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Comparison of modeled and geodetically-derived glacier mass balance for Tiedemann and Klinaklini glaciers, southern Coast Mountains, British Columbia, Canada

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ABSTRACT

Predicting the fate of mountain glaciers requires reliable observational data to test models of glacier mass balance. Using glacier extents and digital elevation models (DEMs) derived from aerial photographs and ASTER satellite imagery, we calculate changes in area, elevation, and volume of Tiedemann and Klinaklini glaciers. Between 1949 and 2009, Tiedemann and Klinaklini glaciers lost approximately 10% of their area. The total area-averaged thinning of Klinaklini was 40.1 ± 1.5 m water equivalent (w.e.) and total mass loss equaled 20.24 ± 1.36 km^3 w.e., whereas Tiedemann Glacier thinned by 25.7 ± 1.9 m w.e. and lost 1.69 ± 0.17 km^3 w.e. of ice. We attribute lower observed rates of thinning at Tiedemann Glacier to thick debris cover in the ablation area. Both glaciers thickened at mid-elevations after the year 2000. Glacier mass balance and volume change were modeled using temperature, precipitation and evapotranspiration fields dynamically downscaled to the mesoscale (8 km resolution) using the Regional Atmospheric Modeling System (RAMS) model and further statistically downscaled to the glacier scale (100 m elevation bands) using modeled surface lapse rates. The mass balance model over-predicts total volume loss by 1.1 and 6.3 times the geodetic loss for Klinaklini and Tiedemann glaciers respectively. Differences in modeled and observed total ice loss are due to (1) the coarse resolution of the downscaled climate fields, and (2) extensive debris cover in the ablation area of Tiedemann Glacier. Future modeling efforts should dynamically downscale at resolutions that capture the topographic complexity of a region and employ strategies to account for time-evolving debris cover.

1. Introduction

Glaciers are integral to many natural and human systems, making them important targets for monitoring and prediction. Although mountain glaciers only constitute 3–4% of global glacierized area, their recent recession significantly contributes to sea level rise (Arendt et al., 2002; Dyurgerov, 2003; Berthier et al., 2004; Larsen et al., 2007; Meier et al., 2007; Berthier et al., 2010). Mountain glaciers are the second largest contributor to recent sea-level rise (Cazenave and Nerem, 2004), and the total volume of glaciers in western Canada and Alaska has been estimated to contain a sea-level equivalence of 5 and 68 mm, respectively (Radić and Hock, 2010). Changes in glacier thickness and volume can also influence the magnitude and timing of surface runoff, affecting water supply for agriculture, consumption, and hydropower generation (Barry, 2006; Stahl and Moore, 2006; Moore et al., 2009). Given recent trends in mean global surface temperatures, and projections of continued warming, glaciers in western North America and throughout the world are expected to continue to retreat. To estimate future changes in volume and area, methods to estimate the mass balance of glaciers under a given climate scenario are required.

Glacier mass balance models to predict the fate of glaciers vary from simple ones that use accumulated air temperature anomalies (positive degree days) to those that employ a full energy balance (Braithwaite and Zhang, 1999; Casal et al., 2004; Hock and Holmgren, 2005). Positive degree day models empirically relate glacier melt and air temperature; these empirical models assume that air temperature integrates the individual fluxes of the surface energy balance. Melt factors for snow and ice have been shown to be similar among glaciers within a region (Shea et al., 2009), but can vary temporally at inter-annual to inter-decadal time scales (Huss et al., 2009; Shea et al., 2009). Temporally varying melt factors introduce uncertainty in mass balance modeling using a PDD approach, but the magnitude of this error is difficult to quantify in data-poor regions. In the current study, the lack of available input data to drive a melt model using an energy balance approach is limited by the lack of required input data. Snow accumulation is typically calculated from the total

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precipitation that falls as snow, and must be melted before ice melt can occur (Braithwaite and Zhang, 1999; Shea et al., 2009).

Predicting the fate of mountain glaciers requires reliable melt modeling strategies and temporally and spatially distributed data that can be used to test these approaches. The use of remote sensing has increased the number of glaciers monitored and extended the mass balance record in regions where few traditional mass balance records exist (Berthier et al., 2004; Luthcke et al., 2008). While glacier length and area are commonly measured, changes in volume and mass balance provide a more direct, reliable indicator of climate change and can be used to verify the results of mass balance models (Kääb, 2002; Berthier et al., 2004; Barry, 2006).

The objectives of this paper are to determine change in area, elevation, and volume at Klinaklini and Tiedemann glaciers in the southern Coast Mountains British Columbia using digital elevation models (DEMs) derived from multiple sets of aerial photographs and satellite images. We expand on the results of VanLooy and Forster (2008) by incorporating DEMs that post-date the Shuttle Radar Topography Mission (SRTM), and also extend our analysis back in time to include pre-1970 data. In addition, we explore the climatic and site-specific factors that explain observed differences in area and volume change for these two glaciers. Finally, we test whether glacier mass balance estimates obtained from a hybrid modeling strategy agrees with geodetically-derived changes in glacier volume.

2. Study area

Tiedemann and Klinaklini glaciers are located in the southern Coast Mountains, approximately 300 km northwest of Vancouver, British Columbia, Canada (Fig. 1). The southern Coast Mountains are primarily influenced by moist maritime air masses, and large precipitation amounts occur as a result of orographic forcing. The winters are wet and the summers are dry with most precipitation occurring between October and March in the form of snow (Koch et al., 2009).

Both glaciers lie in close proximity to Mount Waddington, which is the highest peak in the southern Coast Mountains (4010 m above sea level — asl). Tiedemann and Klinaklini are mountain valley glaciers and, to our knowledge, do not surge. Tiedemann Glacier flows east from Mount Waddington over an elevation range of 3400 m (500–3900 m asl) and has an area of 62 km^2. Debris covers 27% of the surface area of Tiedemann Glacier, mainly in the ablation area. Klinaklini Glacier descends from the Ha-Iltzuk Icefield approximately 40 km west of Tiedemann Glacier. The glacier flows south and coalesces with the westward flowing Silverthrone Glacier some 15 km from the terminus. The total contributing ice covers an area of 480 km^2, about 56% of the Ha-Iltzuk Icefield, and ranges in elevation from about 100 to 2800 m asl. Klinaklini Glacier has little debris on its surface (3%), and it currently terminates in a proglacial lake. We collectively refer to Klinaklini and Silverthrone glaciers in this paper as Klinaklini Glacier.

3. Methods

3.1. Geomatic data

We used DEMs and glacier extents derived from aerial photographs and satellite images to determine area, volume, and elevation change of Tiedemann and Klinaklini glaciers over the past 60 years (Table 1). The National Topographic Database (NTDB) data includes glacier extents and contours derived from photographs acquired in 1970. The geometric accuracy is ±25 m in rural areas and ±125 m in isolated areas, and the contour interval is approximately 40 m (Geomatics Canada, 1996). We also used data from the Terrain Resource Information Management program (TRIM). These data include glacier extents, elevation data, and land cover, derived from 1986 aerial photographs and have a horizontal and vertical accuracy of ±10 m and ±5 m, respectively (BC Ministry of Environment, Lands and Parks, 2002). Both NTDB and TRIM data are horizontally referenced to the North American Datum of 1983 (NAD83) and vertically referenced to Mean Sea Level (Canadian Vertical Geodetic Datum, CVGD). Elevation and volume change of Tiedemann and Klinaklini glaciers for the period 1970–1986 reflect sequential DEM analysis derived from the contours and gridded elevation data.

We also extracted glacier extents and DEMs from digital scans of aerial photographs (AP) for the years 1949, 1965, 1989, 1994, and 2005, and from Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) images for 2000, 2002, 2004, and 2006 using PCI Geomatica OrthoEngine v.10.2 (Table 1). Aerial photographs include those archived in the Canadian National Air Photo Library, the British Columbia Government, and BC Hydro. Dates of the imagery range from the end of July to the end of September. We produced a recent DEM of Tiedemann Glacier from aerial photographs taken on July 29, 2009. The acquired 1:18,000 scale color negatives were photogrammetrically scanned at a resolution of 14 μm which equates to a ground sampling distance of 0.25 m.

3.2. DEM production

The aerial photographs were co-registered in OrthoEngine v.10.2 using TRIM, 1.0 m resolution orthoimages from 2005 for Tiedemann Glacier and TRIM aerial diapositives with triangulation points (PUG points) from 1986 for Klinaklini Glacier, both referenced to NAD83

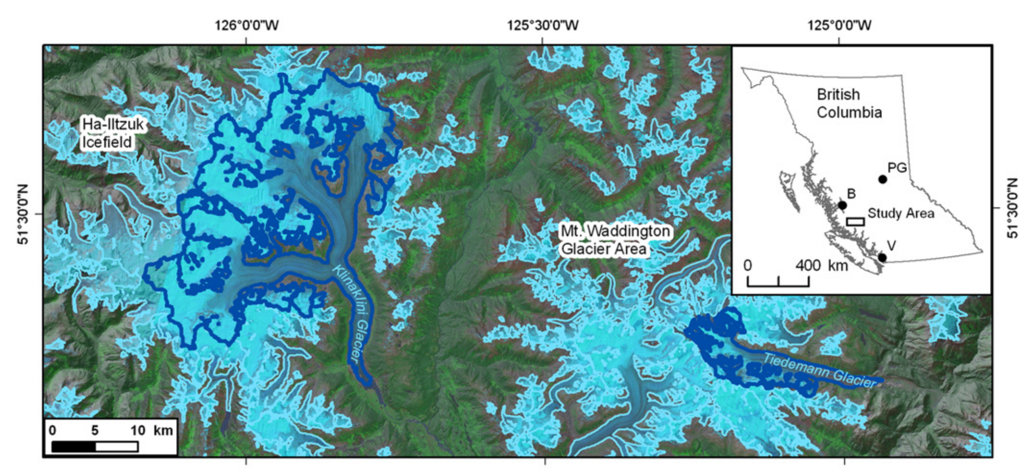

Fig. 1. Location of Klinaklini and Tiedemann glaciers in the southern Coast Mountains, British Columbia. Inset map: PG = Prince George, V = Vancouver, B = Bella Coola.