Title Page

Glacier size in determining the response to climate, Hayes Mountain Range, Alaska.

791334

"Submitted in part fulfilment of the requirements of the degree of Bsc with honours in Physical Geography"

Swansea University
Prifysgol Abertawe

Statement of originality

"The dissertation is the result of my own independent study, and has not been submitted for any other part of my degree assessment. All secondary sources of information have been acknowledged fully in footnotes and references and a bibliography of all literature used in the work has been provided"

Student Signature:……………………..……..(Jack Philpott)

Statement of word length

9550

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Abstract

Mountain glaciers and ice caps are among the best natural indicators of a change in climate. Glaciers is mountainous regions, such as Southeast Alaska have had observed increases in thinning and loss of mass over the past decades. The excess wastage caused from the glacial melt can negatively influence water resources for agriculture and clean water consumption, as well as other socio-economic negative impacts. Changes in glacier terminus are often studied as a key visual indicator of the overall mass balance of a glacier, and its fluctuations in response to climate. This study measures the retreat in glacier termini over four glaciers, located within the Hayes segment of the Alaska Range using remotely-sensed techniques from Landsat- Satellite imagery. The study then compares the glacier length record with climatic records within the same region since 1965, and attempts to make observations of potential relationships in relation to the relative size of the glacier. The size of the glacier is expected to be a determining factor in the temporal distribution of terminus retreat, however the findings of this study established little conclusive evidence of a singular variable, such as area of glacier, to be a dominant factor, instead a mixture of climatic and topographic factors.

Maximum of 6 Key-Words

Glacier, retreat, climate, terminus, subjective,

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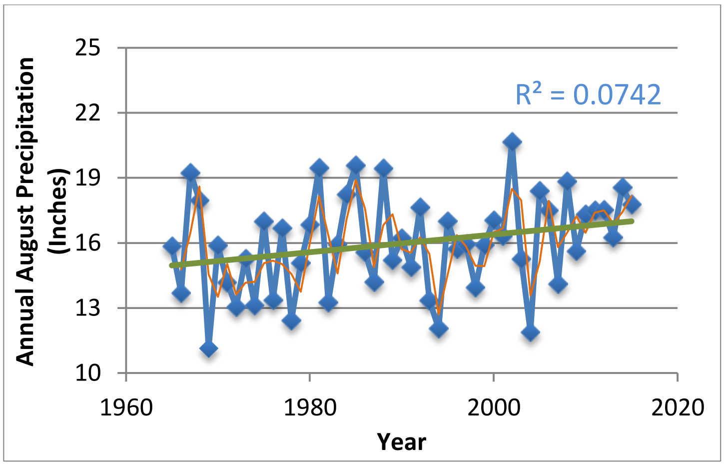
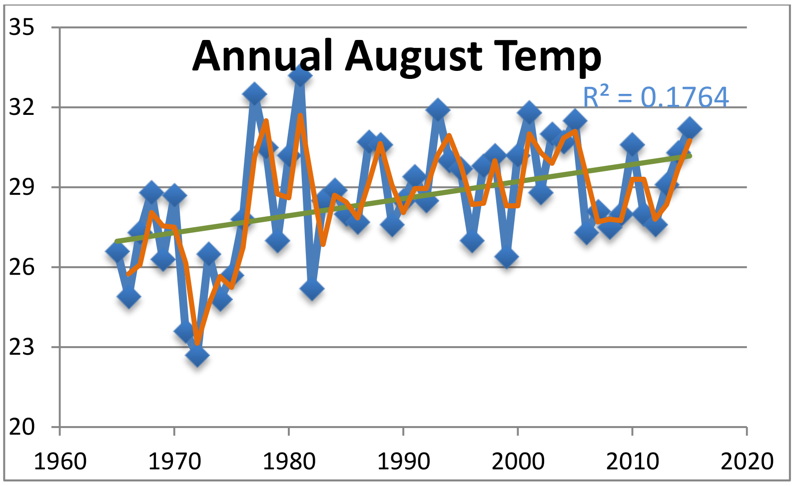




Temperature raw data

	year	prec	5-year average	temp	5-year average
1	1965	15.86		26.6	
2	1966	13.7		24.9	
3	1967	19.24		27.3	
4	1968	17.97		28.8	
5	1969	11.14	15.582	26.3	26.78
6	1970	15.89		28.7	
7	1971	14.19		23.6	
8	1972	13.06		22.7	
9	1973	15.28		26.5	
10	1974	13.13	14.31	24.8	25.26
11	1975	17		25.7	

12	1976	13.36		27.8	
13	1977	16.69		32.5	
14	1978	12.44		30.5	
15	1979	15.08	14.914	27	28.7
16	1980	16.84		30.2	
17	1981	19.46		33.2	
18	1982	13.26		25.2	
19	1983	15.93		28.5	
20	1984	18.23	16.744	28.9	29.2
21	1985	19.58		28	
22	1986	15.58		27.7	
23	1987	14.2		30.7	
24	1988	19.44		30.6	
25	1989	15.21	16.802	27.6	28.92
26	1990	16.23		28.5	
27	1991	14.88		29.4	
28	1992	17.64		28.5	
29	1993	13.35		31.9	
30	1994	12.06	14.832	30	29.66
31	1995	17.01		29.7	
32	1996	15.73		27	
33	1997	15.94		29.8	
34	1998	13.95		30.2	
35	1999	15.92	15.71	26.4	28.62
36	2000	17.05		30.2	
37	2001	16.31		31.8	
38	2002	20.67		28.8	
39	2003	15.27		31	
40	2004	11.88	16.236	30.7	30.5
41	2005	18.4		31.5	
42	2006	17.5		27.3	
43	2007	14.12		28.1	
44	2008	18.84		27.5	
45	2009	15.62	16.896	28	28.48
46	2010	17.32		30.6	
47	2011	17.49		28	
48	2012	17.52		27.6	
49	2013	16.26		29.1	
50	2014	18.56		30.3	
51	2015	17.77	17.4866667	31.2	29.4666667

Raw data used for graphs in figures 9, 10 and 11

	North	South	Nenana	Maclaren
1989		0		
1991	0		0	0
1995	129.24	422.26	-18.5	147.96
1999	115.44	36.92	201.74	
2000				197.02
2005	84.74	115.22	130.26	142.18
2010	25.28	262.87	38.02	420.59
2015	135.96	115.99	84.86	224.28
Cumulative	North	South	Nenana	Maclaren
1989		0		
1991	0		0	0
1995	129.24	422.26	-18.5	147.96
1999	244.68	459.18	183.24	
2000				344.98
2005	329.42	574.4	313.5	487.16
2010	354.7	837.27	351.52	907.75
2015	490.66	953.26	436.38	1132.03
Percentage	7000	17000	16000	17000
1989		0		
1991	0		0	0
1995				
1999				
2000				
2005				
2010				
2015	0.01428571	0.00588235	0.00625	0.00588235
Percentage				
1989		0		
1991	0		0	0
1995	1.84628571	2.48388235	-0.115625	0.87035294
1999	3.49542857	2.70105882	1.14525	
2000				2.02929412
2005	4.706	3.37882353	1.959375	2.86564706
2010	5.06714286	4.92511765	2.197	5.33970588
2015	7.00942857	5.60741176	2.727375	6.659
Percentage				
1989		0		

1991	0		0	0
1995	1.85	2.48	-0.12	0.87
1999	3.5	2.7	1.15	
2000				2.03
2005	4.71	3.38	1.96	2.87
2010	5.07	4.93	2.2	5.34
2015	7.01	5.61	2.73	6.66

Raw data for the original measurements taken from the four glaciers of change in length

Maclaren		Nenana	from left to right	
	(from left to right)		metres	
1991-1995	metres	1991-1995		
1	111.5	1	18.1	-
2	102	2	37.4	-
3	190.3	3	30.9	-
4	169	4	19.2	-
5	167	5	13.1	
average	147.96	average change of the period	-18.5	
average each year	36.99	average change each year	-4.625	
1995-2000		1995-1999		
1	118.9	1	78.1	
2	255.7	2	50	
3	73.4	3	240.7	
4	267.3	4	428.2	
5	269.8	5	211.7	
	197.02		201.74	
	39.404		50.435	
2000-2005		1999-2005		
1	335.9	1	158	
2	113.1	2	44.7	
3	72	3	222.9	
4	62.6	4	127.6	
5	127.3	5	98.1	
	142.18		130.26	

	28.436		21.71	
2005-2010		2005-2010		
1	317.44	1	22.6	-
2	444.2	2	25.7	-
3	495.7	3	100	
4	436.3	4	52.2	
5	409.3	5	86.2	
	420.588		38.02	
	84.1176		7.604	
2010-2015		2010-2015		
1	274.8	1	114.9	
2	259.4	2	72.6	
3	115.2	3	42	
4	144.1	4	111.2	
5	327.9	5	83.6	
	224.28		84.86	
	44.856		16.972	

South	from left to right	North	from left to right
	metres		metres
1989-1995		1991-1995	
1	322.2	1	30.3
2	258.4	2	292.3
3	512.5	3	24.4
4	324.7	4	210.7
5	693.5	5	88.5
average for the period	422.26	average distance of that year	129.24
average for each year	70.376667		32.31
		1995-1999	
1995-1999		1	201
1	79.9	2	61.3
2	85.1	3	137.8
3	35.8	4	113.7
4	21.2	5	63.4

5	5		115.44
	36.92		28.86
	9.23		
		1999-2005	
1999-2005		1	22.9
1	182.5	2	141.7
2	165.3	3	42.4
3	102	4	132.4
4	19.3	5	169.1
5	145.6		84.74
	115.22		14.123333
	19.203333		
		2005-2010	
2005-2010		1	24.8
1	399.4	2	44.1
2	342.46	3	36.3
3	295.2	4	79.5
4	56.8	5	58.3
5	220.5		25.28
	262.872		5.056
	52.5744		
		2010-2015	
2010-2015		1	38.7
1	27.5	2	69.2
2	198.4	3	65.6
3	29.8	4	222.7
4	201.1	5	283.6
5	91.4		135.96
	98.64		27.192
	19.728		

X) Main Body of Text

1. Introduction

1.1- General introduction into area of study.

In recent years it has become more apparent that many glaciers and ice fields across the world are dramatically changing, in most cases negatively reducing their mass balance. A number of studies since the late 19th century of visible and in situ-measured changes of glacial parameters have shown the rate of change of glaciers and ice sheets are becoming an increasing threat, particularly over the past 50 years (Arendt, Walsh, and Harrison, 2009; Larsen et al., 2007; Meier and Dyurgerov, 2002; Stafford, Wendler, and Curtis, 2000; Hodge et al., 1998). Although the generally negative change in glaciers is on a global scale, researchers have noticed glaciers in South Alaska are thinning and losing mass at an alarming rate. Most of the glaciers in South Alaska, despite only accounting for a minor proportion of the world's ice mass, are expelling significant volumes of water contributing to sea-level rise from mass wastage (Larsen et al., 2007).

The sustained negative glacial mass balance, as well as contributing to eustatic sea-level rise, can also disturb the local environment in a number of ways (Meier et al, 2007; Kääb et al., 2002; Meier and Dyurgerov, 2002). Any fluctuation in the storing and discharge of water from glaciers may impact humans both directly and indirectly. For example, glacial melt increases the volume of water within the hydrological system, which usually has a negative influence on the water resources for agriculture, hydropower and clean water consumption, as well as increasing the chance of flooding. The change in glacier regime also has the potential to impact negatively upon the socio-economic status of the region, particularly in regard to the fishing and tourism industries in Alaska (Barnett, Adam, and Lettenmaier, 2005; Gössling and Haller, 2005; Hock, Jansson, and

Braun, 2005; Chapman and Walsh, 1993). Furthermore, prolonged negative mass-balance conditions can cause glacio-isostatic depression and rebound, displacing large amounts of ice and water (Mann and Streveler, 2008; Motyka, 2003).

There are a number of different factors which can influence glacial change, the predominant one being a change in climate. “Climate” is a fairly ambiguous term and can translate to local or regional measurements of variables such as precipitation and temperature (Letreguilly, 1984); therefore, this study uses the definition: “mean large, hemispheric-scale patterns of circulation in the atmosphere and ocean” as described by Hodge et al., (1998). It is widely accepted that an increase in climatological factors, such as precipitation and temperature, is the dominant causal factor in global, and particularly Alaskan glacier negative mass-balances (Larsen et al., 2007; Rasmussen and Conway, 2003). Due to distinct sensitivity of mountain glaciers to climate change, fluctuations in glacier parameters is considered one of the essential terrestrial climate components by the Global Climate Observing System as a natural indicator of climate change (Barclays, Wiles, and Calking, 2009; World Meteorological Organization, 2003; Houghton, Dai, and Griggs, 2001; Oerlemans, 1994).

There is now conclusive agreement between most glaciologists and climatologists that glacial ice, particularly mountain glaciers and ice caps are the best natural indicators of climate change (Barry, 2006; Houghton, Dai, and Griggs, 2001; Oerlermans, 1994). As a result numerous climatic observatory organisations now include glacial data as an essential addition to their observations, due to the complex interaction between glaciers and the climate. Examples of this include: the Intergovernmental Panel on Climate Change (IPCC), which has included data on glacier fluctuations in assessments since 1990 as a potential temperature indicator (Smithson, 2002); and the Global Climate Observing System (GCOS/GTOS), which recognise glaciers as an ‘essential climatic variable’ of the terrestrial environment (Haeberlie et al., 2007).

Glacier mass balance has an immediate response to atmospheric conditions, making it a key indicator of fluctuations in the climate system (Zemp, Hoelzle, and Haeberli, 2009). Mass balance is the quantitative countenance for a glacier's volumetric change over time and is a sum the accumulation plus ablation (Davies, 2015). However, it's virtually impossible to accurately measure ablation and accumulation from space (Bamber and Kwok, 2004; Houghton, 2004), therefore terminus length is one of the most common and preferred measurements of mass balance as parameters such as glacier area and terminus position can be acquired relatively easily from satellite images.

The glacial terminus can be defined as the physical position of the snout of the glacier (Singh, Singh and Singh, 2001). The cumulative terminus positioning of a glacier is a visual representation of variance in mass balance changes, and thus a key indicator of changing climate upon the glacier (Le Bris and Paul, 2013; Leclercq and Oerlemans, 2011; Karpilo Jr., 2009; Racoviteanu, Williams, and Barry, 2008; Haeberli et al., 2007; Barry, 2006; Hoelzle et al., 2003; Kaser, Fountain, and Jansson, 2003).

There are a number of different methods used to measure glacier retreat such as; GPS, in-situ and remotely-sensed measurements. The position of mountain glaciers can make it difficult to acquire in-situ physical measurements, for example GPS measurements due to remote location, potential hazardous terrain and the size of the mountain glaciers, therefore it is becoming more popular in recent studies to use satellite imagery (Paul, Huggel, and Kääb, 2004).

Increased frequency of remote sensing platforms with greater resolution, global coverage and fewer financial expenses makes remotely sensed measurements from satellites or high-flying aircrafts an efficient tool for regularly monitoring mountain glacier parameters (Paul et al., 2015; Paul and Mölg, 2014; Bhambri, Bolch, and Chaujar, 2011; Fountain, Krimmel, and Trabant, 1997). Studies such as this, use remotely-sensed techniques, extend the overall spatial coverage of glacial information available and are important to linking local studies with global application (Haeberli et al., 2007). (Racoviteanu, Williams, Barry, 2008)

Glaciers consist of accumulation and ablation zones, where accumulation continues through the summer and where seasonal snow-cover and melting dominates respectively. In order to remain constant glaciers must have a steady accumulation zone. The relationship between glaciers and climate change often assumes a static glacier, whereas really the mass balance of a glacier in response to changing climate is more complex since the altering surface configuration acts as a feedback to affect the response. As a result of the feedbacks, glaciers will then achieve a new equilibrium in mass balance through the process of advancing or retreating terminus, when retreating a glacier will lose the necessary volume from glacial areas at low elevations where typically negative balances are amplified (ablation zone), re-establishing equilibrium. This dynamic process is visually represented in figure-1. (Pelto, 2011; Larsen et al., 2007; Singh, Singh, and Singh, 2001; Fountain, Krimmel, and Trabant, 1997)

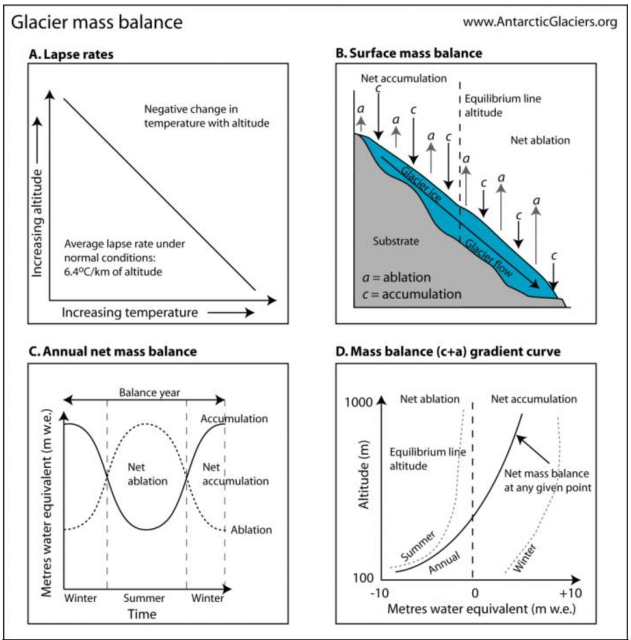


Figure 1: Principles of glacier mass balance. (Davies, 2015)

1.2- Purpose of study

Despite the increased attention and research into glaciated areas, particularly regarding climate-induced changes, due to the complexity of glacier mechanisms and the relationship they have with the climate, there remains much to be investigated. Scherler, Bookhagen, and Strecker (2011) suggest potential future studies could focus on glacier size as a determining factor of glacier response.

The primary aim of this study is to use satellite imagery to measure changes to four glacier termini in the Alaska Range over a 25-year study period, in relation to the size of glacier. A further aim of this study is to investigate this relationship in comparison with changes in climate. The project intends to draw conclusions on the extent to which the size of a glacier (in relation to area) is fundamental in determining both the rate at which, and extent of, a glacier terminus retreats. The need for projects such as this, which investigate the past relationship of glaciers and their environment, are crucial in providing a greater understanding and allow more accurate theoretic predictions of future effects of climatic conditions on glaciers (Meehl and Coauthors, 2007). Furthermore, the predictions of potential future hazards, such as Glacial Lake Outburst Floods, could allow protective policies and regimes to be put in place to reduce the impacts of these hazards (Jha, Bloch, and Lamond, 2012). This study postulates that larger size glaciers will have a more delayed, but also more profound response to climate, as smaller glaciers will be influenced greatly by too many other climatic and non-climatic variables.

Recent climate regimes have been initiated in response to further acknowledgements of the irrefutable trend of climate change, a current example of this which is emphasized in Alaska, is the Presidential remarks made by Barack Obama at the Glacier conference on the 31st of August, 2015. Barack Obama accentuated the need for climate policy changes; not only on a national, but also on a global scale, must take place to reduce the increasing trend of negative mass-balances, which have been noticeably observed in the Artic as "our leading indicator of what the entire planet faces" (Roberts, 2015). Barack Obama continues to state (Office of the Press Secretary, 2016):

> *"If those trend lines continue the way they are, there's not going to be a nation on this Earth that's not impacted negatively. People will suffer. Economies will suffer. Entire nations will find themselves under severe, severe problems. More drought; more floods; rising sea levels; greater migration; more refugees; more scarcity; more conflict."*

1.3- Study Area

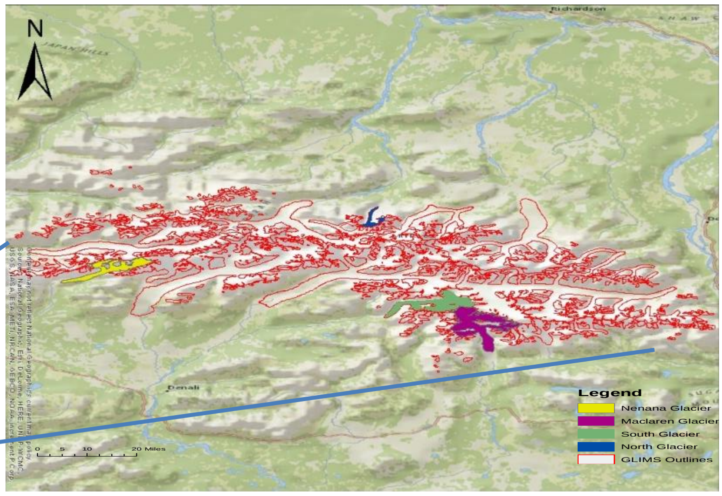


Figure 2: Maps of study area.
The map on the left displays the location of the mountain area used in this map in relation to the whole of Alaska. The image on the right is an enhanced view of the particular segment of Alaska Range used in the study. Also including highlighted and glacier outlines derived from the GLIMS-Viewer extension (Raup et al., 2007).

Alaska is estimated to have about 75, 000km^2 of surface cover from glaciers, translating to approximately 5% of total land cover. Alaskan glaciers are divided between 11 mountain ranges, an island chain, 1 large island and 1 archipelago. The Alaska Range, is a group of adjacent and discrete mountains that stretches more than 750km in an arc and is estimated to have 13, 900km^2 of total glacier area. Within the Alaska Range, there are several thousand glaciers that vary in size, with the largest valley glacier reaching areas and lengths in excess of 500km^2 and 750km respectively. The abundant distribution of glaciers in Southern Alaska indicates this area to be the foremost source of precipitation in the region (Shulski and Mogil, 2009). This study uses four glaciers located within the Mount Hayes section in the Alaska Range (Figure 3- segment 3), which encompasses an estimated 1,900km^2 of glacier-covered area over a 160km-long stretch over Mount Hayes, Mount Deborah and Mount Moffit (Denton and Field, 1975). The majority of glaciers within this area originate from a connected upland accumulation zone. (Molnia, 2008)

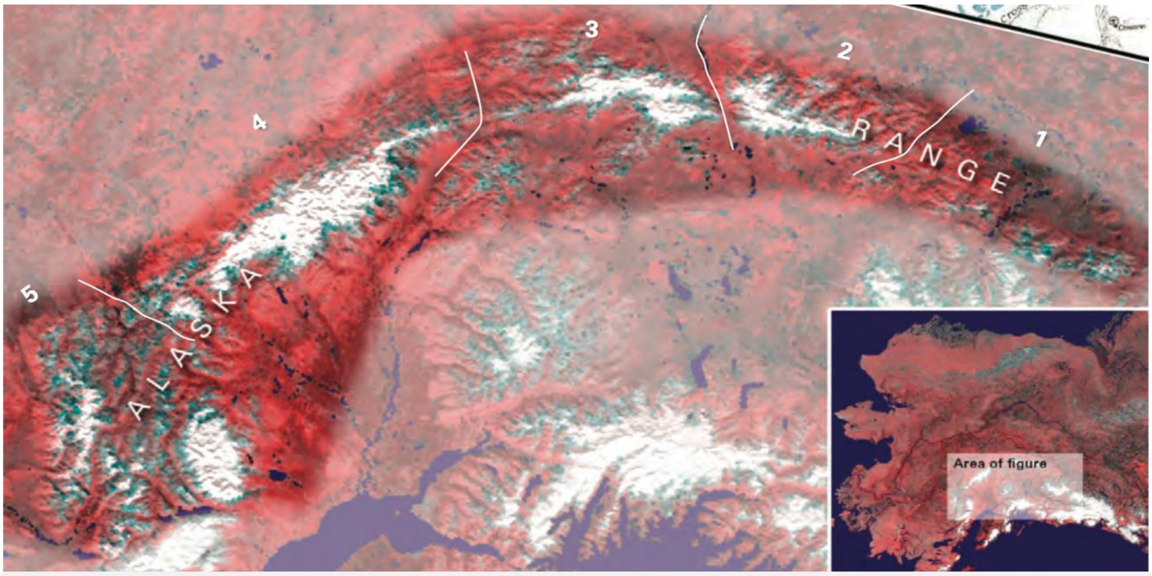


Figure 3: False-Colour image of the Alaska Range.
Image acquired from Molnia (2008), USGS. Showing Alaska Range, with proportional image within Alaska. The Alaska Range can be divided into five principal segments, from East to West: (1) The Mentasta and Nutzotin Mountains; (2) The Mount Kimball- Mount Gakona segment; (3) The Mount Hayes- Mount Deborah segment between the Delta River and Broad Pass; (4) The Mount McKinley- Mount Foraker segment between Broad Pass and Rainy Pass; (5) The Mount Gerdine- Mount Spurr segment between Rainy Pass and Merrill Pass.

The Glaciers chosen for the purpose of this study are: the Unnamed glacier, which descends from Mount Gidings and Mount Skarland, and throughout this study will be referred to as “North”; the Nenana Glacier; the Unnamed glacier, draining into the East Fork Susitna River, and throughout this study will be referred to as “South”; and the Maclaren Glacier (see *Table-1*). The use of unnamed glaciers are due to the U.S. Board on Geographic Names (BGN) have officially named only about 600 glaciers, near 1 percent of total Alaskan glaciers (Molnia, 2008). The glaciers were chosen as they are located within the same mountain range, thus reducing the amount of climatological and topographical variables which could influence the results. A problem which has previously been described by Haeberli et al., (2007), who stated that mass balance, and consequently glacier lengths, are spatially correlated to a region with similar climatic conditions. The glaciers were primarily chosen due to their varying area sizes as can be seen in *Table-1*, where the results could be expected to display a potential linear relationship with the varying area of glaciers.

Glacier Name	RGI Glacier ID	Begin Date	Total Area, km^2	Minimum Elevation (metres)	Median Elevation (metres)	Maximum Elevation (metres)	Glacier type	Length (km)
Maclaren Glacier	RGI40-01.00021	03.07.2009	**56.73**	942	1781	2584	9029	17
Unnamed Glacier (South)	RGI40-01.00022	03.07.2009	**39.76**	884	1904	2445	9099	17
Nenana Glacier	RGI40-01.00040	03.07.2009	**27.45**	972	1771	2650	9099	16
Unnamed Glacier (North)	RGI40-01.00033	03.07.2009	**4.6**	1109	1718	3160	9099	7

Table 1: Inventory of glacier parameters, with 'Total Area (km^2) highlighted red as this is the key variable of the study.

Value	Digit 1: Impact of snow cover	Digit 2: Terminus type	Digit 3: Evidence for surging	Digit 4: Status of divides
0	Hides 0-5% of perimeter	Land-terminating	No signs or reports	-
1	Hides 5-50% of perimeter	Marine- terminating	Reported	Uncertain
2	Hides >50% of perimeter	Lake-terminating	Signs	Compound
3	Perennial snowfield	Dry calving	Signs and reported	Ice cap
4	Seasonal snowfield	Regenerated	-	-
5	-	Shelf-terminating	-	-
9	Not assigned	Not assigned	Not assigned	Not assigned

Table 2: Classification of glacial type used by RGI-4.0.

The data obtained in Table-2 is from the Randolph Glacier Inventory (RGI) is a globally complete inventory of glacier outlines (Arendt et al., 2015). It provides supplementary information to the database, Global Land Ice Measurements from Space initiative (GLIMS) (Raup et al, 2007). The GLIMS project uses optical satellite instruments in order to monitor the world's estimated 160,000 glaciers (Portengen, 2014). The lengths provided in Table-2 were measured by Denton and Field (1975-p583-586), however their estimates of glacier area are noticeably higher than that of the recent measurements by RGI 4.0, therefore it can be assumed that these measurement of glacier lengths would have also changed since measured.

2. Literature Review

2.1- Climate change.

Numerous studies have reported an increase in temperature and varying precipitation patterns over the past 50 years, the global climate of the late 20th century changed beyond averages rate previously measured from proxy records in the last millennium (Kargel et al., 2005). Often attributing the trend to anthropogenic induced origins, resulting from rising levels of atmospheric greenhouse gases such as carbon dioxide (Hastrup, 2013). Stafford, Wendler, and Curtis (2000) conducted a study over a 50-year period from 1949-1998 using different remote stations in Alaska to record mean annual air temperature increase, with a 95% statistical significance. This study also investigated precipitation records for the same period with a significant amount showing an increase during winter, spring and autumn and a reduction in summer. From their temperature increases, winter temperatures had a noticeable significant increase, doubling the increase of summer temperatures respectively. Other studies over the same period had very similar temperature results with increases over the Northern Hemisphere (Dyurgerov and Meier, 2000; Weller et al., 1995). Additionally some studies have varying precipitation results, where decreases in precipitation were discovered over the few decades prior to Stafford, Wendler, and Curtis (2000) study. (Warren et al., 1999; Curtis et al., 1998)

2.2- Glacial Retreat.

A Significant number of glaciers in Southeast Alaska have regularly been observed to have retreated and thinned from their Little Ice Age maximums between 1750 and 1900-AD (Garrett et al., 2015; Molnia, 2008; Larsen et al., 2007; Eisen, Harrison, and Raymond, 2001). Additionally, since the 1980’s more studies like Hodge et al., (1998) have noted an increased rate of negative mass balance in glaciers, particularly occurring over the 1990’s which had exceptionally increased temperatures leading to numerous glaciers loosing considerable volume and area (Paul et al., 2004; Arendt et al., 2002; Sapiano, Harrison, and Echelmeyer, 1998).

This trend of increased glacial reduction was also found by a study by Larsen et al., (2007), who compared Digital Elevation Model's (DEM's) of Southeast Alaska and bordering Canada during the second half of the 20^{th} century to observe changes in glaciers in that region. The study compared data over two periods, 1948-2000 and 1982-2000, which found most glaciers to have strong thinning and retreat during these periods, with volume loss rates of 16.4 ±4.4km^3/ year. These findings indicate roughly double the glacial thinning than previously stated, constructed from sparsely distributed laser altimetry synopses by Arendt et al., (2002). A reason for this could be a result of Arendt et al., (2002) potentially neglecting smaller glaciers, specifically smaller than 1km^2, which may cause significant errors and could be an explanation for the reduced levels of change found (Paul et al., 2004).

Southeast Alaskan glaciers have commonly low elevation and geometry which make them particularly susceptible to climate change (Larsen et al., 2007). Due to this high susceptibility many studies attribute changes in climate, predominantly summer air temperature increases, as the foremost cause of glacier mass loss in Alaska (Arendt, Walsh, and Harrison, 2009; Larsen et al., 2007; Rasmussen and Conway, 2004). Larsen et al., (2007) states this is because summer air temperatures signify the 'variability in solar radiation and heat available for melting, and winter snowfall', and as a result regulates the net surface accumulation for a glacier.

2.3- The effect of climate on glaciers.

Rasmussen and Conway (2004) used a 40-year record of 850mb temperatures to show increased winter and summer warming since 1976 and 1988 respectively, throughout Southeast Alaska. These results were concurrent with the aforementioned literature that also observed similar increases over this period. The study found reduced mass balance records for the two Southern Alaskan glaciers in their study reflected these climatic changes. Rasmussen and Conway (2004) also stated that despite sea-surface temperature and sea-level pressure having a great influence on the atmosphere and in turn on a glacier, upper-air conditions such as temperature and moisture levels at 850mb have a more immediate effect on ablation and accumulation which are essential mass balance components (Houghton, 2004), then resultantly should also dictate the terminus location (Larsen et al., 2007). These findings are coherent with Braithwaite (2006), and Braithwaite and Raper (2007), in which both studies found air temperatures as the focal factor in temporal variability of mass balances, causing changes of mass balances to be spatially correlated within regions (Haeberli et al., 2007), which is an addition reason to why the glacier's used in this study are from the same mountain range, to reduce varying climatic conditions. This is supported by Oerlemans (2005), and Schooner and Bohm (2007), who found that long-term precipitation patterns have little influence on glaciers over time, but noticeably influence glacier changes spatially. Consequently precipitation patterns only seem to have secondary effects behind air temperatures with regard to glacier fluctuations.

Whilst few dispute that the change in climate is having a clear indicative influence on glacier dynamics, it is widely contended under what time-scale these influences occur. Studies such as Dyurgerov and Meier (2000) who observed changes in small glaciers volume's from 1961-1997 states there is an almost immediate change in glacier volume in response with the climate. They go on to say with a 95% confidence level in there statistical analyse that there is roughly a 1-year lag in response, which is attributed to the albedo affect from a non-zero balance year can surplus to the following year. Conversely other literatures have identified a far more delayed glacier adjustment in response to climate changes, regularly spanning decades (Larsen et al., 2007; Hodge et al., 1998; Johannesson, Raymond, and Waddington, 1989). Elsberg et al., (2001) study explains that changes in glacier volume characterise the current and previous effects of climate.

Although the distinguished change in glacier mass balance and retreat is primarily credited to climate fluctuations over varying timescales, glacier response to such change in climate is in fact far more complex, and the sensitivity of glacial mass balance to temperature and precipitation changes often contrasts depending on the seasonal timing of the change (Oerlemans and Reichert, 2000). Rasmussen and Conway (2004) established that winter precipitation, and summer and winter temperature are the foremost climatological components to glacier mass balance processes. This is as winter precipitation and temperature regulate accumulation, while summer temperature regulates ablation, the two main components of glacial mass balance (Houghton, 2004). The seasonal dependency of the changing climate and key climatological components is agreed by Arendt, Walsh, and Harrison (2009) who further clarify that summer precipitation increases would take insignificant effect on glacier mass balance as would most likely occur in the form of rain. In addition, increases in winter temperature may adjust the winter mass balance of a glacier, even if the surface temperature doesn't exceed the melting point of ice as it may influence the partitioning of rain and snow. Together with the evidently complex climatic interactions, the extent to which a change in climate can influence glaciers is also significantly subjective to non-climatic factors such as ice dynamics, glacier configuration, glacier hypsometry and topography (Racoviteanu, Williams, and Barry, 2008; Benn and Evan, 1998).
An example of this is in Paul et al., (2004) study of Alpine glaciers since the 1980's, indicated vastly distinct and non-uniform variations in glacier geometry is evidence of abrupt down-wasting since 1985 as opposed to a change in climate causing the response.

2.4- Contribution of glaciers to sea-level rise.

Sea-level rise (SLR) is a consequence of the climate change process. This is particularly significant in southern Alaska and Canada where a combination of their seasonal climatic fluctuations and expansive ice cover over large proportions of their respective land means that these regions are a specific concern to sea-level rise (Rasmussen and Conway, 2004; Meier and Dyurgerov, 2002).

The increased contribution of Alaskan glacial melt to SLR is noted by many studies, which is believed to as a result of the increase in both summer melting and winter accumulation that causes the intensification of glacial regime (mass exchange) and a lower rate of wastage (Dyurgerov and Meier, 2000). Early predictions from Arendt et al., (2002) stated that losses in ice mass throughout the 20th century directly from Alaska and adjoining Canada made a greater contribution to global seal level rise than losses from the Greenland Icesheet despite the significantly superior levels of ice mass stored within the Greenland Icesheet. A similar study by Kaser et al., (2006) contributed retreating glaciers and ice caps in the preceding 50 years to an increase in sea-level by 0.5mm/ $year^{-1}$. Though Larsen et al., (2007) questions many of these aforementioned study's measurements as they are based upon inadequate number of glaciers along with other uncertainties.

A more recent study of Berthier et al., (2010) used consecutive digital elevations models (DEM) to calculate the changes in elevation from 1962- 2006, using a far more extensive glacier inventory. The study observed a 41.9 ± 8.6km^3/ $year^{-1}$ of water loss from Alaskan glaciers, and contributed 0.12 ± 0.02mm/ $year^{-1}$ to sea-level rise. This is an approximately 34% lower than suggested by Arendt et al., (2002) and Meier et al., (2002). Probable reasons for this variance is that Berthier et al., (2010) used higher spatial resolution data in their glacier inventory which lowered ice thinning below debris at glacier margins, an issue that was unresolved in previous studies. In addition to merely 27% of Alaskan ice-cover in Berthier et al., (2010) study remained unmeasured, where Arendt et al., (2002) study had

80% unmeasured. For these reasons one can acknowledge Berthier et al., (2010) study is more accurate, making the result more reliable.

2.5- Other non-climatic influences on glaciers.

In addition to changes in glacier mass balance being a direct consequence of climate-induced factors, other non-climatic variables must also be taken into account when assessing a glaciers relative response to climate, such as the topography (Evans, 2006). The principal area of research for this study is investigating whether the relative size of a glacier is a key component in determining the rate and extent to which a glacier responds to a change in climate. Studies such as Paul et al., (1994) found a distinctive trend in a scatterplot representing change in glacier size relative to its overall size from 1973-1999, where that the relative percentage change in a glacier would decrease corresponding with an increase in overall size of glacier. This is supported by Bolch, Menounos, and Wheate (2010) who specified from their comparison of a glacier inventory for the Canadian Cordillera, using Landsat Thematic Mapper (TM) scenes from 2005 and 2000 with previous glacier cover for the mid-1980's that smaller glaciers had an increased relative percentage loss than larger ones. With the greatest cumulative loss for glaciers were within the 1-5km2 size class, concluding the reduction rate is primarily induced by glacier size. Bahr et al., 1998 opposes this opinion as their research found under identical climatic conditions, bigger mountain glaciers have a more immediate response than smaller glaciers to an adjustment in mass balance onset by changing climate. However, does agree to the interlinear relationship between the response time of a glacier and its relative overall size.

Baisheng et al., (2003) also identified that sensitivity of glaciers fluctuates with overall size, with the larger glaciers giving the highest rate of retreat, despite the relative alteration to bigger glaciers is respectively lesser and smaller ones. This notion is directly conflicting with Scherler, Bookhagen, and Strecker (2011) who determined that as glacier size increased, as did the response time. They further specified that small glaciers had an instantaneous response to change in climate, intermediate sized glaciers restrain influences of short-term climatic fluctuations but have noticeable responses at decadal time interludes, while large glaciers present the clearest indications of climate induced changes yet it being over the space of centuries. The general consensus, although of limited scope, is that the size of a glacier is a predominant element of both the varying rate and extent to which a glacier is adjusted in response to climate, yet discrepancy in what size glaciers are affected most in either regard.

In addition to the size of a glacier, many other non-climatic influencing mechanisms have been suggested to affect the response of glaciers to climate temporally. The most frequently published of these mechanisms, is the influences of the aspect (orientation) and the degree of slope in which a glacier lies. Suggestions by Johannesson, Raymond, and Waddington (1989) that response times for adjustment to equilibrium conditions, in which terminus retreat is a function of, are slope-dependent because it is dependent of ice thickness divided by the balance of the terminus. Haeberli and Hoelzle (1995) add that as a slope angle decreases towards zero, as does the balance of terminus. Conversely Hall and Fagre (2003) found that the elevation of the glacier was more than twice as powerful in predicting glacial melt than either aspect or slope.

3. Methodology

3.1- Description of instruments and data used

There are several ways in which the glacier terminus can be observed as described by Karpilo (2009), yet within this study satellite images were chosen using remote-sensing techniques. In order to accurately measure the changes in glacier termini without using in-situ measurements, multispectral images from the Landsat- 4 & 5 Thematic Mapper (TM), Landsat- 7 Enhanced Thematic Mapper (ETM), and the Landsat- 8 Operation Land Imager (OLI) and Thermal Infrared Sensor (TIRS) satellites were used in this study. Landsat satellites use tools that collect images from earth in different bands along the electromagnetic spectrum (Portengen, 2014). It is well recognised that the optical part of the electromagnetic spectrum, using multi-spectral imaging in the visible and infrared is easiest way of using remote-sensing to observe ice coverage (Raup et al., 2007).

In this study, images were collected over a 25-year period from 1990-2015, with image acquisition intervals of every 5 years, however due to inconsistency in Landsat images and high levels of cloud cover, some images were unavailable for desired time periods, consequently some images used within this project were obtained in the year proceeding or prior to the designated interval. The reason different satellites were used, is that Landsat -4 & 5 covered the longest time therefore would be used to have greatest consistency in data, yet stopped prior to 2015, so in order to carry on the data acquisition to present, Landsat- 8 images were required in 2015. Also the use of the Landsat -7 satellite was due to irregularities and high level of cloud cover present in Landsat -4 & 5 images, particularly until early 2000's. The reason that the newer and theoretically more 'advanced' Landsat -7 satellite was only used for images for the year-2000 interval, was as a result of a Scan Line Corrector (SLC) failure, meaning that images after May, 2003, were applicable for some studies but found not ideal for this due to the blurred outer reaches of the images (*SLC-off products: Background*, no date).

To measure the influence climate has upon the results of terminus change found from the satellite images. August temperature and precipitation record from 1965-2015 was acquired from the NOAA, National Centers for Environmental Information (Ncdc.noaa.gov, n.d.). The area for climate data used is the Climatic Division-5, Southeast interior of Alaska. The study used august temperature and precipitation in order to reduce the impact of inter-annual variability which can be observed in glaciers due to the ablation and accumulation seasons, therefore the climatic data was chosen in August as the majority of images were also chosen during this month.

Landsat Satellite	**Bands**	**Name**	**Wavelength (Micrometers)**	**Resolution (Meters)**
Landsat- 5 Thematic Mapper (TM) & Landsat- 7 Enhanced Thematic Mapper (ETM) *Band- 8 only available in Landsat- 7.	1	Blue	0.45-0.515	30
	2	Green	0.525-0.605	30
	3	Red	0.63-0.69	30
	4	Near Infrared	0.75-0.90	30
	5	Shortwave IR-1	1.55-1.75	30
	6	Thermal IR	10.40-12.50	120* (30)
	7	Shortwave IR-2	2.09-2.35	30
	8*	Panchromatic	0.52-0.9	15
Landsat- 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	1	Coastal aerosol	0.43-0.45	30
	2	Blue	0.45-0.51	30
	3	Green	0.53-0.59	30
	4	Red	0.64-0.67	30
	5	Near Infrared	0.85-0.88	30
	6	Shortwave IR-1	1.57-1.65	30
	7	Shortwave IR-2	2.11-2.29	30
	8	Panchromatic	0.5-0.68	15
	9	Cirrus	1.36-1.38	30
	10	Thermal Infrared-1	10.6-11.19	100 *(30)
	11	Thermal Infrared-2	11.5-12.51	100 *(30)

Table 3: Specification of Landsat Satellites.

3.2- Research Design

Due to the complexities in inter-annual variability of glacier mass balance (Ramillien et al., 2006; Bitz and Battisti, 1999), it is widely accepted that the optimum time of the year should to obtain satellite or aerial photographic surveys should be at the end of the ablation season in late August and Early September (Riedel and Burrows, 2005; Miller and Pelto, 1999). This is for several reasons depending on the scope of the study as this period provides summer snowline altitude (SLA; Racoviteanu, Williams, and Barry, 2008), which reflects fluctuations in glacier mass balance. In addition, the "terminus will be in its most retracted position; the transient snowline nearest its final, seasonal position; and the accumulation-area ratio at its seasonal minimum" (Fountain et al., 1997), making images acquired during this period the most accurate and consistent in monitoring the change in glacier terminus.

The images used in this study were chosen to be of 5-year intervals starting from 1990-2015, however due to lack of availability of sufficient images over certain periods, some glaciers have images used acquired from a year either prior or following the determined interval year. The reason 5-year intervals were chosen rather than annual measurements were because of unlike the mass balance of a glacier, which changes fluctuates according to annual climatic conditions with little-delayed response. A glacier terminus is a delayed, filtered and enhanced response of cumulative climatic and other glaciological factors over many years (Paul et al., 2015; Le Bris and Paul, 2013; Leclercq and Oerlemans, 2011; Pelto, 2008).

3.3- Description of procedure:

The Landsat satellite images used were attained and downloaded in a Level-1 product form from USGS's viewing platform, Earth Explorer (USGS Survey, 2016). Once downloaded the data was in separated in to each different band which represent the electromagnetic spectral range, these varied from 7-11 bands available depending on the Landsat satellite used. In order to view the images, all bands available were uploaded in a 'tif' format onto a GIS (Geospatial Information System) platform ArcMap, which is a computer application designed to allow the input, store, visualise, export and analysis of geographic information (Goodchild, 1988).

The bands available for a single image were then combined together to create a composite image using the image analysis tool, to create a RGB (Red, Green, Blue) configured layer. Every surface reflects different wavelengths (e.g. bands) uniquely, therefore different band combinations in the RGB scale allow the image to emphasize different surface terrain. In order to best differentiate the ice of the glacier from the surrounding debris, changing the symbology of the composite image by altering the RBG configuration for Landsat's- 4, 5 and 7, to containing a ratio of bands in the order 5, 4, 3 (R-5, G-4, B-3) (Portengen, 2014).
Once the configured band ratios were complete, the position of the glacier terminus is verified using manual digitizing methods, at a level of image magnification to allow delineation of individual pixels. This provided a consistent level of detail throughout the process for differentiating the glacier termini from surrounding terrain (Lea, Mair, and Rea, 2014; Riedel and Burrow, 2005). Using these techniques allowed glacier termini to be measured accurately and consistently, by creating polygon shapefile's in ArcMap around the extent of each glacier for every time-interval specified.

After the polygon shapefile's are created to allow measurements in the change on length between each polygon extent, representing glacial extents for each time-interval. As the retreat of a glacier is often asymmetric along the terminus and therefore a singular measurement of change is not representative of the cumulative change in length. Glacier length is often found difficult to determine due to inconsistencies in methodologies used (Le Bris and Paul, 2013). As a result numerous methodologies have formerly been used to resolve this issue, each having their individual benefits and limitations, which can lead to conflicting and inconsistent results (Lea, Mair, and Rea, 2014).

One of the most frequently used methods is the centre-line approach due to the simplicity and effectiveness of this technique (Kienholz et al., 2013; Nuth et al., 2013; Mernild et al., 2012; Walsh et al., 2012). However for the purpose of this study a similar version of Lea, Mair, and Rea (2014) extrapolated centerline method is derived, as the method is found to be their most accurate technique tested and the only one which can account for a changing glacier orientation, width and terminus geometry. The reason this method was not used was due to irregularities in terminus retreat in the glaciers for this study meant that measurements along the predetermined lines were not accurately representing the retreat.

Therefore the method used in this study, is performed by points along the width of the glacier spaced at regular interval distances, which lie at every fifth of the cumulative width, allowing a grid to be created around the glacier with 5 sections. Within each section, single measurements were then taken of corresponding glacier features along the termini for each polygon, giving 5 representative measurements of change in length along the glacier terminus, which can then be divided by 5 (the amount of measurements) to get a averaging change in length. The above-mentioned technique is visually represented in figure 4.

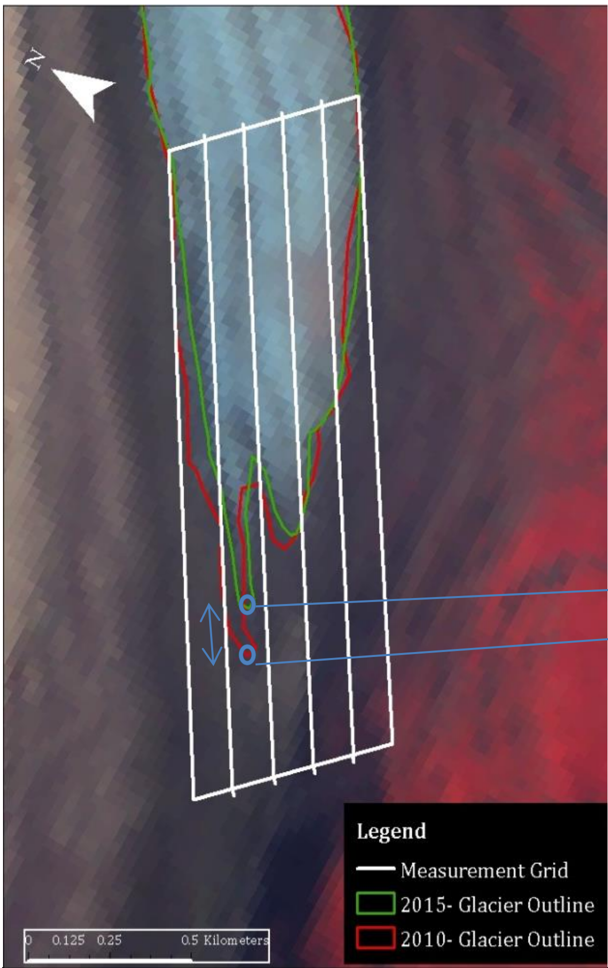


Figure 4- Measurement Methodology
Image showing measurement procedures as described in methods described above.

Distance between glacier lengths for a year is measured at distinguishably parallel changes in glacier. This is repeated for every section on the measurement grid (one measurement between each set of white lines), where an average is derived to represent the mean change in length over the width of the glacier. The raw data for this process is shown in the appendix.

4- <u>Results</u>

4.1- Images showing visible evidence of glacier retreat

Figure 5- False-Colour image (RBG- 5,4,3) of Maclaren Glacier.
The image on the left is a zoomed image with a scale of 1:10,000, showing a more accurate visual representation of the change in glacier.
The image to the right is a zoomed-out image with a scale 1:50,000, showing the change in glacier length retrospective to the size of glacier.

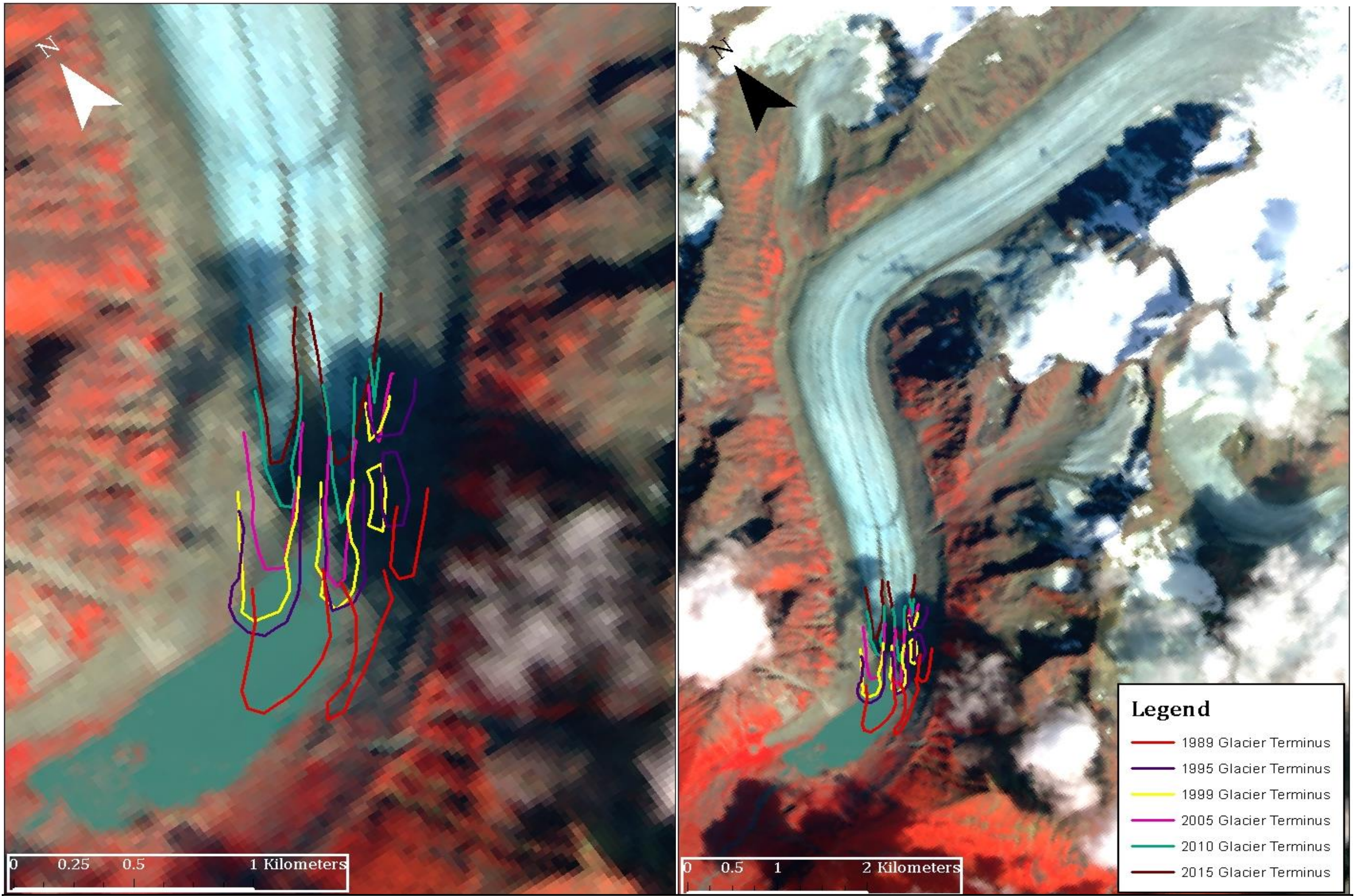


Figure 6- False-Colour image (RBG- 5,4,3) of South Glacier.
The image on the left is a zoomed image with a scale of 1:15,000, rotated by 30°, showing a more accurate visual representation of the change in glacier.
The image to the right is a zoomed-out image with a scale 1:40,000, rotated by 30°, showing the change in glacier length retrospective to the size of glacier.

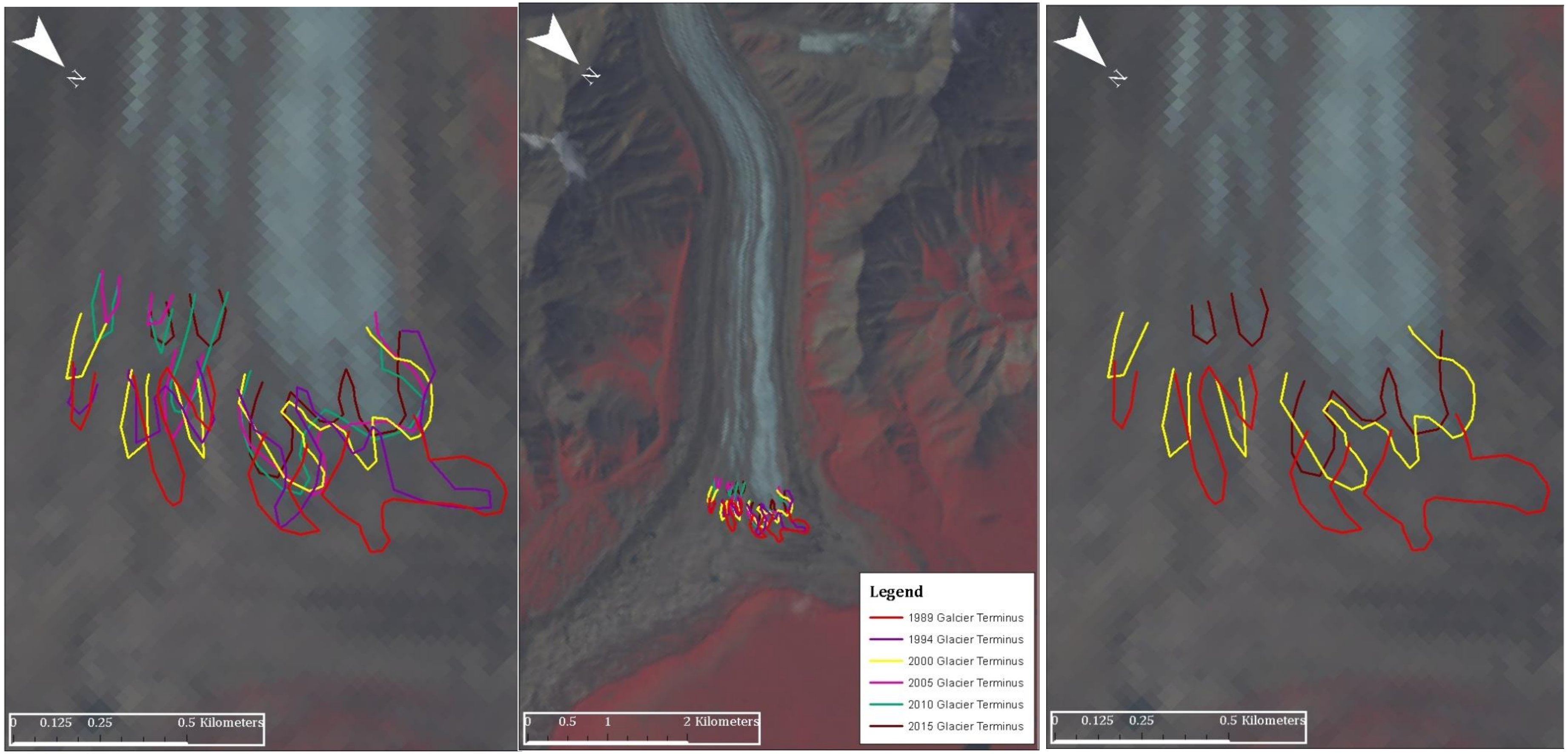
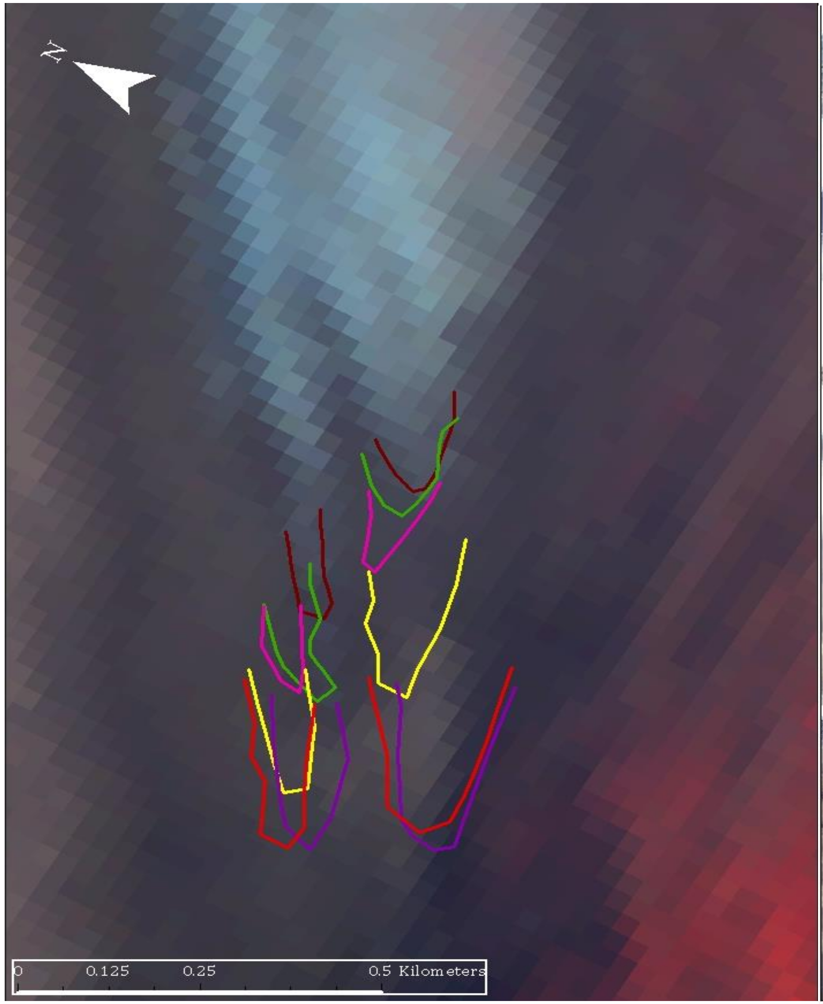


Figure 7- False-Colour image (RGB- 5,4,3) of North Glacier
-The images to the left and right are zoomed-in images to a scale of 1:8000 and rotated to an angle of 225°. Both images are provided as the left image that shows every 5-year interval overlaps extensively and therefore making it difficult to distinguish between years. Hence the need to include the right image which shows the first, last and one of the middle interval years.
-The image in the middle is a zoomed-out image to the scale of 1:35,000 and rotated to an angle of 255°, showing the change in glacier length retrospective to the size of glacier.



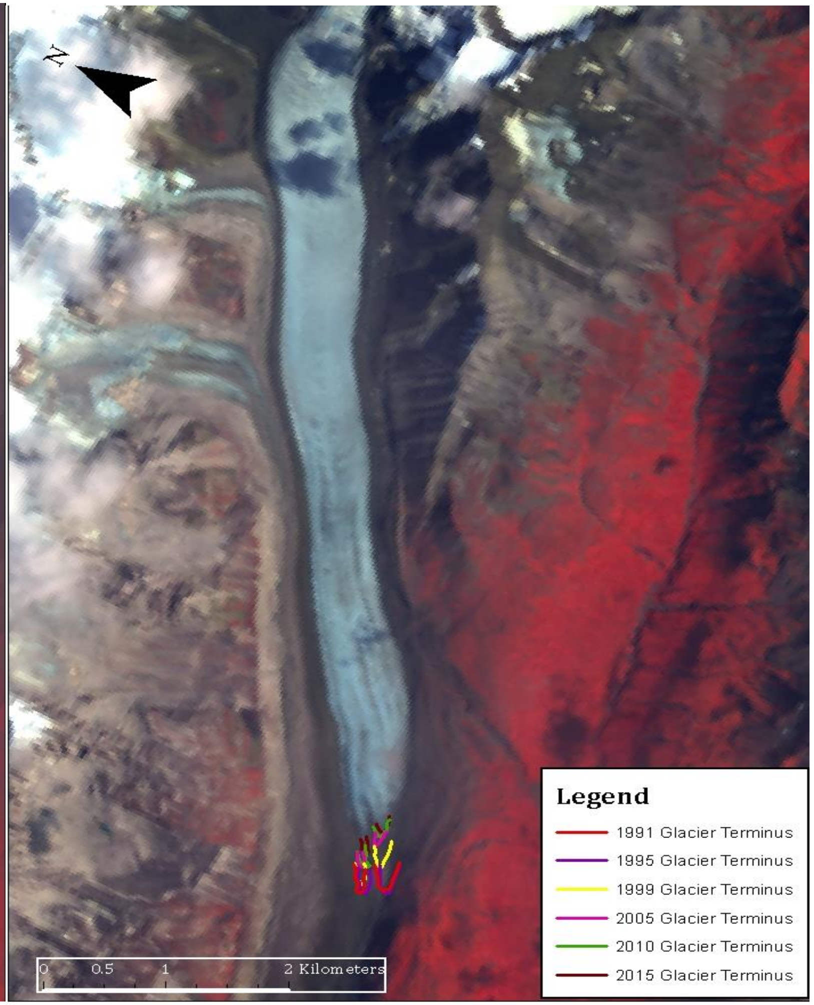


Figure 8- False-Colour image (RGB- 5,4,3,) of Nenana Glacier
-The image on the left is a zoomed-in image with a scale of 1:6000, and rotated to an angle of 60°, showing a more accurate visual representation of the change in glacier.
-The image on the right is a zoomed-out image with a scale of 1:30,000, and a rotated to an angle of 60°, showing the change in glacier length retrospective to the size of glacier.

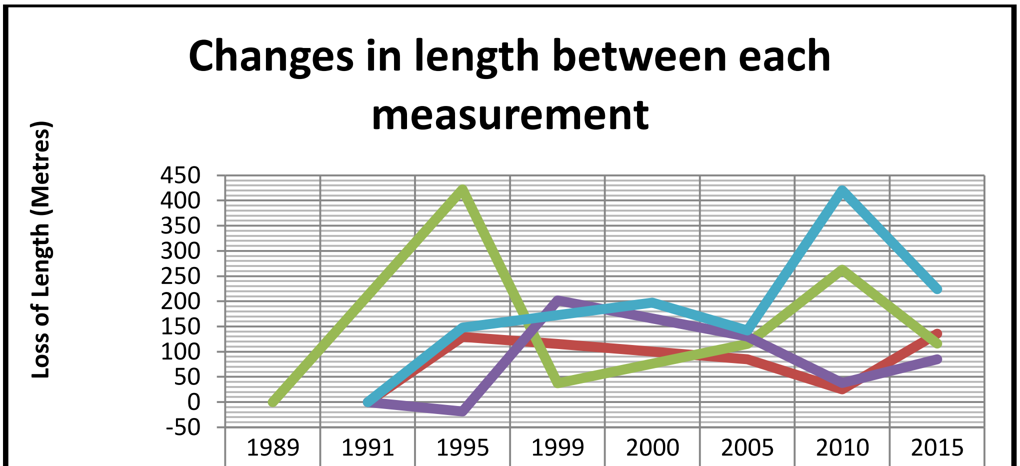
4.2- Describing measure changes in glacier length

Figures 9, 10, and 11, allow for statistical comparisons in addition to that of the optical images of the individual glaciers and how their lengths changed over the study period. These graphs show a numerical representation of figures 5, 6, 7, and 8 (images), which can be difficult to interpret. Analysis of these figures show the Maclaren Glacier has relatively uniform levels of retreat between each period, apart from the period of 2005-2010, which recorded 420.59m of terminus retreat. This extremely high level of loss over a period is displayed well in figure-5, where there is a clear distance between the 2005 (pink) and 2010 (blue) lines. Excluding this relatively anomalous result, the other changes in length vary from the lowest of 147.95m from 1991-1995, to the highest being 224.28m from 2010-2015. As seen in figure 11 the Maclaren Glacier had the highest cumulative loss over the study period recording a terminus retreat of 1132.03m.

Despite this, the North Glacier recorded the highest percentage length loss with 7.01% although recording the second lowest cumulative loss of 490.66m, as opposed to the Maclaren Glacier's 6.66%. The North Glacier also experienced relative uniform levels of change throughout each period, also apart from the 2005-2010 period, although this was due to considerably lower levels of glacier length change over this period, 25.28m, rather the substantially high levels shown in the Maclaren Glacier.

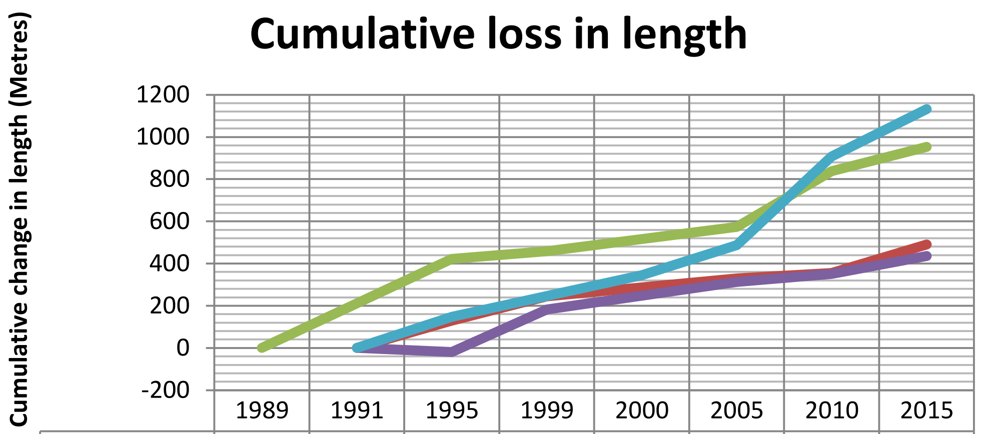
As for the South Glacier, the first observed change (1989-1995) in the study accounted to its largest change in length with 422.26m, which is significantly higher than for any other glacier during this period, and also over any of other periods for this glacier. The highest change in length for a period is followed by the lowest for the South Glacier with only a 36.92m from 1995-1999. This is displayed in figure-6 by noting the difference in change from 1989 (Red-line) to 1995 (Purple-line), and 1995 to 1999 (yellow-line). This glacier has a wide variance of results, but achieves the second highest cumulative loss in length of 953.26m.

Contrariwise the Nenana Glacier exhibits the lowest cumulative loss over the study period (1991-2015) with a total 436.38m's (figure-10), as well as recording considerably the lowest cumulative percentage loss in length of 2.73% (figure-11). The Nenana Glacier is the only glacier within this study to have a period of advance between 1991-1995 (18.5m), which can be seen in figure-8 where the 1995 (purple) glacier terminus exceeds that of the 1991 (red) terminus. After this advance, the following period of 1995-1999 measured the largest figure of terminus retreat for the Nenana Glacier of 201.74m.



	1989	1991	1995	1999	2000	2005	2010	2015
North		0	129.24	115.44		84.74	25.28	135.96
South	0		422.26	36.92		115.22	262.87	115.99
Nenana		0	-18.5	201.74		130.26	38.02	84.86
Maclaren		0	147.96		197.02	142.18	420.59	224.28

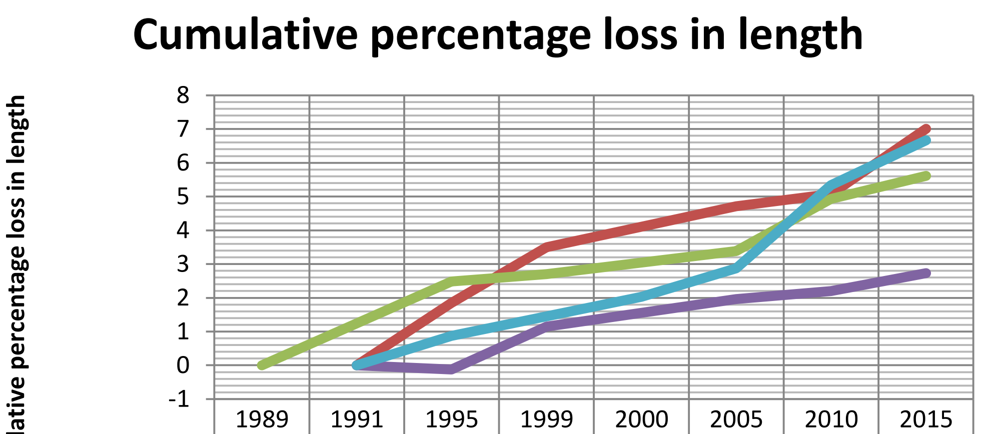
Figure 9: Graph displaying the variance in glacial length over a 5-year time period (e.g. the numerical value given in 2015, will actually be the change in length between 2010-2015).
-raw data found in appendix.



	1989	1991	1995	1999	2000	2005	2010	2015
North		0	129.24	244.68		329.42	354.7	490.66
South	0		422.26	459.18		574.4	837.27	953.26
Nenana		0	-18.5	183.24		313.5	351.52	436.38
Maclaren		0	147.96		344.98	487.16	907.75	1132.03

Year

Figure 10: Graph displaying the cumulative change in length over the study period.
-raw data found in appendix.



	1989	1991	1995	1999	2000	2005	2010	2015
North		0	1.85	3.5		4.71	5.07	7.01
South	0		2.48	2.7		3.38	4.93	5.61
Nenana		0	-0.12	1.15		1.96	2.2	2.73
Maclaren		0	0.87		2.03	2.87	5.34	6.66

Year

Figure 11: Graph displaying the cumulative change in length of a glacier, relative to the original lengths recorded by Denton and Field (1975- p583-586).
-raw data found in appendix.

4.3- Describing measured changes in glacier length in comparison with climate

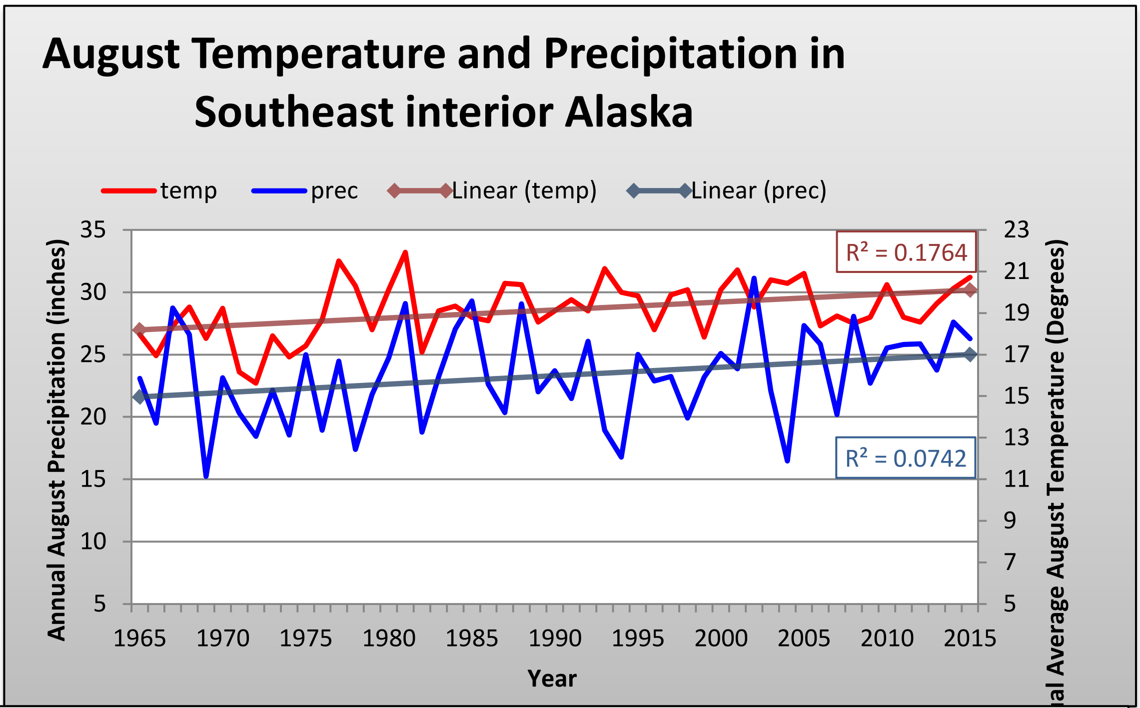


Figure 12- The graph displays annual August mean Temperature (Degrees-Fahrenheit) and Precipitation (Inches) levels from 1965-2015 in South-East Alaska, as provided by NCEI added Alaska climate divisions to its nClimDiv dataset http://www.ncdc.noaa.gov/cag/time-series/us/50/5/pcp/ytd/8/1965-2015?filter=true&filterType=binomial

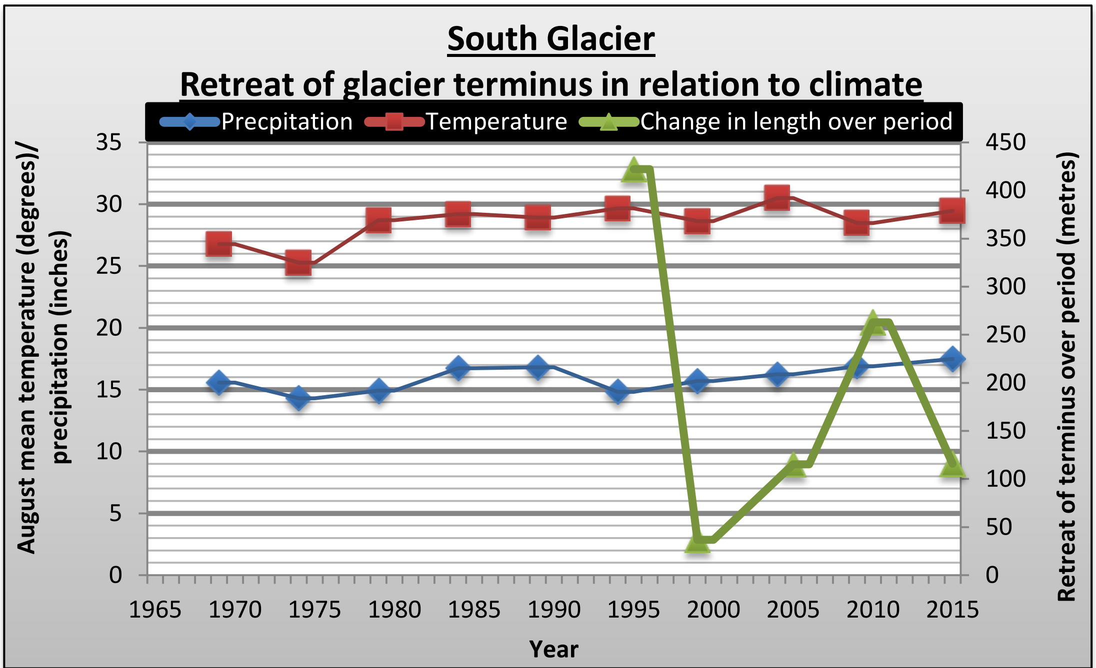


Figure 13- Graph showing the South Glacier plotted against temperature and precipitation record.

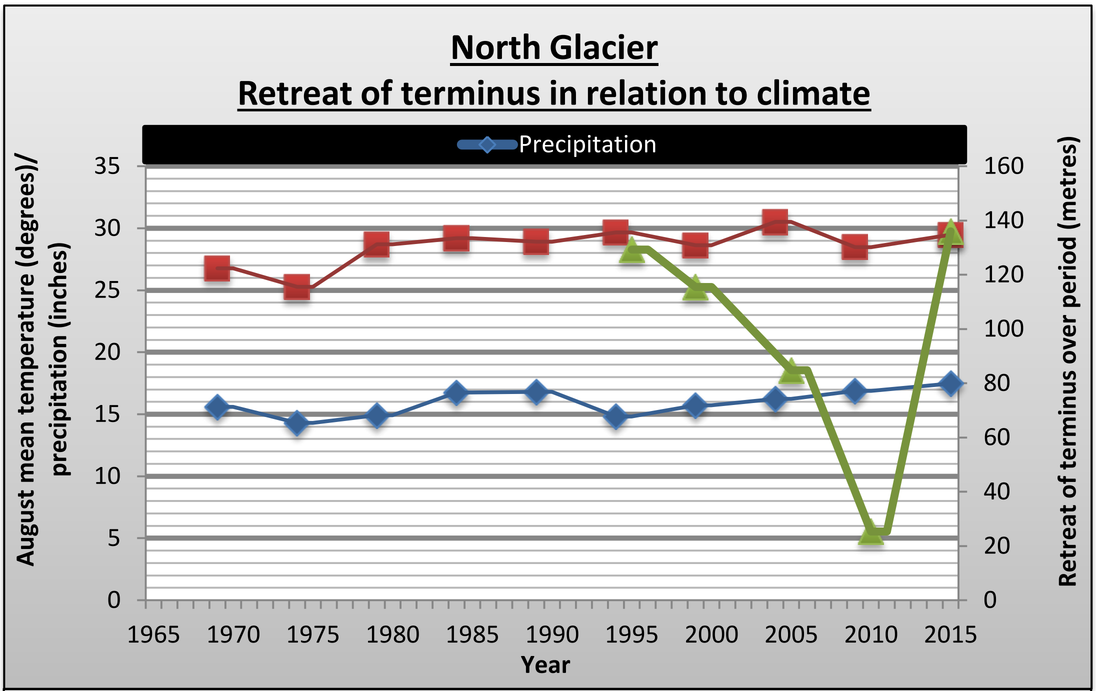


Figure 14- Graph showing the North Glacier plotted against temperature and precipitation record.

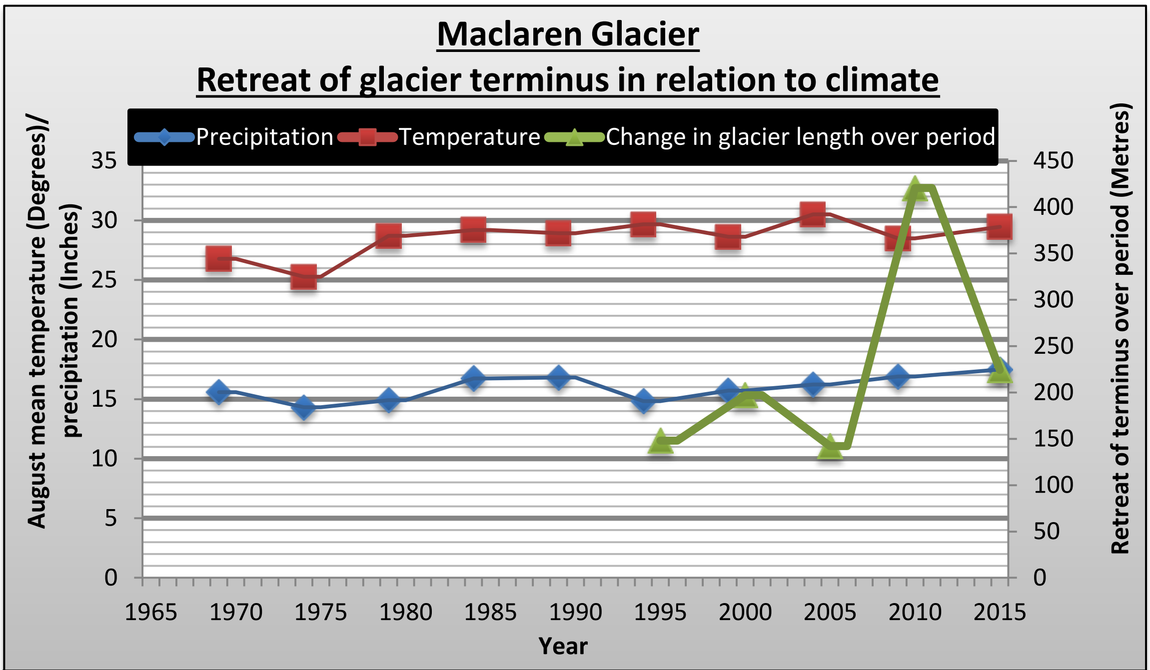


Figure 15- Graph showing the Maclaren Glacier plotted against temperature and precipitation record.

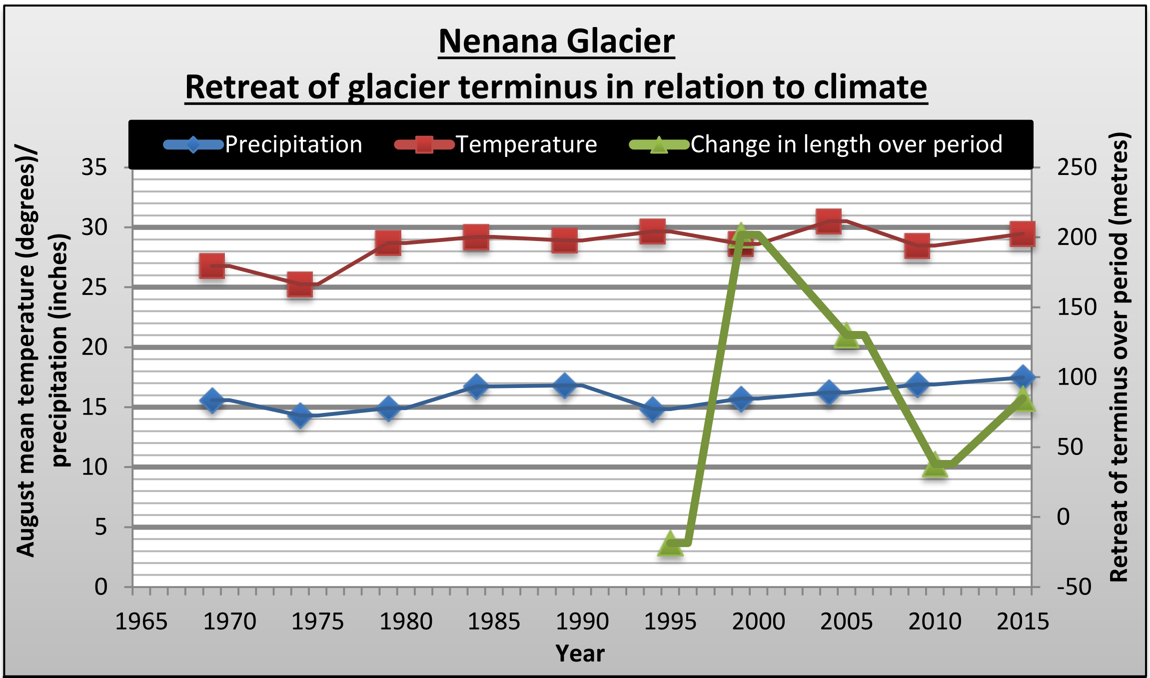


Figure 16- Graph showing the Nenana Glacier plotted against temperature and precipitation record.

Figure-12 shows a clear trend of an increasing temperature and precipitation over the past 50-years in southern interior Alaska. Temperature shows a higher relative increase over the period as can be seen from the trend-line with an r^2 value of 0.18 than in comparison of precipitation increases with r^2 of 0.07 (numbers given to 2 decimal places). In order to use the climate data (temperature and precipitation), 5-year averages were made as many studies state that glacier length responds to long-term in climate, rather than inter-annual responses.

Generally little observations could be made between 5-year averages of precipitation and any of the glaciers used in this study as the precipitation had fairly consistent moving-averages and had very little noticeable spikes or troughs in order to draw comparison with. Some literature suggests a relatively instant response of terminus retreat to precipitation. This is supported by if so the North and South glaciers both show a distinctive drop in rate of terminus retreat as in 1989- and 1991- 1995 period in figures-13 & 14, would be as a result of drop in precipitation in 1989. The opposite observations could be made for the Nenana glacier which had its lowest observed change in length from 1991-1995, and then spiked after when precipitation levels increased again. The Maclaren Glacier doesn't appear to show any clear trends with the 5-year moving average precipitation, however when comparing the abrupt spike in change in length from 2000-2005 period to the 2005-2010 period with the annual precipitation shown in figure-12, then this abrupt increase could be a consequence of the sudden drop in precipitation from 20.67inches in 2002 to 11.88inches in 2004.

Much greater potential correlations were observed when comparing the 5-year moving averages of temperature with the change in glacier terminus. The Nenana glacier shows a potential correlation between the two variables as the initial extremely low value of -18.5m (18.5m advance) to then spike up, could be of a consequence to the drop in temperature as seen from 1969-1974, followed by the increase in temperature from 1974-1979. Changes in both the North and South Glaciers can be perceived to also as a result of the fluctuations in temperature from 1969-1979, which both show sudden decreases followed by sudden increase in changes over a period, shown in a V-shape. Conversely the North Glacier's decrease from 1995-2010 could also be argued is due to responses on a much smaller timescale, whereas the temperature drops in 1999, a drop in glacier change is seen in 2005-2010, and then both increase back up over the following 5-year period, potentially giving the North Glacier roughly a 5-year response period. There is also a case of argument for the Maclaren Glacier also showing a possible 5-year response period to the same temperature fluctuations as North Glacier's hypothetical trend, however it is far likely that variation in change in length over different periods is due to the large fluctuates in temperature from 1969 to 1979.

5. Discussion

5.1- Interpretation of results

When interpreting any observations or trends from the results described in figures-5 - 16, one must consider that glaciers are generally agreed to have a delayed response to climatological variables such as temperature and precipitation. An example of this is that a glacier could have currently favourable climatic conditions in order to gain mass; however, the glacier could be losing volume because its overextended and has large quantities of mass at low elevations (Arendt, Walsh, and Harrison, 2009). Furthermore the timescale at which this delay occurs is controversial, some argue the effects can be observed almost immediately, whereas other literature argues that the effects may become apparent decades, or up to a century, after the climatological events have occurred (Dyurgerov and Meier, 2000; Johannesson, Raymond, and Waddington, 1989; Bahr et al., 1998; Hodge et al., 1998). It should also be noted that the results of this study are subjective and therefore open to interpretation, it is largely due to the complexity surrounding glacial/ climatological interactions. Furthermore, there is little or no documented trend to compare the data to. Despite this, the observations and measurements taken in this study have indicated potential trends between these interactions which I will discuss in further detail here.

As previously mentioned, a glacier retreats as an adjustment mechanism to a change in glacier mass balance in order to reach a new balanced equilibrium between glacier and its surrounding climate (Larsen et al., 2007; Singh, Singh, and Singh, 2001). The results indicate that the size of the glacier may dictate the overall length of retreat that occurs, this can be seen clearly in figures- 9 & 10 which show the two largest glaciers have considerably higher levels retreat than the two smaller glaciers. However, glacial size does not appear to dictate cumulative change in the same way. When measuring the percentage loss of length of the glacier (figure-11) the results were variable, the North Glacier which is the smallest in size (4.6km2) presented the highest percentage loss of 7.01% showing little difference in relative change despite the large comparison in overall sizes of glaciers. These results are contrary to Paul et al., (1994) and Bolch, Menounos, and Wheate (2010) who found smaller glaciers to show much higher percentage changes than larger glaciers.

When then comparing the different size glaciers with the 50-year climatic record, showing the 5-year running trend of both temperature and precipitation in Southeast Alaska (be specific once reference), different interpretations of the results could be made. The clearest trend from the results are that every glacier recorded their respective two most extreme measured changes over period, this being the highest measure change followed by the lowest, or vice versa. This further reinforces the belief that the process of glacial retreat is a function of the glacier to counteract and re-adjust to a changing climate. Also this theory can be supported by the observations that for the Nenana and South Glacier, after the extreme high and low measured changes, the following periods seem to fluctuate at a moderately intermediate level, which could be interpreted as the glacier finding a balance in the rate of terminus retreat after having the extreme periods. Based on the trend indicated by these findings, one would expect moderate to intermediate level of retreat for both the Maclaren and North Glacier's in the years following 2015, until another extremity occurred. It is also noted that for all glaciers apart from the South glacier, the high extreme is following the low extreme, therefore one can suggest extreme levels of glacier terminus retreat is a direct response to a preceding low levels. (Pelto, 2011; Larsen et al., 2007)

The cause of these extremities is believed to be climate-induced, predominantly from temperature, consequently assessments must be made on the relationship between change in temperature and glacier length in a period. The absence of a clear relationship between precipitation patterns and the variability of glacier length can be supported by Oerlemans, (2005) and Schooner and Bohm, (2007) who express that changes in precipitation over an area should have a strong influence, conversely changes in precipitation within the same area, as is this study, appears to only have a secondary effect. Contrastingly, temperature appears to have a primary influence over time, consistent with Haeberli et al., 2007 who states regional air temperature causes mass balances, and therefore terminus lengths, to be spatially correlated throughout the region (Braithwaite and Raper, 2007). This is reinforced by studies observing phases of glacier advance to be in correspondence with Alaskan proxy temperature records. An example of this is Davi, (2003) who used temperature sensitive tree-ring chronologies to show multi-decadal cool intervals matched periods of glacier advance during the LIA (Little Ice Age), therefore evaluations can be made that Alaskan land-terminating glaciers is primarily in correspondence with regional temperature changes (Wiles et al., 2008; Wiles, 2004). Based on judgements on both temperature and glacial length records, most glaciers primarily seem to be in response to climatic fluctuations from 1969-1979 which would give the glaciers about a 30-40 year response time.

For the smallest glacier in the study (North Glacier) and for the largest (Maclaren Glacier), interpretations could be made to support either theory of an increase in glacier size being correspondent with an increase in response period, or alternatively to support the theory that an increase in glacier size results in a shorter response period. The North Glacier's (smallest glacier) distribution of decrease until 2010 where it increases suddenly again could be as a result of the dip and then increase in temperature seen between 1994-2004, giving a roughly 10-year lag in response time. This coupled with observed distribution of change in length for Maclaren glacier, where the slight decrease in rate of terminus retreat followed by sudden increase from the 1995-2000 to 2005-2010 period could be correlated with the small decrease and relative large increase in temperature from 1969-1979. Then the following drop back down to an intermediate level in the change in glacier length over a period and uniform temperature supports the previously mentioned concept of glaciers returning to their 'normal' fluctuation level proceeding an extreme high or low in the length of terminus retreat. These interpretations support the work of Scherler, Bookhagen, and Strecker (2011) and Dyurgerov, and Meier (2000) who both state the increase in size of a glacier directly increases the response time.
On the other hand, the results can be interpreted so that the largest glacier (Maclaren) distribution of glacier length can be seen to fluctuate with a 6-year lag

to temperature where the peak temperature in 2004 (30.7°) corresponds to the peak change in glacier length in 2010 (representing the 2005-2010 period). This combined with the smallest glacier (North) distribution on change in glacier length, potentially in unison with the temperature fluctuations from 1969-1979, as can be seen from the similar "V"-shape in both sets of data, giving the smaller glacier a 36-year lag in comparison to the larger glaciers potential 6-year lag in response. The second described theory of correlation which presents smaller glaciers to have longer response-times than larger ones, is supported by Bahr et al., who stated when other variables are remain constant the response times in mountain glaciers decreases as a function of increasing glacier size. The interpretations of these results show the ambiguity in determining the response time in glacier length reacting to climate fluctuations, this is mainly credited to the long timescale in which the responses can happen, therefore a direct cause and effect relationship can be is difficult to determine for small for relatively small studies such as this (Paul et al., 2015).

5.2- Other potential reasons for observed results

As it is highly debated and rather subjective, determining whether a large glacier size (area) responds to climate over a longer or shorter period than smaller glaciers is difficult. Conversely it is suggested that smaller glaciers lose a higher percentage of overall mass and length, than larger glaciers due to their relative lesser depth (Kulkarni et al., 2007), which would act as insulation against solar radiation. One reason that relative percentage change in glacier length is not as high as one may expect from the North Glacier, could due to regions in the Northern Hemisphere has increased solar radiation and exposure from the south, therefore north-facing glaciers such as the North Glacier in this study, experiences lower levels of solar radiation due to shade from the mountain (Evans, 2006; Srinivasulu and Kulkarni, 2004). This will obviously then cause reductions in the melting regime of a glacier. In addition to the orientation of a glacier affecting the levels of solar radiation, it can cause errors in the methodology of measuring glacier length. Lea, Mair, and Rea (2014) found that inconsistencies and inaccuracies of terminus length measurements can often be attributed to glacier orientation. As the Nenana Glacier has a 240° orientation facing South-West as opposed to other three glaciers either directly facing North or South, the orientation may have caused errors in the collection of measurements. And resulted to the Nenana Glacier recording the lowest levels of cumulative change in length over the period (436.38m), particularly accentuated by having considerably the lowest level of cumulative percentage loss in length over the 25-year period with less than half the percentage loss of the next lowest glacier.

Due to the many non-climatic variables that contribute to influencing changes in glacier mass balance, another component to be considered is that of elevation and slope as previously discussed in the literature review. When comparing differences in elevation (Table 1), the North Glacier has a difference in elevation of 2,151m, whereas, the Maclaren Glacier only has a difference in elevation of 1,642m. When these figures as compared respectively to the individual glaciers size, the North Glacier being the smallest, has a size of 4.6km2, therefore one can assume that in order to distribute the relatively small mass across the large change in elevation, the glacier would be thinly distributed and steep sloped. Which, could be a cause for high percentage glacier change as seen is figure-10 (Johannesson, Raymond, and Waddington, 1989). This further corresponds with Haeberli et al., (2007) who found for relatively thin and steep mountain glaciers, such as the North Glacier, the response times vary typically decadal. While for the relatively thick and gradual slope predicted for the larger Maclaren glacier, response times might reach centuries. In order to test this theory, further research would be necessary; with climatic records spanning over a century, and accurately measured slope angle, rather than assumptions made according to the elevation and relatively mass measurements, which are known in this study.

5.3- Limitations of the study

A limitation of this study is that some of the sources of information such as glacier lengths provided by Denton and Field (1975- p583-586) are relatively old (published fifteen years prior to start of this study), and due to the constant changes in glacier parameters, the true glacier length at the beginning of this study would be expected to be different than proposed, in effect changing the percentage length loss as show in Table-2. An additional constraint, also found in other studies such as Karpilo (2009), was the availability and high cost of obtaining optimal satellite imagery which also span consistently over the study period. This meant that lower, 30-metre resolution satellite images were acquired from Landsat satellites, as opposed to other preferable satellite data with higher spatial resolution.

The foremost limitation of this study is that the 5, 4, 3, -RGB configuration used to accentuate the ice in order to more accurately measure the extent of the glacier, only detects the surface ice and therefore cannot penetrate through potential matter which lie on top of the surface ice. Numerous studies have found the presence of supraglacial debris (on top of the glacier) and periglacial debris (surrounding the glacier) -cover to be an extensive challenge when mapping glacier boundaries, due to the similar visual and NIR (Near-Infrared) spectral signature of debris-cover than the surrounding terrain, such as

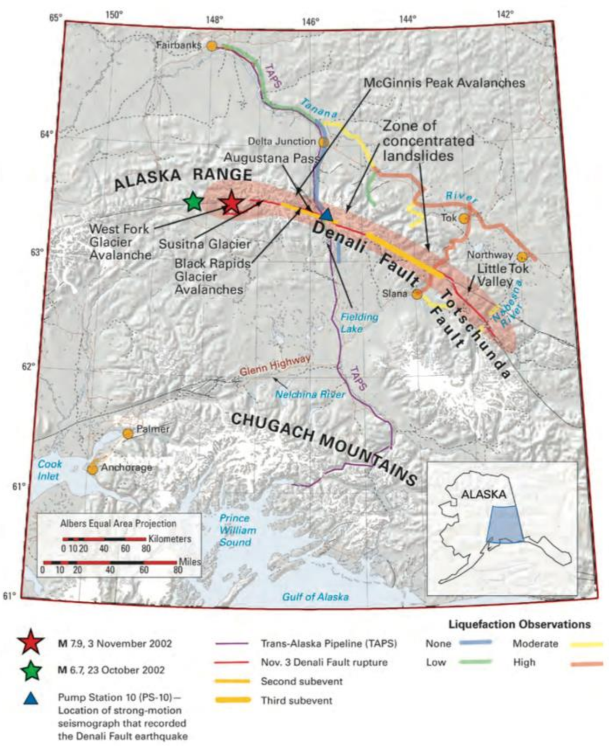


Figure 17: Map showing the tectonic distribution and effects of the 2002 earthquake in this region.

moraines (Racoviteanu, Williams, and Barry, 2008; Paul, Huggel, and Kaab, 2004). This is particularly of note for the glaciers in this study as past tectonic events such as the 2002, magnitude 7.9 earthquake originating from the Denali fault (figure?), has been observed to have caused substantial rock, ice and snow avalanches onto glaciers within this region. Events such as these, which leave large quantities of debris on the surface of a glacier, may lead to inaccuracies in the mapping of glacier parameters undertaken in this study (Harp et al., 2003; Truffer et al., 2002). The snow and rock debris-cover from the earthquake has been suggested to possible increase the mass balance of affected glaciers, as the debris acts as insulating layer to reduce the effects of warm summer temperatures (Molnia, 2008; Truffer et al., 2002). When comparing this with the changes in glacier length over a period for the North and Nenana Glacier's, there is a large observed continuous reduction in change, from the 2000-2005 period to the 2005-2010 period (figures 14 and 16), this could be suggested to be as a result of the insulating debris layer. One way in which future studies can use remote-sensing techniques to overcome the potential hazard in mapping debris-covered glacier's is by using threshold ratio images, for example from Landsat Thematic Mapper's bands 4 and 5 (Paul et al., 2004; (Bayr, Hall, and Kovalick, 1994), which can detect changes in thermal temperatures, allowing the distinguishing of supraglacial and periglacial debris from the colder ice (Shukla, Arora, and Gupta, 2010).

5.4- Concepts for further study

As mentioned previously in the literature review, studies such as Rasmussen and Conway (2004) suggest that winter precipitation, and summer and winter temperature are fundamental climatological variables which influence glacial mass balance, and therefore affect glacier length. In this study, only summer temperature and precipitation was used to determine a relationship between climate and changes in glacier length. Hence, further research could be done using these climatic variables mentioned by Rasmussen and Conway (2004), which may prove to have more significant correlations between climate and glacier length than found in this study.

An additional area of study which has been presented, is to expand-upon research done by Post et al., (2009) and mentioned in Barry (2006). Who note the reduction in glacial area, for example from glacial retreat, will expose new terrain which may not have been uncovered since prior to the LIA (Little Ice Age). This newly exposed landscape can potentially provide an idealistic ecosystem, containing new mineral sources that allow both new flora and fauna species to migrate to the specific region, or for current species to thrive and become a dominant part of the new ecological composition of the ecosystem.

6. Conclusion

6.1- Summary of findings

This study measured changes in glacier termini for four glaciers, all located within the Hayes section of the Alaska Range, over a 25-year period from 1990-2015. Once the changes in glacier termini was measured, these results were firstly compared in conjunction with each-other to observe general trends in the influence of size, spatially and temporally. Following this, temperature and precipitation records for this region were then used to investigate temporal trends in relative size of a glacier against climatic fluctuations.

When analysing climatic trends in association with glacial size (area), the observations proved to be inconclusive as to whether the size of a glacier has a direct causal effect on the response time to climatic fluctuations. The heterogeneous findings were recognised to be due to the subjective nature of these interpretations. This was as particular suggestions of correlating trends were coherent with some current literature. Conversely, the contrasting theories can also be supported when looking for those linear tendencies, making the results extremely subjective and can be misinterpreted depending on the idealised findings of one's study.

Despite the unfounded correlations stated as the primary aim of the study, based on the theory of glacier length fluctuations being a component used to readjust, once again creating equilibrium within the glacier regime, is found to be supported by the results. This is as extremities of high or low terminus change over a period, was nearly always found either prior or after an opposing extremity. This is believed to be as a result of a glacier either under-or over-extending the adjustment needed from glacial retreat, and therefore the opposite reaction is taken over the next period in order to reach a balanced equilibrium. These observations may have global application, as if this theory is proved more reliable from further research, then it could be applied to detect and predict future fluctuations in terminus change and therefore in mass-balance. This is particularly important as it can allow protective measures to be put in place if predicting a period of extreme high terminus loss from mass wastage, to reduce influence of potential hazards events such as flooding and avalanches.

Whilst trying to reduce the individual climatological influences upon a glacier by using ones from the same mountain range, the fact that still many other non-climatic variables such as slope, aspect and elevation, suggested potential justified correlations with terminus retreat was a contributing factor to why these results prove insignificant within this study alone. However, the findings of this study may be in correlation with other similar studies that will allow a more direct conclusive observations to be made and may allow statistical significance.

Studies succeeding this project could investigate relationships of specific climatic variables such as winter temperature which has been suggested to a dominant climatic factor, rather than using summer temperature and precipitation. Furthermore, there has been very little research into the new land exposed from glacier retreat, and the potential implications upon the ecological composition of an area.

6.2- Concluding remark

Furthermore, the size of the glacier was expected to be a determining factor upon the temporal distribution of terminus retreat; however, the results proved to be inconclusive and temporal patterns can be observed subjectively to suit theorised observations, rather than objectively to show the statistical significance of a correlation.

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