MONITORING FOREST AND RANGELANDS TO ANTICIPATE AND RESPOND TO CLIMATE CHANGE: INFORMATION FOR PHASE 4 INDICATORS

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Background

This project is a collaborative effort between the Ministry of Forests and Range and the University of British Columbia's Department of Forest Resources Management. Phases 1 and 2 were conducted during 2008/09 by John Innes and Margie Eddington; Phases 3 and 4 are underway.

Phases 1 and 2 resulted in a selection of recommended indicators for monitoring for natural resource management in BC in light of climate change, along with a list of potential data sources and suppliers that could support analyses of those indicators. Phases 3 and 4 of the project, funded by the Future Forest Ecosystems Council in late 2009 and early 2010, built on work conducted through Phases 1 and 2 to develop a more consolidated monitoring and reporting framework. The first key activity of phase 3 was to more fully identify the framework's target audience and their key information needs and management questions in light of climate change. As well, during this activity, researchers sought to identify and examine pathways and media that may be used for making information generated from the framework available to the target audience. This first activity of Phase 3 was accomplished by surveying about 550 forest and range mangers operating in the province (Eddington and Innes 2008).

During phases 3 and 4, work also began on individual indicators to better determine the extent to which current monitoring and inventory programs are able to support their analysis. This is being done by refining and further developing technical approaches to measuring the indicators and evaluating the extent to which those approaches could be supported using existing data collections and inventory processes available in the Province. This includes examining factors such as the number and distribution of permanent sample sites and the extent of the data collections available. For phases 3 and 4, indicators were divided into two groups (ones addressed during Phase 3 and those left for phase 4) depending on when they received funding. Table 1 lists the indicators and phase of work under which they are included.

Table 1: Indicator work phase

INDICATOR	***WORK PHASE***
Criterion 1 – ecosystem drivers	
Temperature	Phase 4
Precipitation	Phase 4
Snowpack	Phase 4
Streamflow	Phase 4
Water temperature	Phase 4
Water quality	Phase 4
Unseasonable or unexpected weather conditions	Phase 4
Criterion 2 - Natural Disturbances	
Insects and diseases	Phase 3
Wind throw	Phase 4
Fire	Phase 3
Mass movements	Phase 4
Criterion 3 - Biodiversity	
Ecosystem distribution and composition	Phase 3
Ecosystem productivity	Phase 3
Species diversity	Phase 3
Genetic diversity	Phase 4
Ecosystem connectivity	Phase 3

As a result of linkages developed with the South Selkirks Team, approaches for monitoring the Phase 3 indicators have been piloted in BC's Southern Interior.

Work on the Phase 4 indicators began in earnest in late spring of 2011 and is now completed (early 2012). Phase 4 indicators focus on abiotic processes (such as temperature, snowmelt, precipitation, streamflow and wind) rather than the more biological indicators of phase 3 (e.g., ecosystem composition, ecosystem productivity, insects and disease). The split, however, was not purely along abiotic/biotic lines as fire was considered during phase 3 and genetic diversity is considered under phase 4.

In this report, we explore approaches for measuring Phase 4 indicators, and assess the ability of current monitoring programs to support their evaluation. Because there are many indicators under consideration during phase 4, some indicators, specifically those ranking highly in the survey undertaken under Activity 1 of Phase 3, are addressed in more detail than others. Selecting the indicators of primary focus was the beginning step during phase 4.

Priorities for Phase 4 indicators
Abiotic indicators of climate change such as temperature, precipitation, snowpack (including extents of glaciers), streamflow (including water temperature and quality), and unexpected weather conditions were identified by the survey in phase 3 as high priority indicators. Of lower priority were mass wasting, windthrow and genetic diversity.

Phase 4 indicators:

Criterion 1: Ecosystem Drivers

1.0 Temperature and precipitation

Rationale: Temperatures are expected to warm, with BC becoming less cool (minimum temperatures are expected to rise more than maximums). Precipitation is predicted to shift to warmer, wetter years, more frequent wet years, greater year-to-year variability, and more extreme precipitation events. More precipitation is expected to fall as rain and less as snow. In some areas of the Province, summer droughts are expected to increase even though annual precipitation may increase. Recent summaries by Rodenhuis et al. (2009) note positive trends in annual daily minimum temperature +1.7°C (+1.0°C to +2.5°C per century), daily maximum temperature +0.6°C (+0.5°C to +1.5°C per century), and daily mean temperature +1.2°C (+0.5°C to +1.5°C per century). In northern BC, the trends in minimum wintertime temperature were up to +3.5°C per century. [For comparison, the global mean temperature trend is +0.7°C (between +0.6°C and 0.9°C per century)]. Trends in precipitation were also generally positive (+22% per century on average across BC) and some observations of +50% per century occurred in wintertime in the interior. However, there were exceptions, and some of the trends were reversed (negative) for shorter records (50 years). Such changes will almost certainly have significant effects on forest and rangeland ecosystems and monitoring these changes will be important to inform management.

Because temperature and precipitation data are gathered and made available by the same agencies, we present the information for both indicators together. The temperature indicator should include measures of daily maximums, minimums, frost events, and calculated means. The precipitation indicator should monitor precipitation rates, timing and forms. Both indicators should report information Province wide (or by region, or even by catchments of interest) using data from as many climate stations as practicable.

Potential data sources
The main source of temperature and precipitation data useful for broad tracking of climate change is Environment Canada. Other sources are BC Hydro and Province of BC data bases. Fortunately, Pacific Climate Impacts Consortium (PCIC) has undertaken projects to synthesize and analyse the available data. We first describe the data sources (in some detail so that potential users can assess their utility), then PCIC's summaries.

1. **Environment Canada:**

Environment Canada Climate Network for British Columbia and Yukon operates a network of approximately 500 climate stations in B.C. and the Yukon and maintains an associated archive of historical weather information. At 350 of these stations daily measurements of temperature and precipitation are taken. Two climate research and monitoring tools CTVB (Climate Trends and Variations Bulletin) and CANGRD (Canadian Grids of temperature and precipitation) have recently been merged into interactive dynamic up-to-date online application called the new CTVB. Because Environment Canada already tracks these environmental variables for purposes of addressing climate change, they have accepted way of preparing them and a network of sites across the province (and across the country, see: http://www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=F3D25729-1.)

The new CTVB web tool uses Adjusted and Homogenized Canadian Climate Data (AHCCD)[1] which was developed specifically for use in climate research including climate change studies. They incorporate a number of adjustments applied to the original station data to address shifts due to changes in instruments and in observing procedures. Sometimes the observations from several stations were joined to generate a long time series. The adjusted and homogenized data are provided for four climate elements: 1) Surface air temperature, 2) Precipitation, 3) Surface pressure, and 4) Surface wind speed.

The new CTVB displays maps of current and past departures from normal temperature and precipitation conditions for a month, season, or any set of consecutive months, or a year. For each year it computes average conditions over Canada, a province, territory, climate region, or user-defined area, produces a time series and provides graphs with fitted trend lines to assess climate change over the period of interest. The new CTVB ranks wet to dry, or warm to cold years in the time series and provides an option to download and save the rankings. The new CTVB is an interactive dynamic application. It allows the user to select or define the area and time period of interest. It dynamically pulls out the grid point values from the database and computes all averages and trends. The new CTVB is issued every month and covers the recent period from 1948 for all of Canada, and also goes back to 1900 for southern Canada. The old CTVB provided mean temperature and total precipitation departures, while the new CTVB adds two more elements, maximum and minimum temperatures. A major difference is the change in the 30-year averaged reference period, known as the normal. The old CTVB used 1951-1980 normal, whereas the new CTVB uses the 1961-1990 normal. Although this in itself would not change trend or rankings, the departure values from normal can shift with the reference period. Across the country, the new CTVB has about 330 stations for temperature and 470 for precipitation.

The method for calculating area averages is also considerably different. The old CTVB grouped stations that were climatically similar and averaged the departures, then used an area weighted mean to calculate the national value. The new CTVB uses temperature and precipitation at the evenly spaced grid points, which are then simply averaged for national or regional values.

Temperature and precipitation fields come from CANGRD (available on CD). The grid points are spaced every 50 km and were created by applying statistical optimal interpolation on the AHCCD. This method is supported by a spatial correlation model and performs better than many empirical methods in sparsely and unevenly distributed national climate observing networks. The value estimated at the any grid point location is the linear combination of the number of observations from surrounding stations.

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[1] The official records can be obtained at the National Climate Data and Information Archive. Users should be aware that ongoing research on adjustment techniques may result in future revisions of the datasets. The datasets are updated annually with the most recent data.

The weight given to each observation is determined by minimizing the overall differences between the interpolated estimates and the true values of the climatological field.

Historical CANGRD is combined with near real-time observations in the CTVB for up-to-date continuous climate monitoring on a monthly, seasonal and annual basis. The most recent data, for up to two years, is based on synoptic weather observations, which are performed usually at the airports on a 6-hourly or more frequent basis. These observations go through some quality control, but are still subject to change as final data sets are received, processed and retained in Canada's national climate archive, so should be treated as preliminary. AHCCD is updated annually in the spring. At that time, the updated, adjusted data supersedes the near real time data until the end of the previous calendar year.

Although the AHCCD appears to be the more useful data set, Environment Canada's National Climate and Information Archive (http://climate.weatheroffice.gc.ca/prods_servs/index_e.html) has data sets with historical climate data, daily climate data and climate normals. There are 301 stations with climate normals in BC. Stations with an ' * ' indicate that this station meets the United Nation's World Meteorological Organization WMO standards. The Canadian Daily Climate Data contains daily temperature, precipitation and snow-on-the-ground data and is available for download. Data is available for the complete period of record for each location up to 2007. The file contains software that provides access to the data [2], but most data request need to be directed to Environment Canada.

2. BC Hydro's Regional Hydromet Data

BC Hydro's Regional Hydromet data networks collect near real-time hydrometeorological data at various automated data collection stations in or near their reservoir systems across BC to support reservoir operations. Major types of hydrometeorological data collected include precipitation, air temperature, lake levels, stream levels/ flows and snow water equivalents, although water temperature, wind, solar radiation and barometric pressure are also measured at a few locations. B.C. Hydro has hourly data on air temperature, precipitation (mm and snow water equivalents (SWE)).

3. Provincial Climate Related Monitoring Network Initiative

Provincial Climate Related Monitoring Network Initiative is a relatively new joint project to expand B.C.'s hydrometric and other climate-related networks to improve the Province's ability to monitor, predict and adapt to changing climatic conditions that pose new threats for human health, safety and property, such as risks of flooding, storm surges, wildfire and drought. In the first 2 years of the project the goal is to identify and evaluate the existing provincial Climate Related Networks (CRNs) operated by Ministry of Transportation, Ministry of Forest and Range and Ministry of Environment to ensure that core climate data are collected on a year round basis and to advise on needed upgrades. The web site (http://www.env.gov.bc.ca/epd/wamr/crmp.htm) includes a map of BC with all data collection location of the various agencies noted. It appears to be too early to obtain data from this group.

4. PCIC summaries

Rather than assemble the above information, the best present option to obtain temperature and precipitation information is to use summaries by PCIC. Rodenhuis et al. (2009) updated their work of

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[2] The CDCD download file is 212 MB and will require 880 MB of disk space when uncompressed. Download times will vary according to each user's system and internet traffic. The data licensing agreement allows for redistribution of data under certain conditions.

2007 to report on several climate variables, looking at both past trends and future projections. The information on past trends includes information on temperature and precipitation (annual means, maximums, and minimums; seasonal (summer, fall, winter, spring) maximums, minimums; and seasonal trends. Values can be pulled off their figures for any area of BC. Results are based on 1900 to 2004 data and calculated as degree Celsius change per century. They indicate statistically significant values. They use the CANGRID information discussed above; open circles in their figures show the location of Adjusted Historical Canadian Climate Station sites (AHCCD, also noted above). Rodenhuis et al. (2009) also examine affects of ENSO and PDO cycles and note they have had a pronounced influence on seasonal temperature and precipitation in BC, especially in the winter and spring seasons[3].

PCIC intends to repeat the analyses as new data is added. As well, PCIC (Faron Anslow, pers. comm.) is working to provide temperature and precipitation data through a publically available, user-friendly interface. The intention is that by sometime during 2012, users will be able to select the types of data they wish reported (e.g., temperature minimums, means, precipitation maximums, etc) and select and area of the province of interest. Data will be automatically summarized and reported for the variables in the area selected.

2. Snowpack

Rationale: Snowmelt runoff contributes 50 to 80% of the total water flow in nival basins (those dominated by snowmelt) and thus is an important hydrologic variable for recharge and sustenance of baseflow conditions. Snow accumulation and its characteristics are the result of air temperature, precipitation, storm frequency, wind, moisture in the atmosphere, and PDO and ENSO cycles. Changes in these and other climate properties will therefore affect snowpack. Reduced snowpack is anticipated as climate changes and the snowline in mountainous areas is forecast to rise in elevation. Rodenhuis et al. (2009) reported losses of April 1st snowpack of -25% on average at BC sites and as much as -50% at a few sites over the past 50 years. For shorter record lengths, however, the variability was large and not homogeneous across the Province. In addition, ENSO influenced snowpack by -12% to +21%. The geographical complexity of snowpack in BC prevents a simple interpretation of results. Changes in the timing of accumulation and loss of snowpack are uncertain but could have considerable effects on forest ecosystem processes.

Ideally, snowfall depth would be reported Province wide (and by region) using data from as many climate stations as practical. To the extent possible, monitoring of water related indicators should be coordinated within a complementary network (i.e. measurements should be taken from similar locations within catchments) to aid the interpretation of results.

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[3] During the warm phase of ENSO, temperature was higher (+0.5°C to +2.8°C) and precipitation was somewhat less (-5%) compared to the cool phase. There was also a comparable influence of the PDO warm phase on temperature (+2.9°C) although precipitation was not significantly different. However, climate variability responses differ between the seven hydro-climatic regions of BC. The magnitude of climate variability was comparable to climatic trends over the century.

The impact of ENSO on climate in Canada is well-documented, but much less is understood about the PDO, which was identified in the mid-1990s. Therefore, the question remains whether the range and scale of effects observed in instrumental records is representative. It appears that these impacts have occurred for much longer than the instrumental records can demonstrate. BC's record likely shows only a part of the potential range of climate variability.

Potential data sources

A number of potentially valuable data sources exist but the current network of monitoring sites has a strong bias towards lower and more populated latitudes and lower elevations. Forest and range experts have also indicated that these existing monitoring stations are unlikely to be in areas identified as being particularly sensitive to climate changes (including higher elevations and transient snow zones) and are unlikely to be able to capture information on the various forms of precipitation adequately. The Environment Canada Climate Network has several discontinued stations. Just as for temperature and precipitation data, PCIC has summarized many of the available data sources. We first describe the data sources, then the PCIC summaries.

1. MOE River Forecast Centre

The MOE River Forecast Centre (RFC) is the lead agency in the Province responsible for the collection, quality control, analyses and archiving of snow, meteorological and streamflow data to provide warnings and forecasts of stream and lake runoff conditions around the Province. Most of the meteorological and streamflow data are collected by other agencies, but the RFC is the lead agency for flood advisories and warnings, water-supply and drought advisories and, of interest to this project:

- **Automated Snow Pillow (ASP) data,** and
- **Collection, quality assurance, analysis and archiving of snow data**

Manually sampled snow survey data are collected from almost 200 sites around the Province while remotely sensed snow and meteorological data from Automatic Snow Pillows, transmitted via satellite, are collected at over 50 sites around the Province. At the expert workshop, River Forecast Centre staff anticipated that the organization would be able to supply adequate data on snow depth to support a reasonable analysis and interpretation of the indicator.

1) ASP data[4]*:* ASP stations relay data from remote sites via GOES satellite every one to three hours. Snow Water Equivalent data are extracted for each site and plotted with comparisons to previous years'

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[4] *Details of ASP data collection*: British Columbia snow pillows consist of 3 m diameter bladders containing antifreeze solution. As snow accumulates on the pillow, the weight of the snow pushes an equal weight of the antifreeze solution from the pillow up a standpipe in the instrument house. The distance the antifreeze is pushed up the standpipe is recorded by a float connected to a shaft encoder, giving the SWE of the snow. The instrument shelter also contains the electronics, consisting of a Data Collection Platform (DCP), a shaft encoder which tracks the movement of the float in the standpipe from the pillow, batteries and regulators for the externally mounted solar panels for recharging the batteries. The DCP contains a transmitter to send the recorded data to the GOES satellite (**G**eostationary **O**perational **E**nvironmental **S**atellite). The GOES satellite then transmits the data to the River Forecast Centre's satellite data receiving system in Victoria. On the outside of the instrument shelter are the solar panels for the charging system, and an air temperature sensor. At most snow pillow sites, precipitation gauges and snow depth sensors are also installed. To inhibit freezing, the precipitation gauges are "charged" with propylene glycol. The gauges are mounted on top of a 3 m high tower to keep them above the snow pack. The snow depth sensor is mounted on an arm extending from a 6 m high tower, and points toward the ground above the pillow. The ultrasonic sensor works similarly to an

data. The near-real-time data are transmitted without verification from remote sites and posted without checking and are therefore liable to major errors and equipment failures. Data available include hourly temperatures, cumulative precipitation, snow depth and snow water equivalent. The full archived record of Daily Snow Water Equivalent, Maximum and Minimum Temperatures, and Cumulative Precipitation for individual ASP Stations is available for stations listed on their website (http://bcrfc.env.gov.bc.ca/data/index.htm). All of the Ministry of Environment's ASPs are installed and maintained by staff of the River Forecast Centre, their data base and graphs also include ASPs operated by B.C. Hydro and Alcan. Record lengths vary, beginning with date of installation and ending either when the ASP was taken out of service, or at the end of the 2009-2010 snow season. Station Name can be selected to download a zipped CSV data file. Interactive mapped based data selection can be used to select data for various regions and stations of the Province.

2) Manual Snow Survey data: Manual snow surveys are conducted up to eight times per year near the beginning of every month from January through June with extra measurements at mid-month in May and June. Because snow is subject to drifting, melting and natural compaction, it is notoriously difficult to measure. Any point measurement may be quite different from a reading taken only a few metres away. Thus, to measure the quantity of snow in an area, a systematic method for measuring snow has been developed and this is generally referred to as a "snow survey". Such measurements have been made in British Columbia since 1935. The basic principal is that measurements should be made consistently at the same locations so that previous and subsequent measurements can be compared and related to such measures as water supply and flooding. Readings are used as indices as to the quantity of snow in an area.

An ideal snow survey site is located in a relatively sheltered area with as little tree canopy overhead as possible. A forest clearing, where the area is at least as wide as the height of the trees, is ideal. Sites are chosen at elevations representative of the area and that will have snow for a substantial portion of the winter. The majority of snow courses are located between 1000m and 2000m above sea level. Five or ten points within the area are chosen and referenced to trees or other objects which will be visible when there is snow on the ground. At each sampling period, measurements are made at all of the points at the site, the "reading" for that site being the average snow depth and water equivalent of the points measured. Measurements are made by utilizing the "Standard Federal Snow Sampler" which consists of graduated aluminum tubes with a cutter bit affixed to the first section of the tubing. The tubes are driven through the snow to the ground and then carefully withdrawn, extracting a core of snow with them. The tubes and core are then weighed using a scale specially calibrated in centimetres of water. The difference between the empty weight of the tubes deducted from the weight of the tubes and core is the snow water equivalent.

The number of snow courses measured at each sampling period varies through the year. Because the maximum reading at most snow courses occurs near the beginning of April, the greatest number of measurements is made at this date. Also, later in the season, lower elevation snow courses seldom have snow cover, so are not scheduled for sampling. Data are available in MSEXCEL spreadsheets.

2. BC Hydro's system:

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autofocus sensor in a camera in that it measures the distance from the sensor to the surface below it. As the snow depth increases the distance measured decreases.

As noted earlier, BC Hydro's Regional Hydromet Data networks collect near real-time hydrometeorological data at various automated data collection stations in or near their reservoir systems across the province to support reservoir operations. Major types of hydrometeorological data collected include hourly measures of precipitation, air temperature and snow water equivalents; longer interval measures of lake levels, stream levels/flows; and, at some sites, measures of water temperature, wind, solar radiation and barometric pressure. The River Forecast Centre holds BC Hydro's snowpack data (but not their stream flow data).

3. PCIC Summaries

Rodenhius et al. (2009) summarize snowpack data. Their analysis extends previous efforts to examine a comprehensive snowpack dataset from northern and southern BC, updates trend analysis on snowpack to 2007, and highlights historical variability in snowpack over the past century. They estimated trends in snow water equivalent (SWE, % difference) from the long-term average, relative to the initial trend condition at the first year of record over the specific periods: (a) 1951-2007, (b)1961-1990, and (c) 1978-2007. Their figures show magnitude, direction and statistical significance of the changes. They also show affects of ENSO and PDO cycles on snowpack. They use data from the River Forecast Centre (which includes data of BC Hydro and Alcan) and data of Zhang et al. (2001). For most purposes this analyses will be the best available, especially if the summaries are repeated regularly as planned (contingent on funding). Just as for temperature and precipitation data, PCIC plans to add snow data to its publically available, user-friendly data web site. Accessibility to Information on snow will be developed after the temperature and precipitation data interfaces are developed (Faron Anslow, pers. comm.).

3. Glaciers

Rationale: Glaciers are an important water resource in BC. Covering an area of 30,000 km2 and 48% of BC's gauged systems, glacier-melt moderates inter-annual variability in streamflow and helps to maintain higher runoff volume in times of extreme warm and dry conditions. Glacier-melt also supports ecosystem functions by maintaining cooler water temperatures. Glacier retreat may cause changes in the flow patterns and temperature of some forest and rangeland streams and rivers. These changes, along with other climate-driven changes to hydrological systems, are likely to have significant impacts on freshwater and estuarine ecosystems and aquatic species. As glaciers begin to melt they often discharge more water into streams and rivers than before the melt phase, potentially increasing stream turbidity and damaging fish habitat and riparian areas. Dan Moore (pers. comm.) indicates most of BC's glaciers (except for the extreme northwest of the Province) are already in past this stage and in sufficient negative mass balance that glacier retreat now corresponds with reduced water volume in glacier-fed streams and rivers, especially during the summer months potentially, exacerbating changes in streamflow and temperature.

Ideally, the spatial distribution of glaciers would be monitored using either aerial surveys or remotely sensed data to record changes over time. Information should be interpreted in the context of data coming from the water related indicators described above.

Potential data sources

Studies of glaciers can be grouped into those detecting changes in volume and area, and those doing more detailed mass balance calculations. Mass balance studies have focuses on about 20 glaciers in BC. Studies on volume and area change have covered the whole Province.

1. **Canadian Cryospheric Information Network (CCIN)** *w*as developed as a collaborative partnership between the Federal Government (Canadian Space Agency, Meteorological Service of Canada, Natural Resources Canada), Universities and the private sector (Noetix Research Inc.) to provide data and information management infrastructure for the Canadian cryospheric community. It was a consortium of six Canadian universities, two American universities and government and private scientists who were examining the links between climatic change and glacier fluctuations in western Canada. Funding for that network has been discontinued by the Federal government, but substantial work was completed and will be continued under other funding. Key participants from BC included Dr. Brian Menounos (pers. comm.) of UNBC and Dr. Dan Moore (pers. comm.) of UBC. Menounos was a co-author of the most recent study on volume and area change of glaciers by Bolch et al. (2010). They used semi-automated methods to extract glacier extents from Landsat Thematic Mapper (TM) scenes for 2005 and 2000 (see Figure1). They compared these extents with glacier cover for the mid-1980s from high-altitude, aerial photography for British Columbia and from Landsat TM imagery for Alberta. A 25 m digital elevation model (DEM) helped to identify debris-covered ice and to split the glaciers into their respective drainage basins. Glaciers in British Columbia and Alberta respectively lost −10.8±3.8% and −25.4%±4.1% of their area over the period 1985– 2005. The region-wide annual shrinkage rate of −0.55% per year is comparable to rates reported for other mountain ranges in the late twentieth century. The least glacierized mountain ranges with smaller glaciers lost the largest fraction of ice cover: the highest relative ice loss in British Columbia (−24.0±4.6%) occurred in the northern Interior Ranges, while glaciers in the northern Coast Mountains declined least (−7.7±3.4%).

Dan Moore and students have been examining effects of glacial retreat on stream flow and the character of newly-exposed riparian zones. His work focuses on Place and Bridge glacier in the coastal mountains.

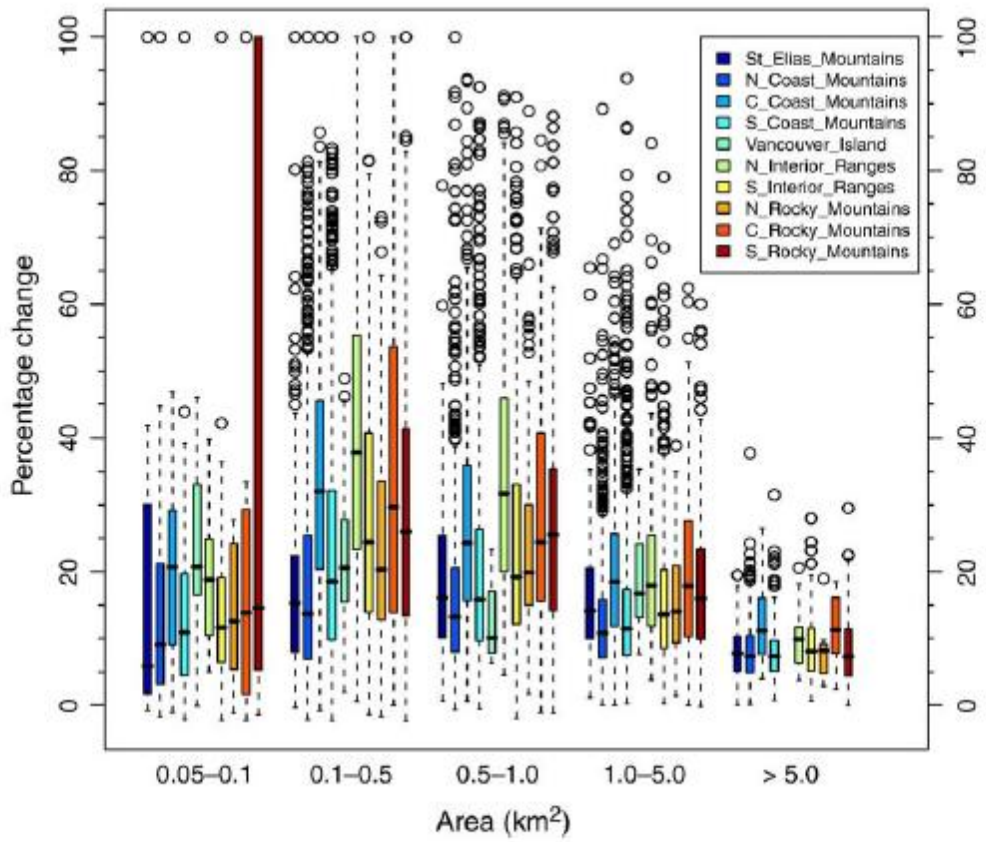

Figure 1. Glacier area loss 1985–2005 for different size classes (size in 1985) in the different regions. Middle of box is median and box width defined by interquartile range (25 and 75 percentiles). Whiskers are 5 and 95 percentiles. Symbols are <5 or >95 percentiles (source Bolch et al. 2010).

2. **Researchers at PCIC** have completed literature reviews on changes in glaciers. Rodenhuis et al. (2009) have collated and summarized known information on glacier expansion and retreat with climate They reviewed studies prior to the 2010 report of Bolch et al., but including similar studies (e.g., Schiefer et al. (2007) who used Shuttle Radar Topography Mission (SRTM) data and digital terrain models from aerial photography to quantify the change of glacier volume in B C for the period 1985–1999). Rodenhuis et al.'s review notes volume loss from all of the glaciers was occurring at a rate of 22.48+-5.53 km3 per year. Rodenhuis et al.'s review also includes Information from other studies which indicate the retreat of glaciers is not a phenomenon that has just recently begun, rather, most glaciers have been in retreat since the late1800s, since the last cool period. For example, glaciated basins in BC showed a statistically significant *decrease* in August streamflow from 1976 to 1961. Since decreases in streamflow resulting from changes in glacier contributions are usually preceded by *increased* streamflow, current glacier conditions appear to be in an advanced state of change. These observations and others indicate a warming trend in BC that has occurred over many centuries but is exacerbated by recent trends in climate change. Even within this general warming trend, some periods of expansion have occurred during cool phase of PDO cycles.

In BC, only a few individual glaciers have been monitored over multiple decades, those glaciers are noted in the figure below.

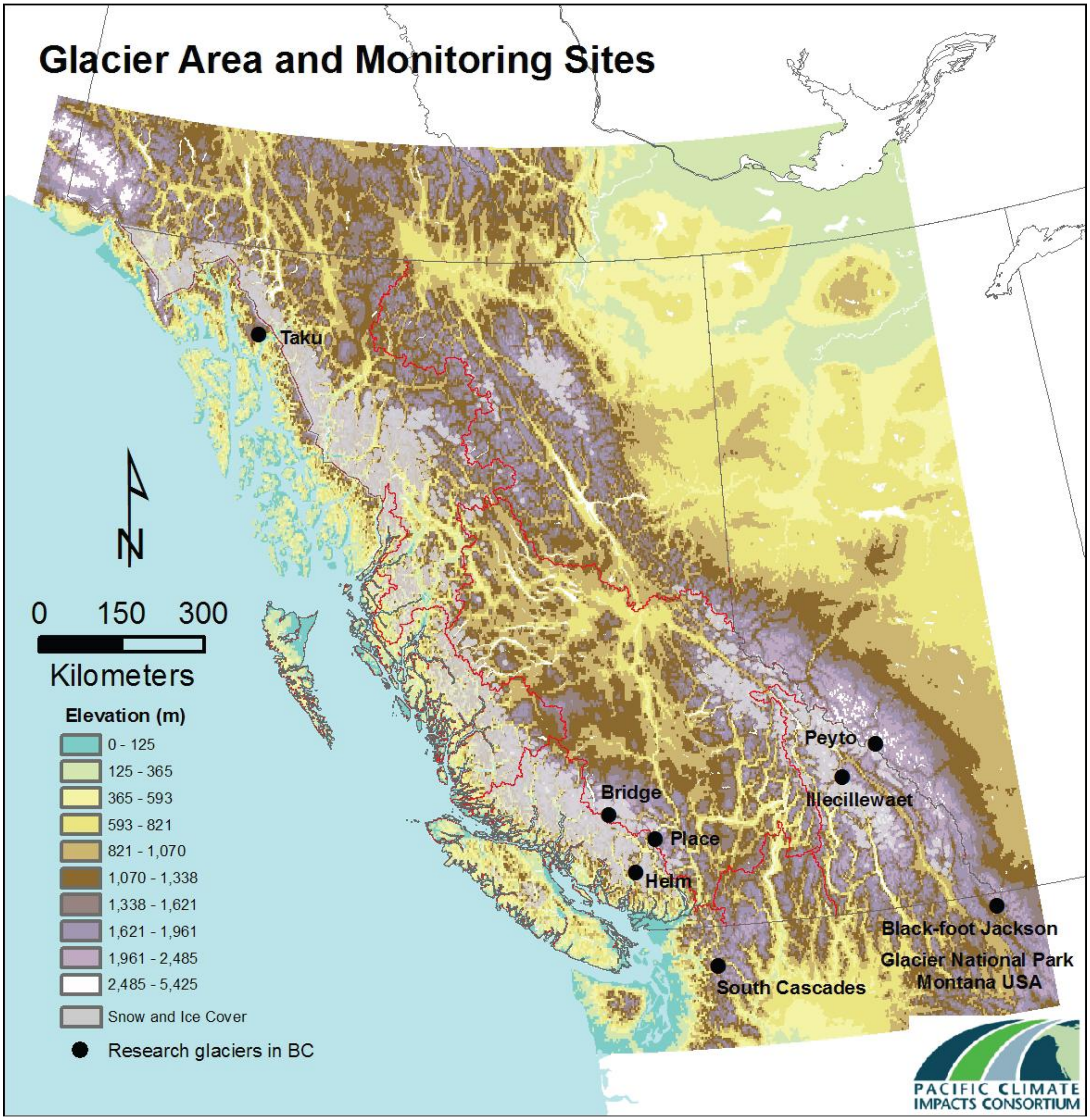

Figure 2. Glacier area and monitoring sites in BC. Source: 1990s Baseline Thematic Mapping data. Rodenhuis et al. (2009).

3. **Canadian Glacier Information Centre (CGIC)** currently controls data and literature about Canadian glaciers. The principal collection element is the Canadian Glacier Inventory, a printed and electronic catalogue of Canada's glaciers, complemented by an air photo collection.

Although not as comprehensive as the above sources, several other studies have examined changes in glaciers, and the findings in those studies may apply to specific areas of interest in the Province:

4. Walker and Pellatt (2001) note that the glacial history of British Columbia is largely revealed in the published works of a small number of Quaternary geologists. Walker and Pellat (2001) summarize some of the findings of those researchers for both the Coast and Rocky Mountain areas (see Appendix 1)[5]. Many glacial advances have been recorded in the past 3500 years, with most glacial maxima dating to the mid 19th century. A general retreat of these glaciers has accompanied the recent warming trend in British Columbia.

5. Pelto (2011) organizes the North Cascade Glacier Climate Project and reports on changes of terminuses of glaciers around the globe. He notes changes in glaciers of the Cascade Range of BC and the USA, but also notes changes in some glaciers of the Canadian Rockies (e.g., Illecillewaet, Athabasca, Bugaboo) and Coast Mountains (e.g., Garibaldi), (as well as many other areas of the US (especially Glacier National Park) and the World).

6. Koch et al. (2009) examined glaciers in the Garibaldi area. Fluctuations of glaciers during the 20th century in Garibaldi Provincial Park, in the southern Coast Mountains of British Columbia, were reconstructed from historical documents, aerial photographs, and fieldwork. Over 505 km^2, or 26%, of the park, was covered by glacier ice at the beginning of the 18th century. Ice cover decreased to 297 km^2 by 1987–1988 and to 245 km^2 (49% of the early 18th century value) by 2005. Glacier recession was greatest between the 1920s and 1950s, with typical frontal retreat rates of 30 m/yr. Many glaciers advanced between the 1960s and 1970s, but all glaciers retreated over the last 20 years. Times of glacier recession coincide with warm and relatively dry periods, whereas advances occurred during relatively cold periods. Rapid recession between 1925 and 1946, and since 1977, coincided with the positive phase of the PDO, whereas glaciers advanced during its negative phase (1890–1924 and 1947–1976). The record of 20th century glacier fluctuations in Garibaldi Park is similar to that in southern Europe, South America, and New Zealand, suggesting a common, global climatic cause. They conclude that global temperature change in the 20th century explains much of the behaviour of glaciers in Garibaldi Park and elsewhere.

7. There is work on the Illecillewaet in Glacier National Park (Sidjack and Wheate 1999).

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[5] They also look at paleo ecological, limnological, and dendrochronological data, which is not of much interest to current climate monitoring, but very interesting to reveal past trends. Abundant evidence preserved in the sediments of British Columbia lakes records the rapid transition from a glacial to an interglacial climate over the interval 12,500 to 9000 14C yr BP. Peak summer temperatures (about 3°C warmer than present) and minimum precipitation were recorded for southern British Columbia ca. 9000 to 7000 14C yr BP, but were likely accompanied by winter temperatures colder than today's. A strong Pacific high prevailed during the summer months. Summer temperatures gradually declined over the interval 7000 to 3000 14C yr BP, as wetter conditions and a stronger Aleutian low developed. Palaeoenvironmental records, such as these, are critical for the development and testing of climate models, and for an understanding of the long-term dynamics of ecosystems. The perspective offered by these long-term changes in ecosystems is needed for the appropriate management of forest resources and development of protected area strategies.

8. Slotnick (2004) examined patterns of glacial expansion and retreat in the Skeena area during the Fraser Glaciation, which most recently dominated British Columbia.

9. Clague and Evans (1994) observed the Grand Pacific and Melbern Glaciers, two of the largest valley glaciers in British Columbia, have decreased over 50% in volume in the last few hundred years (total ice loss = 250-300 km^3). Melbern Glacier has thinned 300- 600 m and retreated 15 km during this period; about 7 km of this retreat occurred between the mid-1970s and 1987, accompanied by the formation of one of the largest, presently existing, ice-dammed lakes on Earth. Grand Pacific Glacier, which terminates in Tarr Inlet at the British Columbia-Alaska boundary, retreated 24 km between 1879 and 1912. This rapid deglaciation has destabilized adjacent mountain slopes and produced spectacular ice-marginal land forms. The sediments and land forms produced by historic deglaciation in Melbern-Grand Pacific valley are comparable, both in style and scale, to those associated with the decay of the Cordilleran ice sheet at the end of the Pleistocene (c. 14-10 ka BP). Rates of historic and terminal Pleistocene deglaciation also may be comparable. Many other works of Clague and colleagues are noted in Walker and Pellat (2001).

10. Anastasiades et al. (2007) mapped the retreat of the Asulkan Glacier in Glacier National Park, British Columbia using five dating techniques (lichenometry, dendrochronology, moraine interpretation, dendroclimatology, and airphoto interpretation).

11. Osborne et al. (2007) used evidence from glacier forefields and lakes to reconstruct Holocene glacier fluctuations in the Spearhead and Fitzsimmons ranges in southwest British Columbia. Radiocarbon ages on detrital wood and trees killed by advancing ice and changes in sediment delivery to downstream proglacial lakes indicate that glaciers expanded from minimum extents in the early Holocene to their maximum extents about two to three centuries ago during the Little Ice Age. The data indicate that glaciers advanced 8630–8020, 6950–6750, 3580–2990, and probably 4530–4090 cal yr BP, and repeatedly during the past millennium. Little Ice Age moraines dated using dendrochronology and lichenometry date to early in the 18th century and in the 1830s and 1890s. Limitations inherent in lacustrine and terrestrial-based methods of documenting Holocene glacier fluctuations are minimized by using the two records together.

4. Streamflow

Rationale: Predicted lower flows in summer and later in the season may reduce the amount of water available to forest and range ecosystems. These lower flows may be further exacerbated when water is drawn for human use. Low flows may be associated with warmer water temperatures and declining water quality, both of which would threaten the health of aquatic ecosystems. Increased storms and precipitation amounts predicted as a result of climate changes may result in higher-than-usual water volume and velocity for winter months in some regions, potentially leading to increased river turbulence, scouring, and reduced in-stream channel stability (although these effects will depend on the nature of the hydrological system, such as whether it is rain or snowmelt dominated). Rodenhuis et al. (2009) reported that in general, annual mean streamflow decreased in the southern parts of the Province, increased in the central and Fraser Plateau regions, and decreased in northwestern areas. Patterns were different for different types of runoff systems (pluvial (rain dominated) or nival (snow dominated)). For watersheds at low elevations and southern latitudes that have lost their glacier influence, the annual mean streamflow decreased and the minimum daily average streamflow decreased. This result was consistent with the impacts of warmer temperatures in mixed snow/glacial runoff regimes. They reported that the onset of spring-melt advanced by 10-30 days over the 1948-

2002 period in runoff regimes dominated by snowmelt. Impacts of ENSO and PDO were greatest in southern BC. These types of changes can have large impacts on BC's forest and range ecosystems.

Ideally, streamflow would be reported by region or by major catchment for the whole Province using data from as many monitoring stations as practical. To the extent possible, monitoring of water related indicators should be coordinated within a complementary network (i.e. measurements should be taken from similar locations or catchments) to aid the interpretation of results.

Potential data sources

Although some data sources exist, the network of streamflow monitoring sites is likely biased towards streams found in lower, more populated latitudes, lower elevations and larger rivers, leaving smaller streams, considered of critical importance to forest and range ecosystems, likely to be underrepresented in the network. Rodenhuis et al. (2009) noted that understanding hydro-climatology in BC relies in part on having an adequate observational network. However, the network of climate stations in BC is inadequate to represent the variable hydrologic regimes present within B.C. Most observation stations are located in the south and information is particularly scarce in non-urban areas, small watersheds and in the northern cold regions of BC. As well, most stations are situated at elevations below 200 m, whereas high elevation areas above 1000 m are not well represented. The current observational network presents a barrier to evaluating changes in temperature, precipitation, glacier cover, snowpack, and streamflow in the Province.

Short record lengths and extended periods of missing data also hamper investigations of the influence of climate change and variability on the hydrology of BC. Often, the influence of climate variability cannot be distinguished from that of climate change because some modes of climate variability such as the Pacific Decadal Oscillation (PDO) operate on multi-decadal time scales. Therefore, a considerably long record is required to adequately distinguish between trends created by the PDO as it switches from one phase to another (cool to warm), from trends occurring due to climate change. We do not have a long record of streamflow in BC.

Pacific Climate Impacts Consortium (PCIC) has undertaken projects to synthesize and analyse available data on streamflow. We first describe the data sources, then PCIC's summaries.

1. **Environment Canada's Water Survey of Canada:**

Standardized, credible river level and discharge data are collected by the Environment Canada's Water Survey of Canada, under a national program jointly administered under federal-provincial and federal-territorial cost-sharing agreements. The web page http://www.wateroffice.ec.gc.ca/index_e.html links to the Water Survey of Canada's "Real-Time Hydrometric Data" website, from which current water level and discharge information from selected hydrometric stations throughout BC can be accessed. This site provides public access to hydrometric (water level and streamflow) data collected at over 1700 locations in Canada. The data are transmitted from the hydrometric station via GOES satellite or telephone telemetry every one to three hours. Unfortunately, the network was in decline for many years and by the late 1990s had been reduced by over 40 per cent. In the last decade, substantial funding was committed to rebuilding the network (specifically for climate change analysis purposes) and indeed some new stations have been established (Lynne Campo pers. comm.). Environment Canada has provided a list and map of discontinued, current and new stations.

2. **Hydro's system:**

BC Hydro's Regional Hydromet Data networks collect near real-time hydrometeorological data at various automated data collection stations in or near their reservoir systems across the province to support reservoir operations. Major types of hydrometeorological data collected include precipitation, air temperature, lake levels, stream levels/flows and snow water equivalents, although water temperature, wind, solar radiation and barometric pressure are also measured at a few locations. All BC Hydro's waterflow information that is not of proprietory concern (historic reservoir data are not made available) are held by (and often measured by) the Water Survey of Canada (Bruce Smiley pers. comm.).

3. US Geological Survey data

Some Rivers crossing the border have streamflow information from the USGS (e.g., the Flathead River, http://waterdata.usgs.gov/MT/nwis/current/?type=flow).

4. British Columbia Streamflow Inventory.

Water resource and hydrology investigations require summaries and analysis that use available hydrologic data in standard formats, period, and methods so that the information is consistent and allows direct comparison from one site to another. To fulfill this goal a project was initiated in the 1995-1996 fiscal year with funding by the Corporate Resource Inventory Initiative (CRII). The culmination of this project was the production of the report, *British Columbia Streamflow Inventory* (BCSI), by the Resources Inventory Branch in the 1997-1998 fiscal year. That report presents a summary of streamflow data compiled in datasheet, map and graphical forms and covers the whole province. A separate project (Obedkoff and Eng 2000), which was a direct progression of the above work, was initiated in the 1998-1999 fiscal year and was also, funded by CRII. The purpose of that study was to characterize the variability of streamflow parameters in various regions of the Ministry of Environment. The reports contain tables that summarize, for every station used: the hydrologic zone, station name, station number, drainage areas and median basin elevation and the following derived variables:

- Normal peak runoff
- Monthly distribution of normal runoff (%)
- 10 year peak (instantaneous) flow for the watershed in m^3/s
- 10 year peak (instantaneous) flow for a 100 km2 watershed in m^3/s
- Ratio of 100 year to 10 year peak flow
- 10 year seven day low flow for the June-September period in m^3/s
- 10 year seven day low flow for the calendar year in m^3/s

For climate stations which were used to estimate peak flow, the station name includes a code for the watershed slope that was used to determine the peak flow parameters: s= steep; i= intermediate, m=moderate, r= rolling, f = flat. Although the reports were accessible, we did not locate or access the data.

5. PCIC Summaries

Rodenhuis et al. (2009) used data from the Water Survey of Canada (which includes BC Hydro's information, but not USGS or BCMoE information) to examine changes in historic streamflows. They restricted their data to Canadian Reference Hydrometric Basin Network (RHBN), which are watersheds relatively undisturbed by human activity (although those watersheds were sometimes affected by natural disturbances such as Mountain Pine Beetle). They caution that feedbacks on streamflow from changing surface groundcover that are already evident in BC forests due to the Mountain Pine Beetle infestation. The ground cover is changing and impacts to hydrology can only be estimated --earlier peak flows, increased low flows, and increased annual runoff are expected consequences.). They divided streams into runoff categories (pluvial, hybrid, nival and nival/glacial)[6]. Their analysis calculated trends for 1976-2005. Annual mean, minimum and maximum streamflows were investigated, as were effects of ENSO and PDO. Their use of runoff categories in part reflected that trends in streamflow over the last 30 years were not uniform within hydro-climatic regions as defined by an amalgamation of the BC watersheds and the Hydrologic Zones of BC. Because of this, trends could not be described by regions and were often more coherent within groups of similar glacier cover, elevation, latitude, and proximity to the coast than within region. Responses were especially diverse across the Fraser Plateau, likely because of the large latitudinal expanse of this region. Furthermore, many of the regions did not have enough observation stations to adequately represent the diversity of the hydrology within a given region. This was especially true in the northern areas of the Province where, if stations do exist, many records do not start until the 1970s. The analysis of trends in minimum and maximum flow was based on average daily values, which created room for potential error in the interpretation of results. Firstly, different runoff regimes generally have minimum and maximum flow at different times in the year. Pluvial regimes generally have low flow in the summer where as nival regimes generally have low flows in the winter. Secondly, there is potential for the daily low value to occur at times outside of the common low flow period. As applied in their study, this analysis provided no information about the season in which the minimum of maximum flow took place. Comparison of streamflow results to trends in temperature, precipitation, and snowpack results was hindered by the lack of overlapping periods. Trends in streamflow were investigated for the latest 30 year period 1976-2005 to update a previous study and to allow the analysis of the largest number of stations. However, this period is not directly comparable with other trend estimates in their report such as with snowpack or temperature and precipitation. Trends in snowpack were carried out for 1950-2007. Temperature and precipitation were analyzed from 1900-2004. Thus, some generalizations had to be made to compare the different variables. Over the 1976-2005 study period, the warm PDO (1977-1998) likely influenced trends in streamflow; effects of PDO and ENSO on streamflow are likely substantial.

PCIC has done the most complete analysis of streamflow province wide, and anyone interested in provincial trends should use that analysis (particularly if it is updated regularly). If, however, a smaller region is of interest, then there may be a longer time-series of data available than used by PCIC and more potential data sources. For a specific region, one should investigate data availability for the region

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[6] Classification of seasonal runoff regimes has recently been carried out for BC and in the past was carried out specifically for the Georgia and the Fraser Basins. Runoff was classified into one of four categories: rain-fall dominated (pluvial), a mixture of rain-fall and snow-melt (hybrid), snow-melt dominated (nival), and snow-melt combined with glacier-melt (nival/glacial). Due to lower temperatures in high latitudes and altitudes, areas outside the Georgia Basin are likely to have either nival or nival/glacial runoff regimes. However, it has been shown that some areas display unique characteristics such as having summer peak flows resulting from summer rains. Yet, classifying rivers within these regimes helps to identify how they are vulnerable in the face of climate change and allows results to be grouped in a way that facilitates discussion.

The timing of peak and low flows is different in each regime. *Pluvial* tends to peak in November and December, with lowest flows occurring in July and August. *Hybrid* can have high flows from October to January and then again in April to June and have low flows in July and August. The proportion of rainfall versus snow-melt in the runoff of the hybrid regime is determined by temperature. Moving inland from the coast, or northwards up the coast, increases the predominance of snow-melt, as would increases in the mean basin elevation. Nival tends to peak in May, June, or July, and has lowest flows in the winter months of December to March when incoming precipitation is stored as snow. Nival/glacial has high flows that extend from May to August or September. Again, from December to March, flows are low as precipitation is stored as snowpack.

from the data sources outline above. Methods of PCIC may be used with those adjusted data sets. Their methods are not entirely clear from their paper, so discussion with the analysts would be required (contact: Arelia Werner PCIC).

5. Water temperature

Rationale: Increased water temperatures are predicted as a result of climate changes especially in northern areas. Warmer temperatures are expected to affect the fitness, survival, and reproductive success of certain fish and other aquatic species. Over the long term, higher temperatures may result in a shift in the distribution of cold-water species to higher latitudes and elevations. However, if other factors such as habitat discontinuities were to limit these range shifts, an overall reduction in the distribution of certain species would be the result. By contrast, river warming may have positive consequences for aquatic species that prefer (or can tolerate) warmer water temperatures. Native warm-water species may be able to expand their range into higher-altitude lakes and more northerly regions. Warmer temperatures may also allow invasive or exotic species to expand in range.

Ideally, water temperature would be reported Province wide (or by region or major catchment) using data from as many monitoring stations as practical. To the extent possible monitoring of water related indicators should be coordinated within a complementary network (i.e. measurements should be taken from similar locations or catchments) to aid the interpretation of results.

Potential data sources

Environment Canada's water quality sites (see below) sometimes include temperature measurements, but their focus is on measuring chemical properties. Nonetheless, B.C. MoE staff in Victoria (Leonne Gaber pers. comm., Robert Gibson pers. comm.) and Nelson Region (Tracy Henderson pers. comm.), indicated the best and most comprehensive water temperature data for BC are held by Environment Canada's Water Survey. Environment Canada network of water survey sites includes BC Hydro data, but does not seem to have other provincial information (perhaps because of the scattered nature of that information). The locations of water survey sites are noted on an interactive web-based map. The map does not indicate which stations have water temperature information, or if the temperature data are gathered by temperature probes or are surface measurements made when technicians are in the field. A request to Water Survey Canada (Lynne Campo) resulted in clarification on which sties had water temperature information; water temperature data is provided quickly when request quickly and is free of cost. Water Survey of Canada holds (and measures) most of BC hydro's waterflow sites; BC Hydro measures water temperature on some sites, but doesn't usually release the data.

B.C. Ministry of Environment has some measures of water temperature but only for selected streams. Eddington et al. (2009) reported that *MOE Water Stewardship Division* Sciences and Information Branch is currently conducting research into how water temperature monitoring can be improved, but at this point in time it seems those plans have been put aside and none are in place to monitor water temperature (Leonne Gaber pers. comm., Robert Gibson pers. comm.). Staff from each Region may know of specific water temperature studies.

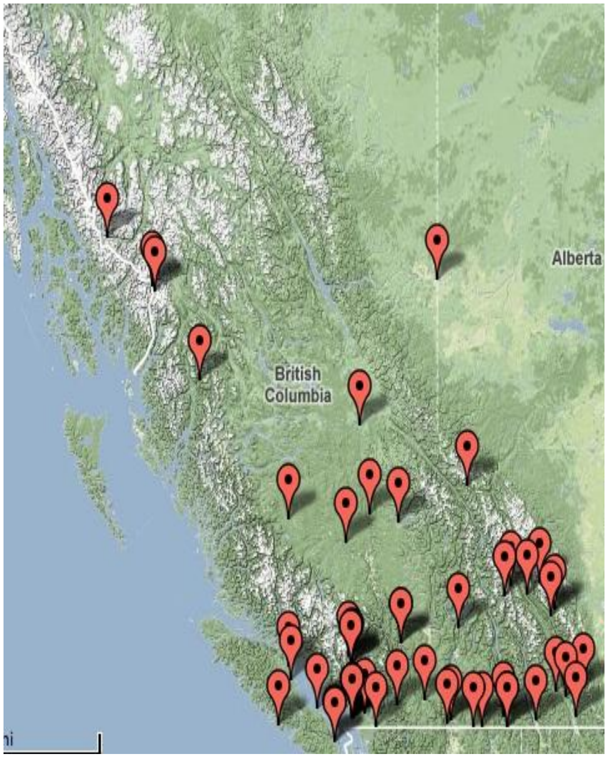
6. Water quality

Rationale: Climate driven changes to hydrological systems are likely to cause changes in the physical, chemical and biological characteristics of water in forest and rangeland streams and lakes. Such changes may impact on freshwater and estuarine ecosystems and aquatic species found within forests and rangelands and may also impact on the quality of water available for human use.

Potential data sources

The most comprehensive water quality data is held by the Water Survey (Environment Canada) as a result of their role in the BC and Yukon Water Quality Monitoring Network. B.C. MoE has other data as do some non-government organizations.

1. The B.C. and Yukon Water Quality Monitoring Network (http://gcmd.nasa.gov/records/CANADA-CGDI_Canada_EC_EnvirodatBCYukon.html) presently consists of 36 long-term ambient water quality monitoring stations on rivers in British Columbia, and 5 stations on rivers in the Yukon. These stations are primarily operated on rivers of federal interest (e.g., transboundary, national parks, major fisheries). Of the stations operated in B.C., 30 are jointly operated by Environment Canada and the B.C. Ministry of Environment, Lands and Parks under the Canada-B.C. Water Quality Monitoring Agreement, on rivers of mutual interest/jurisdiction. The remaining stations (6 in B.C. and 5 in the Yukon), are operated solely by Environment Canada. Most sites are sampled on a bi-weekly basis for a wide range of water quality variables, including trace metals, nutrients, major ions, fecal coliforms, and other parameters of site-specific importance (e.g. dissolved oxygen, pesticides, etc.). A majority of the chemical analysis is performed at the Pacific Environmental Science Centre (PESC) in North Vancouver B.C. Environment Canada archives this data in an Oracle relational database called Envirodat. The primary objective of this water quality monitoring program is to look at the long term changes in water quality to assess trends. This program has been in operation since 1975, but the present format of the network (i.e. long-term, routine monitoring), was formalized under the Canada-B.C. Water Quality Monitoring Agreement in 1985. The data is also used for a variety of other reasons, including: facilitation of water resource planning and environmental assessments, determination of the state of water quality and ecosystem health, assessment of the effectiveness of departmental policies and programs, formulation of water quality guidelines and objectives, assessment of compliance with existing guidelines and objectives, calculation of loadings of contaminants to the environment, and detection of emerging issues. The map below shows station locations:



2. The BC Ministry of Environment has established field procedures for water quality sampling (http://archive.ilmb.gov.bc.ca/risc/pubs/aquatic/design/index.htm), but aside from their participation in the BC Yukon monitoring project (see above), and a status report produced in 1996 (described below), it is not clear how much water quality work has been done (Kevin Rieberger pers. comm.). The B.C. Ministry of Environment has an "Environmental Management System" website which allows retrieval and subsequent analyses of water quality information that is held in the system. The EMS system has water quality information from a variety of sources and for a variety of purposes, but there appears to be no systematic sampling of water quality of streams, rivers, lakes or aquifers.

Ministry of Environment completed a status report in 1996 (MoE 1996) on the quality of water in 124 bodies of water across BC. These include 81 river sections or creeks, 26 lakes, 12 marine bays or inlets, and 5 ground water aquifers. These are areas where information was collected because problems with the quality of the water were expected[7]. A variety of areas are covered by the 124 waterbodies, but almost half come from the lower mainland. In the lower mainland there are 55 status reports covering 5 lakes, 36 stream reaches, 10 marine areas, and 4 ground water aquifers[8]. The Omenica Peace region has 12 status reports covering 1 lake and 11 stream reaches [9]. In the Thompson region there are 33 status reports covering 9 lakes, 23 stream reaches, and 1 ground water aquifer [10]. In the Skeena region there are 9 status reports covering 5 lakes, 2 stream reaches, and 2 marine areas[11]. For Vancouver Island there are 9 status reports covering 3 lakes and 6 stream reaches[12]. For the Kootenay there are 5 status reports covering 2 lakes and 3 stream reaches[13]. The Caribou has only one status report, for Williams Lake. The Ministry of Environment apparently has 3500 sites where water quality is measured, but discussion with several Ministry people did not allow us to locate or access that data. Measurements and frequency of measurements depend on the region. Some of those sites are likely from *MOE Environmental Protection Division* which reports on water quality in the Province although this reporting

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[7] Of the 124 waterbodies considered, 48 percent are ranked as having fair water quality and 35 percent as good. Fair means most uses of the water are protected with conditions only sometimes different from natural levels while good indicates all uses are protected with conditions close to natural levels. The remainder are either excellent (7 percent), borderline (5 percent), or poor (5 percent).

[8] Fraser River Area from Hope to Haney; Ground Water Aquifers in the Fraser River Area from Hope to Haney; Fraser River Area from Haney to the Mouth; Lower Fraser River Tributaries Area; Boundary Bay Area; Burrard Inlet Area; Burrard Inlet Tributaries Area.

[9] Peace River Area; Charlie Lake; Pine River Area; Pouce Coupe River Area; Bullmoose Creek Area.

[10] Thompson River Area; Bonaparte River Area; Okanagan Valley Lakes; Tributaries to Okanagan Lake Near Westbank; Tributaries to Okanagan Lake Near Kelowna; Hydraulic Creek; Similkameen River Area
Cahill Creek Area; Bessette Creek Area; Ground Water Aquifer at Grand Forks.

[11] Kitimat River and Arm Area; Lakelse Lake; Smithers Lakes; Bulkley River Area

[12] Elk Lake Area; Cowichan River Area; Oyster River Area; Middle Quinsam Lake Area.

[13] Columbia River from Keenleyside to Birchbank; Columbia and Windermere Lakes; Toby Creek and the Upper Columbia River.

is biased to a view of water quality in developed areas, rather than for undeveloped watersheds where hydrological systems are in a more natural state.

The Ministry of Environment also has jurisdiction over ground aquifers. At this time information on aquifers is extremely difficult to find or access. MoE holds no systematic reports. Consultants hold some information on some aquifers. 'Well' records are not linked to the aquifers delineated through the Aquifer Classification System. It is not possible to query the well records or the aquifers for all the well records that are found in the area of any given aquifer. Changes in aquifers are likely with climate change, but no system is in place to track those changes

3. Several volunteer groups and non-government organizations track changes in lakes and wetlands. These groups should be contacted for information on any specific areas that overlap their interest areas. The Lake Stewardship Society (http://www.bclss.org/projects/bclsmp.html) is one such group; Ducks Unlimited is another.

4. *Forest and Range Evaluation Program (FREP)* has data on fine sediment generation for site-level water quality sampling (Tripp et al. 2009). An extension report outlining 2008 to 2010 findings will soon be published. These site-level investigations of effects of roads, cutblocks, and other developments on water quality (specifically sediment production) would be almost impossible to relate to climate change.

7. Unseasonable or unexpected weather conditions

Rationale: During periods of climate adjustment there is a strong likelihood of unseasonable or unexpected weather. This may include late or early frosts, extreme snowfalls, ice storms, hail, droughts and other weather-related events. Many of these can have major impacts on forests and rangelands. In addition to changes in temperature and precipitation, global climate change has the potential to increase the intensity of Pacific storms. Increasing sea surface temperatures of the Pacific Ocean and changes in climate variability can also contribute to this effect. The Province lies directly in the path of Pacific storms, and changes in intensity are an important concern for hydroclimatology and water management in the future.

Ideally, reporting under this indicator should include an examination of the frequency and intensity of unseasonable or unexpected weather events over long time periods to see how the current decade compares with those of the past.

Potential data sources

Very little information exists on extreme weather events*. Environment Canada's Meteorological Service of Canada (MSC)* monitors and collects data on severe weather conditions, such as hurricanes, tornadoes, severe thunderstorms, storm surges, strong winds, high heat or humidity, heavy rain or snow, blizzards, freezing rain and extreme cold. *Environment Canada Climate Network for British Columbia and Yukon* operates a network of approximately 500 climate stations in B.C. and the Yukon and maintains an associated archive of historical weather information. That data is available at a cost from Environment Canada.

Environment Canada's data allows derivations of several indicators including extent of dry periods, frost free days, early and late frosts. These indicators will soon be examined by PCIC (Faron Anslow pers. comm.).

Other sources of data have some potential*: Ministry of Forests Lands and Natural Resource Operations Wildfire Management Branch* reports annually on specific events (such as lightning strikes) although is not set up to report on 'diffuse' events such as droughts.

The *Ministry of Agriculture* does not may report unusual frosts or high heats or other damaging weather events, but does track insurance claims and causes. It might be possible to track trends and causes of claims for key sensitive crops to get an indication of unusual and damaging weather events for certain areas of the Province.

Criterion 2: Natural Disturbances

8. Mass movements

Rationale: This indicator was meant to examine the scale and density of mass movements and erosion events (landslides, rockfalls, debris torrents, debris avalanches, debris flows, etc.) in relation to climate change. The frequency and extent of rapid mass movements are influenced by underlying geology, precipitation amount and intensity; snow accumulation, melt rate, and distribution; and land uses such as road construction or forest harvesting. Vegetation also influences the likelihood of mass movements through the soil-stabilizing effects of root systems and the effects of vegetation structure and composition on hydrology. Climate change may affect precipitation, snowmelt and vegetation to alter the frequency and/or magnitude of mass movements and erosion events. Although underlying geology is independent of climate, climate change may affect surficial geology (via changes to soils, hydrology and vegetation) and also affect mass movements.

Landslides in mountainous terrain are strongly influenced by climatic factors, including precipitation and temperature (Geertsema et al. 2006, Clague and Evans 1994). Catastrophic landslides at high elevations may be particularly responsive to increases in temperature. Researchers have suggested that recent melting of glaciers in British Columbia has debuttressed rock slopes adjacent to glaciers, causing deep-seated slope deformation and catastrophic failure (Clague and Evans, 1994; Holm et al. 2004). Alpine permafrost may be degrading under the present warmer climate, decreasing the stability of slopes. Recent large rock avalanches in the European Alps have been attributed to melting of mountain permafrost (Gruber 2011) and this phenomenon may also play a role in initiating landslides in northern British Columbia.

Precipitation also affects landslides (Geertsema et al. 2006, 2009). In a simple sense, the occurrence of landslides will increase in relation to the amount and duration of precipitation; however, slope factors may be more complicated and thus preclude a simple analysis. Some landslides respond rapidly to rainfall, others have delayed responses. In any case, antecedent conditions have been shown to be very important. In general, soils must become saturated, allowing the build-up of pore pressures. Larger, and especially deeper, landslides tend to have delayed responses to precipitation. It takes time for water to infiltrate and saturate potential slide masses. Individual rainstorms, rain-snowmelt events, and outburst floods can indirectly trigger landslides by increasing peak flows in streams. High water flows are known to increase bank erosion which may trigger slides. Timing of precipitation and snowmelt is important. For example, the sudden and delayed melt of above-average snowpacks can lead to increased landslide events caused by increases in pore pressure.

There is evidence that landslides are linked to overall climate as well as to specific weather events (Geertesma et al. 2007). They noted that nearly all of the 58 global circulation models available from the Canadian Institute of Climate Studies (http://www.cics.uvic.ca) predict a warmer and wetter climate for northwestern and northeastern BC. Their historic analysis shows that a warmer, wetter climate is likely to be accompanied by increased landslide activity. In a study of glaciomarine flowslides in the Terrace area, Geertsema et al. (2007 and earlier) noted that more than one-third of the prehistoric flowslides happened between 2000 and 3000 years ago, a period of above-average precipitation in northwestern BC. They predict an increase in landslide activity during the 21st century due to more violent storms, continued glacial debuttressing due to glacier retreat, permafrost degradation, and generally wetter conditions. Climate change has indirect, as well as direct, effects on landslide frequency. Recent climate warming has contributed to insect and disease epidemics that have caused unprecedented forest dieback in northern BC. Reduction of evapotranspiration, hydrophobic soil conditions following wildfires, and salvage harvesting predispose landscapes to increased slope failure. More work needs to be done to define possible links between landslide events and PDO and ENSO patterns. In northern British Columbia, the Pacific Decadal Oscillation strongly influences temperature and, to a lesser extent, precipitation patterns in 20–30 year cycles. The last decade of the current warm phase of the PDO, which started in 1976, was a period of frequent rockslides. Comparisons of landslide frequency and the PDO need to be extended beyond the current phase into the past and also linked, if appropriate, to El Niño-Southern Oscillation.

In the survey (Eddington and Innes 2008), mass movement was seen as moderately important for monitoring in light of climate change. The number of confounding factors (effects of land use rather than climate) that would mask or mislead interpretation of effects of climate change, make this a difficult indicator to pursue. As well, data to support monitoring of the indicator on anything but a case study basis is not currently available. Ideally, Province-wide aerial surveys or remotely sensed data could be used to record mass movements and erosion events over a certain size. This information could be supplemented where possible with information collected on a regional basis in order to aid interpretation and gain some understanding of changes of mass movement with climate change.

Potential data sources

We were unable to find evidence of systematic programs directed at monitoring mass movement frequency and extent (Marten Geertsema pers. comm., Tom Millard pers. comm., Peter Jordan pers. comm., Ray Coupe pers. comm.). The idea of a systematic survey is not new --Perkins (2007) noted that Cruden et al. (1989) recommended that a Canada-wide inventory of damaging landslide be kept (but that seems not to have been initiated, even provincially).

Although not specific to mass wasting, some systematic information could be gleaned from the BC MoF Forest Health Surveys (http://www.for.gov.bc.ca/hfp/health/overview/). Since 1999, the B.C. Ministry of Forests (now Ministry of Forests Lands and Natural Resource Operations) has surveyed the majority of the forested land in the province using the classic sketch mapping technique known as the overview survey method (Westfall and Ebata 2010). The purpose of the survey is to record and report the general trends in disturbance patterns across the provincial forested land base (including provincial parks, private land, and Tree Farm Licences but not Federal Parks). The survey has been a key source of data documenting the development of the current mountain pine beetle outbreak in the interior of B.C. Data from the BC MOF survey is also comparable to data collected from 1914 to 1995 by the Canadian Forest Service's former Forest Insect and Disease Survey Unit (FIDS) and to the US Forest Service’s Forest

Health monitoring surveys. They have codes for slides (one for snow avalanches and one for terrestrial slides), so if those can be seen while flying at 800m altitude at 80 knots, they will be recoded. Recorded slides are not abundant and detecting a trend with climate change may never be possible or take decades to manifest. GIS shape files exist for all disturbances so information specific to an area of interest within the province could be downloaded.

Other sources of information that span the province include those concerned with transportation corridors. Some transportation corridors maintain records of disruption although these have not been traditionally used for monitoring. For example, geotechnical investigations have been undertaken for the Sea-to-Sky Highway. Similar records may be available for the Trans-Canada Highway and for the various rail tracks crossing B.C. Hungr et al. (1999) completed an inventory that spanned 40 years, of damaging rockfall events along BC's major transportation routes. Information on mass movement events that disrupt forest roads was a reporting requirement under the Forest Practices Code but is no longer required. Some Districts, and some licensees (e.g., TEMBEC, Kari Stewart Smith pers. comm.), continue to report such disturbances, but the information is not collected systematically across the Province (Peter Jordan pers. comm.).

Many site-specific studies have examined extent of landslides:

Most studies of landslides in BC are specific to particular areas of the Province. The most extensive studies have been done in northern BC by Geertsema et al. (2006, 2007, 2009). They documented large landslides over much of northern BC and linked those to weather and climate patterns (some information from those reports was noted in the rationale section above).

Vancouver Island and the Queen Charlotte Islands also are areas of other extensive studies. Guthrie (2005) used previously gathered data and new samples to delineate landslide risk zones for Vancouver Island. During that project he recorded 665 landslides over 200 km^2 of terrain. Of these, most were debris slides and flows (69% or 456 landslides), and most of the remainder were rock falls and talus slopes (23% or 151 landslides). Snow avalanches accounted for about 9% (58) of the landslides documented. Guthrie notes the mass wasting findings of several other researchers that completed previous studies on Vancouver Island.

MoE and MoF supported several studies on Vancouver Island and the Queen Charlotte Islands (see http://www.for.gov.bc.ca/rco/research/Geompub.htm for numerous papers by Rollerson, Millard and others). Schwab (1983) documented mass wasting at the Rennell Sound area of the Queen Charlotte Islands. Those slides were triggered during the storm of October30/November 1, 1978. The storm brought heavy rain (120 mm in 12 hours) and high winds. A survey of storm impacts showed the occurrence of 264 mass movements[14].

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[14] Of the mass movements, 113 were in forested terrain; 126 in clearcuts and 25 from roads. The area disturbed by debris avalanches was 64 ha or 0.4% of the steep land area. Debris avalanches in clearcuts caused the largest impacts affecting 46.4 ha (4.3%) of clearcut terrain. In comparison, debris avalanches disturbed 15.4 ha (or 0.1%) of forested slopes, and 2.3 ha (or 1.9%) of roads. Debris torrents scoured 22.3 km o f stream channel, mostly on forested slopes. Mass movements occurred at a frequency of 0.8/km^2 in forested terrain, 11 .6/km^2 in clearcuts, 20 .8/km^2 from roads. The rate of mass wasting on man-modified terrain was 15 times greater than on forested terrain.

Lier et al. (1994 in Perkins 2007) completed an inventory of mass wasting that covers 8000km^2 of the upper Fraser Valley. Eishbacher and Clague (1981) documented storm induced mass wasting in the lower Fraser Valley.

Peter Jordan of the MFLNRO, has inventoried mass wasting events on selected study areas in the South Selkirks area. The work was undertaken pre-2002 and since then there has been no funding to continue. Jordan's approach (Jordan 2002) was to conduct an air photo inventory of all landslides, natural and development-related, in forest land in a study area (centred on the Slocan Valley) which covers roughly 1 million ha. A journal publication summarizing the work is anticipated for March 31 2012. Jordan (2010) also assessed extent and prevalence of debris flows after the 2007 fires in the Kootenays of B.C. Although debris flows were noted after the severe 2003 fire season, the phenomenon has not been well-studied and do not directly relate to general trends of climate-induced mass-wasting.

Several authors have determined that landslide rates vary with bedrock. On Vancouver Island, rates are lower over the Island Plutonic Suite, which consists of Jurrasic-aged granitic rocks, than over Karmutsen Volcanics, which are Triassic pillow and flood basalts that cover most of Vancouver Island, or the Bonanza Volcanics, which are Jurassic sub-aerial andesites (VanDine and Evans 1992; Guthrie 1997; Sterling 1997; Guthrie and Van der Flier-Keller 1998; Guthrie and Evans 2004). Other bedrock types also appear to influence landslide rates or conditions; Rollerson et al. (2002) examined the San Juan River watershed and determined that the Leech River Complex was more vulnerable to landslides than other substraites. The Leech River Complex consists of greywacke, argillite, schists, and weakly metamorphosed siltstones that weather into plastic silts and clays.

The above studies are only examples, many other studies exist. Together, they indicate that the quality of baseline information on mass wasting is very good for some areas of BC. However, even good baseline information does not enable mass wasting to be a particularly useful indicator to track effects of climate change. Guthrie (2005) noted that logging activities increase landslide frequencies by more than 10 times, and the presence of roads increases landslide area by 22 to 43 times. These results corroborate previous studies and point to the large effects of disturbance on mass wasting events. Even if baselines exist and periodic future studies document changing rates of mass wasting, before any changes could be related to climate the effects of changing disturbance (e.g., roads, harvest, fire), forest age, and even simple changes in weather would need to be accounted for.

Suggested potential future directions

For mass wasting to be linked to climate, regular landscape level inventories would need to be done. If the samples were large enough some of the confounding factors would not matter, but for the most part, records of vegetation type, recent human disturbance, recent weather, and other factors affecting stability would need to also be recorded before any correlations to climate change would be possible. Geertsema et al.'s approach of looking at slides in undeveloped areas is better suited to tracking effects of climate change than studies in human-disturbed areas.

Even in natural areas, mass wasting is difficult to interpret as a signal of climate change. Gruber (2011) noted that the assessment of landslide hazard in cold regions (i.e. influenced by snow, glaciers, permafrost) is faced with a two-fold challenge: The magnitude of climate change is expected to be greater there than in many other regions, enabling strong shifts in the probabilities of triggering events such as intense precipitation or snow melt. Additionally, rapid changes such as permafrost degradation or vanishing glaciers can fundamentally alter system behavior and thus strongly change its response to a given forcing. As a consequence, the known difficulties of understanding low-frequency high-magnitude events such as landslides are intensified by continued and nonlinear change.

The detection of changes in the frequency or magnitude of slope failures is fraught with a number of difficulties (Huggel et al. 2011). Documentation of slides becomes increasingly complete with time, which must be considered to avoid deriving erroneous trends. Inventories of high-mountain rock slope failures generally contain a limited number of events, typically <100 over the past ~100 years, limiting rigorous statistical analysis. Limited applications of mechanical slope stability models exist for rock slope failures in permafrost areas, but explicit modeling of different effects of permafrost on rock slope stability has not yet been achieved. Thus, although the human influence on increasing temperatures is detectable in different regions around the world any anthropogenic effect on high-mountain slope failures cannot yet been quantified.

If a periodic region-wide or province wide survey of mass wasting was to be undertaken, several documents could assist in designing the program.

- Risk and Hazard assessment procedures and case studies were presented in the Land Management Handbook “Landslide Risk Case Studies in Forest Development Planning and Operations”. Similarly Land Management Handbook 74 (Neimann and Howes 1992) focused on ways to assess stability.

- Although there are explorations of mass wasting using remote sensing rather than air photo interpretation to track landslides and debris flows, this has not been done at a Provincial scale. Barlow et al. (2009) demonstrated the use of an automated inventory in the geomorphometric evaluation of debris slide initiation for the Chilliwack Basin, British Columbia. Usually detailed study of debris slide activity at the basin scale typically involves landslide inventories generated from aerial photographs. However, they showed that some types of rapid mass movement can be accurately identified using a combination of high-resolution satellite imagery and digital elevation data. This approach is beneficial as the digital products allow for a more accurate and efficient data throughput into various types of geomorphic analysis.

- Brunner et al. (2007) have developed a GPS monitoring system for the investigation of landslides. The applicability of this system was demonstrated by monitoring the deep-seated mass movement Gradenbach, Austria. After monitoring seventeen GPS surveys of at least 48 hours duration during the last seven years, they determined that motions can be determined with an accuracy of 4 mm in horizontal direction and 8 mm in vertical direction.

- If photographs are used, Barlow et al. (2009) note that although it is preferable to examine a complete series of air photos spanning decades, time constraints may necessitate using a more limited number of photo sets. They suggest that aerial or ortho photos at about 1:12,000 to 1:16,000 scale are best for detection of small features; scales of 1:24,000, 1:40,000, and 1:62,500 cover more area with fewer photographs, and are better for terrain evaluation, but provide reduced resolution. Color photographs are preferred, because they allow detection of subtle differences in tone of soil, vegetation, etc.; however, they are more expensive and produced less often.

- Forest and Range Evaluation Program (FREP)'s program on soils examines stability, including mass wasting events, at the cutblock level. Their high resolution photographs have potential to track mass wasting, but the assessment usually does not look upslope or downslope from the cutblocks of interest, so examining sources or extents of any mass movements is limited (Chuck Bulmer pers. comm.). Although a document was crafted exploring a process and protocols to track soil disturbance at the landscape level, that work has not been pursued, in part due to funding, and in part due to the state of appropriate images necessary for the work (Stephan Dube pers. comm.). The Province stopped its regular aerial photography flights in the early 1990s and since then images have been taken for specific areas to meet objectives of specific projects. Full coverage of the province does not reside in the Ministry of Forests data warehouses. Although the province has obtained recent images, these are not generally accessible (some data processing is yet required), researchers could ask for and obtain images for areas of interest. As well, FREP has investigated obtaining images from Landsat or Spot 5 distributors (recent images are costly but old ones are less expensive or free). Although FREP is not presently pursuing the landscape level disturbances, some landscape level information may be available for some areas.

9. Windthrow

Rationale: Increases in the intensity, frequency and severity of stormy weather predicted as a result of climate change are likely to result in increased scale and severity of wind throw damage to forests. Northern Vancouver Island, areas of the central coast and parts of the Queen Charlotte Islands are likely to be most susceptible to these disturbances because of their exposure to the prevailing winds from the ocean. Forests may also become increasingly susceptible to wind damage through the effects of other climate-related factors. For example, increased precipitation could destabilize soils or increased pests could reduce vigour of tree roots.

This indicator is meant to report on the scale and severity of wind throw damage affecting forests. This indicator is currently seen as being of moderate importance to the monitoring framework. It should be monitored using Province wide aerial surveys to record medium to large scale damage resulting from wind throw. This information should be supplemented where possible with information collected on a regional basis especially for those areas expected to experience increases in the intensity, frequency and severity of storms or suffering from other stressors that might predispose them to windthrow (e.g., saturated soils, root disease). As discussed below, stand-level monitoring of windthrow is difficult to relate to changes in climate or weather but is important information for management; landscape-level information has greater applicability to tracking effects of climate change but is still a difficult indicator to assess.

Potential data sources

Stand-level Studies*:*

There are many studies of stand-level windthrow. Most of these examine windthrow over a period of time in retention patches, cutblock edges, or riparian zones. Although these studies could be used as baseline to compare to future levels of stand-level windthrow, the ability to attribute changes in windthrow to changes in climate or weather is limited. Much of the variance in stand-level windthrow can be attributed to design of cutblocks or retention patches, their layout as compared to the orientation of major winds, and attention to windfirm boundaries. As well, risk of windthrow changes with stand age, so examining changes over time would be confounded. Unless those factors were known and taken into account, any changes in levels of stand-level windthrow could not be easily attributed to changing climate and weather patterns. Even if the multitude of stand-level windthrow studies that are summarized below could be repeated in similar places in the future, the ability to say anything about effects of climate are minimal. Landscape-level studies have more potential to link to climate trends. Nonetheless, we note some of the major stand-level studies in BC in case they can be useful baselines for areas of particular interest.

Forest and Range Evaluation Program (FREP) has a cutblock level wind throw monitoring protocol and a review is underway of all FREP protocols to see how best to integrate wind throw monitoring on sites visited for monitoring of other resource values. As well, FREP includes windthrow in its evaluations of Riparian Management Areas and Streams. FREP's latest report (Densmore 2011) on stand-level retention noted an average of 9% windthrow in the 414 cutblocks with retention measured in the northern Interior Forest Region. In the BWBS, the average windthrow was 6.9%. The CWH had 14% windthrow in retention patches. Similar statistics are presented for ESSF, SBS, and ICH. Those statistics could be generated by forest region or other areas of interest; FREP's data are available for broad use.

Steventon (2011) examined standing tree, coarse woody debris, and windthrow characteristics of 159 retention patches left in harvested areas of the Kispiox, Bulkley, and Morice timber supply areas in the early to mid-1990s. The patches were originally surveyed in 1998 (Kispiox) or 1994 (Bulkley/Morice) and resurveyed in 2007. Best estimates of total windthrow rates (fallen basal area/total basal area) were about 9% (Kispiox) and 17% (Bulkley/Morice) after 12–16 years. Little net change in characteristics of the Kispiox patches was observed between the two surveys. However, an estimated 14% reduction in standing basal area was observed for the Bulkley/Morice patches, and a 25% increase in proportion of standing dead trees versus live trees between the two surveys.

Beese (2001) recorded windthrow at the MASS study sites on central Vancouver Island. The MASS site was not considered a high risk site for windthrow, yet losses were substantial after six years. Low levels of dispersed retention resulted in wind damage to 29% (8 stems per hectare (sph)) of the leave trees over 6 years. Greater numbers of windthrown trees (21 sph) occurred under shelterwoods that retained a quarter of the original basal area, which represented about 10% of the leave trees. Edges of patch cuts (1.5 ha) lost fewer stems to wind damage (6 sph) than any other treatment, including the 69 ha clearcut (9 sph). Trees with larger crowns were more vulnerable to wind damage. On well-drained soils, western redcedar appears to be more windfirm than amabilis fir or western hemlock. Wet soils were a contributing factor to windthrow and one that could be altered by climate change.

Jull (2001) studied windthrow of Douglas-fir in the SBS zone. Based on results to October 2000, post-harvest wind damage rates for Douglas-fir leave trees in the cutblocks ranged from a low of 4 % to a high of 32%; the mean rate for all cutblocks and study areas was 10-11%. Of this wind damage, about 90% was windthrow (uprooting), with the remainder being windsnap.

Rollerson et al. (2009) examined effects of wind on various variable retention settings on Vancouver Island, Queen Charlotte Islands and mainland coastal. The project database contains 4648 plots within 172 harvested cutblocks. Plots represent nearly 366 kilometres of external cutblock boundaries, 26 kilometres of large patch edges, 197 hectares of small retention patches and 50 kilometres of riparian and other strip edges. The study showed definite regional differences in wind damage for cutblocks that have experienced at least two winter wind seasons. The average percentage of wind damage along external cutblock edges varied from an average of 11% on southeast Vancouver Island (South Island or Island Timberlands) to 25% on northwest Vancouver Island near Quatsino Sound (Jeune Landing), with an overall average of 16±0.2%2 across all areas. There were similar regional differences in wind damage for retained patches. The average wind damage along the edges of larger patches was 16% in Stillwater (mainland) and South Island and 45% in the Queen Charlotte area with an overall average of 24±0.6%. The average wind damage in small patches (i.e., ≤ 1 hectare in area) ranged from 20% in South Island and 21% in Gold River to 45% in Queen Charlotte and Mid Island areas with an overall average of 39±0.5%. For the edges of strips of retained timber, the wind damage amounts ranged from 15% on southeastern Vancouver Island (South Island) to 38% on northern Vancouver Island(Jeune Landing and Port McNeill), with an overall average of 31±0.6%.

Many other studies by Burton (2001), Delong et al. (2001), Quesnel and Waters (2001,) Huggard et al. (2001), Rollerson and McGourlick (2001, riparian areas), Coates (1997, partial cutting), have documented stand-level windthrow in various areas of the province, and data similar to those described above have been collected. These studies can be used as baselines for comparison with new windthrow results. Again, however, their utility to monitor whether climate change is affecting windthrow is limited. As stated earlier, much of the variance in windthrow can be attributed to design of cutblocks, their layout as compared to the orientation of major winds, attention to windfirm boundaries, and simple changes in weather patterns and stand age or structure. Unless those factors were known, then any changes in stand-level windthrow could not be easily attributed to changing climate.

Landscape-level studies

MfFLNRO Forest Practices Branch has surveyed the majority of the forested land in the Province using aerial survey since 1999 resulting in the production of an annual report summarizing forest health conditions and digitized maps and tables by region and district. They have codes for windthrow, so if the windthrow can be seen while flying at 800m altitude at 80 knots, it will be recoded (Westfall and Ebata 2010). Jus as for mass wasting, occurrence of windthrow is not frequent and thus will be difficult to relate to changing climate

Some studies have documented rates of wind damage across landscape (e.g. Pearson 2001). These studies show the sporadic nature of wind damage at the landscape level and can be used as baselines for future studies. Pearson's study concerns coastal BC.

Other studies have documented windspeeds and gusts. Measuring wind in forested landscapes is complicated. Wind measurements in forested areas are spatially limited, typically restricted to airport locations. As well, local terrain plays a considerable role in modifying wind speed and direction especially in mountainous regions. Murphy and Jackson (2001)'s analysis of historical wind extremes in the central interior of British Columbia revealed that southerly gusts associated with fall and winter cyclones account for most of the extreme wind events. They used synoptic climatology and map pattern classification techniques to identify recurring and representative map patterns for moderate, strong and severe southerly wind events. These "keyday" scenarios were then simulated with a 3D mesoscale numerical model whose output was used to determine wind speed ratios between grid points in the complex forested terrain and a neighbouring airport location. The speed ratios provided an estimate of the winds likely to occur above the forest canopy based on a single wind measurement at the Prince George Airport.

Sagar and Jull (2001) set up wind towers in partial cuts and clearcuts in north central and north east BC. Extreme wind events, which were defined as beginning when the 1-second wind speed exceeded 20m/s

(72km/hr), occurred at every site. Three of the more mountainous or exposed sites measured 1-sec gusts over 28m/s (100km/hr). Return intervals for extreme wind events ranged from as little as 26 days up to 605 days. Wind directions during extreme wind events were typically from southerly to westerly directions as a result of large scale synoptic weather patterns. The spatial and temporal distribution of extreme wind events was very dependent on local topography. Detailed data collected during extreme wind events show the very gusty nature of high winds.

There are opportunities to use remote sensing to estimate windthrow and windthrow trends. Murtha (2001) detailed remote approaches using the Radar Imaging Natural Systems (RAINS). The project has been monitoring 65 riparian leave strips with RADARSAT Fine 2 (F2) beam mode C-band imagery on northern Vancouver Island on 12 dates ranging from December 04, 1996 to April 11, 2000. These data, prepared as multi-temporal colour composites, were used to monitor the riparian strips. Fifty strips were located on 1995 aerial photographs and 15 strips were found on the RADARSAT images. Detectability of riparian strips depends on strip condition, contrast with surroundings, and radar shadows. By Nov 1997, total strip length measured on the air photos and RADASAT images was 24.24 km, with 18.06 km created after December 1993 (Post Forest Practices Code strips). At that time, 3769 m (or 20.86%) of the post Forest Practices Code strip length had been decimated by wind. By April 2000, measurements taken on the RADARSAT multi-temporal colour composites indicated that 6418 m (35.5 %) of post code strip length had been decimated. Holes in strips were confirmed by field work. Most of the post code decimation occurred on two landforms: ground moraine and till/rock, where 37.9 % and 43.9 % respectively of strip length had blown down.

Criterion 3: Biological Diversity

10. Genetic diversity

Rationale

Species are prone to increased risk of extinction when a significant proportion of their genetic diversity is lost. Such loss usually results from factors such as habitat reduction and fragmentation, reduced population levels, pests and disease infestations, and restrictions and/or shifts in former range. Changes anticipated with climate change can increase these threats for some species and potentially reduce genetic diversity, which may in turn result in decreased resilience and ability to adapt to future environmental changes. Although climate change may affect many species and populations and thus affect their genetics, in BC forests, little is known about the genetic diversity of any organisms besides trees, and even for trees it is difficult to track loss of genetic diversity (Sally Aiken pers. comm.).

To monitor genetic change, baseline data on genetic diversity and quantitative information from direct measures of changes (e.g., rate/ direction of loss) in genetic variation would be necessary. These elements are not known for many species or populations. In the absence of such detailed information, it is possible to monitor surrogates. For example, it would be possible to develop a list of forest and rangeland species and populations considered to be at risk from isolation and loss of genetic variation, then monitor shifts, expansions or contractions of their ranges. Shifts in range though, do not necessarily imply loss of genetic variability. A quite different measure, but a useful one given the actions anticipated by the province of BC, would be to monitor the application of formal measures to mitigate declines in genetic variation such as in situ and ex situ conservation programs and assisted migration (moving species/genetic provenances outside their range).

For phase 4 of the project, the treatment of the genetic diversity indicator was limited to considering the diversity of tree species and seed sources used in managed forests. Although changes in tree species in an area affect the genetic diversity present in that area, they do not indicate a change in the genetic diversity of the tree population itself. Although trees (and other species) may migrate in response to climate, this does not mean their genetics has changed. Part of migration is phenotypic plasticity that allows establishment and success in other sites, part may actually be genetic adaptation (e.g., Allendorf et al. in press).

Potential data sources

MFR Tree Improvement Branch, Headquarters Unit undertakes policy development and analysis; risk, impact and vulnerability assessments; criteria and indicator sustainable forest management reporting (CCFM, State of the Forest); evaluation and monitoring; and decision support. This unit is also responsible for the support of genetic resource conservation and management (GRM) spatial and non-spatial data sets, map products and information management systems, including the Seed Planning and Registry system, SeedMap, and GRM linkages to other corporate information management systems (RESULTS, MapView). Responsibilities include the development and support of GRM baseline data for the evaluation and monitoring of genetic diversity indicators and measures including seed selection, use and deployment. Climate change performance measures are also being developed to support climate-based GRM policy and practices (seed transfer). Three years ago, seed transfer guidelines were adjusted so that use of some seed could be extended upslope from past guidelines by 100 to 200 m (depending on seed and location). Subsequently, guidelines were adjusted to allow the use of larch seed from historical area into the Bulkley Valley. Presently, the seed transfer guidelines are undergoing a large revision to facilitate assisted migration. At present there are no monitoring systems reporting how much the flexibility on the guidelines were used (e.g., how often seed was planted at higher elevations than before), nor are stands were assisted migration was implemented monitored to assess stand development. However, data sent to “RESULTS” provincial database would allow investigation of those questions. Because the program is very young, trends in stand development for stands using ‘assisted migration seed guidelines’ are not likely to be different from other stands. The Ministry intends to include a monitoring component in the larger revision and implementation of the seed transfer guidelines (Greg O’Neill pers. comm.). Once the seed transfer guidelines and rules are adjusted, then it would be useful to track how much seed or seedlings have been transferred and how those trees are developing compared to the usual regeneration on those sites. Until there are more entries in RESULTS, the data there will not yet yield useful information.

MFLNRO Research Branch, Forest Genetics Section cooperates with the tree improvement branch and undertakes both theoretical research (quantitative genetics, climate-based seed transfer systems) and the practical applications of forest tree genecology, tree breeding and genetic conservation activities

Centre for Forest Conservation Genetics (CFCG) : The CFCG has a mandate to (1) study population genetic structure of forest trees using existing or new data; (2) assess the current degree of gene conservation both in situ in existing reserves and ex situ in collections, and the need for additional protection (although this is moving to MFLNRO in the future); and (3) evaluate the current degree of maintenance of genetic diversity in breeding and deployment populations of improved varieties to meet current and future environmental challenges.

Despite the mandates of those groups, no data exists to allow examination of changes in tree species distribution or treeline shifts in any systematic say in B.C. BEC, VRI and TEM[15] plots provide information on tree species present; however, tracking change in species composition requires re-measurement, and this has not been done (Sally Aiken pers. comm.). The National Forest Inventory (NFI) plots allow some tracking of change, but these plots also do not have a long period of re-measurement. None of those data sets presently allow tracking of shifts of trees over time, but they do provide useful baselines for studies done in the future, provided, of course, they are re-measured. Thought should be given to establishing the BEC plots as permanent sample plots

Cost/benefit of monitoring
While not considered to be a high priority in the survey of Eddington and Innes (2008), an assessment of genetic level diversity was deemed worthwhile for climate change analysis, especially if costs could be reduced by creating strong linkages with existing programs examining the state of genetic resources in B.C. We note that technologies in this field are advancing rapidly and the type of monitoring considered even five years ago as cost-prohibitive is now feasible. Tracking treelines by remote sensing, tracking species changes in permanent plots, and tracking performance of transferred seed are all feasible undertakings.

11. Ice cover on lakes (an indicator not in the surveys, but added out of interest by L.Kremsater)

Rationale: L*ake* and river ice are an excellent indicator of climate change, especially because decadal and inter-decadal variation due to PDO and ENSO are integrated in melt response (break-up, freeze up and ice duration). Analysis of river and lake ice freeze-up and break-up trends from the mid 1960s to the mid 1990s show contrasting seasonal responses with little change in freeze-up (with some evidence of earlier river ice formation over eastern Canada) but widespread trends for significantly earlier spring break-up (Zhang et al. 2001; Duguay et al. 2006).

Potential data sources
Rodenhuis et al. (2009) computed trends in lake ice cover for 1976-2005 to provide updated results for the most recent 30 year period and trends for 1966-1995 were included to compare to a national study (Dugay et al. 2006). The BC data came primarily from volunteer efforts of the BC Lakes Stewardship Society (http://www.bclss.org/) that records dates of ice on and ice off for various lakes in B.C. Rodenhuis et al. (2009) reported decreased duration of lake ice in the most recent records (0 to 42 days). The spring break-up of lake ice also occurred up to 10 days earlier, although one station in the north-eastern portion of the Province showed a later break-up by 2 days.

The more recent 1976-2005 period showed spatial coherence of trends towards later freeze-up by 7 to 40 days. Trends at two of the three stations were statistically significant. This is consistent with recent warmer temperatures that delayed the onset of freeze-up across BC. Trends in freeze-up dates for the 1966-1995 period were spatially variable which is in agreement with other studies. Factors such as wind may influence freeze-up causing results to be less clear than break-up results. A National study (Dugay

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[15] BEC= Biogeoclimatic vegetation plots
VRI = Vegetation Resources Inventory plots
TEM = Terrestrial Ecosystems Mapping plots
NFI = National Forest Inventory plots

et al. 2006) recorded trends toward earlier break-up dates are observed for most lakes during the time periods of analysis (1990s). Freeze-up dates, on the other hand, showed few significant trends and a low degree of temporal coherence when compared with break-up dates.

The change in lake ice in the 1976-2005 period reflects the enhanced spring and winter warming that occurred in BC during the 20th century, and signals potential increases in lake evaporation and disruption to ecosystems. Trends in lake and river ice have not been linked to trends in phenology (i.e. the emergence of leaves, the first appearance of migratory birds) and other indicators of climate change. Nor have other non-thermal effects that influence lake ice break-up and freeze-up (such as wind) been explored.

Synthetic Aperture Radar (SAR), such as Advanced Synthetic Aperture Radar (ASAR) and optical Advanced Along-Track Radiometer (AATSR) data from the Environmental Satellite (ENVISAT) are also being used to map freeze-up and break-up dates over large areas of Canada, but have not been used on most lakes, rather effort is focused on travelled waterways (large lakes and oceans, data of Environment Canada).

12. Summary

The Phase 4 indicators included temperature, precipitation, snowpack (including extents of glaciers), streamflow, water temperature, water quality, unexpected weather, mass wasting, windthrow and genetic diversity. We used the South Selkirks area as the location to pilot these indicators to see how readily the information theoretically available in BC (see Kremsater and Innes 2012) could be gathered and reported.

The abiotic indicators of ***temperature, precipitation, snowpack***, and ***stream flow*** and are analysed and summarized well by PCIC. They intend their data to be soon publicly available via a user-friendly web interface. PCIC also reports on ***extent of glaciers*** but more recent work by members of the former Western Cryosphere Network presents even more useful information on extents of glaciers applicable to B.C.

The other abiotic indicators – ***water temperature, water qualit****y* and ***extreme weather*** – are not yet reported by PCIC. Water temperature data exist beyond those held by Environment Canada, but those data are very difficult to find or access. The same can be said for water quality data -- unless the Provincial Ministry of Environment recommences its efforts to compile water temperature and quality information, Environment Canada will continue to be the best option for that information. Both data sets (water temperature and water quality) are provided free of cost. Environment Canada also holds weather data that be used to evaluate extreme weather. That data comes at a cost and, at least in this case study, takes time to acquire. The Provincial government also holds weather data but again that data is not easy to access.

For the natural disturbances indicators of ***mass wasting*** and ***windthrow***, no systematic province-wide information exists. Both these indicators would be difficult to relate to climate change even if substantial sampling was undertaken, but regional or landscape level studies have more potential than stand-level studies.

For the ***genetic diversity*** indicator, which was limited to considering ***changes in tree diversity***, it is too early in the assisted migration program to investigate amounts and locations of seed transfer. Changes in treelines or changes in permanent sample plots are not reported in any systematic way. The BEC plots have high potential to be used for tracking changes in tree species and ecosystem composition.

The indicator **of** ***ice on and off lakes*** was not suggested in the survey and is examined out of interest by the author (Kremsater); it is reported by PCIC. Volunteer efforts track this indicator for a number of lakes in BC and provide direct links to climate variability and change.

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Appendix 1 Information on Glacial history

from Walker and Pellatt (2001) – A longer glacial history for context

The extent of glaciers and large ice sheets provides another index of past climatic changes. Growth of the ice sheets is obviously favoured in cold, humid climates, and not in warm or arid settings. Small glaciers and ice caps can respond rapidly to climatic conditions, but larger ice sheets will display a more inertial response (Booth, 1987; Wright, 1984). About 20,000 14C yr BP, the Laurentide Ice Sheet reached its maximum late Wisconsinan extent (Booth, 1987; Fulton, 1989; Fulton et al. 1986). The Cordilleran Ice Sheet attained its maximum somewhat later, with retreat in Hecate Strait evident after 15,600 14C yr BP (Blaise et al. 1990). Farther south, in Washington State, the Puget Lobe of the Cordilleran ice sheet reached its maximum position ca. 14,000 to 15,000 14C yr BP (Booth, 1987; Ryder et al. 1991), and then began to retreat northward into British Columbia. By ca. 11,000 14C yr BP, the Fraser Lowland was completely ice free and the Cordilleran ice sheet had collapsed (Ryder et al. 1991; Souch, 1989). The growth and retreat of the Cordilleran ice sheet seems to have lagged somewhat behind climatic changes in the region (Booth, 1987). Barnosky et al. (1987) note that local alpine glaciers had attained their maximum extent in western Washington between 22,000 and 19,000 14C yr BP, when the Puget Lobe was still advancing. On the Olympic Peninsula, tundra vegetation was displaced by trees 16,800 14C yr BP (Barnosky et al. 1987). At least one major re-advance, the Sumas event, has been recognised in the Fraser lowland. Researchers have long speculated on the climatic significance of the re-advance, with several scientists (e.g., Heusser 1977) suggesting a correlation with the Younger Dryas (a cold interval very prominent in the North Atlantic region). Recently, careful study and dating of deposits in the Fraser Lowland, has revealed that two advances actually occurred (Clague et al. 1997). The first advance occurred before ca. 11,900 14C yr BP, and may correlate with either the Oldest Dryas cold period, or the Older Dryas cold period, in Europe. The second advance began ca. 11,300 14C yr BP, and may correlate with the Amphi-Atlantic (Killarney + Gerzensee) Oscillation (Clague et al. 1997). Although the re-advances may be climatically significant, sufficient evidence is so far lacking. The cooling was certainly minor relative to that evident in regions bordering the North Atlantic, and probably ended before the Younger Dryas began (Clague et al. 1997). Clague et al. (1997) suggest that the re-advances may instead have resulted from dynamic interactions among glacial retreat, isostatic rebound, sea level rise, and glacial surges. By about 9,500 14C yr BP, the glaciers in the Cordilleran region were no more extensive than they are today (Fulton 1989). Porter and Denton (1967) summarised much of the early evidence for subsequent Holocene glacier fluctuations in the North American Cordillera. They inferred that major glacial advances clustered around three time periods, ca. 4600 14C yr BP, ca. 2600-2800 14C yr BP, and ca. 200 to 600 14C yr BP. Ryder (1989) provides a more recent compilation specific to the Canadian Cordillera. She notes that several very late Pleistocene or early Holocene moraines exist in the Shuswap Highlands and Rocky Mountains. The age of the Shuswap Highland advances is not well constrained by dates. Reasoner (1994) has established that the Crowfoot Advance in the Rockies is late-Pleistocene in age, correlating it with the Younger Dryas cold event. In the northern Cascade Mountains of Washington State, Heine (1998) and Thomas et al. (2000) provide evidence of glacial advances dating between 9000 and 9800 14C yr BP and 7700 and 8400 14C yr BP, respectively. Assuming a precipitation regime like that now extant, these advances would indicate temperatures averaging ≤2°C cooler than today's.

Ryder (1989) notes several Neoglacial advances, beginning as early as 6000 14C yr BP. The early Neoglacial, Garibaldi phase advances of Ryder and Thomson (1986) are recorded in the southern Coast Mountains, and probably date between 5000 and 6000 14C yr BP. In the Coast Mountains several neoglacial advances date between about 1900 and 3300 14C yr BP, and are collectively referred to as the Tiedemann advance (Ryder and Thomson, 1986). At this time, advances of the Tiedemann (maximum 2300 14C yr BP), Gilbert (maximum 1900 14C yr BP), Frank Mackie (maximum 2700 14C yr BP) and Berendon (maximum between 2200 and 2800 14C yr BP) glaciers are noted (Clague and Mathewes 1996; Ryder and Thomson, 1986). To the east, the Battle Mountain advance is recorded in the Shuswap Highlands (ca. 2400 to 3400 14C yr BP) and, in the Columbia Mountains, the Bugaboo Glacier was close to its maximum Neoglacial limit about 2500 14C yr BP (Osborn 1986, Ryder 1989). Ryder (1987, 1989) notes abundant evidence of Holocene glacial maxima in the last millennium, dating between 100 and 900 14C yr BP. This interval is commonly referred to as the “Little Ice Age”. Retreat for some of these glaciers began in the 18th century, whereas the response of others was delayed, beginning only in the 19th or early 20th centuries (Ryder 1987, 1989). At Tzeetsaytul Glacier in Tweedsmuir Provincial Park, Smith (2000b) notes evidence for a 17th century advance. A second advance was evident by 1815, culminating in terminal moraine deposition by 1853 (Smith 2000b). Farther north, Wiles et al. (1999) have used tree-ring dating to determine the age of Little Ice Age events. They note three intervals of strongly synchronous glacier movement: 1) a late 12th to 13th century advance, 2) a 17th to early 18th century advance, and 3) a late 19th century advance (Wiles et al. 1999). Using dendrochronology, Heikkinen (1984b) dated moraines on Mount Baker, in northwestern Washington, to the early 16th century, ca. 1740, ca. 1823, ca. 1855-56, ca. 1886-87, ca. 1908-12, ca. 1922, and 1978-79. Heikkinen (1984a, 1984c) also notes abundant evidence for forest expansion on Mount Baker over the last 100 years. In the Rockies, Luckman (1977), used lichen growth curves to estimate the age of a “pre-Little Ice Age” moraine on Mount Edith Cavell. The moraine was dated prior to about 1800 years ago, whereas most other moraines on the same mountain dated to the 18th and 19th centuries. An advance of the Saskatchewan glacier killed trees in its path ca. 2850 14C yr BP (Smith, 2000a). Smith (2000a) considers this event to be contemporaneous with similar episodes at the Peyto, Yoho and Robson glaciers (Luckman 2000), and as further confirmation that the Peyto Advance had regional significance. Luckman (2000), and Luckman and Osborn (1979) report little other evidence of early- or mid-Neoglacial advances. In contrast, Little Ice Age events have been studied in great detail. Luckman (1986) infers, from 14C dated snags, that warm conditions prevailed in the Rockies ca. 700 to 1100 AD. Luckman also notes evidence for a regional glacial advance between 1200 and 1370 AD, followed by episodes of moraine formation in the early 18th and mid 19th centuries (Luckman 1986, 2000). Smith et al. (1995) have recorded glacial advances prior to the 16th century, in the early 17th and 18th centuries, and the mid 19th century in Peter Lougheed and Elk Lakes provincial parks, Alberta. Luckman (2000), however, concludes that although several moraines have been assigned dates prior to 1700 AD, the only convincing evidence for an earlier regional Little Ice Age event is for the 1200 to 1370 AD advance.

Using dendrogeomorphic techniques, the Little Ice Age maxima for several glaciers has been dated between 1830 and 1862 AD (Luckman, 1988b, 2000). Furthermore, Luckman infers from tree-ring evidence that most of the Little Ice Age advances were induced by cool summers, often accompanied with high summer precipitation (Luckman, 2000). However, Luckman also notes that climate varied continuously throughout the Little Ice Age. A long interval of sustained cool summers was only evident in the 19th century (Luckman 2000). In the Premier Range of British Columbia, ice retreated rapidly ca. 1930 to ca. 1955 AD (Luckman et al. 1987). This was followed by glacial re-advances, induced via cool summers (ca. 1954 to 1968 AD) in combination with greater winter precipitation (ca. 1951 to 1976 AD). The glaciers had receded slightly in the 1980s, as warmer summers returned, and winter precipitation decreased (Luckman et al. 1987).

From Rodenhuis et al. (2009) -- more recent glacial history

The net mass balance of glaciers in Western North America tends to be positively correlated with winter precipitation and negatively correlated with summer temperature. A change of mass balance on the Place Glacier occurred after the mid-1970s when the PDO shifted to its warm phase, leading to decreased snow in winter and increased spring and summer temperature.

In the Columbia Basin, glacier-melt was found to supply 10 to 30% of the annual flow and up to 50% of the late summer flow in a 1986 study (based on flows at the Dalles, Oregon). However, a large majority of streams in glaciated basins in BC showed a statistically significant decrease in August streamflow during 1976 to 1996, which suggests that these glaciers are in the later stages of recession where melt-water has decreased as a result of decreased area.

Since the end of the Little Ice Age, glaciers have been receding at many locations globally. Records since 1960 show broad agreement on the evolution of global glacier mass balance (the measured difference between accumulation of snow and ice in winter and loss of snow and ice by ablation in summer). Around 1970, the global mass balance of glaciers was close to zero and has continued to decline to a negative state. The observed decline in glaciers echoes other studies which have found that most alpine glaciers have undergone accelerated mass loss and terminal retreat in recent decades. In BC, glaciers have been receding in recent decades across most of the Province. Due to the lack of annual mass balance data, innovative means have been applied to determine the recent volume loss of glaciers. Radar, LandSat imagery, digital terrain models, and aerial photography have been employed to investigate volume loss in multiple studies. One such study subdivided the glaciated mountain ranges in BC into ten regions and investigated changes in glaciers from 1985 to 1999.

Monitoring of glacier mass balance has been conducted for roughly 20 glaciers in BC, but only two were still monitored at the time of writing; Place Glacier and Helm Glacier. At Place Glacier, precipitation and temperature changes have thrust the glacier out-of-phase with the current climate. Equilibrium, where accumulation is equal to ablation, can only be achieved if the area of Place Glacier shrinks to less than 2 km2 and the terminus moves up to 2060m. Helm Glacier is also receding. The Illecillewaet Glacier (south eastern BC) and Peyto Glacier (on the Alberta side of the Rockies) are located in the interior and are not influenced by coastal effects. However, the Illecillewaet Glacier retreated more than 1000 m from 1887-1962, but advanced 100 m between 1962 and 1984 before resuming its retreat in 1984 Peyto Glacier has shown similar trends to Place Glacier, which suggests that declining trends are far reaching.

Trends in glacier mass balance are similar south of the BC border. In 1971, the North Cascade Glacier Climate Project (NCGCP) surveyed more than 700 glaciers covering 250 km2 within the North Cascade region. All 47 of the observed glaciers retreated during the 1984-2006 period42. The annual mean balance (1984-2006) of 10 glaciers selected for more detailed study indicated glacial decline of 0.54 m per year and a cumulative net loss in mass balance of 12.38 m, which is equivalent to at least 14 m of thickness loss43. The loss of mass ranged from 20% to 40% of total glacier volume, a rate of retreat insufficient for re-equilibrium. All of the glaciers had similar responses in spite of the regional variations in influence on glacier mass balance such as aspect, elevation, and location with respect to prevailing winds. Similarly, in Glacier National Park, Montana over two-thirds of the 150 glaciers surveyed in 1850 had disappeared by 1980 and the remaining glaciers were greatly reduced in area and volume.

The study of changes in glacial volume and area in BC are hindered by the lack of spatial coverage and low frequency of air photos, radar, and laser altimetry for BC and errors within the available datasets. Digital elevation models used in this work have inherent errors that must be corrected to guarantee the accuracy of results. Digitizing the surface area of glaciers depends on how accurately the margins of individual glaciers can be identified, which depends on the resolution of the image, the snow conditions and the contrast between the ice and adjacent terrain. Also, poor photographic contrasts, which are estimated as the reported vertical errors for the Terrain Resource Information Management (TRIM) and National Topographic Database (NTDB) data, also add errors to the estimates of accumulation. Finally, the parameters chosen for the volume-area scaling relationship can contribute error. Mass balance studies can incur error during manual measurement and analysis. Errors in measurements of annual mass balance of a single glacier are said to be about +- 200 kg/m2 per year. The majority of this uncertainty comes from the natural horizontal variability inherent across the surface of the glacier, which cannot be evaluated using point measurements at single elevation bands. Additionally, most studies only measure the surface balance of the glacier, although internal accumulation could be taking place.

In BC, trends in glacier mass balance are based on limited observational data that do not cover all of the different regions. Study sites tend to be selected based on which glaciers are most easily accessible and safe. Therefore, most monitored glaciers are at lower elevations. Hence, findings are biased towards these selected glaciers and cannot be said to be representative of glacial trends in all areas.*

*Note that Bolch et al's (2010) study overcomes many of the limitations noted by Rodenhuis et al (2009).