PACIFIC CLIMATE IMPACTS CONSORTIUM

PCIC SCIENCE BRIEF: THE ACCELERATED LOSS OF WESTERN CANADIAN GLACIERS

As a consequence of global warming, the world's glaciers have been shrinking. Changes to glaciers in BC could have wide-ranging impacts to BC's ecosystems and human communities, across multiple sectors. Remote sensing data has been invaluable in measuring and characterizing changes to the world's glaciers. Recent research published in *Remote Sensing of the Environment* using such data shows that western Canadian glaciers have been melting at an accelerating rate and examines how this is related to changes in seasonal temperature and precipitation. Here we discuss what these results tell us about changes to western Canada's glaciers.

Introduction

As the planet continues to warm due to anthropogenic climate change, the world's glaciers have been shrinking. The trend of decreasing glacier mass is clear in the record of global reference glaciers[1] going back to just before 1950. Over the 2000 to 2019 period, the Earth's glaciers lost about 267 billion tons of mass each year[2], with eight of the ten years with the most loss on record occurring since 2010. In addition to the increase in global average temperatures, global warming is amplified in high latitude[3] and high elevation[4] regions in which glaciers are found.

Glaciers are a dynamic system of dense ice, constantly moving and deforming. They grow from the input of water at their accumulation zone, either from direct precipitation, such as snow, or from windblown snow from elsewhere, avalanches and frost. In their ablation zone, they release water, either by melting or through other processes, such as windblown snow, avalanches, calving into icebergs and the direct sublimation of water vapour into the air.

In western Canada, glaciers are key components of several ecosystems, acting as freshwater reservoirs that provide a steady source of water and nutrients throughout warmer months, and moderating stream temperatures such that they are cool enough for fish and insect species. The water these glaciers supply also flows into rivers in BC that are used for irrigation, recreation and hydroelectric power generation. It is important to understand how climate change is affecting these glaciers, because changes to glaciers can affect the timing, quantity and temperature of water flowing through BC's rivers, which could have multiple impacts on BC's river ecosystems and human communities.

Monitoring glacier changes is a significant challenge. Glaciers are often found in remote, mountainous terrain that is difficult to access and in high-latitude regions that are far from large human settlements. With more than 13,000 glaciers in western Canada alone (and over 160,000 globally), sending teams to physically measure, or even just photograph each glacier would be prohibitively expensive. While a small subset of glaciers are monitored in this way, the dawn of the satellite era has provided scientists with a wealth of remote sensing data on changes to glaciated regions.

Prior research[2], has shown that western Canada's glaciers are losing mass, about 7.4 billion tonnes per year over the 2000-2019 period. Figure 1 uses paired photos to illustrate what glacier loss looks like in part of the region studied

1. The Global Reference Glaciers are a set of 42 glaciers for which there are more than 30 years of mass balance measurements. These are monitored by the World Glacier Monitoring Service (WGMS). More information about these glaciers can be found at: https://wgms.ch/products_ref_glaciers/. For more on the trend of decreasing glacier mass in global reference glaciers and how this compares to other data, see Zemp et al. (2015). See Chapter 9 in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (Fox-Kemper et al., 2021) for information on the general impacts of anthropogenic climate change on the Earth's land and sea ice. For more on changes to ice and snow in Canada, see Chapter 5 in Canada's Changing Climate Report (Derksen, C. et al., 2019).
2. For more on the global and regional loss of glacier mass as estimated from satellite data, see Huggonet et al. (2021).
3. There are multiple mechanisms that contribute to the amplification of warming in the high latitude regions, including ice feedbacks (i.e. warming causes ice to melt, exposing the darker land or ocean, which absorbs more heat and allows for more warming) and changes in energy transport throughout the Earth system. For more on these, see Hahn et al. (2021) and, for the Arctic in particular, Previdi, Smith and Polvani (2021).
4. A number of feedbacks are thought to contribute to elevation dependent warming and amplification, including snow, ice and surface-based feedbacks (similar to the example discussed above, with melting snow and ice exposing the darker underlying landscape, which absorbs more heat) and others that involve water vapour and aerosols. For more on these, see Mountain Research Initiative Elevation Dependent Working Group (2015).

Figure 1: Examples of Changes to Mountain Glaciers in Western Canada (Mountain Legacy Project).
This figure shows what the changes to mountain glaciers can look like on the ground. The top panels show photographs of the Robson Glacier, the largest glacier in the Central Rocky Mountains, as it was in 1911 (left) and in 2011 (right). The lower panels show the Athabasca Glacier, which lies in the Columbia Icefield in the Central Rocky Mountains, as it was in 1917 (left) and 2011 (right). Image credit: left panels, A.O. Wheeler; right panels, the Mountain Legacy Project. All photos courtesy of the Mountain Legacy Project[5].

by the authors. To better characterise the change in western Canadian glaciers, in addition to changes in mass, we would also want to know how the glaciers have been altered in terms of the area that they cover, whether they are fragmenting[6] and forming proglacial lakes[7] as they retreat, and to what extent these changes are related to changes in temperature and precipitation. Writing in the journal *Remote Sensing of Environment*, Bevington and Menounos (2022) use satellite data along with reanalysis data to examine these questions.

Changes in the Area, Fracturing and Melting of Western Canadian Glaciers

Bevington and Menounos focus their attention on glaciers in western Canada, which they define as those glaciers in British Columbia (BC) and Alberta, and including those that lie on the borders that BC shares with Yukon and Alaska, but not including those glaciers that lie entirely within Yukon. The authors use satellite data over the 1984-2020 period and limit their study to glaciers with areas of at least 0.05 square kilometres (km^2), about twice area of an olympic swimming pool. They divide the 14,375 glaciers that existed in this region in 1985 into three categories, with the number in each category as follows: 13,483 clean-ice glaciers covering more than 16,000 km^2, 85 debris-covered glaciers covering over 800 km^2 and 807 proglacial lake glaciers covering over 12,000 km^2. They also divide their analysis into two epochs, 1984-2010 and 2010-2020.

The authors find that, consistent with the research on mass loss, glaciers in the region have been shrinking, fragmenting and disappearing (Figure 2). Of the glaciers that were present in 1985, eight percent had been lost by 2020. The total area of clean-ice glaciers shrunk by about 49 ± 7 km^2 per year (km^2yr^{-1}) over 1984-2010 and this accelerated

5. The Mountain Legacy Project, based in the School of Environmental Studies at the University of Victoria, explores changes in Canada's mountain landscapes through the world's largest collection of systematic high-resolution historic mountain photographs (>120,000) and a vast and growing collection of repeat images (>8,000 photo pairs). Visit MountainLegacy.ca for more information.
6. Fragmentation occurs as glaciers lose mass and tensile strength (i.e. their ability to resist being pulled apart). This can occur at the same time as they are being eroded by meltwater fissures that form ever-deepening cracks. These processes eventually allow internal stresses to pull the glacier apart into smaller glaciers.
7. Proglacial lakes are those lakes that are in contact with the margin of a glacier. They can form in several ways, such as when glaciers block the flow of rivers or meltwater from other glaciers, allowing a lake to form, or when glaciers retreat, leaving low-lying land (carved out and pressed down by the glacier's enormous weight) behind and meltwater accumulates in the low-lying regions that the glaciers once occupied.

to 339 ± 40 km^2yr^{-1} over 2011-2020. The same was true of debris-covered and proglacial lake glaciers. Debris-covered glaciers shrunk by 2.6 ± 0.4 km^2yr^{-1} over 1984-2010 and by 12.3 ± 0.9 km^2yr^{-1} over 2011-2020. Proglacial lake glaciers, shrunk by 27 ± 2 km^2yr^{-1} over 1984-2010 and by 130 ± 27 km^2yr^{-1} over 2011-2020. Vancouver Island, the Central Coast Range and the Southern Coast Range saw the greatest acceleration of relative loss[8] of clean ice glaciers and proglacial lake glaciers. The greatest acceleration of relative loss of debris-covered glaciers was in the Central Coast Range, Saint Elias Mountains (located in the far northwest of BC) and the Southern Coast Range. One feature among these is that the areas within the study region in which glacier area loss is accelerating most quickly are concentrated along BC's coast.

Turning to glacier fragmentation[6] Bevington and Menounos find a very similar pattern in time, with an acceleration in the rate of fragmentation over time. Clean-ice glaciers fragmented at a rate of 26 ± 5.6 fragments per year over the 1984-2020 period and 88 ± 39 fragments per year over the 2011-2020 period. In parallel, debris-covered and proglacial lake glaciers fragmented at rates of 1.7 ± 0.3 and 14 ± 1.5 fragments per year over the 1984-2010 period, respectively, accelerating to 13 ± 1.9 and 84 ± 20 fragments per year over the 2011-2020 period.

The proglacial lakes that form from the meltwater of glaciers in the region increased in area. The lakes grew at a rate of 9.2 ± 1.1 km^2yr^{-1} over the 1984-2010 period and similarly accelerated to a rate of 49 ± 4.5 km^2yr^{-1} over the 2011-2020 period.

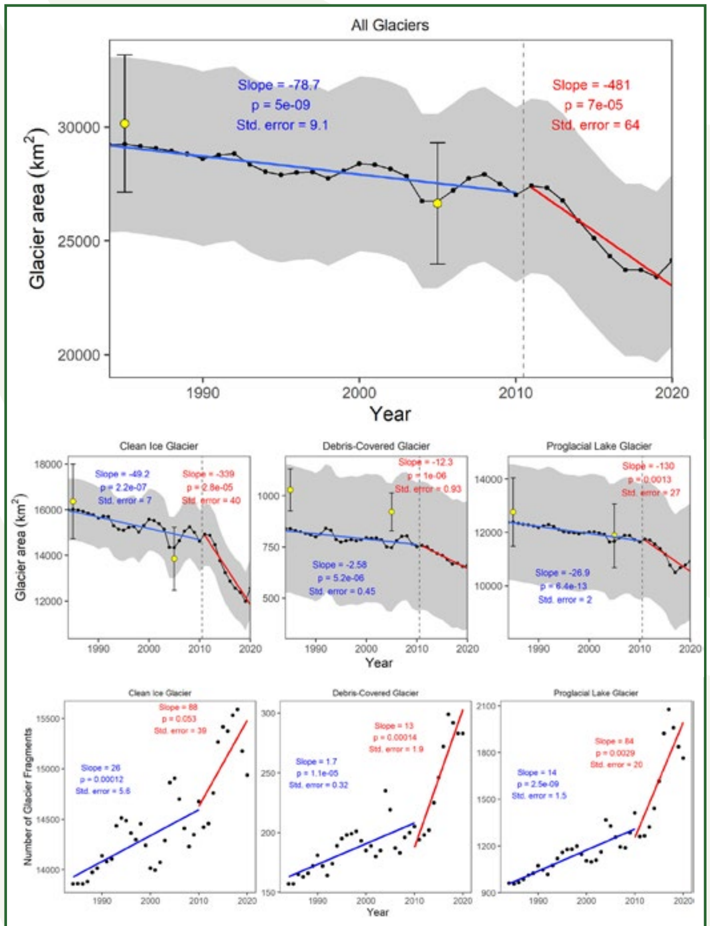

Figure 2: Glacier Area and Fracturing Trends (from Bevington and Menounos, 2022).
This the top and middle panels in this figure show the estimated changes in glacier area for all glaciers in the study region (top panel), and for clean ice glaciers (centre, left), debris-covered glaciers (centre) and proglacial lake glaciers (centre, right) over the 1984-2020 period. The bottom panels on this figure show the estimated changes in the number of glacial fractures in clean-ice glaciers (bottom, left), debris-covered glaciers (bottom, centre) and proglacial lake glaciers (bottom, right). All of the estimates were made using satellite remote sensing data.

Regional Climate Change and Glacier Changes

Bevington and Menounos's analysis characterizes how western Canada's glaciers are shrinking, fragmenting and disappearing. With these results established, they turn to the question of how the changes that they have found in glaciers are related to the changing climate of the region. While it has been established that anthropogenic climate change is likely accelerating the retreat of mountain glaciers, globally, there is still some value in examining the relationship across western Canada.

Beginning with seasonal temperature, the authors find that, compared to the 1984-2020 period, fall and winter air temperatures over 2011-2020 increased most in the north, northwest and the southern interior lowlands of BC (Figure 3). Comparing these periods, spring temperatures cooled in the eastern portion of the study region and warmed in the west. The summer air temperature warmed throughout the region, with the greatest warming found across the south and in the northeast. Fall precipitation decreased in northwestern BC, but increased in the southwest and southeast of the study region. Summer precipitation was to some extent the inverse, increasing in the northwest of BC and decreasing across the south of the study region.

8. Relative loss is the percentage of ice that is lost by glaciers in a given region.

University House 1, PO Box 1700, STN CSC, University of Victoria, Victoria, British Columbia, Canada, V8W 2Y2 Phone: 250-721-6236 | Fax: 250-721-7217 | pacificclimate.org

With the changes in glacier and climate variables established, Bevington and Menounos analyzed what relationships could be found between them. They found that across the study area, changes in glacier area are negatively related to temperature in the spring, summer and fall. The only significant relationships that they found with precipitation were in the Northern Coast Mountains, where glacier areas grew by about 161 km^2 per millimeter of rainfall that fell over the region during the winter months and shrank by about 262 km^2 per millimeter of rainfall over the summer.

Summary: Shrinking, Fragmenting Glaciers Across Western Canada, a Relationship to Spring, Summer and Fall Temperatures and More Melting Ahead

The warming climate has been causing the world's glaciers to lose mass. Given the difficulties involved in directly measuring changes to the world's more than 160,000 glaciers, remote sensing data from satellites has been of paramount importance and has allowed glacier changes to be characterized clearly and with great detail. The work of Bevington and Menounos builds on this, using remote sensing data to show how western Canada's glaciers have been shrinking, fragmenting and melting over the past 36 years.

The authors' work shows that western Canada's glaciers are losing area, fragmenting and melting, and that these processes have dramatically accelerated, in many cases by roughly an order of magnitude, across the region over the past decade. This is consistent with other work that shows an acceleration in glacier mass loss across the region over the same period. This accelerated mass loss is greatest, both in a relative and absolute sense, in those glaciers that lie near the coast of BC. The authors find that there is a relationship between this accelerated glacier loss and temperatures during the spring, summer and fall, but much less of a relationship with precipitation, which is only apparent in the Northern Coast Mountains. Their results show western Canadian glaciers losing mass during a warmer melt season and that this loss is not being offset by the accumulation of ice from precipitation in the winter.

Turning to the future, research using climate model projections to which PCIC contributed suggests continued, widespread glacier loss throughout western Canada in the 21st Century, across all of the emissions scenarios that were used. As Bevington and Menounos note, their work is one further step toward a planetary inventory drawn from remote sensing data that would, in the future, help to characterize glacial changes on an ongoing basis.

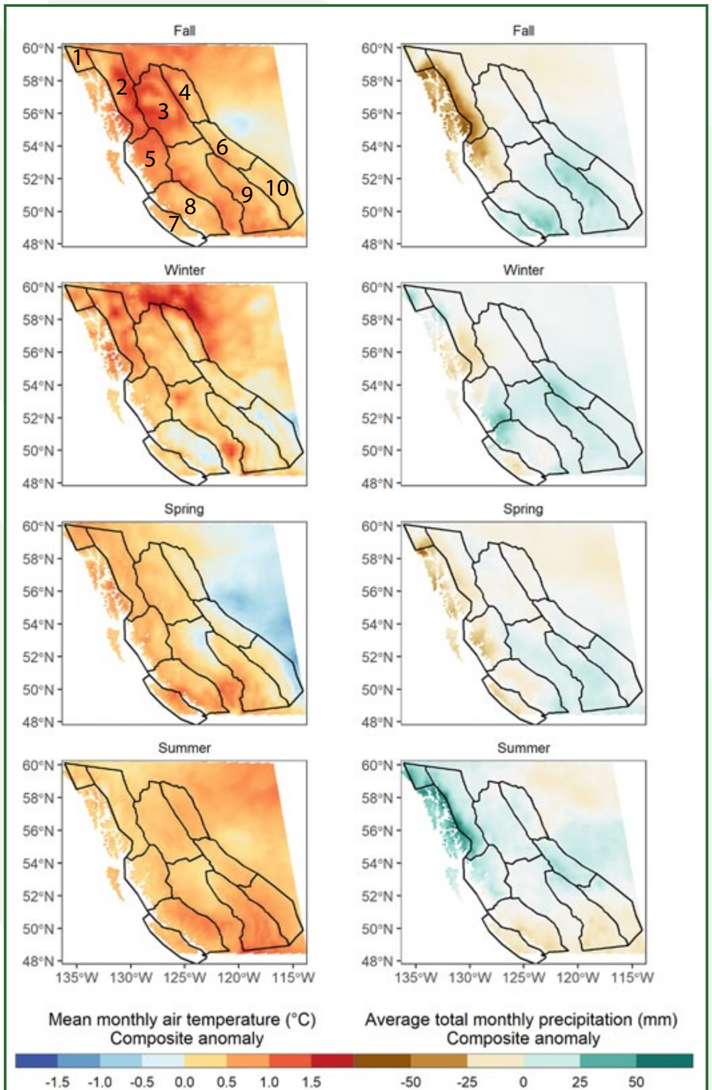

Figure 3: Temperature and Precipitation Anomalies 2011-2020 compared to1984-2010 (edited, from Bevington and Menounos, 2022).

This figure shows the seasonal anomalies (anomalies here just mean differences and are obtained by taking the average of each quantity over the season in the 2011-2020 period and subtracting it from the corresponding average over the 1984-2010 period) in mean monthly air temperature (in degrees Celsius, left column) and average total monthly precipitation (in millimetres, right column) for the the period of 2011-2020 compared to 1984-2010, for the study region in western Canada, from reanalysis[9] data. Seasons, temperatures and precipitation amounts are as indicated. The numbers in the top left panel indicate the following subregions: 1, Saint Elias Mountains; 2, Northern Coast Mountains; 3, Northern Interior Ranges; 4, Northern Rocky Mountains; 5, Central Coast Mountains; 6, Central Rocky Mountains; 7, Vancouver Island; 8, Southern Coast Mountains; 9, Southern Interior Ranges and 10, Southern Rocky Mountains.

9. The fifth version of the European Reanalysis product (ERA-5) was used. A reanalysis is a representation of the historical climate that is created from historical observations that are "assimilated" into a global weather forecast model that is run in a hindcast mode. For more on ERA5, see Hersbach et al. (2020).

The implications of ongoing glacier loss are widespread and have potential impacts for BC's ecosystems and water quality, as well as for multiple sectors, including agriculture, forestry and tourism.

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University House 1, PO Box 1700, STN CSC, University of Victoria, Victoria, British Columbia, Canada, V8W 2Y2 Phone: 250-721-6236 | Fax: 250-721-7217 | pacificclimate.org