An investigation into the effects of Proglacial Lakes on Mountain Glacier Dynamics in New Zealand.

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I confirm that the work submitted is my own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract:

This study explores the impact of proglacial lakes on glacier dynamics in New Zealand's Southern Alps / Kā Tiritiri o te Moana by analysing three key dynamics: glacier velocity, ice thickness, and surface elevation change. Using a range of statistical tests, including Zonal Statistics in ArcGIS Pro, the study examines these dynamics in relation to glacier geometries and the distance from the terminus, aiming to determine whether there are differences between lake-terminating and land-terminating glaciers. Despite previous research suggesting that proglacial lakes can enhance glacier velocity due to processes such as basal melting and calving, this study finds no significant differences in velocity, elevation change, and ice thickness between lake-terminating and land-terminating glaciers. These results suggest that other factors could play a more dominant role in influencing glacier dynamics than the presence of a proglacial lake, such as glacier evolution, debris cover or climate change. Further analysis into the spatial variations of glacier dynamics was also undertaken to assess whether this could be a factor that controls glacier dynamics due to the previously mentioned east west precipitation gradient. The findings of this study highlight the complexity of glaciated systems and the controls on glacier dynamics, suggesting that the presence of a proglacial lake plays a secondary role relative to broader environmental influences.

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1. Introduction

1.1. Global climate change

Globally, there has been an increase in atmospheric and ocean temperatures as a result of anthropogenic activity since the industrial revolution (IPCC, 2023). This has caused shifts in weather patterns, increasing the risk of natural hazards, and is leading the world into a sixth mass extinction event (Christenhusz & Govaerts, 2024). By the end of this century, it is estimated that 200 million people may be displaced by sea-level rise. Sea levels are expected to increase by 30-60 cm if greenhouse gas emissions are reduced to limit warming to 2 degrees, and by 60-110 cm if emissions continue to rise, due to thermal expansion of the oceans and melting of the cryosphere (IPCC 2023, 2024). Overall, the impacts of climate change on the Earth system needs to be well understood in order to develop sustainable adaptation and mitigation strategies.

Changes in Earth's ice cover impacts global sea levels, atmospheric and ocean circulation and the availability of freshwater resources (Vellinga and Wood, 2002; Francis and Vavrus, 2012; Vaughan et al., 2013; Rahmstorf et al., 2015; Huss and Hock, 2018; Slater & Shepherd, 2018; Slater, et al., 2020; Zemp et al., 2019a; Immerzeel et al., 2020). Mountain glaciers represent an important resource for drinking water to millions of people (Immerzeel et al., 2020), with the melt from these glaciers also representing the second-largest contributor to sea-level rise after thermal expansion (Marzeion et al., 2014; Miller et al., 2018).

1.2. Glaciers

The cryosphere describes the global stores of water in the form of ice, and includes snow, glaciers, permafrost, and lake and river ice (IPCC, 2023) and holds over 99% of the world's fresh water (Immerzeel et al., 2020). Glaciers are rapidly melting as a result of climate change, globally losing -490 ± 100 kg m^3 yr^{-1} (-123 ± 24 Gt yr^{-1}) of ice between 2006 and 2015 (Figure 1.1, Hugonnet et al., 2021). The highest mass loss rates (>720 kg m^3 yr^{-1}) were observed in New Zealand, Southern Andes, Alaska, Central Europe and Iceland (IPCC, 2023). These changes in glacier dynamics and characteristics contribute to the risk of glacier destabilisation (Mernild et al., 2015). Further research is needed to assess how these dynamics and characteristics have changed.

1.2.1. Mountain Glaciers

Mountain regions, home to approximately 10% of the global population, are significantly impacted by changes in the cryosphere. These changes have downstream effects on physical, biological, and human systems in surrounding areas, including increased hazards and risks to infrastructure, environmental stability, and socioeconomic systems (IPCC, 2023). Ice velocity, influenced by climatic changes, serves as a key indicator of subglacial characteristics and climate change influencing surface melt and subglacial water availability (Kavanaugh & Clarke, 2001; Quincey et al., 2009; Millan et al., 2022). Ice thickness, varying globally, is crucial for understanding glacier dynamics, impacting glacier evolution projections and deformation under simple shear assumptions (Farinotti, et al., 2009; Millan, 2018; Morlighem et al., 2017; Millan et al., 2022).

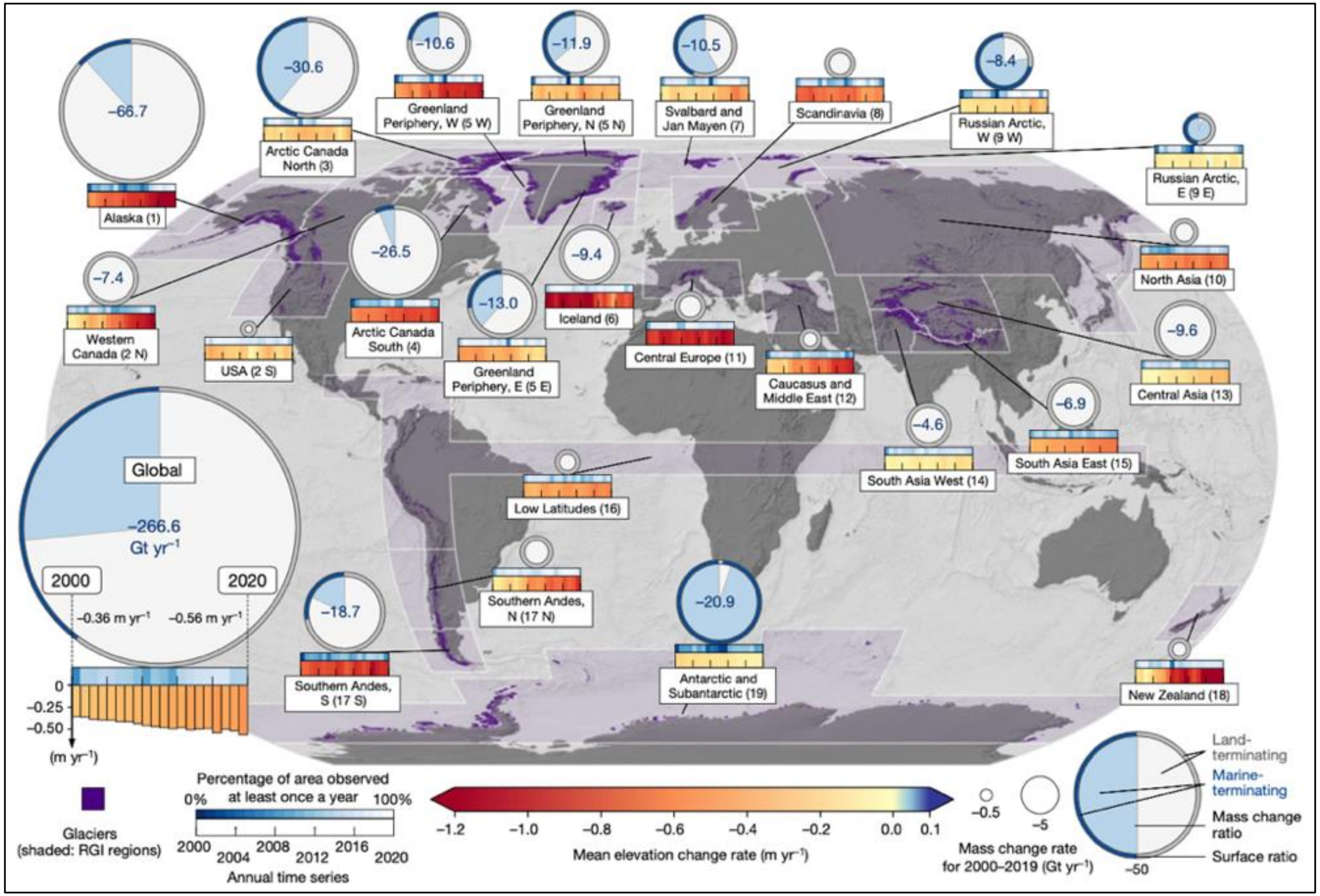


Figure 1.1: Regional glacier elevation change rate and mass change rate (including the percentage of area observed at at least once a year) from 2000 to 2019. Time series of mean surface elevation change rates for glaciers of the 19 first-order RGI 6.0 regions are displayed in the bars next to each region (Hugonnet et al., 2021).

1.2.1.1.New Zealand Glaciers

New Zealand contains over 2900 glaciers (Baumann et al., 2021; Carrivick et al., 2022) spanning over 6500 km, and beyond, the Southern Alps / Kā Tiritiri o te Moana Mountain range and further south (Sturman and Tapper, 1996; Carrivick et al., 2022). Their distribution can be seen in Figure 1.2. Due to their position in the Southern Hemisphere, glacier mass balance in New Zealand is largely influenced by air temperature changes, which is affected by sea surface temperatures and atmospheric circulation, and the glaciers of the Southern Alps / Kā Tiritiri o te Moana are particularly sensitive to climate change based on mass balance sensitivity (1.3 – 2.0 metres of water equivalent (mm w.e.) K^{-1} (Oerlemans, 1997b; Anderson et al., 2006, 2010). Precipitation has a lesser impact on these glaciers (Mackintosh et al., 2017; Vargo et al., 2020). New Zealand glaciers experience significant spatial and temporal variations in mass loss due to the insulating effect of debris. Debris cover, at varying thickness, covers 8% (or 92 km^2) of the glacier surface in the Southern Alps / Kā Tiritiri o te Moana (Anderson & Mackintosh, 2012). Around mid-century, debris reduces net mass loss by 9-13%, dependant on the temperature change scenario (Figure 1.3a), but this effect diminishes to less than 5% by 2100 (Rounce et al., 2023). If global temperatures rise by over 3°C, under a high emissions scenario (Figure 1.3a), as one of the smaller glacierized regions by mass, New Zealand is predicted to undergo near-complete deglaciation. This indicates a high sensitivity to temperature increases between 1.5 and 3°C, with a nonlinear response above 3°C. Overall, New Zealand's glaciers could lose 60 to 100% of their mass depending on the emissions pathway, thus contributing further to sea-level rise (Figure 1.3b).

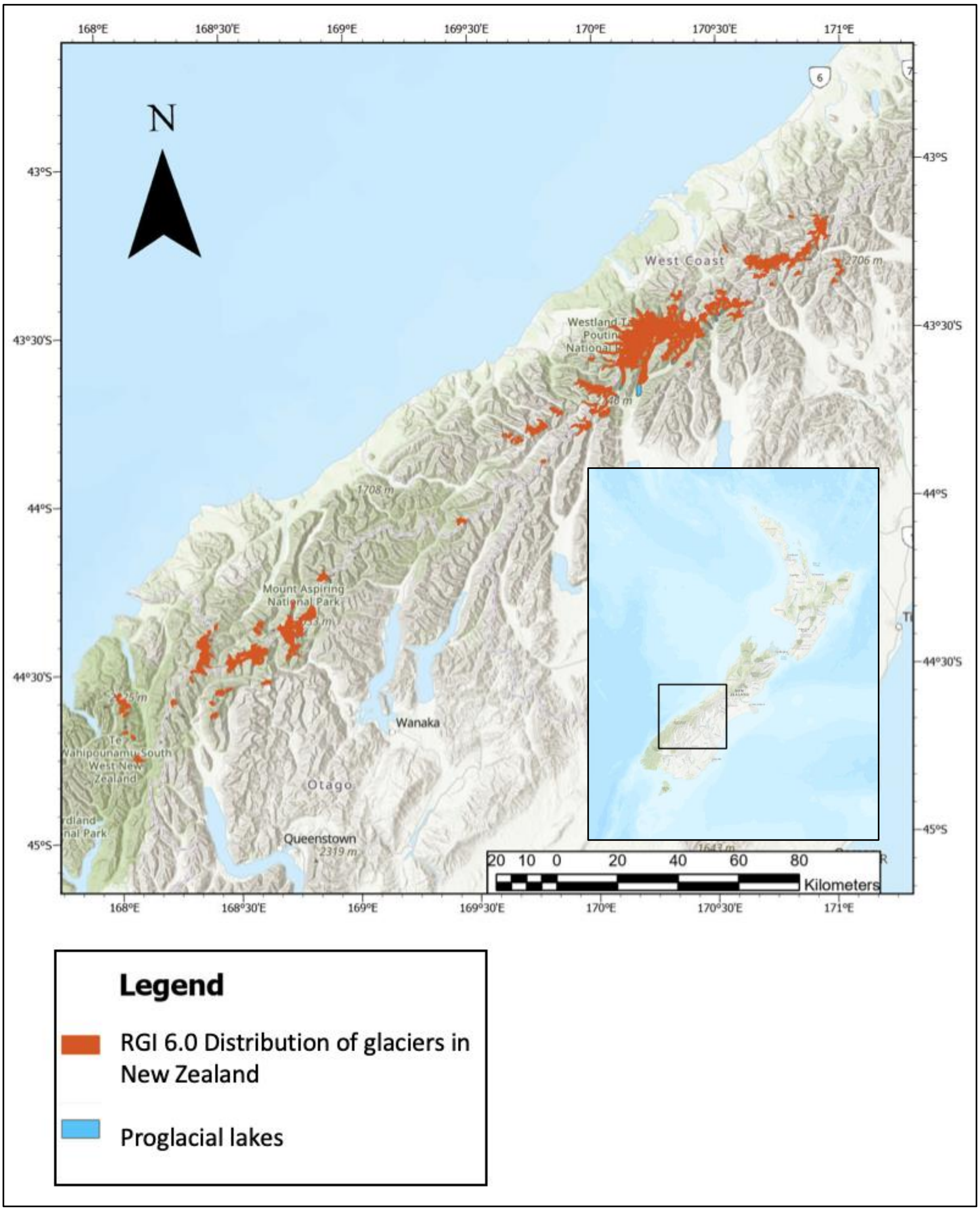


Figure 1.2: New Zealand glacier's location indicated in orange from the RI 6.0.

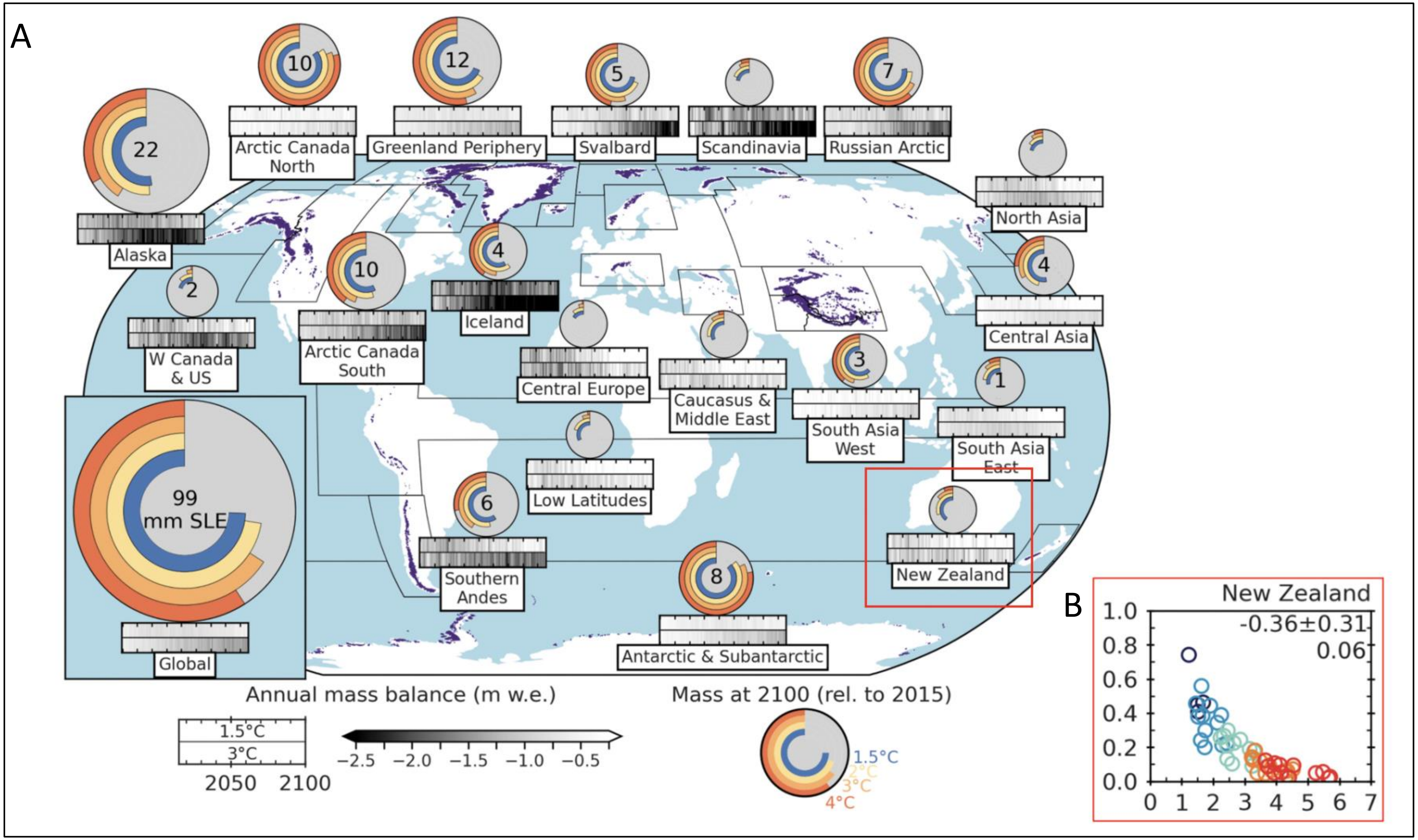


Figure 1.3: A) Regional glacier mass change and contribution to sea level rise from 2015 to 2100, B) Relationship between global mean temperature change (℃) and remaining mass at 2100 (rel. to 2015) for New Zealand glaciers from Rounce et al., (2023).

1.3.Glacial lakes

One important phenomenon associated with some glaciers is the formation of proglacial lakes at their terminus. These lakes serve as indicators of glacial retreat, a direct consequence of climate change, and can accelerate the recession of glaciers as warm lake water promotes melting at the terminus (Sutherland et al., 2020). Earlier stages of proglacial development show little impact on ice flow, however, still enhance ice loss through ablation at the terminus (Carrivick and Tweed, 2013). Later stages of proglacial lake development accelerate mass loss as a result of reduced pressure at the glacier bed increasing ice flow (Dell et al., 2019). As a result, the glacier terminus may float leading to further lake depth increase and glacier recession (Pronk et al., 2021). They can further pose a threat to people living amongst glacierised regions as, when these lakes grow, they can become unstable and prone to sudden outburst floods, known as glacial lake outburst floods (GLOFs) (Veh et al., 2020). In recent years, there has been a growing interest in studying the formation of proglacial lakes, their associated hazards, and how these trends vary in different regions. Existing research disproportionately focuses on specific regions or individual case studies; particularly the Himalaya where there is a greater risk of GLOFs (e.g. Khan et al., 2023).

1.3.1. Glacial lakes in New Zealand

In the Southern Alps / Kā Tiritiri o te Moana, proglacial lakes make up 38% of the total number of lakes in New Zealand (Hamilton et al., 2013), yet less than 1% of New Zealand glaciers have developed proglacial lakes, with this number likely to increase due to climate warming (Chinn, 1999). As a result of glacier surface lowering and calving into proglacial lakes, there has been a 8.4 km^3 reduction in ice volume between 1976 and 2008, equating to a rate of -0.3 $km^3 a^{-1}$ over the last three decades, of New Zealand glaciers (Chinn et al., 2012). The extent to which these proglacial lakes are affecting glacier dynamics in New Zealand glaciers is complex. Studies investigating similar patterns in other regions show that ice contact lakes alter glacier dynamics through two main mechanisms: (1) sub-aqueous melt and (2) calving at the glacier terminus (Scoffield et al., 2024). As a result, the lower elevations of the glaciers are experiencing faster ice flow and dynamic thinning in comparison to land-terminating glaciers (Carrivick et al., 2020).

1.4. Scope of the study

This study will aim to quantify the influence of ice-contact proglacial lakes on New Zealand's glacier dynamics, relating to the glacier velocity, ice thickness and surface elevation change, and to assess whether there are spatial and temporal variations within this influence. New Zealand, an area experiencing one of highest observed mass losses of ice, is disproportionately understudied when looking at the effects of glacial lakes on glacier dynamics, and previous studies have looked at New Zealand glaciers on an individual basis where these effects have been found (e.g. Dykes et al., 2010; Sutherland et al., 2020). To understand the global perspective of what the ice-contact lake and glacier relationship is, an equal balance of research needs to be conducted.

2. Literature Review

2.1.Current state of mountain glaciers

Mountain glaciers, though they only account for approximately 3% of the total global glacier area (Arendt et al., 2002), play a critical role in global water cycles and climate systems. The health of these glaciers is often measured by their mass balance, which refers to the difference between accumulation (mass added, such as from precipitation) and ablation (mass lost, such as from melting) (Meier et al., 2003). When the balance tips towards higher ablation, the glacier experiences negative mass balance, leading to thinning and retreat. These glaciers act as essential proxies for climate change due to their sensitivity to meteorological inputs, making them reliable indicators of shifts in temperature and precipitation patterns (Houston and Hartley, 2003). Furthermore, mountain glaciers are also vital for sustaining downstream water resources, supporting agriculture, and mitigating natural hazards such as landslides and glacial lake outbursts, especially in the regions that depend on their meltwater (Chen et al., 2023). Understanding the dynamics of mass balance and the factors influencing it, such as atmospheric conditions and regional climate variability, is crucial for assessing the future of water availability and the stability of ecosystems.

Accelerated thinning and retreat have been documented in many regions, with global glacier mass loss now exceeding previous worst-case scenarios (Haeberli et al., 2017). Between 2000 and 2019, glaciers have been losing an estimated 267 gigatons of ice annually, contributing significantly to sea-level rise (Hugonnet et al., 2021). Studies have also shown that we are following a trajectory closer to the worst-case scenario in many glaciated regions, where the loss is not just episodic but systematic (Nerem et al., 2018). The regional impacts, including reduced water supply for irrigation and hydropower, as well as increased geological hazards, are already being felt (Chen et al., 2023). It is therefore critical to continue refining models of glacier response to climatic changes and assess whether the current mitigation strategies are sufficient to protect these vital ecosystems.

2.2. Drivers of mass loss in New Zealand

Hugonnet et al. (2021) provides a global summary of glacier mass loss in the 21st century. Due to the Southern Alps /Kā Tiritiri o te Moana high latitude and maritime location, the warm summer inputs of solar radiation results in these glaciers have a high ‘activity index’ or high mass turnover (Hay and Elliot, 2008). These drivers of mass loss are mentioned below.

2.2.1. *Global Warming*

Rising global air temperatures profoundly affect mountain glaciers, speeding up their melt and decreasing their mass balance (Wang et al., 2020). Temperature change in New Zealand also appears to be the dominant force of mass loss of glaciers with the characterisation of a negative mass balance correlating with above average air temperatures, along with a southwest airflow and more blocking patterns, referring to high pressure atmospheric patterns blocking the 'norm' flow of west to east (Chinn et al., 2012). The increase in temperature since 1860 to 2020 from Berkeley Earth [accessed 20/09/24] can be seen in figure 2.1. Global warming can further lead to a reduction in the quantity of snowfall in the accumulation zone and increases the amount of melt, and mass loss in the ablation zone via increased melt (Miles et al., 2020) with the glacier gaining most of its mass during winter, when the air temperature is colder, and more snow falls and losing it during the warmer summer months. On the contrary to this, global warming can also cause an increase in precipitation (see section 2.2.2.), causing glacier velocity to increase (Pepin et al., 2022).

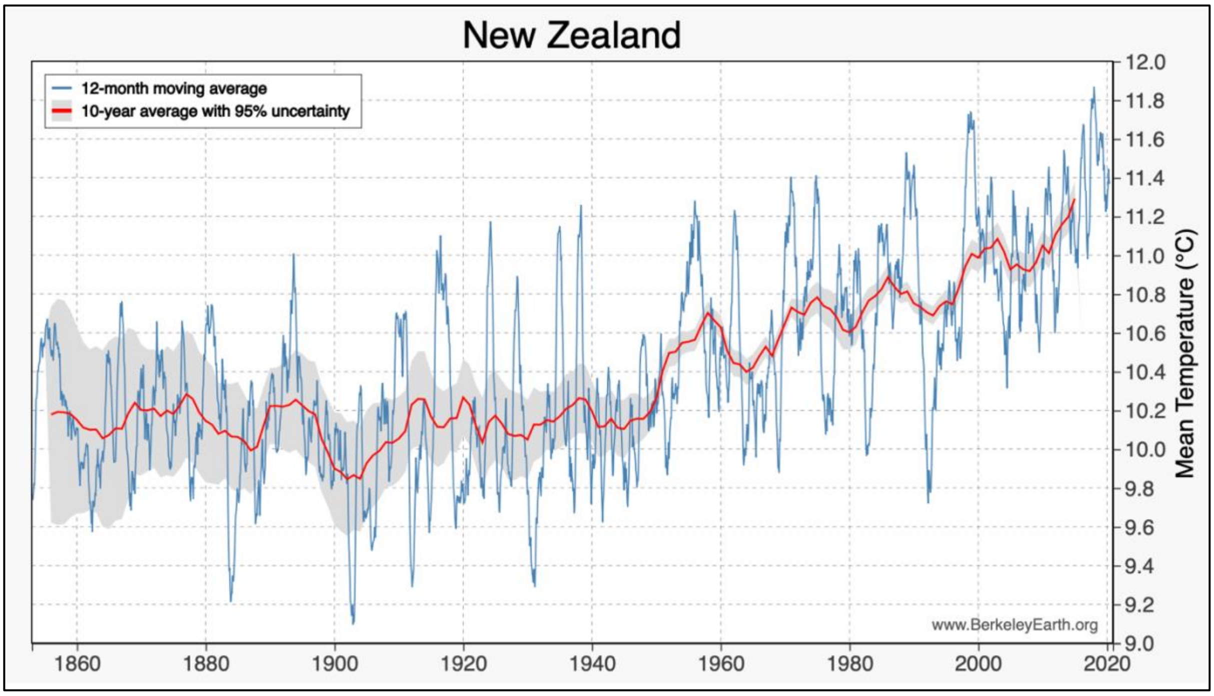


Figure 2.1. from Berkeley Earth, 12-momth moving average (blue) and 10-year average with 95% uncertainty (red) of mean temperature between 1860 and 2020. Access here: https://berkeleyearth.org/temperature-region/new-zealand

Furthermore, mountain glaciers have shown an amplified response to the increase in air temperatures, from Elevation Dependent Warming (EDW) (Thakuri et al., 2019), which is influenced by snow/ice cover, water vapour, aerosols, and soil moisture (Rangwala and Miller, 2012), global radiation and land cover (Tudoroiu et al., 2016). This can be used to explain why lower elevation glaciers are declining at a faster than average rate (Peppin et al., 2022). In New Zealand the glaciers are a few hundred meters above sea level, with these elevations melt rates are much higher and exhibit some of the fastest melt rates on earth (~20m per year) (Anderson et al., 2006), and due to these low elevations, they are likely more prone to the issues associated with EDW, such as the amplified response to global warming.

2.2.2. Precipitation

Glaciers primarily gain mass through precipitation, which falls as snow in the accumulation zone, located at the top of the glacier (Cogley et al., 2011). Additional sources of mass accumulation include wind drift, avalanches, resublimation, and condensation (Kaser et al., 2003). The relative contribution of these processes varies by region. In New Zealand, this is influenced by the east-west precipitation gradient, where the West receives more rainfall than the East on the South Island (Chinn et al., 2012). This variation is particularly significant in mountain glacier environments, where factors such as elevation and proximity to oceans play a key role. While precipitation patterns strongly affect glacier mass balance (Pepin et al., 2022), the exact relationship between climate variables and glacial dynamics remains uncertain (IPCC, 2023). This uncertainty arises from limited weather station data, differences between mountain regions studied, and the challenges of measuring precipitation at high altitudes (Goodison et al., 1998; Kochendorfer et al., 2017; Whiteman, 2000).

In maritime mountain environments, where glaciers are influenced by nearby oceans, the dynamics of precipitation and glacier mass balance are particularly complex (Fitzharris et al., 1992). There is more agreement between datasets about the weakening influence of orographic effects on precipitation than about temperature trends (Wang et al., 2014). Orographic precipitation, which is driven by moist air rising over mountains, plays a crucial role in many maritime glacier regions. For example, the weakening of orographic precipitation has been observed in mid-and high latitudes, potentially linked to a weaker mid latitude jet stream, which could reduce the precipitation contrasts between windward and leeward slopes (Barnes and Screen, 2015; Francis and Vavrus, 2015).

In New Zealand, glaciers are located in high latitude landscapes influenced by the surrounding oceans and the interaction between subtropical and polar air masses (Cullen et al., 2019). These maritime glaciers are strongly influenced by the prevailing westerly airflow, which plays a critical role in their mass balance (Fitzharris et al., 1992; 1997). During winter, precipitation contributes to glacier accumulation, while in the warmer summer months, the same precipitation accelerates glacier melt (Mackintosh & Anderson 2017). The mean climatological precipitation from 1979-2021 (Figure 2.2; Vishwanathan et al., 2024) shows the strong east-west gradient of precipitation influenced by the maritime climate of the area.

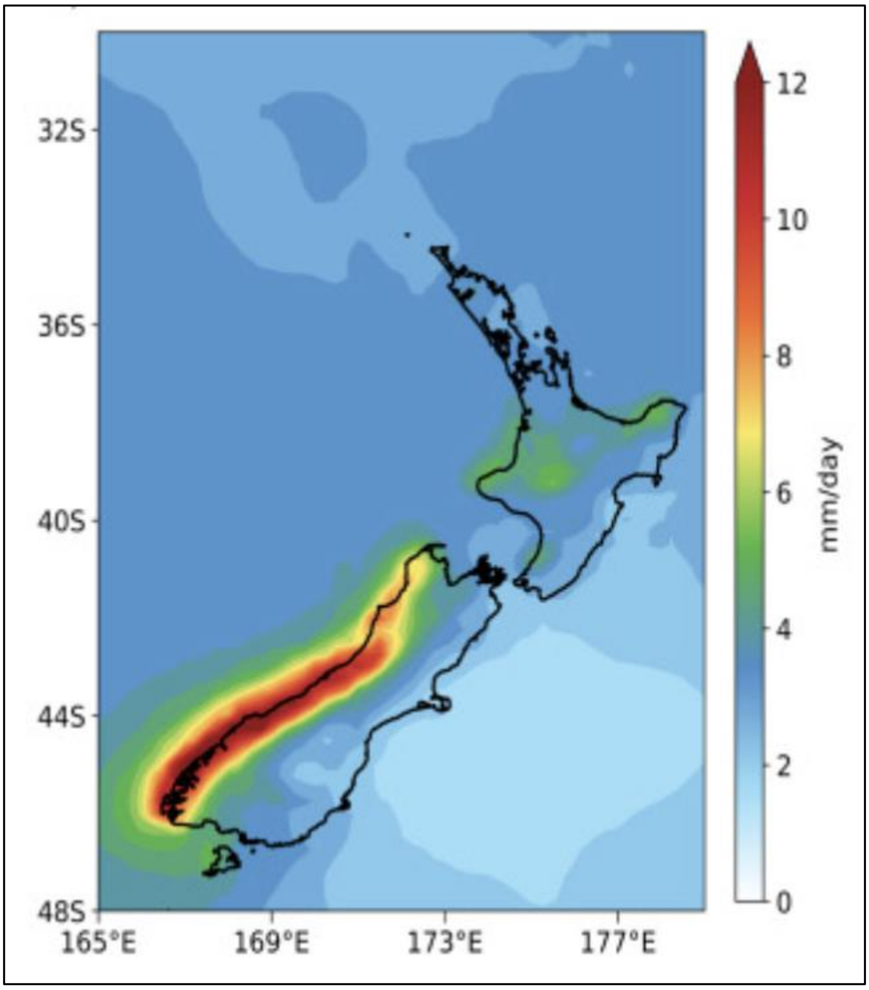


Figure 2.2. Mean climatological precipitation in mm/day obtained using ERA-5 data averaged over 1979-2021 period from Vishwanathan et al., 2024.

2.2.3. Debris cover

Although unique to every individual glacier, the extent and thickness of debris cover on glaciers is influenced by climatic changes, but this is often not reflected in climate models (Herreid and Pellicciotti, 2020). Globally, climate change has led to increased debris cover (Deline, 2005), altering the albedo and the amount of absorbed solar radiation, which affects the glacier's surface energy balance and melt (Shaw et al., 2021). Surface energy balance refers to the amount of absorption of heat onto the glacier surface. If the surface energy balance is positive the surface will warm, if exceeding 0°C, with the excess energy resulting in melt (Arnold et al., 2006). Debris-covered glaciers exhibit more stabilised melt rates during the ablation period, with latent heat flux playing a crucial role (Yang et al., 2017). Thin debris cover increases energy absorption, accelerating melt rates, while turbulent fluxes help maintain nearly constant melt rates (Steiner et al., 2018).

As debris cover increases, it initiates a positive feedback loop, with more shortwave radiation being absorbed, significantly affecting the glacier's mass balance (Pellicciotti et al., 2008). The darker surface resulting from increased debris cover enhances shortwave radiation absorption, making it a dominant factor controlling mass balance (Braithwaite and Raper, 2009). However, once debris reaches a critical thickness, it insulates the glacier, reducing further thinning (Figure 2.3) (Ostrem, 1971). This insulating effect is tied to the degree of gravitational reworking, which can serve as a proxy for the age of the glacier's surface debris. In New Zealand studies have found (Carrivick et al., 2022) that the debris cover has led to the formation of supraglacial ponds and eventually forming proglacial lakes. Even though the presence of lakes at the glacier terminus have previously found to enhance mass loss (King et al., 2019). The debris cover present, has contributed to a reduction in mass balance sensitivity from west to east. With the glaciers in the east being predominantly debris cover lake terminating and the glaciers to the west being "clean ice" land terminating glaciers (Chinn, 2001).

Baumann et al., (2021) emphasize that factors, such as debris cover, also play a crucial role in modulating mass balance sensitivity (see section 5.2.3.), with the western, land terminating glaciers exhibit more 'clean ice' and the eastern, lake terminating glaciers are more debris covered (Berthier et al., 2012).

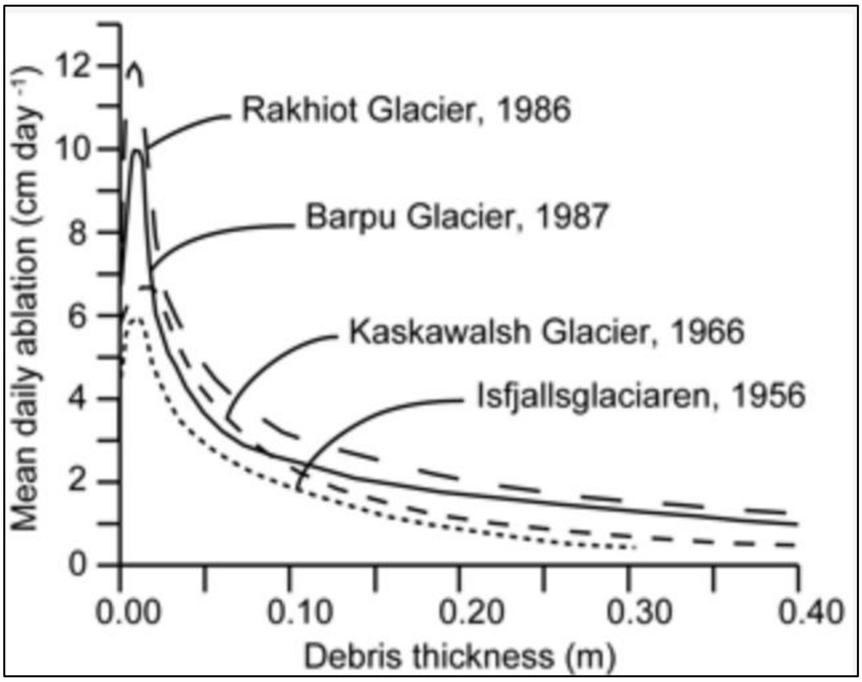


Figure 2.3. Examples of the relationship between supraglacial debris thickness and underlying ice ablation rate (Ostrem, 1971).

Surface ponds are significant contributors to glacier mass loss by absorbing more energy than bare ice through incoming solar radiation (Miles et al., 2018). This contribution to mass loss further leads to surface meltwater drainage through supraglacial/englacial conduits (Benn et al., 2012). These ponds warm seasonally and add to localised surface ablation (Benn et al., 2017). The presence of these ponds is usually determined by surface slope and ice velocities, with glaciers in New Zealand only having supraglacial ponds present with a slope below 2° (Rohl, 2008). Rohl (2008) further found that in New Zealand, specifically the Tasman glacier, supraglacial ponds initiated the development of the Tasman Lake in the 1980s and still continues to contribute to terminus disintegration and ice loss. Between 2000-2003, total pond area increased by 106%, along with the number of ponds increased from 18 to 30. Furthermore, ice loss from the presence of supraglacial ponds is 0.9 x 106 m^3/yr, which accounts for approximately 10% of surface ice loss. As a result of pond development, ice faces are exposed, causing disintegration which causes bare ice to be exposed and trigger rapid back-melting.

Ice cliffs refer to steep or vertical ice faces often associated with glacier streams and ponds (Kneib et al., 2023). Ice cliffs enhance melt due to increasing the absorption of incoming solar radiation, increasing melt and meltwater drainage to the base of the cliffs where possible hydrofracture could occur (Kneib et al., 2021). It was found by Miles et al. (2017) that this increase in melt as a result of ice cliffs was profound in areas at (a) high elevations and (b) where debris is thick. Debris covers around 11% of the glaciers area in HMA, and one-third of the ablation zone – where glaciers mass loss is proficient (Kraaijenbrink et al., 2017). With the increase in air temperatures, causing glaciers to become more debris covered, this ice cliff melt enhancement could further be exacerbated in frequency and extent. Analysis of UAV orthoimages and DEMs showed that 79% of new cliff areas formed were related to streams or ponds (Kneib et al., 2023). Field observations confirmed the association between hydrological features and the formation and persistence of ice cliffs. Cliffs influenced by ponds accounted for 19.5% and those influenced by streams for 38.9% of the total cliff area. Crevasse-originated cliffs, which represent 19.7% of the cliff area can further be related to proglacial lakes or streams entering the glaciated system (Kneib et al., 2023).

As mentioned in section 2.3, lake terminating glaciers are prone to calving events. Glaciers prone to calving events are highly sensitive to bedrock geometry changes in water depth, and lake temperature (Minowa et al., 2023). These glaciers in particular lose mass at the terminus through frontal ablation through calving and subaqueous melt (Truffer and Motyka, 2016). In New Zealand, calving mechanisms are caused by thermal undercutting at the waterline which creates flake calving above (Warren and Kirkbride, 2003). The changes in the lake processes in turn drive changes in the glacial processes. In lake terminating glacier, a linear correlation exists between calving speed (uc) and water depth (hw), expressed as uc = 17.4 + 2.3 hw m. Furthermore, water temperature also positively correlates with calving rates ($r^2 = 0.85$) (Kennett et al., 1997). Warren and Kirkbride (2003) state that, although calving increases glacial retreat rates (average of 12 m/year to 50 m/year) (Chinn 1996; Purdie and Fitzharris, 1999), they are not completely decoupled from climatic forcing, with them occupying a position in-between non-calving land terminating glaciers, being the most sensitive, and tidewater glaciers, being the least sensitive (Warren and Kirkbride, 2003).

2.3. Proglacial lakes

Proglacial lakes develop when glaciers recede and leave behind topographical depressions which fill with meltwater from the retreat. These lakes are characterised by their proximity to glaciers and their dynamic nature as they are consistently influenced by glacial meltwater inputs (Carrivick et al., 2022: Russell et al., 2011). The formation of proglacial lakes in a valley glaciated system, often associated with mountain glaciers, is shown in Figure 2.4. (Bogen et al., 2015). Ice-contact lakes interact with glacier tongues, influencing the morphology of glacier margins and glacier dynamics in various ways (Otto, 2019). The presence of standing water reduces friction, allowing the ice to float and occasionally calve. It is important to note however, many glacial lakes are too shallow for ice to float, therefore calving occurs on grounded ice (Benn & Astrom, 2018). Furthermore, the entry of subglacial meltwater into the lake increases basal water pressure, lifting the glacier tongue (Tsutaki et al. 2011). These factors alter the longitudinal stress balance of the glacier, leading to increased ice flow velocity. This feedback mechanism is entirely separate from changes induced by climate (Carrivick and Tweed 2013).

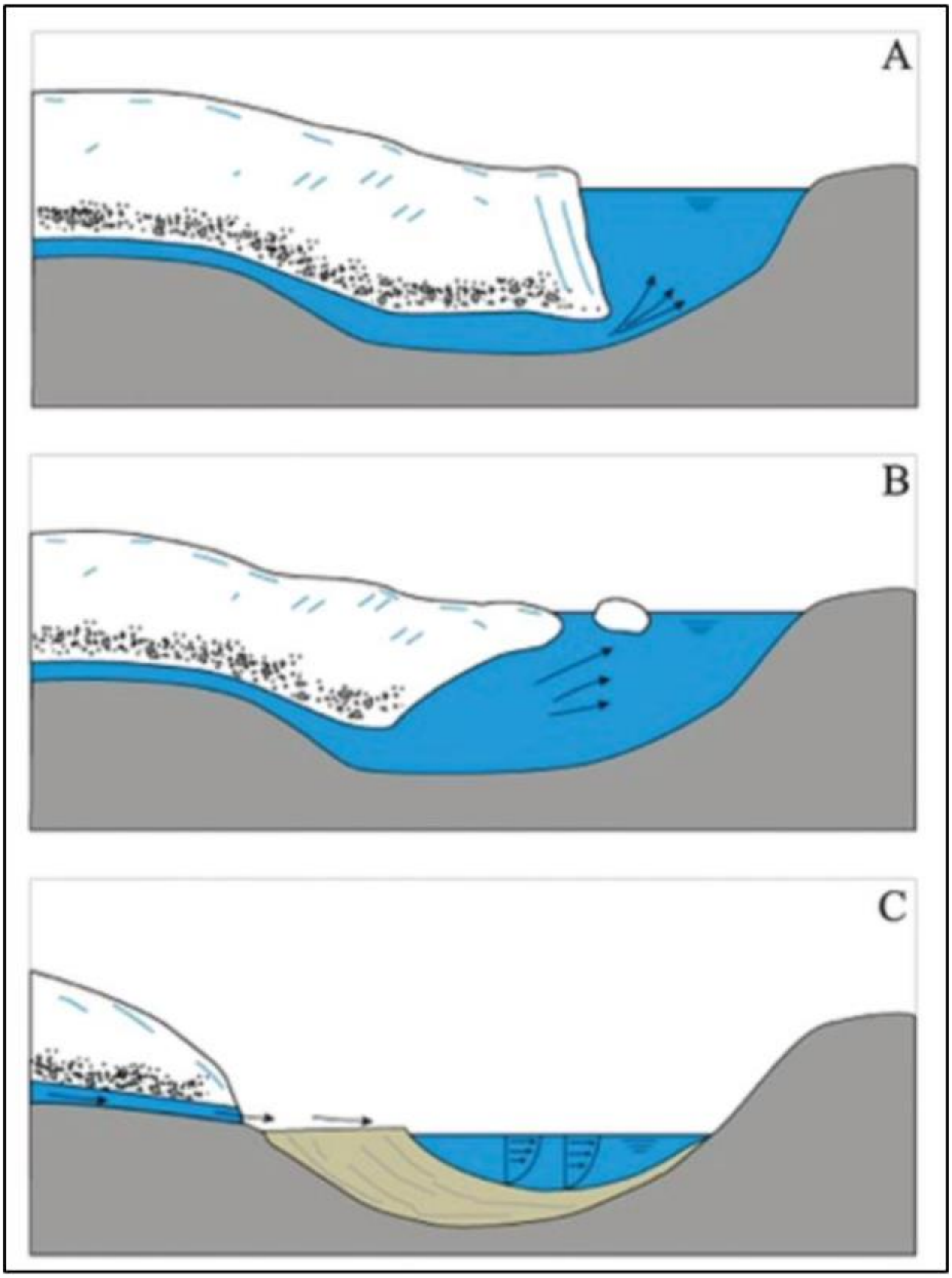


Figure 2.4. Formation of proglacial lakes in a Valley Glaciated System from Bogen et al., (2014). A) Shallow Lake: glacier upon lakebed. Recession of glacier determined by winter precipitation, summer temperature, B) Thin glacier/deep lake: calving, large amount of sediment delivered from melting ice irregular currents in lake. C) Glacier on land: sediment delivered from sub-glacial tunnel at delta front and deposited on delta in glacier fed lake.

Proglacial lakes can also affect the thermal regime of glaciers. Warm lake water increases basal melting of the glacier tongue, or internal melt if it enters the glacial plumbing system from lateral ice-dammed lakes. Within the lake, basal melting reduces ice thickness by creating notches and initiating crevasse formation (Diolaiuti et al. 2006; Benn et al. 2009). This process often leads to calving, and sometimes GLOFs, which rarely occur in New Zealand. Overall, glaciers terminating in lakes experience greater mass loss compared to those without ice-contact lakes (Song et al. 2017).

The projected increase in the number and size of proglacial lakes can be understood by examining the development of previous proglacial lakes and the conditions upon which they formed (Azzoni et al., 2023). In the Swiss Alps, Molg et al. (2021) found that between the LIA (Little Ice Age) and the 1970s, there was an increase in the number and area of proglacial lakes which then decreased between then and the 2000, driven by a decrease in temperature and increased summer precipitations, meaning the mass balance of the glaciers increased due to less ablation, reducing the lake area development. This was then further followed by the largest number and area of lakes recorded up until 2016. Buckel et al. (2018) also found an increase in lakes in the Austrian Alps since the LIA, with observations of 260 more lakes, coinciding with long- and short-term trends of rising temperatures. The increase in size and number of proglacial lakes also leads to a reduction in glacier mass balance in comparison to land terminating (Carrivick et al., 2022), which further contributes to the increase in size and deepening of these lakes. This increase in size and frequency is also expected to increase the risk of GLOFs due to the deglaciation of mountain regions worldwide. In New Zealand specifically, no moraine dammed lake being broken has been recorded, and only a few accounts of dam overtopping's have been mentioned (Brambus, 2017). The Franz Josef/ Kā Roimata o Hine Hukatere glacier is the only glacier within the region which has specifically been studied in terms of outbursts floods (Davies et al., 2003; Goodsell et al., 2005), however no lake is present at the terminus of Franz Josef / Kā Roimata o Hine Hukatere and the floods were caused by englacial water release (Goodsell et al., 2005).

Shugar et al. (2020) mapped the world's glacial lakes and scaled their area to estimate their volume. They found that glacial lake volume increased by ~48% between the years of 1990 and 2018, with an increase in the extent and number by 53% and 51% respectively. Mass loss can further be exacerbated due to lake growth decoupling from climate due to positive feedback cycles (Trussel et al., 2013; Wilson et al., 2018; Bolch et al., 2022) causing rapid retreat of these glaciers. Other studies, such as Cook & Quincey (2015) analysed that the relationship between lake area and volume can produce errors of up to 400% for certain lake types, emphasizing the need for more nuanced approaches. Notably, supraglacial lakes and those with complex bathymetries are particularly difficult to estimate accurately. Verpoorter et al. (2014) also noted a significant variability in lake depth-area relationships globally. But, with the development on further high-resolution satellite imagery and LiDAR more precise data of lake volume has been able to be produced (Messager et al., 2016).

It has been found that lake terminating glaciers experience significantly higher rates of thinning, velocity, and deceleration in comparison to land terminating glaciers within the same regions (Agarwal et al., 2023). Agarwal et al. (2023) found that proglacial lakes within the central and eastern Himalaya from 1975 and 2017 showed an overall growth of 98% and 40% respectively. This increase in both growth and numbers of proglacial lakes led to glaciers experiencing mass loss at a faster rate, further contributing to this growth. Other studies, specifically in New Zealand, have also studied the differences between lake and land terminating glacier dynamics, such as Sutherland et al., (2020), who found that lake terminating glaciers in New Zealand receded >4 times further and flowed up to 8 times faster than the land terminating glaciers in similar climates. Carrivick et al., (2022) further found similar trends where glaciers with a lake present at their terminus experience greater terminus retreat than similarly sized land terminating glaciers, with further analysis showing a positive relationship between mean glacier mass balance and lake growth rate ($r^2 = 0.34$) and the length of the ice contact lake boundary ($r^2 = 0.44$).

2.4. New Zealand glaciers spatial and temporal trends

2.4.1. Temporal trends

Hugonnet et al., (2021) showed an average annual thinning rate increase in New Zealand glaciers of 1.52 ± 0.50 m yrr^{-1} between 2015-2019: a nearly sevenfold increase than the period of 2000-2004. Moreover, New Zealand's temperatures have risen by 1.13°C between 1909 and 2019, which relates closely to the thinning rates of glaciers in New Zealand (Lorrey et al., 2022). This temperature rise predominantly influences glacier mass balance, evident in the accelerated rise of end-of-summer snowlines in recent decades (Lorrey et al., 2022). These findings underscore the urgent need to analyse climate-induced glacier changes in the Southern

Alps / Kā Tiritiri o te Moana due to the increased rates of glacier thinning and mass loss in the region.

2.4.2. Spatial trends

An east-west precipitation gradient contributes to differing glacier dynamics on either side of the Southern Alps / Kā Tiritiri o te Moana divide (Section 2.4.2; Figure 2.2). This is characterised by a humid wet climate on the west and a drier climate on the east, which is heavily influenced by the Southern Alps /Kā Tiritiri o te Moana causing varied precipitation across the country (Chinn, 2001). With mean annual precipitation ranging from 3000 mm on the narrow western coastal plains to over 10,000 mm near the main divide, diminishing to approximately 1000 mm in the eastern ranges (Chinn, 1999; Griffiths and McSaveney, 1983; Henderson and Thompson, 1999). Consequently, glacier mean elevations rise from 1500 m in the west to over 2000 m in the drier eastern regions. Significant precipitation differences, studies indicate that climate response of the glaciers between east and west are different (Chinn, 1996, 1999).

Figure 2.4. shows the mean mass balance of New Zealand's major glaciers (1972–2011), surface debris cover, and proglacial lakes, with the largest ice volume centred around Aoraki/Mt Cook (3,724 m) at 43°S. Significant mass balance gradients exist, influenced by elevation and position relative to the main divide including the previously mentioned precipitation gradient with the wetter west and the drier East. Franz Josef / Kā Roimata o Hine Hukatere and Fox glaciers have snow accumulation rates of ~10 m and melt rates of ~20 m/yr respectively (Mackintosh et al., 2017, figure 2.5.). Surface debris covers the lower elevations of glaciers such as Tasman, Hooker, Mueller, and Murchison. Terminal lakes have grown rapidly at these glaciers since the 1980s.

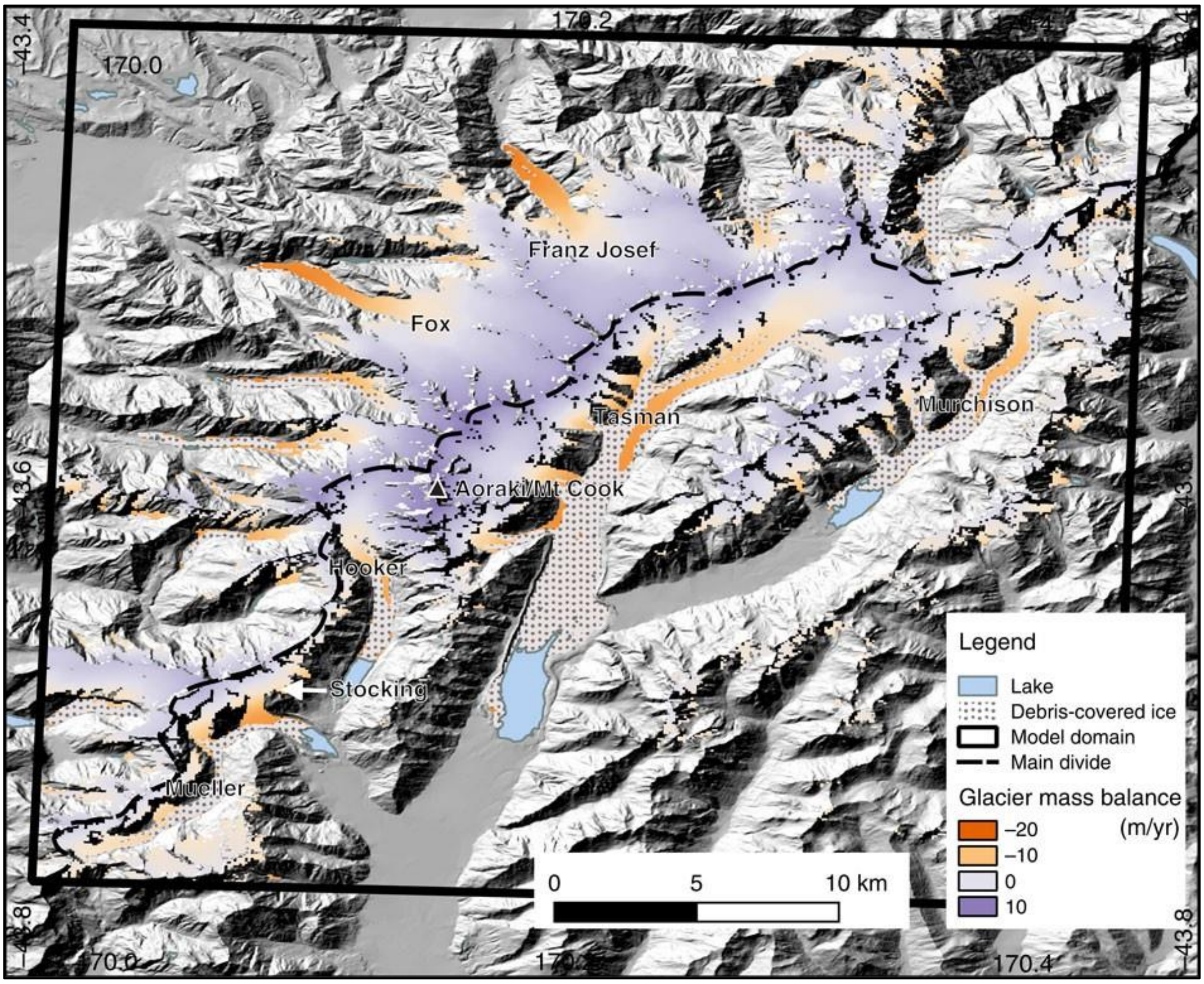


Figure 2.5. From Mackintosh et al., (2017) Mass balance of New Zealand's largest glaciers with mass balance shown in red (net melt) and blue (net accumulation).

2.5. Conclusions

Overall, there is a need for a comprehensive and in-depth assessment of the influence of proglacial lakes on glacier dynamics (Section 2.1), referring to ice thickness, surface elevation changes and velocity, which this project aims to investigate. Many studies have successfully addressed the increase in size, and number of proglacial lakes worldwide using combinations of in-field measurements and remote sensing techniques, many of these using similar, or the same datasets as this study. However there has been limited analysis on the extent of the influence of lakes on glacial dynamics, and the spatial variation of any influence within New Zealand. Given the projected future increase in glacial lake area and volume in this region, by 2100, 29 km² of overdeepenings are expected to become ice-free, forming new ice-marginal lakes, with the historical rate of lake size increase continuing until the 2050s before slowing as more lakes lose contact with the ice margin (Carrivick et al., 2022), it is crucial to assess the impact of proglacial lakes on future glacier mass balance.

2.6. Research Question:
What are the controls of proglacial lakes on New Zealand's Mountain glacier dynamics?

Objectives:

2.6.1. To assess the influence of proglacial lakes on glacier ice thickness in New Zealand.

2.6.2. To assess the influence of proglacial lakes on glacier velocity in New Zealand.

2.6.3. To assess the influence of proglacial lakes on glacier elevation change in New Zealand.

2.6.4. To assess the spatial differences between East and West sloped glaciers response to proglacial lake dynamics in New Zealand.

3. Methodology

3.1. Study Area

New Zealand's Southern Alps / Kā Tiritiri o te Moana, located approximately between 34° and 46°S latitude and 166° and 178°E longitude, are home to over 3,000 glaciers, reaching elevations of up to 3,724 meters (Baumann et al., 2021) (Figure 1.2). The Southern Alps / Kā Tiritiri o te Moana are characterized by a significant precipitation gradient, separating the east and west at the main divide. Western glaciers experience a much more humid and wet environment, while the climate is drier in the east (Ummenhofer and England, 2007). Between 2013 and 2022, average annual rainfall in the west ranged from 1,366 mm to 6,915 mm, while the east received 547 mm to 1,057 mm (Stats NZ). The spatial variations in precipitation can be seen in figure 2.1.

Since 1998, there have been considerable interannual fluctuations in glacier mass loss. The entire glaciated region has undergone significant changes in glacier behaviour, marked by an increase in the rate of glacier mass loss. The ice volume decreased from 26.6 km^3 in 1977 to 17.9 km^3 in 2018, representing a loss of 8.6 km^3, or 33%, at an average rate of 0.21 km^3 per year. Between 1977 and 1997, there was an annual ice gain of 0.30 km^3 per year, but this was followed by an accelerating ice loss of 0.67 km^3 per year from 1998 to 2018 (Salinger et al., 2019). These changes align with shifts in climate parameters and circulation indices

The western slopes of New Zealand exhibit characteristics typical of humid maritime region glaciers due to their proximity to the Tasman Sea, with termini approximately 300 meters above mean sea level (Chinn, 1996). The proximity of these glaciers to the ocean results in heavy precipitation events, which have multiple effects. First, at higher elevations, this precipitation nourishes the glaciers by contributing significant snowfall. At lower elevations, however, the precipitation often falls as rain, directly melting the ice. Additionally, the runoff from valley sides, driven by rain and snowmelt, further lubricates the base of the glaciers. As a result, glaciers experience basal sliding when they reach the pressure melting point. This process is most prevalent in the summer, when the abundance of meltwater accelerates sliding. Because many of these glaciers have low-elevation tongues, they remain close to the melting point throughout the year, leading to fast response times to climatic fluctuations (Fitzharris et al., 1992). Glaciers in the East, which have longer response times, are generally drier which leads to less sensitivity to climate forcing (Fitzharris et al., 1992).

Overall, the Southern Alps / Kā Tiritiri o te Moana glaciated system is highly reactive to climatic and precipitation changes, which is typical of an active warm-based system (Ishikawa et al., 1992; Marcus et al., 1985; Takeuchi et al., 1999). Studying New Zealand's glaciers is crucial due to the northern hemisphere study bias, which has left Southern Hemisphere glaciers significantly understudied (Purdie et al., 2014). Chinn (1996) documented substantial thinning and retreat of the Southern Alps / Kā Tiritiri o te Moana glaciers throughout the 20th century, providing a long-term record of glacier change. From a human impact standpoint, 60% of New Zealand's electricity comes from hydropower, and changes in glacier melt and mass loss could significantly affect systems such as the Waitaki River, which supports eight hydroelectric generators and contributes 35-40% of the country's hydropower (Purdie & Bardsley, 2010). The upper Waitaki glacierised catchment (see figure 3.1) provides ~80% of the inflow to the river system (Borzecki, 2022). Additionally, the glacial lakes present in the Upper Waitaki Basin account for 60% of the controllable water storage available in the country (Sirguey, 2010).

Stuart et al. (2016) explored the impacts of glacier retreat on tourism, specifically in Westland Tai Poutini National Park. Fox Glacier, for example, has retreated over 700 meters since 2008, affecting accessibility and visitor experiences. Many express a "last chance to see" sentiment, and while operators are adapting to the glacier recession, future changes may limit their ability to do so. Tour operators, policy makers and scientists have been advised to work together to try and find a healthy balance between safety, conservation and utilization, and by doing so, hope to find a solution to what can be done in New Zealand regarding glacial tourism (Smiraglia et al., 2008). Overall, New Zealand glaciers provide insights into how glaciers respond to climatic forcing, and given their range of surface characteristics, the spatially varying climatic controls, and the presence and absence of glacial lakes in neighbouring catchments, there is excellent opportunity to examine the major environmental controls in some detail.

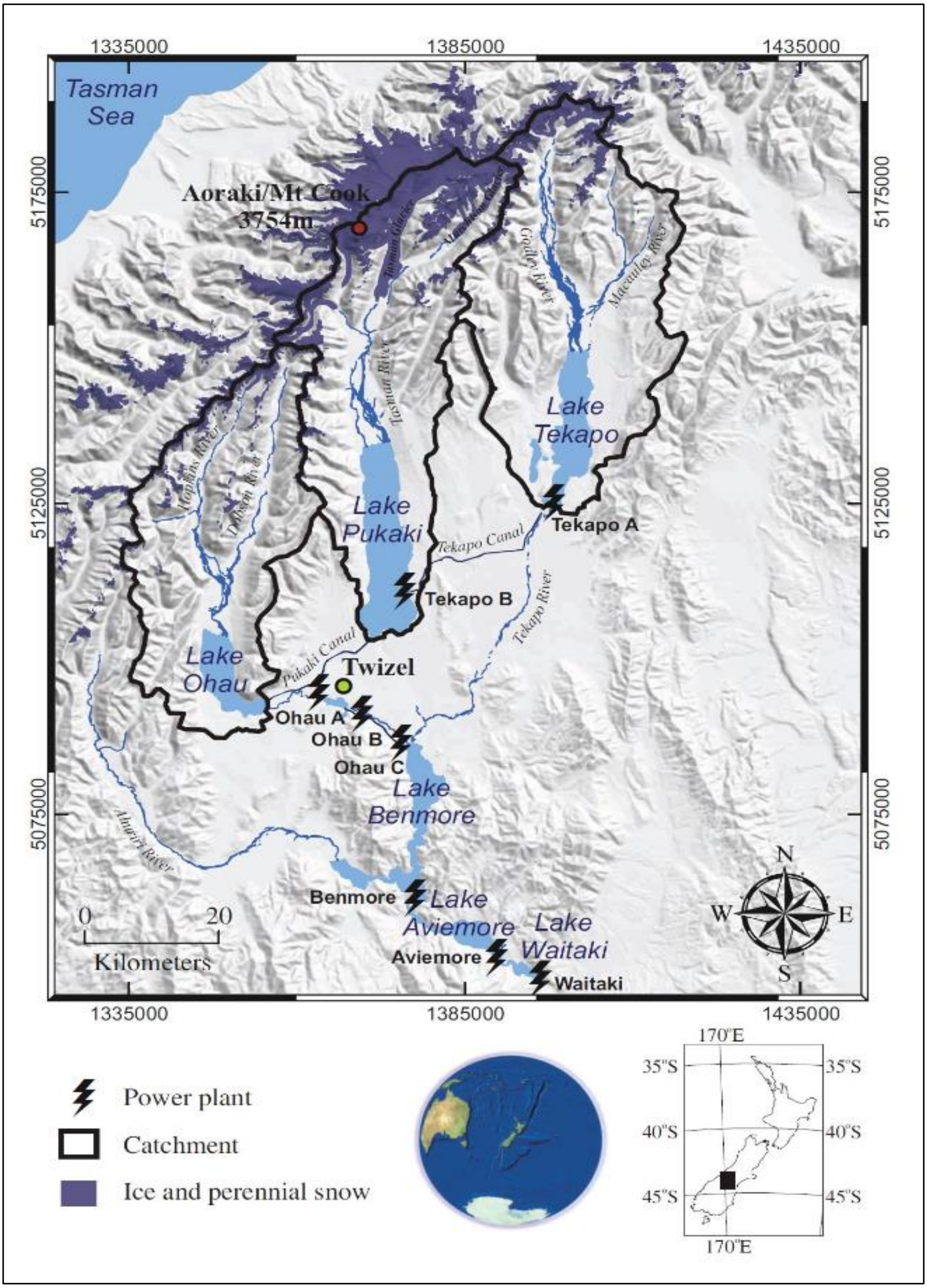


Figure 3.1. From Sirguey (2010), the upper Waitaki catchment location on the South Island of New Zealand.

3.1.1. Glacier Selection

Small glaciers often exhibit different dynamics compared to larger ones, particularly in terms of lake development, which affects their behaviour and measurements. Datasets covering small glaciers can also be highly uncertain given the limited number of data points that are available. Across the NZ Southern Alps / Kā Tiritiri o te Moana there are no lake-terminating glaciers smaller than 1 km^2 so this was set as the minimum glacier size threshold. This filtering left 160 glaciers in total (31 lake-terminating glaciers and 129 land-terminating). This decision was supported by the analysis presented in Figure 3.4, which demonstrates that there is no significant difference in velocity, elevation change or ice thickness, within the range of 1 to 5 km^2, leading to the application of the filter that retained the most data (1 km^2) for subsequent analysis. Notably, all lake-terminating glaciers are larger than 1 km^2, so the impact on the data available for the study was minimal.

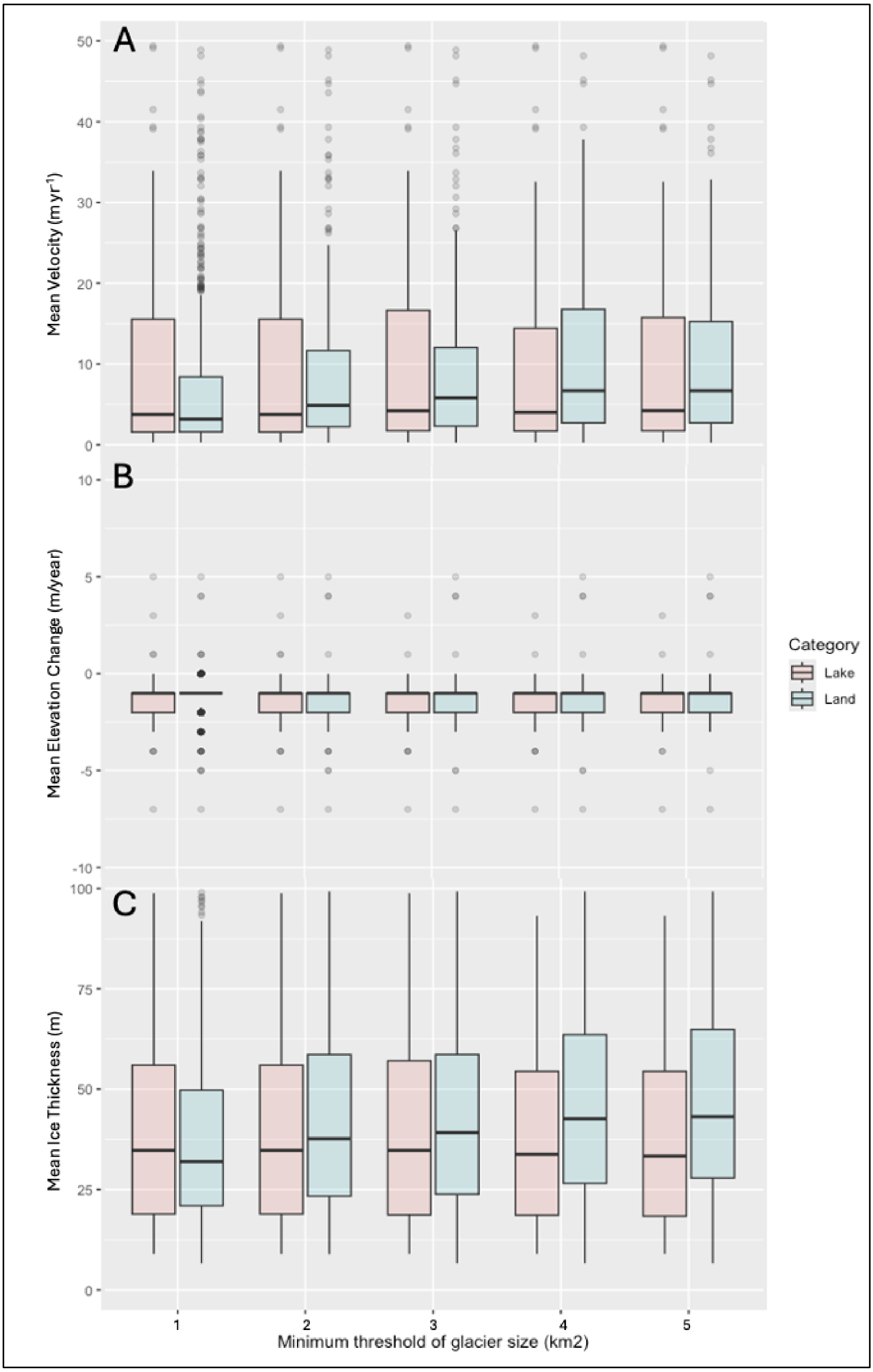


Figure 3.2. a) mean velocity, b) mean elevation change and c) mean ice thickness of lake (pink) and land (blue) terminating glaciers in New Zealand and the differing minimum thresholds for glacier size.

3.1.2. Glacier termination type division

The distribution of all glaciers in the Southern Alps / Kā Tiritiri o te Moana shows that 99.2% (3,505 glaciers) are land-terminating, while only 0.8% (31 glaciers) are lake-terminating, with the latter type mostly located on the east side of the divide. Lake-terminating glaciers in New Zealand glaciers are bigger in size on average by 7 km^2 and also show a larger variation in size between 2 km^2 and 95 km^2. Land terminating glaciers in New Zealand are overall much smaller on average. The largest land terminating glacier area is 35 km^2, which is closely followed by 32 km^2. More than 3000 of these glaciers are smaller than 1 km^2, and only 60 are above 5 km^2 in size.

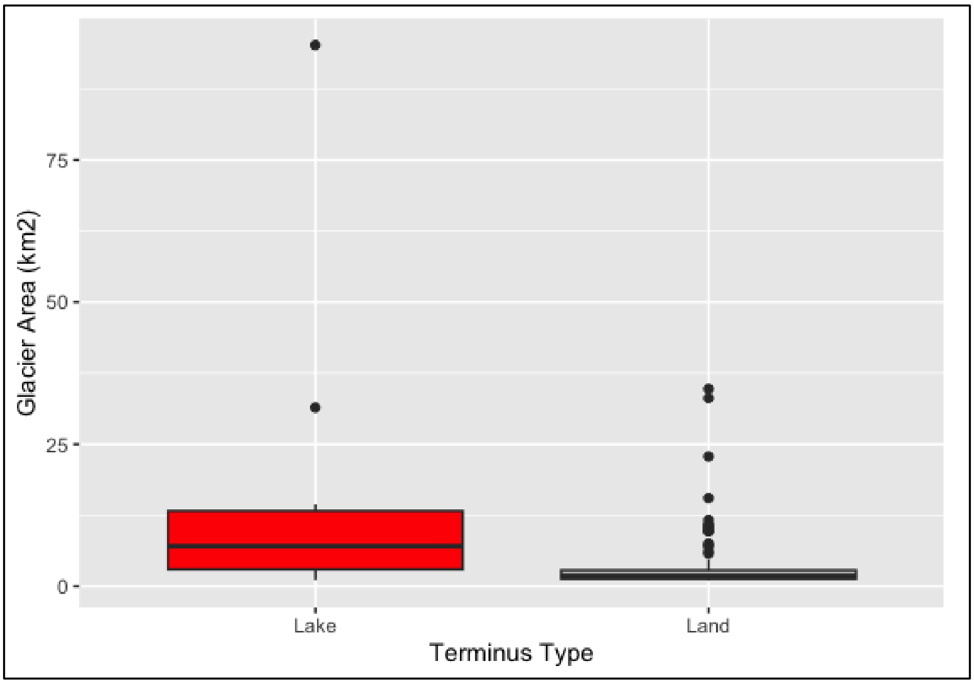


Figure 3.3. Distribution of Area by Glacier Termination Type.

3.1.3. Glacier location in relation to the Main Mountain divide

Using the RGI 6.0 dataset, glaciers were found to vary significantly in shape and size depending on whether they were east or west facing. To evaluate the influence of their location relative to the main divide on glacier dynamics, all glaciers were separated into east- or west-facing groups. This division, based on prior studies that identified the east-west boundary (e.g., Henderson & Thompson, 1999; Purdie et al., 2018), allows for an examination of how factors such as climate and weather patterns, which differ significantly between the two sides (Henderson & Thompson, 1999), may affect glacier behaviour. This analysis is key to understanding whether the location of a glacier, with its associated topographic and climatic differences, or the presence of a proglacial lake at the terminus exerts a more dominant influence on glacier dynamics. By analysing the glacier dynamics in relation to their location to the main divide, the study aims to assess, whether these differing spatial factors, or the presence of lakes, are driving differences in glacier behaviour.

3.2. Data Sources

The datasets used in this study were chosen due to their date (i.e. to capture the most recently available observations), accuracy and global coverage, to enable the techniques used here to be applied to other regions. As a whole the usage of Ice Thickness, Velocity and Elevation Change provide an overall combined image of the glacier's topographic factors, and the climatic forcing of what the glaciers experience along with the glaciers response, each dataset will be discussed further in the next section. Primarily, the response of these dynamic factors to the presence of a lake at the terminus has been addressed by analysing the velocities, ice thickness and elevation change in relation to the glacier terminus type. Ensuring accurate ice thickness distribution is essential for predicting glaciers ice flow controls and how this is distributed across a glacier along with the prediction of the glacier's future (Millan et al., 2022). Furthermore, glacier surface flow velocity and elevation change, are critical for the reconstruction of ice reservoirs, its change through time, and ultimately the evolution of the world's glaciers (Millan et al., 2022). As a result, ice thickness and velocity from Millan et al. (2022) were used along with surface elevation change data from Hugonnet et al. (2021). These data were then analysed by glacier geometry constraints in the form of curvature, slope and aspect. These metrics were split by glacier termination type (e.g. lake terminating or land terminating), to assess whether the geometric controls, or the lakes present were the primary driver of the glacier dynamic differences that were observed.

Table 3.1. Data sources used within this study.

Purpose:	Purpose:	Reference	Source	Spatial Reference (m)	Temporal resolution
Glacier outlines	To be able to characterise the glaciers based on their termination type	Global Land Ice Measurements from Space (GLIMS)	Ranolf Glacier Inventory (RGI 6.0) in NSIDC (National Snow and Ice Data Centre)	-	2000-2010
Lake Outlines	To be able to analyse which glaciers have a lake present at their terminus	Shugar et al., 2020	NISIDC	30	1990-2018
Glacier Geometry	To analyse the topographic characteristics of both lake and land terminating glaciers. Determining whether the geometry or the presence of a lake is the dominant force acting upon glacier dynamics.	Advanced Land Observing Satellite Digital Elevation Model	JAXA ALOS World 3D Digital Surface Model (DSM)	30	-
Velocity and Ice Thickness	To assess the movement and dynamics of the lake and land terminating glaciers	Millan et al., 2022	Service de données de l'Observatoire Midi-Pyrénées	50	2017-2018
Elevation Change	To provide information into the glacier mass balance of lake and land terminating glaciers.	Hugonnet et al., 2021	Theia Data and Services centre	100	2000-2019

3.2.1. Glacier outlines

Glacier outlines were downloaded from the Randolf Glacier Inventory 6.0 (RGI 6.0), for consistency with the other datasets within this study (Shugar et al., 2020; Hugonnett et al., 2021; Millan et al., 2022) as well as being the most recent dataset at the start of this study, released in July 2017. New Zealand's glaciers are in the RGI region 18, with the scale within this dataset being 1:1500,000. The RGI contains a range of glacier components, including the Elevation, Slope (deg), Aspect (°), Length (m) of the glacier's longest flowline.

3.2.2. Lake outlines

Lake outlines were taken from Shugar et al. (2020), a dataset consisting of glacier lake area and volume on a near global scale from 1990-2018, using a 'data cube' built from 254,795 Landsat scenes (missions 4,5,7 and 8). A further elevation threshold was set to 5 m above sea level (ASL) in Shugar et al., (2020) to reduce the classification of oceans being classified as a lake. This dataset uses a modified normalized difference water index approach (NDWI), which has then also been combined with multiple thresholds and filters to ensure the mapping and identification of lakes is accurate. This data was then analysed based on its relationship with the RGI 6.0 dataset, also used within this study, where lake polygons were only kept within the dataset that were within 1km of the glacier polygons. To include recently decoupled lakes, as a result of glacial retreat, a 1 km buffer was used. The RGI 6.0 has also been used in other datasets within this study, mentioned below.

3.2.3. Glacier geometry

Using an ALOS DEM (Advanced Land Observing Satellite Digital Elevation Model), WORLD 3D – 30m (AW3D30), the glacier's curvature, aspect and slope were extracted to establish the topographic and geometric differences between lake and land terminating glaciers (at a 30m resolution), and whether these factors were controlling the dynamics of glaciers. The aspect of the glacier referring to the direction that the glacier surface faces, influencing the solar radiation and melt patterns. The slope of the glacier represents the steepness of the glacier surface which can influence flow and movement of the glacier. Curvature was also included as it indicates how the glacier deviates from being 'flat' and can help identify the areas of accumulation and ablation. Studying the glacier geometry allowed for the isolation of the lake effect to be established. Slope was extracted using the 'Slope' tool which calculates the terrains steepness from the DEM. The 'Aspect' tool extracted the Aspect, which determines the compass direction for each cell in the DEM faces which is based off the steepest downhill slope, and the 'Curvature' tool extracted the curvature which calculates the rate of change in the surface slope, producing values of positive curvature (referring to concaved or depressions in the glacier surface), and negative curvature (referring to areas where of convex surfaces, such as ridges or peaks). Zonal statistics were then performed in ArcGIS Pro on the extracted slope, aspect and curvature to produce one mean value per glacier. Slope aspect and curvature were used as they make up the primary morphometric and topographic parameters of a glaciated system, along with elevation change distribution (Sam et al., 2018), thus all parameters have been used within this study.

3.2.4. Velocity and Ice Thickness

Velocity and ice thickness data were taken from Millan et al. (2022), which presents a global dataset of surface ice flow velocity and the ice thickness of all glaciers between 2017 and 2018. Ice thickness is a topographic indicator of what is occurring within a glaciated system and exerts an influence on the hydrological characteristics of a basin (Farinotti et al., 2017). Similar studies have used Millan et al. (2022) dataset in recent times for studies investigating, for example, surface motion and topographic effects on ice thickness inversion for High Mountain Asia Glaciers (Pang et al. 2023), and the study of mountain glacier slowdown and rapid ice loss in the Andes from Jo et al. (2023).

The velocity data presented in Millan et al. (2022), were calculated using satellite imagery from the American US Geological Surveys Landsat 8, the European ESA's Sentinel-2 and the French-Israel Centre National d'Etudes Spatiales-Israel Space Agency's Venus and synthetic aperture radar images from the European ESA's Sentinel-1. The glacier boundaries were defined using the RGI dataset as mentioned above. To avoid geometric distortions and geolocation areas these data were calibrated. These data are presented at a spatial resolution of 50 m. Ice thickness measurements from Millan et al. (2022) were computed using the basis of surface motion and slopes using the shallow-ice approximation (SIA) with basal sliding further considered. To make these consistent with the consensus estimate, an estimation of ice thickness was made with a degree of connectivity to the ice >2m, defined by the RGI boundary. In the current study, both the velocity and ice thickness products had zonal statistics performed on them, using ArcGIS Pro, with the RGI6.0 as the spatial reference, to produce one mean value of ice thickness and velocity per glacier. This was then separated into lake and land terminating glaciers to establish the differences between the two glacier termination types.

3.2.5. Elevation Change

Hugonnet et al. (2021) derived glacier surface elevation changes and from them computed estimates of glacier mass change between the period of 1st January 2000 to 31st December 2019, using the RGI 6.0 for the glacier outlines, retrieving data from all ASTER, Arctic DEM and Reference Elevation Model of Antarctica (REMA). The dataset presents surface elevation changes at a medium spatial resolution (100 m) of all of Earth's glaciers which have been validated against high precision independent measurements (Hugonnet et al., 2021). Over 150,000 ASTER DEM strips at 30 m resolution were processed using advanced techniques to enhance accuracy and reduce edge effects. To maintain accuracy, the variation in elevation differences were limited to a maximum standard deviation of 10 m before starting a new processing strip. As a result of the high spatial resolution, usage of the RGI 6.0 and global coverage this dataset was best fit for this study. This dataset was integrated into the current study by performing zonal statistics, on ArcGIS Pro, using the RGI6.0. as the spatial reference, to extract the mean elevation change, providing one value per glacier. This was then separated into lake and land terminating glaciers to establish the differences between the two glacier termination types.

3.3. Glacial Lake analysis

The largest proglacial lakes in the Southern Alps/ Kā Tiritiri o te Moana are located to the east of the main divide with a mean lake area of 73.7 km^2 for the 19 proglacial lakes located there, compared to mean lake area of 25.5 km^2 in the west, where 12 proglacial lakes are located. Establishing the extent of ice-lake contact length when investigating the effect of proglacial lakes on New Zealand's glacier dynamics was important due to the direct contact of lakes having an impact on dynamics and was also previously measured by Carrivick et al., (2022). Using QGIS, polylines were created where there were lakes touching the lakes, these were then measured. This extent was then compared in the east and west. This revealed similar trends, with the east having on average a 2.4 km ice-lake contact length and 0.12 km in the west. Figure 3.1. also shows the location of the lakes and the distribution of lake size. The majority of the larger lakes (64 km^2 or more) are present within the northern areas of the Southern Alps/ Kā

Tiritiri o te Moana, and the smaller glacial lakes being present in the southern areas of the Southern Alps / Kā Tiritiri o te Moana.

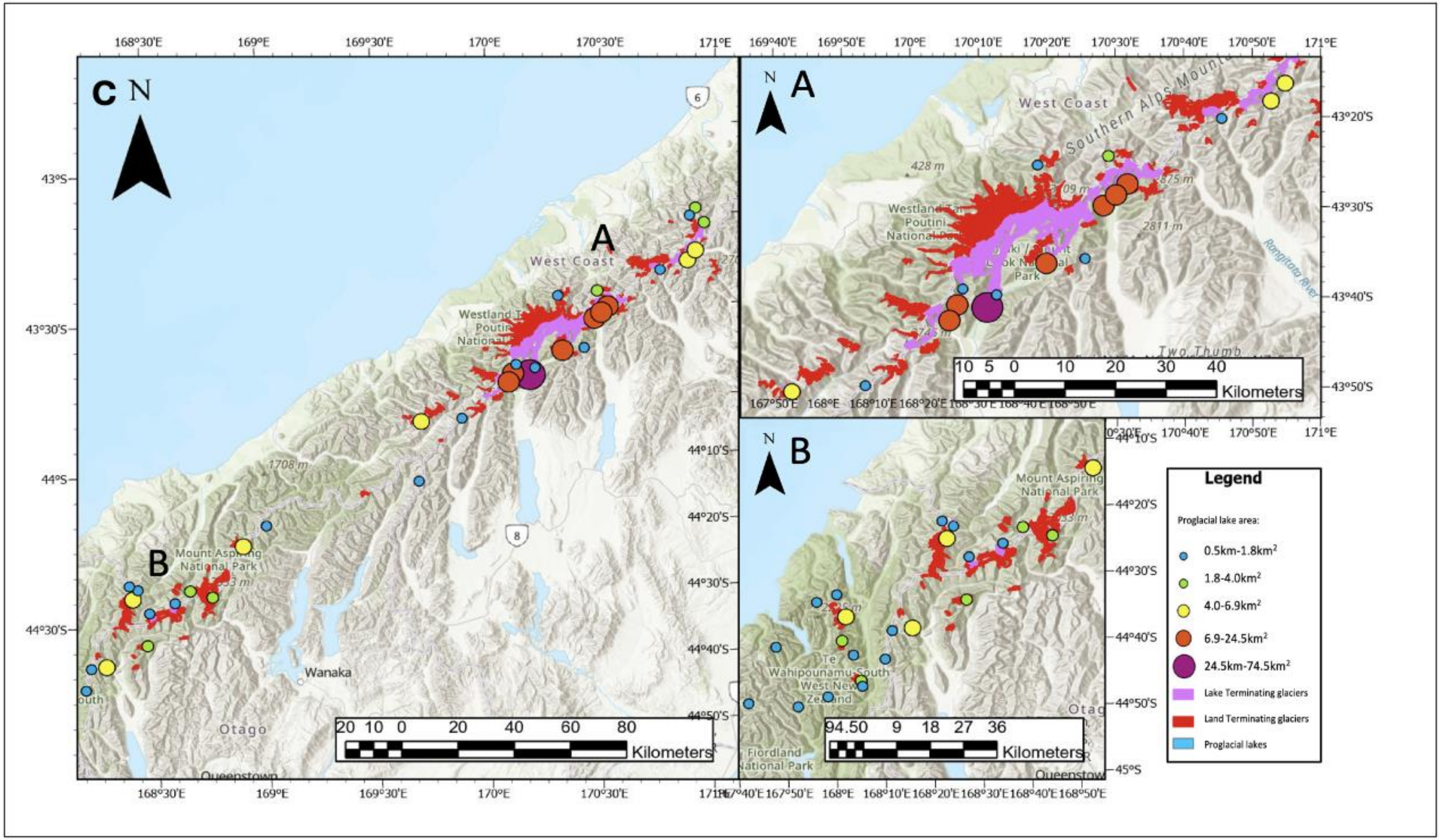


Figure 3.4. Distribution of lake area and lake vs land terminating glaciers in the Southern Alps / Kā Tiritiri o te Moana.

3.4. Glacier pairing

Lake terminating glaciers were paired with land terminating glaciers with similar geometric characteristics, to allow for the sample size to be distributed, and to isolate the influence of the lake on any changes to glacier dynamics. The slope, curvature and area were the determining factors of similarity. This allowed for the two separate datasets to have a fair comparison with the land terminating dataset consisting of 100+ more glaciers which had an area of over 1 km^2. T-tests were conducted on the glacier slope, area and curvature to ensure that they were taken from glaciers with statistically similar geometries.

3.5. Distance from terminus analysis

To investigate the influence of proglacial lakes on mountain glacier dynamics, the distance of any measured lake effect was assessed by measuring distances from the glacier terminus. This was done by creating 10 buffers, each 500 meters apart, starting at the glacier terminus and extending upwards through the glacier (figure 3.5.). Vector lines were drawn across the termini of the glaciers, which were part of the glacier pairs discussed in section 3.4. The termini were derived from the RGI 6.0 dataset, and 500-meter buffers were generated around these lines, ranging from 500 meters to 5000 meters in 500-meter intervals. Using the erase tool, these buffers were then divided into 500-meter segments and clipped to the outlines of individual glaciers. The choice of 500-meter intervals ensured that each glacier (after removing those smaller than 1 km^2) had at least two buffers, allowing for a section-by-section analysis of how the lake effect propagates through the glacier.

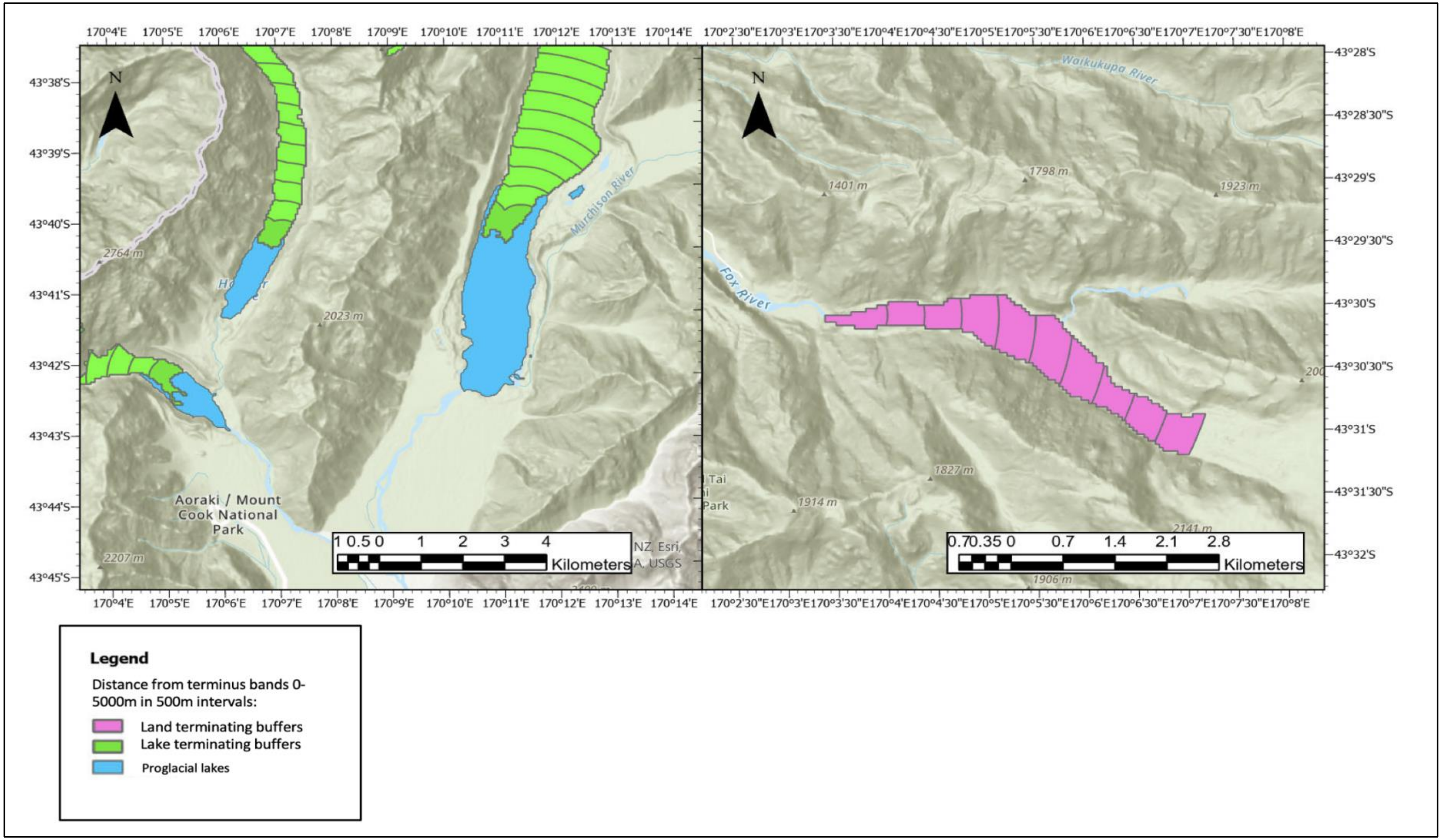


Figure 3.5. Distance from terminus buffer bands from 0-5000m in 500m intervals. Green indicating the buffer bands for lake terminating glaciers and pink for land terminating glaciers.

3.6. Statistical testing

Throughout this study, statistical tests were conducted to assess correlation and differences between datasets. Pearson's correlation coefficient was used for normally distributed data, while Spearman's rank correlation was applied to non-normally distributed data. Differences between datasets were evaluated using either Student's t-test or the Mann-Whitney U test, depending on normality. Normality of the data was assessed using the Shapiro-Wilk test prior to selecting the appropriate statistical test. Zonal statistics in ArcGIS Pro were used to describe key glacier characteristics such as mean elevation change, ice thickness, and velocity on both a whole-glacier basis and per distance bin (see section 3.5). All statistical analyses were conducted in RStudio with a significance threshold of 0.05.

3.6.1. Glacier Geometry and Dynamics relationship

To examine the relationships between glacier geometry (Curvature, Slope, and Aspect) and dynamics (Elevation Change, Velocity, and Ice Thickness) for both lake-terminating and land-terminating glaciers, we first assessed normality using the Shapiro-Wilk test. For lake-terminating glaciers, the results indicated that Curvature ($p = 0.1748$), Slope ($p = 0.4463$), Aspect ($p = 0.7429$), and Elevation Change ($p = 0.3473$) were normally distributed, whereas Velocity ($p = 0.0013$) was non-normally distributed, and Ice Thickness ($p = 0.0937$) was normally distributed. For land-terminating glaciers, Curvature ($p = 0.0513$), Aspect ($p = 0.1727$), and Elevation Change ($p = 0.0018$) were normally distributed, while Slope ($p = 0.00002$), Velocity ($p < 0.0001$), and Ice Thickness ($p < 0.0001$) were non-normally distributed. Based on these results, Pearson's correlation was used for normally distributed variables, while Spearman's rank correlation was applied to non-normally distributed variables. Significant correlations ($p \leq 0.05$) were marked with an asterisk in the results tables. This analysis aimed to identify potential linear associations between glacier geometry and dynamics, with significant correlations indicating possible interactions between a glacier's structural features and its dynamic behaviour.

3.6.2. Glacier Dynamics relationship

The normality of the glacier dynamics datasets was assessed using the Shapiro-Wilk test. The results showed that Ice Thickness ($p = 1.255e\text{-}11$) and Velocity ($p < 2.2e\text{-}16$) significantly deviated from normality. Consequently, the Mann-Whitney U test, a non-parametric test, was used to compare these variables between groups. In contrast, Elevation Change ($p = 0.8388$) did not significantly deviate from normality, justifying the use of a two-sample t-test for this variable. The selection of statistical tests was guided by these normality assessments, ensuring the appropriate method was applied to each dataset. All analyses were conducted in RStudio with a significance threshold of 0.05. This structured approach clarifies the workflow of statistical testing, ensuring transparency in the methodology applied to analyse glacier characteristics and dynamics.

4. Results

4.1.Topographic characteristics and geometry

4.1.1. Glacier location

After the removal of glaciers <1 km^2 in area, 160 glaciers were processed for this study. The total area of land terminating glaciers was 459.40 km^2, which consisted of 142 glaciers. The remining 18 glaciers are lake terminating, with a total area of 234.85 km^2. The largest glacier (lake terminating) was Tasman Glacier (95 km^2). Figure 4.1 shows the spatial distribution of a) glaciers draining east vs west and b) lake and land terminating glaciers. Figure 4.2 shows the distribution of termination type and aspect, with most lake terminating glaciers draining to the east (61%) and most land terminating draining to the west (60%). This relationship becomes 100% with glaciers over 10km^2 in area. With 100% of land terminating glaciers (over 10km^2) being in the West and 100% of lake terminating (over 10km^2) are in the East (Chi-Squared p <0.01).

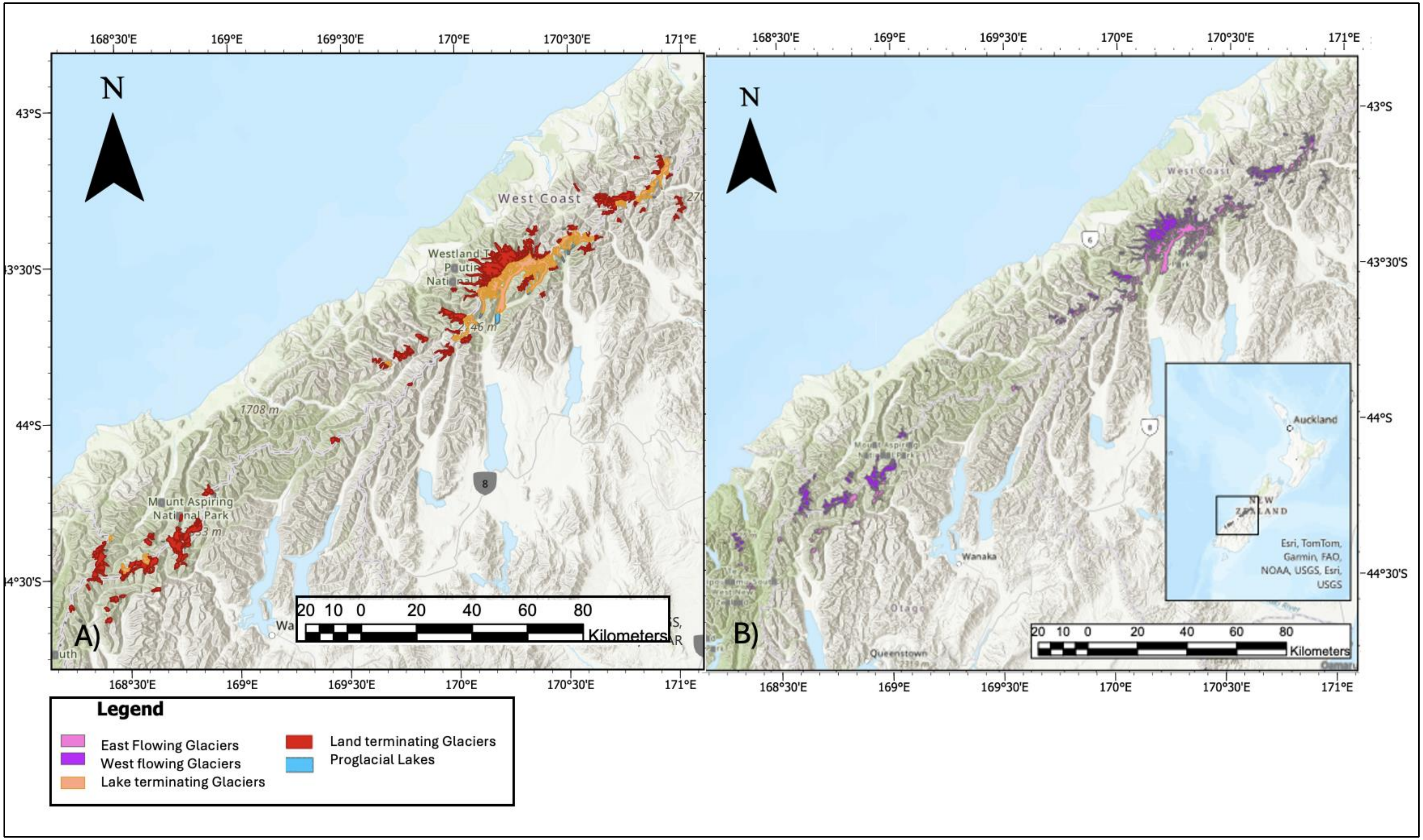


Figure 4.1: a) distribution of glaciers in terms of location in relation to the main divide and b) their termination type.

Table 4.1. Number of glaciers based on their termination type and aspect after the removal of glaciers smaller than 1 km².

	Location	
Termination Type	**East**	**West**
Lake-Terminating	13	5
Land-Terminating	57	85

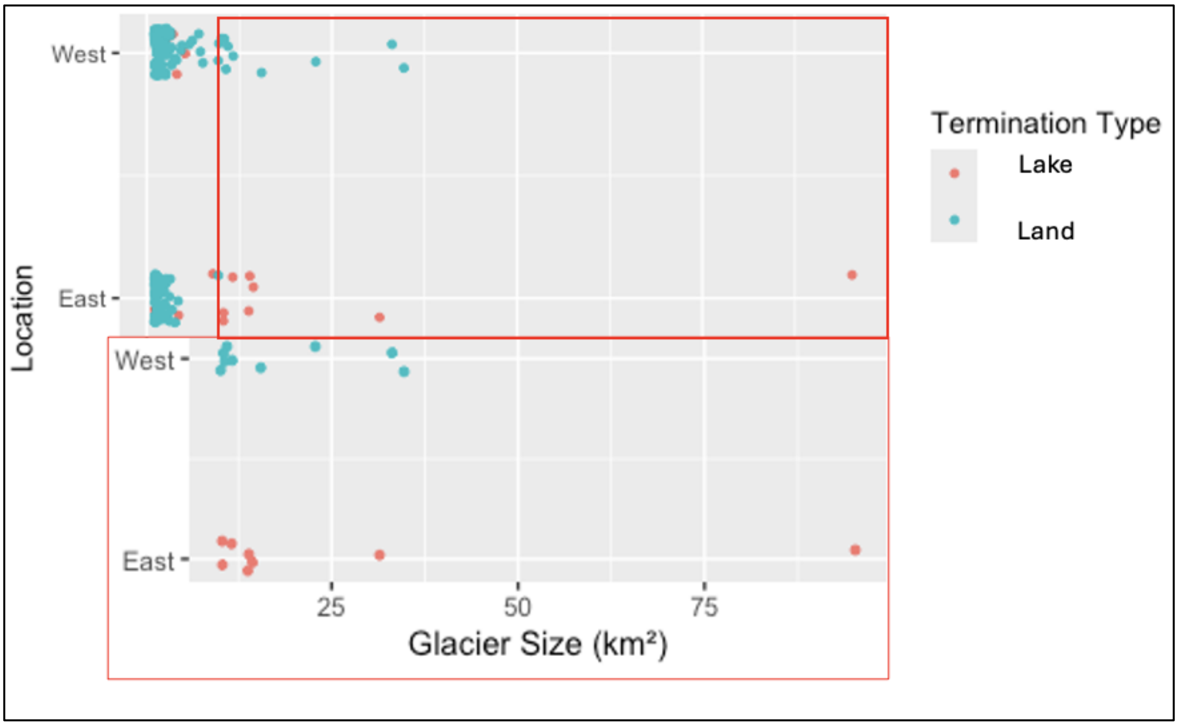


Figure 4.2. a) glacier size vs location relationship, b) relationship between size and location of glaciers <10 km².

4.1.2. Glacier Geometry

Mean glacier curvature shows similar trends in both lake-terminating and land-terminating glaciers (table 4.2, figure 4.3), with a mean curvature of -0.019 in lake terminating glaciers and similarly -0.016 in land terminating glaciers. A Mann-Whitney U tests revealed no statistically significant difference in curvature between the two groups ($W = 1106$, $p = 0.6057$), indicating that curvature is consistent across both lake and land-terminating glaciers. The mean slope of lake-terminating glaciers is notably higher (table 4.2, figure 4.3), with a mean of 15.554° compared to lake-terminating glaciers, which have a mean slope of 12.104°. A Mann-Whitney U test confirmed that this difference is statistically significant, with lake-terminating glaciers having a significantly lower mean slope ($W = 1941$, $p = 0.000031$).The aspect of glaciers reveals further variation. Land-terminating glaciers have a mean aspect 194.221°, which corresponds to an eastward orientation (table 4.2, figure 4.3).. This dataset exhibits more variability compared to lake-terminating glaciers, with aspects ranging from 50° to 290°. In contrast, lake-terminating glaciers have a mean aspect of 170.205°, with the majority of data falling within 50° of this value, showing a much narrower range. A t-test showed that the difference in aspect is statistically significant ($t = -3.197$ $p < 0.003$). This variation can be partly attributed to smaller cirque glaciers skewing the data slightly.

In summary, the t-tests conducted show no significant difference in glacier curvature between lake and land-terminating glaciers. However, significant differences were found in both slope and aspect, with lake-terminating glaciers having lower values for both. These findings suggest that slope and aspect are key distinguishing characteristics between lake and land environments, while curvature remains consistent across both.

Table 4.2. Statistical test results of between lake and land terminating glaciers geometry means.

Geometry Type	Test	statistic	*p*-Value
Curvature	Mann-Whitney U	1106	0.6057
Slope	Mann-Whitney U	1941	0.001*
Aspect	T-Test	-3.197	0.003*
			*Significant Values marked **

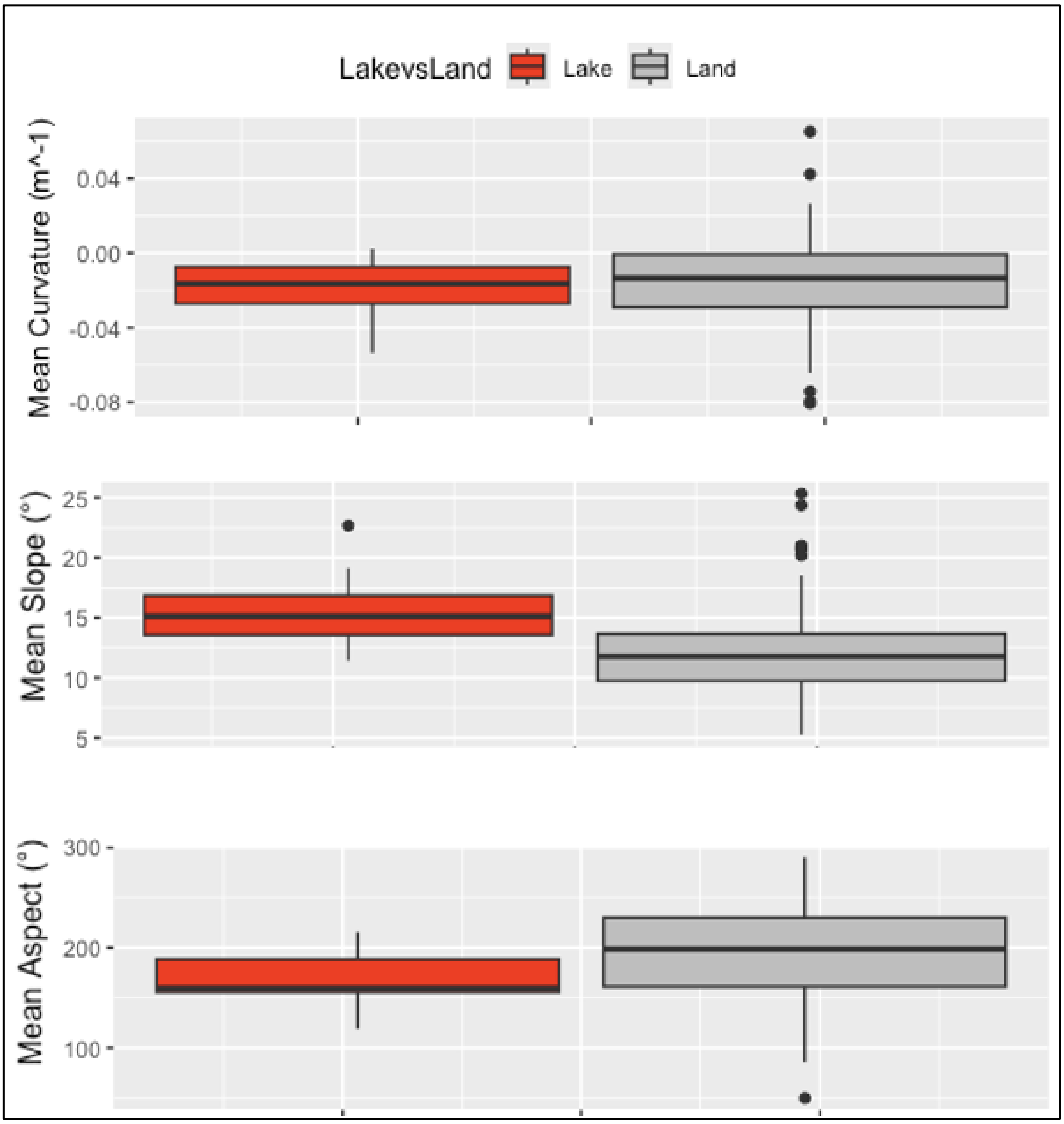


Figure 4.3. Differences between lake and land terminating glacier geometry (Aspect, Slope and Curvature).

4.1.3. Relationship between glacier geometry and dynamics

The investigation into the relationship between glacier geometry (slope, aspect, and curvature) and glacier dynamics aimed to separate the influence of topographic variables in controlling glacier dynamics from the influence of the presence of a lake at the terminus.

Firstly, the relationship between surface elevation change and glacier geometry remains weak and statistically insignificant. For lake-terminating glaciers, the correlation coefficients for curvature (*Pearson's* $r = 0.204$, $p = 0.408$), aspect (*Pearson's* $r = -0.343$, $p = 0.177$), and slope (Pe*arson's* $r = -0.051$, $p = 0.846$) suggest minimal influence of these geometric factors on elevation change. Similarly, land-terminating glaciers show weak and statistically insignificant correlations with curvature (*Spearman's* $\rho = 0.081$, $p = 0.337$), aspect (*Spearman's* $\rho = 0.073$, $p = 0.931$), and slope (*Spearman's* $\rho = -0.135$, $p = 0.120$).

Secondly, the relationship between glacier geometry and velocity appears somewhat stronger, particularly for slope in land-terminating glaciers, where the correlation is moderate and negative (*Spearman's* $\rho = -0.467$, $p = 7.919e\text{-}09$). This suggests that steeper slopes are associated with slower glacier velocities. However, for lake-terminating glaciers, the slope-velocity relationship remains weak and statistically insignificant (*Spearman's* $\rho = -0.045$, $p = 0.697$). The relationship between curvature and velocity is weakly positive for lake-terminating glaciers (*Spearman's* $\rho = 0.385$, $p = 0.128$), while land-terminating glaciers also show weak correlations (*Spearman's* $\rho = 0.198$, $p = 0.185$). Aspect correlations with velocity are weak and statistically insignificant in both glacier types.

Lastly, the relationship between glacier geometry and ice thickness is more pronounced, particularly for slope in land-terminating glaciers. A strong positive correlation between slope and ice thickness in land-terminating glaciers (*Spearman's* $\rho = 0.631$, $p < 2.2e\text{-}16$) suggests that steeper slopes are linked to thinner ice. Lake-terminating glaciers also show a negative slope-thickness correlation, but it is weaker and statistically insignificant (*Pearson's* $r = -0.250$, $p = 0.339$). The correlation between curvature and ice thickness is moderate in lake-terminating glaciers (*Pearson's* $r = 0.439$, $p = 0.078$), while aspect shows a weak but statistically significant relationship in land-terminating glaciers (Spearman's $\rho = 0.157$, $p = 0.037$).

Overall, the data suggest that while the relationship between glacier geometry and dynamics exists, it is generally weak and complex, indicating that glacier dynamics are likely influenced by multiple interacting factors rather than simple geometric controls.

Table 4.3. Pearson's r and Spearman's rank values of glacier dynamics and geometry.

	Curvature		**Slope**		**Aspect**	
	Lake	Land	Lake	Land	Lake	Land
Thickness	Pearson, 0.439 $p = 0.078$	Spearman, 0.187, $p = 0.076$	Pearson, -0.250, $p = 0.339$	Spearman, 0.631, $p < 2.2e-16$	Pearson, 0.241, $p = 0.352$	Spearman, 0.157, $p = 0.037$
Velocity	Spearman, 0.385, $p = 0.128$	Spearman, 0.198, $p = 0.185$	Spearman, -0.045, $p = 0.697$	Spearman, -0.467, $p = 7.919e-09$	Spearman, 0.252, $p = 0.327$	Spearman, -0.066, $p = 0.869$
Elevation Change	Pearson, 0.204, $p = 0.408$	Spearman, 0.081, $p = 0.337$	Pearson, -0.051, $p = 0.846$	Spearman, -0.135, $p = 0.120$	Pearson, -0.343, $p = 0.177$	Spearman, 0.073, $p = 0.931$

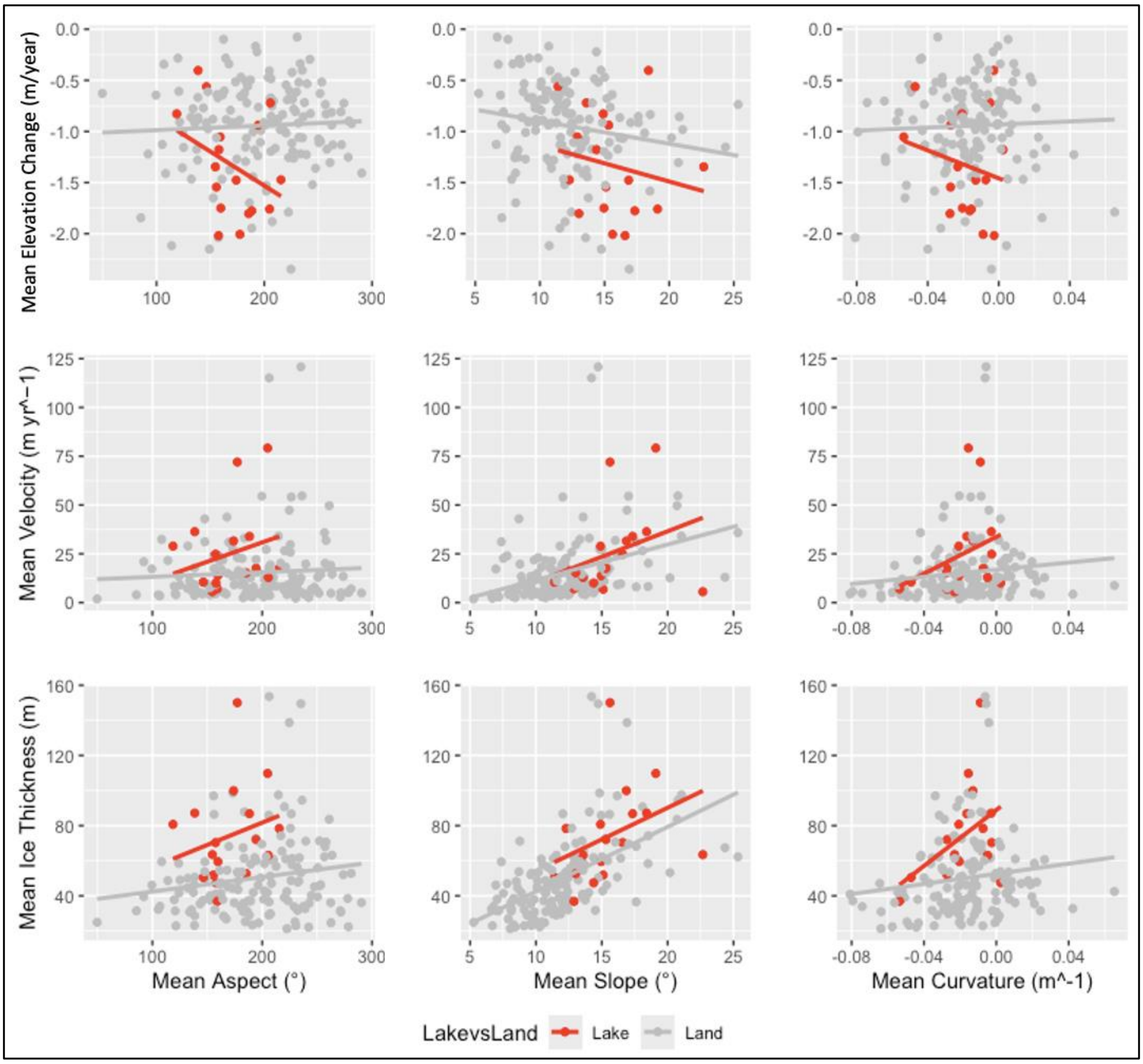


Figure 4.4. relationship between dynamics (Ice Thickness, Velocity and Elevation Change) and Geometries (Aspect, Slope and Curvature).

4.2. Influence of lakes on glaciers

4.2.1. Glacier dynamics

4.2.1.1. Ice thickness

The Mann Whitney tests conducted on ice thickness data reveal significant differences based on both terminus type and its location in relation to the main divide for the comparison between lakes and land, the Wilcoxon rank sum test produces a W value of 1900 with a p-value of 8.373e-05. This indicates a statistically significant difference in ice thickness between lakes and land, with lake-terminating glaciers exhibiting a substantially greater mean ice thickness (74.15 m) compared to land-terminating glaciers (50.31 m). The 95% confidence interval for the difference in means ranges from 9.26 to 38.42, reinforcing the robustness of this finding.

On the other hand, the comparison of ice thickness between east and west reveals a *t*-value of -2.0602 with 153.33 degrees of freedom and a *p*-value of 0.04107. This result suggests a significant difference in ice thickness between these two regions, with glaciers in the east exhibiting a lower mean ice thickness (48.36 m) compared to the west (56.16 m). The 95% confidence interval for the difference in means extends from -15.28 to -0.32, indicating that ice is significantly thinner in the east relative to the west. These findings highlight both regional and locational factors influencing ice thickness, underscoring the need for nuanced analysis in environmental studies (figure 4.5).

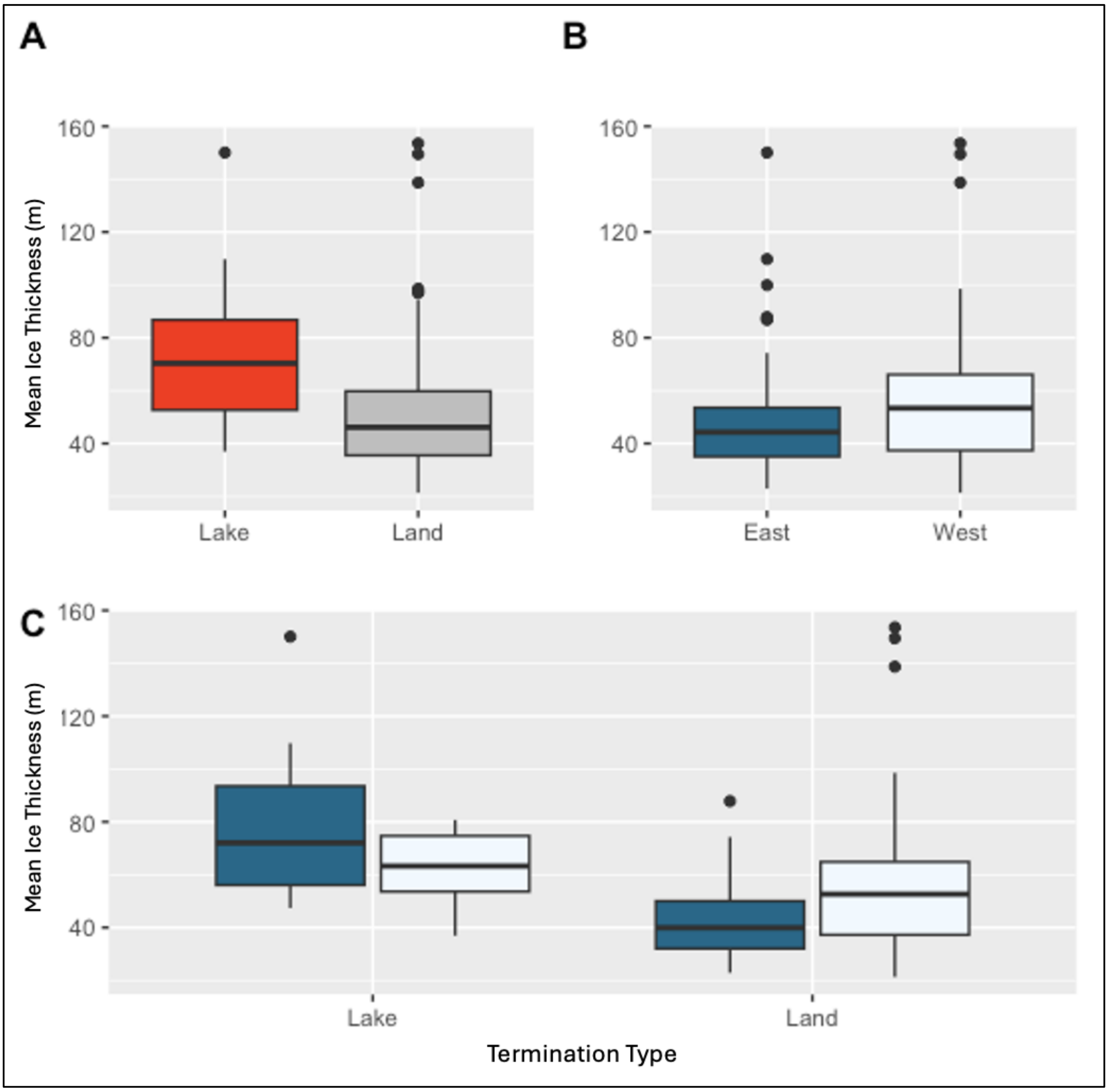
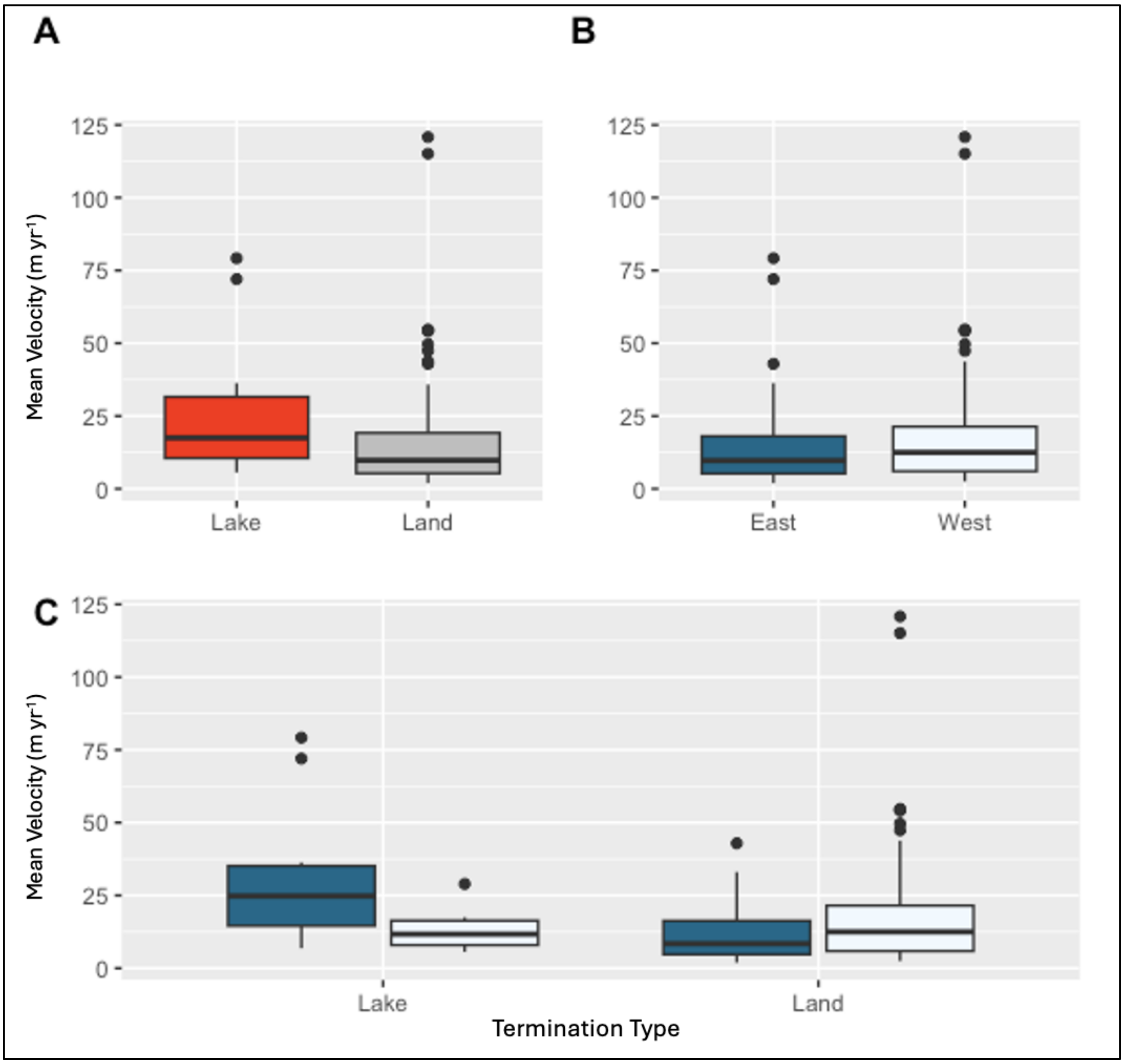


Figure 4.5. Mean ice thickness of a) lake and land terminating glaciers, b) glaciers situated on either east or west of the main divide in and c) lake and land glaciers on either east or west of the main divide.

4.2.1.2. Velocity

There was no statistically significant difference in ice velocity between lake and land-terminating glaciers (w = 1500, p = 0.246) (figure 4.6). The mean velocity was higher in the lake group (24.95 m/yr) compared to the land group (15.38 m/yr), indicating that glaciers with a lake at the terminus tend to move faster on average. In contrast, when comparing velocity between the east and west regions, the t-test produced a t-statistic of -1.13 and a p-value of 0.2614, showing no statistically significant difference in velocity between the two regions. The east group exhibited a slightly lower mean velocity (14.67 m/yr) compared to the west group (17.68 m/yr), but this difference was not meaningful in statistical terms.

Looking more closely at the data, the mean velocities across the dataset do not reveal substantial differences between the groups. However, the spread of the data tells a more nuanced story. On the western side of the divide, land-terminating glaciers showed a higher maximum velocity, one glacier reaching up to 124 m/yr. with the highest velocity value in the Eastern land terminating glaciers reaching 48m/yr. Opposing trends are exhibited in the lake terminating glaciers, with the highest velocity values reaching 80m/yr in the Eastern Lake terminating glaciers and the Western Lake terminating glaciers reaching a maximum value of 29m/yr.



4.6. Mean Velocity of a) Lake and Land terminating glaciers, b) glaciers situated on either East or West of the main divide in and c) Lake and Land glaciers on either East or West of the main divide.

4.2.1.3.Elevation change

Figure 4.7.A demonstrates that none of the glaciers studied in New Zealand experienced a positive mean surface elevation change between 2015 and 2020. The most negative elevation change was observed in a land-terminating glacier (-2.25 m/yr), suggesting that factors other than proglacial lakes also contribute to glacier mass loss. Land-terminating glaciers experienced an average surface elevation change of -0.75 m/yr. Glaciers with a lake at their terminus, however, showed a greater mean mass loss overall (-1.75 m/yr). Figure 4.7B indicates that mass loss of all in the west is slightly higher than in the east, with the west showing a mean mass loss of -0.83 m/yr, compared to -0.78 m/yr in the east. However, this difference is statistically insignificant (chi-squared p >0.005). Figure 4.7.C shows that lake-terminating

glaciers in the east have a mean mass loss of -0.124 m/yr, compared to -1.20 m/yr in the west. Greater differences between east and west are evident in lake-terminating glaciers compared to land-terminating ones, with land-terminating glaciers in the east losing -0.75 m/yr and those in the west losing -1.25 m/yr. Overall, the trends between the west and east are similar, suggesting that the presence of a lake has a more significant impact on elevation change than the climatic factors differentiating the east and west of the glacier divide.

In terms of surface elevation change, significant differences were observed based on the termination type of glaciers The t-test result showed a t-statistic of -3.31 and a p-value of 0.00334, indicating a significant difference between the lake and land groups. The mean elevation change was more negative in the lake group (-1.16 m/yr) compared to the land group (-0.82 m/yr). However, when comparing elevation change between the east and west regions, no significant difference was found, with a t-statistic of 0.90 and a p-value of 0.3706. The mean values were also very similar between regions (east: -0.82 m/yr; west: -0.88 m/yr).

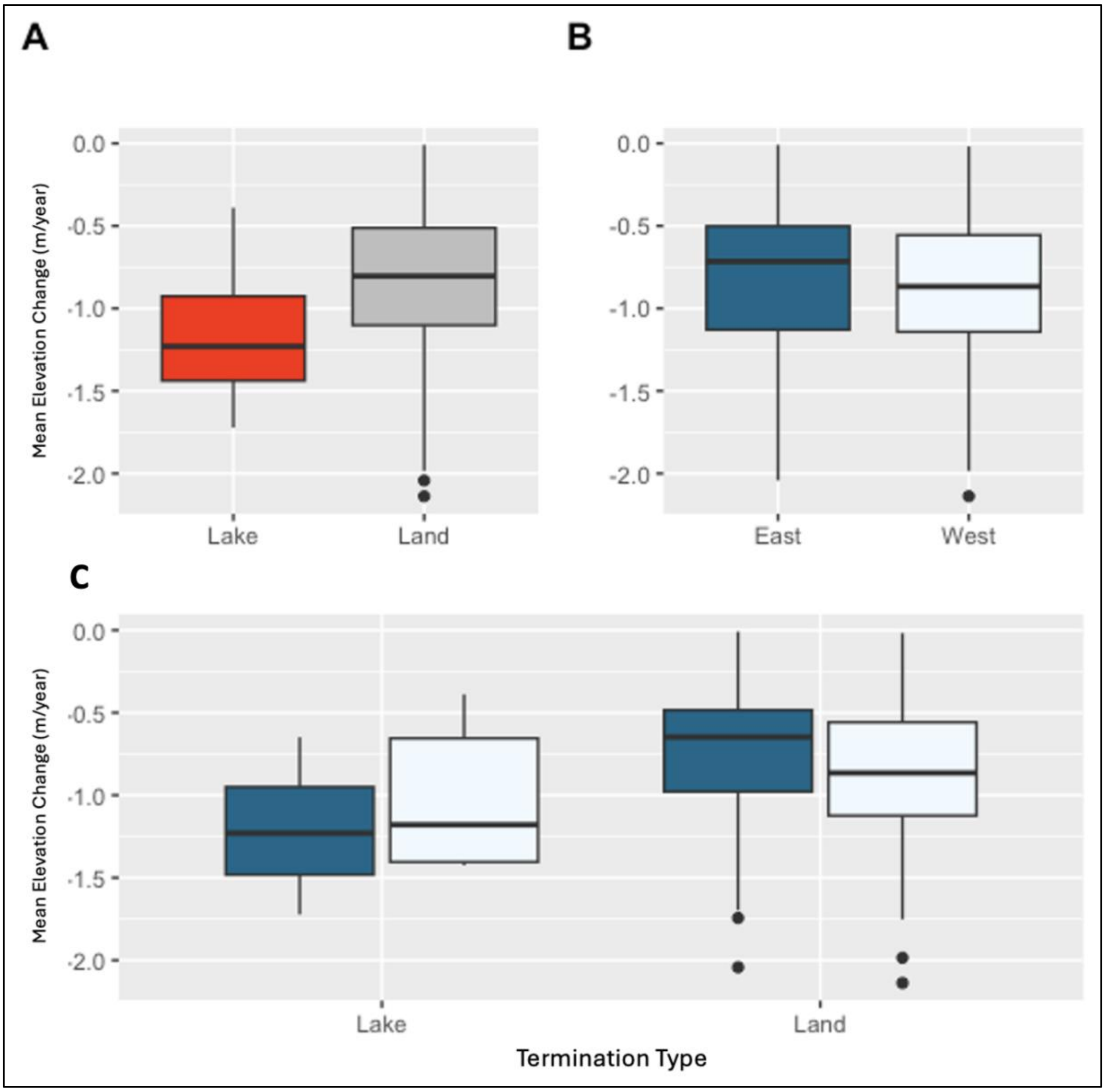


Figure 4.7. Mean Elevation change of a) lake and land terminating glaciers, b) glaciers situated on either east or west of the main divide in and c) lake and land glaciers on either east or west of the main divide.

4.2.2. Distance from terminus analysis

The analysis mentioned in this section is from a subset of glacier pairs, where lake and land terminating glaciers were matched up based on their slope, curvature and area (km^2).

4.2.2.1. <u>Ice Thickness</u>

The analysis of ice thickness between lake and land terminating glaciers reveals no statistically significant differences when examined in relation to distance from the terminus. This conclusion is based on the p-values obtained from statistical tests, which remain well above the conventional significance threshold of 0.05. Additionally, the R^2 values further confirm that distance from the terminus is not a strong predictor of ice thickness. The R^2 value for lake-terminating glaciers is 0.017, and for land-terminating glaciers, it is 0.001, meaning that distance explains only 1.67% and 0.14% of the variance in ice thickness, respectively. These extremely low values indicate that any apparent trends are weak and not statistically meaningful. At all distances from the terminus, the p-values indicate that the differences in mean ice thickness between lake- and land-terminating glaciers are not statistically significant, as the p-values are well above the 0.05 threshold (Figure 4.8, Table 4.4).

However, some subtle trends are visible in the data. The regression lines suggest very weak relationships between distance from the terminus and mean ice thickness, with lake-terminating glaciers (red line) showing a slight upward slope, while land-terminating glaciers (grey line) remain relatively stable or slightly decreasing. However, given the extremely low R^2 values (0.017 for lake-terminating glaciers and 0.001 for land-terminating glaciers), these regression lines explain almost none of the variation in ice thickness. This suggests that any apparent trends are weak and likely driven by noise rather than a true relationship between distance and ice thickness. While the slope of the red line for lake-terminating glaciers appears marginally steeper, implying that ice thickness might increase slightly with distance, the statistical analysis indicates that this pattern is not meaningful or predictive.

The spread of data points for lake-terminating glaciers appears larger at greater distances from the terminus, suggesting greater variability in ice thickness. This contrasts with land-terminating glaciers, which exhibit a more uniform spread across distances. One possible explanation for this increased variability is the influence of localised environmental or glaciological factors, such as differences in meltwater dynamics, calving processes, or variations in bed topography. Given the low R^2 values, it is likely that these other factors exert a much stronger influence on ice thickness than distance alone. Despite these visual differences, the overlapping confidence intervals and the lack of statistical significance in the p-values confirm that these trends are not strong enough to conclude a systematic difference between the two glacier types.

This pattern of non-significant results across all distance bins suggests that, based on this dataset, factors other than distance from the terminus and terminus type might play a more dominant role in determining glacier thickness. The combination of high p-values, low R^2 values, and overlapping confidence intervals strongly suggests that distance from the terminus is not a primary driver of ice thickness variation.

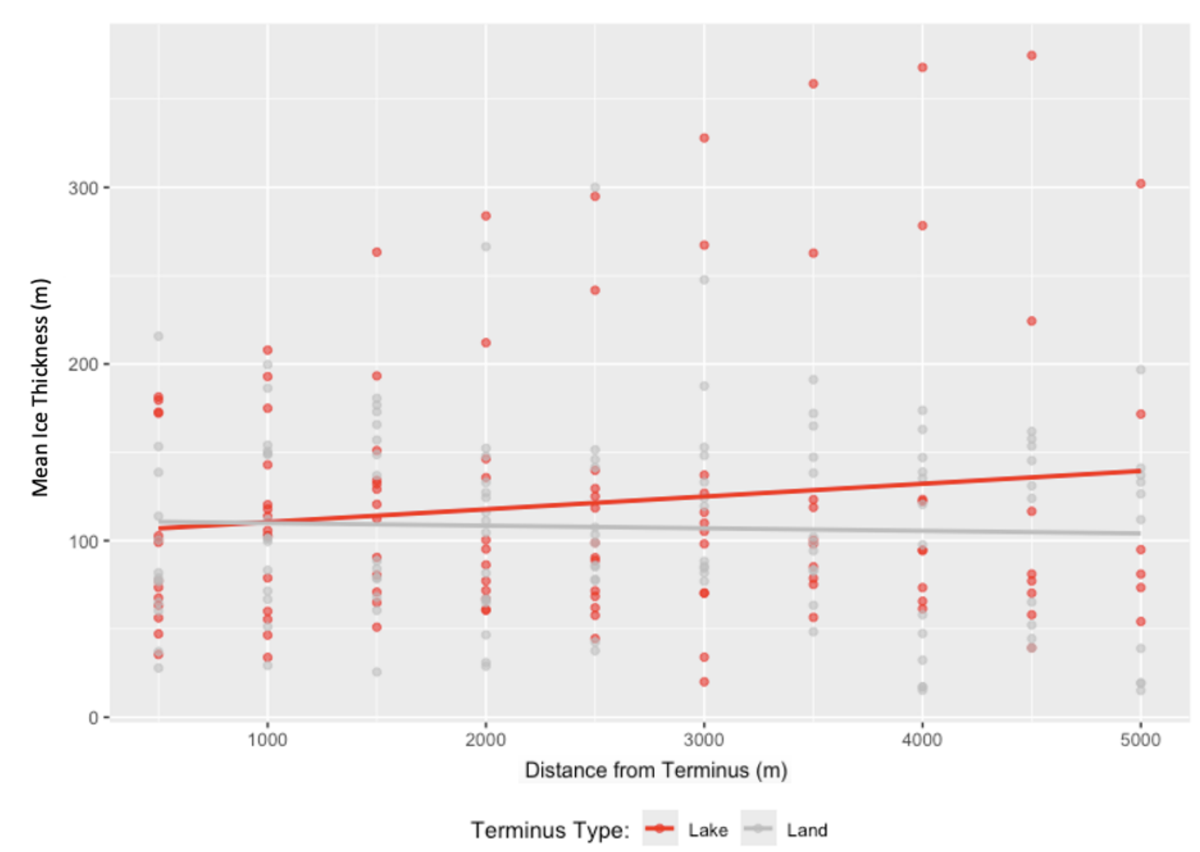


Figure 4.8. Mean Thickness of lake and land terminating glaciers in relation to their distance from terminus from 50 0m-5000 m.

Table 4.4. w and p values of lake and land terminating glaciers mean ice thickness in relation to their distance from terminus from the Mann-Whitney statistical testing.

Distance from Terminus (m)	*w*_Value	*p*-Value
500	95.0	0.846
1000	112.0	0.983
1500	90.0	0.961
2000	101.0	0.816
2500	89.0	0.923
3000	59.0	0.453
3500	58.0	0.895
4000	72.0	0.367
4500	39.5	0.965
5000	35.0	0.587

*Significant values marked with **

4.2.2.2. Velocity

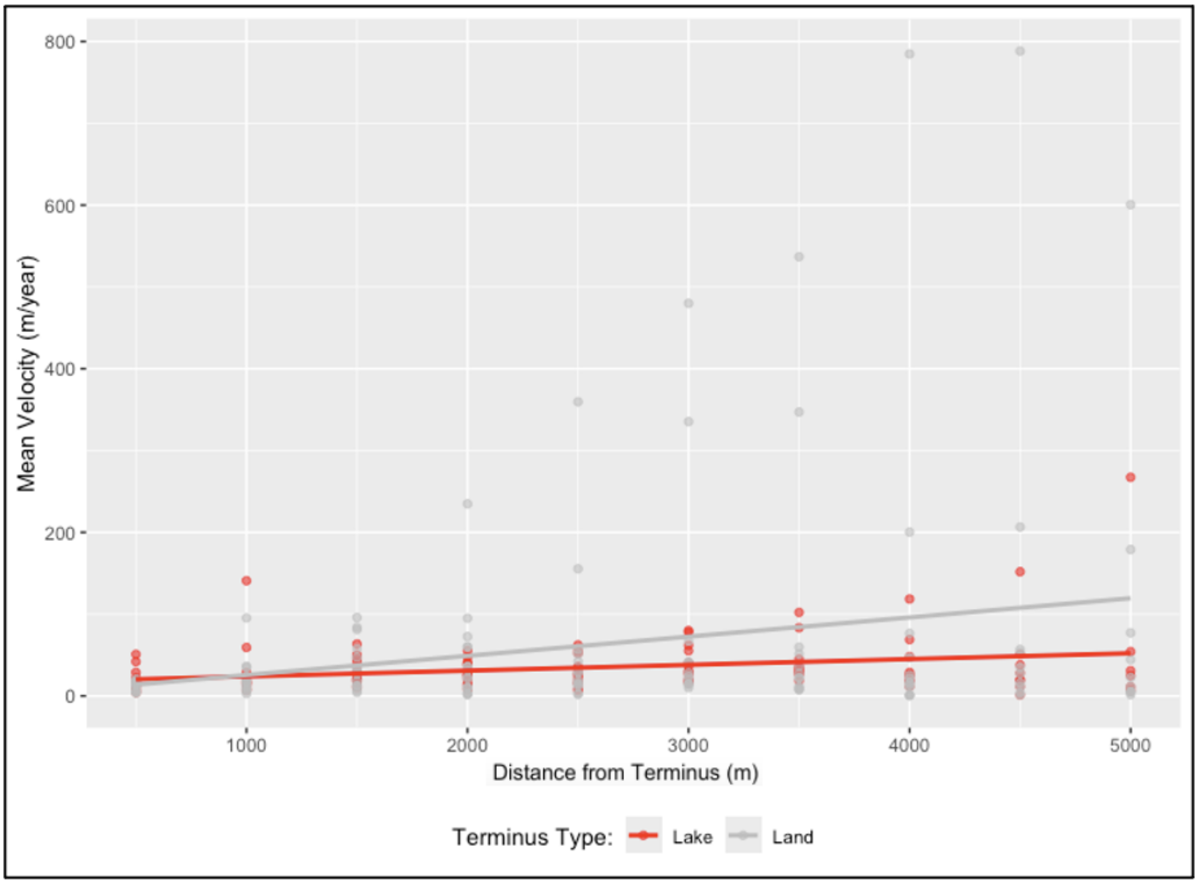
The analysis of ice surface velocity between lake- and land-terminating glaciers in relation to distance from the terminus reveals no statistically significant differences between the two glacier types at any distance. The R^2 values provide further evidence that distance from the terminus has a relatively weak influence on surface velocity. The R^2 value for lake-terminating glaciers is 0.081, and for land-terminating glaciers, it is 0.0560. This means that distance explains only 8.09% and 5.99% of the variation in surface velocity, respectively. These values indicate that the relationship between distance from the terminus and glacier velocity is weak and that other factors are likely influencing the results.

At the 500 m distance bin, lake-terminating glaciers exhibit slightly higher velocities, with a w-value of 119.0 and a *p*-value of 0.174, suggesting a possible trend toward higher velocities for lake-terminating glaciers at lower distances (Figure 4.9, Table 4.5). However, this result does not reach statistical significance at the 0.05 level. The decrease in *w*-values in relation to the distance from the terminus suggests that the difference between the lake and land terminating glaciers decreases with distance, but the *p*-values suggest this is not significant.

Interestingly, the regression lines show differing patterns between the two glacier types. Lake-terminating glaciers (red line) display a relatively flat trend with distance from the terminus, suggesting that surface velocity remains fairly consistent regardless of distance. In contrast, land-terminating glaciers (grey line) exhibit a slightly positive slope, implying that surface velocity tends to increase with distance for these glaciers. However, given the relatively low R^2 values (0.081 for lake-terminating glaciers and 0.060 for land-terminating glaciers), these regression lines explain only a small fraction of the variability in surface velocity, meaning the observed trends are weak.

The spread of data points is notably larger for land-terminating glaciers, especially at higher distances, indicating greater variability in surface velocity. A few extreme outliers among the land-terminating glaciers at higher distances (over 4000 m) contribute to this increased variability. The low R^2 values further suggest that these outliers do not reflect a strong or consistent pattern across the entire dataset. Despite these patterns, the overlapping confidence intervals and the lack of statistically significant p-values across distance bins indicate that these trends are not strong enough to conclude a systematic difference between the two glacier types.

Overall, the data suggest that factors other than distance from the terminus and terminus type may have a more dominant influence on ice surface velocity. The low R^2 values reinforce that distance from the terminus does not explain much of the variation in surface velocity, and other factors may play a more significant role.



4.9. Mean Velocities of lake and land terminating glaciers in relation to their distance from terminus from 500 m-5000 m.

Table 4.5. w and p values of lake and land terminating glaciers mean velocity in relation to their distance from terminus from the Mann-Whitney statistical testing.

Distance from Terminus (m)	***w*-Value**	***p*-Value**
500	119.0	0.174
1000	114.0	0.950
1500	87.0	0.846
2000	100.0	0.853
2500	95.0	0.846
3000	84.0	0.488
3500	73.0	0.391
4000	75.0	0.270
4500	35.5	0.689
5000	36.0	0.515
		*Significant values marked with **

4.2.2.3. Elevation change

The analysis of elevation change between lake and land-terminating glaciers in relation to distance from the terminus shows no statistically significant differences for most distance from terminus 'bins'. For the first 4500 m, the p-values remain above the 0.05 threshold, indicating that the differences in elevation change between lake- and land-terminating glaciers are not statistically significant (Figure 4.10, Table 4.6). The R^2 values further support this conclusion, with lake-terminating glaciers showing an R^2 value of 0.070 and land-terminating glaciers an R^2 value of 0.078. These low R^2 values indicate that distance from the terminus explains very little of the variability in elevation change for both glacier types.

At the 5000 m bin, the t-value of -3.42 and a p-value of 0.006 indicate a statistically significant difference in elevation change at the 0.05 level. This suggests that at greater distances from the terminus, lake-terminating glaciers experience more substantial thinning, with a mean elevation change of approximately -2 m/year, compared to land-terminating glaciers, which show a mean elevation change of about -0.75 m/year.

The regression lines reinforce this trend. Both lake- and land-terminating glaciers show a slight positive slope, indicating that elevation change becomes less negative (or thinning decreases) with increasing distance from the terminus. However, the low R^2 values (0.070 for lake-terminating glaciers and 0.078 for land-terminating glaciers) indicate that these regression lines explain only a small fraction of the variation in elevation change. This suggests that the observed trends in thinning with distance are weak and that other factors may be influencing the results. The red regression line for lake-terminating glaciers lies consistently below the grey line for land-terminating glaciers, suggesting that lake-terminating glaciers generally experience greater thinning at all distances.

The spread of data points is similar between the two glacier types, but the wider range of thinning rates at lower distances from the terminus among lake-terminating glaciers suggests higher variability in elevation change in these glaciers at lower distances. Given the low R^2 values, it's likely that this increased variability is due to other environmental factors rather than distance alone. Despite this variability, the statistically significant result at the highest distance bin highlights that lake-terminating glaciers are more prone to thinning at greater distances from the terminus compared to land-terminating glaciers.

Overall, while the majority of distance bins do not show significant differences, the significant result at 5000 m suggests that elevation change may differ systematically between lake- and land-terminating glaciers at greater distances from the terminus. However, the low R^2 values suggest that distance alone does not fully explain the observed differences, and that other factors, such as glacier dynamics or regional climatic conditions, may play a more significant role in driving these changes.

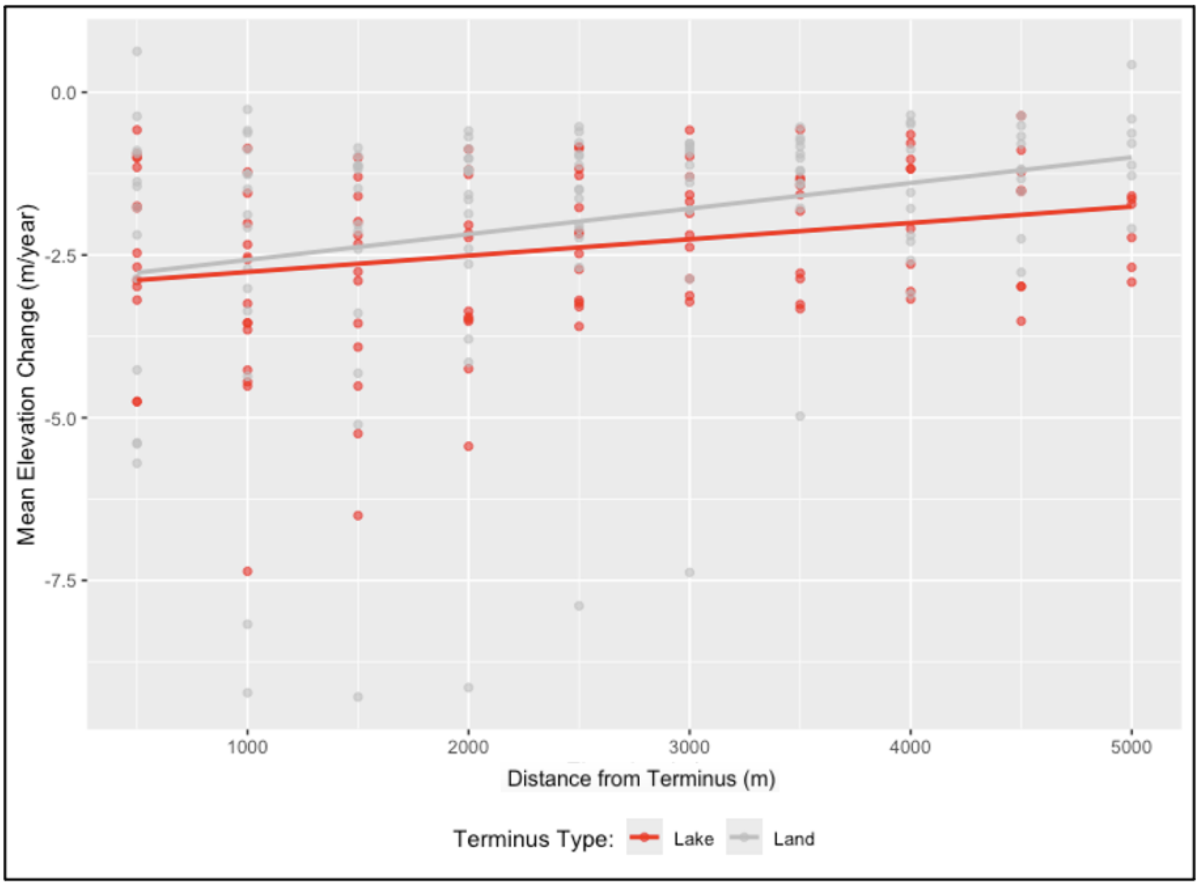


Figure 4.10. Mean elevation change of lake and land terminating glaciers in relation to their distance from terminus from 500 m-5000 m.

Table 4.6. t and p values of lake and land terminating glaciers mean elevation change in relation to their distance from terminus.

Distance from Terminus (m)	***t*-Value**	***p*-Value**
500	0.261	0.797
1000	-0.534	0.598
1500	-0.584	0.565
2000	-0.881	0.386
2500	-0.564	0.579
3000	-0.257	0.801
3500	-1.391	0.180
4000	-0.409	0.688
4500	-1.308	0.216
5000	-3.420*	0.006*

*Significant values marked with **

5. Discussion

5.1. Patterns, Associations and Overall Trends

5.1.1. Topographic influence on glacier dynamics in the Southern Alps/ /Kā Tiritiri o te Moana.

Analysis of glacier geometry metrics curvature, slope, and aspect provides valuable insights into how glaciers interact with their environment (figure 4.5.) (e.g. Etzelmuller & Sollid, 1997; Sam et al., 2018). Particularly in regions with and without proglacial lakes, insights into whether these or the presence of a lake at the terminus, are the dominant controls on glacier dynamic differences between lake and land terminating glaciers can be gained (e.g., King et al., 2018; Pronk et al., 2021). The mean slope of glaciers reveals notable differences: lake-terminating glaciers have significantly higher mean slopes (16°) compared to land-terminating glaciers (12°) (figure 4.5.). A *t*-test further supports this observed significant difference ($p < 0.001$). Oerlemans (1994) found that glaciers with a smaller slope, in this case the land terminating glaciers are more sensitive to climate change, which coincides with the findings of Chinn (1996) who found that the Franz Josef / Kā Roimata o Hine Hukatere and Fox glaciers, both land terminating, are highly sensitive to climate change.

The frequent occurrence of negative curvature values on glacier surfaces (mean curvature of -0.019 in lake terminating glaciers and -0.016 in land terminating glaciers), suggests that substantial areas experience forces causing the glacier to stretch and curve downward. This phenomenon is consistent with previous studies such as Carrivick & Chase (2011), which noted similar patterns in glacier tongues or regions where flow diverges. The relatively narrow range of curvature values indicates that glaciers generally maintain a similar surface profile, with only minor variations influencing their overall behaviour. In addition, the mean aspect of glaciers shows a statistically significant difference between lake and land terminating glaciers (t-Value = -3.197, p-value = 0.003), with land-terminating glaciers in the Southern Alps/Kā Tiritiri o te Moana having a higher mean aspect (194°) compared to lake-terminating glaciers (170°). This is expected, as land-terminating glaciers predominantly flow westward, while lake-terminating glaciers flow eastward. Conway et al. (2016) highlighted that the Brewster Glacier (a land terminating glacier), located west of the divide, absorbed more incoming solar radiation, contributing to its negative mass balance. As shown in table 4.1., 60% of land terminating glaciers are located on the West, and 100% of land terminating glaciers over 10km^2 are on the West of the main divide. This aspect-related trend is not isolated; other geometric differences between glaciers east and west of the divide reflect different climatic factors, particularly the east-west precipitation gradient (as mentioned in Section 2.4.2). These spatial trends could further be characterised by the difference in slope (figure 4.5), elevation change (figure 4.7), and ice thickness (figure 4.8).

5.1.2. Glacier dynamics between lake and land terminating glaciers in the Southern Alps /Kā Tiritiri o te Moana.

In terms of ice thickness, lake terminating glaciers exhibit significantly higher ice thickness ($p<0.05$) compared to land-terminating glaciers in the Southern Alps /Kā Tiritiri o te Moana. However, no significant difference in glacier velocities between lake and land-terminating glaciers was observed ($p = 0.246$, section 4.2.1.1.). This finding contrasts with Pronk et al. (2021), who reported that surface velocities in the Himalayas were twice as high in lake-terminating glaciers compared to land-terminating ones. The East-West orographic precipitation gradient in New Zealand, where precipitation totals range from ~1.5m a-1 in the eastern glacial areas to ~12m a-1 in the north-eastern areas relative to the main divide (Henderson & Thompson, 1999; Carrivick et al., 2022), might contribute to this insignificant difference in velocities. Global warming could exacerbate the situation by drying the east (where lake-terminating glaciers are prevalent) and increasing precipitation in the west (where land-terminating glaciers are dominant) (Chinn, 2001). This climatic shift might explain why glacier velocities remain relatively similar despite the presence of proglacial lakes.

Elevation change was significantly more pronounced in lake terminating glaciers in comparison to land terminating glaciers, when looking at the glacier as a whole ($t=-3.31$, $p= 0.00334$, section 4.2.1.3). Quincey & Glasser (2009) mention that between 1986-2007, the surface lowering of lake terminating glaciers, specifically the Tasman Glacier, was more pronounced in the lower parts of the glacier around the terminus with down-wasting outside of the current lake extent being recorded as high as 4.2 ± 1.4 m a^{-1} (Quincey & Glasser, 2009). Interestingly, an ice fall present at the Tasman glacier (Hochstetter Ice Fall), prevented a 6 km long zone beneath it has not experienced significant net surface lowering since 1986 and 2007. Chinn et al. (2012) and other studies have found a strong west-east precipitation gradient across the Southern Alps /Kā Tiritiri o te Moana, resulting in increased precipitation on the western slopes where land-terminating glaciers are found. Consequently, elevation change, influenced by glacier inputs and outputs, is more pronounced in these regions.

5.1.2.1. Distance from terminus analysis

Overall, no significant difference was identified in lake and land terminating glaciers in velocity, ice thickness and elevation change when analysing these dynamics in relation to the distance from the terminus (Section 4.2.2), which could suggest that the geometric and dynamic differences observed in section 4.1.2. and 4.2.1., are influenced by other factors, and not the presence of a lake at the terminus. This was surprising in terms of ice thickness as a significant difference was indicated in the ice thickness between lake and land terminating glaciers, as mentioned in section 5.1.2. Elevation change also initially showed significant differences when analysing the glaciers as a whole but when looking at the distance from terminus analysis, their differences were insignificant. The only significant difference value between lake and land terminating glaciers was observed in the mean elevation change in the 5000m buffer margin. Where the lake terminating glaciers elevation change was more dramatic ($w = 3.0$, $p < 0.010$), where the mean elevation change of land terminating glaciers was -0.95m and the mean elevation change of lake terminating glaciers was -2.10m. This significant difference could be linked back to the topographic characteristics of the glaciers either side of the main divide (Purdie et al., 2018), which the lake and land terminating glaciers exhibit significant differences in aspect ($p = 0.003$), and slope ($p = 0.001$). Furthermore, the lake terminating glaciers are generally a lot larger (total area of 459.40km^2, in comparison to total area of land terminating glaciers at 234.85km^2), so whilst the top segments of the land terminating glaciers are being compared within this analysis, the 5000m from terminus in lake terminating glaciers may be in a section that's present in the ablation zone. As mentioned previously by Rohl (2008), the Tasman glaciers debris covered tongue ranges for 8 km from the terminus, therefore the factors controlling elevation change may differ than the processes in the upper accumulation zones of the land terminating, smaller glaciers (Quincey & Glasser, 2009). Furthermore Quincey & Glasser (2009) found that the ice fall present on the Tasman glacier preserved some of the glacier's elevation along a 6 km long area (between 1986-2007), which could indicate why the elevation change was not more prevalent in the lake terminating glaciers when looking at it in relation to distance from terminus (section 4.2.2). The highest ablation rates on debris covered glaciers, in this case the predominantly lake terminating glaciers, occur in the middle of the ablation area rather than the lower areas (King et al., 2017). The significantly lower surface elevation change could coincide with this due it being approximately 4.5-5 km from the glacier terminus in lake terminating glaciers (figure 4.10), in this heightened area of mass loss. Furthermore, the significant difference in slope, where lake terminating glaciers mean slope is significantly higher could indicate that the development of ice falls in these glaciers may be more likely to develop. The number of ice falls present in New Zealand is hard to quantify as they have not been studied much, other than the one present at the Tasman Glacier.

In terms of ice thickness, the insignificant difference could be, and not limited to, a few factors. Firstly, it was found by King et al., (2018), that there were insignificant differences in the Himalayan glaciers ice thickness between lake and land terminating glaciers when lake terminating glaciers were either in the early stages of lake development or they were experiencing decoupling from the lakes themselves. Carrivick et al., (2022) mentions that ice marginal lakes have been forming since the 1970s-1980s, with 40% of ice cover being lost since the Little Ice Age (LIA) (Carrivick et al., 2020a; 2020b), causing these lakes to form in over deepened basins. This paper also found that between 2020 and 2030 the amount of ice marginal lakes was set to decrease due to the terminus position of glaciers retreating up the valley out of the lakes, and eventually decoupling. Linking this back to what King et al., (2018) found, this process of decoupling may have already started, earlier than anticipated, therefore the ice thickness of the glacier's termini is not reacting to the lake's presence.

5.2. Cause of non-significance

5.2.1. Glacier geometric differences

The higher slopes in lake-terminating glaciers, compared to land-terminating ones, can be attributed to the dynamic processes that lead to lake formation. As Richardson & Reynolds (2000) suggests, glaciers with steep upper slopes generate more meltwater, which pools in the lower areas, forming supraglacial ponds and eventually lakes. This meltwater accumulation increases the gradient, as water interacts with the glacier front, promoting further retreat and steepening the slope near the lake.

Ice falls, common in lake-terminating glaciers, play a critical role in this process by enhancing melt and facilitating drainage to the glacier base (Kneib et al., 2021). For example, the Tasman Glacier's Hochstetler icefall, which feeds the lowermost 12 km of the glacier, accelerates melt and contributes to meltwater pooling in the ablation zone, which further amplifies the steepness of the glacier tongue near the lake. This interaction between steep slopes, meltwater drainage, and lake formation explains the significantly higher slopes seen in lake-terminating glaciers.

5.2.2. *Glacier evolution*

As mentioned previously, glacier acceleration and ice loss across the Southern /Kā Tiritiri o te Moana of New Zealand are currently the most significant and have been accelerating since the Little Ice Age (LIA) (Carrivick et al., 2020a; Carrivick et al., 2020b). The results presented in this report indicate that there is no significant difference between the dynamics of lake-terminating and land-terminating glaciers, in relation to the presence of a lake at the glacier terminus (see section 4.2.2). This finding contrasts with previous research, where the presence of the lake has been known to speed up glacier velocities and cause differences in glacier ice thickness and elevation change between lake and land terminating glaciers (e.g. Liu et al., 2020; Sato et al., 2022).

Jansson et al. (2003) suggest that glacier mass loss initially increases with intensified melt, but eventually, glacier runoff declines after reaching a peak. In recent years, the Southern Alps /Kā Tiritiri o te Moana of New Zealand have been labelled as one of the fastest-retreating glaciated areas on the planet (Carrivick et al., 2022). This may indicate that glaciers and proglacial lakes in the Southern Alps /Kā Tiritiri o te Moana have evolved to the extent that there is minimal interaction between them. The development of lakes at a glacier's terminus often signifies that the glacier is in its final phase of retreat (Sakai and Fujita, 2010; Benn et al., 2012), this is generally the case for debris covered glaciers. It is possible that glaciers are now experiencing a slowdown in mass loss, particularly in their ablation zones where runoff is declining. This could suggest that lake-terminating glaciers are becoming decoupled from their lakes, as both have reached their peak development. Further research by Carrivick et al. (2022) indicates that proglacial lakes in New Zealand are in varying stages of development. The concept that lakes reach a peak development stage, occupying the basin left behind by the glacier, and then begin a process of disconnection, could help explain why glaciers are not responding significantly to the presence of lakes. Once lakes reach their maximum capacity, they may start to disconnect from the glacier itself.

An example of this is exhibited on the Tasman Glacier, the largest lake-terminating glacier in New Zealand. Supraglacial ponds extend up to 13 km from the terminus (Rohl, 2008) and primarily form through the melting of ice walls. The glacier has an average retreat rate of 7.3–26.0 m/yr. This study found that the relationship between the Tasman Glacier and its proglacial lake has strengthened over time. The lake significantly influences glacier dynamics, accelerating the glacier's movement and resulting in an estimated ice loss of 0.9 x 10^6 m^3/year. This positive feedback loop, where the expansion of ponds leads to increased ice exposure, aligns with the theory of glacier and lake evolution (Carrivick et al., 2022).

5.2.3. Spatial variations in glacial retreat of lake and land terminating glaciers

Analysis of New Zealand's climate and weather systems indicates a significant increase in temperature between 1991 and 2020 (r value of 0.65) (see Figure 5.1), with the average temperature being 1+°C warmer in 2020 than in 1991. However, precipitation between 1990 and 2020 shows no significant difference between 1991 and 2020 (r value of -0.003). Oliver et al., (2017) also found that the Tasman Sea, bordering New Zealand is exerting a prolonged heatwave, warming up and shifting local weather patterns. It is important to note that precipitation exhibits considerable spatial variation. Climate change is expected to alter weather patterns, with the northeast becoming drier and the southwest wetter. This variation could lead to different drivers of mass loss in New Zealand glaciers (Caloiero, 2020) and could contribute to the differences in elevation change between lake and land terminating glaciers (t=-3.31, p-Value= 0.00334, section 4.2.1.3) and ice thickness (p-value < 0.05). Surprisingly no significant difference between lake and land terminating glaciers velocity was observed. Figure 2.1. illustrates spatial variations in precipitation from 2013 to 2022, showing that the South Island's west coast experienced the highest average rainfall during this period, while some of the lowest values were recorded southeast of the divide. As a result, glaciers on the west coast have greater amounts of snowfall (Henderson & Thompson, 1999) than the glaciers of the east (difference of ~30%) (Purdie et al., 2011). Climate change, coinciding with worldwide mountain glacier mass loss (Hugonnett et al., 2021), could be causing the velocities of land terminating glaciers, which are predominantly present in the west, to speed up as a result due to the warmer precipitation inputs. Mackintosh et al., (2017) found that the fox and franz joseph / Kā Roimata o Hine Hukatere glaciers had the highest surface melt rates on earth in accordance to their elevations (~20m per year water equivalent) (Anderson et al., 2006). This in combination with their steep, thin and fast-moving ice and their large mass balance gradients makes them incredibly sensitive to climatic forcing (Mackintosh et al., 2017), one land terminating glacier in the west reached a mean velocity of 124 m/yr, which exemplifies how fast moving some of the land terminating glaciers are. As mentioned previously, the slope of land terminating glaciers was significantly lower than the lake terminating glaciers (figure 4.5), which goes against what was found by Mackintosh et al., (2017). In HMA (High Mountain Asia), the effects of warmer air temperatures and high precipitation rates, show different responses between debris and clean ice glaciers (Fugger et al., 2022). Clean ice glaciers, which are predominantly situated on the west, and are land terminating are heated to the melting point as a result of the warmer precipitation and the debris cover, more predominant on the eastern lake terminating glaciers insulates the glacier bed, reducing mass loss (Fugger et al., 2022). In contrast, east-side glaciers are more influenced by lake presence but are less affected by climate, leading to less pronounced differences between the glaciers based on their termination type (see section 4.2.2). These glaciers also have less inputs in their accumulation zones, meaning less dynamic meltwater systems draining off of them. The pronounced effects of warmer precipitation, as a result of climate change, have higher impacts in wetter glaciated systems rather than the drier systems (Molg et al., 2012; Sun et al., 2014).

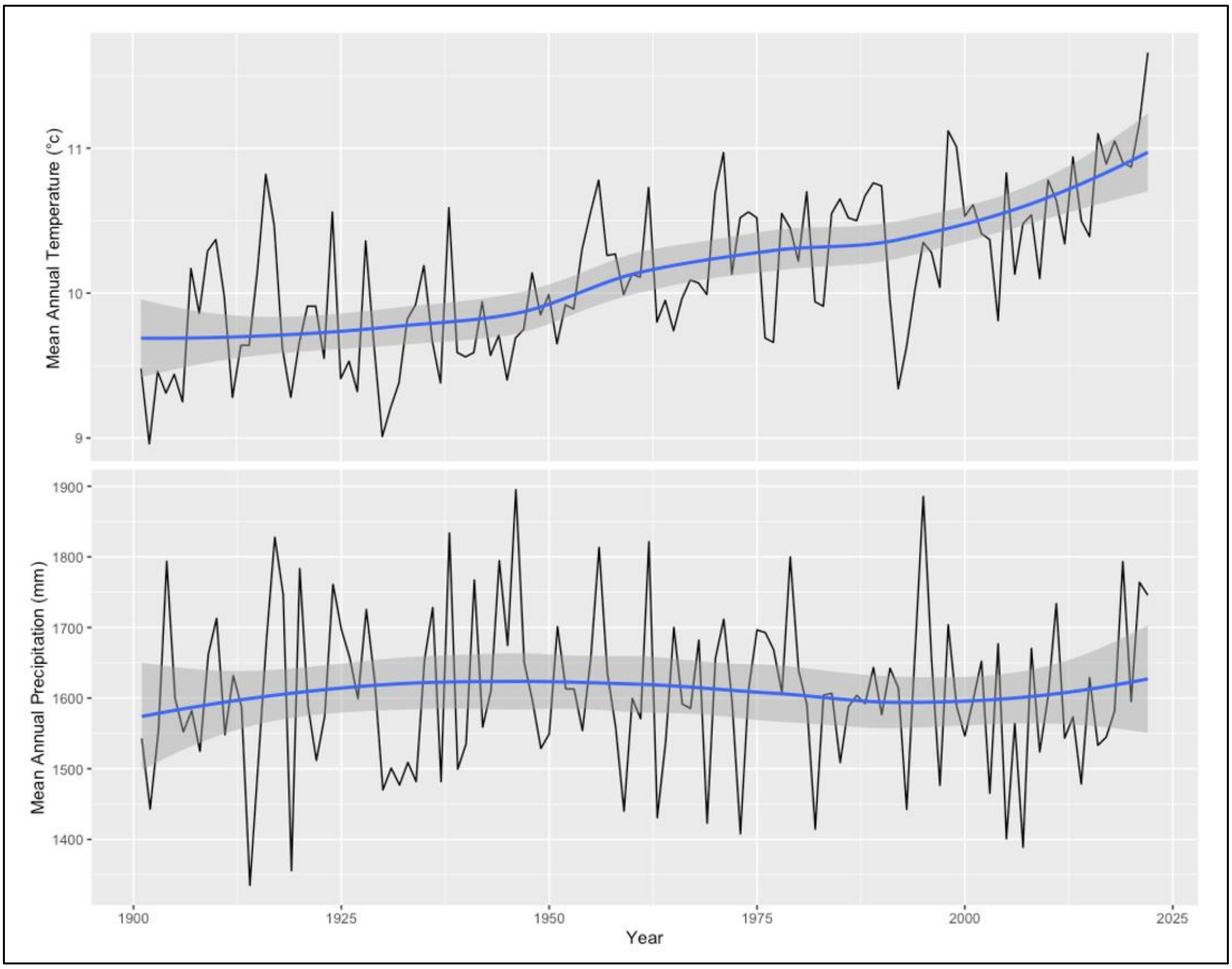


Figure 5.1. from climate NZ showing the mean annual temperature and mean annual precipitation of New Zealand from 1900 to 2020.

Anderson & Mackintosh (2012) build upon this further and found that the mass balance sensitivity of glaciers in the Southern Alps /Kā Tiritiri o te Moana of New Zealand varies significantly between the eastern and western regions, primarily due to differences in precipitation and continentality. Reinstating what was found by Chinn (1996), who found that the glaciers of the West, which are majority land terminating (figure 4.2), are “extreme maritime” glaciers influenced by the west-east orographic precipitation gradient, and glaciers to the east are “dry” balanced. Glaciers of the west experience annual precipitation reaching up to 10–12 m, exhibit a high sensitivity of approximately -1.9 m w.e. a^{-1} K^{-1}, while those in the east, with precipitation dropping to around 1 m, show reduced sensitivity (Henderson & Thompson, 1999). Figure 5.2. illustrates this spatial pattern, highlighting that the most sensitive glaciers are located in the high-precipitation zones of the west, with values ranging from -1.1 to -4.0 m w.e. a^{-1} K^{-1}. Baumann et al., (2021) emphasize that factors, such as debris cover, also play a crucial role in modulating mass balance sensitivity (see section 5.2.3), with the western, land terminating glaciers exhibit more ‘clean ice’ and the eastern, lake terminating glaciers are more debris covered (Berthier et al., 2012). Further leading to the question of which force is more dominant in controlling the dynamics of New Zealand glaciers.

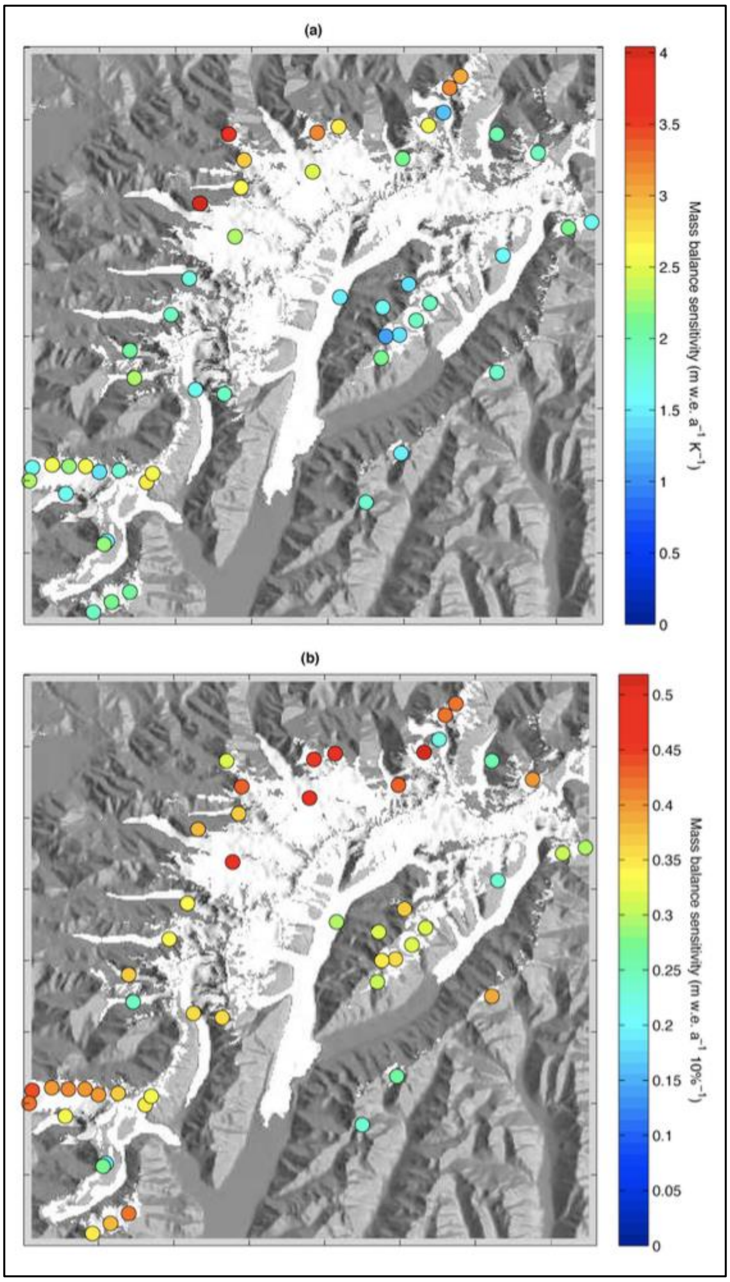


Figure 5.2. from Anderson & Mackintosh (2012), spatial patterns of mass balance a) temperature and b) precipitation sensitivity in the central southern alps /Kā Tiritiri o te Moana. Each circle is plotted at the centroids of a glacier and the colour indicates the magnitude of mass balance sensitivity. For scale, ticks on the axes are at 5 km intervals.

Warren & Kirkbride (2003) also noted that although calving events at the glacier terminus significantly increase terminal retreat rates, they do not entirely detach glaciers from climatic forcing. Climatic factors may be more dominant in recent times, and the minor dynamic differences observed could be due to the glaciers being in the later stages of glacial evolution, as previously mentioned (Dykes et al., 2010). It was also further found by Kneib-Walter et al., (2023) that 'non-calving' glaciers, such as land-terminating glaciers, are more sensitive to climatic forcing than lake-terminating glaciers. Consequently, their terminus positions align more closely with climatic changes, even though their retreat rates may be lower, which could further relate to the insignificant differences between lake and land terminating glaciers when evaluating the effect of a lake at the terminus on the glaciers dynamics (section 4.2.2).

5.2.4. Influence of debris on glacier dynamics

10% of New Zealand glaciers (totalling 92 km^2) are debris covered (Baumann et al., 2020), which is over double the global debris cover average of 4.4.% (Scherler et al., 2018). This debris reaching the glacier via steep alpine slopes, which can then further facilitate proglacial lake formation through supraglacial melt, attributed to increased surface albedo (as discussed in Section 5.2.3). Furthermore, the steep elevations mentioned demonstrated by the lake terminating glaciers (section 4.2.1), along with ice falls, which characterise the lake terminating glaciers more so than the land terminating glaciers (figure 4.5), may lead to the formation of supraglacial ponds that eventually transition into proglacial lakes (Pellicciotti et al., 2008). Surprisingly, the long debris tongue (Rohl, 2008), which characterises the lake terminating glaciers is formed due to flat slopes, which goes against the higher slope values in the lake terminating glaciers. led to the formation of supraglacial ponds which have eventually formed into a lake, as mentioned previously by Pellicciotti et al., 2008. In contrast to this, the glaciers to the west of the divide are predominantly lacking debris cover (Anderson & Mackintosh, 2012). Rohl (2008) investigated this at the Tasman glacier, which is almost 3x larger in area (km^2) than any other lake, or land terminating glaciers in New Zealand and is approximately 30% debris covered (Anderson & Mackintosh, 2012), with an overall debris thickness ranging from 0-3m (Kirkbride, 1989), with a reduction in ablation by 90% in the calculation by the energy balance model.

This difference in glacier style affects their response to climatic changes: glaciers on the West flow faster than those on the East due to their negative mass balance and lack of debris insulation as mentioned previously in 5.2.2. Studies on the effects of debris cover in New Zealand on ice surface ablation are limited (Brook & Paine, 2012), although it is largely important. 92 km^2 or 8% of the southern alps /Kā Tiritiri o te Moana are debris covered (Anderson & Mackintosh, 2012), with the Tasman glaciers having the most comprehensive record. The debris tongues of the lake-terminating glaciers east of the main divide have decreased ablation rates because the debris acts as an insulator to the glacier ice below (Rowan et al., 2015). The thick debris cover on these glacier tongues reduces gradients of ice discharge, surface velocities, and ice thickness, which is independent of climate change (Rowan et al., 2015). As a result, debris cover on the ice over the critical thickness threshold (see section 2.2.5) can lead to the preservation of glacier ice and stagnant conditions, slowing the process of mass loss down.

It has also been found that land terminating glaciers are experiencing an increase in debris cover as a result of a warming climate (Brook et al., 2013), with some glaciers experiencing the insulation effect, meaning melting is reduced, for example the Frans Joseph Glacier (Brook et al., 2013). The effects of debris cover on glaciers is difficult to fully isolate (Anderson & Anderson, 2016) but it does provide some insights into why, overall, the lake and land terminating glaciers of New Zealand may be responding similar when analysing glacial retreat triggers at the terminus, due to, the lake terminating glaciers featuring larger debris covered areas at the front in comparison to the cleaner land terminating ice glaciers. Results investigating the long-term response of debris covered glaciers are complex and non-linear when relating it to changing climatic conditions (Benn et al., 2012; Vaughan et al., 2024).

Although the long debris tongue can contribute to the preservation of ice mass, especially in the lake terminating glaciers, as this is where debris cover is the most dominant, studies, such as Quincey and Glasser (2009) have found that at the Tasman glacier the largest melt component is present on the bare ice areas, which constitutes for 80% of the melt. Conversely, making the glacier, and glaciers of a similar type (lake terminating) sensitive to climatic fluxes as mentioned previously, there is a presence of strong and influential synoptic weather systems present within New Zealand, affecting the accumulation and ablation of glaciers in the Southern Alps /Kā Tiritiri o te Moana, with the highest sensitivity at the greatest temperatures (Kirkbride, 199). Between 1990 and 2007 the debris cover of the Tasman glacier at the terminus decrease due to rapid lake growth (Quincey & Glasser, 2009), this could inter a relationship between debris cover and lake development which previously has been lacking in studies. Studies of other lake terminating glaciers in New Zealand are limited, and all mainly focus on the Tasman glacier due to its size. Section 5.3. discusses the limitations of this study, the findings, and suggestions for future studies.

5.3. Wider Implications

Overall, no significant differences were observed between the dynamics of lake-terminating and land-terminating glaciers, specifically in terms of ice thickness, velocity, and elevation change (Section 4.6.2). However, when considering ice thickness and elevation change alone, lake-terminating glaciers exhibited significant differences when compared to land-terminating glaciers (Figure 4.5, Figure 4.7). The lack of a significant difference in velocity between the two glacier types (Figure 4.6) suggests that other influences may be at play other than the presence of a lake at the glacier's terminus. These influences, potentially linked to climate, geomorphology, or other environmental factors, might override the expected effects of lake-terminating processes on velocity. Further analysis into glacier geometries revealed a significant difference in slope between lake-terminating and land-terminating glaciers (Figure 4.3) as well as notable variations in aspect (Figure 4.3).

The results of this study also provide valuable insights into the evolutionary state of New Zealand's lake-terminating glaciers. It is possible that these glaciers have reached a more advanced stage of retreat, potentially beyond their peak dynamic evolution (see section 5.2.2) This hypothesis aligns with previous studies (Sakai and Fujita. 2010; Benn et al., 2012), which suggest that lake-terminating glaciers may have undergone rapid changes in the past, stabilizing in the current climate conditions. As such, these glaciers may now exhibit slower dynamics irrespective of the presence of a lake at their terminus, offering a different perspective on the potential risks and management strategies for downstream environments.

The decoupling of lake-terminating glaciers from their associated glacial lakes could have significant biological implications (Tiberti et al., 2020). As glaciers evolve and retreat further and decouple, the lakes may become more biologically active, supporting new ecosystems as glacial input diminishes (Cauvy-Fraunie and Dangles, 2019). This could lead to shifts in aquatic flora and fauna, where species that were previously reliant on glacial meltwater must adapt to changing water conditions (Liu et al., 2024). For conservation and natural land management, these findings relating to glacier dynamics (shown in section 4.2.1) the highlight the importance of monitoring these evolving ecosystems to better understand their future trajectories.

The findings of this thesis also shed light on regional sensitivities to climate change, particularly on the western side of the Southern Alps / Kā Tiritiri o te Moana. As previously mentioned, the glaciers in this region, particularly the larger ones, are primarily land-terminating (Figure 4.2). These glaciers are highly sensitive to increased temperatures and precipitation due to their proximity to the prevailing westerly winds and the high levels of precipitation they receive (Chinn, 1996); the east-west precipitation gradient highlighting this spatial difference. The insignificant difference between the lake and land terminating glaciers could allude to this with the lake terminating glaciers of the east being less affected by climate but also have the presence of a lake, which could be driving glacier melt contrasting, the glaciers of the west, which are land terminating, having their melt driven by climatic factors (section 4.2.1). Due to their increase in sensitivity exacerbating melt, leading to increased freshwater input into coastal systems, causing problems for the ocean biodiversity (IPCC, 2023). For coastal communities, this poses significant challenges, particularly in relation to flooding and sea-level rise, which may disproportionately impact these areas (Marzeion et al., 2014; Miller et al., 2018).

In contrast, the glaciers on the eastern side of the Southern Alps / Kā Tiritiri o te Moana are predominantly lake-terminating. The interaction between the warm lake waters and the glacier termini has generally been thought to increase melt rates, typically leading to faster glacier velocities and more pronounced elevation changes (Sutherland et al., 2020). However, as demonstrated by this study, these glaciers have not shown the significantly higher dynamic values that might be expected in comparison to their land terminating counterparts. This insight is crucial for water resource management in the region, especially in light of previous concerns regarding glacier lake outburst floods (GLOFs) (Khan et al., 2023).

5.4. Future opportunity for study

Firstly, many of the larger land-terminating glaciers were excluded from the glacier pairings. This was done to compare glaciers with similar size (by area), slope, and curvature. However, the excluded glaciers (which make up 91% of the number of land-terminating glaciers above 1 km^2) were not accounted for in this analysis. Although this exclusion was intentional, these land-terminating glaciers may hold crucial information about how they respond to climate change.

This study focuses primarily on one driver of mass loss in glaciated environments, this being the presence of a proglacial lake at the glacier's terminus. Although previous studies (e.g. Otto, 2019 & Carrivick & Twee, 2013) have found that the presence of a lake at the terminus increases mass loss by speeding up glacier velocities, this was not observed here. Other controls may have been more dominant in New Zealand’s Southern Alps /Kā Tiritiri o te Moana, such as the position of the lakes and glaciers in their evolutionary stages, debris cover, and the spatial variation in glaciers in relation to the main divide. Furthermore, as mentioned in section 4.1.3, slope was found to have a significant relationship with ice thickness and velocity (table 4.2). The reasoning behind this could be multi-faceted, but it raises an interesting question as to why the same relationship was not observed in lake-terminating glaciers. Future research ought to be conducted at a higher spatial resolution in order to assess the drivers of glacial dynamics within glaciers of the Southern Alps. This may serve to explain the influence of topographic features such as ice falls, or flat tongues in driving differences in glacial dynamics between lake- and land-terminating glaciers

Understanding the evolutionary stage of glaciers is crucial, not only because of their societal importance but also due to their significant contribution to sea level rise (Frederikse et al., 2020; Zekollari et al., 2022). Accurate assessments of these glaciers’ states can be achieved by applying models that focus on glacier mass balance (Hock et al., 2019). In the context of New Zealand's Southern Alps /Kā Tiritiri o te Moana, such models can provide insight into whether glaciers have passed their peak developmental stages and the extent to which lake-terminating glaciers are responding to the presence of a lake at their terminus. This approach also allows for the evaluation of whether the methodologies employed yield accurate representations of glacier dynamics or if they misinterpret the processes due to limitations in the study design.
The dynamics of lake-terminating glaciers versus land-terminating glaciers is an important area of study, as these two types of glaciers often exhibit different responses to climatic changes. This study, however, found no significant difference in the responses of lake-terminating and land-terminating glaciers, a result that contrasts with previous research. Prior studies have shown that lake-terminating glaciers tend to retreat more rapidly due to calving processes and enhanced basal melting from the presence of water at their termini (McKinnon et al., 2012; Carrivick et al., 2022). This discrepancy could be due to a variety of factors, including regional climatic differences, glacier geometry, or the scale of the study.

By applying models such as those from Rowan et al. (2015) to current conditions, future research can compare the temporal evolution of both lake and land-terminating glaciers, thereby extending the temporal coverage of glacier dynamics in New Zealand. While earlier studies focused on the evolution of New Zealand glaciers from the Little Ice Age (LIA), this study's contemporary approach provides a clearer understanding of the current trends. This helps to determine whether lake-terminating glaciers in the Southern Alps /Kā Tiritiri o te Moana are, in fact, evolving differently from land-terminating ones or whether the lack of significant difference observed in this study is due to the unique characteristics of the Southern Alps /Kā Tiritiri o te Moana glaciers or methodological factors.

5.4.1. Broader Implications for Mountain Glacier Environments worldwide.

The findings from New Zealand's lake-terminating and land-terminating glaciers may have broader implications for glacier dynamics in other temperate and alpine regions, such as the European Alps, Andes, and Himalayas. The observed stabilisation of lake-terminating glaciers despite increased meltwater input aligns with patterns seen in the Patagonian Icefields and the Tibetan Plateau, suggesting that some lake-terminating glaciers may have reached an advanced stage of retreat, reducing their dynamic response to climate change (Agarwal et al., 2023; Capps & Clague, 2014). Similar findings have been reported in the Himalayas, where lake-terminating glaciers in the Western and Central regions did not exhibit significantly higher melt rates compared to land-terminating glaciers, suggesting that factors such as lake size, depth, and evolutionary stage may influence this dynamic rather than the mere presence of a lake (King et al., 2018). Scoffield et al. (2024) further supports this, showing that in the Eastern Himalayas, well-developed ice-contact lakes are linked to more negative surface elevation changes, indicating that lake evolution stage plays a critical role in glacier response (Scoffield et al., 2024). Similarly, research on Icelandic glaciers has shown that lakes at glacier terminus can sometimes stabilise glaciers by exerting a buttressing effect through iceberg accumulation, rather than driving increased melting (Howat et al., 2008). Differences in slope and aspect between glacier types highlight the potential role of geomorphology in influencing glacier dynamics, which may also apply to other mountain systems. The east-west precipitation gradient in New Zealand mirrors similar climatic patterns in the Andes and Himalayas, where varying exposure to westerly winds and monsoonal systems influences glacier melt and retreat (Fugger et al., 2022). These insights could improve global models of glacier response to climate change and help develop better management strategies for water resources and flood risks in other glacier-fed systems.

6. Conclusions

Objective 1: To assess the influence of proglacial lakes on glacier ice thickness.

The first objective was to analyse the impact of proglacial lakes on glacier ice thickness. In this study, lake-terminating glaciers as a whole were found to have significantly thicker ice compared to land-terminating glaciers. This suggested that the presence of a proglacial lake may have contribute to more rapid thinning of the ice, possibly due to enhanced melting processes at the terminus. However, when analysing ice thickness from the terminus, the differences between lake and land terminating glaciers and their ice thickness was insignificant and no relation was found between the presence of a lake and glacier ice thickness. This could further suggest that other factors may be contributing to the dynamic movements of glaciers in the Southern Alps / Kā Tiritiri o te Moana, which are more dominant than the presence of a lake at the terminus. Slope and aspect were found to be significantly different between lake and land terminating glaciers. A strong positive relationship was found between slope and ice thickness in both lake and land terminating glaciers suggesting this geometry may be a dominant factor controlling the Southern Alps / Kā Tiritiri o te Moana glacier dynamics.

Objective 2: To assess the influence of proglacial lakes on glacier velocity.

The second objective was to assess the impact of proglacial lakes on glacier velocity. Contrary to previous studies that suggest lake-terminating glaciers should exhibit faster velocities due to enhanced basal melting and calving processes, no significant differences in velocity were found between lake-terminating and land-terminating glaciers in this study when analysing the velocities in relation to the distance from the terminus, but also glaciers as a whole did not exhibit significant differences between lake and land terminating glacier velocities. This suggests that other factors, such as climate influences, may play a more dominant role in controlling glacier velocity. These findings imply that the presence of a lake alone does not necessarily increase glacier movement, and additional research is needed to investigate why this insignificance is the case in the Southern Alps / Kā Tiritiri o te Moana.

Objective 3: To assess the influence of proglacial lakes on glacier elevation change.

In addition to ice thickness and velocity, this study assessed elevation change between lake-terminating and land-terminating glaciers. The results showed significant differences in elevation change, with lake-terminating glaciers exhibiting more pronounced reductions when studying the glacier as a whole. However, when studying this in relation to distance from terminus, no significant relationship was found other than in the 5000 m bracket (4500-5000 m away from terminus), which suggests that other factors are acting upon the glacier dynamics in the Southern Alps / Kā Tiritiri o te Moana.

Objective 4: To assess the spatial differences between east and west sloped glaciers response to proglacial lake dynamics.

As mentioned above, the findings of this study reveal little significant differences between lake and land terminating glacier dynamics. The study also revealed significant differences in both slope and aspect between lake and land terminating glaciers and also strong relationships between these geometries and dynamics, which could indicate other factors are driving mass loss in the Southern Alps / Kā Tiritiri o te Moana. The final objective was to examine spatial differences in glacier dynamics between east and west-sloped glaciers, particularly in relation to proglacial lakes. This study also alludes to the idea that glaciers on the western slopes of the Southern Alps / Kā Tiritiri o te Moana, which are predominantly land-terminating, are highly sensitive to climatic conditions and could pose opportunity for further study to address this in relation to the presence of a lake at their terminus These glaciers, influenced by the prevailing westerly winds and high levels of precipitation, are vulnerable to enhanced melting, which contributes to greater freshwater input into coastal ecosystems (Cauvy-Fraunie and Dangles, 2019).

In contrast, glaciers on the eastern slopes, which are predominantly lake-terminating, experience different dynamics. These spatial variations are important for understanding how regional factors, such as precipitation patterns and the presence of lakes, influence glacier behaviour and retreat, and how these may be more prevalent in affecting mass loss and glacier dynamics than the presence of a lake at the glacier terminus.

7. References

Agarwal, V., de Vries, M.V.W., Haritashya, U.K., Garg, S., Kargel, J.S., Chen, Y.J. and Shugar, D.H., (2023). Long-term analysis of glaciers and glacier lakes in the Central and Eastern Himalaya. *Science of the Total Environment*, *898*, p.165598.

Anderson, B. and Mackintosh, A., (2012). Controls on mass balance sensitivity of maritime glaciers in the Southern Alps, New Zealand: The role of debris cover. *Journal of Geophysical Research: Earth Surface*, *117*(F1).

Anderson, B., Lawson, W., Owens, I. and Goodsell, B., (2006). Past and future mass balance of 'Ka Roimata o Hine Hukatere'Franz Josef Glacier, New Zealand. *Journal of Glaciology*, *52*(179), pp.597-607.

Anderson, B., Mackintosh, A., Stumm, D., George, L., Kerr, T., Winter-Billington, A. and Fitzsimons, S., (2010). Climate sensitivity of a high-precipitation glacier in New Zealand. *Journal of Glaciology*, *56*(195), pp.114-128.

Anderson, L.S. and Anderson, R.S., (2016). Modeling debris-covered glaciers: response to steady debris deposition. *The Cryosphere*, *10*(3), pp.1105-1124.

Arnold, N.S., Rees, W.G., Hodson, A.J. and Kohler, J., (2006). Topographic controls on the surface energy balance of a high Arctic valley glacier. *Journal of Geophysical Research: Earth Surface*, *111*(F2).

Azzoni, R.S., Pelfini, M. and Zerboni, A., (2023). Estimating the evolution of a post-little ice age deglaciated alpine valley through the DEM of difference (DoD). *Remote Sensing*, *15*(12), p.3190.

Barnes, E.A. and Screen, J.A., (2015). The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it?. *Wiley Interdisciplinary Reviews: Climate Change*, *6*(3), pp.277-286.

Baumann, S., Anderson, B., Chinn, T., Mackintosh, A., Collier, C., Lorrey, A.M., Rack, W., Purdie, H. and Eaves, S., (2021). Updated inventory of glacier ice in New Zealand based on 2016 satellite imagery. *Journal of glaciology*, *67*(261), pp.13-26.

Benn, D. I., & Åström, J. A. (2018). Calving glaciers and ice shelves. *Advances in Physics: X*, *3*(1), 1513819.

Benn, D., Gulley, J., Luckman, A., Adamek, A. and Glowacki, P.S., (2009). Englacial drainage systems formed by hydrologically driven crevasse propagation. *Journal of Glaciology*, *55*(191), pp.513-523.

Benn, D.I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D., Thompson, S., Toumi, R. and Wiseman, S., (2012). Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Science Reviews*, *114*(1-2), pp.156-174.

Benn, D.I., Thompson, S., Gulley, J., Mertes, J., Luckman, A. and Nicholson, L., (2017). Structure and evolution of the drainage system of a Himalayan debris-covered glacier, and its relationship with patterns of mass loss. *The Cryosphere*, *11*(5), pp.2247-2264.

Berthier, E. and Vincent, C., (2012). Relative contribution of surface mass-balance and ice-flux changes to the accelerated thinning of Mer de Glace, French Alps, over1979-2008. *Journal of Glaciology*, *58*(209), pp.501-512.

Bogen, J., Xu, M., & Kennie, P. (2015). The impact of pro‐glacial lakes on downstream sediment delivery in Norway. *Earth Surface Processes and Landforms*, *40*(7), 942-952.

Bolch, T., Yao, T., Bhattacharya, A., Hu, Y., King, O., Liu, L., Pronk, J.B., Rastner, P. and Zhang, G., (2022). Earth observation to investigate occurrence, characteristics and changes of glaciers, glacial lakes and rock glaciers in the Poiqu river basin (central Himalaya). *Remote Sensing*, *14*(8), p.1927.

Borzecki, J. (2022). *The long-term impacts of glacier retreat on runoff in the Waitaki Catchment, New Zealand* (Doctoral dissertation, Open Access Te Herenga Waka-Victoria University of Wellington).

Braithwaite, R.J. and Raper, S.C.B., (2009). Estimating equilibrium-line altitude (ELA) from glacier inventory data. *Annals of Glaciology*, *50*(53), pp.127-132.

Brambus, O., (2017). The analysis of glacial retreat of selected mountain regions of New Zealand and natural hazards from GLOFs.

Brook, M.S. and Paine, S., (2012). Ablation of ice-cored moraine in a humid, maritime climate: Fox Glacier, New Zealand. *Geografiska Annaler: Series A, Physical Geography*, *94*(3), pp.339-349.

Brook, M.S., Hagg, W. and Winkler, S., (2013). Debris cover and surface melt at a temperate maritime alpine glacier: Franz Josef Glacier, New Zealand. *New Zealand Journal of Geology and Geophysics*, *56*(1), pp.27-38.

Buckel, J., Otto, J. C., Prasicek, G., & Keuschnig, M. (2018). Glacial lakes in Austria-Distribution and formation since the Little Ice Age. *Global and Planetary Change*, *164*, 39-51.

Caloiero, T., (2020). Evaluation of rainfall trends in the South Island of New Zealand through the innovative trend analysis (ITA). *Theoretical and Applied Climatology*, *139*(1), pp.493-504.

Capps, D.M. and Clague, J.J., (2014). Evolution of glacier-dammed lakes through space and time; Brady Glacier, Alaska, USA. *Geomorphology*, *210*, pp.59-70.

Carrivick, J.L. and Tweed, F.S., (2013). Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, *78*, pp.34-52.

Carrivick, J.L., and Chase, S.E. (2011) Spatial and temporal variability of annual glacier equilibrium line altitudes in the Southern Alps, New Zealand. *New Zealand Journal of Geology and Geophysics*, 54(4), 415-429.

Carrivick, J.L., James, W.H., Grimes, M., Sutherland, J.L. and Lorrey, A.M., (2020). Ice thickness and volume changes across the Southern Alps, New Zealand, from the little ice age to present. *Scientific reports*, *10*(1), p.13392.

Carrivick, J.L., Sutherland, J.L., Huss, M., Purdie, H., Stringer, C.D., Grimes, M., James, W.H. and Lorrey, A.M., (2022). Coincident evolution of glaciers and ice-marginal proglacial lakes across the Southern Alps, New Zealand: Past, present and future. *Global and Planetary Change*, *211*, p.103792.

Carrivick, J.L., Tweed, F.S., Sutherland, J.L. and Mallalieu, J., (2020). Toward numerical modeling of interactions between ice-marginal proglacial lakes and glaciers. *Frontiers in Earth Science*, *8*, p.577068.

Cauvy-Fraunié, S. and Dangles, O., (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, *3*(12), pp.1675-1685.

Chen, P., Xiong, M., Wang, R., Yao, Y., Tang, F., Chen, H., & Qiu, L. (2023). On the Ionospheric Disturbances in New Zealand and Australia Following the Eruption of the Hunga Tonga-Hunga Ha'apai Volcano on 15 January 2022. *Space Weather*, *21*(4), e2022SW003294.

Chinn, T. J. (1996). New Zealand glacier responses to climate change of the past century. *New Zealand journal of geology and geophysics*, *39*(3), 415-428.

Chinn, T. J. (1999). New Zealand glacier response to climate change of the past 2 decades. *Global and Planetary Change*, *22*(1-4), 155-168.

Chinn, T. J. (2001). Distribution of the glacial water resources of New Zealand. *Journal of Hydrology (New Zealand)*, 139-187.

Chinn, T., Fitzharris, B.B., Willsman, A., Salinger, M.J., (2012). Annual ice volume changes 1976e2008 for the New Zealand Southern Alps. Glob. Planet. Chang. 92.

Chinn, T.J., (1999). New Zealand glacier response to climate change of the past 2 decades. Glob. Planet. Chang. 22.

Christenhusz, M.J. and Govaerts, R., (2024). Plant extinction in the Anthropocene. *Botanical Journal of the Linnean Society*, p.boae045.

Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp, (2011). *Glossary of Glacier Mass Balance and Related Terms,* IHP- VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris. 114pp.

Conway, J. P., & Cullen, N. J. (2016). Cloud effects on surface energy and mass balance in the ablation area of Brewster Glacier, New Zealand. *The Cryosphere*, *10*(1), 313-328.

Cook, S.J. and Quincey, D.J., (2015). Estimating the volume of Alpine glacial lakes. *Earth Surface Dynamics*, *3*(4), pp.559-575.

Cullen, N. J., Gibson, P. B., Mölg, T., Conway, J. P., Sirguey, P., & Kingston, D. G. (2019). The influence of weather systems in controlling mass balance in the Southern Alps of New Zealand. *Journal of Geophysical Research: Atmospheres*, *124*(8), 4514-4529.

Davies, T., Smart, C., Turnbull, J., (2003) Water an Sediment Outbursts from Advanced Franz Josef Glacier, New Zealand. Earth Surface Processes and Landforms, 28, 1081-1096.

Deline, P. (2005). Change in surface debris cover on Mont Blanc massif glaciers after the 'Little Ice Age'termination. *The Holocene*, *15*(2), 302-309.

Dell, R., Carr, R., Phillips, E. and Russell, A.J., (2019). Response of glacier flow and structure to proglacial lake development and climate at Fjallsjökull, south-east Iceland. *Journal of Glaciology*, *65*(250), pp.321-336.

Diolaiuti, G., Citterio, M., Carnielli, T., D'agata, C., Kirkbride, M., & Smiraglia, C. (2006). Rates, processes and morphology of freshwater calving at Miage Glacier (Italian Alps). *Hydrological Processes: An International Journal*, *20*(10), 2233-2244.

Dykes, R.C., Brook, M.S. and Winkler, S., (2010). The contemporary retreat of Tasman Glacier, Southern Alps, New Zealand, and the evolution of Tasman proglacial lake since AD 2000. *Erdkunde*, pp.141-154.

Dykes, R.C., Brook, M.S., Robertson, C.M. and Fuller, I.C., (2011). Twenty-first century calving retreat of Tasman Glacier, southern Alps, New Zealand. *Arctic, Antarctic, and Alpine Research*, *43*(1), pp.1-10.

Etzelmüller, B. and Sollid, J.L., (1997). Glacier geomorphometry—an approach for analyzing long-term glacier surface changes using grid-based digital elevation models. *Annals of Glaciology*, *24*, pp.135-141.

Farinotti D, Huss M, Bauder A, Funk M, Truffer M. (2009) A method to estimate the ice volume and ice-thickness distribution of alpine glaciers. *Journal of Glaciology*. 55(191):422-430.

Fitzharris, B. B., Chinn, T. J., & Lamont, G. N. (1997). Glacier balance fluctuations and atmospheric circulation patterns over the Southern Alps, New Zealand. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *17*(7), 745-763.

Fitzharris, B.B., Hay, J.E. and Jones, P.D., (1992). Behaviour of New Zealand glaciers and atmospheric circulation changes over the past 130 years. *The Holocene*, *2*(2), pp.97-106.

Francis, J.A. and Vavrus, S.J., (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical research letters*, *39*(6).

Frederikse, T., Buchanan, M. K., Lambert, E., Kopp, R. E., Oppenheimer, M., Rasmussen, D. J., & Wal, R. S. V. D. (2020). Antarctic Ice Sheet and emission scenario controls on 21st-century extreme sea-level changes. *Nature communications*, *11*(1), 390.

Fugger, S., Fyffe, C., Fatichi, S., Miles, E., McCarthy, M., Shaw, T. E., ... & Pellicciotti, F. (2022). Understanding monsoon controls on the energy and mass balance of Himalayan glaciers. *The Cryosphere*, *16*(5), 1631-1652.

Goodison, B. E., Louie, P. Y., & Yang, D. (1998). WMO solid precipitation measurement intercomparison.

Goodsell, B., Anderson, B., Lawson, W.J. and Owens, I.F., (2005). Outburst flooding at Franz Josef Glacier, South Westland, New Zealand. *New Zealand Journal of Geology and Geophysics*, *48*(1), pp.95-104.

GRIFFITHS, G.A. and McSAVENEY, M.J., (1983). Hydrology of a basin with extreme rainfalls. *New Zealand Journal of Science*, *26*, pp.293-306.

Haeberli, W., Schaub, Y., & Huggel, C. (2017). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, *293*, 405-417.

Hamilton, D.P., McBride, C.G., Özkundakci, D., Schallenberg, M., Verburg, P., de Winton, M., Kelly, D., Hendy, C. and Ye, W., (2013). Effects of climate change on New Zealand Lakes. *Climate change and inland waters: Impacts and mitigation for ecosystems and societies*, pp.337-366.

Hay, J. and Elliott, T., (2008). New Zealand's glaciers. *Darkening Peaks: Glacier Retreat, Science, and Society*, pp.185-195.

Henderson, R. D., and Thompson, S. M., (1999) Extreme rainfalls in the Southern Alps of New Zealand. Journal of Hydrology (NZ), 38: 309–330.

Herreid, S., & Pellicciotti, F. (2020). The state of rock debris covering Earth's glaciers. *Nature Geoscience*, *13*(9), 621-627.

Hock, R., Bliss, A., Marzeion, B. E. N., Giesen, R. H., Hirabayashi, Y., Huss, M., ... & Slangen, A. B. (2019). GlacierMIP–A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology*, *65*(251), 453-467.

Houston, J., & Hartley, A. J. (2003). The central Andean west-slope rainshadow and its potential contribution to the origin of hyper-aridity in the Atacama Desert. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *23*(12), 1453-1464.

Howat, I.M., Tulaczyk, S., Waddington, E. and Björnsson, H., 2008. Dynamic controls on glacier basal motion inferred from surface ice motion. *Journal of Geophysical Research: Earth Surface*, *113*(F3).

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F. and Kääb, A., (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), pp.726-731.

Huss, M. & Farinotti, D. (2012), Distributed ice thickness and volume of all glaciers around the globe. *J. Geophys. Res. Earth Surf.*

Huss, M. and Hock, R. (2018) Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8, 135–140.

Immerzeel, W. W. et al. (2020) Importance and vulnerability of the world's water towers. *Nature* 577, 364–369.

IPCC, 2023: Climate Change (2023): Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115.

Ishikawa, N. , I. F. Owens , and A. P. Sturman , (1992). Heat balance characteristics during fine periods on the lower parts of the Franz Josef Glacier, South Westland, New Zealand. International Journal of Climatology 12:397–410.

Jansson, P., Hock, R., & Schneider, T. (2003). The concept of glacier storage: a review. *Journal of Hydrology*, *282*(1-4), 116-129.

Jó, V., de Vries, M.V.W., Ignéczi, Á., Mari, L. and Nagy, B., (2023). Glacier slowdown and rapid ice loss in the Tinguiririca and Cachapoal Basin, Central Andes of Chile. *Global and Planetary Change*, *231*, p.104287.

Kaser, G., Fountain, A., Jansson, P., Heucke, E. and Knaus, M. (2003) *A manual for monitoring the mass balance of mountain glaciers.* Paris: Unesco.

Kavanaugh, J.L. and Clarke, G.K., (2001). Abrupt glacier motion and reorganization of basal shear stress following the establishment of a connected drainage system. *Journal of Glaciology*, *47*(158), pp.472-480.

Kennett, M., Rolstad, C., Elvehoy, H., & Ruud, E. (1997). Calculation of drainage divides beneath the Svartisen ice-cap using GIS hydrologic tools. *Norsk Geografisk Tidsskrift-Norwegian Journal of Geography*, *51*(1), 23-28.

Khan, S., Ullah, R., Bibi, S. and Ali, M., (2023). Spatio-temporal change in the glaciers of Astore Basin (North-Western Himalaya), between 2016 and 2021 by using Sentinel-2 satellite data.

King, O., Bhattacharya, A., Bhambri, R., & Bolch, T. (2019). Glacial lakes exacerbate Himalayan glacier mass loss. *Scientific Reports*, *9*(1), 18145.

King, O., Dehecq, A., Quincey, D. and Carrivick, J., (2018). Contrasting geometric and dynamic evolution of lake and land-terminating glaciers in the central Himalaya. *Global and Planetary Change*, *167*, pp.46-60.

Kirkbride, M. (1989). The influence of sediment budget on geomorphic activity of the Tasman Glacier, Mount Cook National Park, New Zealand.

Kirkbride, M. (1995). Ice flow vectors on the debris-mantled Tasman Glacier, 1957–1986. *Geografiska Annaler: Series A, Physical Geography*, *77*(3), 147-157.

Kneib-Walter, A., Lüthi, M.P., Funk, M., Jouvet, G. and Vieli, A., (2023). Observational constraints on the sensitivity of two calving glaciers to external forcings. *Journal of Glaciology*, *69*(275), pp.459-474.

Kneib, M., Miles, E. S., Buri, P., Molnar, P., McCarthy, M., Fugger, S., & Pellicciotti, F. (2021). Interannual dynamics of ice cliff populations on debris-covered glaciers from remote sensing observations and stochastic modeling. *Journal of Geophysical Research: Earth Surface*, *126*(10), e2021JF006179.

Kochendorfer, J., Rasmussen, R., Wolff, M., Baker, B., Hall, M. E., Meyers, T., ... & Leeper, R. (2017). The quantification and correction of wind-induced precipitation measurement errors. *Hydrology and Earth System Sciences*, *21*(4), 1973-1989.

Kraaijenbrink, P. D., Bierkens, M. F., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, *549*(7671), 257-260.

Leong, D. and Chesterton, J. (2005) Waitaki catchment, hydrological information. Report commissioned by the Ministry for the Environment for consideration by the Waitaki Catchment Water Allocation Board 582, Ministry for the Environment, Wellington, New Zealand.

Liu, K., Liu, Y., Yan, Q., Guo, X., Wang, W., Zhang, Z., Hu, A., Xiao, X., Ji, M. and Liu, P., (2024). Temperature-driven shifts in bacterioplankton biodiversity: Implications for cold-preferred species in warming Tibetan proglacial lakes. *Water Research*, *265*, p.122263.

Liu, Q., Mayer, C., Wang, X., Nie, Y., Wu, K., Wei, J., & Liu, S. (2020). Interannual flow dynamics driven by frontal retreat of a lake-terminating glacier in the Chinese Central Himalaya. *Earth and Planetary Science Letters*, *546*, 116450.

Lorrey, A. M., Vargo, L., Purdie, H., Anderson, B., Cullen, N. J., Sirguey, P., ... & Chinn, W. (2022). Southern Alps equilibrium line altitudes: four decades of observations show coherent glacier–climate responses and a rising snowline trend. *Journal of Glaciology*, *68*(272), 1127-1140.

Lorrey, A., Vargo, L., Purdie, H., Anderson, B., Cullen, N., Sirguey, P., Mackintosh, A., Willsman, A., Macara, G. and Chinn, W. (2022) Southern Alps equilibrium line altitudes: Four decades of observations show coherent glacier–climate responses and a rising snowline trend. *Journal of Glaciology*, 68(272), 1127- 1140.

Mackintosh, A. N. et al. (2017), Regional cooling caused recent New Zealand glacier advances in a period of global warming. *Nat. Commun.* 8.

Mackintosh, A.N., Anderson, B.M. and Pierrehumbert, R.T., (2017). Reconstructing climate from glaciers. *Annual Review of Earth and Planetary Sciences*, *45*(1), pp.649-680.

Marcus, M. G., Moore, R. D., & Owens, I. F. (1985). Short-term estimates of surface energy transfers and ablation on the lower Franz Josef Glacier, South Westland, New Zealand. *New Zealand Journal of Geology and Geophysics*, *28*(3), 559-567.

Marzeion, B., Cogley, J.G., Richter, K. and Parkes, D., (2014). Attribution of global glacier mass loss to anthropogenic and natural causes. *Science*, *345*(6199), pp.919-921.

McKinnon, K. A., Mackintosh, A. N., Anderson, B. M., & Barrell, D. J. (2012). The influence of sub-glacial bed evolution on ice extent: a model-based evaluation of the Last Glacial Maximum Pukaki glacier, New Zealand. *Quaternary Science Reviews*, *57*, 46-57.

Meier, M.F., Dyurgerov, M.B. and McCabe, G.J., (2003). The health of glaciers: Recent changes in glacier regime. *Climatic change*, *59*(1), pp.123-135.

Mernild, S.H., Beckerman, A.P., Yde, J.C., Hanna, E., Malmros, J.K., Wilson, R. and Zemp, M., (2015). Mass loss and imbalance of glaciers along the Andes Cordillera to the sub-Antarctic islands. *Global and Planetary Change*, *133*, pp.109-119.

Messager, M.L., Lehner, B., Grill, G., Nedeva, I. and Schmitt, O., (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature communications*, *7*(1), p.13603.

Miles, E.S., Willis, I.C., Arnold, N.S., Steiner, J. and Pellicciotti, F., (2017). Spatial, seasonal and interannual variability of supraglacial ponds in the Langtang Valley of Nepal, 1999–2013. *Journal of Glaciology*, *63*(237), pp.88-105.

Miles, K. E., Hubbard, B., Quincey, D. J., Miles, E. S., Sherpa, T. C., Rowan, A. V., & Doyle, S. H. (2018). Polythermal structure of a Himalayan debris-covered glacier revealed by borehole thermometry. *Scientific Reports*, *8*(1), 16825.

Miles, K.E., Hubbard, B., Irvine-Fynn, T.D., Miles, E.S., Quincey, D.J. and Rowan, A.V., (2020). Hydrology of debris-covered glaciers in High Mountain Asia. *Earth-Science Reviews*, *207*, p.103212.

Millan, R., (2018). *Dynamics of Glaciers and Ice Sheets at the Ocean Margin from Airborne and Satellite Data*. University of California, Irvine.

Millan, R., Mouginot, J., Rabatel, A. and Morlighem, M., (2022). Ice velocity and thickness of the world's glaciers. *Nature Geoscience*, *15*(2), pp.124-129.

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M. and Grossman, E., (2018). Projected sea level rise for Washington state: A 2018 assessment.

Minowa, M., Schaefer, M., & Skvarca, P. (2023). Effects of topography on dynamics and mass loss of lake-terminating glaciers in southern Patagonia. *Journal of Glaciology*, 1-18.

Mölg, N., Huggel, C., Herold, T., Storck, F., Allen, S., Haeberli, W., Schaub, Y. and Odermatt, D., (2021). Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland. *Earth Surface Processes and Landforms*, *46*(13), pp.2551-2564.

Mölg, T., Maussion, F., Yang, W., and Scherer, D (2012).: The footprint of Asian monsoon dynamics in the mass and energy balance of a Tibetan glacier, The Cryosphere, 6, 1445–1461.

Morlighem, M., Williams, C.N., Rignot, E., An, L., Arndt, J.E., Bamber, J.L., Catania, G., Chauché, N., Dowdeswell, J.A., Dorschel, B. and Fenty, I., (2017). BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. *Geophysical research letters*, *44*(21), pp.11-051.

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the national academy of sciences*, *115*(9), 2022-2025.

Oerlemans, J. (1994) Quantifying global warming from the retreat of glaciers. *Science,* 264(5156), 243-245.

Oerlemans, J., (1997). Climate sensitivity of Franz Josef Glacier, New Zealand, as revealed by numerical modeling. *Arctic and Alpine Research*, *29*(2), pp.233-239.

Oliver, E. C., Benthuysen, J. A., Bindoff, N. L., Hobday, A. J., Holbrook, N. J., Mundy, C. N., and Perkins- Kirkpatrick, S. E. (2017). The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature communications*, 8(1), 16101.

Østrem, G. (1971). Rock glaciers and ice-cored moraines, a reply to D. Barsch. *Geografiska Annaler: Series A, Physical Geography*, *53*(3-4), 207-213.

Otto, J. C. (2019). Proglacial lakes in high mountain environments. *Geomorphology of proglacial systems: landform and sediment dynamics in recently deglaciated alpine landscapes*, 231-247.

Pang, X., Jiang, L., Guo, R., Xu, Z., Li, X., & Lu, X. (2023). Surface Motion and Topographic Effects on Ice Thickness Inversion for High Mountain Asia Glaciers: A Comparison Study from Three Numerical Models. *Remote Sensing*, *15*(22), 5378.

Pellicciotti, F., Helbing, J., Rivera, A., Favier, V., Corripio, J., Araos, J., ... & Carenzo, M. (2008). A study of the energy balance and melt regime on Juncal Norte Glacier, semi-arid Andes of central Chile, using melt models of different complexity. *Hydrological Processes*, *22*(19), 3980-3997.

Pepin, N. C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., ... & Adler, C. (2022). Climate changes and their elevational patterns in the mountains of the world. *Reviews of Geophysics*, *60*(1), e2020RG000730.

Pronk, J.B., Bolch, T., King, O., Wouters, B. and Benn, D.I., (2021). Contrasting surface velocities between lake-and land-terminating glaciers in the Himalayan region. *The Cryosphere*, *15*(12), pp.5577-5599.

Purdie, H., Anderson, B., Chinn, T., Owens, I., Mackintosh, A., & Lawson, W. (2014). Franz Josef and Fox glaciers, New Zealand: historic length records. *Global and Planetary Change*, *121*, 41-52.

Purdie, H., Anderson, B., Mackintosh, A., & Lawson, W. (2018). Revisiting glaciological measurements on Haupapa/Tasman Glacier, New Zealand, in a contemporary context. *Geografiska Annaler: Series A, Physical Geography*, *100*(4), 351-369.

Purdie, H., Mackintosh, A., Lawson, W., and Anderson, B., (2011), Synoptic Influences on Snow Accumulation on Glaciers East and West of a Topographic Divide: Southern Alps, New Zealand. Arctic, Antarctic, and Alpine Research, 43(1): 82-94.

Purdie, J. M., & Bardsley, W. E. (2010). Seasonal prediction of lake inflows and rainfall in a hydro-electricity catchment, Waitaki river, New Zealand.

Purdie, J., & Fitzharris, B. (1999). Processes and rates of ice loss at the terminus of Tasman Glacier, New Zealand. *Global and Planetary Change*, *22*(1-4), 79-91.

Quincey, D.J. and Glasser, N.F., (2009). Morphological and ice-dynamical changes on the Tasman Glacier, New Zealand, 1990–2007. *Global and Planetary Change*, *68*(3), pp.185-197.

Rahmstorf, S., Box, J.E., Feulner, G., Mann, M.E., Robinson, A., Rutherford, S. and Schaffernicht, E.J., (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature climate change*, *5*(5), pp.475-480.

Rangwala, I., & Miller, J. R. (2012). Climate change in mountains: a review of elevation-dependent warming and its possible causes. *Climatic change*, *114*, 527-547.

RGI Consortium, (2017), Randolph Glacier Inventory (RGI) – A Dataset of Global Glacier Outlines: Version 6.0. Technical Report, Global Land Ice Measurements from Space, Boulder, Colorado, USA. Digital Media. DOI: https://doi.org/10.7265/N5-RGI-60.

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International*, *65*, 31-47.

Röhl, K. (2008). Characteristics and evolution of supraglacial ponds on debris-covered Tasman Glacier, New Zealand. *Journal of Glaciology*, *54*(188), 867-880.

Rounce, D.R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L. and Farinotti, D., (2023). Global glacier change in the 21st century: Every increase in temperature matters. *Science*, *379*(6627), pp.78-83.

Rowan, A.V., Egholm, D.L., Quincey, D.J. and Glasser, N.F., (2015). Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. *Earth and Planetary Science Letters*, *430*, pp.427-438.

Russell, A.J., Carrivick, J.L., Ingeman-Nielsen, T., Yde, J.C. and Williams, M., (2011). A new cycle of jökulhlaups at Russell Glacier, Kangerlussuaq, West Greenland. *Journal of Glaciology*, *57*(202), pp.238-246.

Sakai, A. and Fujita, K., (2010). Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya. *Journal of Glaciology*, *56*(195), pp.177-181.

Salinger, M.J., Fitzharris, B.B. and Chinn, T., (2019). Atmospheric circulation and ice volume changes for the small and medium glaciers of New Zealand's Southern Alps Mountain range 1977–2018. *International Journal of Climatology*, *39*(11), pp.4274-4287.

Sam, L., Bhardwaj, A., Kumar, R., Buchroithner, M.F. and Martín-Torres, F.J., (2018). Heterogeneity in topographic control on velocities of Western Himalayan glaciers. *Scientific reports*, *8*(1), p.12843.

Sato, Y., Fujita, K., Inoue, H., Sakai, A. and Karma, (2022). Land-to lake-terminating transition triggers dynamic thinning of a Bhutanese glacier. *The Cryosphere*, *16*(6), pp.2643-2654.

Sato, Y., Fujita, K., Inoue, H., Sakai, A. and Karma, (2022). Land-to lake-terminating transition triggers dynamic thinning of a Bhutanese glacier. *The Cryosphere*, *16*(6), pp.2643-2654.

Scherler, D., Wulf, H. and Gorelick, N., (2018). Global assessment of supraglacial debris-cover extents. *Geophysical Research Letters*, *45*(21), pp.11-798.

Scoffield, A.C., Rowan, A.V., Quincey, D.J., Carrivick, J.L., Sole, A.J. and Cook, S.J., (2024). Sub-regional variability in the influence of ice-contact lakes on Himalayan glaciers. *Journal of Glaciology*, pp.1-11.

Shaw, T.E., Yang, W., Ayala, Á., Bravo, C., Zhao, C. and Pellicciotti, F., (2021). Distributed summer air temperatures across mountain glaciers in the south-east Tibetan Plateau: Temperature sensitivity and comparison with existing glacier datasets. *The Cryosphere*, *15*(2), pp.595-614.

Shugar, D.H., Burr, A., Haritashya, U.K., Kargel, J.S., Watson, C.S., Kennedy, M.C., Bevington, A.R., Betts, R.A., Harrison, S. and Strattman, K., (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature climate change*, *10*(10), pp.939-945.

Sirguey, P. J. B. (2010). Monitoring snow cover and modelling catchment discharge with remote sensing in the Upper Waitaki Basin, New Zealand. PhD thesis, University of Otago.

Slater, T. and Shepherd, A., (2018). Antarctic ice losses tracking high. *Nature Climate Change*, *8*(12), pp.1025-1026.

Slater, T., Hogg, A.E. and Mottram, R., (2020). Ice-sheet losses track high-end sea-level rise projections. *Nature Climate Change*, *10*(10), pp.879-881.

Smiraglia, C., Diolaiuti, C., Pelfini, M., Beld, M., Citterio, M., Camielli, T., & D Agata, C. (2008). Glacier changes and their impacts on mountain tourism: Two case studies from the Italian Alps. In B. S. Orlove, E. Wiegandt, & B. H Luckman (Eds.), Darkening peaks: Glacier retreat, science, and society (pp. 206 215). Berkeley, CA: University of California Press.

Song, C., Sheng, Y., Wang, J., Ke, L., Madson, A. and Nie, Y., (2017). Heterogeneous glacial lake changes and links of lake expansions to the rapid thinning of adjacent glacier termini in the Himalayas. *Geomorphology*, *280*, pp.30-38.

Stats NZ, n.d. *Rainfall*. Stats NZ. Available at: https://www.stats.govt.nz/indicators/rainfall/ [Accessed 12 Sept. 2024].

Steiner, J.F., Kraaijenbrink, P.D., Jiduc, S.G. and Immerzeel, W.W., (2018). Brief communication: The Khurdopin glacier surge revisited–extreme flow velocities and formation of a dammed lake in 2017. *The Cryosphere*, *12*(1), pp.95-101.

Stewart, E. J., Wilson, J., Espiner, S., Purdie, H., Lemieux, C., & Dawson, J. (2016). Implications of climate change for glacier tourism. *Tourism Geographies*, *18*(4), 377-398.

Sturman, A.P. and Tapper, N.J., (1996). *The weather and climate of Australia and New Zealand*. Oxford University Press, USA.

Sun, W., Qin, X., Du, W., Liu, W., Liu, Y., Zhang, T., Xu, Y., Zhao, Q., Wu, J., and Ren, J. (2014) Ablation modeling and surface energy budget in the ablation zone of Laohugou glacier No. 12, western Qilian mountains, China, Ann. Glaciol., 55, 111–120.

Sutherland, J.L., Carrivick, J.L., Gandy, N., Shulmeister, J., Quincey, D.J. and Cornford, S.L., (2020). Proglacial lakes control glacier geometry and behavior during recession. *Geophysical Research Letters*, *47*(19), p.e2020GL088865.

Takeuchi, Y., Naruse, R., Satow, K. and Ishikawa, N., (1999). Comparison of heat balance characteristics at five glaciers in the Southern Hemisphere. *Global and Planetary Change*, *22*(1-4), pp.201-208.

Thakuri, S., Dahal, S., Shrestha, D., Guyennon, N., Romano, E., Colombo, N. and Salerno, F., (2019). Elevation-dependent warming of maximum air temperature in Nepal during 1976–2015. *Atmospheric Research*, *228*, pp.261-269.

Tiberti, R., Buscaglia, F., Callieri, C., Rogora, M., Tartari, G. and Sommaruga, R., (2020). Food web complexity of high mountain lakes is largely affected by glacial retreat. *Ecosystems*, *23*, pp.1093-1106.

Truffer, M. and Motyka, R.J., (2016). Where glaciers meet water: Subaqueous melt and its relevance to glaciers in various settings. *Reviews of Geophysics*, *54*(1), pp.220-239.

Trüssel, B. L., Motyka, R. J., Truffer, M., & Larsen, C. F. (2013). Rapid thinning of lake-calving Yakutat Glacier and the collapse of the Yakutat Icefield, southeast Alaska, USA. *Journal of Glaciology*, *59*(213), 149-161.

Tsutaki, S., Nishimura, D., Yoshizawa, T. and Sugiyama, S., (2011). Changes in glacier dynamics under the influence of proglacial lake formation in Rhonegletscher, Switzerland. *Annals of Glaciology*, *52*(58), pp.31-36.

Tudoroiu, M., Eccel, E., Gioli, B., Gianelle, D., Schume, H., Genesio, L. and Miglietta, F., (2016). Negative elevation-dependent warming trend in the Eastern Alps. *Environmental Research Letters*, *11*(4), p.044021.

Ummenhofer, C.C., Gupta, A.S. and England, M.H., (2009). Causes of late twentieth-century trends in New Zealand precipitation. *Journal of Climate*, *22*(1), pp.3-19.

Vargo, L.J., Anderson, B.M., Dadić, R., Horgan, H.J., Mackintosh, A.N., King, A.D. and Lorrey, A.M., (2020). Anthropogenic warming forces extreme annual glacier mass loss. *Nature Climate Change*, *10*(9), pp.856-861.

Vaughan, D.G., Comiso, J.C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J. and Rignot, E., (2013). Observations: cryosphere. *Climate change*, *2103*, pp.317-382.

Vaughan, J., England, J. H., Coulthard, R. D., & La Farge, C. (2024). Passage and removal of the Amundsen Gulf Ice Stream, NW Laurentide Ice Sheet, recorded by the glacial and sea level history of southern Banks Island, Arctic Canada. *Quaternary Science Reviews*, *344*, 108880.

Veh, G., Korup, O. and Walz, A., (2020). Hazard from Himalayan glacier lake outburst floods. *Proceedings of the National Academy of Sciences*, *117*(2), pp.907-912.

Vellinga, M. and Wood, R.A., (2002). Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic change*, *54*(3), pp.251-267.

Verpoorter, C., Kutser, T., Seekell, D.A. and Tranvik, L.J., (2014). A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters*, *41*(18), pp.6396-6402.

Vishwanathan, V., Volino, R.J. and Schultz, M.P., (2024). Reynolds Number Effects on Heterogeneous Rough Wall Turbulent Boundary Layers in Zero Pressure Gradient. In *AIAA SCITECH 2024 Forum* (p. 1363).

Wang, C., Zhang, L., Lee, S.K., Wu, L. and Mechoso, C.R., (2014). A global perspective on CMIP5 climate model biases. *Nature Climate Change*, *4*(3), pp.201-205.

Wang, S., Che, Y., Pang, H., Du, J. and Zhang, Z., (2020). Accelerated changes of glaciers in the Yulong Snow Mountain, Southeast Qinghai-Tibetan Plateau. *Regional Environmental Change*, *20*, pp.1-13.

Warren, C.R. and Kirkbride, M.P., (2003). Calving speed and climatic sensitivity of New Zealand lake-calving glaciers. *Annals of Glaciology*, *36*, pp.173-178.

Whiteman, C.D., (2000). *Mountain meteorology: fundamentals and applications*. Oxford University Press.

Wilson, P., Rodés, Á. and Smith, A., (2018). Valley glaciers persisted in the Lake District, north-west England, until~ 16–15 ka as revealed by terrestrial cosmogenic nuclide (10Be) dating: a response to Heinrich event 1?. *Journal of Quaternary Science*, *33*(5), pp.518-526.

Yang, X., Davis, M.E., Acharya, S. and Yao, T., (2018). Asian monsoon variations revealed from stable isotopes in precipitation. *Climate Dynamics*, *51*, pp.2267-2283.

Zekollari, H., Huss, M., Farinotti, D. and Lhermitte, S., (2022). Ice-Dynamical Glacier Evolution Modeling—A Review. *Reviews of Geophysics*, *60*(2), p.e2021RG000754.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I. and Thomson, L., (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, *568*(7752), pp.382-386.