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Landsat-based inventory of glaciers in western Canada, 1985–2005

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ABSTRACT

We report on a glacier inventory for the Canadian Cordillera south of 60°N, across the two western provinces of British Columbia and Alberta, containing ~30,000 km^2 of glacierized terrain. Our semi-automated method extracted glacier extents from Landsat Thematic Mapper (TM) scenes for 2005 and 2000 using a band ratio (TM3/TM5). We 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. The estimated mapping errors are 3–4% and arise primarily from seasonal snow cover. Glaciers in British Columbia and Alberta respectively lost $-10.8 \pm 3.8\%$ and $-25.4\% \pm 4.1\%$ of their area over the period 1985–2005. The region-wide annual shrinkage rate of -0.55% a^{-1} is comparable to rates reported for other mountain ranges in the late twentieth century. Least glacierized mountain ranges with smaller glaciers lost the largest fraction of ice cover: the highest relative ice loss in British Columbia ($-24.0 \pm 4.6\%$) occurred in the northern Interior Ranges, while glaciers in the northern Coast Mountains declined least ($-7.7 \pm 3.4\%$).

1. Introduction

Surface runoff from snowmelt and glaciers is an essential freshwater resource in western North America, especially during summer when the water demand is high (Barnett et al., 2005; Stahl and Moore, 2006). In western Canada glacier runoff is a vital component of surface flows to drainage basins of the eastern Rocky Mountains where runoff is used for agriculture, urban consumption, and industry. Hydroelectric power generation also relies on glacier runoff in glacierized basins of British Columbia (Moore et al., 2009). Finally, decline in glacier extent in western Canada and Alaska significantly contributes to sea level rise (Arendt et al., 2002; Larsen et al., 2007; Schiefer et al., 2007).

The first attempt to inventory glaciers in western Canada used extents from 1:1,000,000 scale maps (Falconer et al., 1966). Later, the Glacier Inventory of Canada aimed to catalogue all glaciers at a scale of 1:500,000 as part of Canada's contribution to the International Hydrological Decade (1965–1974), but was never completed (Ommanney, 1980, 2002b). Pilot studies for the World Glacier Inventory catalogued limited regions of the Canadian Cordillera (Ommanney, 1971; Stanley, 1970). Only the glaciers on Vancouver Island and small regions of the Rocky and Coast mountains are included in the World Glacier Inventory (*WGI*, http://nsidc.org/data/g01130.html). Results from these early glacier inventories are summarized by Haeberli et al. (1989) and Ommanney (2002b). Direct measurements of mass balance exist for only a few glaciers in Western Canada (Moore et al, 2009). Those data show a consistent pattern: slight positive mass balances in the mid 1970s, 1 or 2 years of positive mass balance at the end of the 1990s, and otherwise strong negative mass balance (WGMS, 2007).

There have been recent efforts to document the area and volume loss of glaciers in western Canada, but none of these studies inventories all glaciers in British Columbia and Alberta (DeBeer and Sharp, 2007; Demuth et al., 2008; Larsen et al., 2007; VanLooy and Forster, 2008). Schiefer et al. (2008) presented a glacier inventory for glaciers of British Columbia based on extents obtained from aerial photography in the 1980s. However, their analysis included neither glaciers in Alberta nor more recent extents and changes in glacier cover.

We expand on the work of Schiefer et al. (2008) and report on the approach to generate a glacier inventory from satellite imagery for the year 2005 for British Columbia and Alberta, Canada within the time frame of less than 1 year. We compare these results to earlier extents derived from aerial photography to report on area loss over this 20 year period. We further utilize satellite imagery from the year 2000 for 50% of our study area to extend the temporal coverage of our analysis. The inventory data generated are available through the Global Land Ice Measurements from Space (GLIMS) database (Bolch et al., 2008b).

2. Study area and glaciers in western Canada

Our study focuses on glaciers in the Canadian Cordillera south of 60°N, a broad, mountainous region covering roughly 1,000,000 km^2 that can be subdivided into Western, Interior and Eastern mountain

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systems. The Insular, Coast, and St. Elias mountains encompass the Western System. The Interior System in the south contains the Purcell, Selkirk, Cariboo, and Monashee mountains between 119–115°W longitude and 49–54°N latitude. The Interior Plateau divides mountains of the southern Interior from their counterparts in the north: the Hazelton, Skeena, Cassiar, and Omineca mountains. The Eastern System is defined by the Rocky Mountains that continue north from the US and terminate south of the Liard River. Local relief typically exceeds 600 m for many of these ranges, and some of the highest peaks in the Rocky, St. Elias, and Coast mountains exceed 4000 m above sea level (m a.s.l.). We subdivide the mountains into nine regions based on natural boundaries (Fig. 1). Similar climate and glacier characteristics typify these regions, and they conform to the regions presented by Schiefer et al. (2007).

Located in the zone of mid-latitude Westerlies, strong precipitation gradients are common in the study area with total precipitation declining from west to east. Maximum precipitation occurs in the Coast Mountains during the winter months due to cyclonic activities, while summer precipitation is predominant in the Rocky Mountains (Barry, 2008). Local- to regional-scale precipitation patterns are heavily influenced by topographic factors, which in turn impact glacier mass balance (Letréguilly, 1988; Shea et al., 2004).

Glaciers occupied about 30,000 km^2 in the 1980s in British Columbia and Alberta based on provincial and federal mapping data; this estimate of glacier extent represents about 23% of the North American and 4% of the world's non-polar ice coverage (Schiefer et al., 2007; Williams and Ferrigno, 2002). Glacier types in the Canadian Cordillera range from large ice fields to valley and small hanging glaciers (Schiefer et al., 2008). Debris covers the ablation zone of some large glaciers in many mountain ranges (Ommanney, 2002a), and rock glaciers occur in continental sites. Rock glaciers, however, are not inventoried in the present study. The mean glacier elevation can be lower than 1250 m a.s.l. in the northern Coast Mountains but often exceeds 2750 m a.s.l. in the southern Rocky Mountains (Schiefer et al. 2007, 2008). The predominant aspect of the upper glacier areas is north and north-east (Schiefer et al. 2008).

3. Methods and data

3.1. Glacier mapping: previous applications

Semi-automated multispectral glacier mapping methods include supervised classification (Aniya et al., 1996; Gratton et al., 1990; Sidjak and Wheate, 1999), thresholding of ratio images (Paul et al., 2002; Rott, 1994) and the Normalised Difference Snow Index (NDSI) (Hall et al., 1995; Racoviteanu et al., 2008). Thresholding of ratio images is a robust and time effective approach compared to manual digitization and also enables identification of snow and ice in shadow (Paul and Kääb, 2005; Paul et al., 2003; Bolch and Kamp, 2006). The RED/SWIR ratio (e.g. TM3/TM5) has the advantage over the NIR/SWIR ratio (e.g. TM4/TM5) in that it works better in shadows and with thin debris-cover (Andreassen et al., 2008; Paul and Kääb, 2005). However, this ratio method suffers from two primary limitations: the recorded ratio of reflection of water bodies is similar to snow and ice, and in common with other automated methods based on multispectral data, areas of debris-covered ice are not

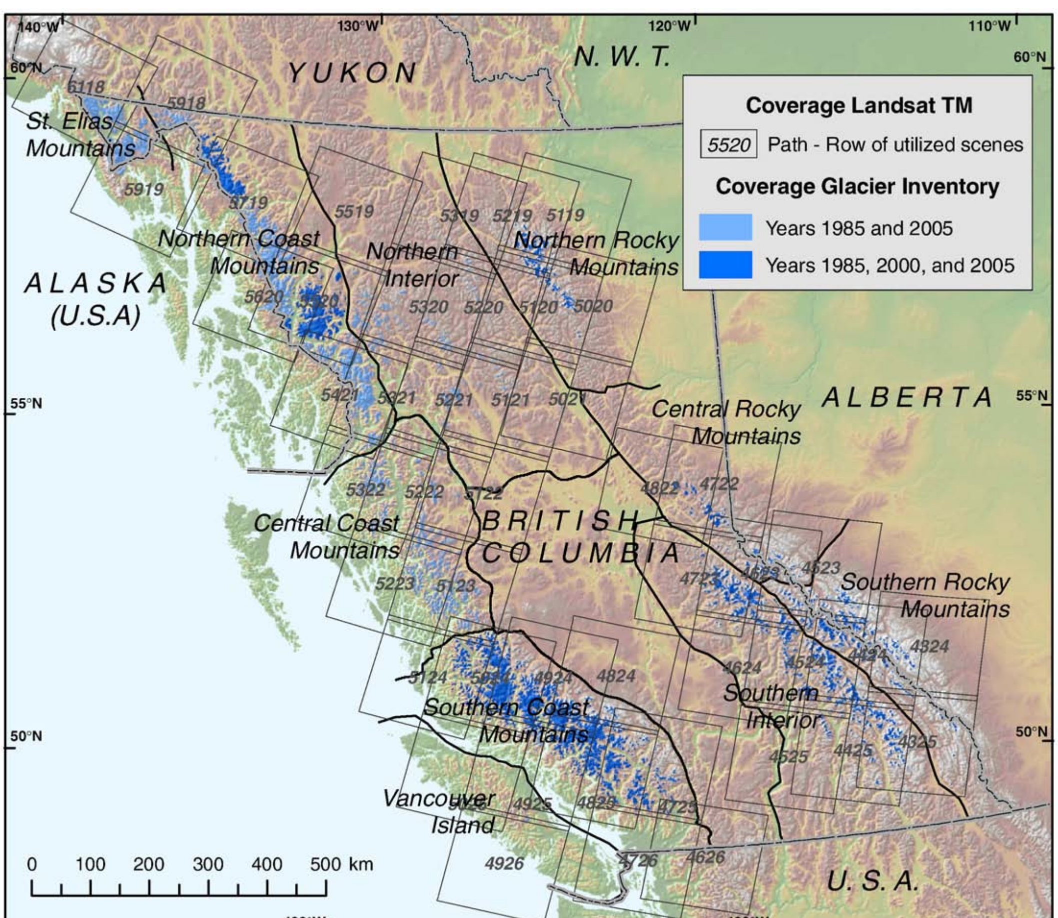

Fig. 1. Study area showing the sub-regions, path and row of the utilized Landsat scenes, and the coverage of the glacier inventory.