COMPARING GEODETICALLY DERIVED MASS BALANCES AMONG THREE SMALL GLACIERS, SOUTH COAST MOUNTAINS, BRITISH COLUMBIA

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Abstract

COMPARING GEODETICALLY DERIVED MASS BALANCES AMONG THREE SMALL GLACIERS, SOUTH COAST MOUNTAINS, BRITISH COLUMBIA

Ashley York

Contribution to sea-level rise from glacier mass loss has increased over recent decades. Current research suggests that the response of glacier mass balance to changes in climate is a function of glacier size, but local topographic factors such as aspect and insolation may have greater effects than size alone. With high quality aerial photography and well-distributed ground control points, digital photogrammetry can be used to develop high-resolution geodetically-derived records of glacier mass balance over time to examine intra- to inter-decadal patterns of glacial change. Stereo pairs of scanned historical aerial photography were viewed in 3D with the Vr Mapping software (Cardinal Systems) and gridded surface elevations were digitized for years between 1965 and 2009. Mass balances were calculated for two small glaciers, Joffre (0.4 km^2) and Unnamed (0.15 km^2) glacier, in the south Coast Mountains, British Columbia, Canada, over four different intervals within 1965-2009, and over the entire study period. These mass balance measurements were compared to those measured for the larger, and adjacently located Place Glacier (3.31 km^2) as calculated by Menounos and Schiefer (2009) using the same geodetic method. All three study glaciers experienced consistently negative mass balances. Over the entire 1965-2009 period, water equivalent mass balances were calculated as -38.0 m, -40.4 m, and -11.6 m for Place, Joffre, and Unnamed glaciers, respectively.

Proportional area losses over the time period were 31%, 59%, and 38%, respectively. There was no clear trend in response of either glacier mass balance or areal extent to climate changes over the study period based solely on size. Some differences in glacier response to climate were likely attributable to differences in glacier aspect and insolation, with south-facing, higher insolation Joffre Glacier losing the most mass, and north-facing, lower insolation Unnamed Glacier losing the least mass. Influences such as accumulation through blowing snow and avalanching did not have a visible effect on any glacier's mass balance. Small glaciers, such as Unnamed Glacier, may be able to sooner take advantage of local topographic influences than larger glaciers by retreating into high elevation, north-facing, low insolation niche environments that promote ice maintenance. Most glaciers in the region are likely retreating towards an extent that is nearer to an equilibrium condition for the modern climate regime, however small glaciers may be closer to reaching this state.

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i. Preface

The purpose of this thesis is to present a paper intended for submission to the Annals of Glaciology journal published by the International Glaciological Society. In Chapter 1, I present the background literature pertaining to the subject of this study. In Chapter 2, I present the manuscript being developed for publication. In the manuscript, I demonstrate the use of analytical photogrammetry, specifically 3D surface digitization in the Vr Mapping software, as an approach to developing geodetic mass balance records for the study of glaciers. I also compare how mass balances of two smaller glaciers are changing relative to the mass balance of an adjacent larger glacier. I then explore possible factors contributing to similarities and differences between responses to local climate among the different sized glaciers based on morphometric and topographic constraints, including aspect and ablation season insolation. Specifically, this paper uses the geodetic method to calculate mass balances of small glaciers, Joffre Glacier and Unnamed Glacier, in southwestern British Columbia, Canada, from 1965 to 2009 using historical aerial photographs. Results are compared with mass balance record of larger Place Glacier calculated using the same geodetic method for the same period by Menounos and Schiefer (2009). I also calculated and compared rates of mass, areal extent, and proportional area change for these three proximally located glaciers.

Chapter 3 presents a summary of my findings. Appendices include mass balance calculations, elevation change figures of Unnamed Glacier for years (1947, 1973, 1987, and 1997) not included in the manuscript.

Please note, due the manuscript style of this thesis, there may be some redundancy among sections.

1. Introduction

1.1. Literature Review

1.1.1. Global Scale

Glacier retreat as a global phenomenon is generally increasing in intensity with time (Dyurgerov and Meier, 2000). Estimates of glacier change are highly variable in time and space, with global periods of dramatic advance to periods of major retreat, as well as simultaneous growth and loss in different locations (Haeberli *et al.,*1999). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimates mountain glaciers and ice caps to contribute approximately one-third to global sea-leave rise despite containing < 1% of the total water contained in glacier ice on Earth (Radić and Hock, 2011). Many large-scale estimates of glacier change do not include small glaciers (<1 km^2), which cannot contribute much to ice volume gain or loss individually, but are numerous enough to create errors near 10% of global volume estimates (Bahr and Radić, 2012). It is impossible to measure each of the 160 000 - 200 000 mountain glaciers on Earth (Meier and Bahr, 1996), so extrapolation is necessary. Individual glacier mass balance measurements are better for determining local climate fluctuations and effects of glaciers on local water resources. The accuracy of extrapolations used for estimating global glacier change can be greatly increased with the addition of more glacier measurements made at the individual basin scale (VanLooy and Forster, 2011). Global estimates of fresh water volume contained in glaciers are based on glacier and ice cap volume-area scaling; however, this does not take into account characteristics unique to each glacier such as hypsometry and local climate (Huss and Farinotti, 2012; Radić and Hock, 2011). Excluding the Greenland and Antarctic ice sheets, the United States and Canada are estimated to contribute about 19% to the total global mass balance of glaciers (Dyurgerov and Meier, 1997).

Mass balance studies are important for understanding glacier processes especially as they relate to energy and mass fluxes at glacier surfaces. Negative changes in contemporary mass balances are often associated with an anthropogenic climate forcing. In general for glaciers around the world, the 1960s were considered to be cool, with a nearly balanced glacial stage and a sea level rise decrease of about 0.5 mm in 1964 (Dyurgerov and Meier, 1997). This period was followed by acceleration in glacier mass decrease, especially since 1987, corresponding to greater glacier contribution to sea level rise (Dyurgerov and Meier, 1997; Arendt *et al.,* 2009). Out of 86 glaciers from around the world studied by Dyurgerov *et al.,* (2009), only 11 glaciers showed positive mass balances at some point between 1961 and 2004 with tropical glaciers showing more rapid change than polar glaciers. The past 100 years of advancement and retreat of alpine glaciers also corresponds with pre-industrial variability based on energy fluxes at the Earth’s surface (Haeberli *et al.*, 1999). Long-term, non-anthropogenic forced phenomena include Milankovitch cycles which determine seasonal proximity to the sun and solar radiation, as well as cold phase coincidence with sunspot minimum (Menounos *et al.* 2009).

Glaciers have a delayed reaction to changes in the climate and most will continue to retreat for varying lengths of time even if contemporary warming ceases, to approach a state of equilibrium for the modern climate regime (Dyurgerov *et al.,* 2009). Alpine glaciers response time takes at least multiple years, potentially decades (Menounos *et al.,* 2009). This results in simple correlations between current glacial extent and current temperature often being inaccurate as glaciers may still be responding to past climate conditions. Based on calculations that account for ice dynamics, Bahr *et al.* (1998) concluded that larger glaciers could theoretically respond in a shorter timeframe to climate change than smaller glaciers. Essentially, glaciers get longer as their thickness increases which, in turn, increases their flow velocity and pushes the glacier termini into lower, more vulnerable elevations (Bahr *et al.,* 1998). Adams *et al.,* (1998) found opposite results for polar glaciers, with 0.6 km^2 Baby Glacier more sensitive to a 1 K increase in temperature than larger glaciers in the Expedition Fiord area of Axel Heiberg Island, Nunavut, Canada.

1.1.2. Regional Scale

In the 1980s, British Columbia was covered by about 28 800 km^2 of glacierized land and glacier retreat in British Columbia alone could have accounted for 0.67±0.12 mm of sea level rise from 1985-1999 (Schiefer *et al.,* 2007). In the Coast Mountains of British Columbia, the rate of glacier mass loss has doubled over the past two decades (Schiefer *et al.,* 2007). From 1951-2001 over an east-west transect excluding icefields and covering the Canadian Rocky, Columbia, and Coast Mountains, changes in area and volume of glaciers between 1 and 5 km^2 contributed most to overall ice loss, while ice loss from glaciers < 0.5 km^2 was insignificant (Debeer and Sharp, 2007).

Because of their remote locations, mass balance measurements of a glacier may offer better local climate information for many high elevation alpine environments than existing weather station networks (Dyurgerov and Meier, 1999; Dyurgerov and Meier, 2000). For monitored glaciers in coastal mountain ranges in the northwestern United States and western Canada, those with upper accumulation zones experienced winter mass balance increases from 1967-1987; however, for lower ablation zones, summer mass balance decreased faster (Dyurgerov and Meier, 1999). Glaciers in more continental locations are more sensitive to climate fluctuations whereas glaciers of the south Coast Range are found to be less variable due to the more stable maritime climate with greater winter precipitation. Mass balance of continental glaciers is found to be steadily decreasing, but maritime glaciers have more variance in year to year balances including some recent advances. The difference in maritime regions is the increased precipitation which comes from increased temperatures and humidity (Dyurgerov and Meier, 2000). Maritime glaciers rely heavily on winter accumulation, although, fluctuations in conditions of either season can contribute greatly to variability in mass balances during some years (Dyurgerov and Meier, 1999). Net balances of more coastal glaciers is found to be more correlated with winter balance, while net balances of continental glaciers is more correlated with summer balance (Walters and Meier, 1989). Over space, a 1ºC temperature increase in the ablation season corresponds to a 109-82 m decrease in glacier relief, and a 1 mm increase in precipitation during the accumulation season leads to a 0.78-2.20 m increase in glacier relief for contemporary glaciers in British Columbia (Schiefer and Menounos, 2010). For the Ha-Iltzuk Icefield in the Coast Mountains of British Columbia, thinning is associated not only with temperature, but also which a change from a snow-dominated precipitation regime to one of increased rainfall (VanLooy and Forster, 2011). Menounos *et al.* (2009) found that a decline in summer insolation in the Northern Hemisphere created occasional growth spurts of alpine glaciers in western Canada, affirmed by lake sediment records.

1.1.3. Local Scale

Based on mass balances of four glaciers in western North America, all glaciers were experiencing summer warming, but Place Glacier was found to be one of two to be warming in the winter as well (Rasmussen and Conway, 2004). Place Glacier has consistently measured negative mass balance from 1965-1999, becoming significantly more negative beginning in 1977 and eventually leading to the exposure of a pro-glacial lake in 1981 (Moore and Demuth, 2001). The average mass balance in water equivalent meters from 1965-1995 for Place Glacier in winter and summer was 1.75 m and -2.56 m, respectively, resulting in a net balance of -0.81 m (Rasmussen and Conway, 2004).

Winter precipitation, the main control of glacier accumulation, and summer temperature, the main source of glacier ablation, both affect whether a glacier advances or retreats, as well as attributes unique to each glacier, such as size, microclimate, hypsometry, and topography (Boon *et al*., 2009). Local distributions of mountain precipitation are largely determined by slope position and aspect (i.e. windward or leeward locations) (Shea *et al.,* 2009). Most precipitation in western Canadian mountain ranges comes with low-pressure systems from the west during the winter and creates a strong west-east moisture gradient (Shea *et al.,* 2009).

The downvalley extent of glaciers depends on climatic conditions, as well as local topography. Variation of altitude between a glacier's accumulation and ablation area can create a dichotomy between its reactions to climate. The relatively small elevation range of Place Glacier means there is less of an issue of a divided precipitation regime with the glacier not often experiencing snow at its highest elevations and rain at its lowest (Rasmussen and Conway, 2004). Although, Place Glacier's more inland Coast Mountain location and high elevation means almost all precipitation comes as snow. At Place Glacier, there are few rain, or rain on snow events compared to lower elevation and ocean-terminating glaciers, or glaciers suffering from dryness associated with greater continentality (Moore and Demuth, 2001).

Decadal trends, such as ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation) have been linked to glacier accumulation variations depending on the local topography (Boon *et al.,* 2009; Bitz and Battisti, 1999). Place Glacier's winter mass balances were correlated with PDO until 1976 when it shifted from a cold phase to the current warm phase (Moore and Demuth, 2001). The relation between local climate, global atmospheric circulations, and glacier mass balance is complex, but understanding short term glacier fluctuations from decadal scale climate trends is necessary for obtaining insight for future climate-glacier interactions (Dyurgerov and Meier, 2000).

Between measurements from July to late September 2002 at two automatic weather station AWS sites at Place Glacier, dramatic differences in amount of precipitation in the form of snow were found with 4.83 mm at the off glacier site AWS and 30.7 mm at the on glacier site (Munro and Marosz-Wantuch, 2009). However, according to a regression between temperatures from each AWS, the off-site station is generally colder due to the katabatic effect of the glacier and the station's location along the lower northwest main terminus of the glacier where the majority of the cold air drains from the higher zone of accumulation (Munro and Marosz-Wantuch, 2009). The rest of the cold air drains to the southeast along a smaller terminus, Joffre Glacier, which results in the glacier's unusual shape and makes it more vulnerable to topographic dependencies and local airflow (Munro and Marosz-Wantuch, 2009).

For very small glaciers (<0.4 km^2) in the Monashee Mountains of British Columbia, topographic factors such as slope, aspect, elevation, and timing of exposure to solar radiation, affect the mass balance of a glacier by allowing it to retreat until it is hidden in a location that favors ice preservation through reduced ablation, and enhanced accumulation (DeBeer and Sharp, 2009). North, northeast, and northwestern facing slopes were favored for ice preservation, as well as those least exposed to late afternoon sun, in high elevations, with a steep accumulation areas. The steep upslope is important for aiding in avalanching which moves snow from the accumulation area down to the ablation area, increasing albedo and protecting the more vulnerable low elevation region (DeBeer and Sharp, 2009). Some large glaciers (>1 km^2) in the study region split into multiple small glaciers, suggesting a trend towards a greater number of small glaciers with the trending climate regime (DeBeer and Sharp, 2009).

Alpine glaciers are reservoirs of winter precipitation that dictate summer runoff and are relied upon water source of downvalley societies during drought periods (Li *et al.*, 2011). There are also ecological impacts that correspond with changes in hydrology and geomorphology as a result of the altered the glacier regime. Glacier retreat affects outflow stream temperatures, sediment concentrations, and water chemistry which have direct implications on stream hydroecology, particularly salmonids and other cold water species (Moore, *et al*., 2009). Stream surface albedo, related to turbidity, can also be altered with changes in the glacier regime. At Place Glacier, albedo was found to increase with discharge (Richards and Moore, 2011). Decreased flows in the late summer results in decreased albedo in proglacial streams and promotes higher stream temperatures (Richards and Moore, 2011). Streamflow at Place Glacier is mostly dependent on winter accumulation and summer temperatures and has been following a negative trend with the most significant decrease in August runoff (Moore and Demuth, 2001). This late summer decrease is indicative of having already passed the initial phase of increased runoff from warming (Stahl and Moore, 2006). Aerial photograph analysis suggests firn depletion associated with temperature increase before 1965 was the cause of the decrease in meltwater (Moore and Demuth, 2001). Down-wasting also led to a split in the drainage and directed some meltwater through Joffre Glacier (Moore and Demuth, 2001).

1.1.4. Geodetic Method

Geodetic mass balance is derived from volume change calculated from topographic measurements over time. Over a surface, the mean elevation of the more recent year is subtracted from the elevation of the previous year to calculate change in volume (ΔV). Ice density (d) assumptions, usually between 800 kg m^{-3} and 900 kg m^{-3}, also need to be included in the calculation to convert balances to water equivalent (B) (Fischer, 2011). The product of volume and ice density then needs to be divided by the larger glacier area (a) between the years.

$$B = \Delta V * d * a^{-1} \qquad \text{(Equation 1.1)}$$

The traditional method of mass balance calculation involves field measurements at a relatively small number of index sites which are then extrapolated over the entire surface of the glacier (Cox and March, 2004). The geodetic method is an alternative method for calculating a glacier’s volumetric change through time from repeated surface elevation measurements (Hubbard and Glasser, 2005). Remote sensing techniques for glacier surface measurements include, satellite imagery, terrestrial and aerial photogrammetry and laser scanning data (Čekada *et al.,* 2012). To analyze volume changes of small glaciers at a large scale, high resolution and precision Digital Elevation Models (DEMs) can be generated from airborne stereo photographs (Keutterling and Thomas, 2006). With ground control points, aerial photography can be absolutely oriented as stereo pairs for 3-dimensional viewing in certain software, such as Vr Mapping by Cardinal Systems. Many polar-orbiting satellites, such as, Landsat, Terra, SPOT, IRS, ERS, and Radarsat also offer suitable resolution imagery for glacier monitoring. There have been many initiatives to solely monitor glaciers using remote sensing technologies including NASA's (National Aeronautics and Space Administration) ICESaT (Ice, Cloud, and land Elevation Satellite) and ICESat 2, as well as the National Snow and Ice Data Center's (NSIDC) GLIMS (Global Land Ice Measurement from Space) project which uses mostly ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer) imagery.

Many studies have been done on the comparison of conventional field mass balance measurements to geodetic reference-surface mass balance measurements. Both types of measurements were found to be highly variable across a Swiss study region and unique to each glacier's microclimate, geometry and other factors, such as debris cover (Huss *et al*., 2012; Fischer, 2011). Huss *et al*., (2012), found that conventional mass balance techniques were better for understanding the effects of short term climate variability, but they generally underestimated the long term trends found by reference-surface balances.

Geodetic techniques are necessary as many glaciers are inaccessible for conventional field techniques. The quality of geodetic measurements depends on the accuracy of the utilized DEMs. Differences between conventional field techniques and geodetic methods of six Austrian glaciers were calculated to range from 0.02 meters water equivalent (m.w.e.) to 2 m.w.e. (Fischer, 2011). A difference of up to 0.7 m.w.e. between the two methods can be attributed to basal melt, seasonal snow cover, and density change (Fischer, 2011). In addition to basal melt, mass loss sources missing from the conventional method include internal melt and ablation at crevasse walls (Krimmel, 1999).

For South Cascade Glacier in Washington, the two techniques yielded different measurements; however, the deviation between them was consistent, suggesting cumulative systematic error attributable to the conventional method (Krimmel, 1999). Using the conventional method, Cox and March (2004) found systematic errors to accumulate linearly with time at Gulkana Glacier, Alaska. The conventional method is thought to be the source of the error because it can only be referenced to the previous year's summer surface, whereas the geodetic method has the control of a non-changing bedrock surface (Krimmel, 1999). When geodetic balances were calculated using aerial photography at Gulkana Glacier, it yielded different numbers than the conventional method; however both techniques showed the same trend of thinning tripling in more recent years (Cox and March, 2004). Fischer (2011) suggests if care is taken when combining them, geodetic and direct mass balance measurements can be complimentary.

Conventional and geodetic techniques have been compared for Place Glacier by Menounos and Schiefer (2009). For time periods of different lengths between 1947 and 2005, the geodetic and traditional measurements were found to be in accordance. Discrepancies were attributable to late-season snow visible in 1973 and 1997 creating difficulty in surface elevation measurements for the geodetic method due to the lack of surface contrast which inhibits stereo viewing and image position matching between the photographs of each stereo pair (Menounos and Schiefer, 2009). Surface elevation accuracy over firn is generally lower due to the lack of contrast within the very white surface in the stereo photographs (Fischer, 2011). With the geodetic approach, fresh snow can also lead to over estimation of mass, as the snow layer is less dense than the assumed density of ice, and therefore, can cause inaccurate measurements of positive balance for a time period. With the conventional approach, a lack of sampling points and errors such as sinking ablation stakes can lead to miscalculations (Menounos and Schiefer, 2009). For Place Glacier, both methods yielded similar results; therefore, the aerial photography-based geodetic technique was found to be an acceptable approach for mass balance calculations.

2. Comparing Geodetically Derived Mass Balances among Three Small Glaciers, South Coast Mountains, British Columbia

2.1. Abstract

Current research suggests that the response of glacier mass balance to changes in climate is a function of glacier size, but local topographic factors such as aspect and insolation may have greater effects than size alone. With high quality aerial photography and well-distributed ground control points, digital photogrammetry can be used to develop high-resolution geodetically-derived records of glacier mass balance over time to examine intra- to inter-decadal patterns of glacial change. Stereo pairs of scan historical aerial photography were viewed in 3D with the Vr Mapping software (Cardinal Systems) and gridded surface elevations were digitized for years between 1965 and 2009. Mass balances were calculated for two small glaciers, Joffre (0.4 km^2) and Unnamed (0.15 km^2) glacier, in the south Coast Mountains, British Columbia, Canada, over four different intervals within 1965-2009, and over the entire study period. These mass balance measurements were compared to those measured for the larger, adjacently located Place Glacier (3.31 km^2) as calculated by Menounos and Schiefer (2009) using the same geodetic method. All three study glaciers experienced consistently negative mass balances. Over the entire 1965-2009 period, water equivalent mass balances were calculated as -38.0 m, -40.4 m, and -11.6 m for Place, Joffre, and Unnamed glaciers, respectively. Proportional area losses over the time period were 31%, 59%, and 38%, respectively. There was no clear trend in response of either glacier mass balance or areal extent to

climate changes over the study period based solely on size. Some differences in glacier response to climate were likely attributable to differences in glacier aspect and insolation, with south-facing, higher insolation Joffre Glacier losing the most mass, and north-facing, lower insolation Unnamed Glacier losing the least mass. Influences such as accumulation through blowing snow and avalanching did not have a visible effect on any glacier's mass balance.

2.2. Introduction

Over recent decades, the contribution to sea-level rise from mountain glaciers and ice caps has increased (Radić and Hock, 2011). Mountain glaciers account for up to 33% of contemporary sea level rise from glacier melt, despite comprising < 1% of the total water contained in glacier ice on Earth (IPCC, 2007). Monitoring glacier behavior is important because changes in their dynamics affect the human and natural environment, locally with their reliability for storage and release of water, and globally with their contribution to sea level rise and coastal salinity (Moore *et al.,* 2009; Walters and Meier, 1989). For glacierized mountain regions, which are typically remote and difficult to access, observations of glacier change may offer better climate-related information than available meteorological station networks (Dyurgerov and Meier, 1999).

The tendency of glaciological monitoring has been to study large glaciers (> 1 km^2), as their effects on the environment are greatest; however, even the presence of a small glacier can have a significant influence on local hydrologic processes (Moore and Demuth, 2001). Although a single large glacier contains a greater amount of mass, cumulatively, small glaciers make up a significant portion of the world's total ice volume (Bahr and Radić, 2012). Estimates of global sea level rise based on glacier inventories may be underestimated due to their lack of inclusion of the approximately 160 000 – 200 000 small mountain glaciers (Bahr and Radić, 2012; Meier and Bahr, 1996; Huss and Farinotti, 2012). Across western North America, glaciers considered to be small (< 1 km^2) make up a large portion of the glacier population (DeBeer and Sharp, 2009).

Mass balance monitoring is the best way to measure a glacier's sensitivity to climate variations because it records the water equivalent difference between accumulation and ablation seasons as a function of time and elevation across the surface area of a glacier (Meier, 1984). The traditional method of mass balance calculation involves field measurements at a small number of index stake sites which are then extrapolated across the entire glacier surface (Cox and March, 2004). The geodetic method is an alternative method for calculating a glacier's volumetric change through time from repeated surface elevation measurement (Hubbard and Glasser, 2005). Remote sensing techniques for glacier measurements include, satellite imagery, terrestrial and aerial photogrammetry and laser scanning data (Čekada *et al.,* 2012). With ground control points, aerial photogrammetry can be absolutely oriented as stereo pairs for 3-dimensional viewing in photogrammetry software and allow for surface elevation measurements. For regions inaccessible for traditional mass balance measurements, photogrammetric analysis of stereo imagery allows for reconstruction of glacier volume changes and more accurate estimates of small glacier contribution to sea-level rise (Barrand *et al.,* 2009). The number of mass balance records for remote glaciers has increased and mass balance records of monitored glaciers have been extended from the use of such remote sensing techniques in recent years (Tennant *et al.,* 2012).

Mass balances of all glaciers are affected by summer ablation and winter accumulation, but topography unique to each glacier's location can affect its sensitivity to variations in temperature and precipitation. Altitude, slope, aspect, and their relationship to solar radiation are just a few of the localized topographic conditions that can directly affect a glacier's seasonal mass balance (DeBeer and Sharp, 2009; Li *et al.,* 2011). In response to climate change, small glaciers may retreat until they reach a critical point at which they have the ability to be sheltered in high elevation, shaded, topographic niches that favor ice maintenance. Small glaciers may be closer to reaching this critical niche but large glaciers can also follow this trend over an extended period. Therefore, glacier size may act as an additional control of a glacier's climatic sensitivity (Bahr *et al*., 1998). From 1951-2001 over an east-west transect excluding ice fields and covering the Canadian Rocky, Columbia, and Coast Mountains, changes in area and volume of glaciers between 1 and 5 km^2 contributed most to overall ice loss, while ice loss from glaciers < 0.5 km^2 was insignificant (Debeer and Sharp, 2007). It is suggested that small glaciers in the Monashee Mountains, British Columbia, have retreated as far as they are likely to under current climate conditions (DeBeer and Sharp, 2009; Li *et al*. 2011).

2.2.1. Study Area

Place Glacier has been avidly studied and is part of the World Glacier Monitoring Service (WGMS) with traditional mass balance being measured since 1965. Although mentioned in literature about Place Glacier, there have been no studies specifically on smaller, nearby Joffre Glacier and Unnamed Glacier, both visible in all years of aerial photography used in this study (Figure 2.1).

Place Glacier (50˚26'N, 122˚36'W) is a 3.31 km^2 north-facing glacier with elevation ranging from ~2600 m above sea level at its head, to ~1850 m a.s.l. at its terminus, based on 2009 mapping. Joffre Glacier is a 0.4 km^2 south-facing glacier ranging in elevation from ~1950-2300 m a.s.l. and Unnamed Glacier is a 0.15 km^2 northwest-facing glacier ranging from ~2150-2400 m a.s.l.

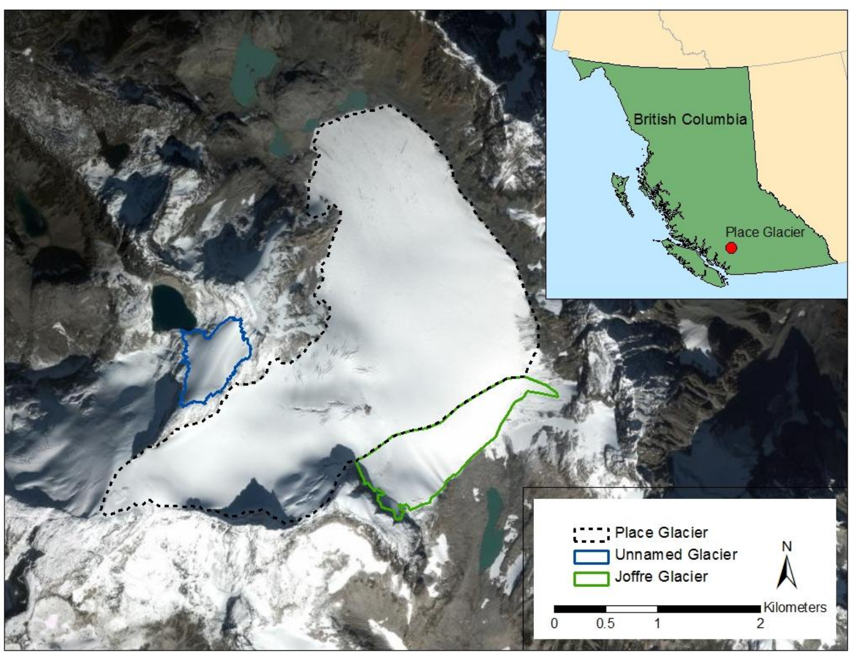

Figure 2.1. Recent color imagery (ESRI World Imagery basemap) and 2009 digitized extents of Place, Joffre, and Unnamed Glacier, Coast Mountains, British Columbia, Canada. The glacier to the west of Unnamed and Place glaciers was not included in this study because it was not within the extent of many of the available aerial photography sets.

Place, Joffre, and Unnamed glaciers are located in the southern Coast Mountains, British Columbia, Canada, ~130 km to the northeast of the city of Vancouver (Figure 2.1). This area of British Columbia experiences maritime climate with moderate temperatures, abundant winter cyclonic frontal precipitation and lesser summer convective precipitation (Figure 2.2.1 and 2.2.2). Mean temperatures range from -7.8°C in the coldest months to 11.5°C in the warmest months, with an annual average of 0.6°C. Average annual precipitation is 1196 mm. The average summer temperature has been generally increasing since 1909, more significantly since 1959, with an overall increase in temperature of 0.72°C over the century (Figure 2.2.2).

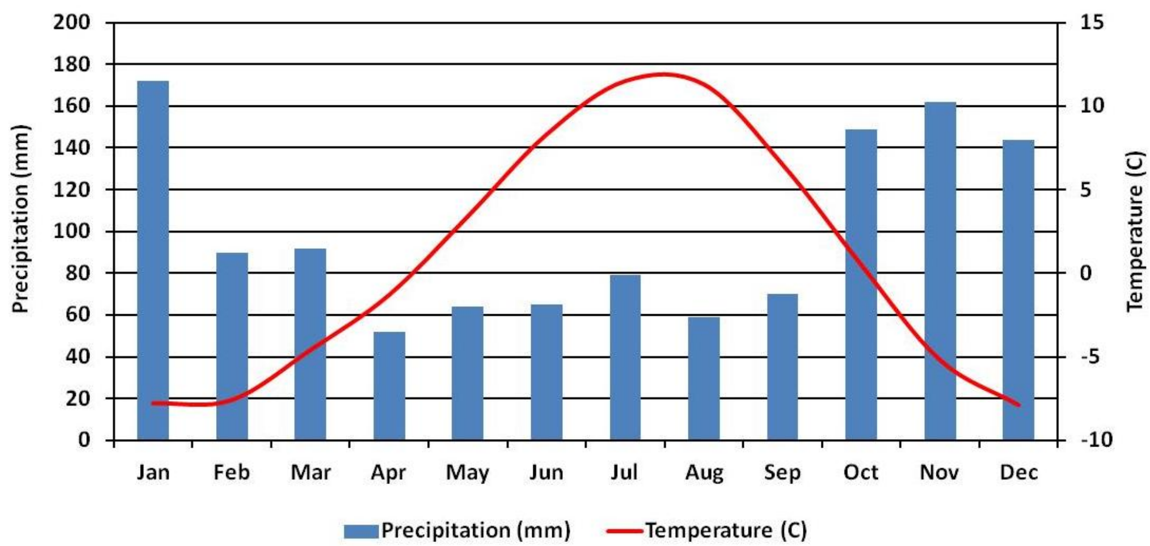

Figure 2.2.1. Average monthly temperature (red line) and precipitation values (blue bars) from ClimateWNA (Wang *et al.,* 2012) for the 1981-2009 climate normal at 50˚26'N, 122˚36'W, 2100 m elevation.

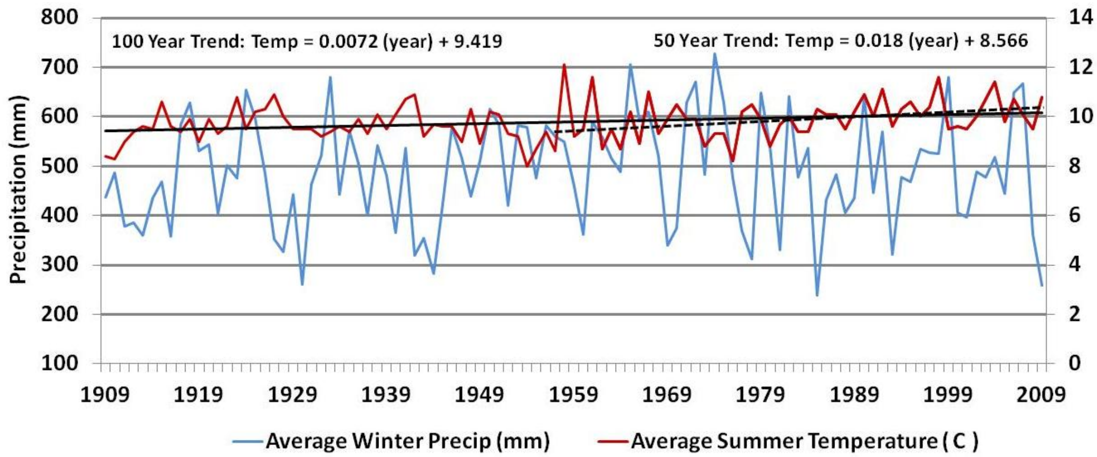

Figure 2.2.2. Average annual summer (June-August) temperatures (red line), average annual summer temperature 100 year trend (solid black line), average annual summer temperature 50 year trend (dashed black line), and average annual winter (December-February) precipitation values (blue line) from ClimateWNA (Wang *et al.,* 2012) for 1909-2009 at 50˚26'N, 122˚36'W, 2100 m elevation.

2.2.2. Geodetic Technique for Glacier Mass Balance

Geodetic mass balance is derived from volume change calculated from topographic measurements of the glacier surface over time (Fischer, 2011). To analyze volume changes of small glaciers at a large scale, high resolution and precision Digital Elevation Models (DEMs) can be generated from airborne stereo photographs (Keutterling and Thomas, 2006). Using two DEMs from different dates, the mean elevation of the glacier surface for the more recent year is subtracted from the mean elevation of the previous year to calculate change in volume (ΔV). In this study, I differenced gridded point elevations, producing high resolution elevation change measurements. Menounos and Schiefer (2009) compared Place Glacier mass balance measurements using standard field techniques with the geodetic method used in this study and found results to be comparable. Therefore, this geodetic method is assumed to be an acceptable approach to mass balance calculations on neighboring Joffre and Unnamed glaciers. The ability of this technique to work with other glaciers depends greatly on glacier surface characteristics in the aerial photographs. Discussed further in Section 2.3.6 (Photograph Quality), characteristics such as amount of firn, debris cover, and shadowing, dictate surface contrast in the images and determine the ability for surface digitization. Ice density (d) approximations, usually assigned to be between 800 kg m^{-3} and 900 kg m^{-3}, also need to be included in the calculation to convert balances (B) to meters water equivalent (m.w.e.) (Equation 2.1) (Fischer, 2011). I used a 900 kg m^{-3} conversion factor for ice density, as used by Menounos and Schiefer (2009). The product of volume and ice density then needs to be divided by the larger glacier area (a) between the years.

$$B = \Delta V * d * a^{-1} \qquad \text{(Equation 2.1)}$$

2.2.3. Purpose

This paper demonstrates the application of analytical photogrammetry, specifically 3D surface digitization in the Vr Mapping software (Cardinal Systems), as an approach to developing geodetic mass balance records for the study of small glaciers. It also compares how mass balance of two small glaciers is changing relative to the mass balance of an adjacent larger glacier. It then explores possible factors contributing to similarities and differences between responses to local climate change among the different sized glaciers based on morphometric and topographic constraints, including aspect, elevation, characteristics of surrounding terrain, and patterns of ablation season insolation. Specifically, this paper uses the geodetic method to calculate mass balances of

Joffre Glacier and Unnamed Glacier in southwestern British Columbia, Canada, from 1947 to 2009 using historical aerial photographs. Results are compared with mass balances of Place Glacier previously calculated using the same geodetic method over the same time period by Menounos and Schiefer (2009). Rates of mass change, areal extent change, and proportional area change were also calculated and compared for these three highly proximal glaciers.

2.3. Methods

2.3.1. Hardware and Software

Vr Mapping software (Ver. 5) was downloaded for free research and academic use from http://www.cardinalsystems.net/download_vrmapping.htm. To use the stereoviewing capabilities of the software, I required a specific hardware set-up including a high refresh rate digital display for 3D vision, 3D shutter glasses, and a specialized graphics card (Table 2.1). Vr Mapping includes 15 program modules for conducting photogrammetric analyses. One of these modules, VrTwo, was used for stereo model viewing and digitizing. I used VrOne® to create files to be edited in VrTwo for the manual creation of glacier extent polygons and surface point elevations. I used VrAirTrig, and VrTwoOrientation for the set-up of stereo models for 2009, a year of additional photography not used by Menounos and Schiefer (2009). I also used AeroSys software by AeroSys Consulting (downloaded for free at http://aerosys.aerogeomatics.com/) which links directly with VrAirTrig for the adjustment of the photographs during the model set-up. The adjustment process creates an exterior orientation file based on the measured ground control points.

Brand	Product	Specifications
ViewSonic	FuHzION	Immersive 3D widescreen LCD VX2268wm 120Hz 22"
NVIDIA	3D Vision Wireless Glasses Kit	Active Shutter Glasses USB IR Emittor
NVIDIA	Quadro 4000 by PNY	256 CUDA parallel processing cores 2GB GDDR5 frame buffer 255-bit memory interface 89.6GB/sec memory bandwidth

Table 2.1. Brand, product, and product specifications for the stereoviewing hardware set-up of the 3D display screen, 3D glasses kit, and graphics card.

2.3.2. Data Acquisition

I acquired the same sets of vertical aerial photographs from eight different years used by Menounos and Schiefer (2009) and an additional more recent year, 2009 (Table 2.2). All years of aerial photography, except 2009, are associated with large-scale to medium-scale, regular mapping and natural resource assessment programs of the province of British Columbia. The 2009 photographs were from a special project mission associated with Place Glacier monitoring. Place Glacier is the dominant glacial feature in most of the photographs; however, a few other small glaciers are also visible. I chose to measure Joffre Glacier and Unnamed Glacier (Figure 2.1) as they were visible in all years of photography.

Nominal scales vary considerably between different years of photography (Table 2.2). All of the aerial photograph surveys were flown near the end of the ablation season, which is ideal for geodetic mass balance measurement using photogrammetry because of minimal snow cover and seasonal consistency.

Photograph negatives were scanned with a photogrammetric scanner at a resolution of 12 µm. The Province of British Columbia provided stereo models for the 2005 photography which was flown with survey-grade GPS receivers on the aircraft for producing “AT scan” products, digital images of photography that include aerial triangulation data. From the 2005 AT scans, stereo ground control points were collected around the glacier at varying elevations. I acquired all of the VrTwo stereo models which had been previously set up by Menounos and Schiefer (2009), and set up the 2009 stereo model using the same setup parameters and suite of ground control points to ensure compatibility and consistency between all of the data sets.

Year	Scale	Roll	Photo Numbers	Color	Photo Quality
1947	30k	BC394	110-112	BW	poor
1965	40k	A19219	025-027	BW	good
1973	15k	BC7548/9	087-089,255-259	BW	fair
1981	20k	BC81116	151-153	BW	good
1987	70k	BC87084	100-101	BW	poor
1993	15k	BCCC93102	078-081	color	good
1997	40k	BCB97068	123-125	BW	poor
2005	20K	BCC05045	73-76, 143-144	color	good
2009	20K	Place_1	003-007	color	good

Table 2.2. Photograph set details including, scale, roll number, photograph numbers, color, and quality for each year of available photography.

2.3.3. Data Collection

Within VrTwo, Menounos and Schiefer (2009) used a fixed 100m grid to measure surface elevations across Place Glacier. To test for user bias of the data collection method, I manually digitized surface elevations across Place

Glacier using a similarly aligned fixed 500m grid; therefore, replicating 20% of the points measured by Menounos and Schiefer (2009).

Using VrTwo, I manually digitized extent polygons of Joffre Glacier and Unnamed Glacier for each year. I determined the flowshed boundary between the adjoining Place and Joffre glaciers based on the highest surface elevation and a standard watershed delineation algorithm in ArcMap™. For the watershed delineation, I used a 25 m provincial DEM based on 1:20 000 scale topographic mapping Terrain Resource Inventory Management (TRIM) from mid-1980s aerial photographs.

I manually digitized surface elevations across the smaller Joffre and Unnamed glaciers using a fixed 25 m grid for each year of aerial photography (Table 2.2). Off-glacier elevations of ground surface were measured between consecutive years to account for elevation change from ice to ground. Off-glacier elevations of ground surface were also measured in the latest year to be matched with on-glacier elevations in the earliest year and calculate total mass balance over the entire time frame.

2.3.4. GIS Analyses

From VrTwo, I exported the extent polygons and point surface elevations to shapefiles for mapping and analysis in GIS software (ArcMap™, Ver. 10). I calculated areas of the glacier extent polygons for each year by adding a field to the attribute table and calculating geometry. I generated a DEM from the point surface elevations for each year using the Radial Basis Function interpolation method with a Thin-Plate-Spline. The Thin-Plate-Spline allows for interpolation above the highest measured value and below the smallest measured value. It proved most accurate when visually compared to other interpolation techniques in a preliminary assessment using the Place Glacier point elevation data. I subtracted the more recent DEMs from earlier DEMs using Raster Calculator, and then clipped the differenced DEMs to the extent of the earlier year. I also calculated mean slope and aspect for each year using the generated DEM surfaces. I calculated solar radiation in ArcMap™ using the 25 m TRIM DEM with the Area Solar Radiation function for July 15, the approximate midpoint of the ablation season.

2.3.5. Geodetic Calculations

Several calculations were made for Joffre and Unnamed glaciers, for each study period and the entire study period, to quantify absolute and relative glacier changes. From VrTwo, I exported point surface elevations to ASCII files to be used in Microsoft Excel (2007) for data processing. In Excel, I matched points between consecutive photograph years based on x-y coordinate, and then subtracted that point's more recent z-value (z_2) from the earlier z-value (z_1) to determine elevation change at every point measured over the 25 m grid across the glacier surface. I converted these point elevation changes to water equivalent by multiplying by a 0.9 (d) ice density factor. I averaged the water equivalent changes by dividing by the total number of points (n) to estimate m.w.e. mass balance (B) over each period for the entire glacier surface (Equation 2.2). I calculated the rate of mass change as the mass balance (B) divided by the difference between the more recent year (y_2) and the earlier year (y_1) (Equation 2.3). The change in total areal extent (ΔA) was calculated by subtracting the area of the earlier year (a_1) from the area of the more recent year (a_2) (Equation 2.4). The percent of area change (ΔA %) was calculated by dividing the change in area (ΔA) by the earlier year (a_1) and multiplying by 100 (Equation 2.5). To make comparisons among the different sized glaciers, I calculated proportions of Joffre and Unnamed glaciers' change relative to Place Glacier's change by dividing Joffre or Unnamed glaciers' calculation by Place Glaciers corresponding calculation (Equations 2.6-2.8).

$$B = [\ \Sigma\ (z_2 - z_1) * d]\ /\ n \qquad \text{(Equation 2.2)}$$

$$R = B\ /\ (y_2 - y_1) \qquad \text{(Equation 2.3)}$$

$$\Delta A = a_2 - a_1 \qquad \text{(Equation 2.4)}$$

$$\Delta A\ \% = (\Delta A\ /\ a_1) * 100 \qquad \text{(Equation 2.5)}$$

$$B_T = B_S\ /\ B_P \qquad \text{(Equation 2.6)}$$

$$A_T = A_S\ /\ A_P \qquad \text{(Equation 2.7)}$$

$$\Delta A\%_T = \Delta A\%_S\ /\ \Delta A\%_P \qquad \text{(Equation 2.8)}$$

2.3.6. Photograph Quality

Photograph quality for glacier surface digitizing varied greatly among the different years of black and white photography based on scale as well as the contrast characteristics over the glacier surfaces. Years of color photography were generally of larger scale and were better for surface digitization, as there was better contrast over the accumulation zone. Digitizing accuracies over accumulation areas is often relatively low because of poor contrast over the consistently white firn surfaces in the stereo photographs (Fischer, 2011). Visual contrast levels can be enhanced in VrTwo by applying histogram stretches; however, this has no beneficial effect on image segments where pixel values are primarily saturated (i.e. 8-bit digital numbers all at 255). Subjectively, I was unable to measure certain portions of the glacier due to the lack of surface contrast in 1947, the oldest year of photography; 1973, which had extensive coverage of fresh snow; 1987, the smallest scale of photography; and 1997, which also had extensive fresh snow. Incorporating years with fresh snow can also lead to over estimation of mass change, as the snow layer is less dense than the assumed density of ice; therefore, causing inaccurate measurements of a more positive balance for the given period. Menounos and Schiefer (2009), specifically refer to lack of contrast in 1973 and 1997 due to the late-season snow causing difficulties when digitizing surface measurements.

For the reasons explained above, I did not include years 1947, 1973, 1987, and 1997 in the calculations of Joffre Glacier’s mass balances or in the proportional comparisons with Place Glacier. All years were measureable for Unnamed Glacier and compared to Place Glacier. The years of higher photograph quality for Unnamed Glacier were also compared separately to Place Glacier as they are expected to have greater accuracy. All photography years and the subset of higher quality years were compared separately between my Place Glacier 500 m grid measurements, and the 100 m grid measurements obtained by Menounos and Schiefer (2009). For comparisons between Joffre and Unnamed glaciers with Place Glacier, I use the higher resolution grid measurements by Menounos and Schiefer (2009). To maintain grid resolution for each period of Place Glacier measurements used in these comparisons, I used a corresponding 100 m grid when calculating 2009 surface elevations of Place Glacier. For the purpose of this paper, beyond the calculations used for demonstrating user bias associated with photograph quality, I focus on the mass balances in years of high quality photography for Joffre Glacier and Unnamed Glacier and how they relate to Place Glacier in these more reliable periods for measurement.

2.4. Results

2.4.1. User Bias

For all years of photography, I compared mass balance measurements I calculated using a 500 m grid across the surface of Place Glacier to the corresponding points obtained by Menounos and Schiefer (2009) who used a higher resolution 100 m grid (Table 2.3). The maximum difference between mass balance measurements for corresponding years of each grid size was 4.86 m.w.e. for the period 1973-1981. The minimum difference between mass balance measurements was 0.36 m.w.e. in the period 1987-1993. The average difference between measurements was 2.44 m.w.e. The difference between measurements for the entire 1947-2005 period was 0.19 m.w.e. Differences between my measurements and those done by Menounos and Schiefer (2009) are attributable to user biases, grid resolution, and photograph quality, primarily associated with contrast characteristics of the glacier surfaces.

As mentioned in Section 2.3.6 (Photograph Quality), I also separately compared the years of higher quality photography between my grid measurements and those of Menounos and Schiefer (2009), (Table 2.4). Differences between geodetic measurements were 0.5 m.w.e., 1.66 m.w.e., and 0.66 m.w.e., respectively for the three periods of 1965-1981, 1981-1993, and 1993-2005. The average difference between measurements was 0.94 m.w.e. The decrease in the average difference between all years of photography and the years of higher quality photography subset was about 38% and should account for some measurement inconsistency associated with photograph quality and user bias.

Mass Balance (m.w.e.)								
Period	1947-1965	1965-1973	1973-1981	1981-1987	1987-1993	1993-1997	1997-2005	1947-2005
This study*	-11.27	-0.44	-10.00	-7.2	-7.2	-6.67	-7.17	-44.83
Menounos and Schiefer (2009) **	-10.14	-3.63	-5.14	-5.89	-6.84	-3.12	-9.88	-44.64
Absolute differences	1.13	3.19	4.86	1.31	0.36	3.55	2.71	0.19

* 500 m grid

** 100 m grid

Table 2.3. Mass balances in meters water equivalent (m.w.e.) calculated between consecutive periods of photography with a 500 m grid (this study), and corresponding 100 m grid points from Menounos and Schiefer (2009), and absolute differences in balances measured between the two studies.

Mass Balance (m.w.e.)					
Period	1965-1981	1981-1993	1993-2005	2005-2009†	1965-2009†
This study*	-8.27	-14.39	-13.59	-4.02	-38.07
Menounos and Schiefer (2009) **	-8.77	-12.73	-12.93	NA	NA
Absolute differences	0.5	1.66	0.66	NA	NA

* 500 m grid

** 100 m grid

† 100 m grid; 2009 This study; 1965, 2005 Menounos and Schiefer (2009).

Table 2.4. Mass balances in meters water equivalent (m.w.e.) calculated between high quality intervals of photography with a 500 m grid (this study) and corresponding 100 m grid points from Menounos and Schiefer (2009), and the absolute differences in balances measured between the two studies.

2.4.2. Joffre Glacier Change

Both Joffre and Place glaciers were measured as experiencing consistently negative mass balances throughout the 1965-2009 study periods (Table 2.5). Joffre Glacier's rate of mass change is greatest for the most recent period of 2005-2009. In three out of the four periods, Joffre Glacier lost more mass per unit area than Place Glacier. Based on the mass balance calculations over the entire period, Joffre Glacier is losing mass at a rate of 106% relative to Place Glacier. Area depletion over the period differed more between the glaciers compared to the mass loss. Joffre Glacier lost less percentage area than Place Glacier in the earliest of the four periods; however, it has consistently lost more area in the three more recent periods retreating almost three times as much from 1981-1993. Over the entire period, Joffre Glacier lost 187% the area relative to Place Glacier.

A) Place	Mass Balance (B) (m.w.e)	Rate of Mass Change (R)	Area End Year (A) (km^2)	Area Change (ΔA)	Area Change % (Δ A%)
1965-1981	-8.77	-0.55	4.48	-0.35	-7.25
1981-1993	-12.73	-1.06	3.96	-0.52	-11.61
1993-2005	-13.00	-1.08	3.49	-0.47	-11.87
2005-2009	-4.02	-1.005	3.31	-0.18	-5.16
1965-2009	-38.07	-0.87		-1.52	-31.47
B) Joffre					
1965-1981	-12.98	-0.81	0.84	-0.06	-6.67
1981-1993	-17.25	-1.44	0.56	-0.28	-33.33
1993-2005	-12.23	-1.02	0.40	-0.16	-28.57
2005-2009	-6.32	-1.58	0.37	-0.03	-7.50
1965-2009	-40.43	-0.92		-0.53	-58.89
C) Joffre/Place	B_T		A_T		$\Delta A\%_T$
1965-1981	1.48		0.19		0.92
1981-1993	1.36		0.14		2.87
1993-2005	0.94		0.11		2.41
2005-2009	1.57		0.11		1.45
1965-2009	1.06				1.87

Table 2.5. Absolute and relative glacier change record for Place and Joffre glaciers including: A) Mass balance and areal extent record for Place Glacier; B) Mass balance and areal extent record for Joffre Glacier; and C) Joffre to Place Glacier proportional change records.

The greatest amount of downwasting occurred across the 2000-2100 m elevations of Joffre Glacier (Figure 2.3). Although the glacier retreated by almost 60%, the downwasting occurring at the terminus of the glacier is less dramatic due to the edges of the glacier being thinner which limits the magnitude of surface lowering. Over the 1965-1981 period, the greatest measured point elevation loss of ~60 m occurred; however, this is also the longest period. The greatest rate of mass loss was ~5 m yr^{-1}, corresponding to maximum point elevation losses of ~15 m, in the shortest, most recent 2005-2009 period. On the contrary, the greatest increase in elevation at a point also occurred in the 2005-2009 period, measuring ~12 m and corresponding to a rate of mass gain of ~3 m yr^{-1}.

Looking at the change in elevation with elevation across the 25 m grid surface, the greatest amount of downwasting typically occurred at ~2025 m mean elevation (Figures 2.4.1-2.4.4). As mentioned above, lower elevation points converge to zero because the glacier thins towards the terminus, and higher elevation points are closer to zero due to their location in the accumulation zone. The ~60 m loss in the 1965-1981 period occurred at ~2025 m elevation, and the greatest rate of mass loss in the 2005-2009 period occurred near 2000 m.

Over the 1965-2009 period, maximum elevation losses increases from the terminus until ~2050 m, is relatively stable until ~2100 m, and then decreases approaching zero towards the upper boundary (Figure 2.5). The greatest amount of elevation losses approached ~100 m occurring between 2050-2100 m elevation. There little mass gain over the period, leading to the average mass balance calculation of -40.43 m.w.e. (Table 2.5).

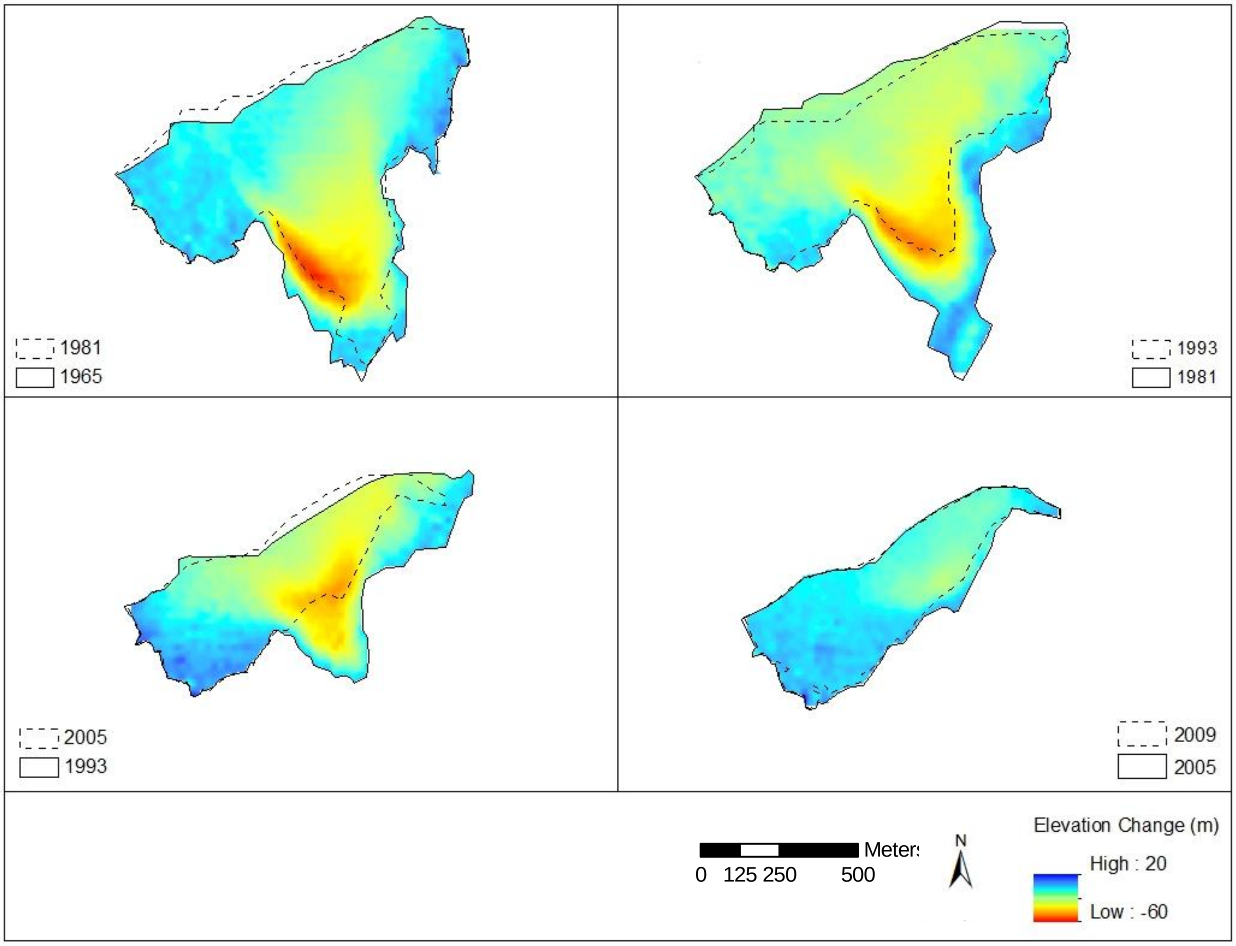

Figure 2.3. Elevation change in meters over the surface of Joffre Glacier for the periods 1965-1981, 1981-1993, 1993-2005, and 2005-2009. Solid lines show areal extent of the earlier year and dotted lines show areal extent for the more recent year.

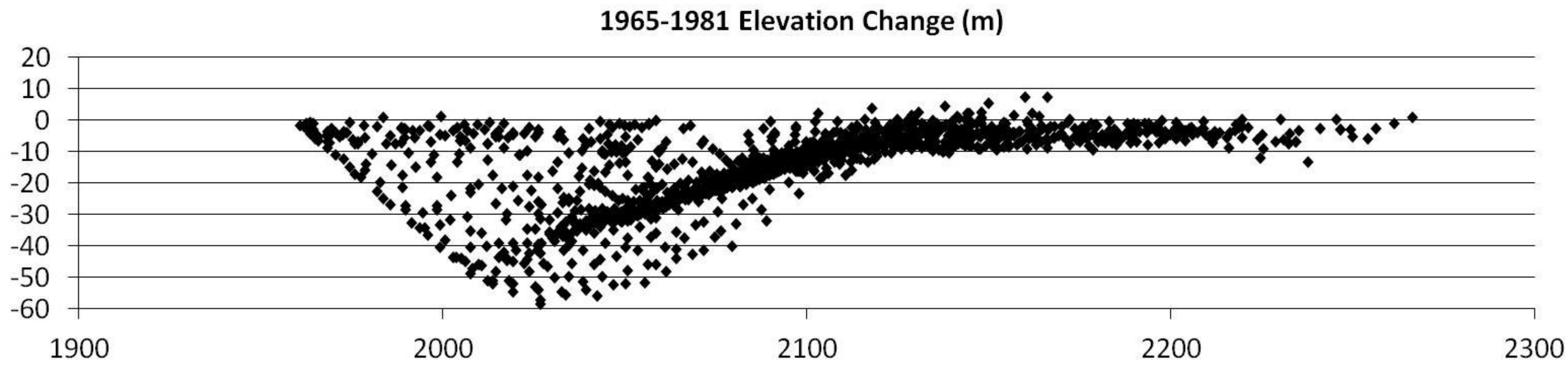

Figure 2.4.1. Elevation changes in meters with elevation across the surface of Joffre Glacier for 1965-1981.

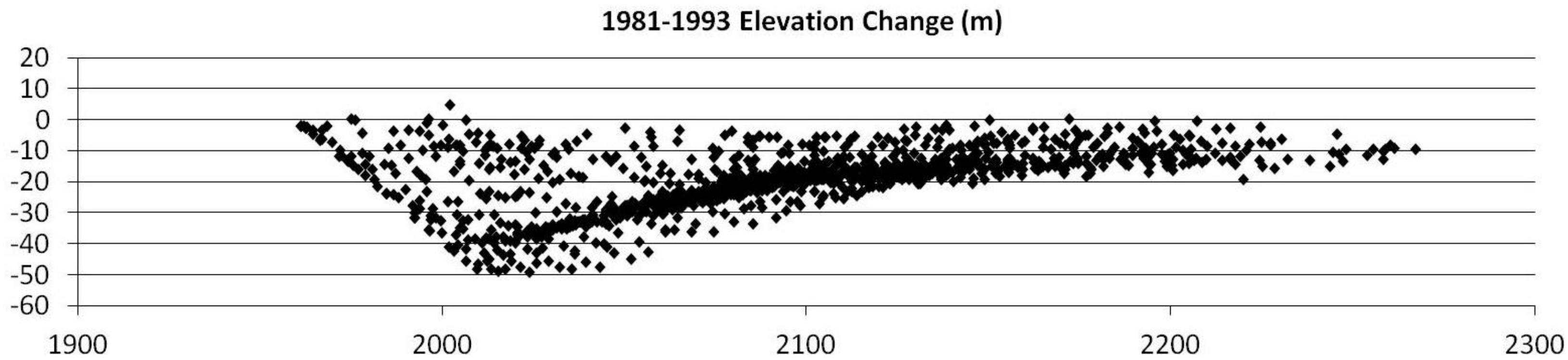

Figure 2.4.2. Elevation changes in meters with elevation across the surface of Joffre Glacier for 1981-1993.

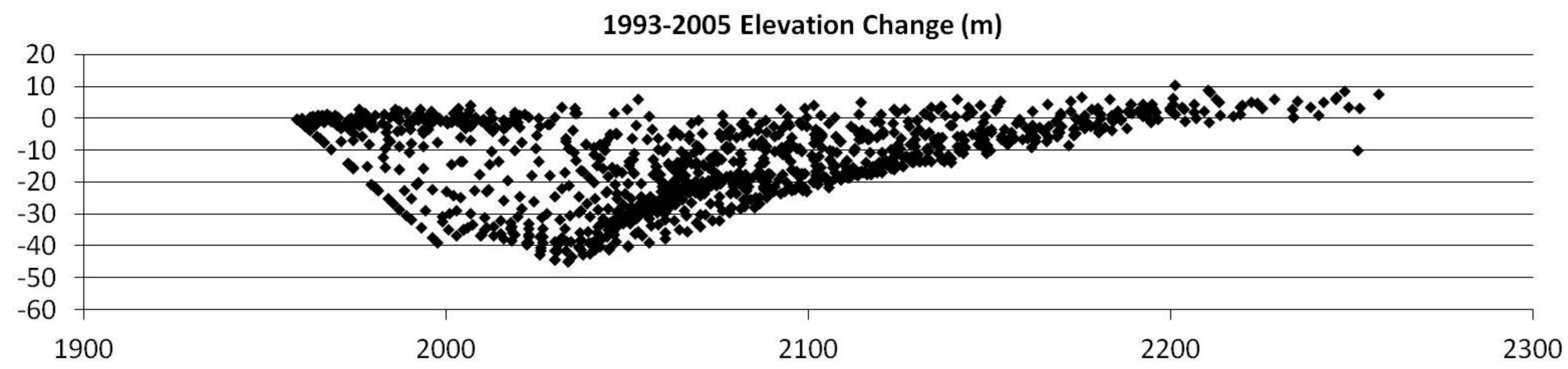

Figure 2.4.3. Elevation changes in meters with elevation across the surface of Joffre Glacier for 1993-2005.

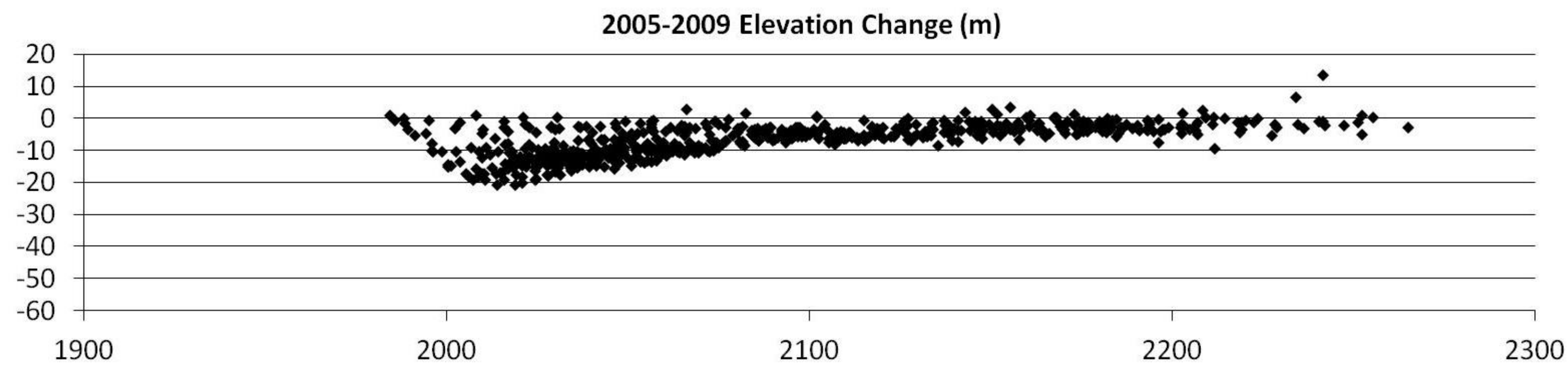

Figure 2.4.4. Elevation changes in meters with elevation across the surface of Joffre Glacier for 2005-2009.

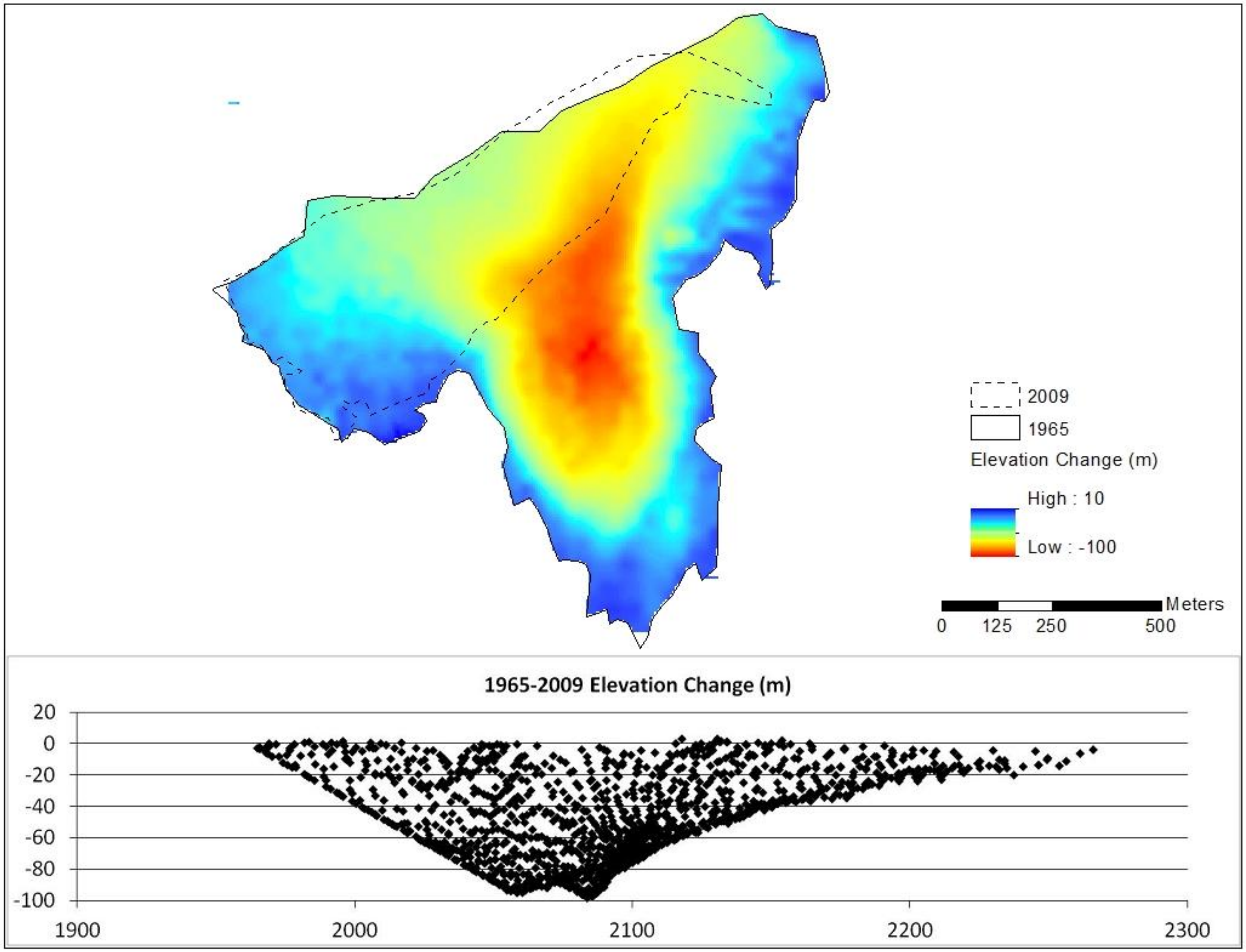

Figure 2.5. Surface elevation changes in meters across Joffre Glacier for 1965-2009. Elevation changes in meters with elevation across the surface of Joffre Glacier for 1965-2009. The solid line shows the 1965 areal extent and the dotted line shows the 2009 areal extent.

2.4.3. Unnamed Glacier Change

Both Unnamed and Place glaciers were measured as experiencing consistently negative mass balances throughout the 1965-2009 period (Table 2.6). Different from Joffre Glacier, Unnamed Glacier lost less mass per unit area than Place Glacier for all four of the periods. Unnamed Glacier's rate of mass change oscillates more than both Place and Joffre glaciers, with the greatest rate of change occurring in 1981-1993. Based on the mass balance calculation for the entire period, Unnamed Glacier is losing mass at a rate of 30% relative to Place Glacier. Area depletion over the periods also varied between the two glaciers. Unnamed Glacier lost less relative area than Place Glacier in the two most recent periods; however, it depleted almost double the amount relative to Place Glacier for the earliest period. Over the entire period, Unnamed Glacier lost 120% the area relative to Place Glacier, but has remained 4% the size of Place Glacier throughout all periods.

A) Place	Mass Balance (B) (m.w.e)	Rate of Mass Change (R)	Area End Year (A) (km^2)	Area Change (ΔA)	Area Change % (Δ A%)
1965-1981	-8.77	-0.55	4.48	-0.35	-7.25
1981-1993	-12.73	-1.06	3.96	-0.52	-11.61
1993-2005	-13.00	-1.08	3.49	-0.47	-11.87
2005-2009	-4.02	-1.005	3.31	-0.18	-5.16
1965-2009	-38.07	-0.87		-1.52	-31.47

B) Unnamed					
1965-1981	-1.15	-0.07	0.198	-0.032	-13.91
1981-1993	-8.25	-0.69	0.160	-0.038	-19.19
1993-2005	-2.93	-0.24	0.150	-0.010	-6.25
2005-2009	-1.46	-0.37	0.143	-0.007	-4.67
1965-2009	-11.55	-0.26		-0.087	-37.83

C) Unnamed/Place	B_T	A_T	$\Delta A\%_T$
1965-1981	0.13	0.04	1.92
1981-1993	0.65	0.04	1.65
1993-2005	0.23	0.04	0.53
2005-2009	0.36	0.04	0.91
1965-2009	0.30		1.20

Table 2.6. Absolute and relative glacier change record for Place and Unnamed glaciers including: A) Mass balance and areal extent record for Place Glacier; B) Mass balance and areal extent record for Unnamed Glacier; and C) Unnamed to Place Glacier proportional change records.

The greatest amount of downwasting occurred near the terminus of Unnamed Glacier accounting for the 38% area loss throughout the periods (Figure 2.6). Over the 1981-1993 period, the greatest elevation loss of ~30 m occurred and corresponded to the greatest rate of mass loss of ~2.6 m yr^{-1}. The greatest increase in elevation of ~7 m occurred in 1965-1981; however, this is the longest period. Similar to Joffre Glacier, the greatest rate of mass gain of ~0.5 yr^{-1} occurred in the shortest, most recent 2005-2009 period.

Looking at elevation change with elevation at each point over the 25 m grid surface, the greatest amount of downwasting typically occurred in the 2200-2250 m elevation range (Figures 2.7.1-2.7.4). Again Unnamed Glacier followed the trend of lower elevation points converging to zero elevation loss because the glacier thins near the terminus, and higher elevation points showing little change because they are in the accumulation zone. The ~30 m greatest elevation loss and rate of loss in the 1981-1993 period occurred at ~2215 m elevation. The ~7 m elevation increase in 1965-1981 occurred just below 2300 m elevation. The greatest rate of mass increase in 2005-2009, occurred between 2300-2350 m.

Over the entire 1965-2009 period, maximum elevation loss increases from the terminus until a point at ~2225 m, then steadily decreases approaching zero towards the upper boundary (Figure 2.8). This differs from Joffre Glacier which had a 50 m elevation range of consistently high negative elevations before beginning to approach zero with increased elevation. The greatest amount of elevation losses approached ~40 m and occurred at almost exactly 2225 m. There was little mass gain over the period, leading to the average mass balance calculation of -11.55 m.w.e. (Table 2.5).

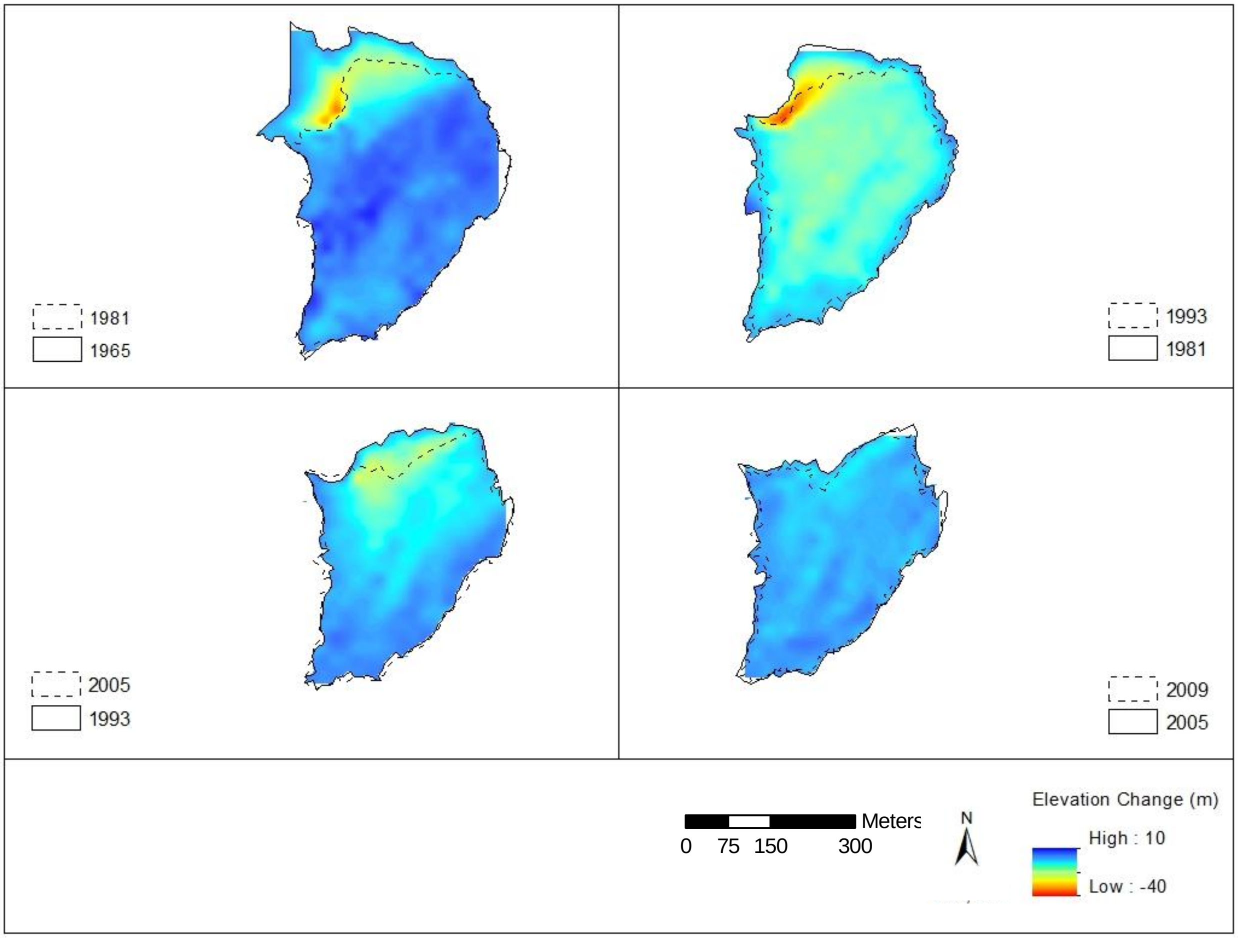

Figure 2.6. Elevation change in meters over the surface of Unnamed Glacier for the periods 1965-1981, 1981-1993, 1993-2005, and 2005-2009. Solid lines show areal extent of the earlier year and dotted lines show areal extent for the more recent year.

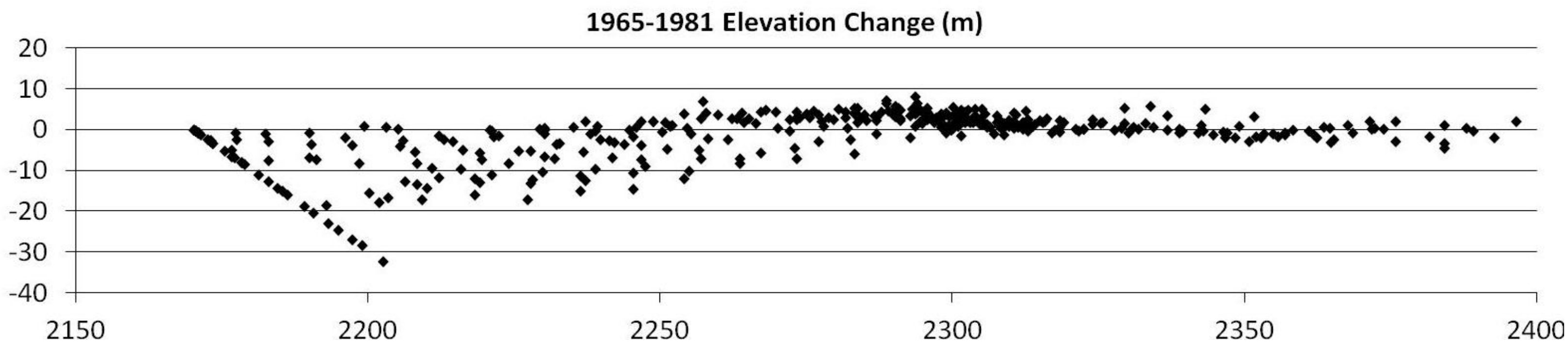

Figure 2.7.1. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1965-1981.

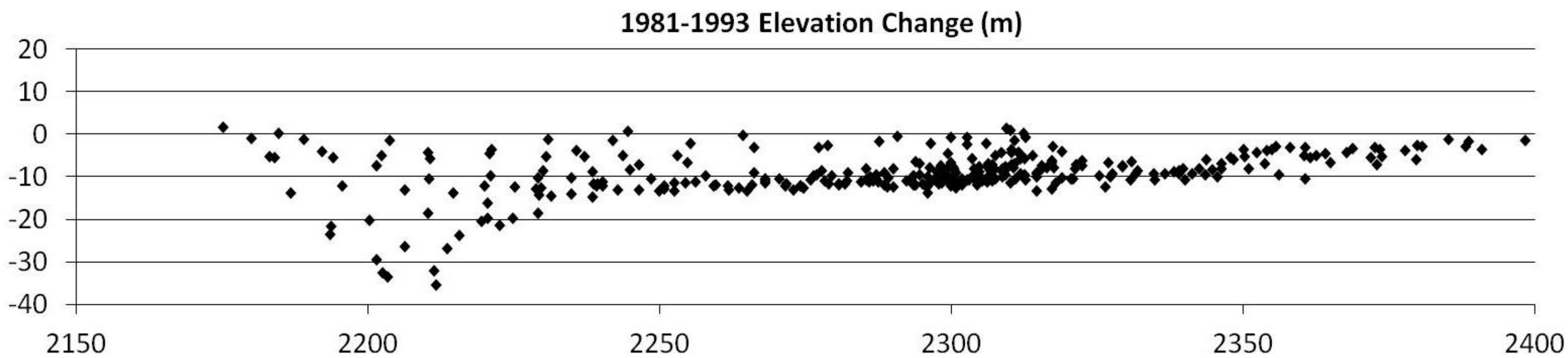

Figure 2.7.2. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1981-1993.

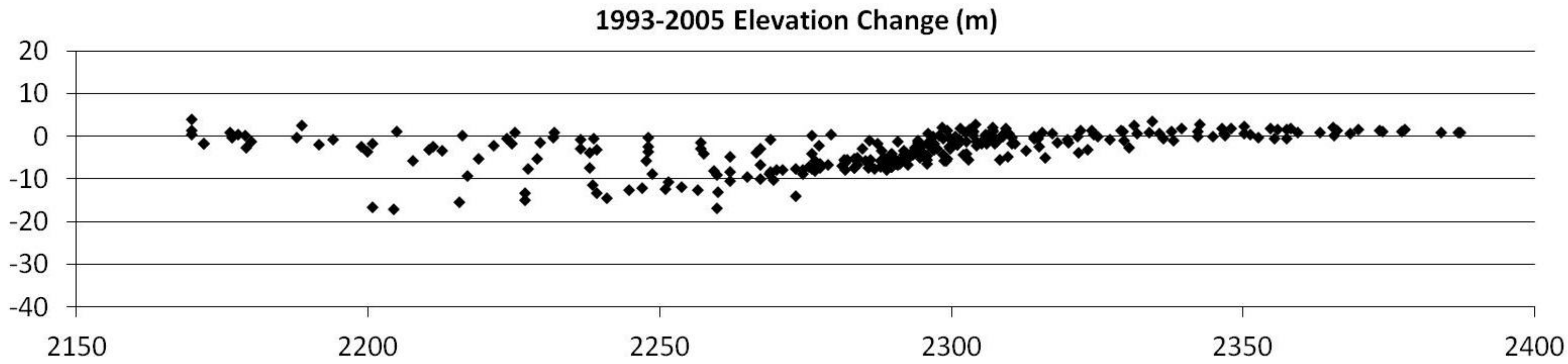

Figure 2.7.3. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1993-2005.

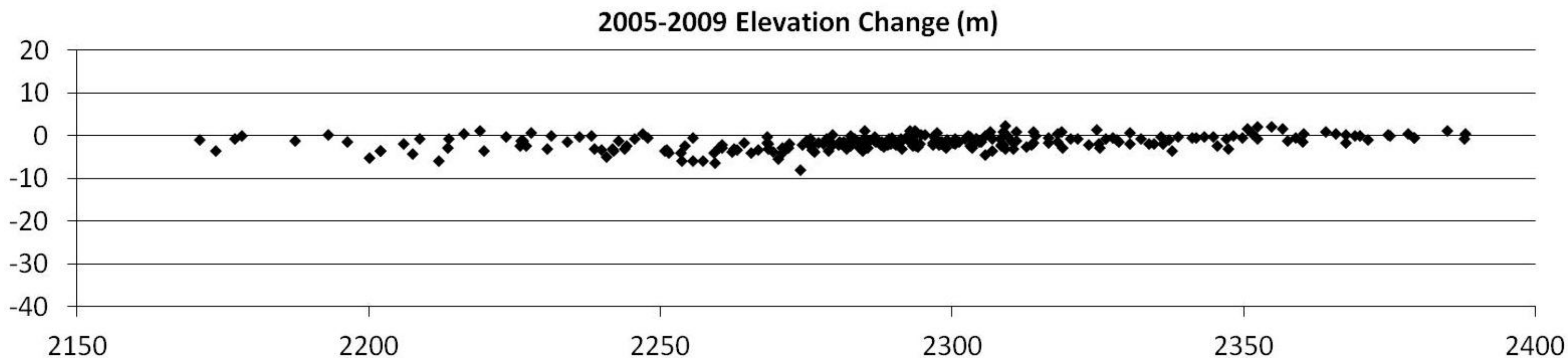

Figure 2.7.4. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 2005-2009.

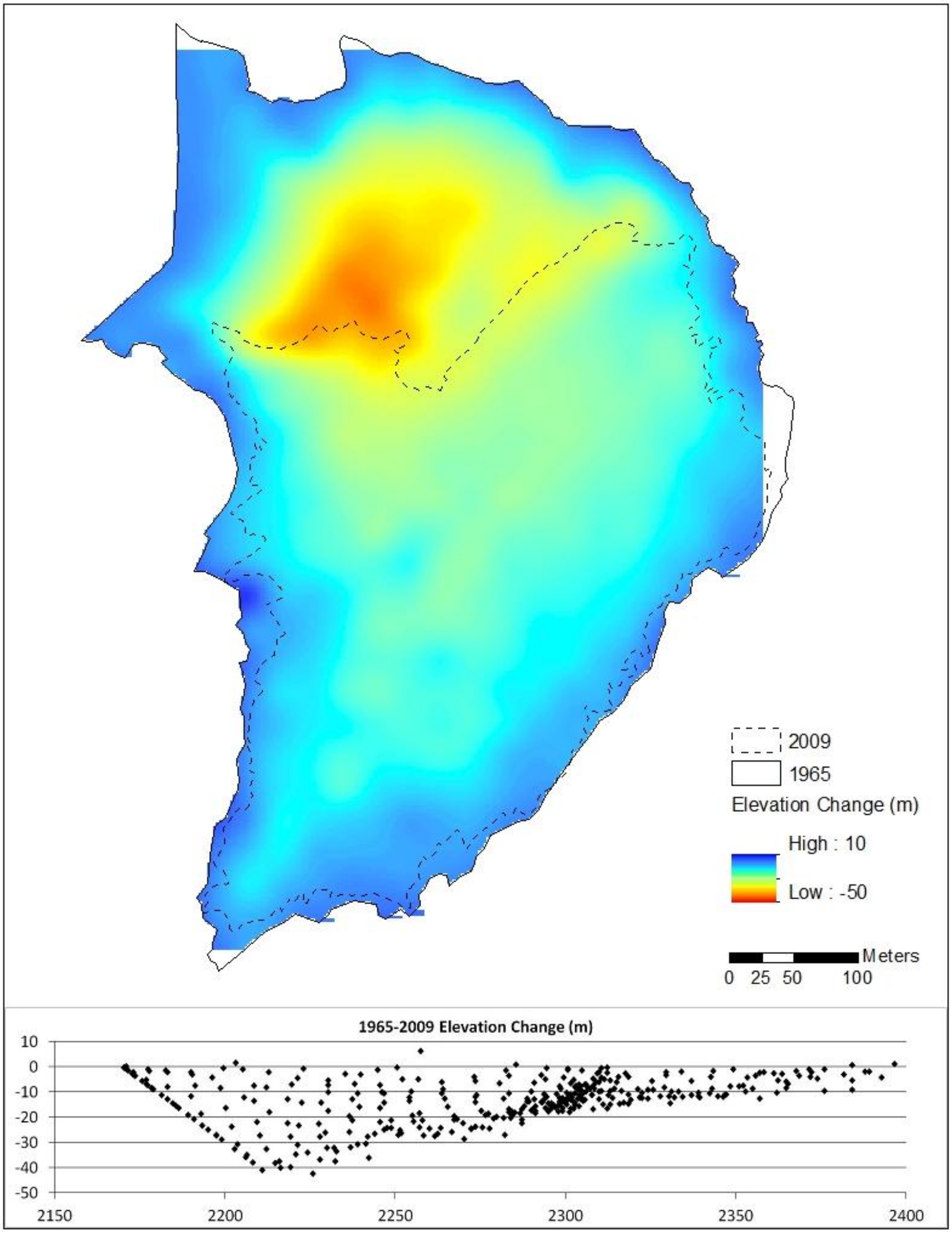

Figure 2.8. Surface elevation changes in meters across Unnamed Glacier for 1965-2009. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1965-2009. The solid line shows the 1965 areal extent and the dotted line shows the 2009 areal extent.

2.5. Discussion

2.5.1. Glacier Size

Despite being in the same category of “small” in the context of this paper and relative to Place Glacier, Joffre and Unnamed glaciers did not experience the same reaction to changes in the climate over the 1965-2009 period. We often assume glaciers reflect changes in the climate with the rate at which their mass balance changes over a given time frame. Based on the three glaciers examined in this paper, if size was the only consideration determining the rate of climate reflection in glacier mass, there would be no definitive relationship. The smallest size glacier, Unnamed, lost mass at the lowest rate; the largest size glacier, Place, lost mass at the median rate; and the median sized glacier, Joffre, lost mass the fastest. Although size may act as a control of a glacier’s sensitivity to climate, as suggested by Bahr *et al*. (1998), it is clearly not the dominate influence for the glaciers over the period in this study. The suggestion by DeBeer and Sharp (2009), and Li *et al*. (2011), that small glaciers have retreated as far as they are likely to under the current climatic conditions does not apply to all small glaciers. The four out of 86 small glaciers that retreated in the Monashee Mountains, British Columbia study by DeBeer and Sharp (2009), were all glaciers attached to larger ice masses, similar to Joffre Glacier which shares its northwest margin with Place Glacier. Attached glaciers are more vulnerable to retreat because their environmental niche is highly dependent on the deficit of heat provided by the larger, adjacent glacier which is also experiencing elevation loss due to climatic warming. Most of the glaciers in DeBeer and Sharp (2009) maintained area over then 1951-2004 period because they were small enough (< 0.4 km^2) to “hide” in topographic locations which enhanced accumulation and decreased ablation based on various local morphometric and solar energy constraints. Although it is smaller than 0.4 km^2 and showed retreat over the 1965-2009 period, Unnamed Glacier is progressing into a higher elevation, low insolation, topographic niche that should eventually favor ice maintenance.

I suggest, local topography, and its relation with solar radiation input and aspect, is the dominant control factor in the different climate reactions between Joffre and Unnamed glaciers for the 1965-2009 period.

2.5.2. Aspect

DeBeer and Sharp (2009) found glaciers in the Monashee Mountains, British Columbia to be most likely to preserve mass in northerly aspects, and most likely to lose mass in south to west-facing aspects. This suggests exposure to late afternoon insolation as the most detrimental to ice maintenance.

In both 1965 and 2009, Unnamed Glacier had no directly south-facing areas and was dominated by north and northwest-facing slopes, favorable for ice maintenance (Figure 2.9). Over the study period, Unnamed Glacier has become increasingly north/northwest-facing, with most area loss occurring on aspects of west and southwest orientation on the north/northeast portion of the glacier. The small northeast portion of Unnamed Glacier that is west/southwest facing in 2009 may be most susceptible to continued depletion. If it is retreating into a niche habitat favorable for ice maintenance, it may reach this position after the loss of the last west/southwest-facing area visible in 2009.

Joffre Glacier was dominated by south-facing aspects in 1965 (Figure 2.9). Over the course of the 44-year study period, these southerly aspects are the areas of the glacier that have suffered the most mass loss. Assuming Joffre Glacier continues this trend of mass loss of southerly aspects, those aspects left across the surface of Joffre Glacier in 2009 are the most susceptible to mass loss.

I suggest, following 2009, Joffre and Unnamed glaciers have continued to suffer mass loss in the remaining southerly aspects until nearing equilibrium in the north-facing areas where they will experience significantly reduced change in response to continued warming, as seen in DeBeer and Sharp (2009). These north-facing aspects are also at higher elevations of the glacier, directly influencing mass balance through air temperature and solar radiation receipt, as to be discussed below.

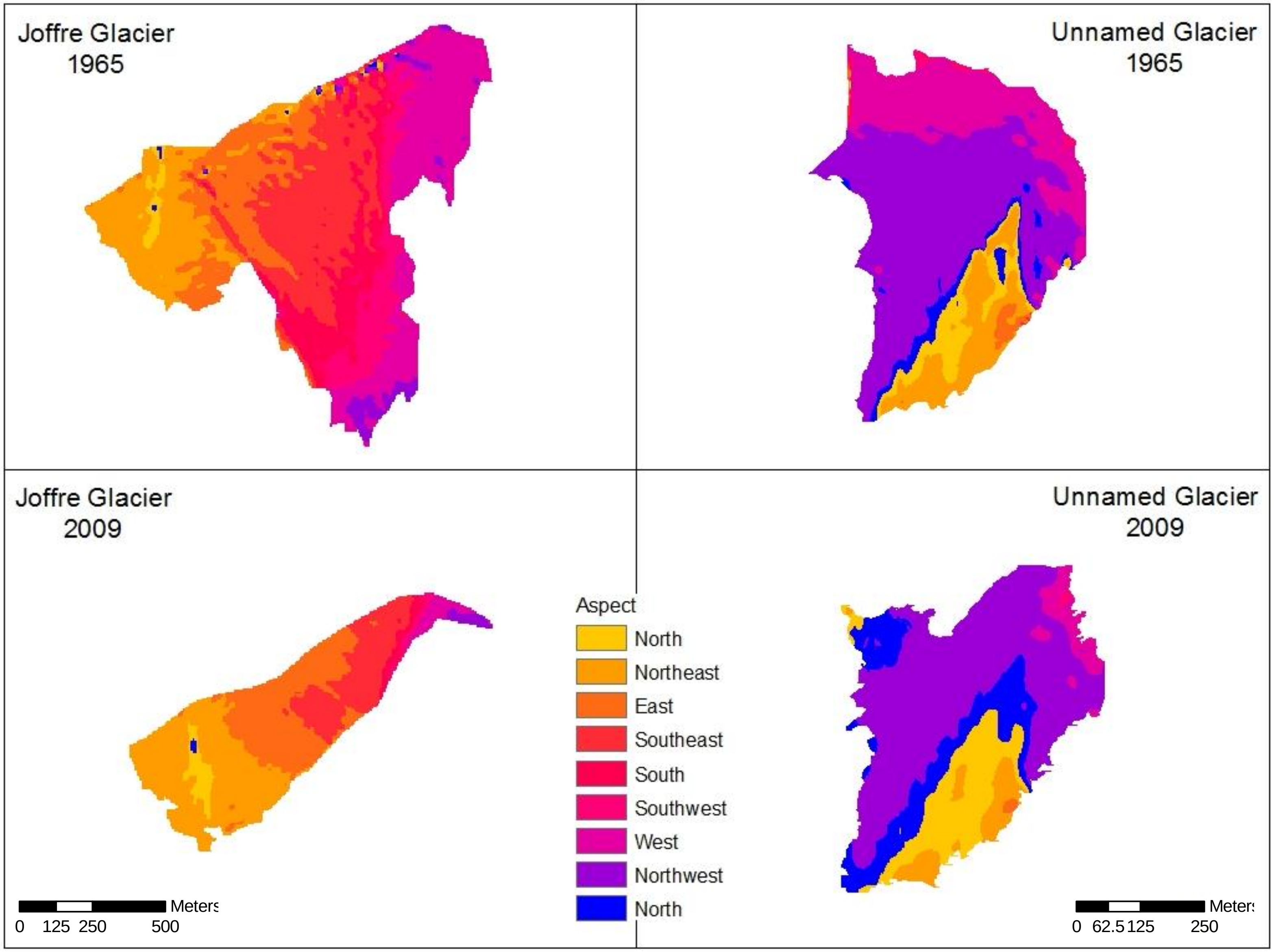

Figure 2.9. Aspect of the surfaces of Joffre and Unnamed glaciers in 1965 and 2009.

2.5.3. Solar Radiation

Seasonal solar radiation, particularly summer insolation, plays a key role in glacier mass balance fluctuations. During the winter, fresh snow with high albedo reflects solar radiation over the surface of the glacier which limits sensible energy gains on sunny days. The cold and relatively humid conditions during the winter in the south Coast Mountains of British Columbia also reduce the potential for mass loss by evaposublimation. During the summer, lower albedos of supraglacial debris and exposed ice increases susceptibility to melting from heating by insolation. Solar radiation in watt hours per unit area across the surface of the three study glaciers was examined during a day in the approximate middle of the ablation season (Figure 2.10). The south-facing mountain ridgelines receive the most solar radiation, but also through shading, protect a small portion of each of the three glaciers. A large north/northwest-facing, high-elevation portion of Unnamed Glacier receives low insolation through the summer. The high elevation, north-facing, accumulation area of Joffre Glacier is also the portion of the glacier that receives the least insolation. I suggest, the summer low insolation areas of Joffre and Unnamed glaciers will be the areas these glaciers retreat into to eventually better maintain their mass as they coincide with high-elevation, north-facing aspects.

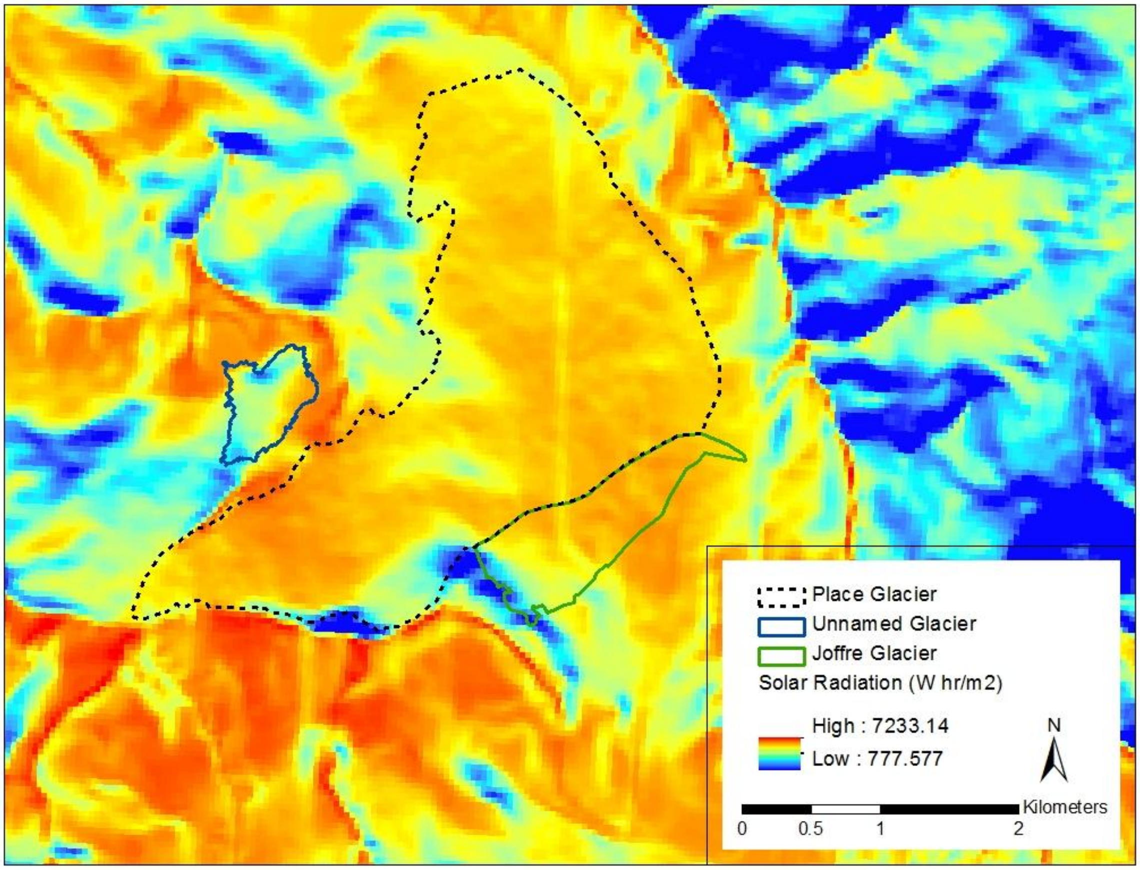

Figure 2.10. Solar radiation in W hr m^{-2} across the surface of Place, Joffre, and Unnamed glaciers on July 15.

2.5.4. Other Topographic Influences

Topography can also aide in other mechanisms which promote ice maintenance, such as snow augmentation by avalanching and differential snow accumulation. Snow deposition depth on slopes is negatively correlated with slope angle (Sovilla *et al.,* 2010). Broken down into elevation ranges, 60°-90° experiences few avalanches due to little snow accumulation on the steep surface, 30°-60° experiences dry, loose snow avalanches, 45°-55° experiences frequent small avalanches, 35°-45° experiences avalanches of all sizes, 25°-35° experiences infrequent but large avalanches, and below 25° experiences few avalanches due to the lack of general incline (McClung and Schaerer, 1993). Avalanche likelihood on a slope also depends on a variety of other morphometric factors including, orientation to the wind and sun, forest cover, and ground surface. Avalanches are more likely on slopes on the lee side of high ridges which accumulate snow through drifting (McClung and Schaerer, 1993). The stability of snowpack on shady slopes increases with temperature, meaning sunny slopes with warmer snow temperatures in winter have greater stability than shaded ones (McClung and Schaerer, 1993). Forest cover and a rougher ground surface protect slopes from large avalanche development (McClung and Schaerer, 1993).

The north-facing accumulation area on the west portion of Joffre Glacier is surrounded by very steep (almost 90º) rocky slopes rising high above the glacier surface which do not likely contribute additional snow from avalanching due to little snow accumulation. The east side of Joffre Glacier has moderately steep surrounding slopes which could avalanche; however, this area is also south-facing, potentially eliminating any additional accumulation on the glacier surface from avalanching through increased insolation.

Unnamed Glacier also has varying avalanche potential over its surface. The western accumulation area of Unnamed Glacier extends up to the edge of the steep topography, leaving little room off the glacier surface for snow accumulation that could significantly contribute through avalanching. Down from the accumulation area, along the eastern side of Unnamed Glacier, the surrounding ridges are moderately steep with some potential of avalanching.

Both Joffre and Unnamed glaciers have steep accumulation areas. The steep upslope is important for aiding in avalanching which moves snow from the accumulation area down to the ablation area, increasing albedo and protecting the more vulnerable low elevation region (DeBeer and Sharp, 2009). Both glaciers have the potential for on-surface avalanching such as this; however, the front of the terminus of Unnamed Glacier is so steep, it is likely there will be little build up in this area. It is unlikely avalanching from either on or off-glacier processes contributes significantly to mass balance of the glaciers in this study. There was no significant avalanche debris visible in the study photographs.

Local distributions of mountain snow accumulation are largely determined by slope position and aspect (i.e. windward or leeward locations) (Shea *et al.,* 2009). Most precipitation in western Canadian ranges comes with low-pressure systems from the west during the winter and creates a strong west-east moisture gradient (Shea *et al.,* 2009). Joffre Glacier's position on the leeward side of a steep ridge may suggest the opportunity for more accumulation through blowing snow. At Castle Creek Glacier which is located at a similar elevation to Joffre Glacier, 2100 m, in the Cariboo Mountains, British Columbia, blowing snow is the main process of accumulation (Déry, *et al*., 2010).

2.6. Conclusions

Based on the comparison of mass balance calculations for Place Glacier done by this study and those done by Menounos and Schiefer (2009), large differences in measurements appear to be mainly attributable to aerial photograph quality, based on contrast characteristics over the glacier surface and photograph scale. With higher quality and larger scale aerial photography, differences between measurements were minimal indicating little bias associated with the user or the 3D stereoviewing technique with the Vr Mapping software. This specific application of analytical photogrammetry is, therefore, a usable approach to developing geodetic mass balance records for the study of small glaciers with appropriate quality photography.

There is no pattern associated with Place, Joffre, and Unnamed glaciers' mass changes over the 1965-2009 period based on glacier size. Over the study period, Joffre Glacier lost more mass and area relative to Place Glacier, and Unnamed Glacier lost less mass and more area relative to Place Glacier. The largest glacier lost mass at a median rate, the median-sized glacier lost mass at the fastest rate, and the smallest glacier lost mass at the slowest rate. The difference in mass balance trends among the three glaciers is based on multiple topographic factors including elevation, insolation, slope, and aspect.

Over the period of study, Joffre and Unnamed glaciers' mass loss occurred on portions of the glaciers that were south facing and in the lowest elevations. Joffre Glacier changed the fastest because surrounding local topography was less promoting for ice preservation. Joffre Glacier was more susceptible to mass loss due to its low elevation, south-facing aspect causing increased insolation. It receives little accumulation from avalanching due to the steepness of the western ridge above its accumulation area. A large portion of the remaining glacier was of south-facing aspect in 2009 and still highly vulnerable to mass loss.

Unnamed Glacier is less susceptible to mass loss because of its higher elevation northwestern aspect and decreased insolation. There are no remaining south-facing aspects over the surface of Unnamed Glacier. Unnamed Glacier changed at the slowest rate, likely because it is the smallest glacier that is nearer to residing in a niche environment that promotes ice maintenance based on the topographic factors studied. Its oscillating rate of mass change makes it difficult to say when it may reach this more stable position with local topography and the modern climate regime. In the most recent period studied, Unnamed Glacier largely possessed the topographic qualities indicative of ice conservation.

It is accepted that temperatures have been increasing over recent decades and glaciers and ice-caps have reflected this through their increase in mass loss and contribution to sea-level rise. The earliest study interval, 1965-1981, experienced locally high winter precipitation and a pause in long-term warming, and coincided with the lowest rates of mass loss for all three of the study glaciers. Following study intervals showed greater rates of mass loss associated with increased temperatures and decreased winter precipitation. However, relative mass changes over the entire study period were asynchronous between the study glaciers.

More glaciers need to be studied to better assess the relation of glacier size and response to changes in climate. All glaciers are likely following a trend of self-preservation in the modern climate regime and some small glaciers may just be closer to reaching it.

3. Conclusions

- With high quality aerial photography, 3D surface digitization in the Vr Mapping software is an analytical photogrammetric approach to developing small glacier geodetic mass balance records.
- Place, Joffre, and Unnamed glaciers all measured negative mass balances and lost more than 30% of their area over the 1965-2009 study period.
    - Place Glacier's mass balance was -38.0 m.w.e, and lost 31% of its area.
    - Joffre Glacier's mass balance was -40.4 m.w.e, and lost 59% of its area.
    - Unnamed Glacier's mass balance was -11.6 m.w.e., and lost 38% of its area.
- Among Place, Joffre, and Unnamed glaciers there was no clear trend in response to climate change over the 1965-2009 period based on glacier size.
- Differences between rates of mass change over the 1965-2009 period among Place, Joffre, and Unnamed glaciers are likely attributable to differences in local topography.
- Areas of Joffre and Unnamed glaciers which suffered from the most mass loss over the 1965-2009 period were of southerly facing aspects.

- Northerly facing aspects of Joffre and Unnamed glaciers coincide with higher elevation and less insolated areas, creating locations favorable for potential ice maintenance.

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5. Appendix

5.1. Tables

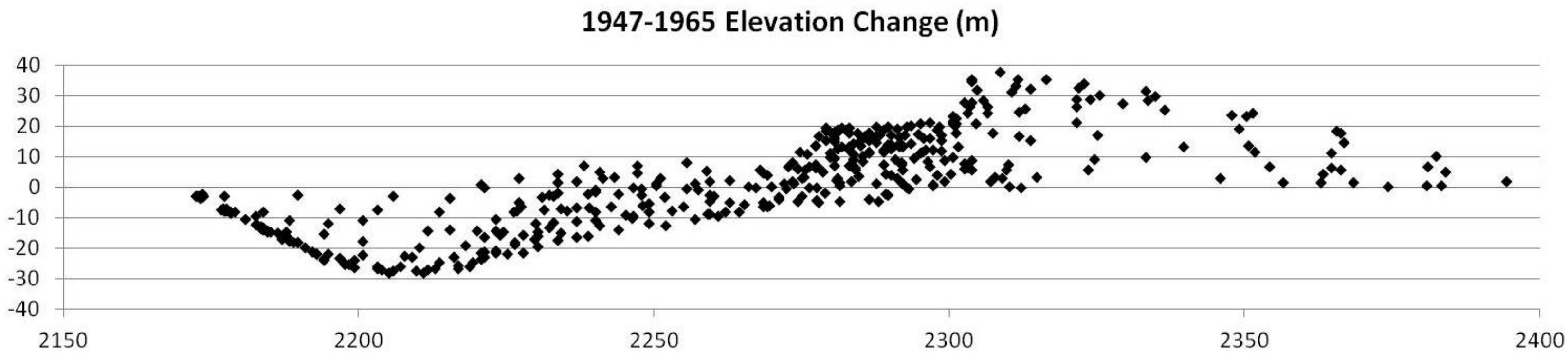
Place	Mass Balance (m.w.e.)	Area End Year (km^2)	Delta Area	Delta Area %
1947-1965	-10.14	4.83	-0.44	-8.35
1965-1973	-3.63	4.68	-0.15	-3.11
1973-1981	-5.14	4.48	-0.2	-4.27
1981-1987	-5.89	4.23	-0.25	-5.58
1987-1993	-6.84	3.96	-0.27	-6.38
1993-1997	-3.12	3.9	-0.06	-1.52
1997-2005	-9.88	3.49	-0.41	-10.51
1947-2005	-43.57		-1.78	-33.78

Appendix 5.1.1. Place Glacier mass balance (calculated by Menounos and Schiefer, 2009), area, area change, and proportional area change for all available years of photography.

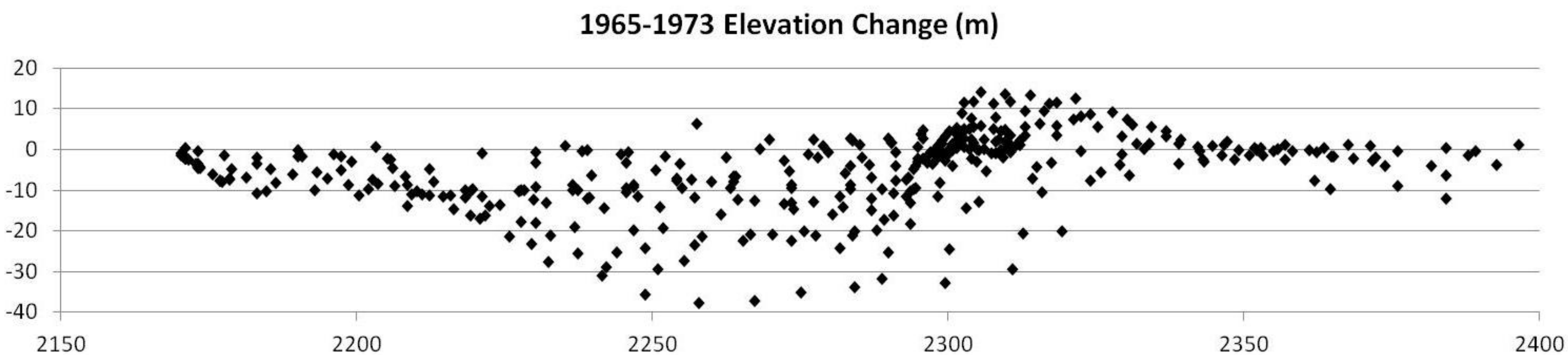
Unnamed	Mass Balance (m.w.e.)	Area End Year (km^2)	Delta Area	Delta Area %
1947-1965	1.49	0.23	-0.04	-14.81
1965-1973	-4.78	0.22	-0.01	-4.35
1973-1981	3.75	0.198	-0.022	-10
1981-1987	-10.39	0.198	0	0
1987-1993	2.11	0.16	-0.038	-19.19
1993-1997	-4.03	0.198	0.038	23.75
1997-2005	1.23	0.15	-0.048	-24.24
2005-2009	-1.46	0.143	-0.007	-4.67
1947-2005	-7.49		-0.12	-44.44
1965-2009	-11.55		-0.087	-37.83

Appendix 5.1.2. Unnamed Glacier mass balances, area, area change, and proportional area change for all available years of photography.

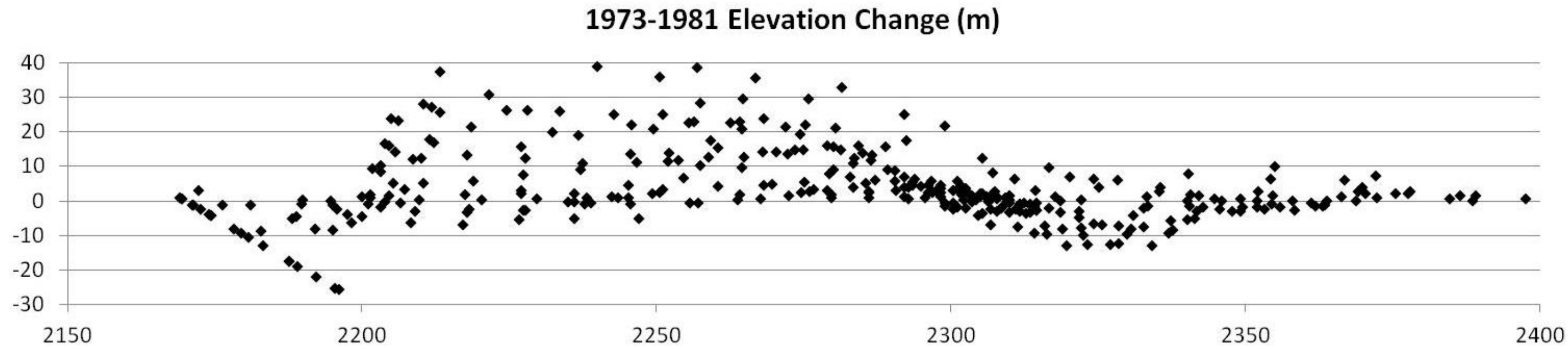
5.2. Figures



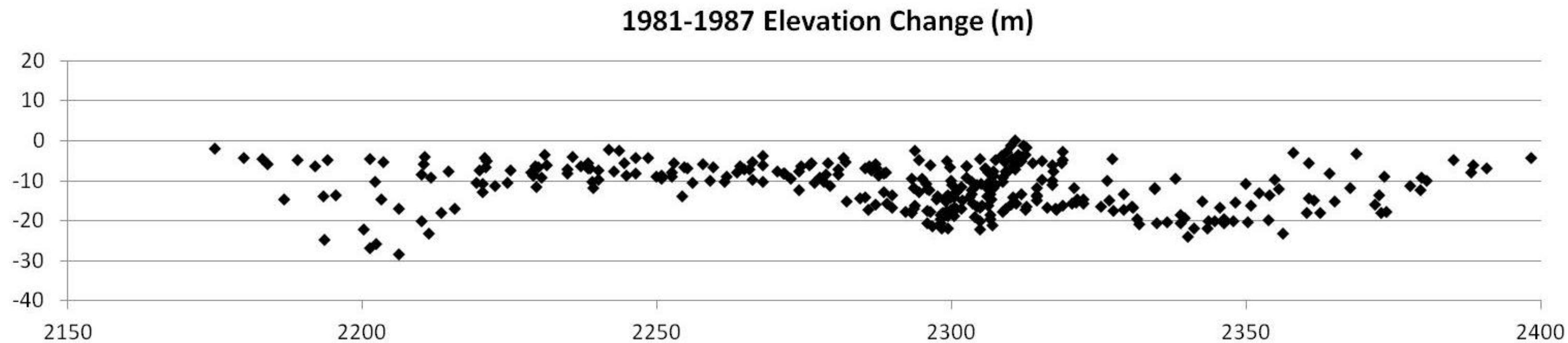
Appendix 5.2.1. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1947-1965.



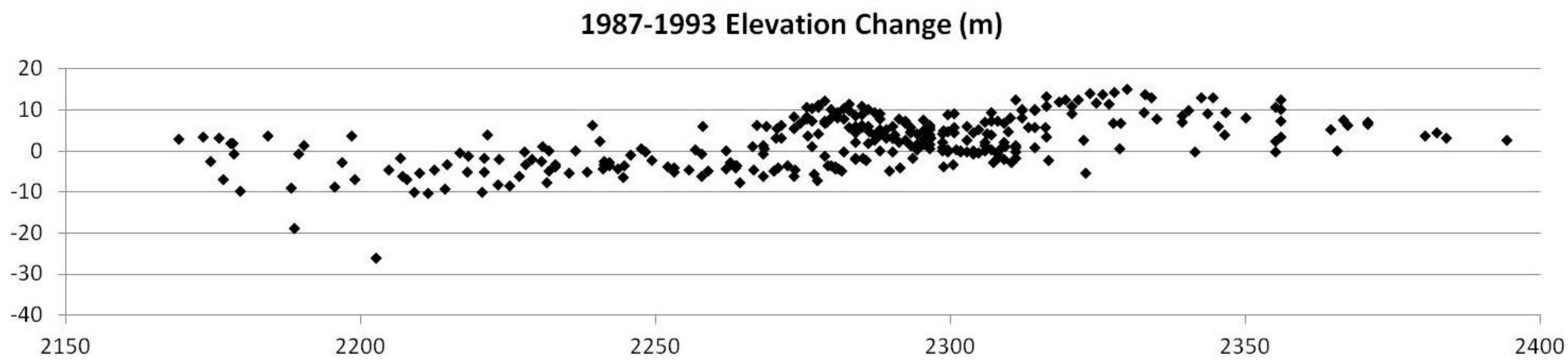
Appendix 5.2.2. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1965-1973.



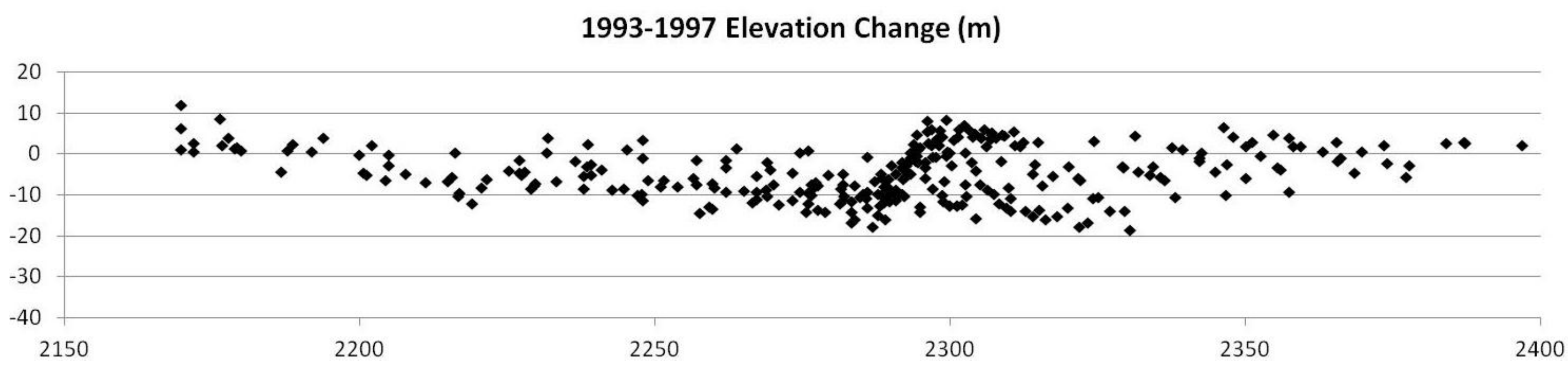
Appendix 5.2.3. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1973-1981.



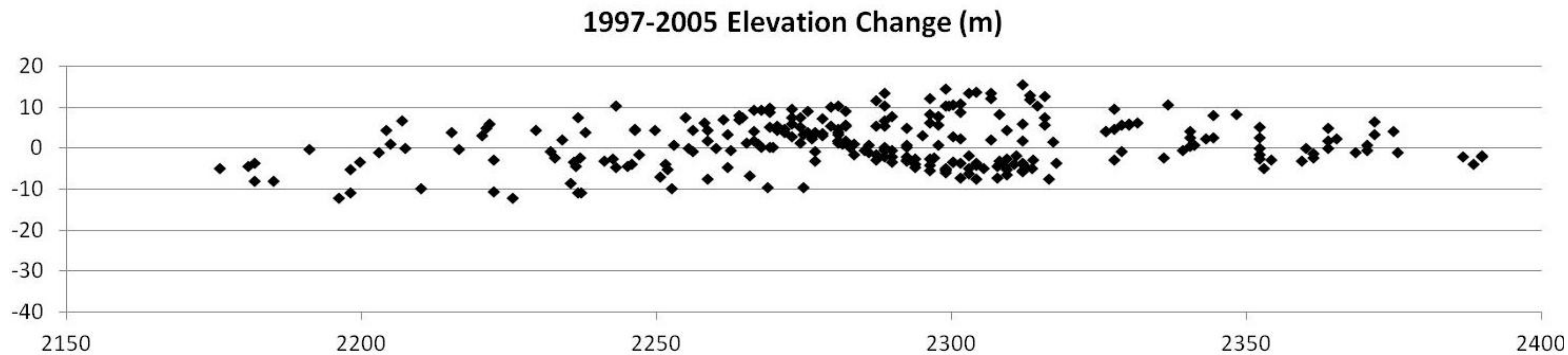
Appendix 5.2.4. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1981-1987.



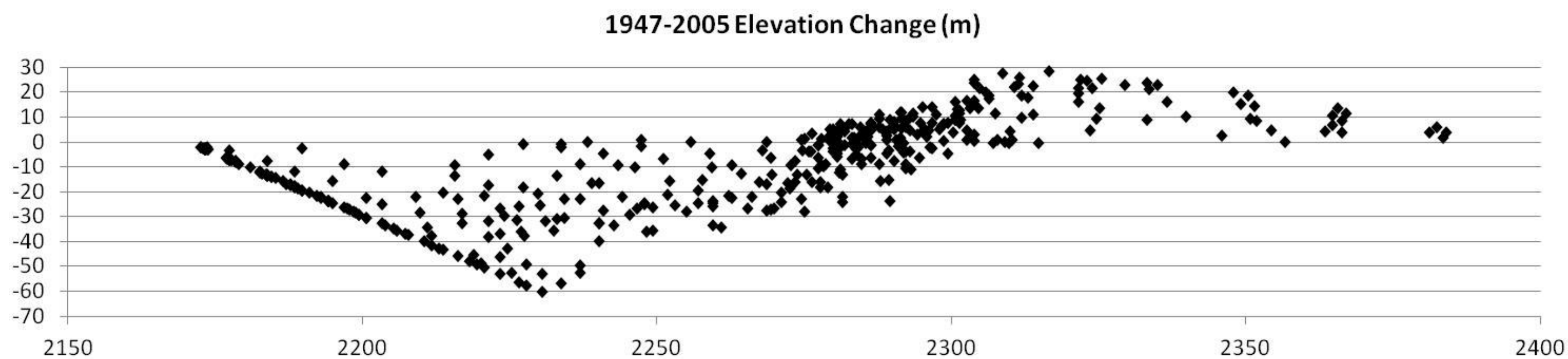
Appendix 5.2.5. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1987-1993.



Appendix 5.2.6. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1993-1997.

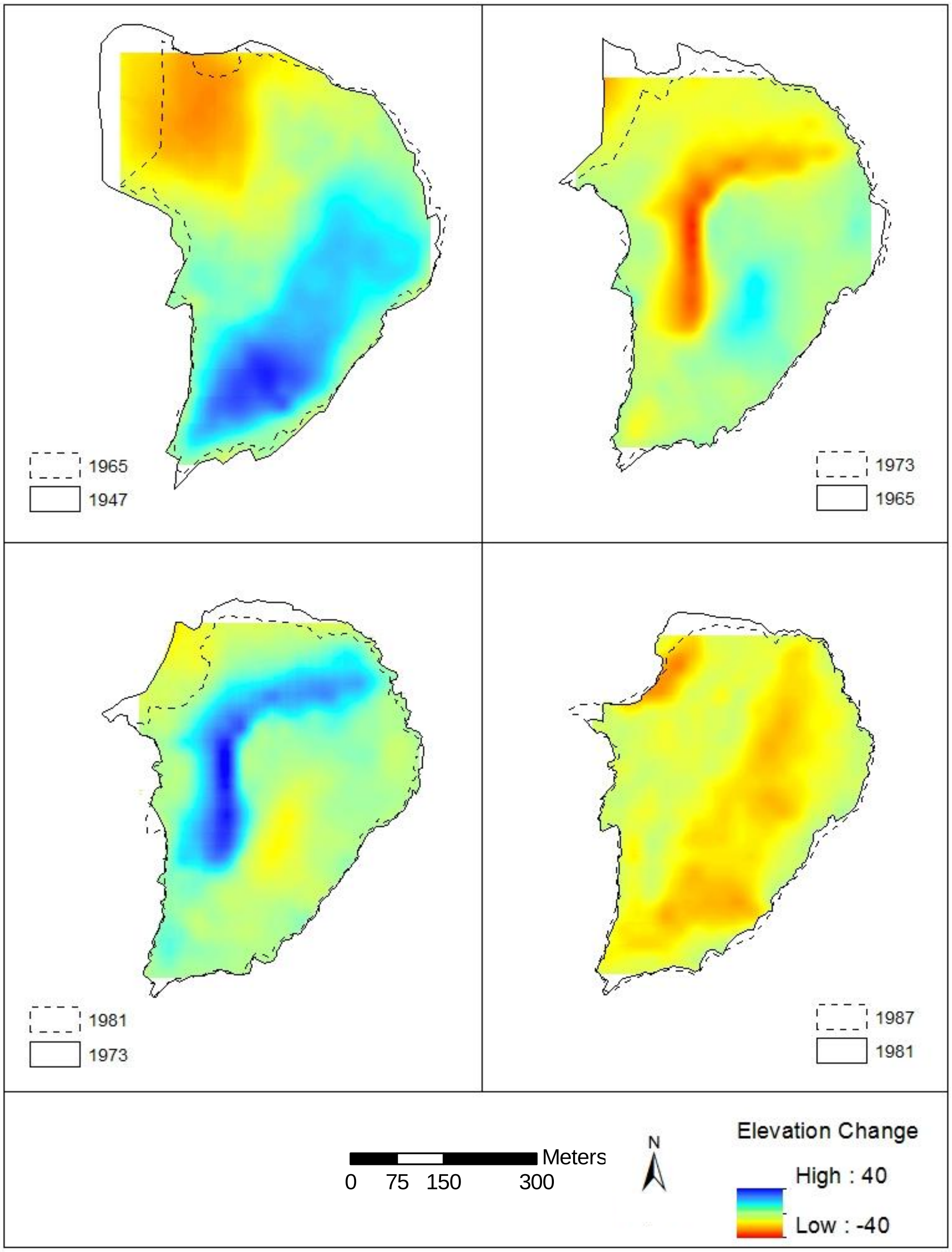


Appendix 5.2.7. Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1997-2005.

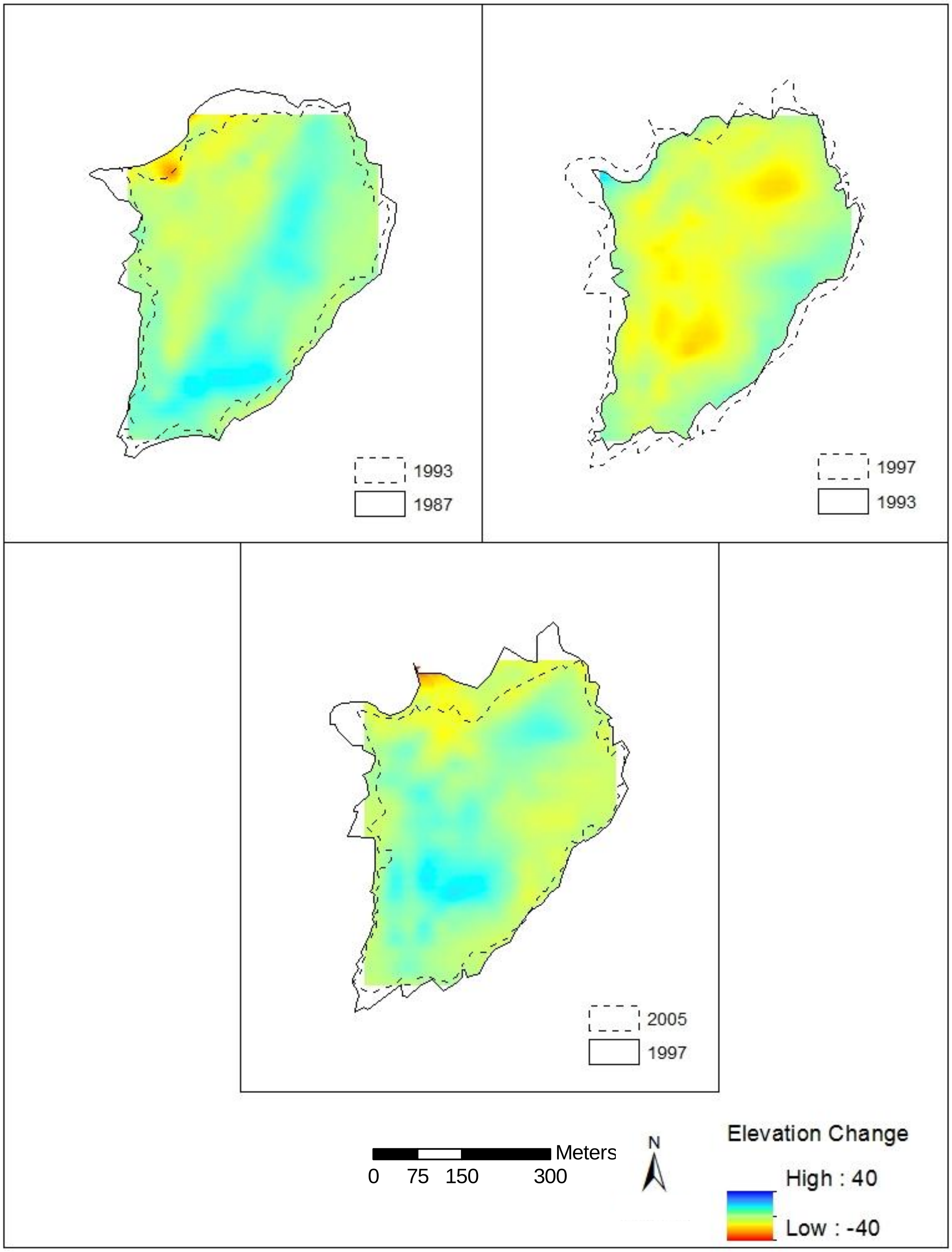


Appendix 5.2.8 Elevation changes in meters with elevation across the surface of Unnamed Glacier for 1947-2005.

5.3. Maps



Appendix 5.3.1. Elevation change in meters over the surface of Unnamed Glacier for the periods 1947-1965, 1965-1973, 1973-1981, and 1981-1987. Solid lines show areal extent of the earlier year and dotted lines show areal extent for the more recent year.



Appendix 5.3.2. Elevation change in meters over the surface of Unnamed Glacier for the periods 1987-1993, 1993-1997, and 1997-2005. Solid lines show areal extent of the earlier year and dotted lines show areal extent for the more recent year.