Circum-Arctic Glaciers, Past, Present, and Future: Current Trends in Mass Balance and Simulation of Mass Balance Sensitivity to Temperature and Precipitation Increase

by

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ABSTRACT

The circum-Arctic is a major contributor to sea level rise. Between 1991 and 2010, 70 % of eustatic sea level rise was attributable to glacier mass loss, 62 % of which was from glaciers in the circum-Arctic (Alaska, Arctic Canada North, Iceland, Svalbard, Scandinavia, and the Russian Arctic). In addition, Arctic temperatures are expected to increase at 2.4 times the magnitude of projected global average warming over the next 100 years. An understanding of how circum-Arctic glaciers are responding to temperature increase, and how they will respond under future climate conditions, is crucial to helping island nations and low-lying coastal communities predict and mitigate the impacts of sea level rise. This thesis has two objectives. The first objective is to a) identify the most effective methodology to calculate regional mass balance trends in the circum-Arctic using spatially and temporally sparse datasets and b) use these data to determine past and present (1961-2016) circum-Arctic mass balance trends. To accomplish this, I explore spatially interpolated mass balance from prior studies and compare these results to specific mass balance calculated using only observational data. I then compare two different time periods from the specific mass balance dataset (1961-2016 and 2000-2016) to determine regional mass balance trends. I find that mass balance calculated through spatial interpolation and specific mass balance are statistically likely to derive from the same population in regions that contain observational mass balance data. However, qualitatively, the variability between the datasets appears to be different for regions in which ≥50 % of observational data are geodetic. In addition, the mean magnitude of mass loss appears different in glacier regions with only high-variability glaciological mass balance data. A comparison of 1961-2016 and 2000-2016 mean specific mass balance in each region determines that glacier mass balance in Arctic Canada North has decreased at the largest rate, followed by Alaska and Svalbard (-0.20, -0.14, and -0.12 m w.e. a^{-1}, respectively). The second objective of this thesis is to: a) determine the circum-Arctic glacier mass balance sensitivity temperature and precipitation increase and then b) investigate the factors driving the sensitivity. To achieve this objective, I use a degree-day model (the Python Glacier Evolution Model, PyGEM) to simulate circum-Arctic mass balance sensitivity to 1-3 °C temperature and 4%°C^{-1}precipitation increase between 2000 and 2100. The model simulations suggest that Iceland glaciers are the most sensitive to temperature and precipitation increase (-0.70 m w.e. a^{-1} °C^{-1}) of all regions studied, and Arctic Canada North is the least sensitive (-0.39 m w.e. a^{-1} °C^{-1}). These results suggest that the degree of continentality (how warm/wet a region is) and the proximity of accumulation season temperatures (the rain/snow threshold) is the primary driver of mass balance sensitivity; warm, wet, 'maritime' regions (Iceland, Scandinavia) are more sensitive to the same temperature increase than cold, dry, 'continental' regions (Arctic Canada North, the Russian Arctic). Secondary factors such as glacier size, altitude, slope, and surface albedo may also impact regional glacier mass balance sensitivity. Small glacier size, low glacier altitude, large surface albedo, and steep glacier slope may increase mass balance sensitivity, while large glacier size, high glacier altitude, small surface albedo, and slight glacier slope may decrease mass balance sensitivity. Overall, the results of this thesis provide incentive for future data collection in rapidly changing regions like Arctic Canada North, and provides a better understanding of how the circum-Arctic may change in response to future climate change.

PREFACE

This thesis is an original work by Anna Serdetchnaia. No part of this thesis has been previously published.

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CHAPTER 1. INTRODUCTION

1.1. Motivation

Earth's cryosphere is degrading in response to global climate warming. Over the next 100 years, global air temperatures are expected to rise 0.3 °C – 4.8 °C from the 1986-2005 average and the Arctic region is expected to experience temperature increase 2.4 times the magnitude of global average warming, in a phenomenon called 'Arctic Amplification' (Cohen et al., 2014). As a consequence of this warming, the rate of global eustatic sea rise has increased from 1.1 +-0.3 mm/year for 1901-1990 to 3.1 +- 1.4 mm yr^{-1} for 1993-2012 (Horton et al., 2018). Approximately 70 % of sea level rise is attributed to mass loss of glaciers and ice caps, while the other 30 % is primarily attributed to the thermal expansion of water (Slangen et al., 2017). Arctic glaciers outside of Greenland currently account for the majority (62 %) of global glacial melt (Zemp et al. 2019) and the meltwater contribution from Arctic glaciers is likely to increase due to the disproportionate temperature increase expected in the region. It has therefore become increasingly important to understand the past and present rates of Arctic glacier mass loss, and how sensitive glaciers in this region are to potential future increases in temperature.

1.2. Objectives

Although Arctic glaciers have been identified as a dominant contributor to eustatic sea level rise, there is poor understanding of historical trends in Arctic mass balance due to sparsity of observational mass balance data and variability in the methodology used to calculate and spatially interpolate regional mass balance change. Data sparsity also contributes to the poor understanding of how glaciers in different Arctic regions are likely to respond to future changes in climate.

The objectives of this study are:

a) Identify the most effective methodology to calculate regional mass balance trends in the circum-Arctic using spatially and temporally sparse datasets and then use these data to determine past and present (1961-2016) mass balance trends. (Chapter 2)
b) Determine the mass balance sensitivity of circum-Arctic glaciers, over space and time, to changes in temperature (by +1 to +3 °C), and to increases in precipitation (4 % $°C^{-1}$) and investigate the factors that contribute to this sensitivity (Chapter 3)

1.3. Scientific Background

1.3.1. Study of glacier mass balance

1.3.1.1. Glacier mass balance calculation

Glacier mass balance, commonly measured in kg m^{-2} yr^{-1} or annual meters water equivalent (m w.e. a^{-1}) (where 1 m w.e. a^{-1} = 1000 kg m^{-2} yr^{-1}), is the sum of accumulation to and ablation from the glacier (Cogely, 2011):

$\Delta M = B_{sfc} + B_i + B_b + A_f$ (1)

$B_{sfc} = C_{sfc} + A_{sfc}$ (2)

$B_i = C_i + A_i$ (3)

$B_b = C_b + A_b$ (4)

$$A_f = D + A_{f(air)} + A_{f(wtr)} \quad (5)$$

where ΔM is total mass balance, which is composed of surface (B_{sfc}), internal (B_i), basal (B_b) mass balance, and frontal ablation (A_f). B_{sfc} is composed of surface accumulation (C_{sfc}), driven by solid precipitation, windblown snow, and avalanching onto the glacier surface, and surface ablation (A_{sfc}), driven by melt, windblown snow, and avalanching from the glacier surface. B_i, the mass balance of ice and firn between the summer surface and glacier bed, is composed of internal accumulation (C_b), driven by refreezing of newly introduced water within the glacier that would have otherwise left the glacier as runoff (and does not include glacier meltwater from the glacier), and internal ablation (A_b), primarily driven by release of heat and potential energy from internal deformation and the downward motion of ice and meltwater. B_b is composed of basal accumulation (C_b), driven by freezing of water to the base of the glacier, and basal ablation (A_b), driven by geothermal heat flux (typically in areas with high volcanism) and by the basal ice reaching the pressure melting point. A_f at or near the glacier terminus is composed of glacier calving (D), driven by ice breakage from a glacier terminus into a lake, sea water, or (occasionally) onto land, subaerial frontal melting and sublimation ($A_{f(air)}$), driven by ice melt and sublimation from glacier terminus interaction with air, and subaqueous frontal melting ($A_{f(wtr)}$), driven by melt from glacier terminus interaction with water (Cogley, 2011).

1.3.1.2. Methods to collect observational mass balance data

A number of methods exist to collect observational mass balance data. The mass balance of select glaciers has been historically measured using a glaciological mass balance approach. Glaciological mass balance is collected through annual or semi-annual interpolation of multiple in-situ accumulation and ablation measurements from numerous stakes drilled into the centerline of the glacier surface. Interpolation of in-situ stake measurements into glaciological mass balance assumes that mass balance will vary with elevation or uses glacier-specific accumulation and ablation patterns. Glaciological mass balance will capture spatial and temporal variability well, but may accumulate error over time due to compounding of small annual biases over multiple decades (Thomson et al., 2016). In addition, the glaciological method only measures surface mass balance (equation 2) and may be unable to capture changes in superimposed ice or internal accumulation, leading to these small biases (Thomson et al., 2016). Another drawback to this method is that the mass balance of glaciological measurements may be more negative than the regional average because glaciological measurements tend to favor small, land-terminating glaciers with more negative mass balance values (Gardner et al., 2013), which may lead to further biases when using glaciological data to make regional assumptions.

More recently, mass balance has also been measured using remote sensing techniques such as altimetry measurements for geodetic mass balance calculation. Geodetic mass balance is determined by measuring changes in glacier surface elevation in the same location over time, and converting these elevation changes to volume by applying density factoring and integration over the glacier area. Geodetic mass balance measurements provide researchers with the ability to expand the number of observed glaciers and to incorporate a different type of dataset into their analyses. Changes in glacier surface elevation may be measured through a number of methods, including satellite (Ice, Cloud, and land Elevation Satellite; ICESat (eg. Brenner et al., 2007; C. Nuth & Kääb, 2011; Nuth et al., 2010; Zheng et al., 2018))or airborne (IceBridge aircrafts (Bezeau et al., 2013; Colgan et al., 2015; Huss & Hock, 2015)) laser altimetry. Unlike the glaciological method, the geodetic method is not limited to small, land terminating glaciers and may capture changes in surface, internal, and basal mass balance in addition to changes in frontal ablation from tidewater glaciers (Thomson et al., 2016). However, geodetic mass balance measurements have a coarse temporal resolution, as repeat measurements are only taken once every few years. In addition, altimetry measurement errors can arise from atmospheric interference, poor measurement density, incorrect projection, and incorrect geo-referencing, which may cause interpretation of surface elevation differences for two unrelated points (Zemp et al., 2013). In addition, converting the volume change to mass balance with the geodetic method requires an estimation of density. Density can vary substantially within and between glaciers and incorrect estimations may lead to large error in calculation of mass balance. Mass balance measurement with both glaciological and geodetic methods have improved with the creation of the Randolph Glacier Inventory (RGI), which provides information on glacier area, shape, and elevation, for each glacier in 19 glacier regions (Kargel et al., 2005). Access to these glacier shape, elevation, and volume data made estimation of regional volume loss, and modelling and spatial interpolation onto entire glacier regions possible.

A new data source for derivation and analysis of mass balance over broad spatial scales is gravimetric data from the Gravity Recovery and Climate Experiment (GRACE) satellites. The GRACE mission uses the changes in distance between its two satellites to determine changes in mass distribution. An area with a greater concentration of mass will pull the lead satellite away from the trailing satellite, which will record the magnitude of the mass anomaly. As the satellites move away from this mass anomaly, the trailing satellite will be pulled towards the leading satellite and record the size of the mass anomaly (NASA, 2012). GRACE does not suffer from the same calculation issues of ice density estimation and regional volume interpolation as geodetic and glaciological methods. This is because GRACE measures change in mass rather than change in elevation and there is no need for ice density estimation or spatial interpolation of a small number of elevation change measurements to a regional scale (Cogley, 2011; Jacob et al., 2012). However, mass balance estimates derived from gravimetric data have no vertical resolution and do not enable the distinction between redistribution of mass due to changes in glacier mass loss, water storage, atmospheric variations, or oceanic fluxes. Therefore, the details and assumptions of methods used to derive glacier mass change from the gravimetric signal are extremely important since differing methodology may create large differences in mass balance derived from the same signal (Wahr et al., 2006). In addition, GRACE suffers from coarse spatial resolution, in which 1 pixel corresponds to approximately 400 km^2 (Mémin et al., 2011). This poor spatial resolution makes measurement of regional variation and of small glacier regions subject to high error. A comparison of mass balance measurements from the GRACE satellite to other methods reveals that glacier mass balance derived from GRACE mass redistribution is approximately 30 % higher than the mass balance derived from geodetic and glaciological sources (Jacob et al. 2012).

1.3.1.3. Prior literature studying glacier mass balance

The first comprehensive study aimed at deciphering regional trends in mass balance was completed by Dowdeswell et al. (1997). This study used available glaciological mass balance data from 12 glaciers in the Arctic and found that glaciers below 70 ˚N exhibited large variability and no specific trends in glacier mass balance over time, while glaciers above 70 ˚N exhibited a consistent downward trend in mass balance.

Since this initial study, research has focused on identifying the advantages and limitations of the different methods for estimating glacier mass balance, and examining the spatiotemporal trends in mass balance and data quality issues inherent to glaciological, geodetic and gravimetric methods. More recent studies have applied combined analyses; Gardner et al. (2013) used a combination of GRACE(gravimetric), ICESat (geodetic), and glaciological data to determine mass balance trends in the circum-Arctic and beyond, and identified Alaska, Greenland, and the Canadian Arctic as the largest contributors to sea level rise in the circum-Arctic between 2003-2009. Using similar methods, Box et al. (2018), confirmed this result and highlighted the need for more data collection, given the acute problem of data-scarcity- and, in turn, mass balance uncertainty- in Arctic Canada.

A recent study completed by Zemp et al. (2019) explored regional Arctic mass balance by using the most extensive geodetic and glaciological mass balance datasets available to determine regional mass balance. Regional mass balance was calculated through a spatial interpolation scheme that considered glacier location, elevation, shape, and volume, creating the most sophisticated and extensive glacier mass balance study conducted to date. The results of Zemp et al. (2019) suggest that regional mass balance may be more negative than suggested in prior studies. These conclusions highlight the importance of conducting mass balance studies which use large, diverse mass balance datasets and that attempt to understand not only individual glaciers but also regional trends. In addition, these conclusions highlight the overwhelming need for improved data collection quality and quantity.

1.3.2. Study of glacier mass balance sensitivity

Glacier mass balance studies are important to understanding how glaciers presently contribute to sea level rise. However, to better understand how glaciers may contribute to sea level rise in the future, study of how glaciers respond to possible climate change is perhaps even more crucial. While glacier mass balance has a number of contributing components (equations 1-5), it is strongly driven by temperature and precipitation due to the sizable influence of surface mass balance and internal accumulation, both of which are strongly impacted by changes in climate. Surface and internal accumulation are grouped into climatic mass balance (B_{clim}) measure the impact of temperature and precipitation (Cogley, 2011):

$B_{clim} = B_{sfc} + B_i$ (6)

The degree to which B_{sfc} and B_i respond to changes in climate depends on a variety of glaciological and geographic factors such as surface albedo, topography, and glacier altitude. The degree to which ΔM (equation 1) responds to changes in climate, and therefore how much it contributes to sea level rise, depends on a variety of factors that may not be strongly linked to climate, such as glacier surging, thermal regime, and frontal ablation (equation 5). For example, frontal ablation, which includes iceberg calving and subaqueous melt from the terminus of ocean-terminating glaciers (equation 5), accounts for approximately 5% of total ablation in Alaska (McNabb et al., 2015), but is effectively negligible in the Canadian Arctic (Lenaerts et al., 2013). Glacier surging, which can cause sudden and extreme mass loss events if the surge transfers ice into an ablation area, is a process that facilitates ablation in approximately 21 % of glaciers in Svalbard, but only approximately 1% of glaciers globally (Sevestre et al., 2015). Glacier thermal regime governs the temperature and pressure at which the glacier ice will melt and impacts the speed at which glacier mass balance responds to temperature increases. Icelandic glaciers are predominantly temperate and warm-based (Björnsson & Pálsson, 2008) and will react quickly to temperature increase, since they are poised closer to the melting point. In contrast, glaciers in the Canadian Arctic which are largely cold-based or polythermal (Wohlleben et al., 2009) and will therefore have a slower response to similar temperature changes.

However, while climate may impact the glacier thermal regime and the way in which the glacier responds to climate change, there are a number of factors, such as glacier thickness and geothermal or volcanic activity, which may also impact the thermal regime (Cogley, 2011).

Glaciological and geographic factors suggest that glaciers in each region will respond differently to the same climatic forcing. For example, Arctic Canada North and Svalbard have experienced a mean annual increase of ~1 °C in the past two decades (Førland et al., 2011; Noël et al., 2018), but Arctic Canada North experienced a greater mass loss (-0.31 m w.e. a^{-1} or -310 kg m^{-2} yr^{-1}) than Svalbard between 2003-2009 (-0.13 m w.e. a^{-1} or -130 kg m^{-2} yr^{-1}) (Gardner et al. 2013). There are no studies that specifically explore why this may be the case, which once more highlights the need for more studies.

Glacier mass balance sensitivity studies explore how sensitive glaciers are to changes in climate. These studies have been conducted on individual (Jóhannesson et al., 2006; Steiner et al., 2008), regional (Anderson & MacKintosh, 2012) and global scales (Fujita, 2008), but few have focused specifically on the circum-Arctic in order to compare regional mass balance sensitivities.

Mass balance sensitivity studies use a number of climate parameterizations to improve understanding of how glaciers and entire glacier regions may respond to changes in climate. The first major study on glacier mass balance sensitivity was Oerlemans and Fortuin (1992), which used glaciological mass balance observations of 12 glaciers from different climatic regions around the world to test glacier sensitivity to 1 °C of warming. Oerlemans and Fortuin (1992) used an energy balance model to determine an average mass balance sensitivity of -0.4 m w.e. a^{-1} $°C^{-1}$ across all 12 glaciers. They concluded that mass balance sensitivity of glaciers in wetter climates was larger (i.e. more mass loss per unit time per 1 °C of warming) than the sensitivity of glaciers in drier climates. At the time of the study, global glacier volume was not well known, nor was glacier contribution to sea level rise. Since this early paper, a number of mass balance sensitivity studies have expanded the knowledge of how mass balance responds to changes in climate (e.g. DeWoul & Hock, 2005; Anderson et al., 2008; Koji, 2008, McGrath et al., 2017).

Glacier mass balance sensitivity can be evaluated as either a static or dynamic phenomenon. Studies of static mass balance sensitivity (e.g. Oerlemans and Fortuin 1992; Oerlemans 1992; De Woul and Hock 2005) assume that glacier size and geometry remain constant through the period of observation to simplify the calculation of mass balance (De Woul & Hock, 2005). In contrast, studies of dynamic mass balance sensitivity use ice flow or glacier evolution models to update glacier size and geometry after every water year (e.g. Anderson et al., 2008; Engelhardt et al., 2015; Johannesson, 1997).Despite these differences in methodology, static and dynamic mass balance sensitivity are not substantially different when integrating the mass balance impacts of minor climatic changes over relatively short time periods (e.g. 1 °C temperature increase over a 100-year period) (De Woul & Hock, 2005; Johannesson, 1997).

Similarly, mass balance sensitivity studies typically use one of two methods, energy balance or degree-day/temperature-index models, to quantify ablation from surface. A number of studies (e.g. Anderson et al., 2010; Andreassen & Oerlemans, 2009; Oerlemans, 1992; Oerlemans, 1997) have employed an energy balance model to determine the energy available for melt:

$$Q_M = I(1-\alpha) + L_{out} + L_{in} + Q_H + Q_E + Q_R + Q_G \quad (7)$$

where Q_M is energy available for melt, I is incoming shortwave radiation, α is glacier surface albedo, L_{out} is the outgoing longwave radiation, L_{in} is the incoming longwave radiation, Q_H is the sensible heat flux, Q_E is the latent heat flux, Q_R is the heat flux of rainfall, and Q_G is the heat flux conducted from the ice (Anderson et al., 2010). The calculated Q_M can then be used to determine ablation:

$$M = \frac{Q_M}{\rho_W L_f} \quad (8)$$

where M is melt, ρ_W is the density of water, and L_f is the latent heat of fusion (Hock, 2005). Properly estimating each component of the energy balance equation may be relatively computationally expensive and requires a significant amount of input data that are difficult to obtain. Therefore, energy balance models are typically used only for a small number of glaciers (e.g. Andreassen & Oerlemans, 2009; Braithwaite & Zhang, 1999; Oerlemans & Fortuin, 1992; Oerlemans, 1997), though there are exceptions (e.g. Koji, 2008; Anderson & Mackintosh, 2012) which use energy balance models on a regional level based on coarse-resolution climate data.

Degree-day/temperature-index models, also commonly used in mass balance sensitivity studies (e.g. Braithwaite & Zhang, 1999; De Woul & Hock, 2005; Huss & Fischer, 2016), rely on the relation between air temperature and ablation:

$$\sum_{i=1}^{n} M = DDF \sum_{i=1}^{n} T^+ \, \Delta t \quad (9)$$

where M is the amount of snow/ice melt, DDF is the degree day factor, T^+ is the sum of positive air temperatures at each time interval Δt, and n is the number of time periods. The DDF is the amount of melt that is expected to occur on a glacier during a positive degree day (Hock, 2003). Degree day models are computationally inexpensive relative to energy balance models, require less input data, and hence can more easily be extrapolated to a large number of glaciers. However, they may overestimate the magnitude of mass balance sensitivity because they rely on the correlation between solar radiation and melt, but do not take into account important mass balance components like albedo (Anderson et al., 2008).

Regardless of methodological approach, high-quality climate data are critical for accurate assessment of glacier balance sensitivity. Many studies, particulary those applied to a small number of glaciers, use meteorological data from nearby climate stations to interpolate the climate for the glacier-specific elevation (e.g. Andreassen & Oerlemans, 2009; Oerlemans, 1997; Six & Vincent, 2014), while larger or regional studies often rely on gridded climate reanalysis products such as seNorge (Engelhardt et al., 2015) or climate models (McGrath et al., 2017).

The majority of studies that test mass balance sensitivity increase temperature by 1-3 °C and precipitation by 10 % (e.g. Anderson et al., 2010; Anderson & MacKintosh, 2012; Six & Vincent, 2014). Under these conditions, the mass balance sensitivity varies by region and by study, spanning a range of -0.2 to -2 m w.e. a^{-1} $°C^{-1}$ (e.g. De Woul & Hock, 2005;Andreassen & Oerlemans, 2009; Engelhardt et al., 2015; Six & Vincent, 2014). Large variation between mass balance sensitivity in different regions, or even in glaciers within the same geographic regions, were attributed to the degree of 'continentality', whereby continental glaciers in drier regions have a smaller amplitude of seasonal temperature and precipitation changes and thereby lower mass balance sensitivity than glaciers in wetter or more maritime climates with a large amplitude of seasonal temperature and precipitation change (eg. De Woul & Hock, 2005…).

Climate model outputs or climate scenarios put forth by intergovernmental bodies are also used to force mass balance in sensitivity studies. Johannesson (1997) used an Iceland-specific scenario of 0.35 °C/decade increase in mean mid-winter temperature, 0.25 °C/decade increase in mean midsummer temperature, and a 5 % $°C^{-1}$ mean annual precipitation increase to study the mass balance sensitivity of Iceland. Oerlemans et al. (2005) used IPCC-B2, an Intergovernmental Panel on Climate Change (IPCC) scenario, that couples climate change to population, economic development, and technological change, to study mass balance sensitivity of circum-Arctic glaciers. Anderson et al. (2008) derived five climate change scenarios from global climate models (GCMs) to test mass balance sensitivity over 100 years; these scenarios included: 'no change' , 'minimum change', 'mean change', 'maximum change', and 'incremental change' scenarios, in which mean annual temperature increased by 0 °C, 0.9 °C, 1.4 °C, 2.1 °C, and 0.02 °C a^{-1}, respectively, from the 1970-1999 mean. McGrath et al. (2017) compared mass balance change between Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5, in which mean annual temperature increased by 2.1 and 4.6 °C and precipitation increased by 9 and 21 %, respectively, over 100 years.

As mass balance sensitivity studies become more sophisticated, recent efforts have sought to assess mass balance sensitivity to factors other than temperature and precipitation. For example, Koji (2008) studied the impact of precipitation seasonality on mass balance sensitivity. He discovered that 'summer-type' glaciers, with high summer accumulation have larger mass balance sensitivity amplitudes than 'winter-type' glaciers, which have low summer accumulation, but high annual accumulation. Anderson and Mackintosh (2012) found that debris cover, temperature lapse rate, and the temperature threshold of rain and snow have a large impact on mass balance sensitivity of New Zealand glaciers. These studies demonstrate that as access to mass balance and climate data improves, it is important to continue evaluating mass balance sensitivity of glaciers and entire regions to changes in climate and other forcing factors in order to better understand future implications of glacier mass loss for sea level rise.

There are two main objectives to this thesis. The first objective is to identify the most effective methodology to calculate regional mass balance trends in the circum-Arctic using spatially and temporally sparse glaciological and geodetic datasets and then use these data to determine past and present (1961-2016) mass balance trends. The second objective is to determine the spatiotemporal mass balance sensitivity of circum-Arctic glaciers to changes in temperature (by +1 to +3 °C), and to increases in precipitation (4 % $°C^{-1}$) and investigate the factors that contribute to this sensitivity.

CHAPTER 2. TRENDS IN GLACIER MASS BALANCE

2.1. Introduction

Sea level rise has become a pressing environmental and sociopolitical concern, threatening the livelihood of island nations and low-lying coastal communities around the globe (Nicholls & Cazenave, 2003). Glaciers and ice caps are the largest contributors to sea level rise; between 1990 and 2015, 70 % of sea level rise is attributable to melt from glaciers and ice caps (Slangen et al., 2017). Circum-Arctic glaciers and ice caps outside of Greenland are the largest contributors to glacier melt globally, accounting for 62 % of global glacier melt between 1961 and 2016 (Zemp et al., 2019). Therefore, in order to understand and mitigate the consequences of future sea level rise, an understanding of the trends in circum-Arctic glacier mass loss is crucial.

Glacier mass balance studies typically rely on observational mass balance data, which observe changes in mass and volume of select glaciers through a variety of techniques. With the exception of gravimetric methods (the shortcomings of which are discussed in section 1.3.1), no method can capture the change in mass balance of all glaciers in a region of interest; at present, regional glacier area covered by observational mass balance data ranges from approximately 0.5-60 %, depending on glacier region (Zemp et al., 2019). Therefore, the majority of studies that use observational mass balance data (area weighted, specific mass balance) to determine glacier mass balance use available records as representations of the entire region (e.g. Box et al., 2018; A. S. Gardner et al., 2013; Moholdt et al., 2010; Zheng et al., 2018).

In an attempt to reduce uncertainty in calculating regional mass balance, Zemp et al. (2019) used newly available, spatially dense geodetic mass balance data (Robert McNabb, pers.

commun. 2018) in combination with available glaciological data to determine 1961-2016 mass balance trends. Zemp et al., (2019) used spatial interpolation techniques that considered glacier hypsometry and location to derive regional mass balance values. In addition, Zemp et al., (2019) used interannual variability recorded by the temporally dense glaciological data to assign interannual variability in the regional mass balance. These spatial interpolation techniques are substantially more sophisticated than those of the majority prior studies that do not use a glacier melt model to supplement data (e.g. Box et al., 2018; A. S. Gardner et al., 2013; Moholdt et al., 2010; Zheng et al., 2018). Therefore, this study considers the spatial interpolation of Zemp et al. (2019) as the most accurate representation of regional mass balance presently available.

Whether the spatial interpolation conducted by Zemp et al. (2019) significantly changes regional mass balance, or whether this interpolation changes the magnitude of mass loss and interannual variability, has not been explored. It is important to understand whether this complex spatial interpolation is useful to studies that attempt to determine magnitude of mass loss and interannual variability. In addition, the new geodetic mass balance data from Robert McNabb (pers. comm., 2018), presents an opportunity to re-evaluate not only regional glacier mass balance, as done by Zemp et al. (2019), but also the trends in glacier mass balance over time. Such a study may provide insight into how trends in mass balance are changing over time, and potentially, what can be expected for the future.

Therefore, the objective of this study is to: identify whether the spatial interpolation of Zemp et al. (2019) significantly changes regional mass balance calculated using available geodetic and glaciological observational mass balance data, and investigate past and present glacier mass balance trends between 1961 and 2016 for seven regions of the circum-Arctic using these data.

2.2. Methodology

2.2.1. Study Area

The study area for this project encompasses Arctic (defined as >55 °N latitude) glaciers and ice caps outside of Greenland. These glaciers are separated into regions defined by the RGI and include: Alaska, Arctic Canada North, Arctic Canada South, Iceland, Svalbard, Scandinavia, and the Russian Arctic, as outlined in Figure 2.1. The island of Jan Mayen, located midway between Svalbard and Iceland, is excluded from the analysis of Svalbard due to lack of mass balance data from the WGMS and its distance from mainland Svalbard.

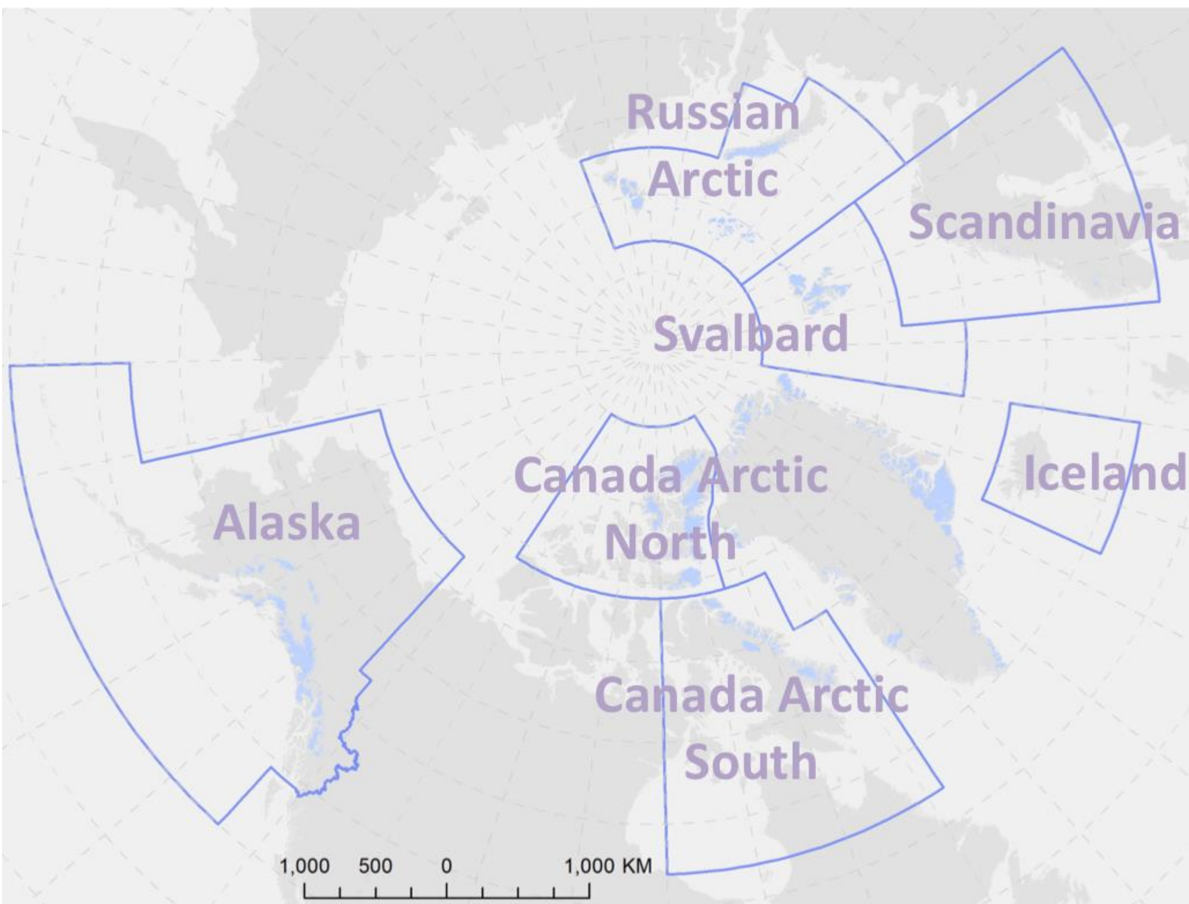


Figure 2.1. The seven glacier regions covered in this study, as defined in the RGI.

2.2.2. Dataset overview

This study uses glaciological and geodetic mass balance data from three different sources and glacier location and shape data from the RGI. Glaciological mass balance data, collected by the WGMS, includes long continuous mass balance records for 83 glaciers in Alaska, Arctic Canada North, Svalbard, and Scandinavia that start between 1950 and 1960 (covering approximately 0.6 %, 0.8 %, 0.5 %, and 7 % of total glacier area, respectively, over the period of observation (Figure S.6.1)) and shorter continuous mass balance records for 16 glaciers in Iceland that start around 1990 (covering approximately 30 % of total glacier area) (Figure 2.2, Figure S.6.1) (WGMS, 2018). For Arctic Canada South and the Russian Arctic, there are few glaciological mass balance data from the WGMS.

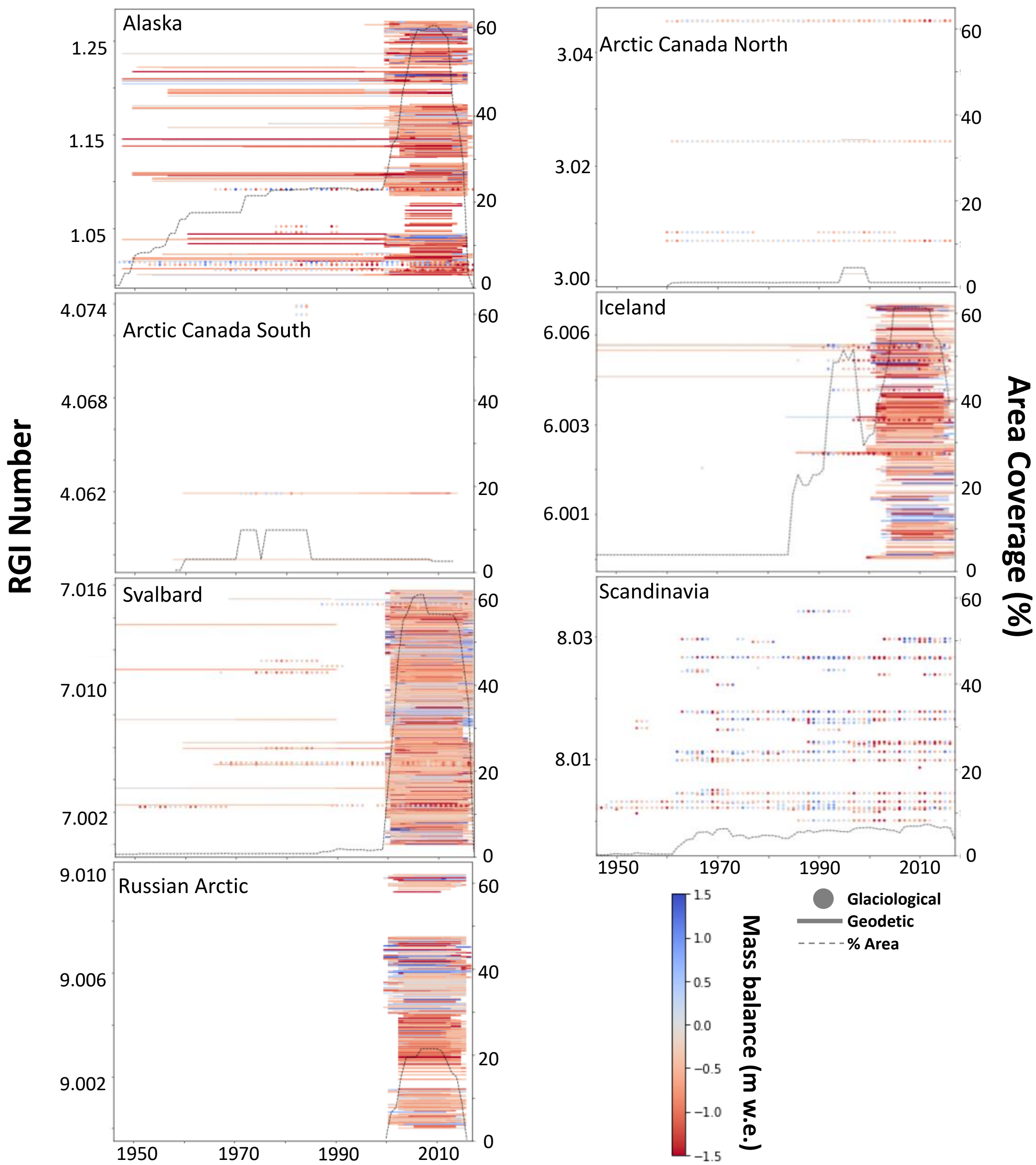


Figure 2.2. Available observational glacier mass balance data, organized by region and RGI number. The percentage of the regional glacier area covered by available data is also included. Geodetic data is indicated by lines while glaciological data is formatted by dots. Glacier numbers are formatted consistent to the RGI. Annual mass balance is indicated through the color scheme. Alaska, Iceland, Svalbard, and the Russian Arctic have a large number of records between 2000 and 2016. All other regions except Arctic Canada South have a number of long, continuous mass balance records.

The geodetic mass balance data used in this study were compiled from Cogley (2009) and provided directly by Robert McNabb (pers.commun, 2018). The Cogley (2009) dataset contains sparse, discontinuous mass balance data between 1946 and 2013 in Alaska, Arctic Canada North, Arctic Canada South, Iceland, and Svalbard, with records for only 182 glaciers across all five regions. Geodetic mass balance data from Robert McNabb are available for Alaska, Iceland, Svalbard, and the Russian Arctic for 2000-2016 and are extremely dense, covering up to approximately 60 % of regional glacier area (Figure 2.2, Table S.6.1).

2.2.3. Methods

This study compares two different techniques of regional mass balance calculation to determine the degree to which spatial interpolation techniques of Zemp et al. (2019) impact calculation of regional mass balance using presently available data. The first method, termed B_{spec}, calculates the annual regional, area-weighted (specific) mass balance of glaciers with available observational data. The second method, termed B_{int}, uses a complex spatial interpolation of a dataset similar to the one used to determine B_{spec}. The results of this methodology are presented by Zemp et al. (2019). The two methods are compared over two time intervals: 1961-2016, which encompasses the full range of available data; and 2000-2016, which includes substantial geodetic mass balance data for Alaska, Iceland, Svalbard, and the Russian Arctic (Robert McNabb, pers. comm. 2018) (Figure 2.2).

A Wilcoxon Rank-Sum test was used to test the null hypothesis between mean B_{spec} and B_{int} over 1961-2016 and 2000-2016. The Wilcoxon Rank-Sum test is used to test statistical similarity between nonparametric datasets by comparing data distribution of each dataset. All the data from both datasets are ranked based on their magnitude (i.e. the smallest data point will have a rank of one, the second smallest data point will have a rank of two). These ranks are then once more separated by dataset and then summed. In order for the null hypothesis to be rejected (in which the p-value is <=0.05), the difference between the summed ranks of each dataset must be below a certain threshold, decided by the number of points in each dataset (Nahm, 2016).

Difference in mass balance between the 1961-2016 mean B_{spec} and the 2000-2016 B_{spec} is compared to determine whether mass balance has increased or decreased over time. A Wilcoxon Rank-Sum test is used to test the null hypothesis between the mean magnitude of mass loss between 1961-2016 and 2000-2016 $B_{spec.}$

2.3. Results

The difference between mean B_{spec} and B_{int} (specifically, B_{int} subtracted from B_{spec}) between 1961 and 2016 was 0.24, 0.24, 0.17, 0.06, 0.03 and 0.02 m w.e. a^{-1} in Iceland, Arctic Canada South, Scandinavia, Alaska, Svalbard, and Arctic Canada North, respectively (Table 2.1, Figure 2.3). The null hypothesis can be rejected for the 1961-2016 mean B_{spec} and B_{int} in Arctic Canada South and Iceland at the >95 % confidence interval but cannot be rejected in any other region. The difference between mean B_{spec} and B_{int} between 2000 and 2016 was 0.44, 0.19, 0.09, 0.05, 0.04, 0.02, and 0 m w.e. a^{-1} in Arctic Canada South, Scandinavia, The Russian Arctic, Arctic Canada North, Alaska, and Iceland, respectively (Table 2.1). The null hypothesis can be rejected in the 2000-2016 mean B_{spec} and B_{int} in Arctic Canada South at the >95 % confidence interval but cannot be rejected in any other region (Table 2.1). The interannual variability in B_{spec} and B_{int} are qualitatively similar in Arctic Canada North and Scandinavia (Figure 2.3) since the observational mass balance data in these two regions are primarily composed of glaciological data (Figure 2.1).

However, the interannual variability in the B_{spec} and B_{int} datasets from glaciological data alone are qualitatively similar in Alaska, Arctic Canada North, Iceland, Svalbard, and Scandinavia, which all have long, continuous glaciological mass balance records (Figure 2.1, Figure 2.3). The threshold at which the ratio of glaciological to geodetic mass balance data required for B_{spec} to be qualitatively similar to B_{int} is beyond the scope of this study.

Table 2.1. Comparison of mean annual B_{spec} and B_{int} for 1961-2016 and 2000-2016. Additionally, the absolute difference between mean B_{spec} and B_{int} ($B_{int\text{-}spec}$) is included. P-values were calculated using the Wilcoxon Rank-Sum test. Uncertainties for specific mass balance were calculated using uncertainty recorded in the original geodetic data.

	Historical Average Mass Balance (1961-2016)				**Recent Mass Balance (2000-2016)**			
Study Region	B_{spec} (m w.e. a^{-1})	B_{int} (m w.e. a^{-1})	$B_{int\text{-}spec}$ (m w.e. a^{-1})	**P-Val**	B_{spec} (m w.e. a^{-1})	B_{int} (m w.e. a^{-1})	$B_{int\text{-}spec}$ (m w.e. a^{-1})	**P-Val**
Alaska	-0.65 ± 0.82	-0.59 ± 0.48	0.06	0.14	-0.79 ± 0.99	−0.83 ± 0.45	0.04	6.2E-2
Canada North	-0.16 ± 0.62	-0.18 ± 0.87	0.02	0.68	-0.36	−0.41 ± 0.87	0.05	0.72
Canada South	-0.42 ± 0.59	-0.18 ± 0.77	0.24	8.8E-5	-0.85 ± 0.78	−0.41 ± 0.78	0.44	3.1E-2
Iceland	-0.47 ± 0.57	-0.23 ± 0.93	0.24	1.9E-3	-0.64 ± 0.41	−0.64 ± 0.79	0	0.48
Svalbard	-0.34 ± 0.59	-0.37 ± 0.37	0.03	0.95	-0.46 ± 0.75	−0.48 ± 0.34	0.02	0.90
Scandinavia	-0.072	-0.24 ± 0.48	0.17	0.26	-0.47	−0.66 ± 0.45	0.19	0.34
Russia	-	-0.37 ± 0.48		-	-0.39 ± 0.89	−0.48 ± 0.45	0.09	0.48

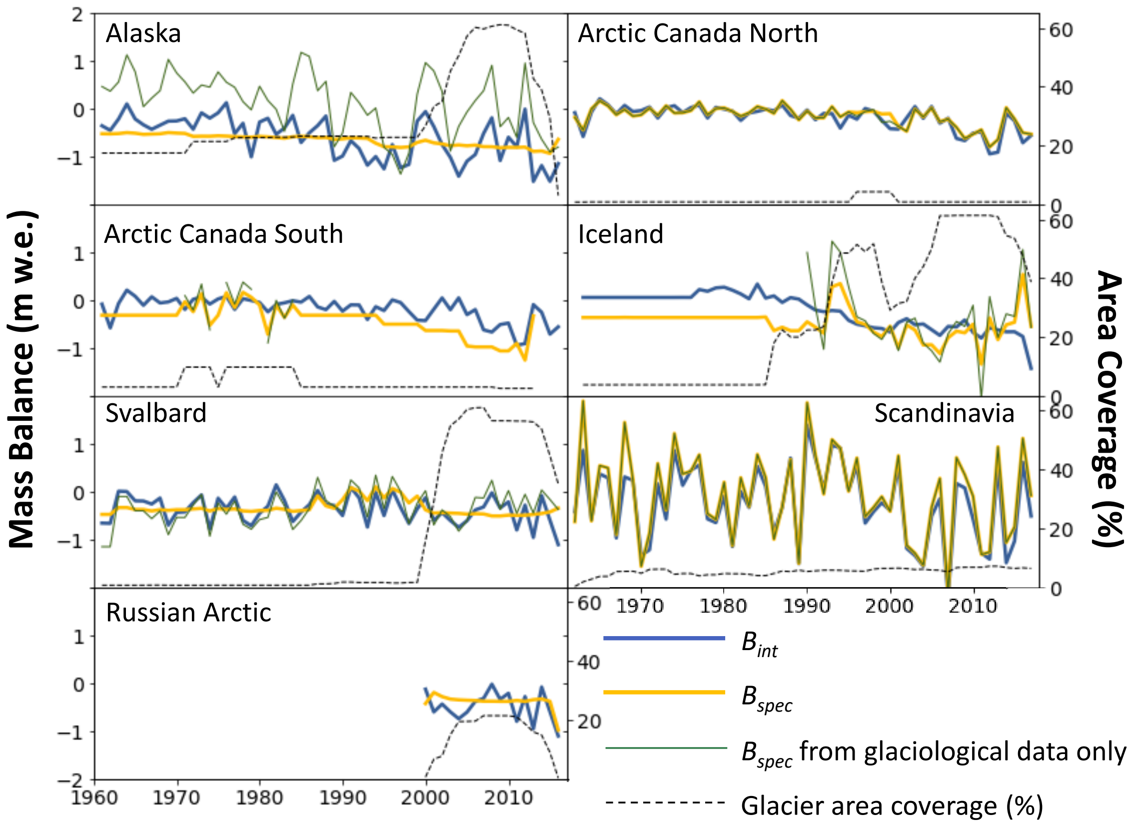
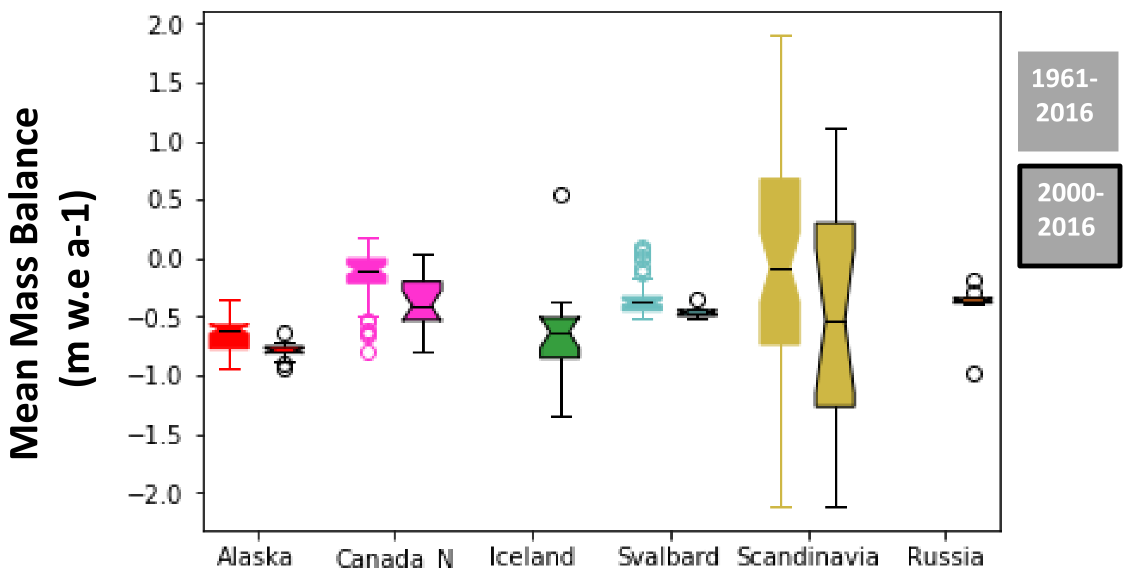


Figure 2.3. Comparison of mean B_{spec}, B_{int}, and mean annual specific mass balance from glaciological data only. The total glacier area covered (in percent) by observational mass balance data in each region is also included. Glaciological mass balance data provided the interannual variability for B_{int}

The B_{spec} of Iceland was only analyzed between 2000 and 2016, due to lack of data before the 1990's, while Arctic Canada South was removed from analysis entirely due to lack of data. The mean B_{spec} for Scandinavia, Arctic Canada North, Alaska, and Svalbard was -0.16, -0.42, -0.34, and -0.072 m w.e. a^{-1}, respectively, between 1961 and 2016 and -0.36, -0.85, -0.46 and -0.47 m w.e. a^{-1}, respectively, between 2000 and 2016. The mean B_{spec} between 2000 and 2016 in Iceland and the Russian Arctic was -0.64 and -0.39 m w.e. a^{-1}, respectively (Figure 2.4). The difference between 1961-2016 and 2000-2016 B_{spec} was -0.40, -0.20, -0.14, and -0.12 m w.e. a^{-1} for Scandinavia, Arctic Canada North, Alaska, and Svalbard, respectively. The null hypothesis for the mean annual mass balance between 1961-2016 and 2000-2016 B_{spec} can be rejected at a >95 % confidence in Arctic Canada North, Alaska, and Svalbard, and cannot be rejected in Scandinavia (Figure 2.4). The standard deviation for the 1961-2016 and 2000-2016 mean specific mass balance was <0.4 m w.e. a^{-1} in Arctic Canada North, Alaska, Svalbard, and >0.9 m w.e. a^{-1} in Scandinavia (Figure 2.4).



	Alaska	Canada_N	Iceland	Svalbard	Scandinavia	Russia
Difference in mean (m w.e. a-1)	-0.14	-0.20	-	-0.12	-0.40	-
1961-2016 STDev	0.07	0.23	-	0.05	0.97	-
2000-2016 STDev	0.12	0.21	0.30	0.16	0.90	0.16
P-Value	1.3E-4	6.5E-3	-	1.5E-4	0.17	-

Figure 2.4. Change in mass balance trends between 1961-2016 and 2000-2016; Distribution of mean specific mass balance for 1961-2016 and 2000-2016, with a summary of the difference in means, the standard deviation and the p-value from the Wilcoxon Rank-Sum test for each region.

2.4. Discussion

2.4.1. Comparison between B_{spec} and B_{int}

In regions with predominantly geodetic mass balance data (Alaska and Svalbard for 1961-2016 and 2000-2016 and the Russian Arctic between 2000 and 2016), the null hypothesis cannot be rejected, which suggests statistical similarity between B_{spec} and B_{int}. However, calculation of B_{int} would be beneficial for study of interannual variability. In regions with predominantly glaciological mass balance data (Arctic Canada North and Scandinavia across all time periods), the null hypothesis cannot be rejected for B_{spec} and B_{int}, which suggests statistical similarity. However, calculation of B_{int} may be beneficial for study of magnitude of mass balance in regions where the amplitude of interannual variability is high. Regions in which glaciological and geodetic mass balance data have relatively equal percent glacier area coverage (Iceland between 2000 and 2016), the null hypothesis is likely to be rejected for B_{spec} and B_{int} and are therefore likely to be statistically similar. However, calculation of B_{int} would be beneficial for study of interannual variability. The null hypothesis can be rejected for B_{spec} and B_{int} in data-scarce regions (Arctic Canada South between 1961-2016 and between 2000-2016 and Iceland between 1961 and 2016), suggesting statistical dissimilarity. Therefore, B_{int} calculation may be valuable in such regions.

Spatial interpolation of B_{int} does not significantly change regional glacier mass balance in comparison to B_{spec} in regions where the mass balance observational data are predominantly or entirely geodetic, such as Svalbard and Alaska and the Russian Arctic. However, for studies that attempt to understand interannual variability in regional mass balance may benefit from B_{int} calculation. The null hypothesis cannot be rejected for B_{spec} and B_{int} in Alaska and Svalbard between 1961-2016 and 2000-2016 and the Russian Arctic for 2000-2016. Alaska and Svalbard have a number of long, continuous glaciological mass balance records between 1961 and 2016 and a large number of geodetic mass balance measurements between 2000 and 2016, while the Russian Arctic has a large number of geodetic mass balance data between 2000 and 2016 (Figure 2.2). The glaciological mass balance data accounts for <1% of total glacier area coverage in Alaska and Svalbard (Figure S.6.1), and the geodetic mass balance data covers up to approximately 60% of total glacier area in all three regions (Figure 2.3). However, the ratio of geodetic to glaciological data which qualifies as 'predominantly geodetic' is beyond the scope of this study. Although such data yield statistically similar results between B_{spec} and B_{int}, there are still dissimilarities which must be addressed. While the magnitude of mass loss in Alaska is qualitatively similar between B_{spec} and B_{int} over both 1961-2016 and 2000-2016 (Figure 2.3), and technically, the null hypothesis cannot be rejected, the degree of statistical dissimilarity between these datasets is relatively high (with a p-value of 0.93 for 2000-2016) (Table 2.1). This result is likely due to difference in interannual variability in the B_{spec} and B_{int} datasets; interannual variability is recorded through annual glaciological mass balance measurements and may be masked in the calculation of B_{spec} in regions with large, geodetic datasets (with course temporal resolution), such as Alaska. In contrast, B_{int} disproportionally weighs the relative interannual variability (decoupled from the magnitude of mass balance) of the glaciological data to create interannual variability within the time series (Zemp et al., 2019) (Figure 2.3). The magnitude of mass loss in Svalbard and the Russian Arctic is qualitatively similar for B_{spec} and B_{int} for 1961-2016 and 2000-2016, and 2000-2016, respectively (Table 2.1), and interannual variability of the glaciological mass balance records in these regions are missing from B_{spec} due to the overwhelming influence of geodetic mass balance records (Figure 2.2, Figure 2.3). Therefore, calculation of B_{spec} would be sufficient (in which the null hypothesis cannot be proven in comparison of B_{spec} and B_{int}) for studies interested in determining magnitude of mass loss in regions with a similar number and ratio of geodetic to glaciological data. However, studies interested in interannual variability of mass balance would benefit from the spatial interpolation of B_{int}.

Spatial interpolation of B_{int} does not significantly change regional glacier mass balance in comparison to B_{spec} in regions with only long, continuous glaciological mass balance records, such as Arctic Canada North and Scandinavia. However, for studies that attempt to calculate the regional magnitude of mass loss B_{int} may be useful in regions with large amplitude of interannual variability. The null hypothesis cannot be rejected for B_{spec} and B_{int} in regions only with long, continuous glaciological mass balance records. Arctic Canada North and Scandinavia have a number of long, continuous glaciological mass balance records between 1961 and 2016, covering approximately 0.8 % and 7 % of glacier area, respectively (Figure 2.2, Figure S.6.1). The magnitude of mass loss and the interannual variability of B_{spec} and B_{int} are qualitatively similar in Arctic Canada North over these time periods (Table 2.1) because the majority of available data are glaciological (Figure 2.3) and thereby retain the interannual variability recorded from annual field measurements. Although the null hypothesis cannot be rejected for B_{spec} and B_{int} in Scandinavia and the interannual variability between these datasets is qualitatively similar, the magnitude of mass loss differs by approximately 0.20 m w.e. a^{-1} for both 1961-2016 and 2000-2016 between B_{spec} and B_{int} (Table 2.1). These differences in the magnitude of mass loss may be due to the large amplitude of interannual variability in Scandinavia (Figure 2.3), as a relatively small change in the amplitude may create a large difference in the magnitude of mass loss in comparison to other Arctic regions. In addition, the magnitude of mass loss from B_{int} is consistently lower than from B_{spec} (Figure 2.3), suggesting that Zemp et al. (2019) may have had access to different data or that the B_{int} methodology intentionally lowered the magnitude of mean mass balance. These results suggest that in regions with predominantly glaciological data, like Arctic Canada North and Scandinavia, B_{spec} and B_{int} are not statistically different and have qualitatively similar interannual variability and would therefore not benefit from calculation of B_{int}. However, caution must be used in the study of magnitude of mass loss, as differences in data availability and methodology may create qualitatively different results between B_{spec} and B_{int} in regions with high amplitude of interannual variability.

Spatial interpolation of B_{int} does not significantly change regional glacier mass balance in comparison to B_{spec} in regions with similar glacier area coverage between glaciological and geodetic data, such as Iceland. However, studies of interannual glacier mass balance variability may benefit from the calculation of B_{int}. The null hypothesis cannot be rejected for B_{spec} and B_{int} for regions in which geodetic and glaciological mass balance have relatively equal area coverage over the period of observation. Iceland has spatially dense geodetic mass balance data and a number of glaciological records that each cover over 30% of total glacier area between 2000 and 2016, which provides statistically similar mean B_{spec} and B_{int} for this time period (Figure 2.2, Table 2.1, Figure S.6.1). The magnitude of mass loss for B_{spec} and B_{int} is qualitatively similar in Iceland (Table 2.1, Figure 2.3). However, variability in B_{spec} and B_{int} for Iceland is qualitatively dissimilar, likely due to differing methodology. In Iceland, B_{spec} has larger amplitude of interannual variability than B_{int} (Figure 2.3) due to the large influence of glaciological mass balance data on B_{spec}. Therefore, regions in which glaciological and geodetic mass balance observations cover a relatively similar amount of glacier area, calculation of B_{spec} would be sufficient (in which the null hypothesis cannot be proven in comparison of B_{spec} and B_{int}) for studies interested in determining magnitude of mass loss. However, differing methodologies may create qualitative differences in interannual variability between B_{spec} and B_{int}. Therefore, studies that attempt to understand interannual variability may benefit from calculation of B_{int}.

Spatial interpolation of B_{int} significantly changes the regional mass balance in comparison to B_{spec} in regions with few observational data, such as Iceland for 1961-2016 and Arctic Canada South for 1961-2016 and 2000-2016. The null hypothesis can be rejected for B_{spec} and B_{int} for regions with few observational data. Iceland and Arctic Canada South have very few mass balance data between 1961-1990 and 1961-2016, respectively (Figure 2.2, Figure 2.3). The lack of data in these regions is reflected in the rejection of the null hypothesis and the qualitatively different magnitude of mass loss and interannual variability of B_{spec} and B_{int} between 1961 and 2016 in these regions (Table 2.1). These results suggest that regions with little mass balance data may benefit from the spatial interpolation of B_{int} determining the magnitude of mass loss and interannual variability. Spatial interpolation that incorporates relatively consistent variables such as glacier shape and location may improve the ability to interpret mass loss and interannual variability in such regions.

2.4.2. Glacier mass balance trends

The difference in mean B_{spec} between 1961-2016 and 2000-2016 was highest in Arctic Canada North followed by Alaska, and Svalbard (Figure 2.4). There was no statistical dissimilarity in B_{spec} between 1961-2016 and 2000-2016 for Scandinavia.

The difference between 1961-2016 and 2000-2016 B_{spec} is highest in Arctic Canada North (Figure 2.4), suggesting that this region has the highest rate of change in mass balance of all three studied regions. Alaska has the second largest difference in B_{spec} and Svalbard has the smallest difference out of the three regions studied (Figure 2.4). However, while mass balance is decreasing most rapidly in Arctic Canada North, the regional magnitude of mass loss between 1961 and 2016 is largest in Alaska (-0.65 m w.e. a^{-1}, in comparison to -0.34 m w.e. a^{-1} and 0.16 m w.e. a^{-1} in Svalbard and Arctic Canada North, respectively) (Table 2.1). These results suggest that Alaska has and will continue to be the largest contributor to sea level rise in m w.e. of all three regions. If the rate of mass balance decrease in Arctic Canada North continues to be higher than the rate of mass balance decrease in Alaska, Arctic Canada North may eventually surpass Alaska as the largest contributor to sea level rise in m w.e. of the three regions. In contrast, mass balance in Svalbard is decreasing least rapidly of the three studied regions and the magnitude of mass loss between 1961 and 2016 is second smallest (Table 2.1), suggesting Svalbard will continue to have similar contributions to sea level rise.

The difference between 1961-2016 and 2000-2016 mean B_{spec} in Scandinavia is not statistically significant (Figure 2.4), suggesting that there has been little change in the rate of change in glacier mass loss. The relatively large amplitude of interannual variability (Figure 2.3) and high standard deviation of B_{spec} (Figure 2.4) makes determination of regional trends in glacier mass balance difficult.

2.5. Conclusions

This study examined whether the spatial interpolation of Zemp et al. (2019) significantly changed circum-Arctic mass balance calculated from available observational data. This study also analyzed the mass balance trends between 1961 and 2016 found in the observational data. There are specific scenarios in which the spatial interpolation of B_{int} would be valuable, where the mass balance is significantly different (to a 95 % confidence interval) or the magnitude of mass loss and/or the interannual variability is qualitatively different. Regions with little to no observational data (Arctic Canada South between 1961 and 2016 and Iceland between 1961 and 1990) would benefit from the spatial interpolation of B_{int} as such an interpolation would at least incorporate glacier location and hypsometry in its calculation. Regions in which approximately 50 % or more of the observational mass balance data are geodetic (Alaska and Svalbard between 1961 and 2016 and Iceland and the Russian Arctic between 2000 and 2016) would benefit from the spatial interpolation of B_{int} in the studies of interannual variability. Regions with predominantly glaciological mass balance in which the amplitude of interannual variability is high (Scandinavia between 1961-2016) would benefit from the spatial interpolation of B_{int} in the studies that look at the magnitude of mass loss. Outside of these specific scenarios, the simple area-weighted calculation of B_{spec} would be sufficient for analysis. An understanding of the situations in which a spatial interpolation (such as B_{int}) would make a statistically significant or qualitative difference to mass balance results may improve understanding of the most appropriate methodology for different research questions.

This study determined that Arctic Canada North is experiencing the largest changes in glacier mass balance, followed by Alaska and Svalbard. These results suggest that Arctic Canada North should be a priority in future mass balance studies, as the magnitude of mass loss is changing more quickly in this region when compared to the rest of the circum-Arctic. In contrast, the magnitude of mass balance may remain relatively similar for a long time in Svalbard. Assessing the rate of change in the magnitude of mass balance can provide insight into which regions should receive priority for future mass balance studies

Future studies would benefit from larger observational mass balance datasets to reduce uncertainty and improve understanding. While spatial interpolation may help incorporate geographical data into regional mass balance calculations, it is unlikely to improve measurement accuracy without more observational data. More observational data would improve understanding of glacier mass balance trends and therefore assist in creating better tools to combat sea level rise.

CHAPTER 3. GLACIER MASS BALANCE SENSITIVITY

3.1. Introduction

The rate of global sea level rise has increased from 1.1 +-0.3 mm yr^{-1} between 1901-1990 to 3.1 +- 1.4 mm yr^{-1} between 1993-2012 (Horton et al., 2018). Mass loss from glaciers and ice caps accounted for 70 % of sea level rise between 1990 and 2015 (Slangen et al., 2017) and 62 % of this global glacier mass loss came from Arctic glaciers outside of Greenland between 1961 and 2016 (Zemp et al. 2019). The contribution of Arctic glaciers to global mass loss is predicted to increase as the region is expected to experience temperature increase at 2.4 times the global average (Collins et al., 2013).

Glacier mass balance is driven by climatic inputs such as temperature and precipitation. The degree to which these climatic inputs impact mass balance is driven by a number of local glaciological and geographic factors. Glaciological factors may include frontal ablation, surging, and thermal regime, while geographic factors may include surface albedo, topography, annual glacier temperature, and glacier altitude (Cogley, 2011).

Glacier mass balance sensitivity studies are conducted to better understand how glaciological and geographic factors may impact regional mass balance. These studies are most effective when using modelling techniques that are able to control and vary climatic inputs (e.g. Anderson et al., 2008; De Woul & Hock, 2005; Huss & Fischer, 2016; Oerlemans, 1997). Glacier mass balance sensitivity studies have been conducted on individual (Jóhannesson et al., 2006; Steiner et al., 2008), regional (Anderson & MacKintosh, 2012) and global scales (Fujita, 2008), but few have focused specifically on the circum-Arctic in order to compare regional mass balance sensitivities, particularly to a coupled temperature and precipitation effect. Such studies are important to improve understanding of how the circum-Arctic, as one of the largest contributors to sea level rise, may respond to changes in climate, and therefore how sea level will change in the future.

This study aims to determine the mass balance sensitivity of circum-Arctic glaciers, over space and time, to changes in temperature (by +1 to +3 °C), and to increases in precipitation (4 % $°C^{-1}$) and investigate the drivers of this sensitivity

3.2. Methodology

3.2.1. Model selection

The majority of mass balance sensitivity studies alter temperature and precipitation to determine how mass balance would change on glaciers or in regions of interest (e.g. Anderson et al., 2008; De Woul & Hock, 2005; Huss & Fischer, 2016; Oerlemans, 1997) through the melt and accumulation-related inputs in energy balance (e.g. Anderson et al., 2010; Andreassen & Oerlemans, 2009; Oerlemans, 1992; Oerlemans, 1997) or degree day models (e.g. Braithwaite & Zhang, 1999; De Woul & Hock, 2005; Huss & Fischer, 2016). The use of a model that streamlines the input of climate, glacier shape, and glacier location information is the most efficient option for regional sensitivity studies in which the mass balance sensitivity of thousands of glaciers needs to be calculated. Modelling techniques that consider glaciers with no observational measurements and factors like refreeze and frontal ablation are optimal in regional mass balance sensitivity studies, as these studies attempt to capture glaciological and geographic factors that may impact the entire region.

The Python Glacier Evolution Model (PyGEM) is the most sophisticated glacier evolution model currently available for use. PyGEM is a process-based degree day model that calculates the climatic mass balance in 10m elevation bins for every glacier on a monthly timescale using thickness, area, surface elevation, and climate data (Rounce et al., 2019). PyGEM is one of the two global scale models that incorporates a dynamic meltwater refreeze and a frontal ablation component into the mass balance model (Huss & Hock, 2015). The glacier thickness, surface elevation, and extent are updated at the end of every mass balance year.

3.2.1.1. Model inputs

PyGEM requires a variety of inputs to model glacier evolution and mass balance over time. Glacier identification data, latitude and longitude data, slope, elevation-band area, ice thickness, and width are required to provide parameters under which glacier mass balance is computed. Monthly gridded climate data, including 2 m air temperature, precipitation, and temperature lapse rates, from a climate reanalysis product are required to calculate the ablation, accumulation, refreeze, and frontal ablation components of the model. Mass balance data for each modelled glacier are required for calibration (Rounce, 2019).

3.2.1.2. Model physics

PyGEM calculates monthly specific climatic mass balance at each 10 m elevation bin using the following equation:

$$b_{clim} = a + c + R + F \quad (10)$$

in which *a* represents ablation, *c* represents accumulation, *R* represents refreezing and *F* represents frontal ablation in m w.e. (Cogley, 2011).

A degree-day model is used to calculate ablation (*a*), as follows:

$$a = f_{snow,ice,firn} \cdot (T_m^+ \cdot f_{temp}) \cdot n \text{ (11)}$$

in which $f_{snow,ice,firn}$ is the degree day factor of snow, ice, or firn on the glacier surface in m w.e. d^{-1} $°C^{-1}$, T_m^+ is the mean monthly temperature that is positive in °C, f_{temp} is the temperature bias used for calibration, and *n* is the number of days in the month with positive temperature, at which melt can occur (Cogley, 2011).

Accumulation (c) at each elevation bin is calculated with the following equation:

$$c = \delta_m \cdot P_m \cdot f_{prec} \text{ (12)}$$

in which δ_m is the fraction of solid precipitation in the month, P_m is the total monthly precipitation (Huss and Hock, 2015), and f_{prec} is the precipitation factor used for calibration. Temperature and precipitation on which the degree day model relies to compute accumulation ablation uses the nearest neighbor from the gridded elevation-dependent temperature (corrected for bias) and lapse rate calculated from the ERA-Interim climate reanalysis pressure-level temperature.

Refreezing (*R*) is calculated using the following equation:

$$R = -0.0069 \cdot T_a + 0.000096 \text{ (13)}$$

in which T_a is the weighted mean annual air temperature, which accounts for the number of days in each month (Woodward et al., 1997). Frontal ablation (*F*) is calculated using the model created by Oerlemans and Nick (2005).

Once initial mass balance is calculated with default model parameters, the model is calibrated using observational data, these parameters are updated, and the calibrated model can be used for prediction and analysis. Parameter adjustment is made to the degree-day factor of snow, temperature bias (equation 11), and the precipitation factor (equation 12). These parameters account for physical processes, such as debris cover, that are not accounted for in a degree-day model, or bias in the input temperature and precipitation data. The parameters are adjusted until the modelled mass balance matches the observational mass balance for the each glacier. Each glacier is calibrated individually such that:

$\Delta M_g = \Delta M_{obs}$ (14)

$\Delta M_{reg} = \sum_{i=1}^{n} \Delta M_g$ (15)

in which ΔM_g is the modeled specific mass balance for a glacier, ΔM_{obs} is observational mass balance for the glacier, and ΔM_{reg} is observed regional mass balance. The observed regional mass balance (taken from prior literature) should be equal to the sum of the observed mass balance of all (n) individual glaciers in the region.

3.2.2. Area of study

This study examines mass balance sensitivity across the circum-Arctic, including Alaska, Arctic Canada North, Arctic Canada South, Iceland, Scandinavia, Svalbard, and The Russian Arctic, as defined by the RGI. The island of Jan Meyen is excluded from the region of Svalbard due to its distance from the Svalbard mainland. Before mass balance sensitivity analysis, these regions are subject to model validation to ensure proper parameterization.

3.2.3. Dataset overview

Glacier location, and number were obtained from the RGI, and 10 m elevation band glacier thickness, width, and area were obtained from Huss and Farinotti (2012) for each glacier. 2 m air temperature, precipitation, and temperature lapse rates at a resolution of 0.7° were obtained using the ERA-Interim climate reanalysis product. Model calibration was conducted with glaciological mass balance data from the WGMS, geodetic mass balance data from Cogley (2009) and Robert McNabb (pers. commun., 2018), and regional mass balance data (used to assign mass balance measurements to glaciers without observational data and provide ΔM_{reg} for calibration purposes), which were obtained from prior literature (Table 3.1). Model validation was conducted using Zemp et al. (2019) data.

Table 3.1. Data overview; inventory, climate, and mass balance datasets used for glacier mass balance sensitivity study.

Type	Regions	Spatial Coverage	Temporal Coverage	Source
		Inventory Data for Model Input		
Glacier area, RGI Number, Individual	All	All glaciers	2017	Global Land Ice Measurements from Space
Glacier thickness, width, area, individual, 10m bands	All	All glaciers	2000	Huss and Farinotti (2012)
		Climate Data for Model Input		
2m temperature, precipitation, air pressure temperature	All	0.7 degrees	1980-2017	European Centre for Medium-Range Weather Forecasts
		Glacier Mass Balance Data for Model Calibration/Validation		
Glaciological, Individual	Alaska, Canada North, Canada South, Iceland, Svalbard, Scandinavia	52	1946-2017	World Glacier Monitoring Service
Geodetic, Individual	Alaska, Iceland, Svalbard, Russian	7432	2000-2016	Obtained directly from Robert McNabb

	Arctic			
Geodetic, Individual	Alaska, Canada North, Canada South, Iceland, Svalbard	100	1946-2013	Cogley (2009)
Regional	Alaska, Scandinavia	All	2003-2009	Gardner et al. (2013)
Regional	Canada North, Canada South	All	2003-2009	Gardner et al. (2011)
Regional	Iceland	All	1995-2010	Bjornsson et al. (2013)
Regional	Svalbard	All	2003-2008	Moholdt et al. (2010)
Regional	Russian Arctic	All	2003-2009	Moholdt et al (2012)
Calving	Alaska	27	1985-2013	McNabb et al (2015)
Calving	Canada North	65	1999-2015	Van Wychen et al. (2015; 2017)
Calving	Canada South	10	2007-2011	Van Wychen et al. (2015)
Calving	Svalbard	163	2000-2006	Blaszczyk et al (2009)
Calving	Russian Arctic	9	2014-2016	Glazovsky et al (2018)
Regional	All	All	1946-2016	Zemp et al. (2019)

3.2.4. Model validation

Mean annual regional mass balance for 1980-2016 was modelled and compared to the spatially interpolated mean annual regional mass balance of Zemp et al. (2019). These results (Table 3.2, Figure 3.1) were tested for statistical similarity using an empirical test which determined whether the mean and standard deviation of compared datasets were within range of each other.

Table 3.2. PyGEM model validation results; PyGEM and Zemp et al., (2019) 1980-2016 mean annual mass balance, standard deviation of mass balance used to determine similarity between datasets for PyGEM model validation.

Study Region	PyGEM (m w.e. a^{-1})	PyGEM STDev (m w.e. a^{-1})	Zemp et al. (2019) (m w.e. a^{-1})	Zemp et al. (2019) STDev (m w.e. a^{-1})
Alaska	-0.31	0.27	-0.75	0.43
Arctic Canada North	-0.42	0.15	-0.26	0.26
Arctic Canada South	-0.49	0.31	-0.26	0.26
Iceland	-0.60	0.40	-0.38	0.35
Svalbard	-0.24	0.22	-0.38	0.29
Scandinavia	-0.40	0.55	-0.30	0.85
Russian Arctic	-0.54	0.23	-0.38	0.29

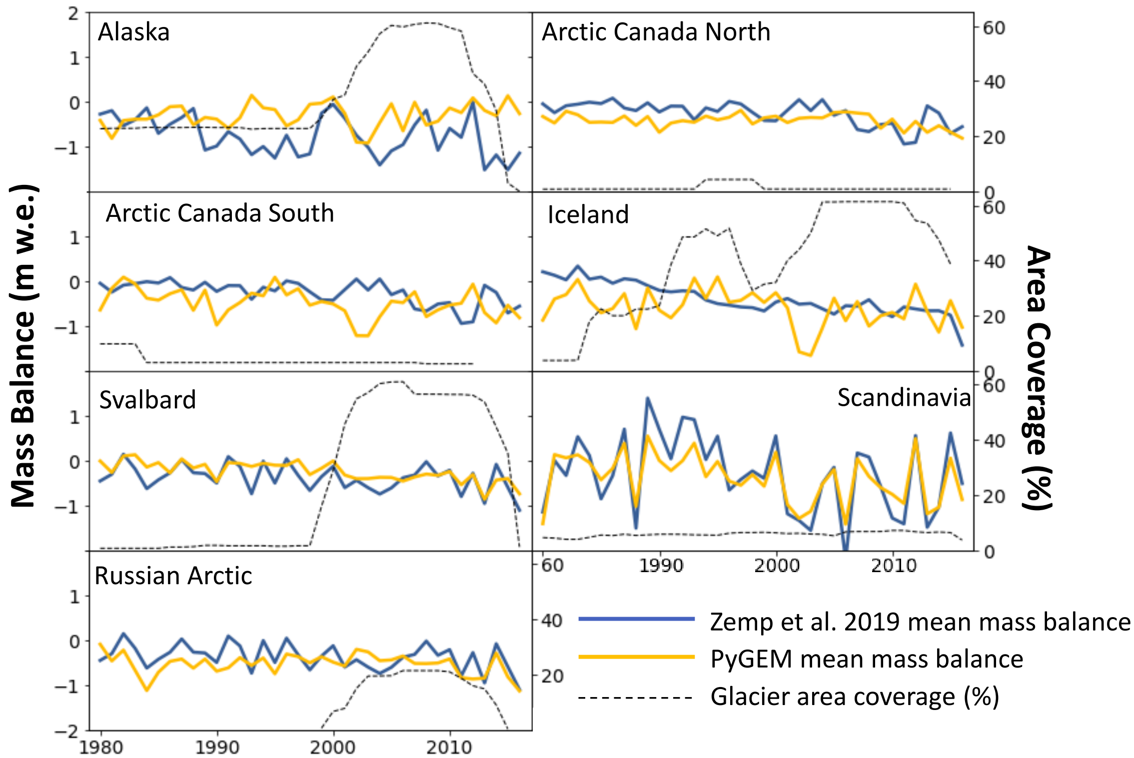


Figure 3.1. PyGEM v.s. Zemp et al., (2019) modelled mean regional mass balance. These datasets are compared against the percentage of regional glacier area covered by observational mass balance data.

With the exception of Alaska and Svalbard, the mean annual regional mass balance modelled by PyGEM was moderately lower than the mean annual regional mass balance from Zemp et al., (2019) spatial interpolation. The empirical comparison of the mean and standard deviation of the datasets reveals that, with the exception of Alaska, the mean of each dataset falls within the standard deviation of the dataset it is compared to. These results suggest that the PyGEM and Zemp et al., (2019) mean regional mass balance datasets may be similar.

Due to problems modelling of the calving component, Alaska and Svalbard have been excluded from the mass balance sensitivity study, as both regions, when modelled to and past 2100, experienced unconstrained growth. This irregularity is likely due to scarcity of calving data that caused the model to assign a disproportionate amount of loss to calving of specific glaciers.

At present, a single calving value in each region is used to calculate the frontal ablation of all glaciers in that region. The magnitude of mass loss due to frontal ablation for individual glaciers is proportional to glacier width and thickness at the terminus. In Alaska and Svalbard, mass loss from frontal ablation is relatively large in the first few years of modelling (Figure 3.2) due to glaciers with wide and thick glacier termini. Glaciers without observational mass balance measurements (ΔM_{obs}) are assigned a mass balance from a regional mass balance (ΔM_{reg}) which adjusts to fit observational data such that:

$$\Delta M_{reg} = \sum_{i=1}^{n} \Delta M_{obs} + \sum_{i=1}^{n} \Delta M_{obs\_reg} \quad (10)$$

in which ΔM_{obs_reg} is glacier mass balance of an individual glacier derived from regional mass balance, assigned to glaciers without observational data. PyGEM model physics dictate that regional mass balance must be equal to the sum of mass balance from all individual glaciers. Due to wide and thick (marine-terminating) termini of a number of glaciers in Alaska and Svalbard, the calculated mass loss from frontal ablation for these glaciers are relatively large. During calibration, the model has to compensate for such a low mass balance by increasing ΔM_{obs_reg} so the model can satisfy the conditions of equation 15. The increased mass balance of these glaciers leads to unconstrained growth over >100 year timespans (Figure 3.3).

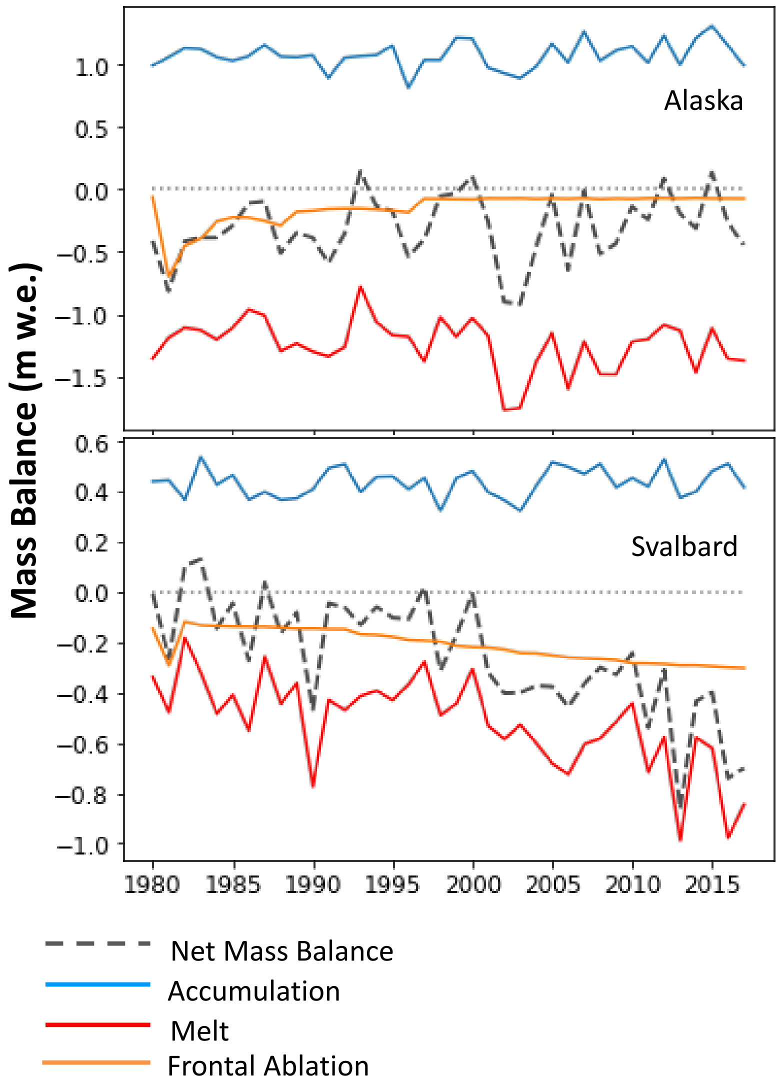


Figure 3.2. Mass balance components Alaska and Svalbard, modelled between 1980 and 2016. Accumulation, melt, and frontal ablation, as modelled by PyGEM. The refreeze component, which does not sizably contribute to mass balance in Alaska and Svalbard between 1980 and 2016, was omitted for clarity and figure interpretability.

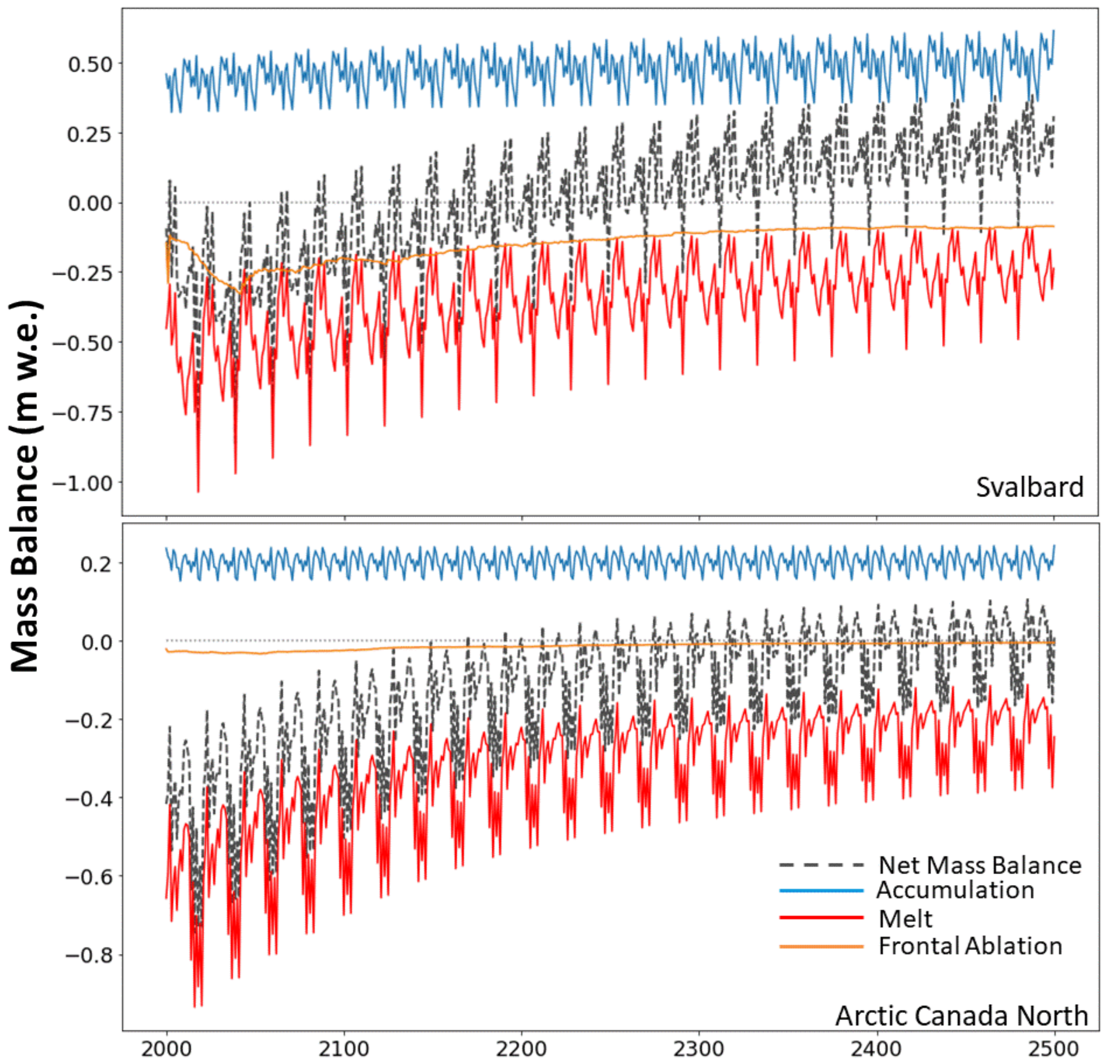


Figure 3.3. Components of net mass balance (accumulation, melt and frontal ablation) for a PyGEM simulation between 2000-2500 to demonstrate the unconstrained growth in Svalbard. The same plot for Arctic Canada North (a region which does not experience unconstrained growth) has been provided for comparison. The refreeze component, which does not sizably contribute to mass balance was omitted for clarity.

3.2.5. Regional glacier overview

Glacier area, altitude, and slope were investigated to better understand regional mass balance sensitivity. Scandinavia and Arctic Canada South had the smallest mean glacier area (0.863 and 5.51 km^2, respectively), while the Russian Arctic and Arctic Canada North had the largest (48 and 23.1 km^2, respectively) (Table 3.3, Figure 3.4). However, the mean maximum altitude of glaciers is lowest in the Russian Arctic and highest in Scandinavia (602 and 1462 m a.s.l., respectively) (Table 3.3, Figure 3.5). In addition, the mean slope of glaciers was lowest in the Russian Arctic and highest in Scandinavia (18.8 and 14 °, respectively), although glacier slope was relatively similar across all regions (Table 3.3, Figure 3.6).

Table 3.3. Summary statistics for glacier size, elevation, and slope in all regions studied.

	Canada North	**Canada South**	**Iceland**	**Scandinavia**	**Russian Arctic**
Max Area (km^2)	3085	2771	1561	55.4	1413
Min Area (km^2)	0.01	0.01	0.044	0.01	0.249
Mean Area (km^2)	23.1	5.51	19.5	0.863	48.0
Mean Max Altitude (m a.s.l.)	1053	1120	1295	1462	602
Mean Median Altitude (m a.s.l.)	834	942	1124	1343	416
Mean Min Altitude (m	510	700	893	1208	178

a.s.l.)					
Max Altitude (m a.s.l.)	2429	2129	2087	2418	1307
Min Altitude (m a.s.l.)	0	0	24	70	0
Max Slope (°)	59.5	53.7	48.1	49.5	36.1
Min Slope (°)	1.5	2.2	2.9	1.7	2.6
Mean Slope (°)	15.4	17.7	17.6	18.8	14.0
No. Glaciers >= 100 km^2	169 (3.7%)	53 (7.1E-3%)	23 (4.0%)	0	121 (11.3%)
No. Glaciers >= 50 km^2	301 (6.6%)	119 (1.6%)	33 (5.8%)	1 (2.9E-4%)	211 (19.7%)
No. Glaciers >= 10 km^2	973 (22%)	607 (8.2%)	65 (11%)	42 (1.2%)	471 (44%)
% of glaciers > 1500 m a.s.l.	11	12	16	47	0
% of glaciers > 1000 m a.s.l.	57	64	91	93	5.2

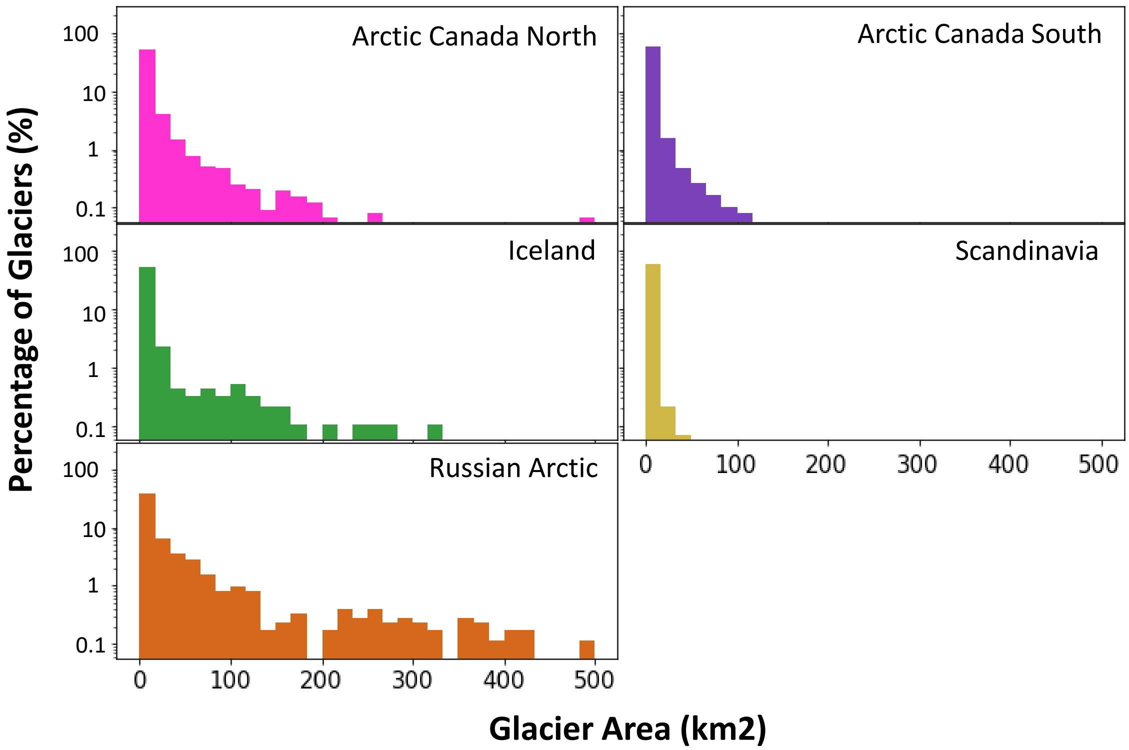


Figure 3.4. Regional glacier area distribution**.** A substantial number of glaciers in each region are >50 km^2. Therefore, to improve interpretability, the percentage of glaciers (y-axis) scale is logarithmic.

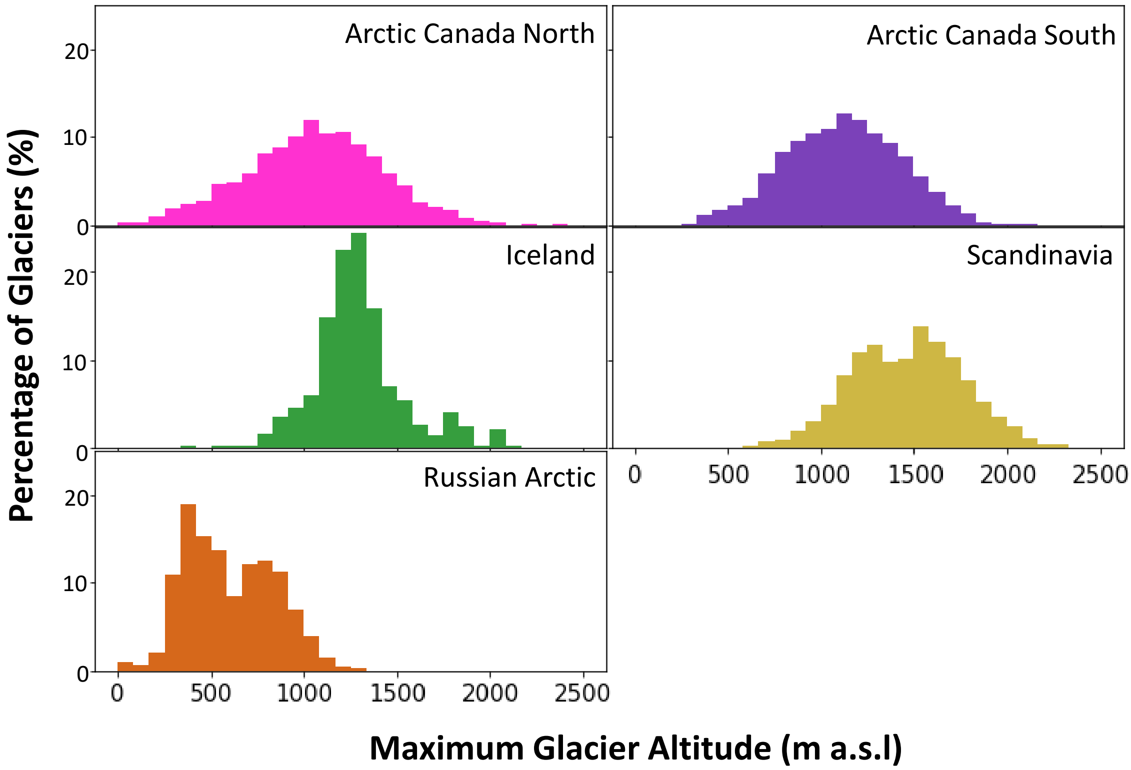


Figure 3.5. Regional maximum glacier altitude distribution.

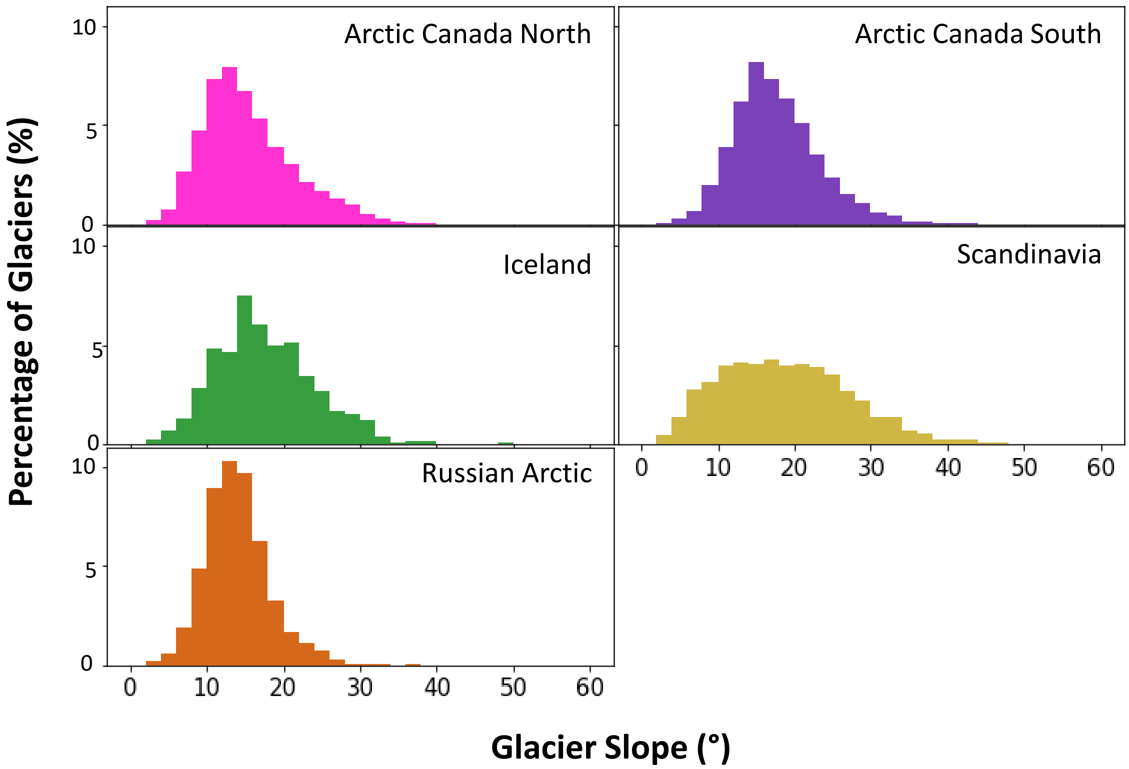


Figure 3.6. Regional glacier slope distribution.

3.2.6. Simulation of mass balance sensitivity

With the exception of studies that use future-projection climate models, most mass balance sensitivity studies decouple mass balance sensitivity from changes in temperature and precipitation change. In contrast, this study intentionally models mass balance sensitivity to both changes in temperature and precipitation change. Temperature and precipitation are coupled in this approach because they are also coupled in the natural environment; studies indicate that as temperature changes, precipitation changes by a corresponding, region-dependent amount (an average of 4 % $°C^{-1}$ (Bintanja & Andry, 2017; Bintanja & Selten, 2014)). This method of modelling creates mass balance sensitivity measurements that consider the impact of precipitation as a buffer on mass loss.

Glacier mass balance sensitivity to temperature and precipitation increase was studied in Arctic Canada North, Arctic Canada South, Iceland, Scandinavia and the Russian Arctic. A synthetic, steady climate was created from a continuous replication of 1995-2015 ERA-Interim, 2 m air temperature, precipitation, and temperature lapse rates for > 100 years for use as PyGEM model climate input. For all simulation runs the temperature was adjusted by 1-3 °C, and for some runs the precipitation was adjusted 4 % $°C^{-1}$ (as demonstrated in Figure 3.7) (Bintanja & Andry, 2017; Bintanja & Selten, 2014). The mean annual regional mass balance between 2000-2100 was evaluated with the temperature and precipitation adjustment and compared against a control scenario, in which temperature and precipitation were not adjusted from the 1995-2015 values.

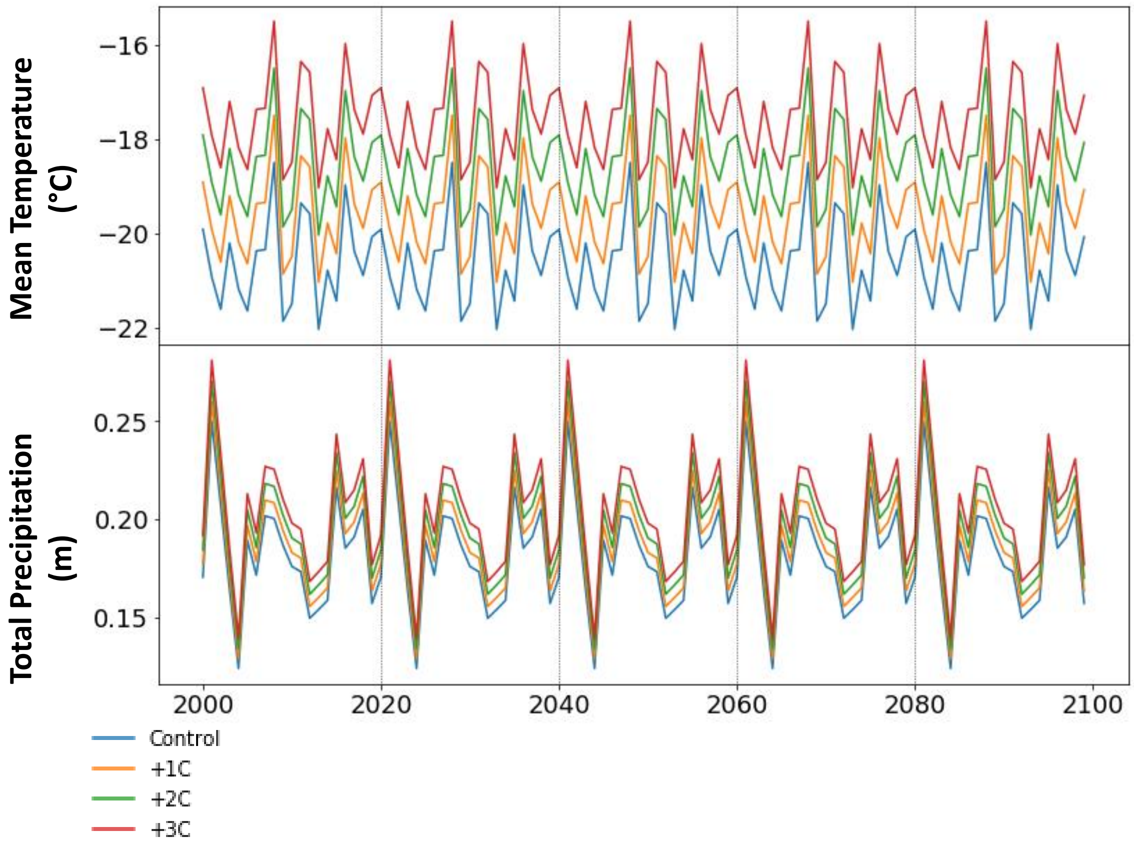


Figure 3.7. Simulated 2 m air temperature and precipitation; adjustments to mean annual 2 m air temperature (1-3 °C) and total annual precipitation (4 % °C^{-1}) between 2000 and 2100 in Arctic Canada North. 100-year temperature and precipitation data obtained by selecting 20 years from the ERA-Interim climate record and repeated five times (the start and end of the 20-year tiles are indicated by the vertical black lines on both plots)

PyGEM simulated mass balance and volume data for 2000-2100 were used to analyze how sensitive circum-Arctic glacier regions are to temperature and precipitation changes, and what are the primary drivers of this sensitivity. Specifically, this study aims to analyze: the sensitivity of regional mean mass balance and volume to increases of 1-3 °C in temperature and in 4 % °C^{-1} precipitation, the difference between model simulations with and without a 4 % °C^{-1} precipitation increase, and the relative impact of melt, accumulation, frontal ablation, and refreeze on mass balance. A Wilcoxon Rank-Sum test was used to determine statistical difference between compared datasets (the methodology of which is explained in detail in section 2.2.3).

3.3. Results

3.3.1. Glacier mass balance sensitivity

3.3.1.1. Mass balance change in response to 1-3 °C temperature and 4 % C°$^{-1}$ precipitation between 2000 and 2100

The mass balance change in response to 1-3 °C temperature and 4 % °C^{-1}precipitation increase between 2000-2100 was highest in Iceland, followed by Arctic Canada South, Scandinavia, the Russian Arctic and Arctic Canada North. Mass balance change in response to 1-3 °C temperature and 4 % °C^{-1} precipitation increase was highest in Iceland between 2000 and 2100, in which mean annual regional mass balance decreased -0.62 m w.e. a^{-1} (+1 °C) to -2.4 m w.e. a^{-1} (+3 °C) from the control scenario (no temperature or precipitation increase)(Figure 3.8). Arctic Canada South, Scandinavia, and the Russian Arctic experienced a mean annual regional mass balance decrease of -0.52 m w.e. a^{-1} (+1 °C) to -1.9 m w.e. a^{-1} (+3 °C), -0.52 m w.e. a^{-1} (+1 °C) to -1.9 m w.e. a^{-1} (+3 °C), and -0.47 m w.e. a^{-1} (+1 °C) to -1.7 m w.e. a^{-1} (+3 °C) , respectively, from the control scenario. Mass balance change was lowest in Arctic Canada North, in which mean annual regional mass balance decreased -0.32 m w.e. a^{-1} (+1 °C) to -1.3 m w.e. a^{-1} (+3 °C) from the control scenario (Figure 3.8). The change in mean annual regional mass balance in response to 1-3 °C temperature and 4 % °C^{-1} precipitation increase was statistically significant in all regions.

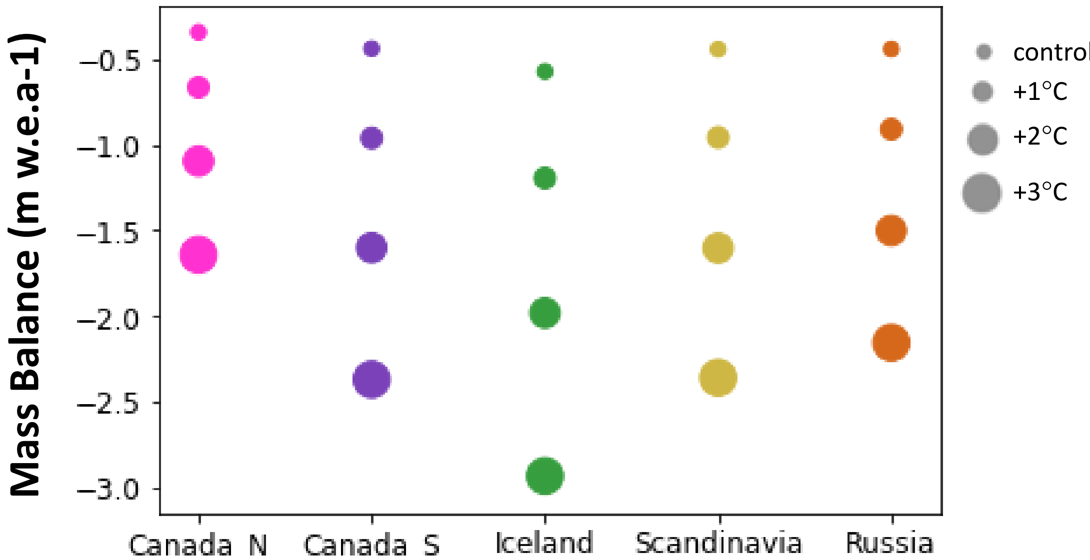
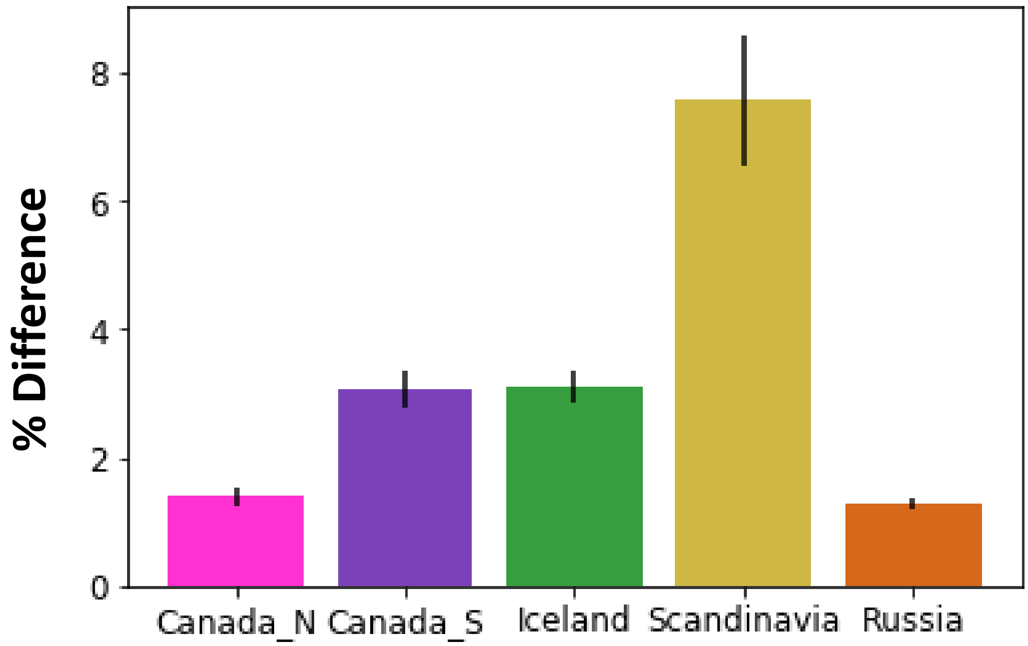


Figure 3.8. Mean annual regional mass balance between 2000-2100 in response to 1-3 °C temperature and 4 % $°C^{-1}$ precipitation increase.

3.3.1.2. Impact of 4 % $C^{°-1}$ precipitation increase on mass balance

Precipitation increase in response to 1-3 °C temperature increase had the greatest impact on the mass balance of Scandinavia, where mass balance was an average of 8.5 % higher in simulations with precipitation increase than without (to a 93 % confidence interval (p-val: 0.07), which does not meet the requirements to reject the null hypothesis at a 95 % confidence interval, but is an order of magnitude smaller than all other results (p-val: 0.4-0.7)) between 2000 and 2100 (Figure 3.9). The influence of precipitation was not statistically significant in Arctic Canada North, Arctic Canada South, Iceland, and the Russian Arctic over the same time period (Figure 3.9).



	Canada_N	Canada_S	Iceland	Scandinavia	Russia
Difference in mean (%)	1.4	3.2	3.3	8.5	1.3
P-Value	0.68	0.41	0.38	0.068	0.69

Figure 3.9. Impact of precipitation increase on mass balance. Percent increase in mean annual regional mass balance between 2000-2100 for a 1-3 °C temperature increase with and without a 4 % °C^{-1} precipitation increase. Error bars represent the standard deviation of mean annual regional mass balance for different temperature scenarios. P-values are calculated using the Wilcoxon Rank-Sum test.

3.3.1.3. Mass balance sensitivity with and without precipitation increase, and comparison to prior literature

Across the circum-Arctic, the mass balance of Iceland was most sensitive to changes in both temperature and precipitation, followed by Arctic Canada South, Scandinavia, the Russian Arctic, and Arctic Canada North. Sensitivity with and without increase in precipitation is highest in Iceland, followed by Arctic Canada South, Scandinavia, the Russian Arctic and Arctic Canada North. With the exception of Scandinavia, the mass balance sensitivity found in this study is different from the mass balance sensitivity of prior literature. The mass balance sensitivity between 2000-2100 (without precipitation increase) for Scandinavia is -0.65 m w.e. a^{-1} °C^{1}, which is identical to the mass balance sensitivity calculated by prior literature(De Woul & Hock, 2005; Oerlemans et al., 2005) (Table 3.4). For all other regions, the mass balance sensitivity found by this study varies greatly from the mass balance sensitivity found by other studies. The mass balance sensitivity (without precipitation increase) found by this study is -0.39, -0.61, -0.74, -0.65 and -0.53 m w.e. a^{-1} °C^{1} for Arctic Canada North, Arctic Canada South, Iceland, Scandinavia, and the Russian Arctic, respectively (Table 3.4). The mass balance sensitivity with a 4 % °C^{-1} precipitation increase is -0.39, -0.58, -0.70, -0.58, and -0.52 m w.e. a^{-1} °C^{1} in Arctic Canada North, Arctic Canada South, Iceland, Scandinavia, and the Russian Arctic, respectively (Table 3.4). The mass balance sensitivity from prior literature for Arctic Canada North, Arctic Canada South, Iceland, Scandinavia, and the Russian Arctic is -0.12, -0.19, -1.23, -0.65, and -0.27 m w.e. a^{-1}°C^{1}, respectively (Table 3.4) (De Woul & Hock, 2005; Oerlemans et al., 2005).

Table 3.4. Mean annual regional mass balance sensitivity between 2000-2100 for a 1-3 °C temperature increase**.** Results with and without without a 4 % $°C^{-1}$ precipitation increase are included and compared to the mass balance sensitivity found in prior studies (which decouple temperature and precipitation change).

Study Region	With Precipitation (m w.e. a^{-1} $°C^{-1}$)	No Precipitation (m w.e. a^{-1} $°C^{-1}$)	Previous Studies (m w.e. a^{-1} $°C^{-1}$)	Citations
Canada North	-0.39	-0.39	-0.12	(Oerlemans et al., 2005)
Canada South	-0.58	-0.61	-0.19	(Oerlemans et al., 2005)
Iceland	-0.70	-0.74	-1.23	(De Woul & Hock, 2005; Oerlemans et al., 2005)
Scandinavia	-0.58	-0.65	-0.65	(De Woul & Hock, 2005; Oerlemans et al., 2005)
Russia	-0.52	-0.53	-0.27	(De Woul & Hock, 2005; Oerlemans et al., 2005)

3.3.2. Contribution and sensitivity of glacier mass balance components

Change in the components of mass balance (melt, accumulation, frontal ablation, and refreeze) between 2000-2100 were evaluated for 1-3 °C temperature and 4% $°C^{-1}$precipitation increase and then each component was normalized to net mass balance to determine the relative change in mass balance components with temperature increase. This study determined that melt and accumulation are the largest contributors to net mass balance, but as temperature increases, the influence of accumulation on net balance decreases towards 0 % while the influence of melt consistently increases across all regions (Figure 3.10). The Russian Arctic experienced the largest increase in the relative influence of melt on net mass balance, with an increase from 45 % to 84

% of net mass balance over a 1-3 °C temperature increase while the relative influence of accumulation and frontal ablation on net mass balance decreased from 24 % to 7.7 % and 25 % to 6.5 %, respectively (Figure 3.10, Table S.6.2). The Russian Arctic is the only region studied with a frontal ablation component that accounts for >5 % of net mass balance (Figure 3.10, Figure S.6.2, Table S.6.2). The relative influence of melt on net mass balance increased from 68 % to 88 %, 62 % to 83 %, and 63 % to 84 % and the relative influence of accumulation on net mass balance decreased from 25 % to 10 %, 37 % to 17 %, and 37 % to 16 % in Arctic Canada North, Arctic Canada South, and Iceland, respectively. Melt in Scandinavia experienced the smallest increase in the relative influence on net mass balance, with an increase from 57 % to 73 %, while the relative influence of accumulation decreased from 42 % to 27 % (Figure 3.10, Table S.6.2). The relative influence of refreeze on net mass balance was <6 % across all regions (Figure S.6.2, Table S.6.2)

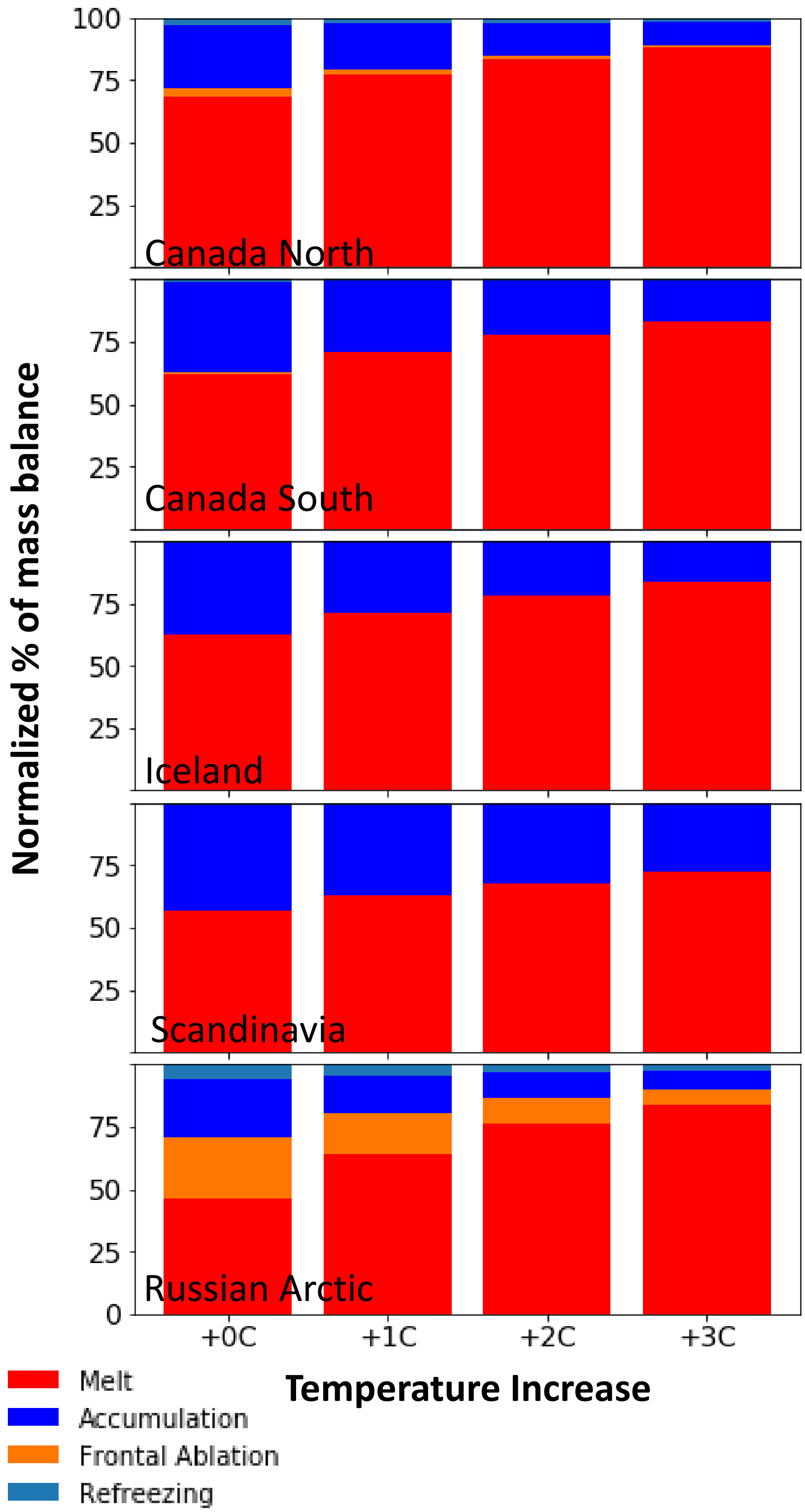


Figure 3.10. Normalized components of mass balance for 1-3 °C temperature and 4 % °C^{-1} precipitation increase between 2000-2100.

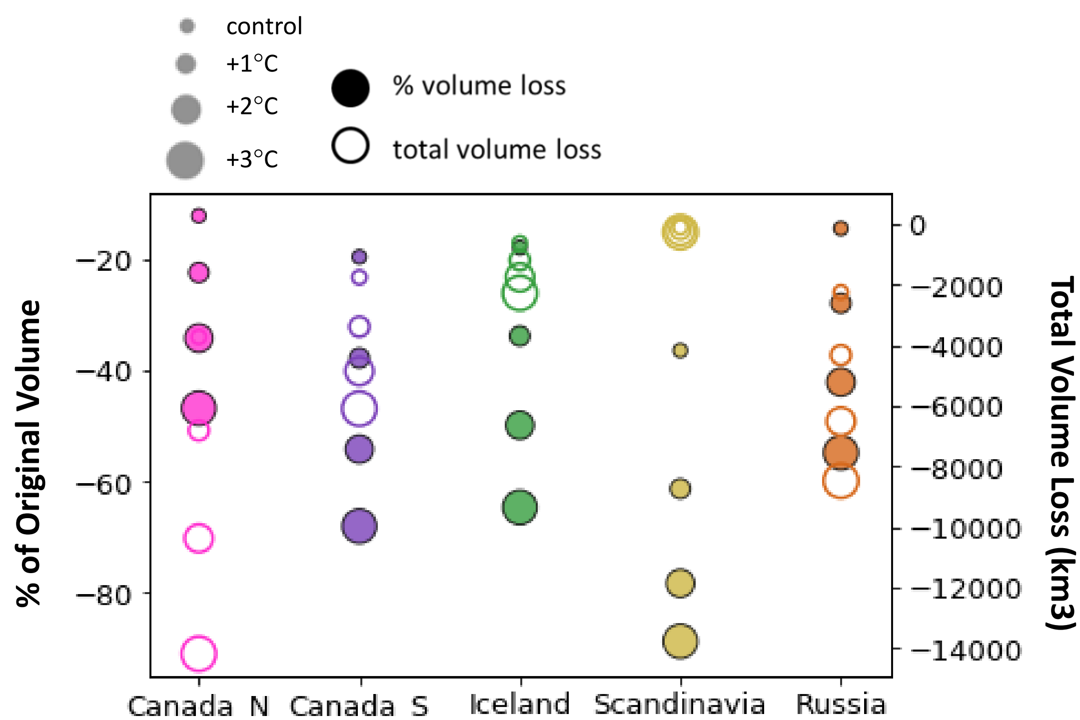
Across all regions, melt was most sensitive to temperature increase, followed by accumulation, refreeze, and frontal ablation (Table 3.5). The relative sensitivity of melt in proportion to net mass balance was -0.39, -0.56, -0.67, -0.60, and -0.53 m w.e. °C^{-1} a^{-1}, for Arctic Canada North, Arctic Canada South, Iceland, Scandinavia, and the Russian Arctic, respectively (Table 3.5). The mass balance sensitivity of accumulation, refreeze, and frontal ablation was <0.05 m w.e. °C^{-1} a^{-1} relative to net mass balance in all regions (Table 3.5).

Table 3.5. The sensitivity of melt, accumulation, frontal ablation, and refreeze components normalized to net mass balance for 1-3 °C temperature and 4% °C^{-1} precipitation increase between 2000-2100.

Study Region	Melt (m w.e. °C^{-1} a^{-1})	Accumulation (m w.e. °C^{-1} a^{-1})	Frontal Ablation (m w.e. °C^{-1} a^{-1})	Refreeze (m w.e. °C^{-1} a^{-1})
Arctic Canada North	-0.39	4.01E-4	4.4E-3	5.6E-3
Arctic Canada South	-0.56	-0.017	3.8E-4	-2.6E-3
Iceland	-0.67	-0.031	1.4E-5	-3.7E-3
Scandinavia	-0.60	0.033	0	-6.6E-3
Russian Arctic	-0.53	-0.017	0.028	2.4E-3

3.3.3. Glacier volume loss

The regional glacier volume loss between 2000-2100 in response to 1-3 ˚C temperature and a 4 % ˚C^{-1} precipitation increase was measured in km^3 and as a percentage of initial volume. All regions lost >40 % of their initial glacier volume under simulations with a 3 °C temperature increase. However, the rate of volume loss and the total volume loss (in km^3) is highly variable across regions (Figure 3.11). Arctic Canada North had the largest volume loss (-3730.3 and -14177.6 km^3) under simulations with temperature and precipitation increase between 2000 and 2100. Arctic Canada South, Iceland, and the Russian Arctic lost between -1765.4 and -6095.4, -637.9 and -1765.0 km^3, and -2255.7 and -8473.4 km^3, respectively. Scandinavia lost between -112.5 and -241.1 km^3 in response to 1-3 ˚C temperature and 4 % $˚C^{-1}$ precipitation increase, which is the smallest magnitude of volume lost for all studied regions (Figure 3.11).



Total Volume ($km^3\ a^{-1}{}^{\circ}C^{-1}$)	3.3	1.5	0.56	0.065	2.1
Percent of Total Volume ($\%a^{-1}{}^{\circ}C^{-1}$)	0.011	0.017	0.016	0.021	0.014

Figure 3.11. Simulated regional glacier volume loss between 2000-2100. Volume loss (in km^3 and as percentage of initial volume) in response to for 1-3 ˚C temperature and a 4 % ˚C^{-1} precipitation increase between 2000-2100. The sensitivity of volume (in km^3 and as percentage of initial volume) between 2000-2100 to the same temperature and precipitation increase is provided in the table

Scandinavia lost between 36 % and 88 % (Figure 3.11) of its initial volume between 2000-2100 in response to 1-3 ˚C temperature and 4 % ˚C^{-1} precipitation increase, which is the largest percent loss across all studied regions. Arctic Canada South, Iceland, and the Russian Arctic lost between 20 % and 68 %, 18 % and 65 %, and 15 % and 55 % of initial volume, respectively. Arctic Canada North lost between 12 % and 46 % of initial volume in response to 1-3 ˚C temperature and 4 %

$^{\circ}C^{-1}$ precipitation increase, which is the smallest percent loss across all studied regions (Figure 3.11).

The relative and absolute change in volume between 2000-2100 in response to 1-3 $^{\circ}C$ temperature and 4 % $^{\circ}C^{-1}$ precipitation increase are inversely related to each other as regions with the largest volume loss had the smallest percent volume loss (Figure 3.11). The sensitivity of volume to temperature increase is highest in Arctic Canada North, 3.3 $km^3\ a^{-1}\ {}^{\circ}C^{-1}$, followed by the Russian Arctic, Arctic Canada South, Iceland, and Scandinavia, with a sensitivity of 2.1, 1.5, 0.56, and 0.065 $km^3\ a^{-1}\ {}^{\circ}C^{-1}$, respectively. The sensitivity of regional glacier volume as a percent of initial volume in response to 1-3 $^{\circ}C$ temperature and 4 % $^{\circ}C^{-1}$ precipitation increase is highest in Scandinavia, 0.021 %, followed by Arctic Canada South, Iceland, the Russian Arctic, and Arctic Canada North, with a percent volume sensitivity of 0.017, 0.016, 0.014, and 0.011 %, respectively.

3.4. Discussion

3.4.1. Mass balance sensitivity

Prior studies suggest that mass balance sensitivity varies sizably across regions (e.g. McGrath, et al., 2017; De Woul & Hock, 2005; Oerlemans et al., 2005; Radić et al., 2014); Large interregional variability is reinforced by this study, in which mass balance sensitivity ranges from -0.39 to -0.74 m w.e. $a^{-1}\ {}^{\circ}C^{-1}$ across regions. The largest and smallest mass balance sensitivity, found in Iceland and Arctic Canada North, are substantially larger and smaller than the mass balance sensitivity in all other regions studied. The mass balance sensitivity in Iceland (-0.70 m w.e. $a^{-1}\ {}^{\circ}C^{-1}$, -0.74 m w.e. $a^{-1}\ {}^{\circ}C^{-1}$ when decoupled from precipitation) is >= 9 m w.e. $a^{-1}\ {}^{\circ}C^{-1}$ higher than any other region in scenarios coupled and decoupled from precipitation (Table 3.4, Figure 3.8). Meanwhile, the mass balance sensitivity in Arctic Canada North (-0.39 m w.e. a^{-1} ◦C^{-1} when coupled with and decoupled from precipitation) is >10 m w.e. a^{-1} ◦C^{-1} smaller than the mass balance sensitivity in any other region (Table 3.4, Figure 3.8). The mass balance sensitivity in Scandinavia and Arctic Canada South are similar (-0.58 m w.e. a^{-1} ◦C^{-1} in both regions when coupled with precipitation, and -0.65 and -0.61 m w.e. a^{-1} ◦C^{-1} in Scandinavia and Arctic Canada South, respectively, when decoupled from precipitation) (Table 3.4, Figure 3.8). The comparatively large decrease in mass balance in Scandinavia with the addition of precipitation increase suggests that precipitation has a large influence on the mass balance sensitivity of the region. The mass balance sensitivity in the Russian Arctic is closer to the Scandinavia and Arctic Canada South than it is to the mass balance sensitivity of Arctic Canada North (-0.52 and -0.53 m w.e. a^{-1} ◦C^{-1} when coupled with and decoupled from precipitation, respectively). How these glaciers respond to temperature and precipitation increase may be dependent on a variety of factors.

3.4.2. Factors contributing to mass balance sensitivity

This study suggests that there are a number of primary and secondary controls on mass balance sensitivity. Primary controls on mass balance sensitivity are climate-specific, such as the regional degree of continentality and proximity of accumulation season temperatures to the snow/rain threshold temperature. Secondary controls directly impact the way a glacier responds to temperature/precipitation increase, such as glacier size, altitude, slope, and albedo.

3.4.2.1. Primary controls: degree of continentality and proximity to the snow/rain threshold temperature

In the context of glaciology, continentality describes the impact of marine climate on the temperature and precipitation of glacierized regions (Holmlund & Schneider, 1997). Regions with a low degree of continentality (maritime regions) are at close proximity to marine climates and thereby have high rates of precipitation (some of which falls as snow during accumulation months) from the moisture evaporating from this marine environment. In addition, relatively consistent ocean temperatures (dictated by the thermohailine circulation) greatly influence the temperature of maritime regions (Wunsch, 2002) by limiting amplitude of temperature fluctuation throughout the year (Holmlund & Schneider, 1997). In warm, maritime glacier regions, where temperatures are above 0˚C through most of the year, precipitation is likely to fall as rain, and thus the accumulation season may be short with temperatures close to the snow/rain threshold temperature (approximately 0 °C) (Anderson & MacKintosh, 2012). However, the accumulation season in such regions is likely to bring large amounts of snowfall due to the availability of moisture from the maritime climate and the large capacity of the relatively warm air to hold this moisture (Anderson & MacKintosh, 2012). These warm, maritime glacier regions often have a large magnitude of annual melt (from the generally warm temperatures) and of annual accumulation (Anderson & MacKintosh, 2012). Temperature and precipitation increase in warm, maritime glacier regions may breach the sensitive snow/rain threshold and even further shorten the accumulation season, reduce the magnitude of annual accumulation, and substantially decrease net mass balance. Additionally, increase in temperature in a warm, maritime region during the melt season is likely to exacerbate already large melt rates, and thereby further reduce mass balance.

Iceland and Scandinavia are warm, wet, maritime regions that experience low seasonal temperature amplitude (approximately 0-10 ˚C), high annual precipitation due to their proximity to marine climates (up to 7000 and 5000 mm of annual precipitation in Iceland and Scandinavia, respectively), and a short but intense accumulation season (Holmlund & Schneider, 1997; Ólafsson et al., 2007). The mass balance sensitivity in Iceland may be larger than in Scandinavia because the accumulation season in Iceland may be shortening at a more rapid rate, as evidenced by the inverse relationship between temperature/precipitation and accumulation in Iceland (-0.031 m w.e. $°C^{-1}$ a^{-1}), which suggests that as temperature and precipitation increase, annual accumulation decreases (Table 3.5). In contrast, the relationship between temperature/precipitation increase and accumulation in Scandinavia is positive (0.033 m w.e. $°C^{-1}$ a^{-1}), which suggests that as temperature/precipitation increase, so does annual accumulation (Table 3.5). Increase in solid precipitation may also contribute to the positive relationship between temperature/precipitation change and accumulation in Scandinavia, which is the only region in which the addition of precipitation increase significantly decreased mass balance sensitivity (-8.5 m w.e. a^{-1} difference to a 93 % confidence interval) (Figure 3.9). In Iceland, however, there is no significant difference between mass balance with and without precipitation increase, which once more suggests that the accumulation season is becoming too short for an increase in snowfall to make a significant difference in mass balance.

In contrast, regions with a low degree of continentality (continental) are not substantially impacted by far away marine climates and therefore do not receive a lot of moisture for precipitation (Anderson & MacKintosh, 2012). The large distance from marine environments makes continental glacier regions dry, with low annual precipitation (Anderson & MacKintosh, 2012). The temperature in continental regions is not regulated by marine environments and instead is primarily governed by the energy from incoming solar radiation and from changes to surface air temperature via turbulent heat fluxes (Anderson & MacKintosh, 2012). Cold, continental regions have high seasonal temperature amplitude, where winter (and annual) temperatures are substantially below 0 ˚C and summer temperatures may be close to 0 ˚C (Bradley & England, 1978; Maxwell, 1981; Zeeberg & Forman, 2001). Because the mean temperature in these regions is below 0˚C for the majority of the year, the accumulation season is long and the melt season is short (Anderson & MacKintosh, 2012). In addition to scarcity of precipitation due to distance from marine environments, the atmosphere in cold, continental regions does not have the capacity to hold moisture for the majority of the year, which may reduce precipitation even further (Lenderink & Van Meijgaard, 2010). Therefore, cold, continental glacier regions often have small annual melt and accumulation magnitudes (Anderson & MacKintosh, 2012). A small temperature/precipitation increase is unlikely to substantially increase the length of the melt season in cold, continental regions due low regional temperature. Also, such an increase may not have substantial impact on accumulation since there are very few sources from which the atmosphere could receive moisture for precipitation (Lenderink & Van Meijgaard, 2010).

Arctic Canada North and the Russian Arctic are both cold, continental regions that experience high seasonal temperature amplitude (approximately -40 to 10 °C (Maxwell, 1981; Zeeberg & Forman, 2001)) and low annual precipitation (a maximum of approximately 80 and 800mm in Arctic Canada North, respectively (Bradley & England, 1978; Zeeberg & Forman, 2001)), though these values vary across both regions. The larger annual precipitation in the Russian Arctic in comparison to Arctic Canada North (though the precipitation in both of these regions is low in comparison to Scandinavia and Iceland) suggests that precipitation has a greater impact on mass balance in the Russian Arctic than in Arctic Canada North. If accumulation season (in which glaciers actually accumulate mass) were to reach the snow/rain threshold through temperature increase, the annual accumulation of glaciers in the Russian Arctic may decrease, mass balance may decrease, and, therefore, the mass balance sensitivity may increase (Table 3.4, Figure 3.8). Continentality and proximity to the snow/rain threshold temperature alone may not fully explain why the mass balance components in the Russian Arctic are more sensitive to temperature/precipitation increase than in Arctic Canada North; additional factors may need to be considered to explain these differences.

Although Arctic Canada South has a relatively high seasonal temperature amplitude (approximately -25 to 5 ˚C (Jacobs, 2018)) and annual precipitation is moderate (approximately 2000 mm (Fisher et al., 2012)), the mass balance sensitivity in this region is high (Table 3.3). Perhaps a combination of a shortening accumulation season that contributes relatively moderate rates of accumulation causes mass balance to decrease with temperature/precipitation increase. However, there is great uncertainty in both the glacier mass balance and climate in Arctic Canada South due to lack of consistent, long-term data (Fisher et al., 2012). Additionally, there are a variety of additional factors that may contribute to the mass balance sensitivity.

3.4.2.2. Secondary controls: glacier altitude, size, slope, and surface albedo

The secondary controls on mass balance sensitivity, glacier altitude, size, slope, and albedo, can vary across and within regions. With the exception of albedo, secondary controls often have a comparatively smaller impact on mass balance sensitivity than primary controls (Anderson & MacKintosh, 2012) but may alter mass balance sensitivity for glaciers with identical climate.

Glacier altitude may impact surface air temperature on the glacier and the amount of precipitation that falls as snow (Anderson & MacKintosh, 2012). Temperature most often decreases with increasing altitude, though the rate of this relationship varies with rate of adiabatic cooling, atmospheric conditions, regional topography, albedo, etc. (A. S. Gardner et al., 2009). The relationship between altitude and precipitation is less complex; as altitude rises and temperature falls, air condensation increases and is likely to cause precipitation in areas with moisture content in the atmosphere (typically windward mountain slopes within proximity of marine climates (Sevruk, 1997). Therefore, glaciers at higher altitude may experience lower surface air temperature, a shorter melt season, and more total accumulation, due to increase in volume and duration of snowfall, in comparison to a similar glacier at lower altitudes (Anderson & MacKintosh, 2012). In contrast, glaciers at lower altitudes may experience higher air surface temperature, a longer melt season, more total melt, and less total accumulation, due to decrease in volume and duration of snowfall, in comparison to a similar glacier at higher altitudes (Anderson & MacKintosh, 2012).

Comparatively high glacier altitude in Scandinavia may have reduced the regional mass balance sensitivity, as it has the highest mean maximum altitude, median altitude, and minimum altitude (1462, 1343, and 1208 m a.s.l., respectively) (Table 3.3) of all studied regions. Approximately half (47 %) of Scandinavian glaciers have a maximum altitude of over 1500 m a.s.l., which is substantially more than in any other region (Table 3.3, Figure 3.5). This high glacier altitude may contribute to the substantially higher mass balance sensitivity in Scandinavia in comparison to Iceland (which have similar climates, degree of continentality, etc.), in which only 16 % of glaciers have a maximum altitude of over 1500 m a.s.l. (Table 3.3, Figure 3.5).

In contrast, low glacier altitude in the Russian Arctic may have increased the mass balance sensitivity. The Russian Arctic has the lowest absolute maximum, mean maximum, and mean median glacier altitude of any studied region (1307, 602.4, and 415.5 m a.s.l., respectively). The Russian Arctic has no glaciers with a maximum altitude above 1500 m a.s.l., and the majority (95%) are below even 1000 m a.s.l. (Table 3.3, Figure 3.5). These low altitudes may have contributed to the substantial difference between the mass balance sensitivity in the Russian Arctic in comparison to Arctic Canada North (which has a similar climate, degree of continentality, etc.) where glaciers are found at higher altitudes; More than half (57%) of the glaciers in Arctic Canada North have a maximum altitude of 1000 m a.s.l. (Table 3.3, Figure 3.5).

Glacier size, particularly of valley glaciers and icefields, is commonly constrained by subsurface topography (Cogley, 2011) and substantially impacts glacier mass balance sensitivity. Glacier size has an inverse, though not linear, relationship to magnitude of mass loss (Bahr et al., 1998); therefore, small glaciers are likely to respond more quickly to temperature/precipitation increase than larger glaciers. Small glaciers are likely to lose more mass than a similar but larger glacier under the same climate conditions, since a larger percentage of total glacier volume of the smaller glacier is exposed to the impacts of surface air temperature and solar radiation (Bahr et al., 1998).

Small glacier size may be a factor of the relatively large mass balance sensitivity in Arctic Canada South (Table 3.4) despite large seasonal temperature amplitude and cold winters (Jacobs, 2018) that are more similar to the cold, dry, continental regions with small magnitudes of mass balance (Arctic Canada North and the Russian Arctic) than the warm, wet, maritime regions with large magnitudes of mass balance (Iceland, Scandinavia). The mean area of glaciers in Arctic Canada North (23.1 km^2), the region at closest proximity to Arctic Canada South and one that has a comparatively similar climate (Jacobs, 2018; Maxwell, 1981), is approximately five times larger than the mean area of glaciers in Arctic Canada South (5.51 km^2) (Table 3.3). Under similar climate conditions, the smaller glaciers in Arctic Canada South are likely to react more quickly to temperature/precipitation increase and therefore have a larger mass balance sensitivity. Although Scandinavia has the smallest glaciers of all studied regions (mean area of 0.86 km^2) (Table 3.3, Figure 3.4), the high glacier altitude may help buffer the impact of small size and help reduce the mass balance sensitivity.

Glacier slope may impact the amount of accumulation on the glacier surface; the steeper the slope, the more glacier surface needs to be covered by a unit of accumulation. In addition, a steeper slope increases runoff that may have otherwise refrozen within the glacier system (on a comparatively slighter slope), and increases the likelihood of snowfall leaving the glacier before being incorporated into the glacier system (Anderson & MacKintosh, 2012). Finally, a steeper slope may increase glacier velocity through internal deformation or basal sliding, and move a larger portion of the glacier into the ablation zone where ablation can accelerate (Anderson & MacKintosh, 2012).

The mean slopes of glaciers in the regions studied are relatively similar (ranging between 14 and 18.8°) (Table 3.3, Figure 3.6). Glaciers in the Russian Arctic have the slightest slopes (Table 3.3, Figure 3.6), which may contribute to the larger amount of total precipitation the region receives in comparison to Arctic Canada North (Bradley & England, 1978; Zeeberg & Forman, 2001). In contrast, the alpine glaciers of Scandinavia have the steepest slopes (Table 3.3, Figure 3.6), which may contribute to increasing the mass balance sensitivity in the region. However, the higher altitude of glaciers in this region likely buffers the impact of increased slopes on mass balance sensitivity.

Glacier surface albedo can have a substantial impact on the amount of energy glaciers have for melt. Albedo describes the proportion of incoming radiation that is reflected and absorbed into the glacier (Cogley, 2011). For example, fresh snow cover on a glacier surface will reflect a large amount (approximately 80 %) of the incoming solar radiation, thereby accumulating less energy that is available for melt in comparison to a similar glacier with ice or debris cover (Cogley, 2011). The total melt on this glacier will be comparatively smaller, which may lead to a higher mass balance and a lower mass balance sensitivity. In contrast glaciers with exposed ice, a rough surface texture, and debris cover will have a lower albedo and have more energy that is available for melt (Dumont et al., 2012). The impact of albedo on mass balance and mass balance sensitivity may be exacerbated on low-altitude glaciers that do not receive frequent snowfall and are more likely to expose low-albedo bare ice (Dumont et al., 2012).

The cold annual temperatures of Arctic Canada North allow for a portion of precipitation that occurs during the melt season (July-October) to fall as snow, thus increasing albedo and leaving less energy available for melt (Bradley & England, 1978). Temperatures on many parts of Arctic Canada North rarely go above 0 °C (Maxwell, 1981), suggesting that accumulation may stay on the glacier surface, relatively undisturbed, with high albedo, for the majority of the year. The high albedo of glaciers in Arctic Canada North may help decrease the mass balance sensitivity in Arctic Canada North, particularly in comparison with the Russian Arctic (much of which experiences accumulation in the winter and melt in the summer (Geir Moholdt et al., 2012). The high altitude and large accumulation rates likely increases the albedo of Scandinavian glaciers, which may contribute to its lower mass balance sensitivity in comparison to Iceland.

3.4.3. Future implications

3.4.3.1. Glacier contribution to sea level rise

Although Iceland, Scandinavia, and Arctic Canada South have the highest magnitudes of mass balance sensitivity, their glacier area and volume are relatively small (Table 3.3). In contrast, while the magnitudes of mass balance sensitivity in Arctic Canada North and the Russian Arctic are small, their glacier area and volume are relatively large (Table 3.3). These results suggest that even though Arctic Canada North and the Russian Arctic have the smallest mass balance sensitivity, these regions will contribute the most to sea level rise of all studied regions. For example, this study projects that with an increase of 3 °C, Scandinavia may lose approximately 90 % of its initial glacier volume, but only contribute less than 300 km^3 of ice to the ocean (Figure 3.11). Meanwhile, Arctic Canada North may lose less than 50 % of its initial glacier volume under the same temperature increase but contribute over 14,000 km^3 of ice to the ocean (Figure 3.11).

3.4.3.2. Beyond an increase of 3 °C

As temperature increases beyond 3 °C in the circum-Arctic, this study suggests that the influence of precipitation may effectively disappear as melt becomes the increasingly dominant driver on mass balance (Figure 3.10) and precipitation moves increasingly towards rain (Bintanja & Andry 2017). Rain-dominated precipitation may occur more quickly in already warm, wet, maritime regions, such as Iceland and Scandinavia, which are close to reaching the snow/rain threshold during accumulation months. The coasts of cold, dry, regions like the Russian Arctic and Arctic Canada North, may eventually be warm enough to hold moisture content (Trenberth & Shea,

2005) that can substantially contribute to the mass balance of these regions before also moving towards rain-dominance.

3.4.4. Study limitations

There are many limitations to modelling mass balance sensitivity, including dataset uncertainty, availability of data, and model interpretation of observational data. Uncertainty is inherent to the datasets used to model mass balance with PyGEM. For example, temperature and precipitation results modelled by the ERA-Interim reanalysis product have an estimated uncertainty of ±2 °C and 2 %, respectively (Solman et al., 2013). Such an uncertainty may be particularly problematic in the circum-Arctic, a region extremely sensitive to temperature changes and may thereby impact the mass balance sensitivity. Glacier hypsometry, thickness and area data used to determine mass balance change at 10m intervals, was calculated by applying an ice flow model to RGI glacier outlines and glacier thickness derived from digital elevation models (DEMs) (Huss & Farinotti, 2012). These datasets have uncertainties as well; for example, there is little information on date and source of much imagery used to determine glacier outlines and few data quality checks are conducted. Validation of the modelled hypsometry dataset revealed an approximately 12 % uncertainty for glacier volume (Huss & Farinotti, 2012). Such uncertainty can impact the sensitivity of individual glaciers to temperature and precipitation increase, since size is a secondary control on mass balance sensitivity. As outlined in section 1.3, there are a number of potential errors associated with the calculation of both geodetic and glaciological mass balance. Uncertainty in glaciological mass balance may arise due to changes in basal and internal accumulation, which may not be represented by surface processes and may therefore be missing from mass balance measurements (Thomson et al., 2016). Unknown glacier density and altimetry measurement errors may create uncertainty in geodetic mass balance calculations (Zemp et al., 2013). These mass balance measurement uncertainties may impact the simulation of mass balance sensitivity, but may also impact the regional mass balance values acquired from prior publications, as these values also rely on observational mass balance data to draw their conclusions. In addition, because these datasets are used in combination to determine mass balance sensitivity in the circum-Arctic, the errors of each dataset may compound when combined. Quantifying uncertainty of mass balance sensitivity using PyGEM is important but beyond the scope of this study.

Data availability may further increase uncertainty in mass balance sensitivity simulations. In regions that have few observational data, like Arctic Canada North, there is substantial uncertainty in regards to regional mass balance. While glacier hypsometry and climate data may be available for these regions (and these data come with their own uncertainties), observational measurements would be required to constrain uncertainty in mass balance observations. Without observational mass balance data, it is difficult to quantify uncertainty in these regions.

Model use and interpretation of available observational data may increase uncertainty, particularly in the calculation of the temperature bias (equation 11) and precipitation factor (equation 12). The temperature bias and precipitation factor are a substitute for the contributors to mass balance that are missing from the degree day model, such as glacier debris cover or geothermal heat flux, which are not determined by temperature or precipitation inputs. For each glacier, these factors remain constant throughout the entire period of modelling. However, these factors may change over time or with changes in glacier hypsometry, as, for example, a glacier recedes from a geothermal hotspot, or geothermal activity is overall reduced (Björnsson & Pálsson, 2008). While these changes may not directly impact how sensitive glaciers are to changes in only temperature and precipitation, they may impact the secondary controls on mass balance sensitivity. For example, if geothermal impact on mass balance is reduced, thus reducing the magnitude of annual mass balance, the glacier will shrink more slowly, and thus be less sensitive to temperature.

3.5. Conclusions

This study examined how glacier mass balance in the circum-Arctic would change in response to 1-3 °C temperature and 4 % °C^{-1} precipitation increase and then attempted to analyze the drivers of this sensitivity. This study determined that glaciers in Iceland are most sensitive and Arctic Canada North is the least sensitive to 1-3 °C temperature and 4 % °C^{-1} precipitation increase. The study of mass balance sensitivity can improve the way in which future projecting climate models impact glaciers. While climate models will dictate temperature and precipitation change, an understanding of mass balance sensitivity of glaciers is key to helping understand how these glaciers will respond to such change.

Mass balance sensitivity may still be primarily driven by the degree of continentality, specifically, the proximity of glaciers in a region to the regional rain/snow threshold. Glaciers in warmer regions, in which annual temperature is close to 0 °C (such as Scandinavia and Iceland), will be more sensitive to temperature increase than regions with lower annual temperatures. Temperature during accumulation season in these warm regions is close to 0 °C, and may shorten considerably with only a few degrees of warming. In contrast, glaciers in cold regions, in which temperatures of the accumulation season are well below 0 °C, are unlikely to see a substantial shortening of accumulation season from only a few degrees of temperature increase. There are a number of secondary controls such as glacier altitude, size, slope, and surface albedo that may also impact mass balance sensitivity. An understanding of the factors contributing to mass balance sensitivity may help future research better understand the observed changes in glacier mass balance with temperature increase and may improve the factors that need to be taken into consideration with construction of new glacier models.

CHAPTER 4. CONCLUSIONS

Glacier and ice cap melt from the circum-Arctic is a growing concern for low-lying coastal communities and island nations impacted by sea level rise (Nicholls & Cazenave, 2003; Zemp et al., 2019). To understand how sea level rise may change in the future, studies of present and potential future glacier mass loss from the circum-Arctic, such as those conducted in this thesis are important to mitigate the impacts of sea level rise. There were two main objectives to this thesis. The first objective was to identify the most effective methodology to calculate regional mass balance trends in the circum-Arctic by determining whether the spatial interpolation of Zemp et al., (2019) significantly changes the calculated regional mass balance using available geodetic and glaciological observational mass balance data. Then, these data were used to investigate past and present (1961-2016) circum-Arctic mass balance trends. The second objective was to determine the spatiotemporal mass balance sensitivity of circum-Arctic glaciers to changes in temperature (by +1 to +3 °C), and to increases in precipitation (4 % $°C^{-1}$) and investigate the factors contributing to this sensitivity.

To achieve the first objective, 1961-2016 glacier mass balance for Alaska, Arctic Canada North, Arctic Canada South, Iceland, Svalbard, and Scandinavia (and the Russian Arctic for 2000-2016), determined by the spatial interpolation of Zemp et al. (2019) was compared to the glacial mass balance over the same time period obtained through an area-weighted (specific) mass balance calculation using only observational data. A Wilcoxon rank-sum test was used to determine statistical significance between the two datasets. In addition, the magnitude of mass loss and interannual variability between the two datasets was compared qualitatively. The mean annual mass balance for 1961-2016 and 2000-2016 for each region was compared and tested for statistical significance using the Wilcoxon rank-sum test to determine how mass balance has changed over time.

To achieve the aims of the second objective, glacier thickness and elevation data, 2 m air temperature, precipitation, and temperature lapse rates from the ERA-Interim climate reanalysis product, glaciological and geodetic observational mass balance data, and regional mass balance calculated by prior studies were used to calibrate the Python Glacier Evolution Model (PyGEM). At present, PyGEM is the most sophisticated glacier evolution model available. PyGEM was validated by comparing the 1980-2016 PyGEM modelled mass balance to mass balance from Zemp et al. (2019) over the same time period. PyGEM was then used to simulate 2000-2100 mass balance with no temperature or precipitation increase, and then a +1 to +3 °C temperature and 4 % °C^{-1} precipitation increase. To simulate this mass balance, a synthetic, steady climate was created from a continuous replication of 1995-2015 ERA-Interim, 2 m air temperature, precipitation, and temperature lapse rates for > 100 years for use as PyGEM model climate input. Mean annual regional mass balance for to 1-3 °C temperature and 4 % °C^{-1} precipitation increase was used to determine regional mass balance sensitivity to temperature increase alone and the coupled temperature and precipitation increase.

4.1. Summary of results

4.1.1. Chapter 2: trends in glacier mass balance

When compared to specific (area-weighted) mass balance (B_{spec}) that only uses available observational data, the spatial interpolation of Zemp et al. (2019) (B_{int}) significantly impacts the mass balance calculated in regions with little to no observational data. The regional mass balance calculated by Zemp et al. (2019) is the most recent and extensive mass balance study conducted, and uses the largest number of observational data in comparison to all other studies. Therefore, this thesis considers the Zemp et al. (2019) mass balance calculations as the most accurate available. Interannual variability is qualitatively different between B_{spec} and B_{int}, in regions where ≥50 % of observational data are geodetic, suggesting that B_{int} spatial interpolation may be useful for interannual variability studies in such regions. Additionally, the magnitude of mass loss is qualitatively different between B_{spec} and B_{int}, in regions where the majority of observational data are glaciological and the amplitude of interannual variability is high.

Circum-Arctic observational mass balance trends indicate that Arctic Canada North has experienced the largest decrease in glacier mass balance between 1961-2016 and 2000-2016, followed by Alaska and Svalbard. However, the magnitude of mass loss and contribution to sea level rise remains highest in Alaska. If mass loss continues to decrease at such a rapid rate in Arctic Canada North, the region may eventually contribute more volume to sea level rise than Alaska.

4.1.2. Chapter 3: glacier mass balance sensitivity

This thesis has determined that glaciers in Iceland are most sensitive to 1-3 °C temperature and 4 % $°C^{-1}$ precipitation increase of all studied regions, followed by Scandinavia and Arctic Canada South, the Russian Arctic, and Arctic Canada North. The proximity of regional accumulation season temperature to the melting point of snow, or, the degree of 'continentality' (how warm and wet a region is) is the primary factor contributing to regional differences in mass balance sensitivity. Temperature during accumulation season in warm, wet regions is close to 0 °C, and may shorten the accumulation season considerably with only a few degrees of warming. In contrast, glaciers in cold regions, in which temperatures of the accumulation season are well below 0 °C, are unlikely to see a substantial shortening of accumulation season from only a few degrees of temperature increase. Secondary factors such as glacier size, albedo, slope, and altitude impact mass balance sensitivity, though to a lesser degree than continentality and proximity to melting point of snow during accumulation season.

4.2. Recommendations for the future

4.2.1. Continued monitoring and collection of glacier mass balance data

Data availability was a persistent problem throughout these studies. The most useful action researchers can take in the future is to continue collecting observational glacier mass balance data to create more spatially and temporally dense datasets in order to continue mass balance studies. It is important that collection of mass balance data prioritizes circum-Arctic regions with few data, such as Arctic Canada North and South; little is known about the glacier mass balance in these regions beyond the few glaciers with glaciological measurements. Glaciers in Arctic Canada North may be particularly important to measure since this region may be experiencing the largest decrease in mass balance of all circum-Arctic regions.

4.2.2. Modelling global glacier mass balance sensitivity using PyGEM

In order to better understand mass balance sensitivity in the circum-Arctic, future studies should focus on constraining how PyGEM interprets the calving component of Alaska and Svalbard, so that the mass balance sensitivity of these regions to temperature increase can be properly modelled. In addition, the mass balance sensitivity of all glacier regions in the world to a 1-3 °C temperature and 4 % $°C^{-1}$ precipitation increase would be useful in order to contextualize mass balance sensitivity of the circum-Arctic and provide an understanding of how sensitive glaciers in other parts of the world are to mass balance change. An understanding of global mass balance sensitivity using the most sophisticated glacier evolution model (PyGEM) in combination with projections of future temperature and precipitation change would allow researchers to better predict how much glacier mass these regions may be expected to lose and how much each region will contribute to sea level rise.

4.2.3. Modelling mass balance sensitivity to factors other than temperature and precipitation

Beyond sensitivity to temperature and precipitation increase, studies of glacier mass balance sensitivity to additional factors should be studied. While the primary driver of mass balance sensitivity is temperature-driven, there is currently limited understanding of how additional factors (such as albedo, thermal regime, etc.) impact mass balance sensitivity. PyGEM treats these additional components as static factors that do not change over time, which is unrealistic over large enough timescales. An understanding of how such factors may contribute to mass balance sensitivity may aid in creating model in which they are treated as dynamic components in mass balance sensitivity, which may improve the accuracy of mass balance models in evaluating glacier mass balance sensitivity.

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APPENDIX 1

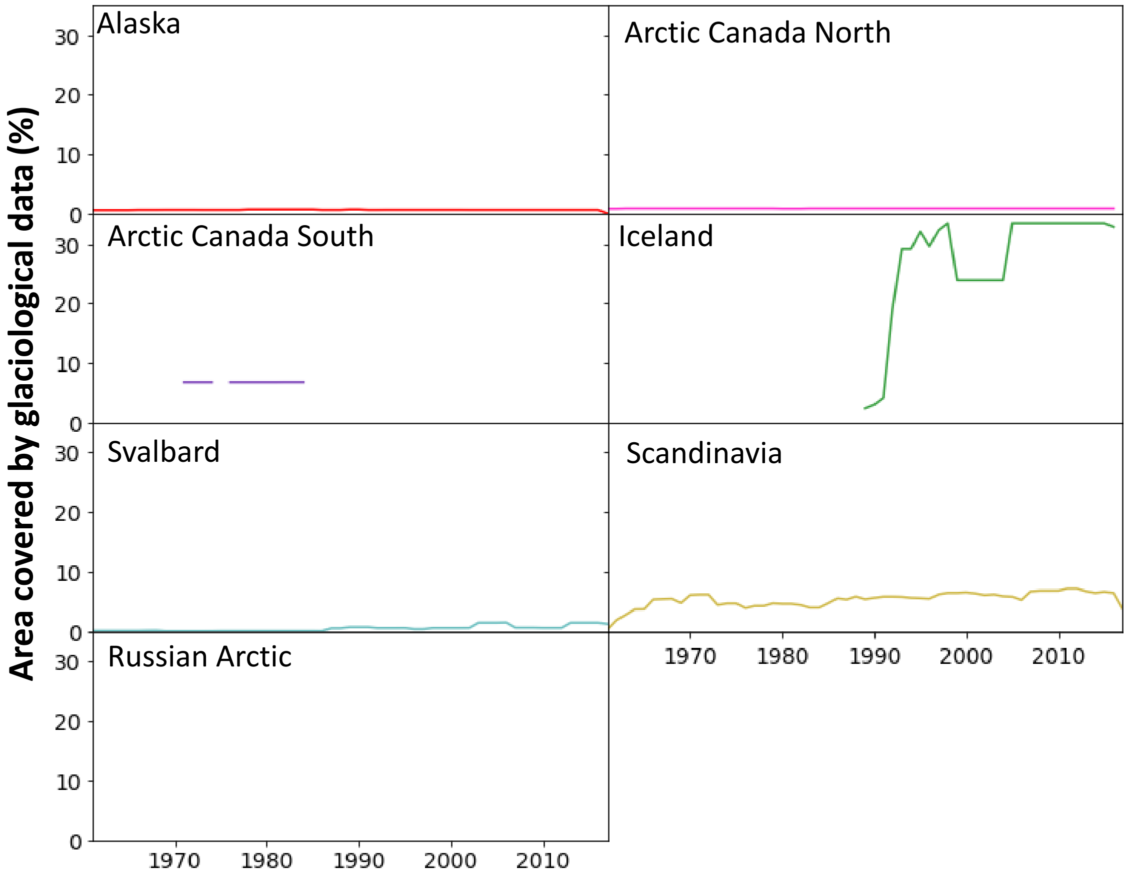

Figure S.6.1. Regional glacier area covered by glaciological mass balance data from the WGMS.

Table S.6.1. Summary of spatial data coverage, temporal data coverage, and mean annual mass balance for the entire period of observation in each glacier region for all glaciological and geodetic data used in these studies.

Study Region	Temporal Coverage	Mean Glacier Count	Mean Area Coverage (%)	Mean Annual Specific Mass Balance (m w.e. a^{-1})
Alaska	1946-2017	996	24	-0.60 +- 0.81
Arctic Canada North	1960-2016	5	1.2	-0.16 +- 0.62
Arctic Canada South	1958-2016	2	4.5	-0.42 +- 0.60
Iceland	1946-2016	59	22	-0.45 +- 0.61
Svalbard	1946-2016	259	13	-0.334+- 0.59
Scandinavia	1946-2016	12	4.3	-0.15
Russia	2000-2016	357	15	-0.39 +- 0.93

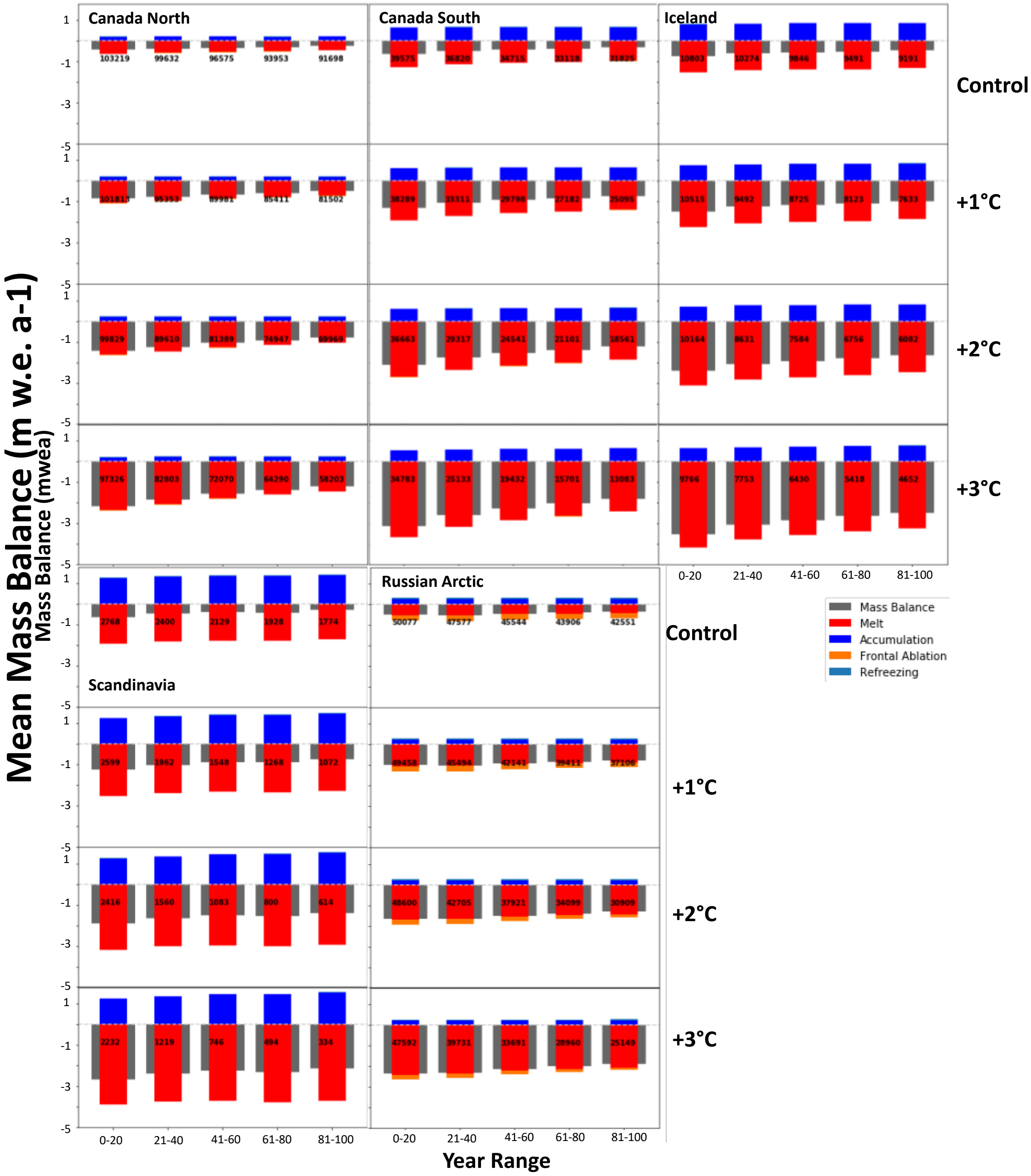

Figure S.6.2. Mean glacier mass balance (and components) for each region and scenario, in 20-year intervals between 2000 and 2100. Modelled with a 1-3 °C temperature and 4 % °C^{-1} precipitation increase.

Table S.6.2. Mass balance components as a percentage of net mass balance for 1-3 °C temperature and 4 % $°C^{-1}$ precipitation increase for 2000-2100.

Region	Scenario	Melt %	Frontal Ablation %	Accumulation %	Refreeze %
Arctic Canada North	control	68	3.8	25	2.8
	+1°C	78	2.1	18	2.6
	+2°C	84	1.2	13	2.1
	+3°C	88	0.77	9.5	1.7
	Mean	**80**	**2.0**	**16**	**2.3**
Arctic Canada South	control	62	0.25	37	0.74
	+1°C	71	0.16	28	0.47
	+2°C	78	0.14	22	0.28
	+3°C	83	0.11	17	0.14
	Mean	**74**	**0.17**	**26**	**0.41**
Iceland	control	63	2.0E-3	37	0.45
	+1°C	71	9.4E-4	29	0.21
	+2°C	78	4.9E-4	22	0.073
	+3°C	84	2.7E-4	16	0.017
	Mean	**74**	**9.3E-4**	**26**	**0.19**
Scandinavia	control	57	0	42	0.95
	+1°C	63	0	37	0.63
	+2°C	68	0	32	0.38
	+3°C	73	0	27	0.21
	Mean	**65**	**0**	**35**	**0.54**
Russian Arctic	control	46	25	24	5.6
	+1°C	63	16	15	4.4
	+2°C	76	10	11	3.1

+3˚C	84	6.5	7.7	2.2
Mean	**67**	**14**	**14**	**3.8**