

A Comparison Between Mass Balance of the Taku and Lemon Creek Glaciers Derived from Glaciological Methods and GRACE

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Abstract

Glacier mass balance is of increasing concern due to climate change, and for this reason it is important to determine and refine the best methodology for obtaining mass balance data. The present study compares the use of in situ field measurements with gravimetric mass measurements obtained by the satellite GRACE. Field mass balance data from both the Taku and Lemon Creek glaciers in southeast Alaska was compared to GRACE data for the years 2003-2014, and a linear regression analysis was performed to determine the correlation between these two data types. GRACE and field data show similar long term trends, however year to year mass variations are quite different between the two data sets. The correlation between the mass balance estimates from GRACE and field measurement is stronger for Taku glacier and somewhat weaker for Lemon Glacier, which is most likely due to the issues of scale and signal leakage. The results suggest that GRACE is better suited for looking at large ice caps and ice sheets rather than individual glaciers.

Introduction

What is Mass Balance?

Glacier mass balance is a valuable indicator of climate change. Individual glaciers may be affected by local environmental factors or past climates, so to better understand links between mass balance and recent climate change, it is important to look at glacier activity on a global scale. A warming climate is typically manifested as a global average of retreating glaciers,

whereas a cooling climate is typically manifested by a global average of advancing glaciers. The term 'mass balance' pertains to the difference between snowfall during the winter (accumulation), and ice melt during the summer (ablation) of a glacier. A good analogy for mass balance is a glacier's bank account; accumulation is an addition to the bank account, and ablation is a loss from the bank account. Thus, a typical glacier exhibits a positive value for winter balance, and a negative value for summer balance. The sum of winter and summer balances determines an annual balance. Glacier advance is thus characterized by having winter accumulation exceed summer mass loss, whereas glacial retreat is characterized by having a higher value for summer ablation (Burgess 2005). The separation between the accumulation zone and the ablation zone is defined as the Equilibrium Line Altitude, or ELA. This is the point on a glacier where mass balance is zero at the end of a mass balance year. The transient snowline (TSL), on the other hand, is the distinction between wet snow and ice, and is often used as an approximation for the location on the ELA at the end of the ablation season (Cogley et al. 2011). Glaciological mass balance is expressed as an area average. Thus, the units represent an average water depth which is gained or lost by a glacier in a given year. For example, a glacier with an annual balance value of -10 cm snow water equivalent (cm SWE) is indicative that the glacier lost an average depth of 10 cm of water surface-wide. The annual balance at any point on a glacier refers to the totality of accumulation over a year minus the total ablation during the same year. Annual mass balance indicates the mass gained or lost from a glacier as a whole (Burgess 2005, McNeil 2013).

The Importance of Studying Mass Balance

Global climate change is gaining attention, in large part due to its impacts on global ecosystems and people worldwide. The average global surface air temperature have risen by 0.85°C since 1888, and has been attended by widespread ecological changes (IPCC 2014). In northern latitudes, the temperature increase is greater, which is particularly concerning to residents living in Alaska, Canada, Siberia and Eurasia. In these regions, annual ice melt is being recorded earlier and earlier with each passing year (Burgess 2005).

As already introduced, glaciers are sensitive to climatic variations. The size of a glacier determines its sensitivity; large ice sheets typically respond slowly to climatic variations, whereas small individual glaciers respond much more quickly. Thus, the mass balance for the culmination of many individual glaciers is a good indication or metric of climate change. Glacier mass balance provides critical information regarding present-day trends, and is also relevant to reconstruction of past climate regimes, and prediction of future glacial responses to climate. Climatic and glacial dynamics are key in mountain hydrology. A loss of glacier mass balance occurs as snowmelt, and associated water runoff, which is linked directly to local and regional hydrology, and sea level rise. In addition to the possibility of low-lying coastal flooding, there is a potential for flooding of glacial outflow drainages. Maintenance of infrastructure near these drainages is hence dependent upon mass balance. This study highlights the importance of studying mass balance to predict future changes to landscapes, and to conduct hazard assessment and risk management. (Kaser et al. 2002).

The Present Study

The present study compares two differing methods of determining mass balance in southeast Alaska; glaciological methods (or field data), and gravimetric methods (satellite retrieval of balance values from the Gravity Recovery and Climate Experiment, or GRACE). Glaciological measurements are expensive and can be difficult to conduct due to the remoteness of study sites. Currently, detailed mass balance measurements are collected on only a handful of glaciers in Alaska. This study aims to determine the efficacy of using satellite data to determine mass balance, which has the potential to understand glacier change on the regional scale by ground truthing with glaciological data.

Glaciers in southeast Alaska exist in a warming maritime climate, characterized by major fluctuations in annual snowfall and melt patterns. The effect of the warming maritime climate is very rapid retreat of most glaciers. The sensitivity of Alaskan glaciers to climatic variations makes them useful for monitoring their growth and decline to make predictions for the future (Burgess 2005). For this reason, Taku and Lemon Creek glaciers were selected to determine whether the glaciological and gravimetric mass balance calculations provide similar information. It is important to note that satellite determination of mass balance has been used extensively on large scales, particularly for the Greenland and Antarctic ice sheets. The Taku and Lemon Creek glaciers are relatively small compared to the footprint of gravimetric measurements, and so the key aim of this study is to uncover whether the footprint of the satellite data is small enough to capture the mass balance of individual glaciers. Taku glacier is quite a bit larger than Lemon

Creek, so it is hypothesized that GRACE will be a better job of capturing Taku's mass balance variations and trends.

Background

Taku Glacier

The Juneau Icefield (1820 km²) is situated just east of Juneau, AK (see Figure 2), and its primary outlet drainage is Taku Glacier (726 km²). Pelto et. al (2013) determined that from 1946-1985, Taku glacier advanced, and from 1986-2011, it retreated. Taku Glacier is unique for several reasons. Firstly, Taku Glacier is up to 1500 m thick, the greatest in all of Alaska. Additionally, it exists in a maritime temperate climate, and often receives massive amounts of winter snowfall, and experiences strong summer ablation (Truffer et al., 2009). Perhaps the most defining characteristic of Taku Glacier is that it has advanced over the last century. This sets it apart from the global pattern of retreat during the same time period. Much of this advance can be attributed to the fact that Taku is a tidewater glacier, terminating in the ocean, and has been in the advancing stage of its tidewater cycle. (Motyka and Echelmeyer 2003).

A tidewater glacier is a glacier which terminates in the sea, has a floating tongue or grounded terminus, and is unique in that it is driven primarily by processes at the glacier's terminus (Cogley et al. 2011). More specifically, the advance in the terminus occurs due to increases in ice thickness of the glacier itself, and also by lodging into soft basal sediments below the glacier (Truffer et al. 2009). Whether a tidewater glacier will advance or retreat depends on glacier length, the bedrock topography (for instance a terminus on a reverse bed

slope is typically unstable), submarine melt rates, sensitivity to climate, and erosional or depositional processes at the terminus (Amundson 2013). More specifically, the base of the floating tongue of a tidewater glacier is melted due to the convection of ocean waters below, which in turn melts the glacier. The interface between water and ice is characterized by a large temperature gradient, and supplies the latent heat of fusion for basal melting to occur. The weight of the floating tongue itself is supported by seawater, and lateral stress which gets applied by the valley walls (Cogley et al. 2011). In the case of the Taku Glacier, periods of retreat are characterized by low flow velocity, and thus a decrease in the amount of ice that reaches the terminus. This decline in ice thickness at the terminus leads to greater ice storage upstream, which eventually must make its way to the terminus. The Taku Glacier undergoes this episodic terminal retreat and advance process, and is currently in its 'advance' phase (Truffer et al. 2009). Currently, the Taku Glacier no longer terminates in the ocean. This is because it has pushed debris out past the terminus creating an outwash plain large enough to fill the inlet that it drains into (Burgess 2005).

Lemon Creek Glacier

The Lemon Creek Glacier is located at the southernmost tip of the Juneau Icefield (see Figure 2). Located just 6.5 km northeast of Juneau, Alaska, Lemon Creek Glacier is a subarctic alpine glacier in a maritime climate, and ranges in elevation from 600 m at the terminus to 1500 m at the accumulation zone. It flows northward from its accumulation zone, and has a maximum thickness of more than 200 m located 1 km above the icefall. The Lemon Creek Glacier has been extensively studied due to its ease of access, and because it was designated as a representative

glacier for the 1957/58 International Geophysical Year global glacier network. Its long term mass balance record reveals that since that the Lemon Creek glacier has been retreating since 1953 (Pelto et al. 2013). The Lemon Creek Glacier was chosen for the present analysis due to its long mass balance record as well as its recent rapid retreat, which contrasts with the advance of the Taku Glacier.

Traditional Mass Balance Technique

The mass balance data for the Taku and Lemon Creek glaciers has been collected as part of the Juneau Icefield Research Program (JIRP). JIRP is an expeditionary training program in the fields of glaciology, glacial geology and climatology. It is the longest running surface mass balance measurement program in North America. Mass balance data has been collected by JIRP since 1946, including data on the Taku and Lemon Creek glaciers, which are both monitored by JIRP's traditional mass balance techniques. JIRP's annual mass balance determination methods are as follows; digging snow pits at fixed locations, measuring short-term ablation by repeating height measurements of ablation stakes, and measuring the location of the transient snowline (TSL) and equilibrium line altitude (ELA).

During a six week period in the summer, snow pits are dug at fixed locations that are deep enough to include old snow that accumulated over the last accumulation season, and the underlying firn layer. The snow water equivalent of the present year's accumulation is calculated in the pits by measuring snow density every 10 cm as well as recording ice lenses present in the pit. Ablation stakes are also placed at pit locations, and the ablation data is collected at the end of the field season. This accounts for any additional ablation that may occur after snow pits are dug,

and the end of the ablation season. The next step in determining mass balance is generating a balance gradient, which is the relationship between accumulation and elevation on the glacier. At the end of the ablation season, JIRP uses satellite data (namely the Moderate Resolution Imaging Spectroradiometer and LANDSAT, which are useful due to their high temporal resolution), to identify the ELA, which is used to make adjustments in the balance gradient to account for the final ablation during the season (McNeil 2013, Pelto et al. 2013, Miller and Pelto 1999).

Mass Balance from GRACE

GRACE utilizes Newton's Law of Gravity to detect local anomalies and changes in the earth's gravitational field. Thus, it is referred to as a gravimetric method. Mapping earth's gravity field enables users of GRACE data to determine changes in mass balance on the surface. GRACE data is provided as mascons (see Figure 1), which can be defined as "equal-area surface mass concentration parcels in equivalent heights of water" (Luthcke et al. 2013). The GRACE mission was launched by the National Aeronautics and Space Administration (NASA) in 2002.

GRACE can detect large scale variations in the gravity field (such as associated with mountains and deep trenches in the ocean), as well as smaller scale temporal variations in mass such as associated with the movement of water through the hydrologic cycle. These small scale mass variations are referred to as variations in earth's time-variable gravity field. GRACE obtains this information by operating as a single primary instrument, but actually consists of two identical satellites. These two satellites are separated by a distance of about 220 km, and orbit earth in the same plane. As the first satellite approaches an area of higher mass concentration, it

accelerates and hence pulls away from the second, so the distance between the two satellites increases. The second satellite accelerates back towards the first satellite when it reaches the gravity perturbation. A precise onboard microwave system keeps track of the distance between the satellites. Additionally, an accelerometer located at the center of mass of each satellite measures acceleration due to non-gravitational causes (such as drag from the atmosphere). Satellite Global Positioning Systems (GPS) are able to detect GRACE's location to within a centimeter of accuracy. The distance between the two satellites, acceleration of each, and their geographical location are used in combination to determine the location of mass anomalies every 30 days (Ward 2004). GRACE has a number of advantages over other satellite systems to obtain mass balance. Laser altimetry systems such as from the NASA ICESat (Ice, Cloud and land Elevation Satellite) mission (which transform elevation differences into mass variability) are influenced by firn density. Incorrect firn density measurements can confound laser altimetry mass variability estimates. Another shortcoming of optical remote sensing techniques, especially with respect to the Juneau Icefield, is that the icefield is often cloud-covered. While GRACE transcends these problems, it does have a disadvantage - GRACE is unable to differentiate between mass changes between the icefield itself and mass changes of the earth's surface below, such as variations resulting from glacial isostatic adjustments (this refers to the delayed response time of a viscous rising lithosphere due to melting of previously glaciated areas), ocean tides, atmospheric mass variations, and terrestrial water storage. Additionally, the spatial resolution of GRACE is low (Luthcke et al. 2013).

Previous Studies Using GRACE

Numerous studies have utilized GRACE mascon solutions to study mass balance, especially on large spatial scales such as the Greenland and Antarctic ice sheets. For Greenland, Velicogna and Wahr (2005) preferred GRACE for mass balance estimates over laser altimetry and model estimations because of Greenland's complexity and massive extent. Additionally, they pointed out that mass determination from GRACE is straightforward as it is derived directly from Newton's Law of Gravity, and thus the values are viewed as trustworthy. The one shortcoming of GRACE that they encountered was its inability to differentiate between mass changes on the ice sheet itself and postglacial isostatic rebound of Earth's underlying surface (Velicogna and Wahr 2005).

In a more recent study, Arendt et al. (2013) compared mass balance derivations from GRACE mascons and from ICESat for two Gulf of Alaska glaciers, and found a strong correlation between the two time series. However, there was still a strong discrepancy between field observations and GRACE mascon solutions which they attribute to signal leakages across glaciers and mascon boundaries, the nonuniform distribution of Gulf of Alaska glaciers, and ocean-glacier interface dynamics. Additionally, the study highlights that the snowpack on the ground that surrounds glaciers doesn't always melt in a given year, likely contributing to discrepancies between GRACE and ICESat (Arendt et al. 2013).

Data

The following sources were used in the present analysis:

- Version 12 GRACE mascon solution 1352 for the years 2003-2014 (mascon refers to mass concentrations of local mass variation parameterizations) (Arendt et. al 2008)
- Version 12 GRACE mascon 1353 for the years 2003-2014
- Annual surface mass balance for Taku glacier (2003-2014)
- Annual surface mass balance for Lemon Creek glacier (2003-2014)
- Temperature and precipitation record for Juneau, AK (2003-2009, as of this writing, data were unavailable past 2009)

Annual surface balances for Taku and Lemon Creek glaciers were provided as conventional balances, which were then summed to determine cumulative balances; or long term trends. Conventional mass balance is useful for determining the amount of water stored and released in one mass balance year, and thus is referred to as the annual balance (Huss et al. 2012). Cumulative balance is defined as the cumulative sum of annual balances over a span of time. This is useful in looking at long-term mass balance trends (see Figure 3). To make direct comparisons between annual surface balance values from GRACE mascon solutions and those derived from traditional methods, the GRACE data had to be converted into the same units as the field-based data (meters of water equivalent per year). Raw mascon data are provided in centimeters of water equivalent per year, which was divided by 100 and divided by the area over which the data was collected. Use is made of the GRACE Version 12 Data described by Lutcke et al. (2013). Version 12 GRACE data simply refers to the fact that it has been corrected for glacial isostatic adjustment, ocean tides, terrestrial water storage, and atmospheric mass

variations, and thus increases the confidence that the mass values reported are due to inter annual glacial mass fluctuations (Lutheke et al. 2013).

Methods

Before the analysis could begin, it was necessary to first assemble the required data sources. Recall that the glaciological measurements include data from snow pits and ablation stakes, and the gravimetric measurements were obtained from GRACE. The next step was to import all the data into the analysis program R to create graphs for initial comparisons between the gravimetric and glaciological mass balance values. Lemon Creek glacier was compared to the 1352 mascon, because the entirety of the Lemon Creek glacier lies within the area of the 1352 mascon. Taku glacier was compared to the average annual mass balance between mascons 1352 and 1353 because it straddles both. While the graphs provided a useful visual, the next step was to perform a statistical analysis between glaciological and gravimetric datasets. Linear regression was used to compare the gravimetric and glaciological estimates, as well as the glaciological estimates for Lemon Creek and Taku glaciers. Finally, the data was detrended to determine a more accurate correlation between Taku and GRACE, and Lemon Creek and GRACE (trends can artificially inflate correlations).

Results

It can be seen that the general patterns are the same between GRACE and the glaciological data (Figure 4). For instance, the years 2004 and 2009 had negative balances in each dataset, whereas 2008 and 2012 had positive balances in each dataset. That being said, there are notable differences in mass balance magnitudes. Lemon Creek glacier undergoes more dramatic negative balance years, whereas Taku's record shows smaller fluctuations. Moreover, both mascon 1352 and GRACE's mean annual balance follow the same general patterns as Lemon Creek and Taku, however the GRACE variations from year to year are quite small.

A comparison between the raw Lemon Creek record and the raw time series from GRACE mascon 1352 yields an R-squared value of 0.82 (with a p-value of .0003), indicating that 82% of the variance in the observed Lemon Creek record can be explained by the mass balance estimate from GRACE mascon 1352 (see Figure 6). This is a fairly strong association between the two datasets. A comparison between the raw Taku record and the corresponding GRACE time series yields an R-squared value of 0.80 (with a p-value of .0005), indicating that 80% of the variance in the field-based time series can be explained by the GRACE record (see Figure 5). This is also a fairly strong association.

However, the presence of trends will tend to inflate linear correlations. In the basis of detrended time series, the squared correlation between the Lemon Creek records versus GRACE mascon 1352 drops to 0.56 (with a p-value of .01), meaning that 56% of variation in GRACE mascon 1352 can be explained by Lemon Creek's values (see Figure 8). In turn, the squared

correlation between the two detrended time series for Taku falls to .63, with a p-value of .006 (see Figure 7).

Discussion

As shown in Figures 3 and 4, year to year mass balances for Taku and Lemon Creek glaciers are quite dynamic. To help understand these mass balance fluctuations, it is useful to compare precipitation and temperature data from Juneau for 2003 (a very negative balance year for both Lemon Creek and Taku glaciers) to data for 2008 (a strongly positive balance for Lemon Creek, and positive but less so at Taku). The year 2012 also had a strong balance year and would be useful for comparison, but meteorological data were unavailable. As shown in Figure 10, significantly more precipitation fell in Juneau during October of 2008 (38 cm) than in October of 2003 (11.8 cm). October marks the start of the accumulation season (and thus, the start of winter mass balance), so the fact that October of 2008 received three times as much precipitation as recorded in 2003 is consistent with 2008 being a positive balance. Figure 11 reveals that both summer and winter temperatures in Juneau were lower in 2008 as compared to 2003. The summer temperatures in particular also helps to explain the negative mass balance values for Taku and Lemon Creek glacier in 2003, and the positive mass balances in 2008. These conclusions of course assume that the climate data at Juneau is at least broadly representative of conditions over the glaciers. Unfortunately, Alaska is a data sparse region. Given the fact that Lemon Creek glacier is significantly closer to Juneau than Taku is, Lemon Creek's mass balance

values should arguably be more closely aligned with Juneau's meteorologic data. Interesting in this regard is that Taku also show a negative dip in 2003 and a positive spike in 2008, but to a lesser extent than Lemon creek. The stronger variability in Lemon Creek's mass balance can be explained by both the geographical orientation and size of the glaciers: Lemon Creek is a small glacier strongly influenced by coastal climate, whereas Taku glacier is further inland and less influenced by the coastal climate, and it is a significantly larger tidewater glacier.

Recall that the primary question at hand is whether GRACE captures the same variations in mass balance as the glaciological measurements. From Figure 4 it is evident that GRACE and glaciological measurements do show the same overall patterns, yet the GRACE data depict much smaller year to year variations. This can be attributed to the very different measurement scales. The GRACE footprint covers a much larger area than just the Taku and Lemon Creek glaciers, and thus is influenced by mass changes of surrounding glaciers on the Juneau Icefield. This would be acceptable if all the glaciers on the icefield behaved in the same manner, but it is clear from Figure 3 that this is not the case. To reiterate, the mass balance time series for Taku and Lemon Creek glaciers are strongly correlated, yet differences between the two glaciers in the magnitude of year to year variations are substantial. Besides comparing Taku and Lemon Creek mass balance to one another, the question at hand cannot be answered without looking at how Taku and Lemon Creek compare to GRACE itself.

The raw Taku and Lemon Creek time series show almost identical squared correlation with GRACE (80% vs. 82%). The correlations using the detrended data, as expected, are somewhat lower (63% for Taku, 56% for Lemon Creek). Based on the detrended data, the results

suggest is that overall, GRACE does a slightly better job at picking up on mass balance signals on the Taku glacier. This again may relate to scale. Taku is a large glacier, and thus it takes two GRACE mascon areas to even capture the whole extent. Lemon Creek is much smaller, and its mass balance values as reported by GRACE are more likely to be confounded by other glacier mass signals within the mascon. Additionally, recall that the GRACE data used for this analysis is the Version 12 data, which contains corrections for potential extraneous mass signals. This method of correction uses atmospheric models and relies on meteorological data, which as mentioned is very sparse in the mountainous regions of Alaska. The mascon extents include both glacial ice and ice-free land cover, and there is less ice cover around Lemon Creek versus Taku glacier (Arendt et al. 2009). Arendt et al. (2008) determined that “the ability of GRACE mascon solutions to resolve regional glacier changes increases with the amount of ice cover within a region.” This helps explain why Taku shows a slightly stronger correlation with GRACE than Lemon Creek. An r-squared value of 0.63 is actually a relatively strong correlation.

Conclusion

Traditional mass balance measurements are expensive and labor intensive, and are sometimes impossible to conduct due to the remoteness of glacial study areas. The use of gravimetry is thus an efficient and desirable alternative for areas which are inaccessible, and to gain a regional glacier change understanding when combined with glaciological data. GRACE has successfully been used in determining the mass balance of the Greenland and Antarctic ice

sheets. However, as the present study shows, GRACE must be used with caution when applied to smaller scales. The quality of gravimetric data has improved over the years. For example, while Vilacogna and Wahr (2005) were discouraged by the inability of GRACE to discern between isostatic rebound and true glacial mass, Arendt et al. (2013) had the advantage of using the Version 12 GRACE data which has corrections for noise covariance, including isostatic rebound. However, there are still concerns in applying GRACE to assess the mass balance of mountain glaciers. The largest sources of error lie in the inferred glacier mass that gets transferred between mascons, and the nature of the gravimetric measurement itself. In the present study, it was shown that while GRACE was able to capture the basic patterns of fluctuation in observed mass balance, the correlation between the two datasets, while actually quite strong, is lower than desired. However, in the case of Taku and Lemon Creek glaciers, GRACE nevertheless can be viewed as doing an adequate job in capturing mass balance.

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Figures

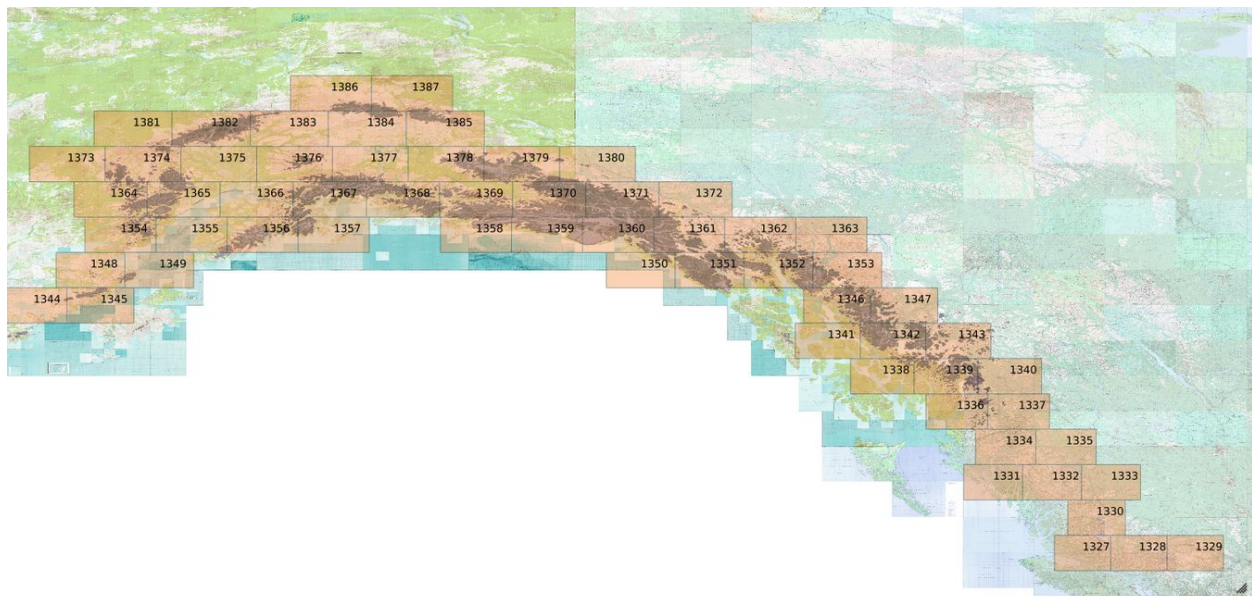


Figure 1. Map of southeast Alaska showing the location of GRACE mascons. The present study uses data for mascons 1352 and 1353. Taku Glacier lies between the two mascons, whereas Lemon Creek is contained within mascon 1352 only.

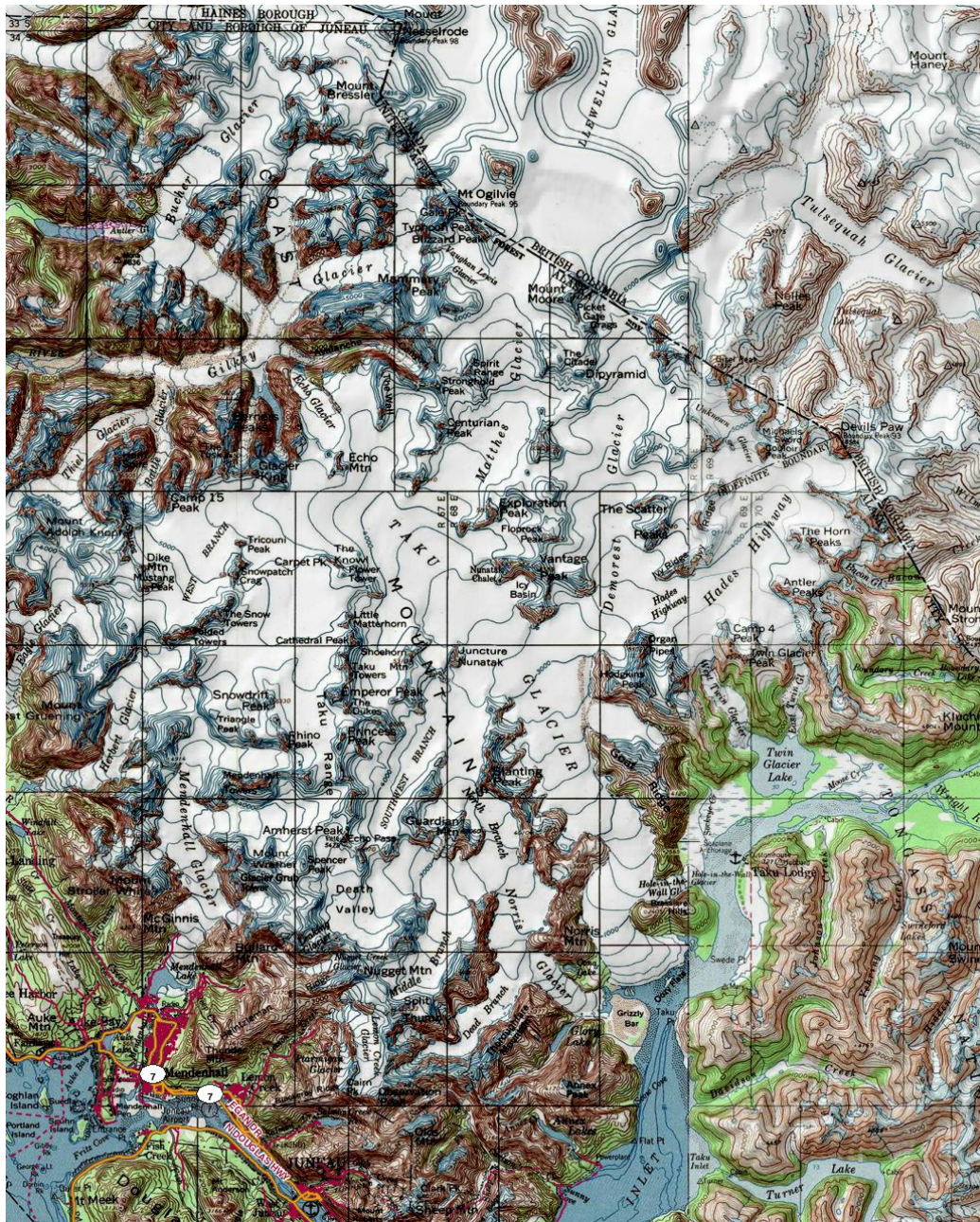


Figure 2. Topographic map of the Juneau Icefield, showing the Lemon Creek glacier (southernmost glacier on the icefield) and the Taku glacier (large glacier running from NW to SE).

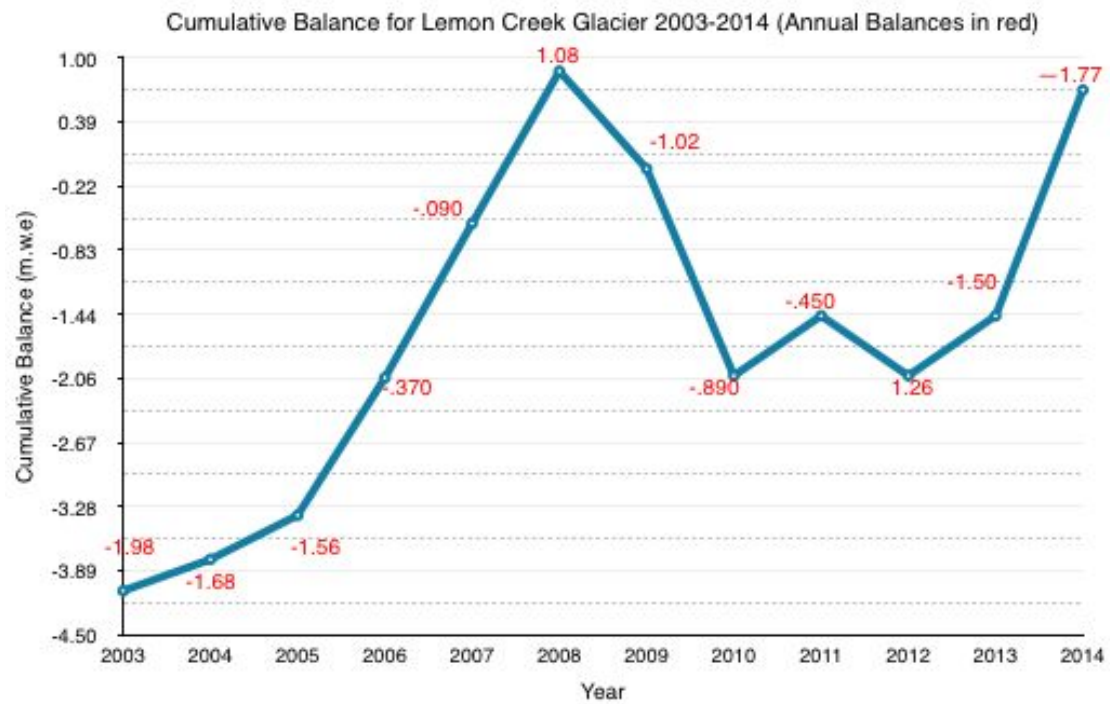
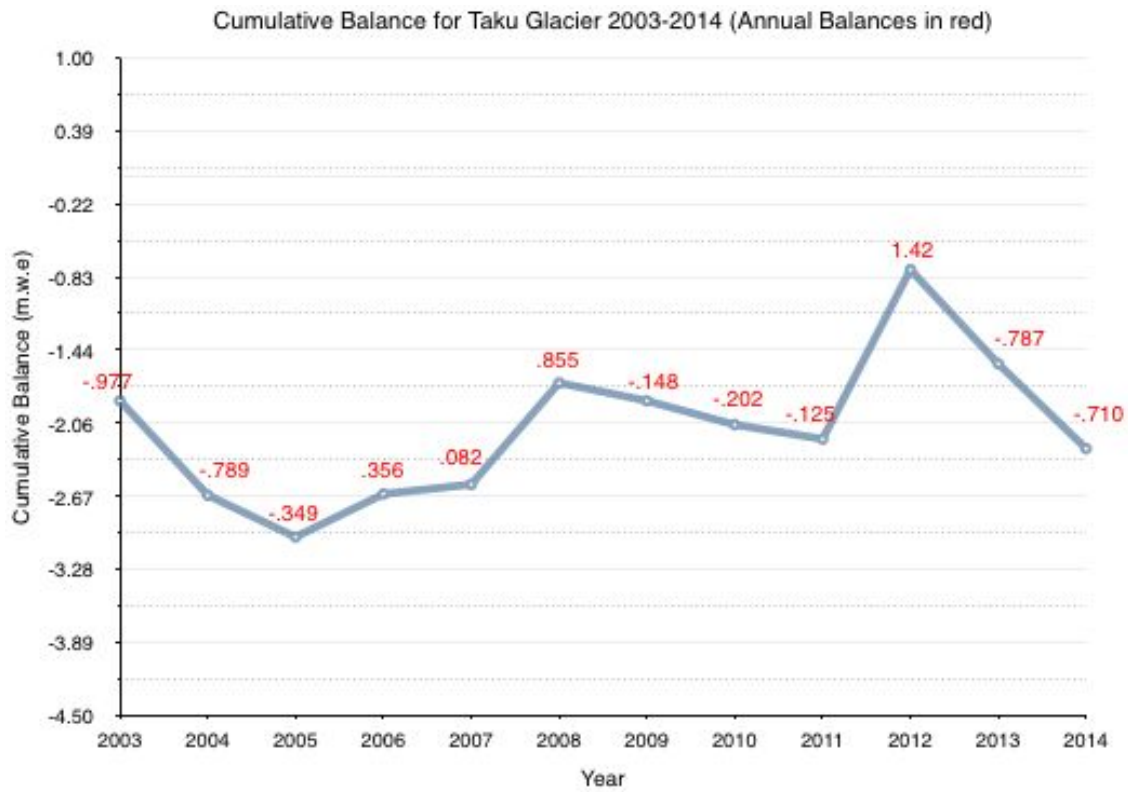


Figure 3: Time series of the cumulative mass balance (blue lines) Taku and Lemon Creek Glaciers for the years 2003-2014 and mass balance values for individual years (values in red).

Comparison of Gravimetric vs. Glaciological Annual Balances of Taku and Lemon Creek Glaciers for 2003-2014

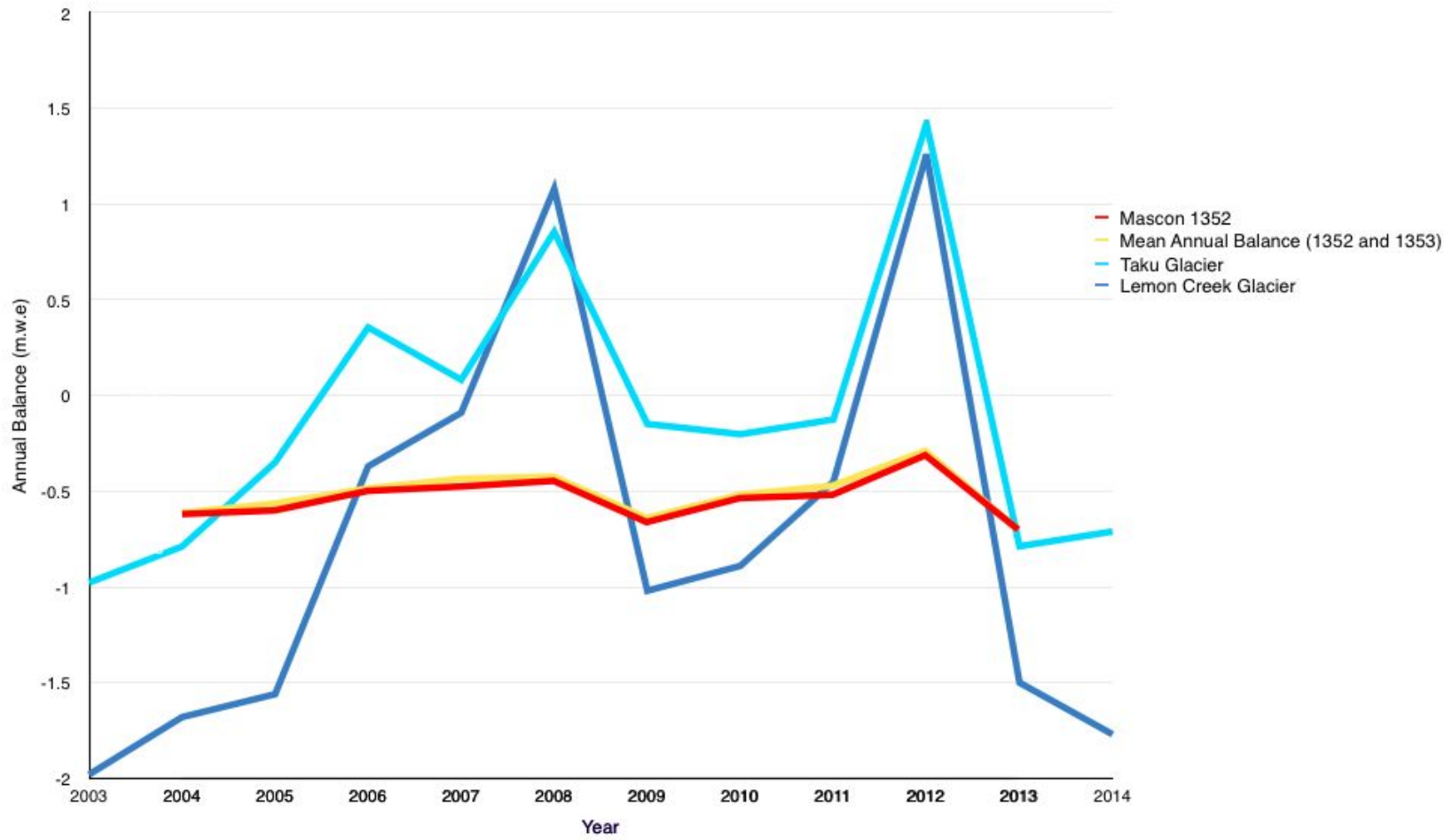


Figure 4: Comparison of glaciological measurements and GRACE annual mass balances for the Taku and Lemon Creek glaciers.

Correlation Between Gravimetric and Glaciological Measurements of Mass Balance on Taku Glacier

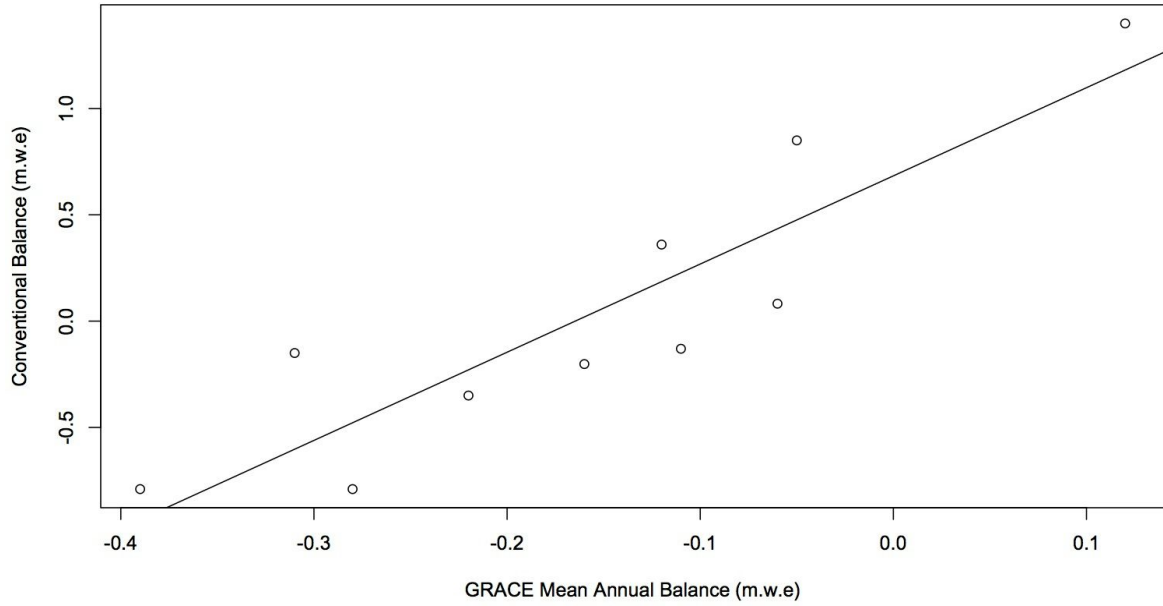


Figure 5: Linear regression between GRACE and glaciological mass balance measurements for Taku glacier. R-squared = .799

Correlation Between Gravimetric and Glaciological Mass Balance Measurements of Lemon Creek Glacier

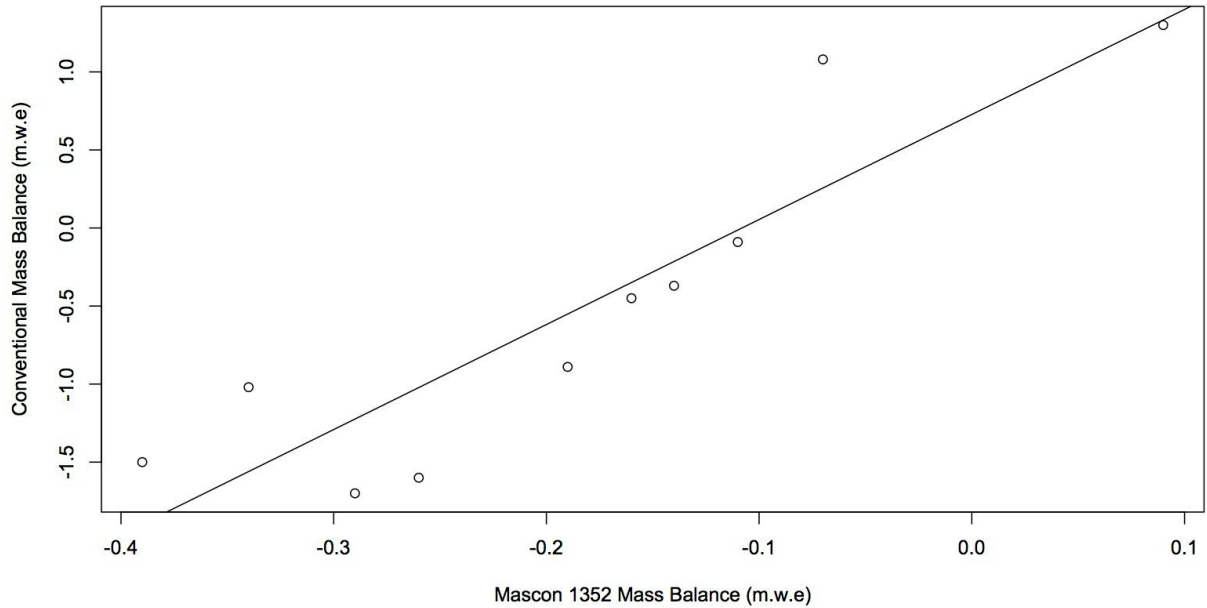


Figure 6: Linear regression between GRACE and glaciological mass balance measurements for Lemon Creek glacier. R-squared = .8154

Linear Regression Between De-Trended Gravimetric and Glaciological Measurements of Taku Glacier

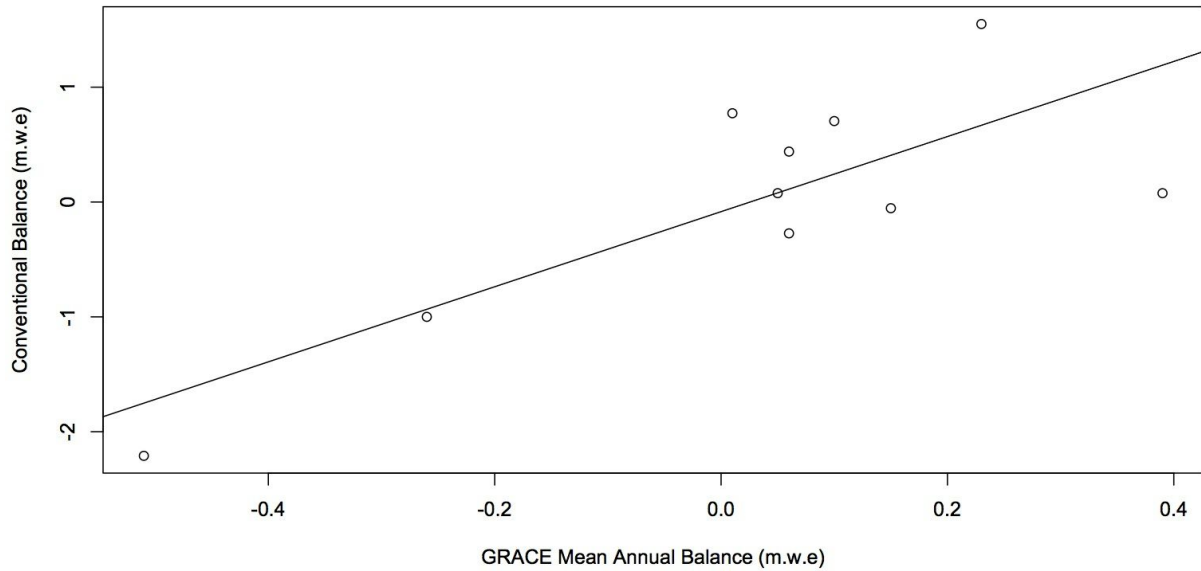


Figure 7: Linear regression between detrended GRACE and glaciological mass balance measurements for Taku glacier. R-squared = .6281

Linear Regression Between De-Trended Gravimetric and Glaciological Measurements of Lemon Creek Glacier

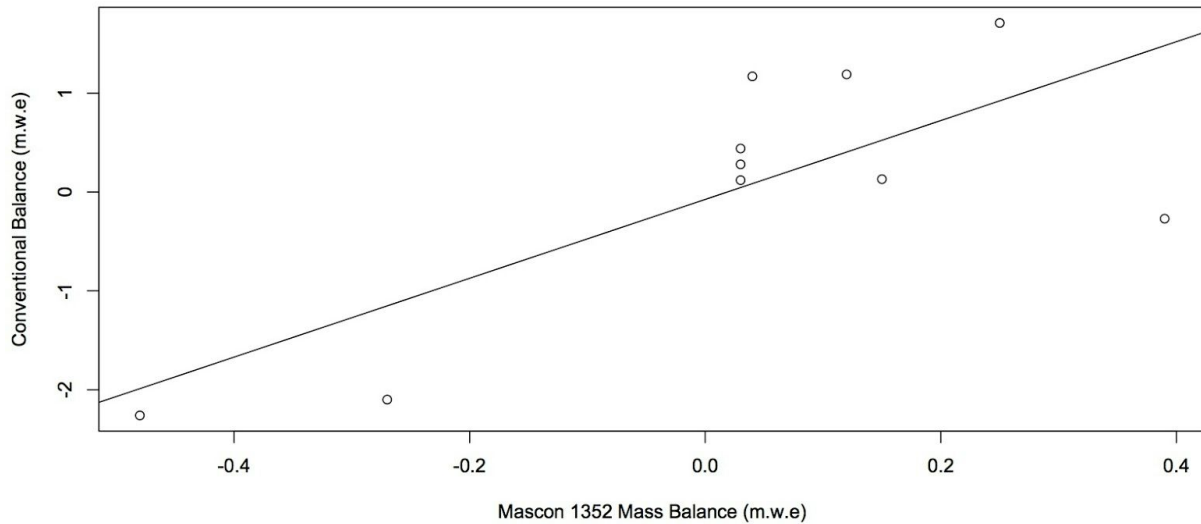


Figure 8: Linear regression between detrended GRACE and glaciological mass balance measurements for Lemon Creek glacier. R-squared = .5621

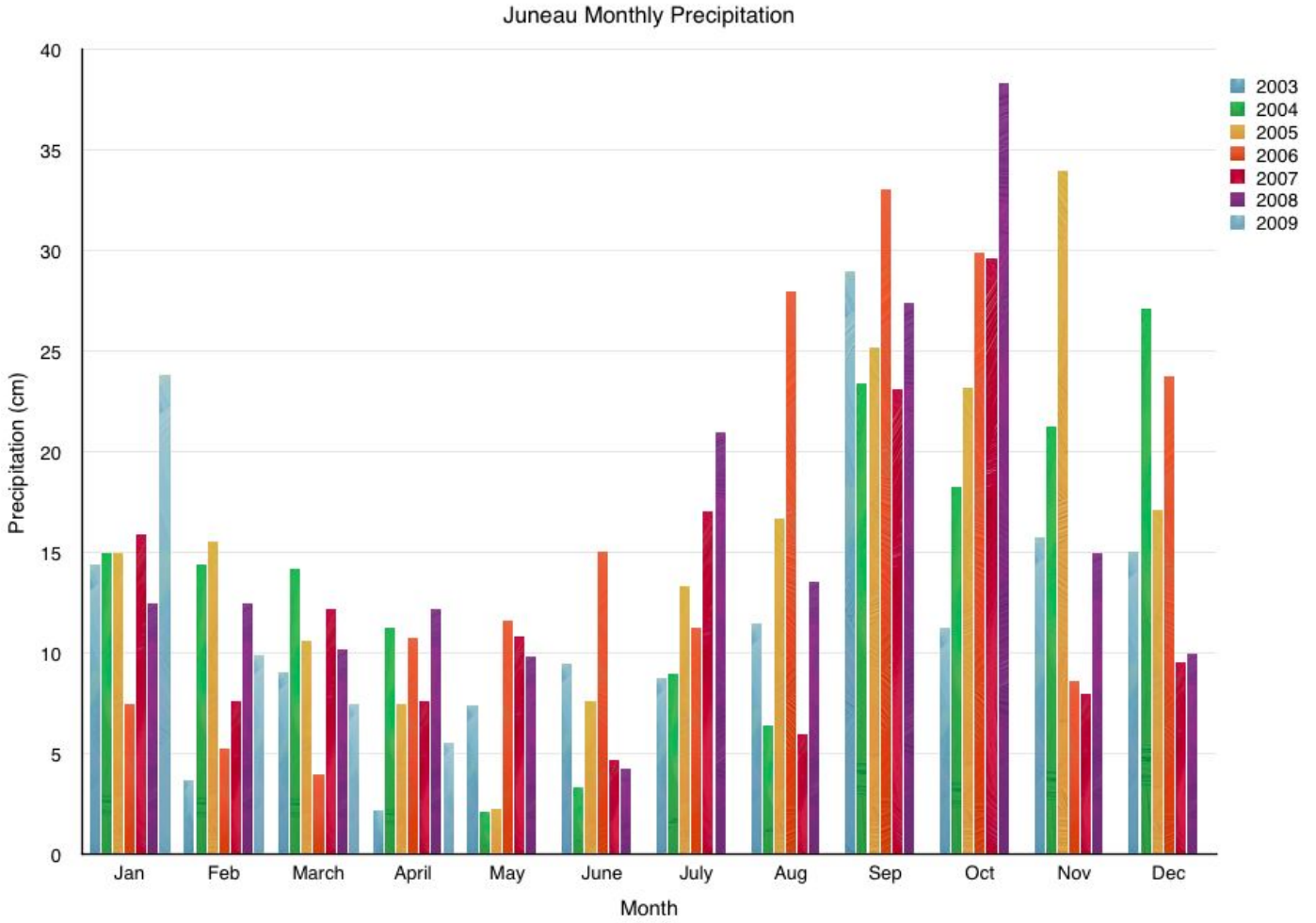


Figure 10: Juneau monthly precipitation

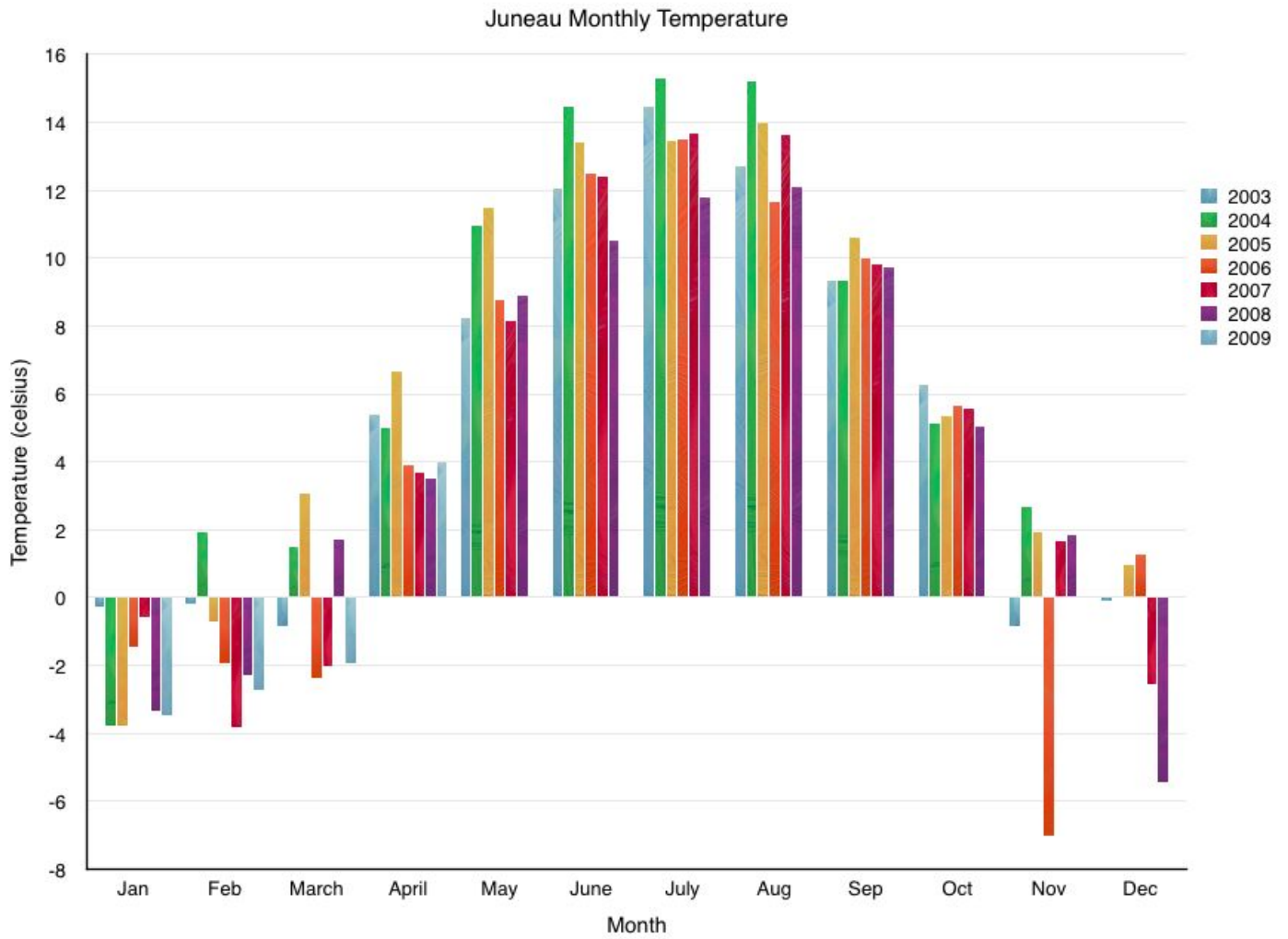


Figure 11: Juneau monthly temperature