GLACIER AND CLIMATE FLUCTUATIONS IN SOUTH-CENTRAL ALASKA AS OBSERVED THROUGH THE PTAA MODEL

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
Glaciers in Alaska have been increasingly losing mass over the last several decades. This trend is especially apparent in South-Central Alaska where many glaciers are undergoing rapid changes and contributing substantially to rising sea levels (Arendt et al., 2002). It is important to understand the rates at which these glaciers are losing mass as well as the important climatic drivers to better prepare for what the future holds in this region and the rest of the world. This thesis compares glacier mass balance data modeled through the Precipitation-Temperature Area Altitude (PTAA) mass balance model for several glaciers in South-Central Alaska to observed data from the USGS and other sources in order to help validate the model. Once this step is completed, the measured and modeled data are then correlated with climate data in order to understand the main climatic drivers of the glacier mass balance in this region.
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CHAPTER I

INTRODUCTION

Most of the world’s glaciers are melting and more and more evidence points towards human-induced climate change as a major cause. Specifically, mountain glaciers are key indicators of climate change since they are very sensitive to small changes in temperature and/or precipitation (IPCC, 2007). Mountain glaciers are melting at an alarming rate that has extreme implications worldwide from the loss of precious water resources to global sea level rise. It is clear that in order to try and minimize the impacts melting mountain glaciers have on human population, scientists need to understand what is causing glaciers to melt at such an alarming rate. The most important issue for scientists to understand is how a warming climate will affect these mountain locations.

One area that has garnered a lot of attention over the last several decades is Alaska. While there is no exact count, it is estimated that there are more than 100,000 glaciers in Alaska,
with a large number of them being small, upland cirque glaciers (Molnia, 2007). A large body of research exists dealing with the relationship between climate and glacier mass balance in Alaskan glaciers, mostly related to understanding how a warming climate is affecting the glaciers in this region. With almost 13% of the mountain glaciers on Earth (Meier and Dyurgerov, 2002), covering an area of around 75,000 square kilometers (Molnia, 2007, Shulski and Wendler, 2007), it is important to understand how Alaskan glaciers are changing. This region currently has a large impact on eustatic sea level rise, as many studies indicate that mountain glaciers are contributing 0.2 to 0.4 mm/year (Arendt et al., 2002), with Alaska being the largest contributor. Therefore, it is important to understand the health of Alaskan glaciers to understand the impacts that climate change will have on the local, regional, and global scales.

Alaska covers a large geographic area in the Northern Pacific, spanning some 20 degrees of latitude and reaching well above the Arctic Circle (Shulski and Wendler, 2007). Due to this large size and its location, there are many different climatic regimes covering the state. The southern parts of the state that border the Pacific Ocean generally have a maritime climate due to the effects of the ocean. While these areas do not get as cold as the interior and northern sections of the state, the moist air coming off the ocean brings copious amounts of moisture into these regions (Shulski and Wendler, 2007). With the coastal mountain ranges that lie just inland from the ocean, this cool, moist air that comes in from the Pacific is forced to rise and we have the perfect setting for the growth of large, maritime glaciers. These glaciers are therefore dominated by the winter precipitation that Pacific storms bring into the region. Going north and away from the coast, the climate dries out, and once into the interior of Alaska we encounter a continental climate. The continental climate in the interior of Alaska is much drier than along the coast and large temperature extremes are much more typical. As an example, Fairbanks in central Alaska
ranges 36°C between average summer and winter temperatures (Shulski and Wendler, 2007). In between these two areas is another mountain range, the Wrangell Mountains. These mountains contain many glaciers, but being more inland than the coastal ranges experience much less precipitation and can be considered continental glaciers. Continental glaciers are typically controlled more by the summer (ablation) season temperatures than their maritime counterparts due to the large temperature swings in these regions.

It is in these two regions of Alaska, the south-central coastal mountains and the Wrangell Mountains where this thesis will focus (Figure 1).

**Figure 1.** Google Earth image of the south-central Alaska study region, with pinpoints locating the study glaciers. A 1:250k USGS DRG map lies over the GE image, courtesy of the UAF-GINA project.

The main research topics will be to first model the mass balance of several glaciers in these regions using the Precipitation-Temperature Area Altitude (PTAA) mass balance model.
These modeled balances will then be compared to measured mass balances in the region to help validate the model. This will be done for the Wolverine Glacier located on the Kenai Peninsula in south-central Alaska and for the glaciers in the Wrangell Mountains.

The Wrangell glaciers are first modeled as glacier masses, divided into north and south regions. Then one glacier in the north region (Nabesna Glacier) and one glacier in the south region (Kennicott Glacier) are modeled in order to better compare the balances to actual measurements. The next portion of this thesis deals with understanding the climatic drivers of the glacier mass balance in this region, both the modeled and measured balances. Temperature and precipitation measurements in these areas, along with several climate indices are compared to the mass balances to understand how they affect the mass balance of these glaciers. Overall the goal will be to understand the key climatic drivers of the glacier mass balance in these regions and to determine whether these relationships have changed over the last several decades due to the warming climate of Alaska.

The study of glacier mass balance attempts to understand changes in the mass of a glacier, generally looking at the year to year trends. Glaciers generally gain mass through snowfall (accumulation) and lose mass through melting (ablation) and iceberg calving (Braithwaite, 2002). When accumulation exceeds ablation the glacier is said to have a positive mass balance and when ablation exceeds accumulation there is a negative mass balance.

Mass balance is measured as a net balance for the entire year, as well as individual balances for both summer and winter. All of these can be put together to obtain the net mass balance for a given year in the following mathematical form:

\[ b_n = b_w + b_s \]
where \( bn \) is the total net balance and \( bw \) and \( bs \) are the winter and summer net balance, respectively. There are several different methods to determine mass balance, the conventional one being the direct glaciological method (Barry, 2006). This method uses stakes on the glacier, placed in the accumulation and ablation areas, where repeated measurements are taken to determine the mass balance. The indirect method involves determining mass balance from geodetic measurements of the fixed bedrock as a reference. This method was used by Hubbard et al. (2000) along with Digital Elevation Models (DEMs) and photogrammetric data to analyze the Haut Glacier d’Arolla (Barry, 2006). There have been many comparisons of the two different methods over the last decade. Elsberg et al. (2001) looked at conventional methods and some of the indirect methods and quantified the differences between them. Their results actually found that the indirect method correlated better to climatic variations then did the conventional method, and that the conventional method sometimes overestimated the mass balance. They theorized that this could be caused by the use of extrapolation of field measurements from one or several areas on the glacier to the whole glacier area.

The traditional field methods associated with measuring glacier mass balance are expensive and labor intensive, so the PTAA model attempts to alleviate some of this required work and expenditure. The model takes temperature and precipitation observations from nearby low-altitude weather stations on a daily basis (best to be within 150 km), and through a series of algorithms, outputs daily values for glacier mass balance, snowline altitude, zero balance altitude (ZBA) (sometimes also referred to as ELA), and accumulation area ratio (AAR). The use of low-altitude meteorological data compared to using data from on or near the glacier is important, as precipitation gauges in open, high altitude areas tend to significantly under catch precipitation, which would lead to erroneous results (Tangborn, 1999). One of the most important aspects of
the model is the use of the area-altitude (AA) profile of the glacier. Every glacier has its own unique AA profile, which is a direct representation of the erosional history of the glacier. It is then reasoned that combining the weather observations (which represent the climate) and the AA profile (representing the erosion) will give the needed information to accurately calculate the mass balance of a given glacier (Tangborn, 1999). The PTAA model accomplishes this objective using the available meteorological data and a glacier’s unique AA profile as input, giving glacier mass balance and associated variables as output.

Study Area

Two areas have been selected for this research which will better enable the understanding of how the climate affects glaciers in south-central Alaska. The regions differ in that one experiences a maritime climate while the other a continental climate. The Wolverine Glacier was selected as a maritime glacier representative, and this was done because there is a long record of glacier mass balance data for comparisons. The USGS has monitored the Wolverine Glacier since 1966 as part of their ‘benchmark’ glacier monitoring program (Molnia, 2008). The glaciers of the Wrangell Mountains were chosen to represent continental glaciers, and while there is not a long mass balance record for comparison, there are some studies and measurements to compare to the modeled data.

Wrangell Mountains

The Wrangells are volcanic mountains located inland of the southern coastal ranges of Alaska in the Copper River Basin, lying on a west to east line as they merge with the St. Elias Range entering into Northwestern Canada, centered at approximately 61.5N lat, 143.3W lon (Figure 2).
These mountains receive less precipitation than the coastal ranges, due to their more inland location, giving them a continental climate. Thus glacier mass balance in this region would generally be controlled more by temperature, whereas in the maritime glaciers precipitation would be the dominant factor. The glaciers in the Wrangell Mountains cover an area of approximately 4725 km$^2$, with roughly half of them (2418 km$^2$) oriented north and the other half (2307 km$^2$) south. This makes for an easy divide, and for this study the glaciers were divided into a north region and a south region and then modeled as whole glacier masses. Also one glacier from each region was chosen as a representative glacier in order to do a smaller scale modeling study to better compare to existing data. The Nabesna Glacier was chosen for the north facing glaciers and the Kennicott for the south facing glaciers.
Wolverine Glacier

The Wolverine Glacier is located on the southern end of a relatively small, unnamed ice field in the northern Kenai Peninsula in south-central Alaska, centered at approximately 60.41N lat, 148.90W lon (Kennedy, 1995, Molnia, 2008) (Figure 3).

![Figure 3](image.png)

**Figure 3.** 1:250k USGS DRG map of the Wolverine Glacier displayed in Google Earth. Image courtesy of the UAF-GINA project and Google Earth.

This area comes under a strong maritime influence with high annual precipitation totals and moderate temperatures. The Gulf of Alaska, just south of this region, remains ice-free all winter keeping the temperatures moderate and allowing the moist air from the Pacific to flow into this region giving this area some of Alaska’s highest precipitation totals (Shulski and Wendler, 2007). Thus, the mass balance of the Wolverine Glacier is predominantly controlled by winter precipitation. The area of the Wolverine Glacier is estimated to be around 19 km².
CHAPTER II
LITERATURE REVIEW

Alaska Glacier Research

Mayo and March (1990) looked at air temperature and precipitation at the Wolverine Glacier in Alaska correlating these climatic parameters to glacier mass balance. Temperature and precipitation data were collected at 990 meters of altitude in the glacier’s drainage basin, estimated to be about 100 meters below the average ELA. These data were collected from 1967-1988 and were the only climate data collected near the ELA of a glacier in this region of southern Alaska. For the same time period, glacier mass balance data were collected using the standard glaciological observations of snow and ice at three monitoring stations. From 1976 to 1988 the mass balance increased, gaining approximately 6 meters of ice averaged over the glacier surface. Over this same time period temperature increased by 0.76° C per decade and precipitation increased by 0.42 m per decade. The increases in temperature and precipitation mainly occurred during the winter months; with the temperature increases occurring on
temperatures that were initially well below freezing. This would be expected to cause increases in glacier mass since the temperature is still remaining below freezing, but more precipitation is occurring. It was noted that many global climate models had predicted these increases in glacier mass in southern Alaska with modest temperature increases. The authors concluded that these results were good illustrations of how glaciers are sensitive indicators of climate change, and that these relationships are far from simple.

Hodge et al. (1998) looked at the mass balance of three glaciers in Western North America, two of which are the Gulkana and Wolverine Glaciers in Alaska. The third glacier in this study is the South Cascade Glacier in Washington State and this is important because this glacier along with the Wolverine Glacier is a coastal maritime glacier. The authors in this study show that the mass balance of both coastal maritime glaciers react to climatic patterns similarly, even though they are over 2000 km apart. Conversely, the Wolverine and Gulkana Glaciers are only 350 km apart, yet they exhibit very different behaviors in relation to climatic patterns. The mass balance on each of these three glaciers was measured using standard field methods such as accumulation and ablation stakes and snow pit stratigraphy, and records exist for over 30 years on each of these glaciers. Hodge et al. compared the mass balances of these glaciers to four climatic indices including the Pacific-North American (PNA) and central North Pacific (CNP) indices, trying to correlate variations in the mass balance to shifts in these indices. The authors noticed a striking similarity between North Pacific conditions and winter mass balance of the maritime South Cascade and Wolverine Glaciers. The continental Gulkana Glacier on the other hand shows no relationship to these conditions and instead is more dominantly controlled by summer balances according to the authors. These results follow the general thinking that coastal maritime glaciers are controlled by winter accumulation whereas continental glaciers are
dominated by summer ablation. In their final conclusion however, the authors mentioned that since 1989 all of the observed teleconnections have broken down and all three glaciers are showing increasing mass loss at the highest rate throughout the record. This they say is most likely a signature of climate warming as no other pattern can explain this relationship.

Trabant and March (1999) looked at mass balance measurements on the two USGS benchmark glaciers in Alaska (Wolverine and Gulkana Glaciers) and suggested how to use the components of the program along with climate patterns and the time-series of data obtained in order to design programs to measure the mass balance on other glaciers. Field measurements are made on these glaciers three times each year using accumulation and ablation stakes, as well as snow pits. Seasonal and net mass balances along with ELA and AAR have been calculated on these glaciers since 1966 as part of the USGS monitoring program. For the Wolverine Glacier, a maritime glacier in south-central Alaska, the average ELA was reported to be about 1200 meters, with a net thinning of 9.8 m w.e. since 1966. The Gulkana glacier, a continental glacier in interior Alaska, had an average ELA of 1770 meters, with a net thinning of 14.6 m w.e. since 1966. These same measurement techniques have been used on some other glaciers in Alaska as well, but not as continuously as on these two glaciers. The main point of this study is to show that this is the real problem. There needs to be more continuous mass balance measurements on glaciers, as well as carefully recorded and standardized field techniques in order to have accurate data. The authors conclude that just recording measurements in the field near the ELA, even for a long period of time, and attempting to correlate these results to climate records is not a viable method. There should be a minimum of three measurement sites, one in the accumulation area, one near the ELA, and one in the ablation area. And there should be regular updates of area-altitude distributions in order to perform proper area integration of the balance measurements.
Overall, one needs long-term programs of measuring seasonal and annual mass balances in order to make climatic correlations.

Bitz and Battisti (1999) compared climate and glacier variations at six glaciers along the Pacific coast from Washington State up to Alaska correlating trends in temperature and precipitation patterns with trends in the net winter, summer, and annual mass balances of the different glaciers. They noticed the net winter and net annual mass balance anomalies of the southern maritime glaciers positively correlate with local precipitation anomalies and negatively correlate with local temperature anomalies. The net winter and annual balances of the Wolverine Glacier in coastal Alaska also showed the positive correlation with the local precipitation, but was also positively correlated with the local winter temperature. Thus the authors noted the Wolverine Glacier's mass balance variability is controlled by changes in the moisture advected into the region by anomalies in the wintertime circulation patterns of the North Pacific. As other studies have noted as well, the authors saw the seesaw pattern between the Pacific Northwest Glaciers and Alaskan coastal glaciers, controlled by the patterns of the wintertime 500-mb circulation patterns. When the net winter balance is high in the Alaska region glaciers, it is generally low in the Pacific Northwest glaciers, since the storms are either steered toward the Alaska coast or south toward the Pacific Northwest. They also discussed how a decadal ENSO-like climate phenomenon previously discussed by Zhang et al. (1997) affects these patterns, since this phenomenon exerts a strong control over the 500-mb wintertime circulation pattern. This was unlike the actual ENSO climate pattern which has a weak influence on moisture transport into this region due to its influence being more prominent further south in the Pacific.

Arendt et al. (2002) estimated volume changes in 67 glaciers in Alaska from the mid-1950s to the beginning of the 21st century using airborne laser altimetry, extrapolating this to all
Alaskan glaciers in order to estimate the contribution of Alaskan glaciers to sea level rise. The authors flew profiles along the centerlines of these glaciers and compared the data to topographic maps made from aerial photographs from the 1950s to 1970s, depending on the location. The authors calculated volume changes by applying the measured elevation change over an entire elevation band for each of seven study regions. These changes were then integrated over the original area-altitude distribution of the glacier. Glacier-wide average thickness changes were then found by dividing the total volume change by the average of the old and new areas. Changes in length and area were also computed by comparing the mapped termini to the measured. The authors found that almost all of the glaciers in their study had thinned, with drastic thinning seen on several glaciers. Rates of thickness change went from -0.7 meters per year from the mid-1950s to the mid-1990s, increasing to -1.8 meters per year from the mid-1990s to the early 2000s. They then extrapolated these rates to all of Alaska and determined that Alaskan glaciers were contributing 0.14 ± 0.04 mm water equivalent per year to sea level rise from the 1950s to mid-1990s and 0.27 ± 0.10 mm per year from the mid-1990s to early 2000s. This accounts for 9% of the observed sea level rise over the last 50 years and is the largest contribution of any glaciological source according to the authors.

Arendt et al. (2008) acquired more centerline surface elevation profiles of glaciers in the St. Elias Mountains of Alaska and northwestern Canada from 2000-2005 and then again in 2007, this time to validate mascon estimates of glacier mass change from the Gravity Recovery and Climate Experiment (GRACE) satellite. They first used repeat flights from 2007 to compare to the 2000-2005 data in order assess glacier change during that time period, giving a value of -21.2 ± 3.8 Gt yr⁻¹ over the time period. High-resolution regional GRACE mascon solutions for this time period were then scaled to the St. Elias glaciers, resulting in a mass change of -20.6 ± 3.0 Gt
yr\(^{-1}\). It was noted that the small difference between these two measurements was well within the estimated errors and showed that the GRACE mascon solutions could be used to assess glacier changes for mountain glacier regions.

In a companion study to the Arendt et al. (2008) study, Luthcke and others (2008) looked at glacier mass changes in the Gulf of Alaska region using GRACE mascon solutions. The Gulf of Alaska glacier region was divided into 12 mascon solutions and each one was independently analyzed for glacier mass change. As in other GRACE glacier mass change studies, models were used to remove impacts of atmosphere, ocean, tides, terrestrial water storage, and glacial isostatic adjustment in order to get the best estimate of only the mass change from the loss of glacier ice. All 12 of the Gulf of Alaska mascon solutions showed negative mass balances for the April 2003 – September 2007 time period studied. The total mass loss for the entire Gulf of Alaska region was \(-84.2 \pm 5.0\) Gt yr\(^{-1}\) with the largest mass losses being seen in the Yakutat and Glacier Bay regions.

Meier and Dyurgerov (2002) looked at the effects of Alaskan glaciers on the world, commenting on the above Arendt et al. (2002) study as well as some others, noting that these studies show that models underestimate the amount of ice mass that Alaskan glaciers are contributing to sea level rise. They discussed the fact that while Alaskan glaciers cover an estimated 90,000 km\(^2\) of land, and include some of the largest glaciers outside of the polar regions, there are only long-term mass balance time series on three relatively small glaciers in the region. As to questions of whether these three glaciers are representative of the entire region, they say that the error limits of studies such as the Arendt et al. (2002) study confirm that they are fairly representative of the region. Meier and Dyurgerov conclude that more studies of glacier mass balance using laser altimetry are needed, particularly in important areas such as
Alaska and where there are few other mass balance measurements, in order to better predict future sea level rise.

Motyka et al. (2002) looked at how thinning of Mendenhall Glacier during the twentieth century was related to climate, lake calving, and glacier run off. The authors measured mass balance on the glacier from 1997-2000 using the direct glaciological method. They placed 13 to 14 stakes in the glacier at intervals of 300 meters in order to cover the length of the glacier. They also dug snow pits near the divide of the glacier in the late summer of these same years and measured snow densities. ELAs were determined each fall using differential GPS, and accuracies of several meters were obtained. Ice velocities were determined for the spring and fall by measuring the positions of the mass balance stakes with differential GPS. Terminal positions of the glacier from the early 1900s were obtained from several earlier studies and aerial photos were used to obtain more recent positions. Since 1997, seasonal terminus positions have been obtained using differential GPS. In order to examine glacier thinning, centerline profiles of the surface of the glacier were constructed from maps and DEMs for early periods and then from airborne laser altimetry systems from 1995 to 2000. This technique was similar to what was done by Arendt et al. (2002). Volume changes and glacier-wide average changes in thickness were then computed for all years with complete elevation change coverage at all elevations. Long-term average mass balances were then computed from the volume changes, assuming that Sorge’s Law holds true at all elevations. Sorge’s Law states that density structure remains constant in an unchanging climate (Bader 1954). Some interesting results were found using these methods. The 2000 ELA was estimated to be 820 meters, whereas the 1998 and 1999 ELAs were 1250 and 1100 meters, respectively. There was exceptionally high accumulation at higher elevations in 2000, so this is not unexpected. The snow pack at the end of the melt season
in 2000 was measured in crevasses near the head of the glacier, ranging from 7.5 to 9.5 meters thick. Using a measured snow density of 600 kg/m³ gives an average of 5.1 meters water equivalent (w.e.). For 1998 this number was only 1.6 meters w.e., and while numbers were harder to come by for 1999, an estimate was made to be no less than 4.0 meters w.e. Ablation numbers, however, for the years 1998 and 2000 were similar, with approximately -12 meters w.e. for both years. The average mass balance for the entire glacier was +1.1 meters w.e. for 2000 and -1.5 meters w.e. for 1998, with estimates of the 1999 mass balance being somewhere in between the two and close to zero. While the mass balance fluctuated over these years, the glacier has continued to retreat, with the terminus retreating 3 km through the 20th century and the glacier thinning up to 200 meters at lower elevations since 1909 and up to 50 meters at higher elevations since 1948. Overall, the temperature and precipitation data matched well with the mass balance information, with the summer conditions being the dominant factors controlling the mass balance. This can be clearly seen in that the winter precipitation and temperatures were consistent through the 1998-2000 time period, while summer 2000 was much wetter and cooler, and thus had a positive mass balance. The authors concluded that their results matched closely with studies on other glaciers in the southeast Alaska region and that the Mendenhall Glacier is a good representative glacier in this region.

Rasmussen and Conway (2004) used a simple mass balance model driven by upper-air NCEP-NCAR reanalysis data to look at two glaciers in southern Alaska (Wolverine and Gulkana), one in western Canada (Place), and one in Washington (South Cascade). They argued that while sea level pressure and sea surface temperatures in the Pacific exert a strong influence on the climate of the Pacific coast, the temperature and moisture flux at 850 mb actually have a more direct influence on mass balance processes on the glaciers. Using a simple glacier mass
balance model of accumulation and ablation, with inputs from the 850 mb height fields of the reanalysis data, they proved that the temporal variability of upper air conditions matched the mass balance records of the glaciers in this region better than the seasonal averages of sea surface temperature.

Molnia (2007) looked at the behavior of Alaskan glaciers in 14 different regions from the late 19th until the early 21st century as indicators of changing regional climate. Looking at climate data from all over Alaska, temperatures have risen an average of around 2°C across the state since the mid-20th century. For this study, the author examined changes in glacier length and area for hundreds of glaciers in these regions using data from historical observations, maps, ground and aerial photographs, and satellite images. Ground photographs date back to 1883, aerial photos to 1926, and satellite photos and imagery date back to the early 1960s. The methods used to determine the glacier parameters depended on the type of image being used, but ultimately the author was looking at the terminus positions on the different images and supplementing this with field measurements extracted from other studies. The author found that all 14 glacierized regions of Alaska are characterized by significant glacier retreat and thinning, especially at lower elevations. All but a few glaciers that extend below 1500 meters are retreating and thinning, with the exception of tidewater, or recent tidewater glaciers, of which some are currently advancing and thickening. This is generally due to dynamics and not related to climatic effects. Some glaciers have completely disappeared in the 20th century and others that started retreating in the 18th century are still retreating today. In some cases, due to glaciers retreating up valleys and tributaries, the number of glaciers has actually increased as glaciers split into pieces, but the volume and area are still decreasing. Higher elevation glaciers are not being affected in the same way, and most are still showing very little change. The author
estimates that out of the approximately 700 named Alaskan glaciers, around 12 are currently advancing. According to Molnia, this general retreat and thinning of the lower elevation temperate glaciers is one of the most visible affects of Alaskan glaciers to changing regional climate.

Josberger et al. (2007) compared the 40 years of glacier mass balance records for the three United States Geological Survey (USGS) benchmark glaciers in the Pacific Northwest and Alaska, USA to climate records and discussed the controlling climatic conditions at regional and global scales. The Wolverine and Gulkana Glaciers in Alaska and the South Cascade Glacier in Washington are part of the USGS benchmark glacier monitoring program, which has monitored these three glaciers since the late 1950s for the South Cascade Glacier and the mid 1960s for the two Alaska glaciers. Both the South Cascade Glacier in Washington and the Wolverine Glacier in Alaska are maritime glaciers, so while they are separated by 2200 km, they have similar climates, receiving heavy snowfall in the winter and significant melting in the summer. Gulkana Glacier on the other hand is a continental glacier, farther inland from the moisture source of the Gulf of Alaska. It receives less moisture in the winter, but also generally experiences less melting in the summer. The authors found that the net balance of all three of these glaciers showed different and distinct long term phases. The South Cascade Glacier was found to have four distinct periods, with 1959-1970 having a net loss of 4.6 m w.e. The period from 1970-76 had a positive mass gain of 2.9 m w.e., the only positive period of the entire record. 1977-95 was a long period of mass loss, with a total loss of 16.5 m w.e. and then 1995-2004 was negative overall, but had some positive years mixed in. Other glaciers in the North Cascade Range showed similar balance losses during the time period. Wolverine Glacier was found by the authors to have three distinct periods. From 1966-76 the negative mass balance trend led to a
total mass loss of 7.1 m w.e. Then from 1976-88 Wolverine gained 5.9 m w.e., although it was not a uniform gain throughout that time period. According to the authors this gain was the result of several years of large positive balances. Since 1988 Wolverine Glacier has been losing mass, with a total loss from 1988-2004 of 14.4 m w.e. Gulkana Glacier also showed three different trends, with the first one from 1966-73 showing almost no change in balance. 1974-85 had a total mass loss of 2.9 m w.e. and then from 1985-2004 Gulkana went much more negative losing an additional 12.8 m w.e. during that time period. The authors compared the mass balance trends of these three glaciers and showed that early in the records they all seemed to behave differently. Then starting in 1977, South Cascade Glacier began losing mass consistently and Wolverine and Gulkana followed suit in 1989, all continuing through 2004. The authors then compared the mass balance records to climate records and the PDO climate index in order to understand how the climate patterns in the North Pacific affect these glaciers. They noticed a strong correlation between the PDO and the maritime glaciers, as one would expect, although the correlation with the PDO and the Wolverine Glacier had weakened in the later years. The Gulkana Glacier did not correlate well with the PDO due to its continental location.

Berthier et al. (2010) used satellite imagery to estimate the contribution of Alaskan glaciers to sea-level rise. They estimate that from 1962 to 2006 Alaskan glaciers lost 41.9 ± 8.6 km³ yr⁻¹ of water and contributed 0.12 ± 0.02 mm yr⁻¹ to sea-level rise. These numbers are up to 34% lower than previous estimates and they reason that many of the previous studies did not have the high spatial resolution of their glacier inventory. Many earlier studies use site specific measurements and then extrapolate to neighboring glaciers and even entire regions. This can lead to large errors, especially in Alaska where the topography is so varied and changes rapidly. The authors compare DEMs created from earlier topographic maps and recent satellite imagery
in order to come up with a much higher spatial resolution than many earlier studies. They also use ICESat altimetry data to adjust the systematic errors in the DEMs and make them more comparable. All of this allows them to get greater coverage over the glacier areas, leaving only 27% of the glacier area in Alaska unmeasured in this study. The 27% unmeasured area was then estimated by integrating the measured elevation changes over the altitude distribution of the unmeasured area for each mountain range. Many previous studies had up to 80% of the glacier areas unmeasured and then extrapolated from the measured area, leaving large unknowns and possible errors. This gives the authors more confidence in their results and they suggest this technique could be used in other mountain regions to revise earlier estimates using large amounts of extrapolation as well.

**PTAA Model Studies**

Zhang et al. (2007) describe a climate/glacier modeling system they developed to estimate the mass balance of glaciers in Alaska, both present and future, in order to estimate their potential contributions to sea level rise. They downscale data from a regional atmospheric model, which is driven by global NCEP/NCAR atmospheric reanalysis data, in order to force their model. The model is a precipitation-temperature-area-altitude (PTAA) glacier mass balance model with daily maximum and minimum temperature and precipitation data. The ultimate goal of the model is to assess how changes in climate will affect the mass balance of glaciers. They validate the model by hindcasting the mass balances of Gulkana Glacier in Alaska, which is measured as part of the USGS benchmark glacier monitoring program. They did the hindcasting for a ten-year period from October 1994 to September 2004. Using the NCAR Arctic MM5 model, the authors downscale daily minimum and maximum temperature and precipitation data and then interpolate it to the locations of the weather stations within their
glacierized region. These data are then used to force the PTAA model into simulating the mass balance of the Gulkana Glacier. The forced mass balances are then compared to the actual mass balances obtained from the USGS measurements over the ten-year period. The average mass balance over the ten year hindcasting period from their model was $-0.86 \pm 1.04$ meters per year w.e., which matched quite closely with the actual measurements from the USGS of $-0.88 \pm 0.70$ m per year w.e. These results suggest this is a promising approach for estimating future mass balance of glaciers and their corresponding sea level rise.

Bhatt et al. (2007) dynamically downscaled temperature and precipitation data from the Arctic mesoscale model (MM5) in order to drive the PTAA model for the mass balance of the Bering and Hubbard glaciers in south-central Alaska. They compared the projected mass balances versus elevation for these two glaciers with the hind cast balances, which were forced by the MM5 model downscalings and projected that accumulation would increase on the higher elevations of both of these glaciers. The future balance projections covered the time period of October 2010 to September 2018, and it was determined that the increase was mainly due to increased precipitation during the winter under the A1B climate scenario. For lower altitudes on the glaciers, their model runs projected ablation of about $-5$ m/yr water equivalent (w.e.) at the terminus of the Hubbard Glacier and $-10.5$ m/yr w.e. at the terminus of the Bering Glacier. These values decreased to about zero on the upper reaches of the Hubbard Glacier and at about 4,000 meters on the Bering. The hind cast from the PTAA model and the MM5 downscaled precipitation and temperature data was run for the period 1 October 1994 to 30 September 2004. For the Bering Glacier, the mean annual balance for this hind cast was $-1.3$ m/yr w.e., whereas the future projection had a value of $-2.0$ m/yr w.e., giving a slight increase in melting over the
next 8 years or so. The Hubbard glacier had values of 0.4 m/yr w.e. for the hindcast and 0.3 m/yr w.e. for the future projection showing not as much change as the Bering Glacier.

**General Glacier Mass Balance Methods**

Braithwaite and Zhang (1999) use a degree-day model to calculate mass balance on 37 glaciers in different parts of the world, giving results for Storglaciären to illustrate their approach. While discussing that the future of improved glacier mass balance models for single glaciers lies in energy balance modeling, the authors conclude there are still many problems to solve in this field. Thus they prefer to use the degree-day model for its ease of use to conduct a large-scale assessment of the sensitivity of glacier mass balance to climate change involving glaciers in many different parts of the world. The degree-day model determines the annual accumulation of snow, the annual melt, and the annual refreezing of water at each given elevation. This is done by calculating accumulation and melt from precipitation and temperature records, using specific assumptions. Accumulation is calculated from precipitation records by taking into account the probability of below-freezing temperatures, while melt is assumed to be proportional to the positive degree-day sum that is calculated from mean temperatures. Refreezing is estimated for sub-polar glaciers by the assumption that all annual melt is refrozen within the snow cover up to a fraction of the annual accumulation of 0.58. This fraction is used in this study, assuming snow density changes from 375 to 890 kg m\(^{-3}\) before runoff can occur, and was derived from an earlier study (Braithwaite et al., 1994). The temperature and precipitation data are extrapolated to each altitude on the glacier from either a nearby weather station or from gridded climate data. The model can be tuned to each glacier until the results consistently agree with field data. The authors have used this degree-day modeling approach on 37 glaciers, but for this study focus on the results for Storglaciären. They choose not to treat
Storglaciären as a sub-polar glacier and so they leave out the meltwater refreezing parameter for these model runs. They compare 30 years of data (1961-1990) of measured values on the glacier and the modeled results and they have near perfect agreement. The net balance they calculate from the degree-day model is -0.13 m w a⁻¹, while the observed over the time period is -0.12 m w a⁻¹. The authors then use a sensitivity analysis to project how the glacier will change with various degrees of climate warming and precipitation changes, giving an estimated static sensitivity of the mass balance of Storglaciären of about -0.64 m water a⁻¹ deg⁻¹.

Rupper and Roe (2008) developed a full surface energy and mass balance model to look at the relationship between glacier equilibrium-line altitudes (ELA) and climate at a regional scale over central Asia. They had two main questions to address through their modeling: Can the relative importance of accumulation and ablation in controlling the mass balance of glaciers be understood at a regional scale, and how observed patterns of glacier response reflect regional climate changes. The authors discuss how the ELA is directly related to climate, so the main goal of their model is to understand how the ELA changes in response to climate changes. There are two nested balance algorithms in their model, a surface energy balance and a mass balance, and by definition the ELA is the elevation where these two balances both apply. They use NCEP-NCAR reanalysis data as the inputs to the model, and the general pattern of the ELAs are modeled reasonably well. The authors noted that due to the use of the surface energy balance approach, they were able to look at the importance of sublimation and melt in the ablation process. They found that where precipitation was low, ablation at the ELA was dominated by sublimation, while high precipitation caused ablation at the ELA to be dominated by melt and surface runoff. Thus, the authors concluded the ELA sensitivity to changes in climate is strongly tied to the dominant ablation process.
Cogley (2009) compared the geodetic and direct glacier mass balance measurement methods and then compiled the available data to create an updated estimate of average global mass balance of ‘small’ glaciers. While direct measurements of glacier mass balance are few and far between, especially for multiple years on the same glacier, geodetic measurements are more prevalent. So the goal of Cogley’s work is to use all available data to create the best guess for an updated global average mass balance. The problem, however, is that there is a time mismatch between these two types of measurements as direct measurements are generally annual, while geodetic measurements are almost all multi-annual. So Cogley develops a new method to standardize these measurements to be comparable. After going through several statistical methods to allow comparisons of these data, Cogley now estimates the small-glacier contribution to sea-level rise as $1.12 \pm 0.14 \text{ mm a}^{-1} \text{ SLE}$ (sea level equivalent) for 2001-05. This number is higher than other estimates and excludes Greenland and Antarctic glaciers.
CHAPTER III

THE PTAA MODEL

The PTAA (Precipitation-Temperature-Area-Altitude) model is a glacier mass balance model developed to use low-altitude meteorological observation data, mainly temperature and precipitation, along with the area-altitude profile of a glacier in order to estimate glacier mass balance and associated variables. The traditional field methods associated with measuring glacier parameters are expensive and labor intensive, so this model attempts to alleviate some of this required work and expenditure. The model takes temperature and precipitation observations from nearby weather stations on a daily basis, and through a series of formulas, outputs daily values for glacier mass balance, snowline and zero balance altitude (ZBA), and accumulation area ratio (AAR). The use of low-altitude meteorological data compared to using data from on or near the glacier is important, as precipitation gauges in open, high altitude areas tend to significantly under catch precipitation (Barry, 1992), which would lead to erroneous results. One of the most important aspects of the model is the use of the area-altitude (AA) profile of the
glacier. Every glacier has its own unique AA profile, which is a direct representation of the erosional history of the glacier. It is then reasoned that combining the weather observations (which represent the climate) and the AA profile (representing the erosion) will give the needed information to accurately calculate the mass balance of a given glacier. The PTAA model accomplishes this objective using the available meteorological data and a glacier’s unique AA profile as input, giving glacier mass balance and associated variables as output.

The PTAA model uses inputs of daily temperature and precipitation from low-altitude weather stations nearby the glacier to be modeled. The closeness of the weather stations that work best can depend on many factors and it can be a tedious process to find the stations that work best. The best way to do this involves running the model in calibration mode many different times with different combinations of nearby weather stations. The combination of weather stations that produces the lowest values of the calibration error (ERRPC) in the model output is then chosen to run the model in normal mode. This is then done in order to lower the value of ERRPC to the lowest value possible, and then the model is run in the final mode to produce the yearly mass balance results. The other input for the model is the area altitude (AA) profile of the individual glacier. The area altitude profile contains the amount of area within the glacier’s boundary for each given altitude increment. The profiles are usually in 30 m altitude increments, but can vary depending on the maps that were used to produce the specific AA profile. The profile reflects the interaction of the regional climate with the bedrock on which the glacier lies. Over time the erosion produced by the movement of the glacier carves a distinctive bed into the underlying rock, leaving this signature in the AA profile (Tangborn, 1999).
Algorithms

There are eight algorithms used in the PTAA model that convert the daily temperature and precipitation data, along with the AA distribution into the daily mass balance results. There are also fifteen empirically derived coefficients used in these algorithms. In order to convert the daily precipitation from the low-altitude weather stations to the height of the glacier, four coefficients are used in 3 different algorithms. First, the precipitation in meters per day, for each altitude band is determined using the following formula:

\[ P(i, z)_{\text{glacier}} = \beta(z) p(i)_{\text{gage}} \]

where \( P(i, z)_{\text{glacier}} \) is the precipitation in m/day at the glacier on day \( i \) and at altitude \( z \). \( \beta(z) \) is a multiplier determined by calibration and \( p(i)_{\text{gage}} \) is the observed precipitation (in m/day) at a low-altitude weather station on day \( i \).

Then the following formula is used to convert the gage precipitation to high altitude precipitation using 3 calibration coefficients:

\[ \beta(z) = (C_1 - C_2) \left( E_t(z) / C_3 \right) + C_2 \]

where \( E_t(z) \) is the vertical distance above glacier terminus (m) and \( C_1, C_2, \) and \( C_3 \) are a precipitation multiplier at maximum altitude, precipitation multiplier at the terminus, and the altitude of maximum precipitation (x 100), respectively.

Four coefficients are then used in an algorithm to determine the daily lapse rate, which is calculated on the basis of four general conditions: cloudy/cool (mean temperature is below normal for the day); cloudy/warm (mean temperature above normal); clear skies/cool; and clear
skies/warm (Tangborn, 1999). Cloudiness can be estimated from the daily temperature range, with a small daily temperature range generally indicating cloudy conditions. The mean temperature deviation is found by subtracting the daily mean from the normal mean for that day. It can be seen in the formulae for the daily lapse rate that these are simple linear equations in the form of \( y = mx + b \), where the \( C_5 \) and \( C_7 \) coefficients are the slope of the lapse rate and the \( C_6 \) and \( C_8 \) coefficients are the intercept values:

\[
L_r(i) = C_5(D_r(i) + C_6)
\]

(For days where mean temperature is above normal)

\[
L_r(i) = C_7(D_r(i) + C_8)
\]

(For days where mean temperature is below normal)

where \( L_r(i) \) is the lapse rate (in °C/100 m) on day \( i \), and \( D_r(i) \) is the temperature range (in °C) on day \( i \).

Next, four coefficients are used to calculate ablation on the glacier, using both mean daily temperatures and the diurnal temperature range. The next two equations use the mean temperature applied as a turbulent heat transfer index, depending on whether there is precipitation for that day or not, in order to determine ablation (Tangborn, 1999):

\[
A_w(i, z) = C_9(T_w(i, z))
\]

\[
A_p(i, z) = C_{10}(T_p(i, z))P_r(i, z)
\]
where $A_n(i,z)$ is the ice ablation rate on days without precipitation (m/day) on day $i$ and altitude $z$, $C_9$ is an ablation from temperature without precipitation coefficient, $A_p(i,z)$ is the ice ablation rate on days with precipitation (m/day) on day $i$ and altitude $z$, $C_{10}$ is the ablation from temperature with precipitation coefficient, $T_b(i,z)$ is the mean temperature (°C) on day $i$ at altitude $z$, and $P_r(i,z)$ is the precipitation as rain (m/day) on day $i$ and at altitude $z$. It is assumed to be rain since the data refer to the ablation zone.

Another part of the ablation process of the model is the short-wave ablation factor, which is calculated from the daily temperature range and can be assumed to be a rough measure of cloudiness or solar radiation depending on the temperature range. A large temperature range would coincide with a clear, sunny day, while a smaller temperature range would represent a cloudy day with limited solar radiation available for ablation (Tangborn et al, 1991, Tangborn, 1994):

$$A_r(i, z) = C_{11}(D_t(i))(CF(z))$$

where $A_r(i,z)$ is the ablation rate (m/day) on day $i$ and altitude $z$, $C_{11}$ is a temperature threshold coefficient, $D_t(i)$ is the diurnal temperature range (°C) on day $i$, and $CF(z)$ is the ice ablation factor, which is calculated using the following formula:

$$CF(z) = C_{12}(1 - E(z) / S_1)$$

where $C_{12}$ is an ablation from solar radiation coefficient, $E(z)$ is the altitude at interval $z$ (m), and $S_1$ is the snowline altitude (m).

If $CF(z)$ is less than zero, it is set equal to zero, since there is generally no ablation above the snowline. So this is applied only below the snowline and it decreases with altitude (Tangborn,
It is also assumed that solar radiation is not a significant ablation factor for highly reflective snow, but it is important with lower albedo ice, leaving the total ablation each day to be simply the sum of either $A_n$ or $A_p$ and $A_r$ (Tangborn, 1999).

The next set of algorithms deal with snow accumulation on the glacier and the snowline altitude. The model looks at each altitude interval and simply says that if the simulated temperature for that interval is less than or equal to 0°C then the precipitation is falling as snow and of the temperature for the interval is greater than 0°C, then the precipitation is rain. Internal accumulation has not always been a part of the PTAA model, but has been added for glaciers such as those in Alaska, as it can be quite important in this region. The internal accumulation algorithm first calculates the internal temperature of the snowpack at each altitude interval, and if this index is below zero, while the simulated air temperature is above zero then any snowmelt and rain is retained in the snowpack as accumulation. The index is increased whenever water from rain or snowmelt is introduced into the snowpack as it releases latent heat. The index eventually reaches zero as more meltwater and rain are added. Once it reaches zero, the meltwater and rain percolate through the snowpack and occur as runoff, not accumulating in it any further (W. Tangborn, personal communication, October 1, 2008).

The snowline altitude is controlled by the freezing level altitude along with the ablation rate of snow. If the freezing level is found to be within an altitude increment on the glacier during a storm, then the snowline is set to that altitude. During the spring and summer months, the snowline rises up the glacier with higher temperatures and exposes darker, low-albedo ice, helping to increase ablation rates. Summer snowstorms can have the opposite effect, dropping fresh snow and increasing the albedo, hence lowering the snowline. This fresh snow from summer storms usually melts quickly, with the snowline rising rapidly back up the glacier.
(Tangborn, 1999). This snowline can be called the seasonal snowline, while the lowest it reaches for the summer season is deemed the transient snowline. Each one of these snowlines is represented by a formula in the model:

\[ DS_s = C_{13} \Delta A \]
\[ DS_T = C_{14} \Delta A \]

where \( DS_s \) is the seasonal snowline altitude increase in meters and \( DS_T \) is the transient snowline altitude increase in meters. \( C_{13} \) is the coefficient that controls the rate that the seasonal snowline rises, while \( C_{14} \) does the same for the transient snowline (Tangborn, 1999). The following formula is for \( \Delta A_{sm} \):

\[ \Delta A_{sm} = \sum(A_n + A_p) \]

which just represents the ablation summed from the snowline to the glacier head.

Once the above algorithms have been used, the next step the model takes is to begin to calculate the balances, calculating daily snow accumulation and ablation for each altitude interval. Each altitude intervals’ balance is calculated independently, and then they are integrated to come up with the total balance for the glacier. To get the balance for each interval:

\[ b(z, i) = c(z, i) + a(z, i) \]

where \( b(z, i) \) is the balance at interval \( z \) on day \( i \), \( c(z, i) \) is the snow accumulation at altitude interval \( z \) on day \( i \) and \( a(z, i) \) is the ablation for the same and treated as a negative (Tangborn, 1999). The sum of the balance for each interval is then determined to obtain the balance for the total glacier:
where \( B(i) \) is the balance of the glacier on day \( i \), and \( a_a(z) \) is the fraction of total surface area of the glacier in each altitude interval (Tangborn, 1999).

The zero balance altitude (ZBA) is the next parameter that the model calculates, which is simply where the accumulation and ablation are equal and cancel each other out:

\[
ZBA(i) = \frac{(E(i, z) - b(i, z))}{(b(i, z) - b(i, z-1))(E(i, z) - E(i, z-1))}
\]

where \( ZBA(i) \) is the zero balance altitude on day \( i \), \( E(i, z) \) is the altitude at interval \( z \), \( b(i, z) \) is the balance at interval \( z \) and must be positive, \( b(i, z-1) \) is the balance at interval \( z-1 \) and it is negative, and \( E(i, z-1) \) is the altitude at the interval \( z-1 \) (Tangborn, 1999).

The accumulation area ratio (AAR) is the fraction of area above the ZBA to the total glacier area, and it is calculated daily in the model from the first day ice becomes exposed at the terminus:

\[
AAR(i) = \sum_{z=n}^{z=h} a_a(z)
\]

where \( AAR(i) \) is the accumulation area on day \( i \), and the formula is summing the fraction of total glacier area at each altitude interval \( a_a(z) \), from the zero balance altitude on day \( n \) to the head of the glacier, \( h \) (Tangborn, 1999).

Glacier mass moves down the glacier to lower altitudes, eroding the bedrock below it and giving the glacier its unique area altitude distribution. As this flux of mass occurs across the ZBA, it is effectively relating erosion and mass balance since it helps determine where the mass balance is positive, negative, or zero (Tangborn, 1999). For each day during the ablation season, the model calculates this balance flux as:
\[ E_{xm}(i) = V_c(i) - V_a(i) \]

where the flux on day \( i \), \( E_{xm} \) is equal to the volume above the ZBA, \( V_c(i) \) minus the volume below the ZBA, \( V_a(i) \).

\( V_a(i) \) and \( V_c(i) \) are calculated using the following formulae:

\[ V_a(i) = \sum_{z=1}^{z_{max}} aa(z) b(i, z) \]

\[ V_c(i) = \sum_{z_{min}}^{z_{max}} aa(z) b(i, z) \]

where \( V_a(i) \) is the volume of glacier ice below the ZBA (m.w.e), and it is a negative value, \( aa(z) \) is the fraction of total glacier area at the altitude interval \( z \), and \( b(i, z) \) is the balance on day \( i \) and at altitude interval \( z \). \( V_c(i) \) is the volume of glacier ice above the ZBA (Tangborn, 1999)

**Calibration**

Optimum values of the fifteen coefficients are found through a simplex optimization process in order to begin the model calibration. The simplex optimization process is a mathematical approach to minimizing or maximizing a linear function with multiple variables (Nelder and Mead, 1965). Starting values for all fifteen coefficients are first chosen, not by tuning the model or from field data, but intuitively. In the case where nearby glaciers have been modeled using the PTAA, one can start with the final coefficients from those model runs, otherwise some educated guesses can be made to determine the proper starting values for the coefficients. This can be a long process, running the model once and changing each coefficient one at a time until the optimization is minimized by obtaining the lowest value for \( 1-r^2 \), the
regression error of the complement of \( r^2 \). Nineteen linear regressions are run for each day of the ablation season, which varies from year to year, but if we assume the ablation season runs from June 1 and ends September 30 (121 days), then there would be a total of 2,299 regressions (121 days \( \times \) 19 regression pairs). The nineteen linear regressions are listed in Table 1. Once this is complete and the lowest value of 1-\( r^2 \) is obtained, the model has been calibrated and it can then be run to obtain the final mass balance results.

<table>
<thead>
<tr>
<th>Number</th>
<th>The nineteen regression pairs run to optimize the coefficients.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Net Balance vs. Zero Balance Altitude</td>
</tr>
<tr>
<td>2</td>
<td>Net Balance vs. Snowline Altitude</td>
</tr>
<tr>
<td>3</td>
<td>Mass Flux vs. Accumulation Area Ratio</td>
</tr>
<tr>
<td>4</td>
<td>Net Balance vs. Accumulation Balance</td>
</tr>
<tr>
<td>5</td>
<td>Maximum Balance vs. Zero Balance Altitude</td>
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<tr>
<td>6</td>
<td>Maximum Balance vs. Snowline Altitude</td>
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<tr>
<td>7</td>
<td>Maximum Balance vs. Accumulation Area Ratio</td>
</tr>
<tr>
<td>8</td>
<td>Accumulation Area Ratio vs. Zero Balance Altitude</td>
</tr>
<tr>
<td>9</td>
<td>Minimum Balance vs. Snowline Altitude</td>
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<td>10</td>
<td>Minimum Balance vs. Zero Balance Altitude</td>
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<tr>
<td>11</td>
<td>Minimum Balance vs. Accumulation Area Ratio</td>
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<tr>
<td>12</td>
<td>Minimum Balance vs. Mass Flux</td>
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<tr>
<td>13</td>
<td>Snowline Altitude vs. Zero Balance Altitude</td>
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<tr>
<td>14</td>
<td>Zero Balance Altitude vs. Accumulation Area Ratio</td>
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<tr>
<td>15</td>
<td>Zero Balance Altitude vs. Mass Flux</td>
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<tr>
<td>16</td>
<td>Snowline Altitude vs. Accumulation Area Ratio</td>
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<tr>
<td>17</td>
<td>Snowline Altitude vs. Mass Flux</td>
</tr>
<tr>
<td>18</td>
<td>Accumulation Area Ratio vs. Mass Flux</td>
</tr>
<tr>
<td>19</td>
<td>Zero Balance Altitude vs. Snowline Altitude</td>
</tr>
</tbody>
</table>

Table 1. The nineteen regression pairs used to optimize the coefficients in the PTAA model.
CHAPTER IV
DISCUSSION AND RESULTS

Wrangell Mountains

For this research, the glaciers of the Wrangells were divided into two regions based on the north and south orientations of the glaciers. These regions are almost identical in size, 2418 km$^2$ for the northern and 2307 km$^2$ for the southern, totaling about 4725 km$^2$ of glacierized region. The area-altitude distributions of these two regions were determined in ArcGIS from DEMs and divided into 30.5 m elevation intervals. Figure 4 shows the area-altitude distribution of the northern Wrangell region and Figure 5 shows the southern area-altitude distribution. As can be seen from these graphs, the North and South Wrangell regions have similar area-altitude distributions, with the bulk of the area in both regions falling between about 1600 meters and 3200 meters. The South Wrangell region does extend lower down in elevation, reaching below 500 meters, while the North region just barely reaches below 900 meters. Both regions extend up to almost 5000 meters in elevation.
Figure 4. Area-altitude distribution of the Northern Wrangell Glaciers
Figure 5. Area-altitude distribution of the Southern Wrangell glaciers.

Temperature and precipitation data to model both the North and South Wrangell glaciers came from the McKinley Park and Big Delta weather stations. These stations are both approximately 350 km from Mt. Wrangell, which lies generally in the middle of the Wrangells. The McKinley Park weather station has an elevation of 631 m and the Big Delta station is at 387 m. There are closer weather stations to the Wrangell Mountains, but no combination of them produced a lower ERRPC, the optimization function, than the two chosen stations. McKinley Park and Big Delta were also the stations that produced the lowest ERRPC for an earlier model run on the Gulkana Glacier, which is located farther north in the Alaska Range (Zhang et al., 2007). Therefore, to start the calibration of the model for the North and South Wrangell Mountain regions the final coefficients from the Gulkana glacier were used. The simplex
optimization process then produced new coefficients for each of the north and south glacierized regions (Tables 2 and 3).

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**Table 2. North Wrangell Final Coefficient Values**

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<td>TEMP. SNOWLINE RISE MULTIPLIER</td>
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<td>0.8375621438026428</td>
<td>CFF15</td>
<td>INTERNAL ACCUMULATION MULTIPLIER</td>
</tr>
</tbody>
</table>

**Table 3. South Wrangell Final Coefficient Values**
The simplex optimization function, ERRPC, consisted of approximately 2700 linear regressions (19 regressions x ~140 days) for each of the north and south glacierized regions for the Wrangells, for each model iteration. This was run until the lowest value of ERRPC was obtained and can be seen in Figure 6 (North Wrangells) and Figure 7 (South Wrangells).

Figure 6. Calibration error (ERRPC) versus iteration for the North Wrangell Range. The first 15 errors are determined by the pre-set coefficients.
Figure 7. Calibration error (ERRPC) versus iteration of the South Wrangell Range. The first 15 errors are determined by the pre-set coefficients.

It should be noted that once the fifteen preset coefficients are applied, the remaining errors are derived solely from the simplex optimization process. The high final values seen for these two regions (over 40%) should not be seen as significant and are not related to the accuracy of the balance results. These values are merely a result of the simplex optimization process, which is an average of all of the regressions used to relate the balance parameters. Some of these relationships between the balance variables are weak, so they produce rather high r-squared values, but it has been shown in previous work that these relationships, while weak, are still important in producing accurate mass balances. So since the ERRPC is an average of all of these results, it can have a relatively high value, but has still been minimized through the simplex optimization process (W. Tangborn, personal communication, June 10, 2010).
Mass Balance Results for North and South Wrangells

The mean annual balance produced by the PTAA model for the period 1950-2006 for the North Wrangell Glaciers is -0.23 m.w.e and for the South Wrangells it is -0.66 m.w.e. Figures 8 and 9 show the final balances for north and south respectively, versus the calibration error, as they are determined once the lowest calibration error is reached.

Figure 8. The mean annual balance of the North Wrangell glaciers, determined for the 1950-2006 period, versus the calibration error for each iteration. The minimum error is reached when the mean balance is –0.23 MWE.
**Figure 9.** The mean annual balance of the South Wrangell glaciers, determined for the 1950-2006 period, versus the calibration error for each iteration. The minimum error is reached when the mean balance is $-0.66$ MWE.

Once the mean annual balance has been calculated, the final coefficients are run through the model again to determine the annual balances for each year of the time period, 1950-2006 (Figure 10).
It can clearly be seen from the annual balances that both the North and South Wrangell glaciers are affected by similar climatic conditions and have similar annual patterns, although the South Wrangell balances have two to three times the ablation as their northern counterparts. This is an interesting pattern, as the PTAA model has no information about the orientation of the glaciers, and one would expect the south facing glaciers to have more ablation due to the angle of the sun at this latitude. It can be reasoned then that the model senses the orientation of the glaciers from the AA profiles, especially since both the north and south glacier regions use the same weather stations as inputs.

Since there are not a lot of actual mass balance measurements in the Wrangell Mountains, the PTAA model was also run individually on the Nabesna Glacier to represent the north Wrangells and the Kennicott Glacier to represent the South Wrangells. This was done to
compare these data to aircraft laser altimetry data collected by the University of Alaska, Fairbanks (Arendt et al., 2002). These model runs also used the McKinley Park and Big Delta weather stations for the temperature and precipitation data inputs. The Nabesna Glacier PTAA model run covered the time period 1957-2008 and had a total thickness change of -33 meters of ice, or -0.57 m/yr for the 52 year period (Figure 11).

![Nabesna Glacier Annual Balance](image)

**Figure 11.** Annual Balances of the Nabesna Glacier as determined by the PTAA model for the time period 1957-2008.

While this result does not match too well with the -0.17 m/yr reported in Arendt et al. (2002) for the Nabesna Glacier, covering the time period 1957-2000, it does match closely with the -0.52 m/yr they reported for the average rate of thickness change for all 67 Alaskan glaciers they measured for the time period. It should also be noted that the -0.17 m/yr value reported by Arendt et al. (2002) for the Nabesna Glacier contains quite a few errors, as many areas of the
glacier were unreachable and so extrapolation was used to estimate the whole glacier (S. Zirnheld, personal communication, March 12, 2010). The single glacier PTAA model runs for the Nabsena and Kennicott Glaciers show the same patterns as the full area model runs, with the south oriented Kennicott Glacier’s mean annual mass balance (-0.96 m.w.e) (Figure 12) being some 40% greater than that for the north facing Nabesna Glacier (-0.57 m.w.e).

![Kerrickott Glacier Annual Balance](image)

**Figure 12.** Annual Balances of the Kennicott Glacier as determined by the PTAA model for the time period 1957-2008.

This again seems to agree well with theory that south facing glaciers, due to their higher sun exposure, have higher ablation than north facing glaciers. This is especially true using the PTAA model since the same weather stations are being used as input, so no bias based on precipitation or temperature differences between the glaciers would be assumed.
Wolverine Glacier

The Wolverine Glacier is located on the Kenai Peninsula in South-Central Alaska, in the northernmost of the ice fields in the Kenai Mountains (Molnia, 2008). The Wolverine Glacier has been monitored since 1966 as part of the USGS long-term glacier monitoring program, along with the Gulkana Glacier in Alaska and the South Cascade Glacier in Washington State (Molnia, 2008). This makes the Wolverine ideal for testing the PTAA model since there is a stable long-term record of mass balance measurements to compare to the model data. According to previous research, the Wolverine was stable in mass balance from 1966 to 1976, and then from 1977 to 1982 it increased in thickness, as measured at several sites, by more than 8 meters (Mayo and Trabant, 1984). After that time, it thinned by more than 20 meters, in these same locations.

A climate station does exist on the Wolverine glacier, located at an elevation of 990 meters along the western boundary of the basin on the crest of a tundra-covered glacial moraine (Molnia, 2008). This location is slightly lower than the average ELA of the glacier and about 500 meters from the western edge of the glacier. The average annual air temperature at this station is about -1°C, and the average annual precipitation collected in the gage is approximately 1,100 mm. The dominant form of precipitation is snow, which generally falls from September to mid-June (Kennedy, 1995).

The Wolverine Glacier has a total area of approximately 18 km². The area-altitude distribution of the glacier was determined in ArcGIS from a DEM and divided into 30.5 m elevation intervals. Figure 13 shows the area-altitude distribution of the Wolverine Glacier.
The PTAA model was run for the Wolverine Glacier for the time period 1966 to 2004 to match the available USGS measurements. Many different regional weather stations were tested to see which ones produced the lowest calibration errors, and in the end the Seward weather station was chosen both for precipitation and temperature data. This station is located approximately 56 km from the Wolverine Glacier at an altitude of 38 m.

**Mass Balance Results for Wolverine Glacier**

The mean annual balance produced by the PTAA model for the Wolverine Glacier for the time period 1966-2004 was -0.38 m.w.e. Once this value was determined using the final coefficients produced by the model, the model was run again to produce the annual balances for the Wolverine Glacier. Figure 14 shows the annual balances for the 1966-2004 time period.
Figure 14. Annual mass balance of the Wolverine Glacier for the time period 1966-2004 as modeled through the PTAA model.

These results show that the mass balance has been mostly negative for the entire 39 year time period. There are, however, some positive years that begin around 1977-1978 that do match well with data from previous studies which show thickness increases during this time (Mayo and Trabant, 1984, Hodge et al., 1998, Bitz and Battisti, 1999). The cumulative mass balance over this entire time period was modeled to be -14.97 m.w.e.

These results were then compared to the measurements taken by the USGS for the Wolverine Glacier monitoring program and agree quite well. The mean annual mass balance for the Wolverine Glacier from the USGS measurements for the 1966 -2004 time period was -0.37
m.w.e and the cumulative mass balance over the time period was -14.36 m.w.e. Figure 15 graphically shows how the modeled and measured annual mass balances compare.

**Figure 15.** USGS measured balance compared to the PTAA modeled balance for the 1966-2004 time period.

Comparing these two balances graphically one can see they track reasonably well, with the USGS measurements generally having a larger magnitude positive or negative mass balance than the PTAA model mass balances. But as mentioned previously, the mean annual balances are remarkably similar (-0.37 m.w.e for the USGS vs. -0.38 m.w.e for the PTAA model). The
correlation coefficient (r-value) for the USGS measured versus the PTAA modeled annual mass balances is 0.67, which is statistically significant at the 95% level.

Comparing the cumulative balances we see similar results (Figure 16).

*Figure 16.* Comparison of the cumulative mass balance between the USGS measurements and PTAA model for the 1966-2004 time period.

Again we see the cumulative results have very similar trends, with the USGS measurements having larger magnitude changes during several years, obviously corresponding to the same years when the measured mass balances were substantially different than the modeled balances. But, as mentioned previously, the cumulative results are quite close as well (-14.36 m.w.e for the USGS measurements vs. -14.97 m.w.e. for the PTAA model).
Overall, the results for the Wolverine Glacier PTAA model runs are very encouraging and seem to produce realistic mass balance results that compare quite well to actual measurements taken by the USGS for the benchmark glacier monitoring program.
Climate is the most important driver of the mass balance of a glacier. Solid precipitation inputs to the glacier help increase the mass balance, while temperature aids in either keeping the accumulated precipitation or in inducing melt on the glacier surface. Solid precipitation inputs can include snowfall and both avalanche and wind deposited snow on the glacier. If we get more solid precipitation accumulated on the glacier than melt, then the mass balance is positive and the glacier grows. If less precipitation is received than melt, then the mass balance is negative and the glacier loses mass. As the climate warms, glaciers have become key indicators of climate change due to this direct relationship between climate and glacier mass balance. Therefore, it is important to understand the relationship between a glacier, or glacier system, and the regional climate that is controlling its mass balance. This next section will focus on correlations between the mass balances modeled through the PTAA model for the Wrangells and Wolverine Glacier, along with the Wolverine Glacier data from the USGS benchmark program and the regional
climate. The main regional climate factors that will be used are temperature and precipitation from weather stations located very near to these glaciers. The Wolverine Glacier has a weather station located on the glacier, at an altitude of 990m ASL, which collected data from around 1968 through 1998. It would seem that this station could be used to drive the PTAA model, but precipitation gauges on mountains, where winds are generally strong, tend to underestimate the amount of snow (Barry, 1992). So, while not an ideal station to use in driving the PTAA model, this station will be more suitable to compare to the mass balance records, in an attempt to understand the controlling factors that are driving the changing mass balance of the Wolverine Glacier.

For the Wrangell Mountains, a weather station exists on the Nabesna Glacier, located at lat 62.23°N, long 142.59°W, at an altitude of 884 m ASL. This station, while again not ideal for driving the PTAA model due to the problems listed above, will be good for comparison to the mass balance data modeled for the Wrangell glaciers.

In addition to comparing the glacier mass balance data to temperature and precipitation trends, these data will also be compared to three climate indices that are important in this region, the PDO, PNA, and AO. This correlation will help understand how longer-term circulation patterns over the Pacific Ocean and the Northern Hemisphere affect the mass balance of the glaciers in this region.

**Climate Indices**

The Pacific Decadal Oscillation (PDO) is the leading principal component of monthly sea surface temperature anomalies in the North Pacific Ocean (poleward of 20°N), so it plays a large role in driving the climate for the glaciers in south central Alaska. The PDO is similar to the more common El Nino/Southern Oscillation (ENSO) pattern, except it tends to persist for 20-30
years at a time, as opposed to ENSO which usually lasts 6-18 months (Mantua et al., 1997) In the warm (positive) phase, the PDO tends to be associated with more northerly storm tracks, while the cold (negative) phase shifts the storm tracks to the south. So the warm phase tends to create more storminess in the Gulf of Alaska region, while the cold phase shifts storm tracks southward towards the northwestern continental US. One would therefore expect the south-central Alaska glaciers, especially the maritime Wolverine, to receive enhanced precipitation during the warm phase of the PDO. The PDO index values used in this study were derived by Mantua (2010) and obtained from the Joint Institute for the Study of the Atmosphere and the Ocean (JISAO) at the University of Washington. Figures 17 and 18 show the PDO climate index from 1950 -2008, for the ablation and accumulation seasons, respectively.

![PDO Climate Index](image)

**Figure 17.** The PDO climate index averaged over the months June-September for the years 1950-2008. The black line represents a 5-year moving average.
Figure 18. The PDO climate index averaged over the months October-May for the years 1950-2008. The black line represents a 5-year moving average.

It is clear from the above graphs that there was a significant change in the phase of the PDO from negative to positive in the late 1970s. This shift is well known and significant in previous literature (Hartmann and Wendler, 2005) and also corresponds well to the research by Mayo and Trabant (1984) which showed that the Wolverine Glacier mass balance began increasing in 1977. It increased until 1982 and then after that it began decreasing and has continued that way since then. We see the PDO begin to decrease again in the mid 1980s and since then it seems to have cycled back and forth from positive to negative every 4-5 years or so. It is since this mid-1980s
time period that the PDO effect on the Wolverine Glacier seems to have decoupled, as the
Wolverine has generally been declining since then.

The Pacific/North American Pattern (PNA) is another climate index that impacts the
northern Pacific region. This climate index compares pressure anomalies at four nodes across
the Pacific Ocean and North American continent. The two Pacific Ocean nodes are located near
Hawaii (20°N, 160°W) and in the North Pacific (45°N, 165°W), and the two continental nodes
are near Alberta, Canada (55°N, 115°W) and over the Gulf Coastal region of the United States
(30°N, 85°W) (Wallace and Gutzler, 1981). Typically the Hawaii and Alberta nodes are
positively correlated, as are the North Pacific and Gulf Coast nodes. Positive values of the PNA
are generally associated with an amplified wave pattern that leads to a deep Aleutian low
(Wallace and Gutzler, 1981). This causes an increase in precipitation in the southern coastal
areas of Alaska, as this deepened Aleutian low drives storms into this region. When negative the
low is anomalously weak. The PNA index used for this study was obtained from the JISAO at
the University of Washington (2010). Figures 19 and 20 show the PNA climate index for the
years 1950-2008, for the ablation and accumulation seasons respectively.
Figure 19. The PNA climate index averaged over the months June-September for the years 1950-2008. The black line represents a 5-year moving average.
The Arctic Oscillation (AO) is described as the teleconnection between the strength of the polar vortex and mid-latitude atmospheric pressure patterns. A negative phase of the AO occurs when higher than normal pressure occurs over the Polar Regions and low pressure over mid-latitudes. The conditions are reversed for the positive phase. The negative phase tends to cause above normal Arctic temperatures and cold, stormy weather in the northern hemisphere mid-latitudes, while in the positive phase high pressure centered over mid-latitudes drives storms farther north bringing wetter weather to places such as Alaska (Thompson and Wallace, 1998). The AO index for this study was obtained from the National Oceanic and Atmospheric Administration’s Climate Prediction Center (2010). Figures 21 and 22 show the AO climate index for the years 1950-2008, for the ablation and accumulation seasons respectively.
**Figure 21.** The AO climate index averaged over the months June-September for the years 1950-2008. The black line represents a 5-year moving average.
Figure 22. The AO climate index averaged over the months October-May for the years 1950-2008. The black line represents a 5-year moving average.

Wrangell Glaciers Climate Analysis

The Wrangell Glaciers lie inland from the Pacific Ocean and are in a continental climate regime. Weather systems coming in from the Pacific first encounter the coastal Chugach Range and drop a lot of their moisture there. So once they get to the Wrangells they contain much less moisture. This type of continental climate generally favors temperature as the controlling factor for the mass balance of the glaciers during the ablation (summer) season. The temperature swings are large here, with very low temperatures in the winter and higher temperatures in the summer. So if the temperatures rise enough in the summer, melt occurs. Continental type glaciers do not get a lot of precipitation, and a large amount of it falls in the summer as rain, so it
is clear why summer temperatures are expected to be the main controlling factor of these glaciers.

The PTAA model data for the Wrangell North and South regions, as well as data from the individual runs on the Nabesna and Kennicott Glaciers was compared to the climate indices and weather station data in order to understand the climatic factors that control the mass balance of these glaciers. Simple linear correlation was first performed between each glacier region’s model output and each different meteorological parameter or climate index. Correlation coefficients (r-values) are the main results obtained using this method. This simple statistical method was used because it most nearly measures real world correlation between two independent parameters. It has also been widely used in previous work to assess how climate affects glacier mass balance (Hodge et al., 1998; Bitz and Battisti, 1999; Rasmussen and Conway, 2004). The meteorological and climate index data were broken up into accumulation (winter) and ablation (summer) season averages, using October through May as the accumulation season and June through September as the ablation season. This was done in order to understand how the climate conditions in the different seasons affect the glacier mass balance. The statistical significance for each correlation was also calculated, using the common 95% confidence level. This means that there exists a 5% probability that this result tested by chance, and a 95% probability that the tested relationship is due to the two variables sharing some type of connection. This significance relies on the sample size of the tested variables; as the sample size (n) increases, the correlation needed to obtain statistical significance decreases. The following formula defines the minimum value of correlation needed in order to have significance at the 95% level:
As expected the correlations between the ablation season temperatures at the Nabesna weather station and the Wrangell glacier mass balances were the greatest, with a strong negative correlation existing. Summer season precipitation had a significant correlation as well, and this makes sense since more precipitation falls in the summer than the winter in this region (Shulski and Wendler, 2007). The PNA climate index averaged for the ablation season significantly correlates (negatively) with the Wrangell North mass balances. Table 4 contains the correlation coefficients (r-values) for Wrangell mass balances and meteorological parameters and climate indices.

<table>
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<tr>
<th>Variable/Index</th>
<th>Wrangell N</th>
<th>Wrangell S</th>
<th>Nabesna</th>
<th>Kennicott</th>
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<td>PDO (Jun-Sept)</td>
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Table 4. Correlation coefficients between climatic drivers in the Wrangell Mountain region and the glacier mass balance data from the PTAA Wrangell model runs. Statistically significant results at 95% are in bold.

We can analyze some of these trends in more detail, starting with the AO. While the AO does not show a statistically significant correlation for the entire time period, when we break it up into two time periods we can see it was previously significantly correlated. From 1950-1989 the AO did show significant correlation with the Wrangell mass balances. From the 1990s on
there seems to be hardly any correlation in the trends. This break down in the trend is not unexpected, as since this time warming in the Arctic has become extremely pronounced and is most likely now the main driver of glacier mass balance in this region (IPCC, 2007). Table 5 shows these correlations and shows that the correlations are indeed strong and statistically significant for the first period, but completely break down during the second period.

<table>
<thead>
<tr>
<th>Climate Index/Time Period</th>
<th>Wrangell N</th>
<th>Wrangell S</th>
</tr>
</thead>
<tbody>
<tr>
<td>AO (1950-1989)</td>
<td>0.41</td>
<td>0.39</td>
</tr>
<tr>
<td>AO (1990-2006)</td>
<td>-0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 5. Correlation coefficients between the AO ablation season climate index and the Wrangell North and South region PTAA glacier mass balance model data broken into two time periods. Bold values are significant at 95%.

The negative correlation seen between the ablation season PNA index and the Wrangell glacier mass balance does not agree well with theory, as when the PNA is in its negative phase it tends to bring high pressure to this region, causing subsidence, warming and decreased precipitation. Thus, one would expect a positive correlation during the summer, meaning if the index was negative then you would get more negative mass balances. This correlation does break down, however, in more recent years, and is not considered statistically significant since 1990.

The PDO ablation season index also shows statistically significant negative correlation with the mass balance on the Kennicott Glacier. The PDO is generally stronger during the winter, but overall brings more storms into the region when in the positive phase. It seems in this case that maybe the effects of increasing temperatures during the summer might be overshadowing the PDO as we would expect to have a positive correlation between these two parameters. And this is also supported by the fact that the correlation breaks down in later years
as well, as the correlation after 1990 is not statistically significant. These analyses fit well with previous research that show the climate index correlations with glacier mass balance have broken down over the last several decades due to the effect of warming from human-induced climate change becoming the dominant driver (Hodge et al., 1998).

Multiple regression statistical analysis using the ordinary least squares (OLS) method was then used between the mass balances and the meteorological data, in order to better assess how these data drive the balances. The results from these regressions strengthened the initial findings, with the strongest correlations and $r^2$ values existing between all of the Wrangell mass balances and the ablation season meteorological parameters. The $r^2$ value for the multiple regression between the Kennicott Glacier mass balance and the ablation season temperature and precipitation data was the strongest at 0.48. From the analysis of variance on this model, the regression had an F-value of 11.7, with a p-value of 0.001, showing a strong likelihood of statistical significance at the 95% confidence level. The equation for this model is as follows:

$$Y_1 = 13.27982642788-0.29829247817403*X_1+7.77727934976693E-02*X_2$$

where $Y_1$ is the mass balance, $X_1$ is the ablation season temperature and $X_2$ is the ablation season precipitation. $X_1$ had the strongest probability of being significant, with the t-value lying within the 95% probability range.

The Nabesna Glacier mass balance regression against the ablation season temperature and precipitation data had an $r^2$ value almost as strong as the Kennicott, at 0.46. The analysis of variance on this regression gave an F-value of 10.8, with a p-value of 0.000, also showing a strong likelihood of statistical significance at the 95% confidence level. The equation for this regression is:

$$Y_1 = 10.9486876734888-0.242501229340847*X_1+0.102334375977109*X_2$$
Where $Y_1$ is the mass balance, $X_1$ is the ablation season temperature and $X_2$ is the ablation season precipitation. Again with this regression, the ablation season temperature had the strongest statistical significance of the model parameters.

The Wrangell North and South mass balance regressions against the ablation season meteorological data had $r^2$ values of 0.47 and 0.34, respectively. The North regression had an F-value of 10.2, while the South had an F-value of 6.0. Both had high probabilities of being statistically significant, and also showed the stronger relationships to be with the ablation season temperatures. The $r^2$ values for the accumulation season regressions were much lower and insignificant.

**Wolverine Glacier Climate Analysis**

As mentioned above, the Wolverine glacier has a weather station located at lat 60°23'N., long 148°55'W, on the glacier at an altitude of 990 m. Data collections began at the Wolverine Glacier weather station in 1967 and are available until 1998. The data from this station will be ideal to compare to the trends seen in the mass balance modeling, since separate weather stations were used for the inputs into the modeling for the Wolverine Glacier. The Wolverine Glacier mass balance data will also be compared to the three climate indices discussed previously. And both the measured and modeled mass balance data will be compared to the climate data in order to understand any differences that might be present between the two records.

As has been discussed, the Wolverine Glacier is located on the Kenai Peninsula in south-central Alaska in a maritime climate regime. This region experiences abundant moisture, particularly in the winter and in the form of snowfall, when the Aleutian low steers storms directly into this region. Temperatures remain moderate since the Gulf of Alaska remains ice-free, allowing the air to be moderated by the warmer ocean water. All of these factors lead to the
assumption that winter precipitation should be the dominant driver of the mass balance of the

glaciers in this region.

The temperature and precipitation records from the Wolverine meteorological station
cover the time period 1967-1998, although there are several missing years. Monthly averages
were missing from this record if more than 9 records were missing, and then the annual averages
are not available if any month is missing for that year (Kennedy, 1995). These data were then
averaged into accumulation and ablation season averages for each year in order to be able to
understand the differences in the seasonal climatic drivers. Simple linear correlation was first
performed between both the Wolverine USGS measured mass balance data and the PTAA model
data and the accumulation and ablation season temperature and precipitation data and climate
indices. The statistical significance for each correlation was also calculated, using the 95%
confidence level. The most significantly correlated (positive) results were between the
accumulation season precipitation and both the measured and modeled Wolverine mass balance
results. These results again agree with theory in that they show that the accumulation season
precipitation is the main climatic driver in this maritime region. Table 6 shows the correlations
between the climatic drivers and the Wolverine measured and modeled balances.
Table 6. Correlation coefficient (r-values) between the climatic drivers and measured and modeled mass balances for the Wolverine Glacier. Correlations statistically significant at the 95% level are in bold.

Further inspection of these values shows that there was much more correlation between several of the climatic factors and the USGS measured mass balances. Temperature for both seasons significantly correlated with the USGS measured balances, with negative correlation for the ablation season, as expected, but positive correlation for the accumulation season. Only the negative correlation between the ablation season temperatures and the Wolverine modeled mass balance data was statistically significant. The PTAA modeled mass balance correlations with the temperature and precipitation data seem to make more sense, leading one to believe that there could be errors in the USGS measurements. This seems reasonable, as looking back at Figures 15 and 16 the balances between the measured and modeled track quite well against each other except for a few years where they are completely different. It is possible that the model is incorrect in these cases, but since the model seems to produce realistic results for the rest of the years it could be that measurements were not as accurate in those years. It should be noted, however, that Bitz and Battisti (1999) also found positive correlations between the Wolverine
mass balance and winter temperatures. Further research into the specifics of these possible errors is beyond the scope of this thesis.

The temperature and precipitation correlations with the mass balances were also broken down into two time periods, 1968-1989 and 1990 onward to see if anything has changed in more recent times. And indeed the negative correlations between the ablation season temperatures and both the USGS and PTAA mass balance data have greatly strengthened since 1990 (Table 7).

<table>
<thead>
<tr>
<th>Meteorological Parameter</th>
<th>Wolverine (USGS)</th>
<th>Wolverine (PTAA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (1968-1989)</td>
<td>-0.44</td>
<td>-0.35</td>
</tr>
<tr>
<td>Temperature (1990-1998)</td>
<td>-0.69</td>
<td>-0.73</td>
</tr>
</tbody>
</table>

Table 7. Correlation coefficients between the ablation season temperatures and the Wolverine Glacier mass balance data broken into two time periods. Bold values are significant at 95%.

This lends more evidence to the increasing Arctic temperatures becoming a dominant factor in controlling the glaciers in south-central Alaska.

Looking at the correlations between the climatic indices and the Wolverine mass balance results we again see differences between the measured and modeled balances. The accumulation season averages for the PDO, PNA, and AO climate indices are all significantly correlated with the Wolverine USGS measured balances. The PDO and PNA are both positively correlated with the USGS measurements and the AO is negatively correlated. This negative correlation between the accumulation season AO and the mass balance is interesting, as when the AO is positive it usually strengthens the Aleutian low and steers more storms into southern Alaska. Thus you would expect a positive correlation since more storms coming into the region should mean more accumulation on the glacier and therefore lead to a positive mass balance. In this case the lack of correlation between the PTAA modeled balances and the AO index makes more sense.
The significant positive correlation with the accumulation season PDO index and the Wolverine measured mass balance agrees with theory, as well as previous research by Josberger et al. (2007), as when the PDO is in the positive phase, the coastal areas of south-central Alaska tend to experience enhanced cyclonic flow and heavier than normal precipitation (Mantua et al., 1997). This correlation has broken down in recent years, however, and is no longer statistically significant (Table 8).

<table>
<thead>
<tr>
<th>Climate Index/Time Period</th>
<th>Wolverine Mass Balance (USGS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDO (1966-1989)</td>
<td>0.49</td>
</tr>
<tr>
<td>PDO (1990-2004)</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 8. Correlation coefficients between the PDO accumulation season climate index and the Wolverine measured glacier mass balance data broken into two time periods. Bold values are significant at 95%.

As mentioned above, there is no correlation in this case between the accumulation season PDO and the Wolverine modeled balance, although there is a negative correlation between the ablation season PDO and the Wolverine modeled balance. These correlations (or lack of them in some cases) seem to indicate that the climate index correlations with glacier mass balance in this region are breaking down, as increasing temperatures becoming the dominant factor controlling the mass balance.

The significant positive correlation with the accumulation season PNA index and the Wolverine Glacier measured mass balance also agrees with theory, as the Aleutian low deepens during the positive phase, driving storms into the south-central Alaskan coast and increasing precipitation (Wallace and Gutzler, 1981). In this case again, the lack of significant correlation between the PTAA modeled balance for the Wolverine Glacier and the PNA is cause for concern, as we would expect to see this correlation if the PTAA results are to be believed. Both of the Wolverine Glacier mass balances were negatively correlated with the ablation season
PNA, which could also be a sign of the increased summer warming becoming the dominant driver of the glacier mass balance in this region.

Multiple linear regression statistical analysis, using the ordinary least squares (OLS) method, was used next to better understand how temperature and precipitation affect the Wolverine Glacier mass balance. This was done with both the accumulation and ablation season meteorological data being regressed against the PTAA and USGS Wolverine mass balance data. These results were encouraging and helped support the fact that accumulation season precipitation is the dominant driver of the glacier mass balance in maritime climates. The strongest correlations occurred with the USGS measured mass balance and the accumulation season meteorological data, with an $r^2$ value of 0.79. The analysis of variance for this regression had an $F$-value of 36.2, with a high probability of statistical significance at the 95% confidence level. The equation for this regression is as follows:

$$Y_1 = -1.65076317319943 + 2.46628135604452 \times 10^{-2} \times X_1 + 0.143415516923827 \times X_2$$

with $Y_1$ representing the USGS Wolverine mass balance, $X_1$ being the accumulation season precipitation and $X_2$ being the temperatures. The accumulation season precipitation had the strongest statistical significance of the two parameters, temperature and precipitation.

The PTAA modeled balance regressed against accumulation season meteorological data, while having a lower $r^2$ value (0.41), was still statistically significant, with precipitation again being the more important factor in the model. The $F$-value for this model was 6.6, with the precipitation parameter still having a high probability of being statistically significant at the 95% confidence level. These lower values were to be expected, as the PTAA simple linear regression values were lower than the USGS measured values. The equation for this model is:

$$Y_1 = -1.8809168405935 + 1.02389260347929 \times 10^{-2} \times X_1 - 0.143750879344999 \times X_2$$
The ablation season multiple regressions had much lower $r^2$ values, and were not statistically significant.
CHAPTER VI
CONCLUSION

Mountain glaciers are key indicators of climate change and they are melting at alarming rates. Alaskan glaciers are no exception, and many of them are wasting away and dumping massive amounts of fresh water into the ocean. In fact, over the last several decades Alaska has contributed more to eustatic sea level rise than other source regions (Arendt et al., 2002), although some recent estimates have decreased these values (Berthier, et al., 2010). It is therefore important to understand the rates of change of Alaskan glaciers, and to understand the key climatic factors driving this melt. Unfortunately only a handful of Alaskan glaciers are routinely monitored for glacier mass balance, as many of them are difficult to access due to the extreme topography and remoteness of this region. This presents a key challenge in understanding how these glaciers are changing. One of the easiest ways to overcome this challenge is to develop a mass balance model that can successfully catch the change taking place
on these glaciers. Many different glacier mass balance models have been developed over the years, but most of them have been tuned to work in only limited regions with very specific conditions. A mass balance model has been developed in recent years that only requires low-altitude temperature and precipitation data from nearby weather stations along with the area-altitude profile of the glacier (Tangborn, 1999). The PTAA model has been used in several previous studies and it was shown that it can produce realistic mass balances for several different types of glaciers (Tangborn, 1999; Tangborn and Rana, 2000; Wood, 2006; Bhatt et al., 2007; Zhang et al., 2007; Medley, 2008). If it can be further proved that this model can be used to correctly predict mass balances for different types of glaciers, it could eventually be run on many different glaciers worldwide. It could also be used predict the future behavior of glaciers worldwide using climate model data to drive the model. This thesis research attempts to continue to validate the PTAA model, comparing the output data to measured mass balances. Also, a second goal of this research is to understand the climatic factors that are driving the modeled and measured glacier mass balances in the region of study.

The PTAA model was used to model the glacier mass balance for the Wolverine Glacier on the Kenai Peninsula and for the glaciers in the Wrangell Mountains, both located in south-central Alaska. These regions represent two different types of glaciers, as the Wolverine Glacier is located in a maritime climate and the Wrangell Glaciers are more continental in nature. This gives the model two different types of glaciers to help continue the validation efforts that have been going on for over a decade.

The Wolverine Glacier was modeled using precipitation and temperature data from the Seward weather station located 56 km from the glacier at an altitude of 38 m. Many previous PTAA model runs have used two or even three weather stations to drive the model, but after...
many different attempts to minimize the calibration error, it was determined that using only the Seward weather station would produce the most realistic results. The area-altitude profile to complete the PTAA model run was created from USGS topographic maps, and was divided into 30.5 m altitude increments. Using these inputs, the mean annual mass balance for the time period of 1966-2004 was modeled to be -0.38 m.w.e. This almost perfectly matched the mean annual mass balance of -0.37 m.w.e. for the same time period that was measured on the glacier by the USGS monitoring program. The cumulative mass balances were also quite similar for this time period, with -14.97 m.w.e. from the PTAA model and -14.36 m.w.e. from the USGS measurements. These balances show that the PTAA model can produce realistic mean mass balance results.

The Wrangell Mountain glaciers were modeled in two different ways. First, all of the glaciers were divided into two regions, a north region and a south region. Each of these regions was then modeled as a whole glacier mass, so two separate model runs were done. Both regions used the same two weather stations to serve as meteorological inputs to drive the model, therefore eliminating any possible bias that could exist when comparing results. The stations used were Big Delta, at an altitude of 387 m and McKinley Park, at an altitude of 631 m. Both of these stations are about 350 km from the Wrangell Mountain region. The area-altitude profile was also created from USGS topographic maps and divided into 30.5 m altitude increments. Using these inputs, the modeled mean annual mass balance for the North Wrangell glacier region for the time period 1950-2006 was -0.23 m.w.e. and -0.66 m.w.e for the South Wrangells. These are interesting results as the mass balance results for the south region are almost three times as negative as the north region. This would seem to make sense, as south facing glaciers experience more solar radiation than their north facing counterparts. And, as mentioned above, since the
same weather stations were used for both regions, no bias has been introduced from the meteorological inputs. Also, when calibrating the model for each region, the ablation from solar radiation coefficient adjusted itself to be higher for the south region. Nothing else is input into the model that would account for this difference, so it is assumed that the model is correctly sensing the orientation of these glaciers. This is another important positive result for the validation of the PTAA model.

While no long-term measurement program exists for the glaciers in the Wrangell Mountains, as does for the Wolverine Glacier, several aircraft laser altimetry measurement campaigns have been conducted in this region, mainly on the Nabesna Glacier in the North Wrangells and the Kennicott Glacier in the south region. So the second attempt at modeling the glaciers in this region focused on modeling the Nabesna and Kennicott Glaciers individually. The same weather stations as used for the north and south regions, Big Delta and McKinley Park, were also used to model these two glaciers. The area-altitude profiles were created in the same fashion as the previous runs as well. For the Nabesna Glacier, the mean annual mass balance for the 1957-2008 time period was modeled to be -0.57 m.w.e and for the Kennicott Glacier the balance was -0.96 m.w.e for the same period. These results were then converted to thickness values in order to better compare to the laser altimetry data. The Nabesna Glacier lost -0.57 m/yr of ice and the Kennicott Glacier lost -1.1 m/yr, neither comparing reasonably well to the -0.17 m/yr of ice estimated through the laser altimetry measurements (Arendt et al., 2002). However, the two results agree reasonably well with the -0.52 m/yr area-averaged thickness change that Arendt et al. (2002) derived from aircraft laser altimetry data. The Nabesna and Kennicott Glacier model runs also show the same pattern as the north and south Wrangell region runs, with
the south facing Kennicott Glacier having a much greater mass loss due to the increased solar radiation experienced on south facing slopes.

Several other studies have been done using the PTAA model to simulate glacier mass balances in areas such as Alaska, the Pacific Northwest and the Himalaya (Tangborn, 1999; Tangborn and Rana, 2000; Wood, 2006, Zhang et al., 2007). These studies all compared the simulated mass balances to actual measurements and found similar issues as were found in this study. Tangborn (1999) and Zhang et al. (2007) both found consistently more negative simulated balances compared to measured balances, blaming greater ablation rates from the model runs as the cause. Wood (2006) found that the simulated balances increased or decreased coherently on a yearly basis with the measured balances, but there were differences in the magnitudes. All of these simulated results, however, were found to have significant correlations with the measured balances, and were considered successful PTAA model runs. Overall the PTAA model runs on the Alaskan glaciers in this study showed promising results and seem to produce realistic mass balance estimates.

The second goal of this research was to determine the climatic factors that drive the glacier mass balance in these two regions. The Wolverine Glacier is a maritime glacier, which usually means the winter precipitation drives the mass balance, since a lot of winter precipitation falls here, but temperatures are moderate. The Wrangells are the opposite, as they are continental, which means they are much drier and also have much lower temperatures in the winter (and higher in the summer). In this type of climate, summer temperatures usually drive the mass balance.

Temperature and precipitation data from weather stations located on these glaciers were compared to the mass balance results to determine the correlations between the two. The
meteorological data were divided into winter and summer season averages in order to differentiate between the accumulation and ablation seasons, respectively. And overall, the results agreed well with theory, as the correlations were highest between winter precipitation and the Wolverine Glacier mass balances (positive correlation) and between Wrangell Glacier mass balances and summer temperatures (negative correlation). It was noticed, however, that some of these correlations have changed over the last several decades, most likely in response to climate change. Enhanced warming has been noted in the Arctic, and specifically in Alaska where temperatures have risen between 2-3° C since the 1970s. Specifically, the negative correlation between ablation season temperatures and the Wolverine Glacier mass balance has become very strong; a clear signal of the effect of rising temperatures in this part of Alaska. The Wrangell Glacier balances versus temperature correlations did not go through the same changes as the Wolverine Glacier, and this is most likely due to the fact that the temperatures are already the dominant driver of the mass balances here, and they remain so with higher temperatures. These results also help validate the PTAA model data, as unrealistic mass balance results would not be expected to correlate correctly in this fashion.

The mass balance results were also correlated with three climate indices that are important for controlling climate in this region – the PDO, PNA, and AO. The climate indices were also divided into accumulation and ablation season averages in order to better understand how the different season’s indices affect the mass balances. The PDO and PNA accumulation season climate index averages were found to be positively correlated with the Wolverine Glacier mass balance, and this was to be expected as both of these teleconnection patterns bring more storms into the region in the positive phase. But this correlation was only found between these indices and the USGS measured balances on the Wolverine Glacier. The PTAA modeled
balances for the Wolverine did not correlate with either of these indices or the AO. This lack of correlation is not well understood, as the PTAA and USGS balances were compared together and matched quite closely. The most likely cause was the fact that while the cumulative balances and average annual balances for the two were similar, the magnitude of the accumulation and ablation season averages were off by a factor of two. So the trends were similar between the measured and modeled balances, but the USGS measurements showed larger values for the accumulation balances and more negative values for the ablation season balances. The differences between the two cancelled each other out to produce similar overall annual balances. Again the climate index and glacier mass balance correlations were all broken out into two time periods, an earlier one up to 1989 and then a later period, which is expected to correlate with temperatures really starting to accelerate in their rate of warming in this region. And the results were quite interesting, as almost all of the significant correlations between the glacier mass balances and climate indices have become statistically insignificant after 1989. The correlation between the AO ablation season average and the Wrangell Glacier mass balances completely broke down after 1989, as did the PNA and PDO correlations with the glaciers in this region. For the Wolverine Glacier, the significant correlation between the accumulation season PDO and the mass balance also broke down and became statistically insignificant, as did the negative correlation with the winter season AO. These results strengthen the idea that warming in the Arctic, specifically Alaska, has become strong enough to drown out the signals of these teleconnection patterns.

To conclude, the results of the PTAA glacier mass balance modeling for this thesis research were encouraging, as realistic mass balance results were obtained. The values were compared to existing measured values and found to match reasonably well. The climatic drivers
of the mass balance in this region also correlated as expected, with winter precipitation being the
dominant driver of the mass balance in the maritime Wolverine Glacier, and summer
temperatures the dominant driver in the continental Wrangell Glaciers. While the factors that
control the climate indices have also played important roles in driving the climate in this region,
they have broken down in recent years, and overall increasing temperatures are starting to have a
profound effect on the glaciers in south-central Alaska. As temperatures continue to rise in this
region, the glaciers will continue to retreat and lose mass at alarming rates, and sea levels will
continue to rise. If projections of continued warming over the next century are correct, then the
glaciers of south-central Alaska (as well as the rest of Alaska) will retreat to levels not seen for
thousands of years.
BIBLIOGRAPHY


