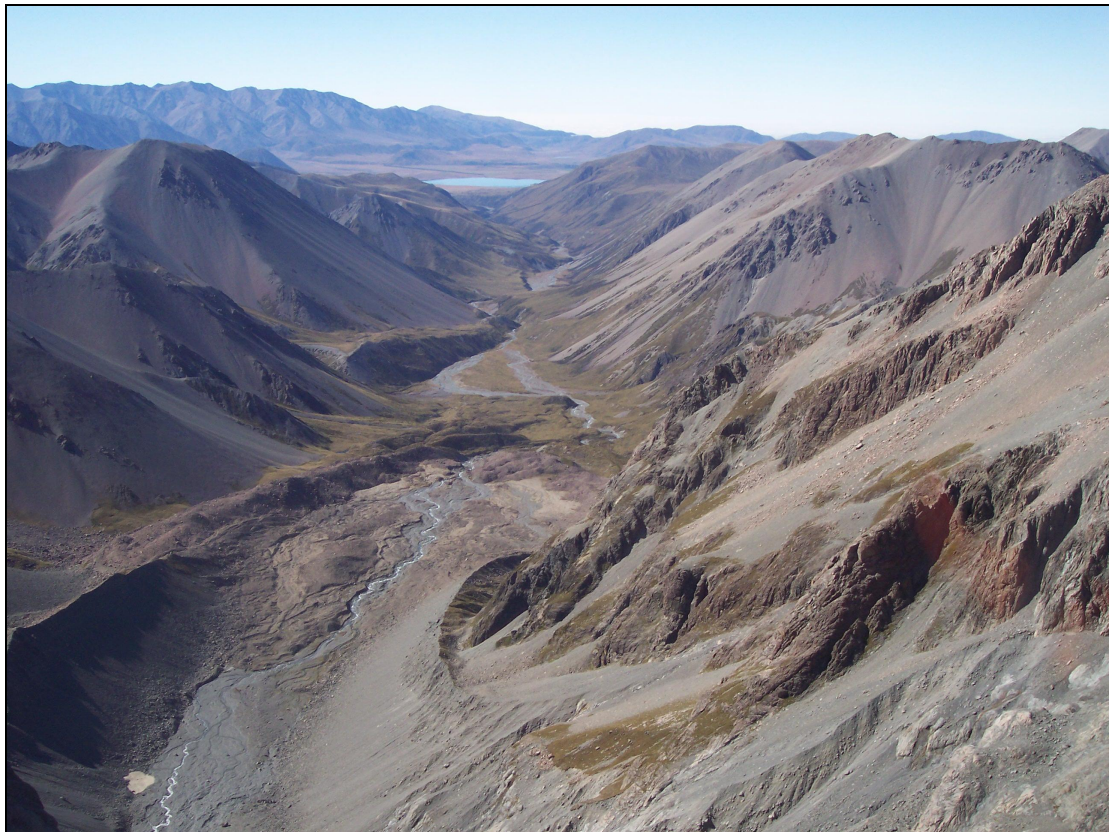


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**Using glacier models to reconstruct climate change**  
**over the last 13,000 years**

Proposal for Thesis

March, 2010



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## **I. ABSTRACT**

Instrumental weather data in New Zealand extend back to about 1860 AD, leaving great uncertainties about longer-term natural climate variability. Glaciers exhibit one of the clearest and most direct responses to climate change and past glacier extents afford an opportunity to decipher paleoclimate. Now that the accuracy and precision of moraine chronologies has improved through advances in surface exposure dating (SED) techniques, multi-proxy and global climate comparisons have become more refined. Interhemispheric climate event relationships are valuable when looking for causes or triggers of climate change; however, the interpreted temperature changes from glacier fluctuations are generally qualitative rather than quantitative. Here we use numerical modelling as a tool to quantify paleoclimate fluctuations with a combination of mapped moraine positions, surface exposure dating chronologies, and modern and proxy climate data for model construction and tuning. We will evaluate the effects that precipitation, temperature, and solar radiation have on glaciers through empirical field evidence and numerical modelling from four sites distributed throughout the Southern Alps of New Zealand. This approach will allow us to constrain an envelope of possible climatic conditions necessary for the glacier to advance and stabilise at specified lengths. Detailed moraine chronologies now exist at three of these sites and a multiple-year glacier mass balance study exists at the fourth site. The modelling results have the potential to help us better understand (1) the regionality and seasonality of past climate change within New Zealand, (2) what climatic signals the glaciers are responding to, and (3) interhemispheric differences in glacier extent, such as why the "Little Ice Age" in New Zealand was such a minor event compared to others during the Holocene.

## **II. TOPIC DEVELOPMENT**

### ***A) Background***

Recent technological advances in surface exposure dating (SED) methods have allowed for more precise moraine chronologies than previously possible (Putnam et al., in press; Putnam et al., in prep; Schaefer et al., 2009). These chronologies offer the unique opportunity for paleoclimate reconstructions with highly accurate ages. Previous paleoclimate investigations of these moraines focused on geometric reconstructions assuming an accumulation area ratio (AAR) of 0.66 (Chinn, 2006; Kaplan et al., submitted; Putnam et al., in prep) and resulted in equilibrium line altitude (ELA) depression estimates (Porter, 1975). Although these are reasonable estimates, they can only represent a 'snapshot' or steady state reconstruction and cannot account for the time-dependent evolution of glacier length. Moreover, they do not account for valley-specific topography, shading, local mass balance, or glacier response time (Oerlemans, 2005). Here we implement numerical glacier models, based on the physics of glacier dynamics and modern climate data to interpret paleoclimate from these moraine ages and positions. This proposal focuses on four paleo-glaciers, each different in catchment size, valley topography, and local mass balance.

The paleoclimate history of New Zealand, as expressed by moraine chronologies and marine and tarn sediment cores since the Last Glacial Interglacial Transition (LGIT), differs from records in the Northern Hemisphere (Schaefer et al., 2009; Vandergoes et al., 2003; Vandergoes et al., 2008; Newnham and Lowe, 2000; Newnham and Lowe, 2003). Glacier retreat from the last full glacial to today was interrupted by a series of short-lived stagnations resulting in moraine sequences in certain valleys in central South Island, New Zealand (Andersen et al., in prep). Fortunately, unlike in the European Alps, glaciers retreated steadily during the Holocene in New Zealand and the "Little Ice Age" (LIA) event was relatively minor and the glaciers did not override and destroy earlier Holocene moraines. Likewise, New Zealand glaciers retreated steadily during the Younger Dryas Chron when

European Alps glaciers readvanced (Kaplan et al., submitted). This climate asynchrony between the Northern and Southern Hemispheres has been attributed to the bipolar seesaw, atmospheric CO<sub>2</sub>, and regional climate feedbacks (Broecker, 1998; Kaplan et al., submitted; Putnam et al., in prep; Schaefer et al., 2009).

It is essential to test what the New Zealand temperate, maritime glaciers are responding to, be it temperature, precipitation, or nonclimatic factors. Rother and Shulmeister (2005) suggest that increased accumulation due to synoptic climate change can be the sole cause of glacier advances in high precipitation regions. Roe (in prep) suggests that glaciers in maritime climates are subject to a high degree of precipitation variability and therefore have muted sensitivity to temperature. In contrast, Oerlemans (2001) states that glaciers in wetter climates exhibit increased sensitivity due to a stronger albedo feedback, a larger effect on the partitioning of precipitation between snow and rain, and a longer ablation season because glaciers extend farther down in elevation. Based on the New Zealand End of Summer Snowline Survey (EOSS), ELA values of individual glaciers are highly co-related to the “mean ELA”, demonstrating a single climate zone influence (Chinn et al., 2006). That is to say, whatever New Zealand glaciers are responding to, they are doing so together, across the Southern Alps and across precipitation gradients.

### ***B) Previous Work and Geologic Setting***

Oerlemans (2005), Oerlemans and Hoogendoorn (1989), and Plummer and Phillips (2003) emphasised several reasons why numerical models of ice for paleoclimate reconstructions are more desirable than other methods. By including features such as aspect, slope, bed topography, local climate and overhead insolation, these models have the potential to produce more accurate climate histories than AAR / ELA calculations. For example, Anderson and Mackintosh (2006b) used a glaciological model based on the physics of glaciers and validated against field evidence from Franz Josef Glacier. They adjusted temperature and precipitation independently in the model to drive the glacier out to the Waiho Loop moraine. The test showed that either a 4.1-4.7 °C drop in mean-annual temperature, 400% increase in mean-annual precipitation, or some combination of the two would be necessary for the glacier to advance 10 km down valley from its modern position (Anderson and Mackintosh, 2006b).

Recent efforts to date New Zealand moraines, led by the Denton (University of Maine) group, have focused on the best preserved, most complete moraine sequences (Putnam et al., in prep; Kaplan et al., submitted; Schaefer et al., 2009). To accompany the SED ages, the digitised Central South Island Glacial Geomorphology (CSIGG) map assembled by Andersen et al. (in prep) includes detailed moraine positions and other geomorphic interpretations. These maps have been on display at several paleoclimate conferences and preliminary examples are available online (Andersen et al., in prep). Most of the glacier systems chosen for the modelling project are included in the CSIGG map coverage (Barrell and Suggate, in prep). Detailed Holocene moraine chronologies exist for Hooker, Mueller and Tasman glaciers (Schaefer et al., 2009), but these glaciers have a significant surface debris cover and proglacial lakes, making them difficult to simulate (Hubbard et al., 2000; Kirkbride, 1993).

The New Zealand Southern Alps (41-46°S, 167-173°E) intersect the strong southern middle latitude westerly winds, which are also influenced by the ocean currents (Subtropical Front and Antarctic Circumpolar Current). The precipitation gradient from the west (wet) to east (semi-arid) partly determines the mass balance and accumulation area ratios of glaciers across the divide (Chinn and Whitehouse, 1980). Mean annual precipitation peaks near the central western névés and decreases almost exponentially with distance east from the main divide of the Southern Alps (Salinger and Mullan, 1999; Chinn and Whitehouse, 1980). The areas of interest for this study are the Cameron Glacier in the Arrowsmith Range, Irishman and Whale streams in the Ben Ohau Range, and Brewster Glacier in the Young Range (Figure 1).

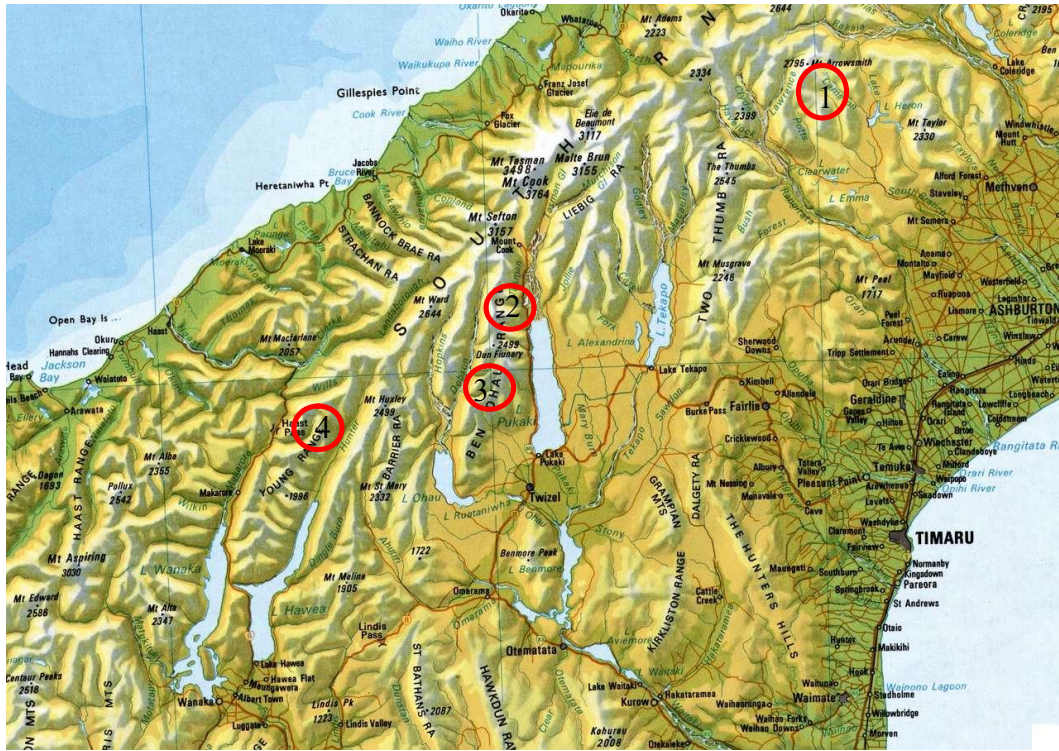


Figure 1 - Section of a topographic map of central South Island, New Zealand (-43.5 to -44.5°S and 168.5 to 171.5°E). 1) Cameron Glacier, 2) Whale Stream, 3) Irishman Stream, 4) Brewster Glacier.

Cameron Glacier - Cameron Glacier lies within the Arrowsmith Range of western Canterbury (-43.340°S, 171.011°E). Southeast of Cameron Glacier, 46 km away, the Mt. Hutt Skifield shows a modern seasonal temperature fluctuation from -5°C to 30°C at 1600 m asl (metres above sea level) (NIWA CliFlo, 2007). No previous mass balance data exist for the Cameron Glacier, but the glacier appears suitable for flow rate and ablation stake studies. Sir Julius von Haast, who named it Hawker Glacier during his visit in 1864, was the first to record the presence of the glacier. He also drew the terminal ice position, and remarked on the high mountain walls, but left no detailed record (Burrows, 2005). A detailed <sup>10</sup>Be exposure-age chronology now exists for Holocene moraines in the Cameron valley (Putnam et al., in prep). There is also potential for studying the adjacent Ashburton valley, where sampling for <sup>10</sup>Be dating has been carried out, but this is still tentative (G. Denton, personal correspondence). For these reasons, the Cameron site is the most promising candidate for my study.

Ben Ohau Range - The Ben Ohau Range is a long, narrow, north-south trending range, which is located between Lake Pukaki and the Dobson Valley, in the Mt. Cook region (-44.26 to -43.72°S, 169.90 to 170.11°E). The Irishman and Whale stream sites are both within this range. The precipitation gradient is steep from north to south with distance from the Main Divide of the Southern Alps. Rock glaciers still exist in the heads of many of the valleys, and are not suitable for mass balance studies to aid in this project. The valley floor is therefore largely exposed and accurately displayed in topographic maps. Much work has been done describing the formation of the valley systems in the Ben Ohau (Kirkbride and Matthews, 1998), the distribution of modern rock glaciers (Brazier et al., 1998), and the glacial deposits (Birkland, 1982; Kaplan et al., submitted; Chinn et al., in prep). Nearby weather stations include Mt. Cook Village and Twizel, which show the astounding precipitation gradient mentioned earlier.

Irishman Stream valley is located in the southern end of the Ben Ohau Range (-43.989°S, 170.050°E). The stream drains southwest toward the Dobson River, which then flows south into Lake Ohau. Due to its distance from the Main Divide, precipitation rates here are relatively low, aiding in the preservation of moraines. Close to the valley head lies the moraine sequence that is now well-dated, displaying Late Glacial ages. These new ages show a marked retreat of the glacier from 13,000 to 11,400 years ago during the Younger Dryas (Kaplan et al., submitted).

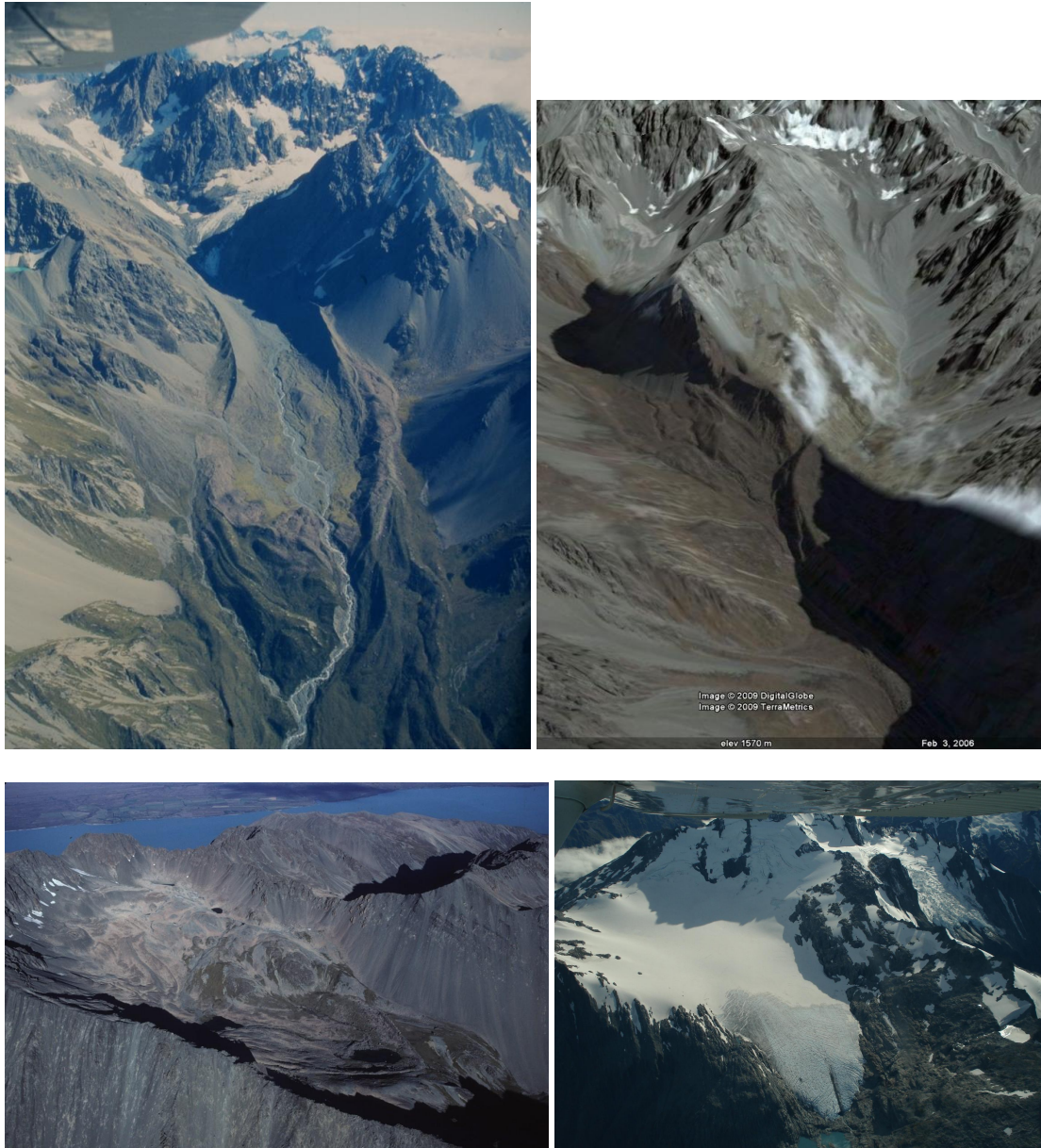
Whale Stream valley is located north of Irishman Stream and is on the east-facing side of the Ben Ohau Range (-43.915°S, 170.035°E). Whale Stream drains southeast into Lake Pukaki. The two main tributaries of the valley, North Branch and South Branch, join near the position of the dated Late Glacial moraines (Kaplan et al., in prep). Comparisons between glacial deposits in the different valleys along the Ben Ohau demonstrate an increase in elevation of the ELA toward the southern end (Chinn et al., in prep; Porter, 1975; Chinn and Whitehouse, 1980).

Brewster Glacier - Brewster Glacier ranges in elevation from 1660 to 2400 m asl and is in the West Coast region of the Southern Alps (-44.073°S, 169.436°E). Extensive and detailed mass balance measurements exist from previous glaciological studies (Anderson et al., in press), which will aid in producing realistic model results. The glacier terminus was drawn by Sir Julius von Haast in 1863 (Burrows, 2005) and today is one of the New Zealand index glaciers monitored annually for snowline (Chinn, 2006). Although a moraine chronology does not yet exist for this glacier, a single Late Holocene moraine is available for dating. With a few rock samples from boulders on this moraine, a cosmogenic age will assist in our modelling efforts.

Each study site provides its own advantages and disadvantages. Ideally, long moraine records, extensive glacier mass balance studies, and selecting glaciers in different climatic regimes would strengthen the model validity and the goals of regional climate comparisons, but such data does not exist for multiple glaciers in New Zealand. Thus, with local weather station data, previous geomorphic and glaciologic studies, and several dated moraine sequences, regional paleoclimate comparisons are still attainable. See Table 1.

	<b>Cameron</b>	<b>Irishman</b>	<b>Whale</b>	<b>Brewster</b>
Mass Balance Study	This study	-	-	√
Proximal Weather Station	Mt. Hutt	Twizel/Mt. Cook	Twizel/Mt. Cook	Haast
CSIGG - Mapped	√	√	√	This study
Moraine Chronology	√	√	√	This study
Glacier Elev. (m asl)	1500-2300	-	-	1700-2400
Moraine Elev. (m asl)	1100-1300	1800-1900	1200-1700	~1720
Moraine Age Range	Holocene	Late Glacial	Holocene + Late Glacial?	LIA?

Table 1 - Summation of the resources and characteristics of the various sites in this study.



*Figure 2 - (top left) Oblique aerial photograph (by T. Chinn) looking northwest toward the Arrowsmith Range, Cameron Glacier, and the associated Holocene moraines. (top right) Google Earth image looking northwest to both the North and South Branches of Whale Stream, Ben Ohau Range. (bottom left) Oblique aerial photograph (by G. Denton) looking east over Irishman Stream in the Ben Ohau Range toward Lake Pukaki. (bottom right) Oblique aerial photograph (by T. Chinn) looking northeast toward Brewster Glacier, Young Range.*

### **III. PROPOSED RESEARCH**

#### ***A) Scope of Research Project***

The overall purpose of our numerical modelling is to determine a climate history from several dated moraine sequences in South Island, New Zealand. These results will help us assess the relationships between temperature, precipitation, and New Zealand glaciers. More specifically, I hope to address the following research questions:

- What climatic conditions are required to advance the glaciers to their various moraine positions?
- What are the characteristic response times of the glaciers?
- Are the variations in moraine ages from basin to basin a result of microclimate conditions, valley-specific topography, or glacier sensitivity / response time?
- What does the climate reconstruction (compared with other proxy records) tell us about past changes in the ocean and atmosphere?

#### Possible Outcomes-

- Sensitivity test results, which will aid in the discussion of glacier drivers.
- An envelope of possible climatic parameters necessary for the glaciers to advance to specific moraine positions.
- Comparisons of the different modelled New Zealand glaciers.
- Comparisons of the model results with other New Zealand proxy records.
- The model results will compliment paleoclimate information included in the Central South Island Glacial Geomorphology map.
- An on-going collaboration between Victoria University of Wellington, the University of Maine, and the Lamont-Doherty Earth Observatory to investigate New Zealand paleoclimate.

There are four phases to this research project. Phase one includes simulating the glacier as it is today, followed by a series of sensitivity tests (to investigate the roles of temperature, precipitation, solar radiation, etc.). Phase two is to force the glaciers out to the dated moraine positions and develop an envelope of climatic possibilities for each glacier extent. Phase three involves forcing the energy balance model with a pre-existing temperature curve sourced from tree ring, pollen (pre-human arrival), foraminifera (SST), or CO<sub>2</sub> proxy records. Comparisons between pollen and moraine records have shown discrepancies in the timing and magnitude of climatic events, leading to multiple interpretations of New Zealand's paleoclimate (Newnham and Lowe, 2003; Newnham, 1999; Singer et al., 1998; Vandergoes et al., 2008). I hope to gain insight as to why glaciers and vegetation are recording different climate signals and if this is a regionality or seasonality issue. Phase four is the discussion and comparison of the different glacier valleys and their chronologies with regards to the model results and other proxy records.

#### ***B) Research Methodology***

Numerical models are becoming increasingly common in reconstructing paleoclimate from alpine glaciers (Oerlemans, 1986; Hubbard, 1997; Shroder and Bishop, 2002; Mackintosh et al., 2002; Huybers and Roe, 2009; Rupper et al., 2009; Ward et al., 2009; Kull and Grosjean, 2000; Plummer and Phillips, 2003; Anderson and Mackintosh, 2006b). They can account for the effects of topography, albedo, shading, and mass balance implicitly, which allows an individual glacier's 'sensitivity' and response time to be considered (Oerlemans and Hoogendoorn, 1989). Another benefit of an energy balance model is that solar radiation, cloudiness, temperature, and precipitation amounts can be adjusted independently, therefore testing the glacier's sensitivity to each climatic factor.

Numerical models are most valuable when their boundary conditions are realistic and when model output can be compared to data during a 'verification period'. For this, measurements from the modern glaciers will be obtained where possible. Cameron Glacier will be the focus of my field research because little glaciological work has been done here previously. Mapped glacial extents are somewhat out of date for the modern terminal position, but reasonably accurate in the upper catchment, judging by aerial photographs and satellite images. Flow rates will be measured using ablation stakes, which are also used to measure the summer's snowmelt (installed at the end of winter 5 December 2009, and then measured and removed at the end of the summer season 15 March 2010). Ground Penetrating Radar data record the ice thickness and a bedrock profile, which will be included in the model topography.

Multiple research projects in the past have focused on Brewster Glacier, thus flow and mass balance rates are readily available (Anderson et al., in press). A spatially distributed energy balance model showed that near half of the energy available for melt comes from turbulent heat fluxes (and thus temperature). Modelled sensitivity of the glacier to temperature is -2 m water equivalent per year per degree Celsius (m w.e. a<sup>-1</sup> °C<sup>-1</sup>). Meltwater runoff also showed a high sensitivity to temperature change. At this high-altitude, high precipitation site, it is likely that small interannual changes in temperature are driving large changes in mass balance, with precipitation variations playing a secondary role (Anderson et al., in press).

Current glaciers in the Ben Ohau Range are too small to extract meaningful mass balance measurements. Energy balance models for this range will be constructed and tuned by nearby weather station data instead of glaciological studies. Weather stations in New Zealand's alpine regions are sparse and usually short term, but a database of meteorological records is available on the NIWA CliFlo website (NIWA CliFlo, 2007). Mt. Cook Village and Twizel weather stations monitor current temperature, precipitation, and humidity data. Using a lapse rate of -6°C km<sup>-1</sup> I will adjust temperature data to the elevation of the accumulation areas.

The one dimensional coupled flowline-energy balance model used for this project was developed by B. Anderson and later modified by myself in the software package MATLAB. By coupling the two models the glacier geometry is updated as the glacier adjusts. As glacier height increases, for example, the mass balance feedbacks will be captured when the models are coupled. Each glacier-specific code includes a Digital Elevation Model (DEM), and climatic data as the boundary conditions. Mass balance is determined using the Energy Balance equation (Eq 1).

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

Where  $Q_m$  is the energy available for melt,  $I$  the incoming short-wave radiation,  $\alpha$  the albedo,  $L_{out}$  the outgoing longwave radiation,  $L_{in}$  the incoming longwave radiation,  $Q_H$  the sensible heat flux,  $Q_E$  the latent heat flux,  $Q_R$  the heat flux from rainfall,  $Q_G$  the heat flux from the ice. The values for these components are calculated from climatic and topographic data (for details, see Anderson et al., in press).

Measured accumulation and ablation rate data for Brewster and Cameron glaciers will be used to test and therefore evaluate the model. During this phase, I will carry out a series of sensitivity experiments, increasing the mass balance by regular increments (0.5, 1, 1.5 m snow). Each simulation will allow an animation of the glacier's reactions to disturbances in the climate to be produced.

### **C) How the Proposed Research Builds on the Topic**

The aforementioned field sites provide a unique opportunity to reconstruct paleoclimate in New Zealand over the past 13,000 years using a numerical modelling approach. The

approach of combining moraine chronologies and models has been tried elsewhere, in the Swiss Alps (Kerschner *et al.*, 2006) and in the Sierra Nevada (Plummer and Phillips, 2003) for example. Results will be aimed toward clarifying the debate about Late Glacial and Holocene climate in the Southern Alps, an important region distant from previous investigations of this type.

A temperate maritime glacier's response to climatic drivers can be misleading at times. The reason maritime glaciers are so sensitive to temperature change is because of high rates of precipitation (Anderson and Mackintosh, 2006a). In addition, because New Zealand currently receives one of the highest precipitation rates in the world, a further increase is unlikely. The overall amount of annual precipitation in general is not highly variable, but the difference between rain and snow can fluctuate dramatically year to year (Oerlemans, 2001). A change from liquid to solid precipitation may lead to increased spill-over of snow across the main divide. Thus, the precipitation gradient across the main divide toward the eastern ranges could have been less-steep during colder periods compared to the near-exponential decrease seen today (Chinn *et al.*, in prep). I will examine the glaciers' sensitivity to increased snow accumulation in the selected catchments to gain insight into a possible shift or levelling-out of the precipitation gradient.

Discrepancies between interpretations of paleoclimate in New Zealand are numerous in the literature from the past four decades (Denton and Hendy, 1994; Burrows, 1975; Birkeland, 1982; Kaplan *et al.*, submitted; Putnam *et al.*, in prep; Rother and Shulmeister, 2005; Vandergoes *et al.*, 2008; Newnham, 1999; Newnham and Lowe, 2000; Ivy-Ochs *et al.*, 1999; Tovar *et al.*, 2008; Fitzsimons 1997). As technologies and chronologies improve, a more consistent picture of climate since the Late Glacial Chron emerges (i.e. recent SED chronologies). The proposed modelling results will accompany the ages, making for a more robust climate history, as well as stand alone as a vital test of New Zealand glacier responses.

#### ***D) Preliminary Results***

Site Selection - Over the last few years, I have assisted in the collection of rock samples used in the Schaefer *et al.* (2009), Kaplan *et al.* (submitted), and Putnam *et al.* (in prep) SED chronologies. I visited Cameron valley and thought it would be the perfect opportunity to combine glacial geology and glaciology. Other areas, such as the Holocene sequences near Mt. Cook, would be difficult to model due to the complexity of multiple glacier catchments, proglacial lake calving, extensive debris cover, and steep valley walls (Kirkbride, 1993; Hubbard *et al.*, 2000). Remaining are the well-dated Ben Ohau sequences. Brewster Glacier has a five-year mass balance study that will be used to validate the model. The CSIGG maps include detailed moraine locations, lengths, and ages.

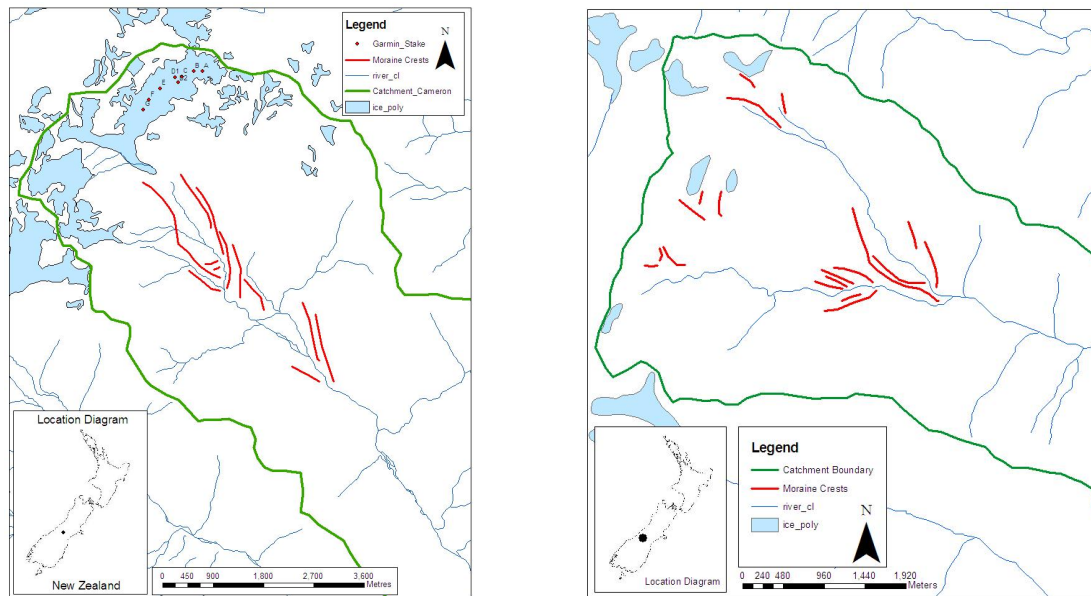


Figure 3 - Preliminary maps of the (1) Cameron and (2) Whale valley catchments, rivers, and moraine remnants (ArcGIS data available through Victoria University of Wellington).

Field Work - In February 2009, I accompanied A. Mackintosh to Brewster Glacier for ablation stake measurements and stream gauge data. Afterwards, we travelled to Cameron valley and flew over the glacier to assess hazards and possible camping sites. In December 2009, I led a team of four to the Cameron Glacier neve where we camped for three days. During this expedition, we drilled eight ablation stakes (up to 8 m long), dug a 4 m snow pit for a snow stratigraphy and density profile, completed five Ground Penetrating Radar (GPR) transects with both the 500 MHz (for snow depth) and the 25 MHz (for a sub-glacial bedrock profile) antenna, and collected Global Positioning System (GPS) data along those transects for the modern glacier surface elevation. A return trip to re-measure stake position, measure the amount of melt out, and retrieve ablation stakes is scheduled for March, 2010. These data of mass balance as well as nearby weather station data will be used to 'tune' the energy balance model. The bedrock profile will be included in the flowline model.

Computer Modelling - Model code from previous numerical models of South Island glaciers are available in the Antarctic Research Centre of Victoria University of Wellington. Under the instruction of my advisor B. Anderson, I have been able to set up and run several flowline, mass balance, and energy balance models in the programme MATLAB. Initial steps include setting up the DEM for each glacier valley, determining and marking the centre flowline, and calculating the local mass balance (estimations at first and then later tuned, if necessary, using field data). Figures 4-6 show some of the preliminary modelling runs. Once the actual mass balance and flow rates have been measured for the Cameron Glacier (March, 2010), this model will be refined and improved.

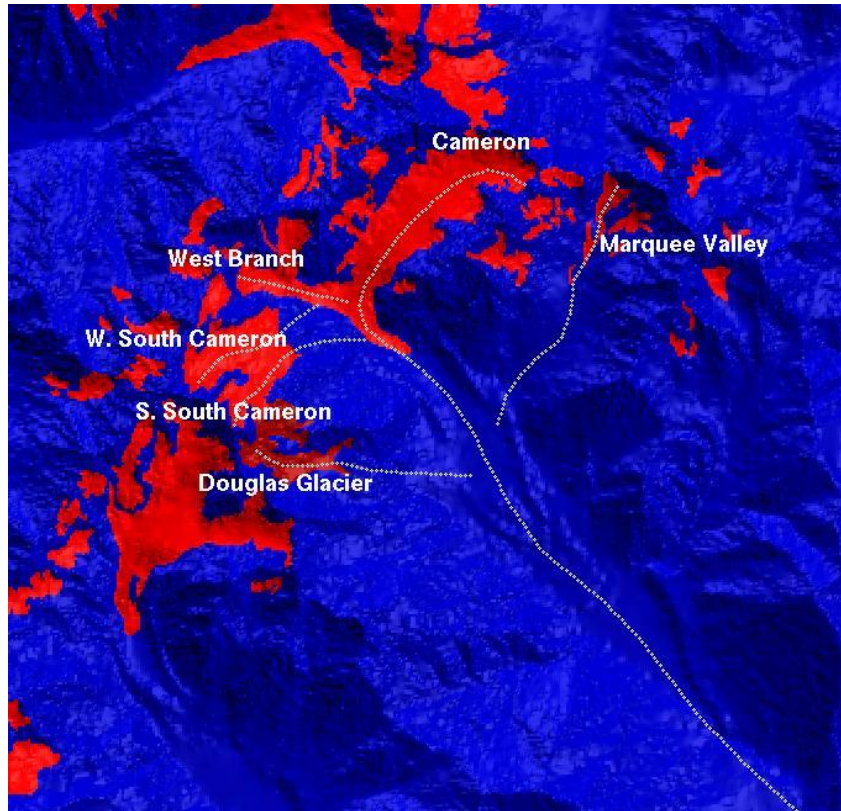


Figure 4 - Plan view of the flowlines and tributaries of Cameron Glacier. Red represents modern day ice cover, the background in blue is the digital elevation model.

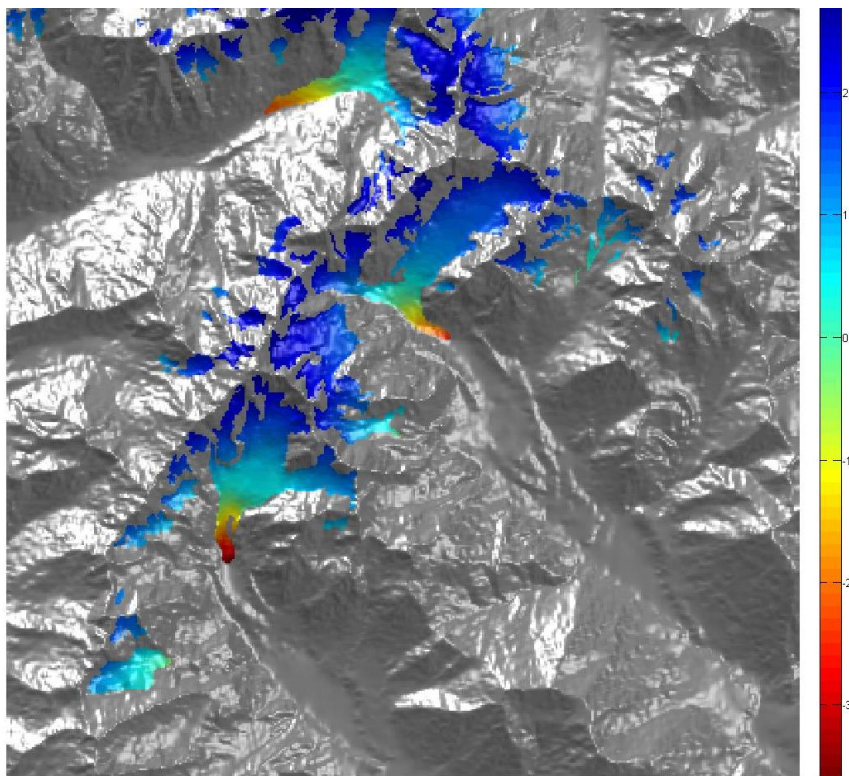


Figure 5 - Plan view image of the Energy Balance Model for modern day conditions at Cameron Glacier. Warm colours represent negative mass balance (melt) whereas cool colours represent positive mass balance (snow accumulation).

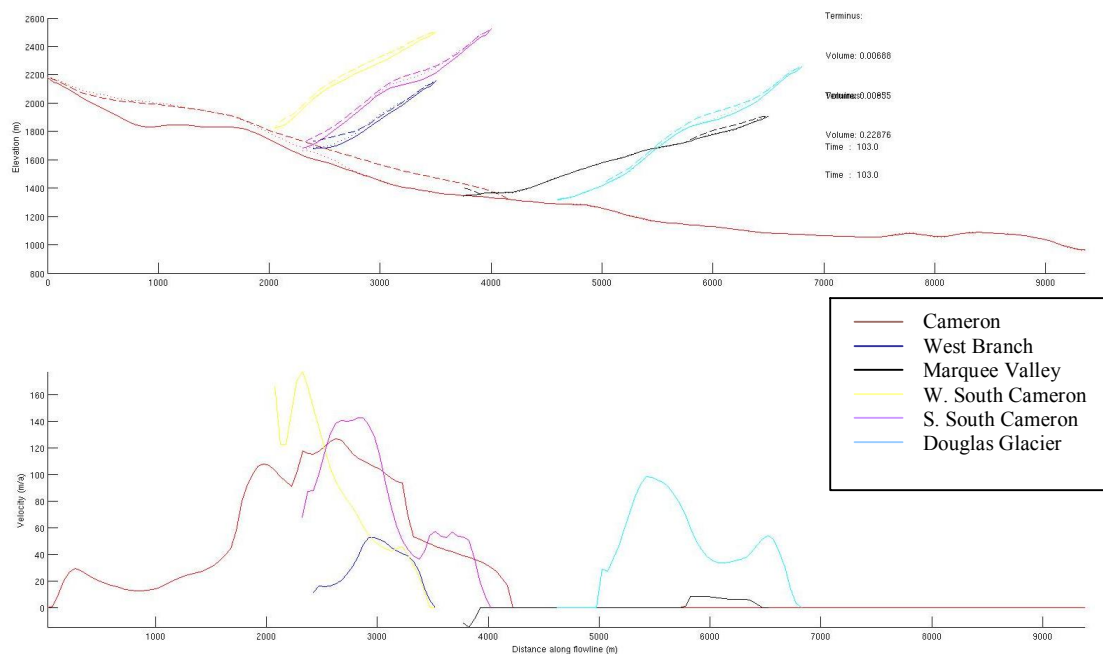


Figure 6 - Preliminary results from a flowline model of Cameron Glacier including nearby tributary glaciers when annual mass balance is positive. Top panel shows a cross section (distance and elevation) of the Cameron Valley and all the separate flowlines (also see Figure 4). The bottom panel shows ice velocities for each part of the different flowlines.

### E) Potential Problems and Limitations

The energy balance model does not include proglacial lake calving, wind redistribution of snow, and snow avalanching. This is not a problem because the models deal largely with mass balance over a yearly timestep and a 100 m grid spacing, and the precise distribution of snow is not essential. Likewise, large proglacial lake development is unlikely due to the steep topography of each valley, and modelling calving is not a necessary component to the project.

There have been varying degrees of success with deciphering paleoclimate from moraine sequences and numerical modelling results (Rupper et al., 2009; Hubbard, 1997; Shroder and Bishop, 2002). Mass balance studies are the best way to monitor climate change with glaciers but often more records are from length (Oerlemans, 1994). Although the model is based on modern mass balance studies of Brewster and Cameron glaciers as well as weather station data, it is possible that there are other climatic factors that affected the glaciers in the past for which we have no modern analogue (for example, a levelling in the precipitation gradient across the Southern Alps due to lower annual temperatures). Large scale changes (such as a shift in the precipitation gradient) will not be tested specifically, because each model is for a single glacier catchment, not the larger range. Comparing individual glacier catchment modelling results to one another is when we will detect large-scale differences, if possible.

With regards to the SED chronologies, it is essential to define what the ages represent in terms of climate. Most studies of SED moraines will associate the ages to a time when the moraine stabilised after the glacier retreated from the moraine (Putkonen and Swanson, 2003; Putnam et al., in prep). This is how I have chosen to interpret SED ages for the comparisons between the proxy records.

#### **IV. FORMAT**

I intend to structure my thesis as a series of chapters modified from journal articles that have or will result from this thesis.

ABSTRACT

INTRODUCTION

##### CHAPTER 1: The Potential to Infer Paleoclimate through Moraine Chronologies and Glacial Numerical Models

Chapter 1 will be based on a literature review and I will aim to explain the benefits of modelling glacier fluctuations in an area with high resolution moraine chronologies. I will present the conflicts amongst the published New Zealand paleoclimate records and from this, set goals for what I hope to learn from my proposed experiments.

##### CHAPTER 2: Climatic Sensitivity of Several New Zealand Glaciers - Modelling Tests

Here, I will discuss the methods and models used in my research before explaining the results from the sensitivity tests. The numerical model will allow each glacier's unique response to shifts in climate to be assessed, by accounting for the topography of the glacier valley as well as the shape, size, elevation, mass balance, and number of tributary glaciers. Detailed data from the Brewster Glacier (Anderson et al., in press) are invaluable for evaluating the model.

##### CHAPTER 3: Late Glacial Climate in the Ben Ohau Range

Whale and Irishman stream valleys contain Holocene and Late Glacial moraines. Because the Late Glacial climate in New Zealand is unresolved in several proxies (Williams et al., 2005; Alloway et al., 2007), it is vital to interpret the behaviour of glaciers at that time. Estimates of changes in past temperature and precipitation could lead to further understanding of regional differences in paleoclimate (Chinn et al., in prep).

##### CHAPTER 4: A Holocene Climate Record of Cameron Glacier based on Numerical Modelling and Moraine Ages

This chapter includes a summation of the modelling, glacial setting, and field measurements on the Cameron Glacier. In addition, I hope to investigate possible causes of the glacier's terminus fluctuations, climatic or otherwise.

##### CHAPTER 5: Climatic Variations over the Last 13,000 Years

With the combined modelling results from several locations, I will present the problem of precipitation versus temperature when referring to glacier mass balance and what these New Zealand glaciers appear to be responding to. I will include comparisons with multiple proxy records (pollen, tree ring, SST, and CO<sub>2</sub>) that reflect precipitation and temperature over the past 13,000 years.

##### CHAPTER 6: A Synthesis of Using Glacier Models to Reconstruct Climate in New Zealand

Here I will discuss my overall findings and understanding of temperate alpine glaciers, their mass balance, their reactions to climate, and the interpreted paleoclimate from the preserved moraine systems.

##### CHAPTER 7: Conclusions

APPENDIX

REFERENCES

V. TIMELINE

RESEARCH GOALS	Year 1				Year 2				Year 3				Year 4	
	2009				2010				2011				2012	
	F M A	M J J	A S O	N D J	F M A	M J J	A S O	N D J	F M A	M J J	A S O	N D J	F M A	M J J
<b>Phase I: Project Development</b>														
Review computer modelling of glacier systems literature	█	█	█	█										
Review physics of glaciers and their reactions to climate	█	█	█	█										
Reconnaissance field work - <i>Brewster + Cameron glaciers</i>	█													
Attend Outdoor First Aid, Alpine Instruction, and Defensive Driving courses		█	█	█										
Begin using MATLAB and familiarise myself with code		█	█	█										
Explore existing computer models		█	█	█										
Literature review of the Cameron, Brewster, and Ben Ohau glaciers and their climatic histories			█	█	█									
Compile preliminary maps in ArcGIS & FreshMap			█											
Plan and execute field work on Cameron Glacier - GPR, GPS, snowpit, ablation stakes			█	█	█									
Present at Geol. Soc. NZ Meeting, Oamaru				█										
Present at a departmental seminar					█									
Submit research proposal					█									
<b>Phase 2: Data Collection</b>														
Begin GPR and GPS analyses of Cameron					█									
Computer modelling of Cameron, Whale, Irishman, and Brewster glaciers					█	█	█	█	█					
Present talk at SIRG Meeting, Queenstown					█									
Prepare manuscript on Ben Ohau model results					█	█								
Complete followup fieldwork on Cameron					█									
Prepare manuscripts on forcing glaciers to moraines, and forcing glaciers using pollen temperature records					█	█								
Glacial Modelling Course - Karthaus, Italy							█							
Adjust course material to improve this project							█							
Present at AGU 2010 Meeting, San Francisco								█						
Potential field work on Brewster Glacier								█						
Prepare manuscript on spatial variations								█	█	█				
Prepare manuscript on what drives glaciers to advance								█	█	█	█			
Compare findings to similar studies on a global scale, discuss the habits of maritime glaciers with glaciologists								█	█	█	█	█		
Present talk at SIRG Meeting, North Island								█						
<b>Phase 3: Completion</b>														
Publish papers, assemble thesis, compile questions and issues to explore in future research										█	█	█	█	
Thesis write-up and editing										█	█	█	█	

## VI. BUDGET AND RESOURCES

- *Access to Linux workstation, capable of running high resolution glacier models*
- *Software: MATLAB, ArcGIS, Freshmap Map Toaster Topo, Google Earth, DNR Garmin, Paraview, GPS Pathfinder, REFLEX, and CorelDRAW*
- *Topographic maps, Central South Island Glacial Geomorphology Maps (GNS), GPS unit, GPR unit, snow ablation stakes*
- *Travel to field sites (plane, rental car, helicopter), accommodation, and food*
- *Collaboration with SIRG, GNS, T. Chinn, University of Maine, and Lamont-Doherty Earth Observatory for New Zealand Paleoclimate records*
- *Glacial modelling computer code from B. Anderson and New Zealand DEM*
- *Personal alpine field equipment (harness, crampons, helmet, skis, ice axe, rope, snow stakes)*

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## **VIII. LIST OF ACRONYMS**

- SED - Surface Exposure Dating - method used to date the age of moraine deposits
- ACR - Antarctic Cold Reversal - Southern Hemisphere Late Glacial climate event
- ELA - Equilibrium Line Altitude - line separating the accumulation and ablation zones on a glacier
- AAR - Accumulation Area Ratio - Accumulation to ablation area, typically 0.66
- LGIT - Last Glacial-Interglacial Transition
- LIA - Little Ice Age - a brief cooling in recent centuries, a much bigger event in the Northern Hemisphere
- EOSS - End of Summer Snowline Survey - 29 year record of snowline observations on 50 index glaciers in New Zealand
- CSIGG - Central South Island Glacial Geomorphology - map of moraines and associated ages
- M asl - Metres above sea level - elevation in reference to present day sea level
- DEM - Digital Elevation Model
- SST - Sea Surface Temperature - Oxygen isotope data, commonly from planktonic foraminifera, often provides a reasonable proxy for the temperature at sea level.
- GPR - Ground Penetrating Radar - instrument used to retrieve a two-dimensional image of the ground layers without being invasive
- GPS - Global Positioning System
- SIRG - Snow and Ice Research Group - New Zealand
- GNS - Geological and Nuclear Sciences - New Zealand Government funded geologic institution
- AGU - American Geophysical Union - International conference for geologists