in to Excel for analysis.

Projected weather data: Daily historic and projected data for the In-SHUCK-ch area were obtained from PCIC's database of downscaled daily Canada-wide climate change scenarios (PCIC 2014). The data were downscaled from GCM output using Bias Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ). BCCAQ is a hybrid approach that combines the methods of Maurer et al. (2010) and Gudmundsson et al. (2012). Maximum and minimum air temperature and precipitation are available for grids with a resolution of 300 arc-seconds (0.0833 degrees, or roughly 10 km) for the period of 1950-2100. The data represent a point at the centre of a grid at an elevation determined in creating the 1951-2005 Anusplin data base (McKenney et al. 2011). The point value is assumed to represent the whole grid. The model data are Global Climate Model (GCM) projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). The Anusplin data were used to determine downscaling parameters for each GCM. This information was then used to downscale the projections of future climate for specific Representative Concentration Pathways (RCP) (Taylor et al. 2012) for 1951-2100. The 1951-2005 data used are the downscaled GCM weather data and thus individual days and months may not match the actual weather of these days at a station. The GCM data should be viewed as providing distributions of the weather conditions that occur over a number of years, e.g., 30-year normals periods.

PCIC used an ensemble of 12 models for RCP 4.5 and for 8.5 to determine projected changes in climate for the In-SHUCK-ch boundary area. Assessment for specific grids/location was done by Dave Spittlehouse using four GCMs based on the recommendation on the PCIC web site (PCIC 2014) that provide a wide spread in projected future climate (CNRM-CM5-r1, CanESM2-r1, ACCESS1-0-r1, inmcm4-r1). The gridded data were accessed via an interactive map to select the appropriate grids and download scenarios as csv files. Data were analysed in Excel.

The 1950-2005 Anusplin data used to downscale the GCM data was created with data from Environment Canada's network. The PRISM base data used by ClimateBC was developed with these data plus data from weather station networks of provincial agencies. This increased station density should improve the spatial climate mapping and provide useful information to evaluate and adjust the BCCAQ data for BC. Projections of normals for 2041-2070 and 2071-2100 periods were obtained using ClimateBC v5.1 and the 1 km grid of latitude, longitude and elevation for an area 10 km either side of the In-SHUCK-ch road.

Defining Threshold Weather Conditions

Friele (pers com 2015 –Appendix I) summarizing data from Septer (2006) indicated that floods, landslides and debris flows have occurred roughly every 5 years in the Pemberton area over the last 80 years. A December 2014 storm caused extensive damage to the In-SHUCK-ch road (Schultz 2015). Determining the weather conditions that could have been at least part of the cause of such damage is important for assessing risk to infrastructure in warming climate. In this exercise, data for weather stations adjacent to In-SHUCK-ch road area were used to describe October 2003 and December 2014 storms. Local knowledge of the area and expert opinion provided during the workshop was also used help define thresholds for weather variables. However, as Church and Miles (1987) and Jacob et al. (2006) note, not all extreme weather events cause problems. There can be an accumulation of a number of events before the trigger event occurs. Consequently, it may be best to be cautious and not "set the bar too high" when defining threshold weather conditions above which there may be risks to infrastructure. The selected weather conditions and their relevance to the road as determined in the workshops are shown in Table 2. High amounts of precipitation appear to be a major concern. Consequently, the return periods of 1-, 3- and 5-day total precipitation events were determined for the October 2003 and December 2014 storms.

Table 2: Climate variables identified at the workshops for evaluating risk to road infrastructure.

Climate variables	Relevance
Days above a maximum temperature	Bridge design
Average maximum temperature over 7 days	Measure of short term high temperature relevant to fire indices, landslide trigger
Extended period with warm to high temperatures and minimal rain	Implications for dryness leading to: dust abatement, cut slope ravelling, rockfall & wildfire effects (increased runoff, debris flow potential)
Daily temperature variation	Implication for bridges
Number of days with freeze-thaw events	This parameter measures how much frost growth will occur in subsoil, below foundations etc. Rock fall related to freeze/thaw (e.g., km 1 on the In-SHUCK-ch)
Continuous number of days with maximum temperature below threshold	Ice build-up on rock faces resulting in rock and ice fall onto road prism. Ditch and culvert ice build up
Degree days below 0°C	Mainly affects how thick the road gravels need to be to deal with frost heaving in the subsoil. Frost >2ft depth
Annual Precipitation	Water management
Extreme rainfall in 24 hour period	Culvert and bridge design, road surface, safety
Sustained rainfall: number of consecutive days greater than a threshold	Culvert and bridge design, road surface, safety
Antecedent rainfall followed by a significant event	Impacts to cut/fill slopes, landslides
Snow frequency: days with snow fall > 10 cm	When need to plow road
Snow accumulation: days above a specific snow pack depth	Measure of how much snow accumulates on road edges due to snowfall and from snow ploughing. Snow on hills above road.
Rain-on-snow: Number of events	Excessive runoff
Rapid snowmelt	Driver for lake levels during melt period
Rain on frozen ground	Rain on frozen ground resulting in surface icing - traction and runoff issues

Evaluation of Gridded Data

Creation of the Anusplin grids required interpolation between weather stations to areas with no measurements. This and downscaling the GCM data to the 10 km grids increases the uncertainty of the data. Also, the gridded data represent a specific elevation within the grid. In mountainous terrain there is a range of elevations within the grid and the data may not well represent the specific location of interest or provide a true spatial average. Weather station data and the ClimateBC data were used to evaluate the gridded data. The 1971-2000 normals were generated from the daily data for the four GCMs noted above for grids containing the weather stations (Table 1) and compared to the normals of the weather stations. Normals were also generated using ClimateBC for the station and for selected grids with the In-SHUCK-ch boundary area. Monthly differences in temperature and ratio of precipitation between stations or ClimateBC and grid data were calculated. Annual extreme 1-, 3- and 5-day total precipitation and the number of snow events at the weather stations were also used to evaluate the grid-based data. The snow events variable is important because it requires reliability in temperature and precipitation variables and because it involves thresholds that would be affected by bias in a variable.

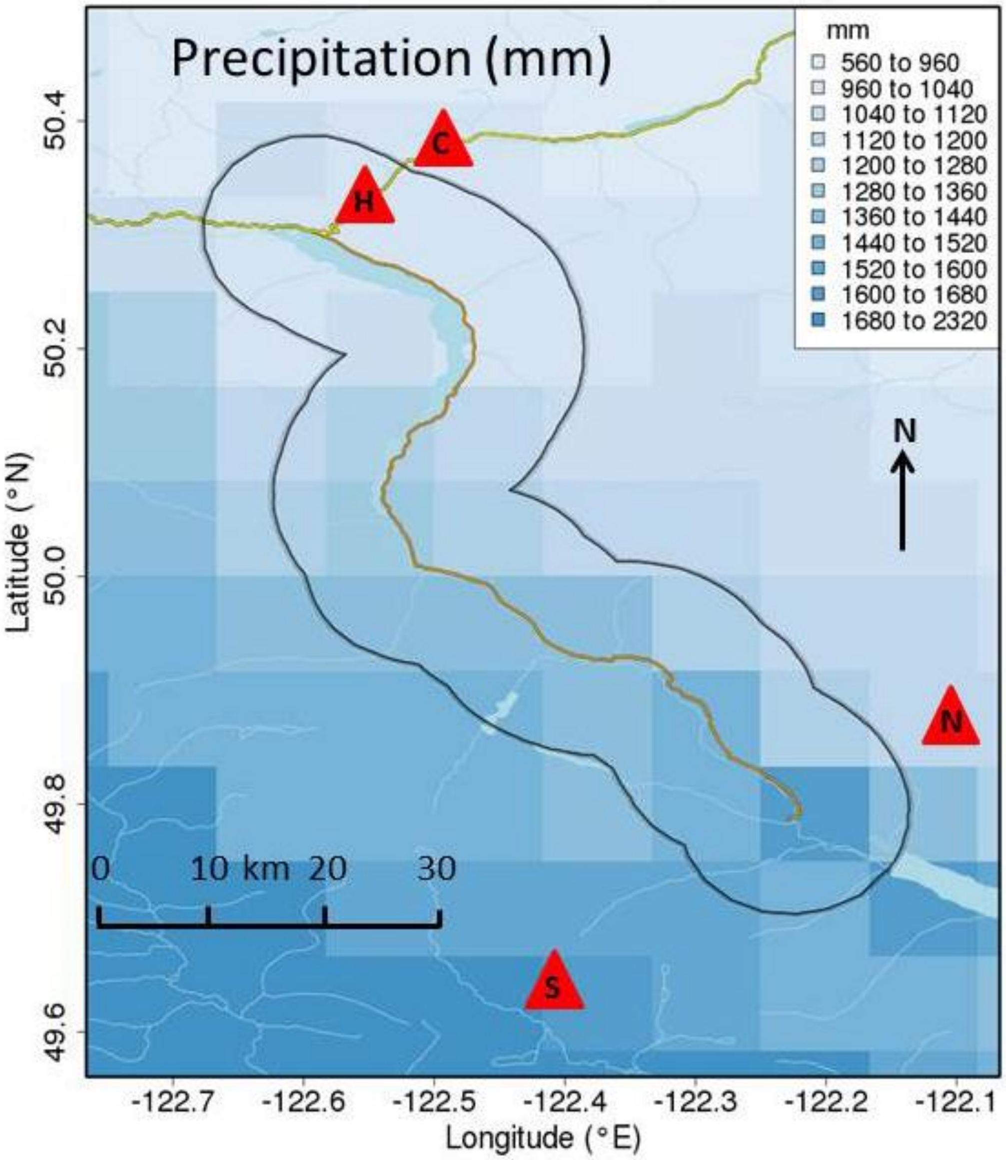


Figure 2: Gridded mean annual precipitation (mm) for 1971-2000 normals. The orange line is the In-SHUCK-ch road, the green line is highway 99, the black line is the boundary of the area for spatial averages and the red triangles indicate the weather stations. H=Pemberton Hatchery, C=Cayoosh Summit, N=Nahatlatch, S=Stave Upper. Precipitation map produced by Pacific Climate Impacts Consortium (PCIC 2015).

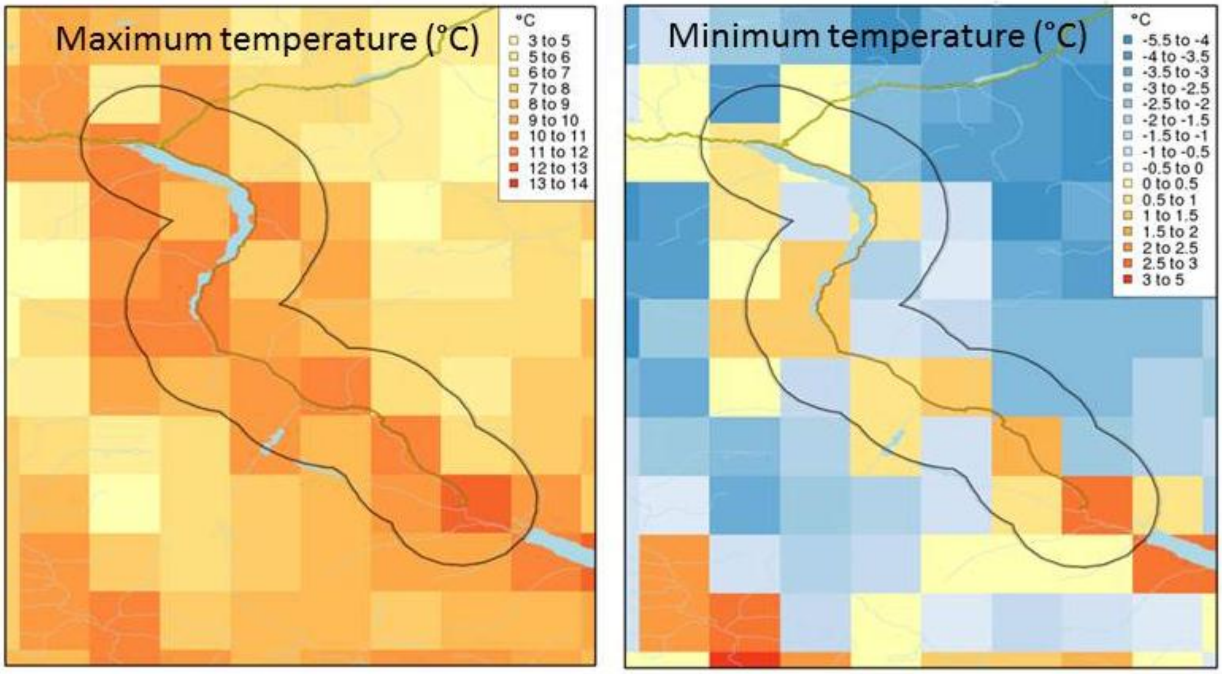


Figure 3: Gridded mean annual maximum and minimum temperature (°C) for 1971-2000 normals. The orange line is the In-SHUCK-ch road, the green line is highway 99 and the black line is the boundary of the area for spatial averages. Graphics produced by Pacific Climate Impacts Consortium (PCIC 2015).

Synthesis

PCIC produced spatial averages of 1971-2000 normals (Figures 2 and 3) and projected future climates for the boundary area. These data include areal average, Climdex indices, extremes and return periods of various measures precipitation and temperature. I produced the comparisons between stations and grids. The difference or ratios of monthly grid data to weather station or ClimateBC data were used to adjust the daily gridded temperature and precipitation data to specific locations as necessary. This bias correction is similar to the climate imprint method of Hunter and Meentemeyer (2005).

Daily data from grids or stations were imported into spreadsheets. These automatically calculated a range of climate variables and days above or below thresholds identified at the workshops. A 1-dimensional snow accumulation and melt model (modified from Spittlehouse and Winkler 2004) was used to calculate snow pack depth, melt rate, and rain on snow occurrence. The model uses a temperature index method to melt snow when the pack is ripe for days with <25 mm rain and mean daily air temperature >-1°C. Higher rainfall events are assumed to be windy and melt is driven by the sensible and latent heat fluxes to a pack at 0°C and a daily wind speed of 5 m/s or 7.5 m/s (rain>75 mm). If forest cover is present, snow is intercepted and sublimated, and the temperature melt coefficient and wind speed reduced. In this analysis calculations are for a non-forested area only.

Table 3: 1971-2000 normals for weather stations of annual average maximum (Tmax) and minimum (Tmin) temperature, precipitation (Ppt), maximum 1-day (1dPx) 3-day (3dPX) and 5-day (5dPx) precipitation in the 30 years and average number of days with >15 cm snow fall. Grid is values for the 10 km grids, and Grid Adjust is from the daily grid values adjusted using the difference or ratio of the grid normals to the weather station. ClimateBC is the estimate for the station location from ClimateBCv5.1.

a) Whistler

Location	Tmax °C	Tmin °C	Ppt mm	1dPX mm	3dPx mm	5dPx mm	Snow days
Whistler	11.2	1.0	1262	79	143	204	8.1
Grid	10.1	0.3	1417	78	148	182	8.5
ClimateBC	11.1	1.4	1307	N/A	N/A	N/A	N/A

b) Cheakamus Upper

Location	Tmax °C	Tmin °C	Ppt mm	1dPX mm	3dPx mm	5dPx mm	Snow days
Cheakamus	9.4	2.0	2021	131	250	292	16.1
Grid	9.6	-0.1	1449	82	143	187	18.5
Grid Adjust	9.4	2.0	2021	128	199	242	12.5
ClimateBC	9.8	0.9	1901	N/A	N/A	N/A	N/A

c) Stave Upper

Location	Tmax °C	Tmin °C	Ppt mm	1dPX mm	3dPx mm	5dPx mm	Snow days
Stave U	10.3	3.0	3052	190	334	399	17.5
Grid	8.5	-0.2	1669	110	167	203	12.8
Grid Adjust	10.3	3.0	3053	186	260	334	17.8
ClimateBC	9.8	2.0	2966	N/A	N/A	N/A	N/A

d) Cayoosh Summit (1979-2014)

Location	Tmax °C	Tmin °C	Ppt mm	1dPX mm	3dPx mm	5dPx mm	Snow days
Cayoosh	8.6	-3	930	78	136	181	5
Grid	6.6	-3	997	62	94	106	6
Grid Adjust	8.6	-3	938	72	102	114	5.1
ClimateBC	8.0	-1.9	983	N/A	N/A	N/A	N/A

Results

Evaluation of Gridded Data

The annual 1971-2000 normals for maximum and minimum air temperature and precipitation for the stations, ClimateBC and the gridded downscaled GCM data (BCCAQ) are presented in Table 3. BCCAQ compares favourably with Environment Canada's Whistler station. Monthly temperatures (not shown) are within 0.2°C and consequently well predicted on an annual basis. Similarly, monthly and annual precipitation agrees to within 5% (not shown). The extreme 1- and 3-day precipitation is well predicted but the 5-day is under estimated. Cumulative distributions of annual maximum precipitation over the 30 years (not shown) show a similar shape. Snow events are also well predicted for Whistler. As expected, ClimateBC gives monthly temperature and precipitation data similar to the measured values.

There is a small difference between the GCMs in the values for normals. Temperatures agree to ±0.1°C while annual precipitation is usually within ±50 mm. This is a result of downscaling process being calibrated with data for all of 1950-2005. Consequently, there will be discrepancies between the GCMs as the time period becomes shorter.

Whistler and the grid elevation are similar and a large part of the area in the grid is at relatively low elevation. The Cheakamus Upper, Stave Upper and Cayoosh Summit weather stations are at higher elevations than Whistler and within narrow valleys. The BCCAQ temperature and precipitation data do not match the stations and grid elevation is different (Table 1). This elevation difference may partially explain discrepancies in temperature but not the substantial underestimation in the precipitation. The latter probably results from data from these stations not being available in creating the Anusplin data base and a conservative approach being used in spatial interpolation of precipitation. As expected, ClimateBC gives monthly temperature and precipitation data similar to the measured values. The climate base layers it uses included the above-mentioned weather stations in its creation.

Table 4: 1971-2000 normals for annual average maximum (Tmax) and minimum (Tmin) temperature, precipitation (Ppt) for grids of BCCAQ data and from ClimateBCv5.1. BCCAQ is one value for a grid at the elevation noted while ClimateBC is based on 55 points within the grid (ClimateBC ave) that account for the variation in elevation. ClimateBC estimates are also given separated into three elevation range within the grid. Coordinates are the centre of each grid and the elevation.

a) 50.125N, 122.541W, 682 m

Location	Tmax °C	Tmin °C	Ppt mm
Grid	11.4	1.2	1200
ClimateBC ave	11.1	1.1	1171
100-500 m	12.7	2.1	993
>500-1000 m	10.8	0.9	1225
>1000 m	8	-0.8	1461

b) 49.792W, 122.291W, 833 m

Location	Tmax °C	Tmin °C	Ppt mm
Grid	10.2	0.8	1510
ClimateBC ave	10.5	2.1	1742
100-500 m	12.8	3.9	1589
>500-1000 m	11.2	2.6	1669
>1000 m	8.1	0.3	1926

c) 49.875N, 122.291W, 667 m

Location	Tmax °C	Tmin °C	Ppt mm
Grid	11.4	1.8	1565
ClimateBC ave	11.2	2.2	1543
100-500 m	13.1	3.6	1309
>500-1000 m	10.8	1.9	1632
>1000 m	7.7	-0.4	1924

Adjusting the daily BCCAQ data using differences between the station and BCCAQ monthly normals resulted in an improvement in the annual values (Table 3). The estimate of the extreme 1-day maximum precipitation is substantially improved but the 3- and 5-day values are still under predicted. The estimate of snow events is improved.

Selected BCCAQ grids within the In-SHUCK-ch road area and ClimateBC spatial averages are presented in Table 4. The BCCAQ grids are in mid-range of elevations within the grid and two of the three examples (Table 4a and 4c) provide a reasonable representation of the climate compared to ClimateBC. The wetter grid (Table 4b) is not as well represented by BCCAQ at any elevation. It is close to the Stave Upper weather station which is not well represented without a grid adjustment (Table 3).

Defining Extreme Events

20-year return period 1-, 3- and 5-day precipitation totals for the weather stations with sufficient record length are presented in Table 5. The 1-, 3-, and 5-day totals for the upper half of the road boundary are 75, 135 and 160 mm, respectively. The lower portion of the road would have values between these and those for Stave Upper. Data for grid cells for the area (Table 4) suggest values of 80 and 150 mm for 1 and 3 day periods, though as noted above the 3-day value may be underestimated.

Table 5: 20-year return period 1-, 3- and 5-day precipitation totals calculated for the length of the weather station record (see Table 1). Cayoosh Summit is based on a combined record of the manual and auto stations.

Station	Cayoosh Summit	Pemberton Hatchery	Pemberton Meadows	Whistler	Cheakamus Upper	Stave Upper
1-day (mm)	76	74	86	80	132	198
3-day (mm)	136	130	138	164	232	318
5-day (mm)	161	181	175	199	284	402

Table 6: 1-day and 5-day precipitation totals measured by the Cayoosh, Nahatlatch, Stave Upper and Whistler weather stations for the October 2003 and December 2014 storms.

Station	16, 17 Oct2003	16-20 Oct 2003	9, 10 Dec 2014	8-12 Dec 2014
	1-day mm	5-day mm	1-day mm	5-day mm
Cayoosh Summit	50, 51	158	40, 78	144
Nahatlatch	112, 96	283	59, 99	214
Stave Upper	153, 136	425	94, 171	394
Whistler	77, 71	222	90, 74	217

The storms in October 2003 and December 2004 are known to have resulted in infrastructure problems. Stave Upper and Lower, Whistler, Nathatlach, Big Silver 2 and Cayoosh Summit all have reliable precipitation records for these storms with temperatures well above 0°C indicating it was raining. The highest 1-day rainfall totals in the December 2014 storm (Table 6) had return periods of 2- to 20-years for Cayoosh Summit and Stave Upper. For Whistler, the December event was a greater than the 30-year return for 1- and 5-day events. The 3-day totals were similar to 20- to 30-year return events. Nahatlach had 10 hours of 4 to 6 mm/h in the December 2014 storm (Its record is not long enough to estimate a return period for the daily totals). . Freezing levels were above 2000m indicating rain-on-snow (Schultz 2015).

For Cayoosh, Stave and Whistler the October 2004 storm had 2- to 10-year return periods for 1-day precipitation totals. The October 2003 storm was preceded by a large amount of rainfall in the previous week. The October storm had the highest 1- and 5-day total in the 57 year record for the Stave Upper and Lower stations. Nahatlatch had more rain in the October storm than in the December storm

The above analysis suggests that the 20-year return period would be suitable as the threshold for evaluating the effects of a changing climate on infrastructure. Different values will be used for the upper and lower areas of the road based on the weather station data.

In-SHUCK-ch Road Boundary Area - Projections of Future Climate

Figures 2 and 3 present the spatial distribution of the 1971-2000 normals of annual precipitation and temperature. The trend for decrease in precipitation northward on the road is accompanied by a decrease in temperature. As discussed earlier there is likely an underestimate of the precipitation at the higher elevations in the south west. Temperatures at road level will be warmer than indicated in the gridded data. However, projected changes in climate for the future are well represented by the spatial averages. Tables 7 and 8 present the projected changes in temperature and precipitation for the business as usual scenario (RCP 8.5). The variation between models in projected change is shown in Figure 4. Models project a 2 to 4°C warming by 2050s (2041-2070 period) and a 4 to 7°C warming by 2080s. Summers are projected to be drier and winters wetter. Spring and fall (not shown) are also wetter so that the net effect of the changing climate is an increase in the annual precipitation. Projections for the RCP 4.5 scenario show slightly smaller changes through to the 2050s than RCP 8.5, and in 2080s are similar to the projections for the 2050s for RCP 8.5.

Table 7: Change in winter, summer and annual average temperature referenced to 1971-2000 for the 2011-40, 2041-70 and 2071-2100 periods. Data are for the In-SHUCK-ch boundary area and are an average of 12 global climate models for RCP 8.5. ± indicates 10th and 90th percentiles. Data supplied by PCIC (2015).

Period	Change °C	Change °C	Change °C
	Winter	Summer	Annual
2011-2040	1.5±0.3	1.7±0.8	1.6±0.4
2041-2070	2.7±1.0	3.6±1.6	3.0±1.2
2071-2100	4.8±1.3	5.8±2.5	5.0±1.6

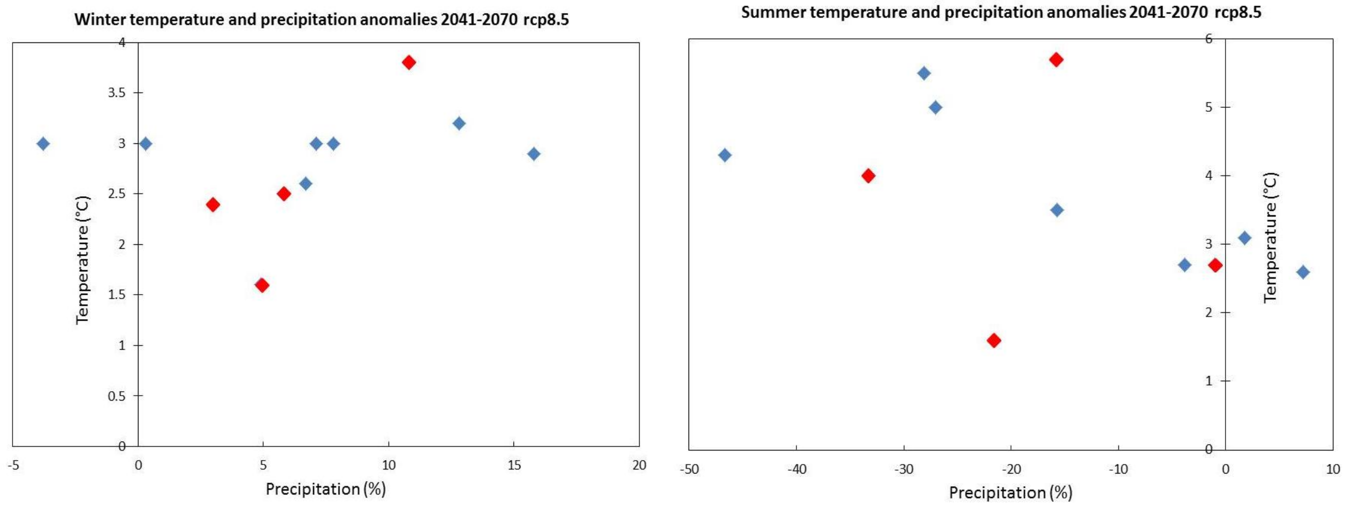


Figure 4: Change in winter and summer precipitation (% change) and average temperature (°C) for the 2041 to 2070 period referenced to 1971-2000 for 12 global climate models and RCP 8.5. Data are averages for the In-SHUCK-ch boundary area (Figure 1). Red diamonds indicate the 4 GCMs used in the analysis for specific locations. Winter is December, January February and summer is June, July, August. Data provided by Pacific Climate Impacts Consortium (2015).

Table 8: Change in winter, summer and annual precipitation referenced to 1971-2000 for the 2011-40, 2041-70 and 2071-2100 periods. Data are for the In-SHUCK-ch boundary area and are an average of 12 global climate models for RCP 8.5. ± indicates 10th and 90th percentiles. Data supplied by PCIC (2015).

Period	% change	% change	% change
	Winter	Summer	Annual
2011-2040	6±6	-9±16	3±3
2041-2070	7±6	-16±16	6±4
2071-2100	14±12	-25±25	12±7

Extreme temperature: The 20-year return maximum temperature averages 34°C for the area. This is projected to increase to 38±2°C by 2050s and 41±2°C under rcp 8.5. Temperatures will be greater at the road level reaching the mid 40s by 2080s. Extreme minimum temperatures increase by a similar amount as the maximums. The 20-year return minimum temperature averages -32°C for the area. This is projected to increase to -27±4°C for RCP 4.5 and -22±3°C for RCP 8.5 by 2080s.

Extreme precipitation: Extreme precipitation events are almost always in the late fall and early winter. They are projected to increase such that the 20-year return 1-day total could increase in size by 20 to 50% over the century (Table 9). Applying these changes to data in Table 5 suggests that 1-day events would be about 100 mm by 2050s in the upper part of the valley and double this at the lower end. A similar percentage change can be expected for the 20-year return 3-day totals. Figure 5 presents for one scenario (Access RCP 8.5) and grid point to illustrate projected change. However, the other 3 scenarios and other grids show the same trend. Along with a shift in the distribution there is a stretching of the tail of the distribution for the most extreme events.

Table 9: Change the 20-year return period precipitation referenced to 1971-2000 for the 2011-40, 2041-70 and 2071-2100 periods and for RCP 4.5 and RCP 8.5. Data are for the In-SHUCK-ch boundary area and are median vales for 12 global climate models. Data supplied by PCIC (2015).

	% change	% change	% change
Period	2011-2040	2041-2070	2071-2100
RCP 4.5	23	23	27
RCP 8.5	17	32	48

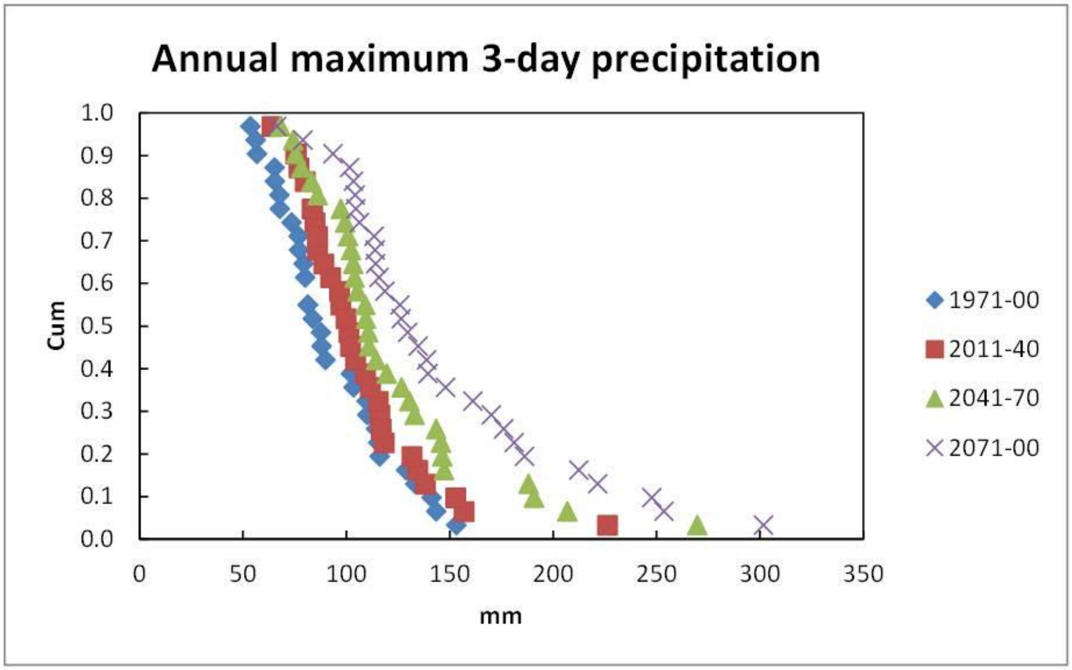
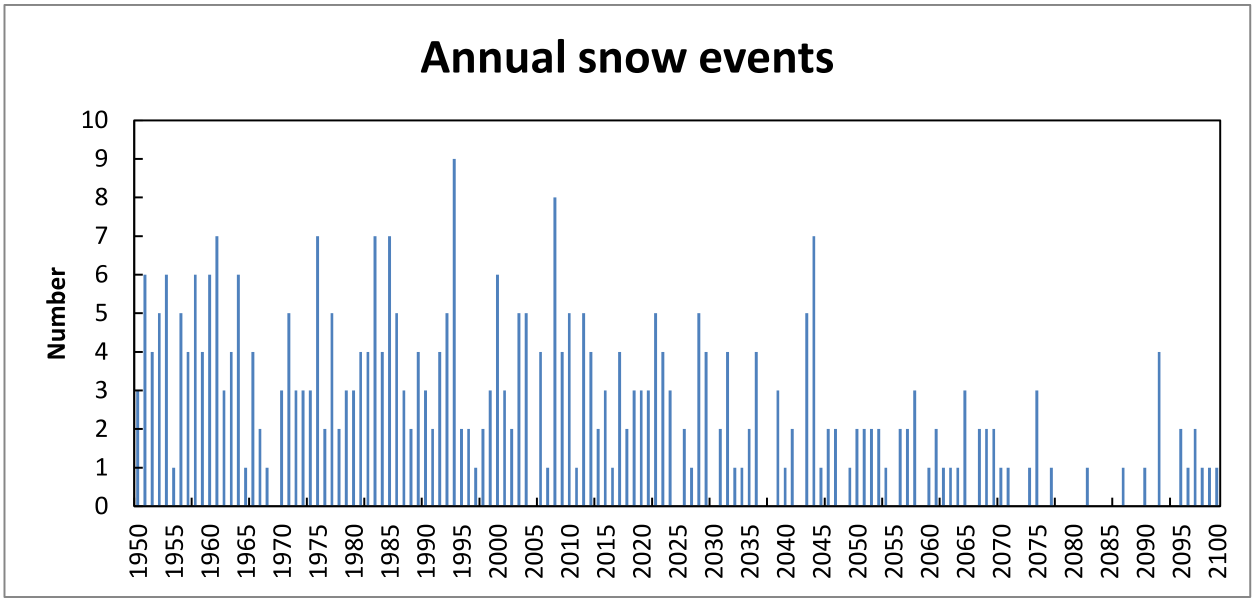


Figure 5: Cumulative distribution of the annual maximum 3-day precipitation for the 1971-2000, 2011-2041, 2041-2070 and 2071-2100 periods. Data are from the global climate model Access RCP 8.5, grid point 49.875 N, 122.292 W, 617 m with no adjustment to BCCAQ data.

Winter Snow Regime: Figure 6 shows the time series and cumulative distribution for snowfall events greater than 10 cm per day (defined as average temperature <1°C and 15 mm of liquid precipitation which assumes settling of snow once fallen to density of 0.15). The declining trend and shift in the distribution are quite dramatic. The data presented are for one scenario (CanESM RCP 8.5) but the trends are similar for all model projections and are less severe for RCP 4.5. The data also show that an increase in fall and winter precipitation will not be sufficient to offset the effect of warming on the winter snow pack. Such potential future changes in snow pack depth and occurrence have been noted by others, e.g. Elsner et al. (2010), Pike et al. (2010), and the resulting changes in streamflow regime may change the risk to infrastructure.



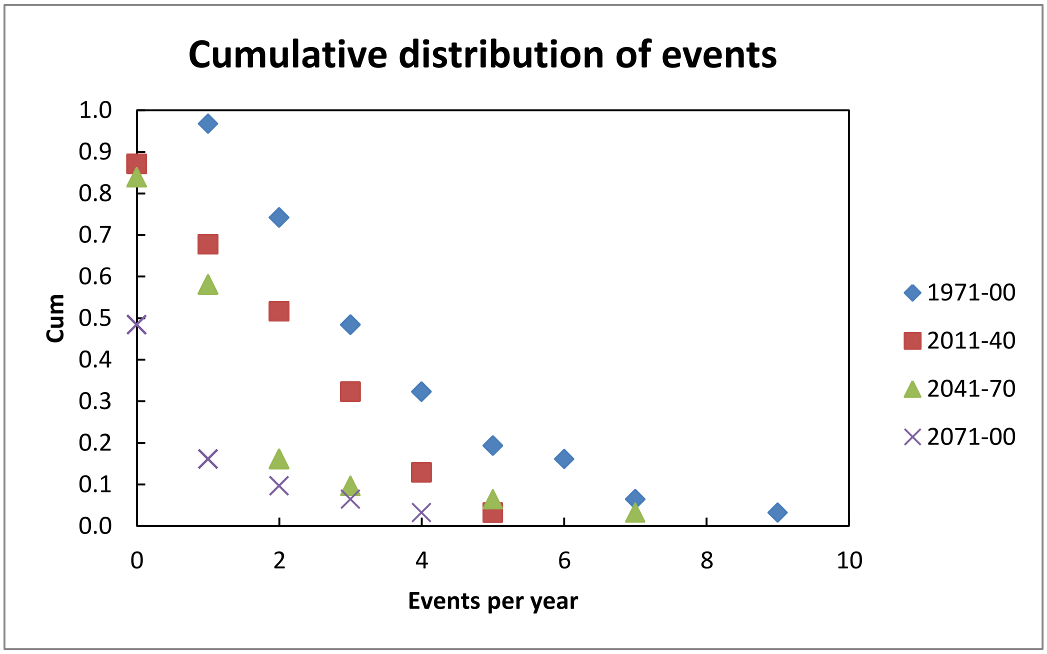


Figure 6: Time series of annual snowfall events (upper panel) and cumulative distribution of events (lower panel) the 1971-2000, 2011-2041, 2041-2070 and 2071-2100 periods. A snowfall event is defined as >10 cm depth of snowfall on a day and is calculated as >15 mm of precipitation with the average daily air temperature < 1°C. Calculations are for the global climate model CanESM RCP 8.5, grid point 50.208 N, 122.458 W, 716 m with no adjustment to BCCAQ data.

Maximum snow melt rates do not increase because melting occurs earlier in the season when solar radiation is lower. Furthermore, with a shallower snow pack there is no snow remaining to respond to the potentially higher melt rates under the higher temperatures in late spring. The number of rain-on-snow days does not appear change under any of the warming scenarios. This is because a shorter snow season and shallow packs reduce the opportunity for these to occur. The greater amount of rain in the storms may mean an increase in the amount of water draining from the pack.

High elevation areas: Consideration of higher elevation as well as at the road is important. The high elevations drive stream flow through the tendency of increased precipitation and snow accumulation with elevation. The influence of a changing climate at higher elevations and effects on stream flow was not part of the current analysis.

Discussion

Populating the PIEVC Scoring Table

Extreme precipitation is likely a result of the interaction of the upper level topography with the weather system. However, extremely warm summer temperatures or cold winter temperatures may be better represented by conditions at the elevation of the road. The grid cells smooth the topography and tend to be representative of higher elevations. Consequently, grid data may adequately represent the 1- and 3-day total precipitation but likely needs to be adjusted to better represent the temperatures experienced in the valley.

As noted earlier, there is a climate gradient from north to south along the road. There is also an elevation gradient in climate above the road. Consequently, defining one value for a variable as a threshold to evaluate risk is not possible in many cases, though the relative change in risk is likely to be less variable with geography within the boundary area. For this analysis I have chosen two grid boxes, one in the upper and one at the lower end of the boundary area (50.125N, 122.541W, and 49.875N, 122.291W, Table 4) to illustrate potential changes. For some variables, the gridded data may be adjusted to the level of the road. The analysis does not consider rain-on-snow and snow melt at high elevations and consequences for streamflow.

The workshops made suggestions for thresholds for some of the climate variables. Others were defined by MoTI for their PIEVC analyses. Septer's analysis (Appendix I) indicates that landslides and floods have occurred frequently in the Pemberton area in the past 70 years. Precipitation for the October 2003 and December 2014 storms were within the 20 to 30 year return period for 1-day and 3-day totals. This indicates that for the In-SHUCK-ch precipitation thresholds based on the 20-year return period value for 1- and 3- day totals (Table 5) are appropriate for evaluating risks under a changing climate. It was noted that the downscaled data appear to predict 1-day extreme values adequately (Table 3), slightly underestimate the 3-day and substantially underestimate the 5-day values. Consequently, the 1-day 20-year return period value is used for the one day extreme rainfall measure. The three-day sustained precipitation variable is based on a value that is 10% less than the 3-day 20 year return period value for the adjacent weather stations. An analysis of weather conditions for other disturbance events listed in Appendix I would in refining the thresholds.

The historic and projected changes in the climate variables presented in Table 10 are summarized as normals for the 1971-2000 2041-2070 and 2071-2100 periods. The 30 year average and the 90th and 10th percentile values are presented for 1971-2000. The future periods have the average and range of the 4 GCMs. Variables based on projections of temperature are considered to have a high reliability while those using precipitation are considered of medium reliability. The most noticeable features are the increase in summer heat (maximum temperatures indices) and a reduction in the waiting time for what are currently 20-year 1- and 3-day precipitation totals. Increases in the winter temperature will likely result in a decrease in weather events that influence road conditions; for example, a reduction in the number of freeze/thaw events, a reduction in snow pack depth and less snow fall events.

Table 10: Climate variables and thresholds for evaluating risk to road infrastructure for the In-SHUCK-ch FSR. Data are for the 1971-2000 normals and from projections for the 2011-2040, 2041-2070 and 2072-2100 periods. For 1971-2000 normals, the range is the 90th and 10th percentiles, the projections have ±1 standard deviation on the period mean (n=4). R indicates the reliability of the projected climate - high (H), medium (M) and low (L). See text for discussion of how thresholds were chosen and limitations to data. Table 2 indicates the relevance of each variable.

Climate variables	1971-2000	2011-2040	2041-2070	2071-2100	R
Days with maximum temperature > 35°C	4 days per year, range 12 to 0 days	10±2 days	20±7 days	36±15 days	H
Average maximum temperature over 7 days	33°C, range 29-37°C	35±1°C	38±2°C	40±3°C	H
Extended period with warm to high temperatures and minimal rain : >30 consecutive days with Tmax > 15°C & rain < 2.5 mm	Every 2 years, range 0-60+ days	0.5±0.2 periods per year	1±0.5 periods per year	2±0.5 periods per year	M
Days with daily temperature variation of more than 25°C	Every 2 years, range 0-2 days	Every 1.5 years, range 0-2 days	2±2 days per year	4±3 days per year	H
Freeze-thaw events: Number of days when Tmax >0°C and Tmin <0°C	113 days per year, range 85-135 days	90±9 days per year	75±14 days per year	50±17 days per year	H
7 days continuous with maximum temperature< -5°C	2 periods per year, range 0-7 periods	1.5±0.5 days per year	1.5±1 days per year	0 days per year	H

Table continued on next page

Table 10 continued

Climate variables	1971-2000	2011-2040	2041-2070	2071-2100	R
Degree days<0: For Tave<0°C and adjusted for days with Tave>0°C in months with Ddays<0	310 Ddays per year, range 100-500 Ddays	175±30 Ddays per year	115±45 Ddays per year	30±20 Ddays per year	H
Annual Precipitation – north and south areas of road	1050±250 mm 1480±300 mm	1090±25 mm 1515±30 mm	1150±50mm 1580±50mm	1200±50mm 1660±50mm	M
Extreme rainfall: > 20-year return period of 1-day precipitation, 60 mm/d north, 80 mm/d south	20 year return period	10±3 year return	7±3 year return	4±2 year return	M
Sustained rainfall: 20-year return period of 3-day precipitation, 100 mm north, 150 mm south	20 year return period	20 year return period	8±4 year return	4±2 year return	M
Antecedent rainfall followed by a significant event: 14 consecutive days with > 150 mm rain total and then 24 h rainfall > 50 mm	20 years return period on upper part Return period of 2 to 4 years lower part of road	15 year return period upper road 2.5±1 year return period lower road	10 year return period upper road 2±1 year return period lower road	5 year return period upper road Annually lower road	L
Snow frequency: Days with >15 mm of precipitation as snow (Tave < 1°C)	5 days per year, range 2-10 days	3±1 days	2.5±1 days	2±2 days	M
Snow accumulation: 5 or more consecutive days with a snow depth >60cm	87days per year, range 40 to 140 days	40±10 days	20±10 days	4±4 days	M
Rain-on-snow: Rain (50 mm/24 hours) on >50 cm of "ripe" snow pack	Rare, range 0-1 days per year	Rare	Rare	No events	L
Rapid snowmelt: snow melt > 30 mm/day, no rain	4 days per year, range 0 to 6 days	4±1 days	4±1 days	3±1 days	M
Rain on frozen ground	No information available	No information available	No information available	No information available	

Reliability of downscaled projections

The projected future climatology in Table 10 is based on the downscaled daily data. This BCCAQ data base is a useful tool for climate change impact analyses but it must be used with caution. Changes in temperature and precipitation are reasonably well represented because they are derived directly from the global climate models at a much larger scale than the downscaled data. Also of importance for this report was the reliability of the spatial interpolation of the absolute values of precipitation and temperature. Analysis of the BCCAQ 1971-2000 normals using weather station data and ClimateBC found that some areas were adequately downscaled and others not. There are two reasons for this. First, the 10 km gridded data represent a specific elevation within the grid and cannot be expected to adequately describe the climatology at substantially different elevation within the grid. Second, limits to the spatial distribution of weather stations (particularly at high elevations) affect the reliability of the Anusplin-based spatial interpolation of temperature and precipitation. These issues could be addressed because the data base used by ClimateBC is based on more stations and uses climatological knowledge (Daly et al. 2008) to improve spatial interpolation. A bias correction method similar to the climate imprint method of Hunter and Meentemeyer (2005) applied to the daily BCCAQ data resulted in a reasonable match to station or ClimateBC data. In particular, the estimate of the extreme 1-day maximum precipitation was substantially improved. In conclusion, we can be confident that the projected values reported in Table 10 are reliably downscaled.

Conclusions

Substantial changes in climate over the next 90 years are projected by the global climate models. The greatest increase in risk to the In-SHUCK-ch forest road appears to be from increasing precipitation, particularly extreme events. Other climate related concerns such as freeze thaw events may decrease. These projections come with a level of uncertainty resulting from the unknown future trajectory of greenhouse gas concentrations, limitations to the capabilities of the global climate models and the downscaling procedures. Our knowledge of earth system processes and current global efforts to curb emissions suggests that the data presented here are a reliable guide to aid the PIEVC risk analysis. However, adaptive responses must be robust to a range of possible future climatic conditions.

References

Church, M. and M. J. Miles. 1987 Meteorological antecedents to debris flow in southwestern British Columbia. In: Debris Flows and Avalanches, J. E. Costa and G F Wieczorek (eds.), *Geological Soc. Am., Reviews in Engineering Geology* VII, p. 63-79.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, and J. Curtis. 2008. Physiographically sensitive mapping of temperature and precipitation across the conterminous United States. *Int. J. Climatol.*, 28, 2031–2064.

Elsner, M.M., L.Cuo, N. Voisin, J.S. Deems, AF. Hamlet, J.A., Vano, Ke.E.B. Mickelson, S.-Y. Lee and D.P. Lettenmaier. 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* 102:225–260.

Fettig, C.J., M.L. Reid, B.J. Bentz, S. Sevanto, D.L. Spittlehouse, and T. Wang. 2013. Changing climates, changing forests: A western North American perspective. *J. Forestry* 111: 214-228.

Gudmundsson, L., J. B. Bremnes, J. E. Haugen, and T. Engen-Skaugen, 2012: Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations - a comparison of methods. *Hydrology and Earth System Sciences*, **16**, 3383–3390, doi:10.5194/hess-16-3383-2012.

Hunter, R. D., and R. K. Meentemeyer, 2005: Climatologically aided mapping of daily precipitation and temperature. *J. Applied Meteorology*, **44**, 1501–1510, doi:10.1175/JAM2295.1.

Jakob, M., K. Holm, O. Lange, and J.W. Schwab. 2006. Hydrometeorological thresholds for landslide initiation and forest operation shutdowns on the north coast of British Columbia. *Landslides* 3:228–238. DOI 10.1007/s10346-006-0044-1.

Lapp, D. 2011. PIEVC Engineering Protocol For Infrastructure Vulnerability Assessment and Adaptation to a Changing Climate – Revision 10 BETA. Canadian Council of Professional Engineers, Ottawa, ON. http://www.pievc.ca/e/Part_I_-_PIEVC_Engineering_Protocol_-_Revision_10_-_BETA_-_October_2011.pdf

Maurer, E., H. Hidalgo, T. Das, M. Dettinger, and D. Cayan, 2010: The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. *Hydrology and Earth System Sciences*, **14**, 6, 1125–1138, doi:10.5194/hess-14-1125-2010.

McKenney, D.W., M.F. Hutchinson, P. Papadopol, K. Lawrence, J. Pedlar, K. Campbell, E. Milewska, R. Hopkinson, D. Price, and T. Owen, 2011: Customized spatial climate models for North America. *Bulletin of the American Meteorological Society*,**92**, 12, 1611-1622. doi:10.1175/2011BAMS3132.1.

Pike, R.G., K.E. Bennet, T.E. Redding, A.T, Werner, D.L. Spittlehouse, R.D. Moore, T.Q. Murdock, J. Beckers, B.D. Smerdon, K.D. Bladon, V.N. Foord, D.A. Campbell and P.J. Tschaplinski. 2010. Chapter 19 - Climate Change Effects on Watershed Processes in British Columbia. In: *Compendium of Forest Hydrology and Geomorphology in British Columbia*, R.G. Pike et al. (eds.), B.C. Min. Forests and Range, For. Sci. Prog., Victoria, B.C. and FORREX Forest Research Extension in Natural Resources, Kamloops, B.C. Land Management Handbook 66. http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm.

PCIC 2013. Climate summary of the South Coast Region. Pacific Climate Impacts Consortium, Victoria BC, 4 pp. http://www.pacificclimate.org/sites/default/files/publications/Climate_Summary-South_Coast.pdf

PCIC 2014. Statistically Downscaled Climate Scenarios. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC. Downloaded from http://www.pacificclimate.org/data/statistically-downscaled-climate-scenarios January-March 2015.

Schultz, M. 2015. December 2014 storm damage report. Sea to Sky Natural Resource District, Ministry of Forests, Lands and Natural Resource Operations, Squamish, BC, 21 pp.

Septer, D. 2006. Flooding and Landslide Events Southern British Columbia 1808-2006. British Columbia, Ministry of Environment, Victoria, BC. http://www.env.gov.bc.ca/wsd/public_safety/flood/pdfs_word/floods_landslides_south1.pdf

Sillmann, J., V.V. Kharin, F.W. Zwiers, X. Zhang, D. Bronaugh. 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *J. Geophysical Research: Atmospheres* 118: 2473–2493, doi:10.1002/jgrd.50188

Spittlehouse, D.L. and R.D. Winkler. 2004. Snowmelt in a forest and clearcut. Proceedings 72nd Western Snow Conference, Richmond, BC, pp. 33-43.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, **93**, 485–498. doi: 10.1175/BAMS-D-11-00094.1.

Wang, T., A. Hamann, D.L. Spittlehouse and S.N. Aitken. 2006. Development of scale-free climate data for western Canada for use in resource management. *International J. Climatology* 26:383-397.

Wang, T, A. Hamman, D.L. Spittlehouse and T.Q. Murdock. 2012. ClimateWNA—High-Resolution Spatial Climate Data for Western North America. *J. Applied Meteorology and Climatology* 51:16-29.

Appendix I: Incidents of floods, landslides and rockfall around Pemberton, 1931-2005

Edited from information provided by Pierre Friele, P.Geo.(Cordilleran Geoscience) in an email to Dave Spittlehouse, Tuesday, March 3, 2015 3:08 PM.

Septer (2006) data-mined newspaper and published literature to create a provincial record of flooding and landslide activity. This data catalogue was reviewed to develop a record of event generating storms affecting the Pemberton area. For Pemberton, the first record is the Meager 1931 debris flow related to October rains. Other significant events are major flooding on Lillooet River in October 1940, 1984 and 2003, and events in 1981 and 1991 that destroyed bridge crossings on Rutherford Creek. The incidents of flood, rockfall or landslides around Pemberton are listed below:

* October 1931 (Meager)
* January 20-27, 1935
* October 27-29, 1937
* October 19-20, 1939
* October 17-20, 1940 (flood of record since July 19, 1918)
* July 13-15, 1946
* November 27-Dec 4, 1951
* December 1-3 1955
* September 5-6 1957
* April 29-30, 1959
* January 8-17, 1961
* November 20-25, 1966
* October 30-Nov 1, 1967
* January 12-20, 1968
* October 29, 1968
* July 22, 1975 (Devastation)
* October 29-November 6, 1975
* December 23-27, 1980
* October 27-31, 1981
* January 1-4, 1984
* October 6-12, 1984 (Preacher’s quote: the biggest one since 1940)
* October 4, 1990

- November 6-13, 1990
- November 16-24, 1990
- August 7-9, 1991
- August 27-31, 1991
- October 23-24, 1992
- March 17-26, 1997
- May 31-June 1, 1997 (Gowan)
- June-July 1999
- October 16-22, 2003 (Largest to date)
- January 16-31, 2005.

Between 1930 and 2006 Septer records 32 event storms affecting the Pemberton area, or one every 2 to 3 years. These storms are candidate storms for triggering landslides on Cataline Creek. Historical records and API suggest that there were events on Cataline in the early 1940s, between 1982 and 1986, possibly about 1991, 2004, 2010 & 2013. On average, Cataline Creek responds to (generates debris flows) about 15% of regional storm events. The record is non-stationary, and/or may be censored for the period before development in the 1970s, and more local, non-regional event storms have triggered events at Cataline (e.g., 2004), so these averages should be interpreted with caution. In summary, it appears that Cataline Creek does not spawn debris every time threshold rainfall conditions are exceeded, but rather some time is needed between events to recharge the system. This is a common phenomenon in debris flow channels (Church and Miles 1987), and makes debris flow prediction very challenging. In statistics, non-stationary refers to processes in a time series that have characteristics that change systematically through time (e.g. seasonal effects, climate change, post-glacial period, etc.)