Examining the Glacial Mass Balance of the Arikaree Glacier, Front Range, Colorado Using GIS and Degree Day Methods

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ABSTRACT

The health of glaciers around the world is threatened by anthropogenic climate change as rising temperatures and changing precipitation patterns affect mass balance of glaciers. The manifestations of global climate vary at the regional level, in both magnitude and direction of temperature and precipitation changes. For this reason, glacier response is not expected to be uniform across different seasons and in different places. Based on precipitation totals and wind patterns, there is evidence that alpine glacier mass balance might actually be positive in some locations. This study focuses on the Arikaree Glacier in the Front Range of Colorado, USA. I use snow depth measurements taken on the glacier at peak accumulation and measured air temperatures to derive a degree day calculation of ablation and to produce a plausible mass-balance for each year from 1997 to 2017. I found that the Arikaree Glacier has experienced a negative mass balance each year since 1997. Future research should utilize a more detailed approach to this form of mass balance calculation and assess other small mid-latitude glaciers to see if they are experiencing the same results.

INTRODUCTION

Mass balance studies of glaciers are good indicators of climate change, particularly small cirque glaciers (Barreto, 1994). This is because there is no distinct accumulation and ablation areas, so the entire glacial surface is more responsive to changes in surface mass balance. Increasing temperatures from anthropogenic climate change are causing many glaciers to melt and experience negative mass balance (Gregory, Stocker, Lemke, & Bindoff, 2007). This is particularly noticeable in higher latitude, maritime environments where small changes in temperatures are causing lower elevation snow to melt out or even fall as rain in the winter season. In a study of 67 Alaskan glaciers, Arendt et al. (2002) found that from the mid-1950s to mid-1990s, the Alaskan glaciers studied had an average rate of thickness change of -0.52 meters per year. A secondary study of 28 of the 67 glaciers found an even greater increase in rates of thinning. From the mid-1990s to early 2000s, glaciers thinned at an even greater average rate of -1.8 meters per year (Arendt, Echelmeyer, Harrison, Lingle, & Valentine, 2002). In the Cascade mountain range in the Pacific Northwest, there have been large losses in both snowfall and snowpack during the 1900s, with some regions experiencing declines of 60-80% of the snowpack (EPA, 2016; Mote, Hamlet, Clark, & Lettenmaier, 2005), which can be seen in Figure 1.

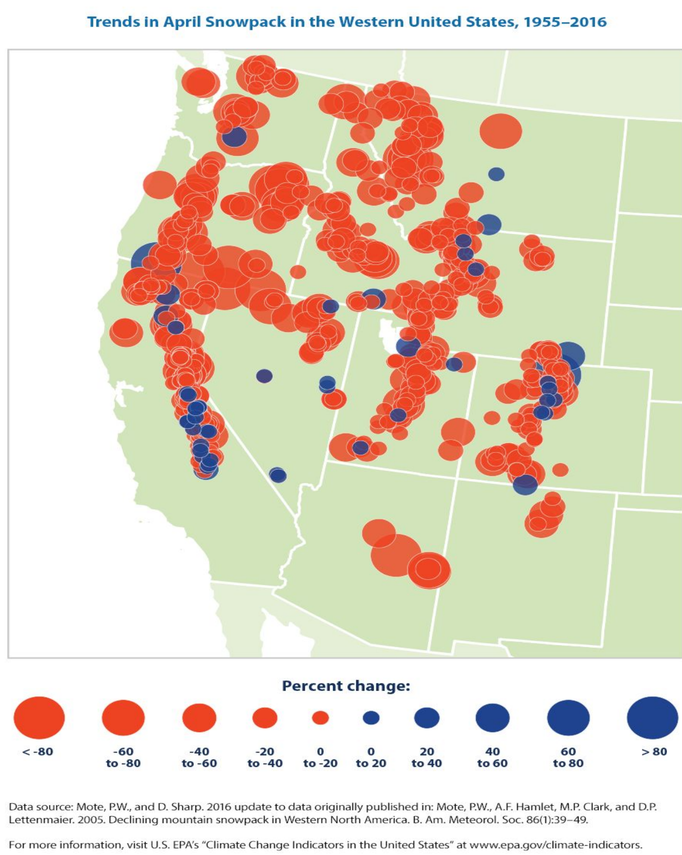

Figure 1. Snowpack trend in the Western United States from 1955 to 2016 (retrieved from (EPA, 2016). The Pacific Northwest has seen significant losses in April snowpack, indicating that snow is melting earlier than normal or falling as rain.

Climate in the Southern Rockies is less consistent and varies considerably from year to year. Some years can yield very large snowpack and others can be very dry. The Indian Peaks receive roughly 35-60 inches (~89-152 cm) of precipitation each year, well above the average of 15.47 inches (~39 cm) for the state of Colorado (National-Atlas, 2005). Winter weather is generally cold and windy, with some gusts reaching above 20 m/s in velocity (Barreto, 1994). Summers are typically mild and much less windy than winters. Temperatures can get above 60 °F (~15.5 °C) on the high peaks and afternoon thunderstorms are notorious (Barreto, 1994). Inconsistencies in weather also occur during summer. Some summers can be wet and stormy, and others hot and dry. These climate factors heavily influence the mass balance of the Arikaree Glacier (Barreto, 1994; Johnson, 1979).

Two major mass balance studies have already been done on the Arikaree Glacier. The first was done by James Johnson in 1979 and the other was done by Henrique Barreto in 1994. These mass balance studies involved stake methods to measure the ablation and were conducted using data collected over multiple years: 1969-1974 (Johnson, 1979) and 1992-1993 (Barreto, 1994). Both revealed that the overall swings of positive or negative mass balance are largely influenced by how stormy the ablation (summer melt) season is. If the ablation season is stormy, there is increased cloud cover, which inhibits the amount of incoming direct solar radiation on the glacier (Johnson, 1979). Due to the high variability in net mass balance of the Arikaree Glacier, some years can yield large positive mass balances and others can be large negative mass balances.

Colorado and the Southern Rockies do not receive enough annual snowfall during the winter to allow persistent snow year-round. The 40°N latitudinal position results in a high angle of inclination of the sun during summer, resulting in a complete melt during the summer. The reason glaciers persist in Colorado to this day is because these glaciers receive a large portion of the total accumulation during winter as wind-blown snow which enhances the winter snow accumulation. These regions are also typically protected by large cirque walls, which limits the amount of solar radiation received throughout the day during summer (Johnson, 1979). Large windstorms during the winter season in combination with some of the highest rates of snowfall in the state provide the Arikaree Glacier with a large accumulation of snow during winter, while the cirque walls limit the amount of ablation during summer.

Maintaining a high albedo is also critical to the survival of the glacier for periods when it is sunny. A high albedo reflects more sunlight and limits the amount of melting that occurs on the glacier. Refreshing the albedo is achieved after each snowfall, but it is most important in late-spring and early-summer snowfalls to provide a refresh during the ablation season when solar incidence is highest. New snow is the most reflective form of snow with about 90% reflectance (Warren, 1984). As the snow sits, larger crystals form from snow metamorphism (Cuffey & Paterson, 2010; Warren, 1984). Larger crystals have a greater surface area and can absorb more sunlight, hence, lowering the albedo. Other factors influencing the albedo are dust and soot, which are often dark in color.

Despite increasing temperatures globally, there is reason to believe that the Arikaree Glacier might actually be gaining size due to recent findings that indicate greater precipitation totals in winter and small increasing trends in precipitation during summer (Kittel et al., 2015). The increasing trends in precipitation are observed at nearby climate station D-1 (Fig. 2), which show large increases in winter precipitation over a long period indicating that more snowfall is occurring on average. There is also a slight increase in precipitation during summer, giving reason to believe that summers are stormier as well. Stormier summers would indicate more cloud cover to limit the ablation on the glacier. Kittel et al. (2015) conclude that the D-1 site experienced significant increasing trends in winter precipitation due to changes in synoptic weather patterns across North America and changes in precipitation generation from mesoscale interaction of synoptic circulation with local topography. They found increases of 21-126% monthly wintertime precipitation totals at the D-1 site. It was concluded that a shift from southwesterly to northwesterly winds favored more orographic uplift and increased precipitation on the windward side of the Continental Divide, as well as the areas just east of the divide due to a “spillover” effect.

Southwesterly winds favor precipitation in the lower elevations and northwesterly winds favor precipitation in high elevations (Kittel et al., 2015).

Despite ablation being the greatest influence on survival of the Arikaree Glacier, increased accumulation on the glacier certainly helps in refreshing the albedo and creating a larger mass of snow to be melted before ice layers are potentially being melted. In other words, if there is a heavy ablation season, the resulting ice layers that would be melted will be delayed until all the accumulated snow is melted first. By obtaining accumulation and ablation data, a mass balance can be calculated over twenty-one years. The health of the Arikaree Glacier can then be determined and give insight into the fate of other glaciers in Colorado's Front Range and to potentially see if there are other small mid-latitude alpine glaciers around the world experiencing the same results as the Arikaree Glacier. It might also provide further research opportunities to study how areas are experiencing increased levels of precipitation and gains in snow accumulation.

BACKGROUND

The Arikaree Glacier is nestled in between Arikaree Peak and Navajo Peak in Colorado's Front Range Indian Peak Wilderness Area (Fig. 2). The location coordinates of the Arikaree Glacier are 40°3'10"N 105°38'20"W (Johnson, 1979). The majority of the glacier sits at the base of Arikaree Peak but extends out toward Navajo Peak in a half moon shape. The glacier is located within the Green Lakes Valley as part of the upper Boulder Creek watershed. The northern boundary of the watershed is Niwot Ridge, where alpine research occurs as part of the Niwot Ridge Long-Term Environmental Research (LTER) program within the University of Colorado's Mountain Research Station. The true size of the Arikaree Glacier is still unknown. The Global Land Ice Measurements from Space (GLIMS) data suggests that the glacier is 52,556 m^2 in size ("Arikaree Glacier CO," 2016). When creating a polygon overlay in Google Earth, the calculated size is just over 50,000 m^2. Both of these estimates are smaller than what Johnson (1979) and Barreto (1994) determined. Johnson estimated the glacier to be 55,000 m^2, while Barreto estimated the glacier to be 64,000 m^2.

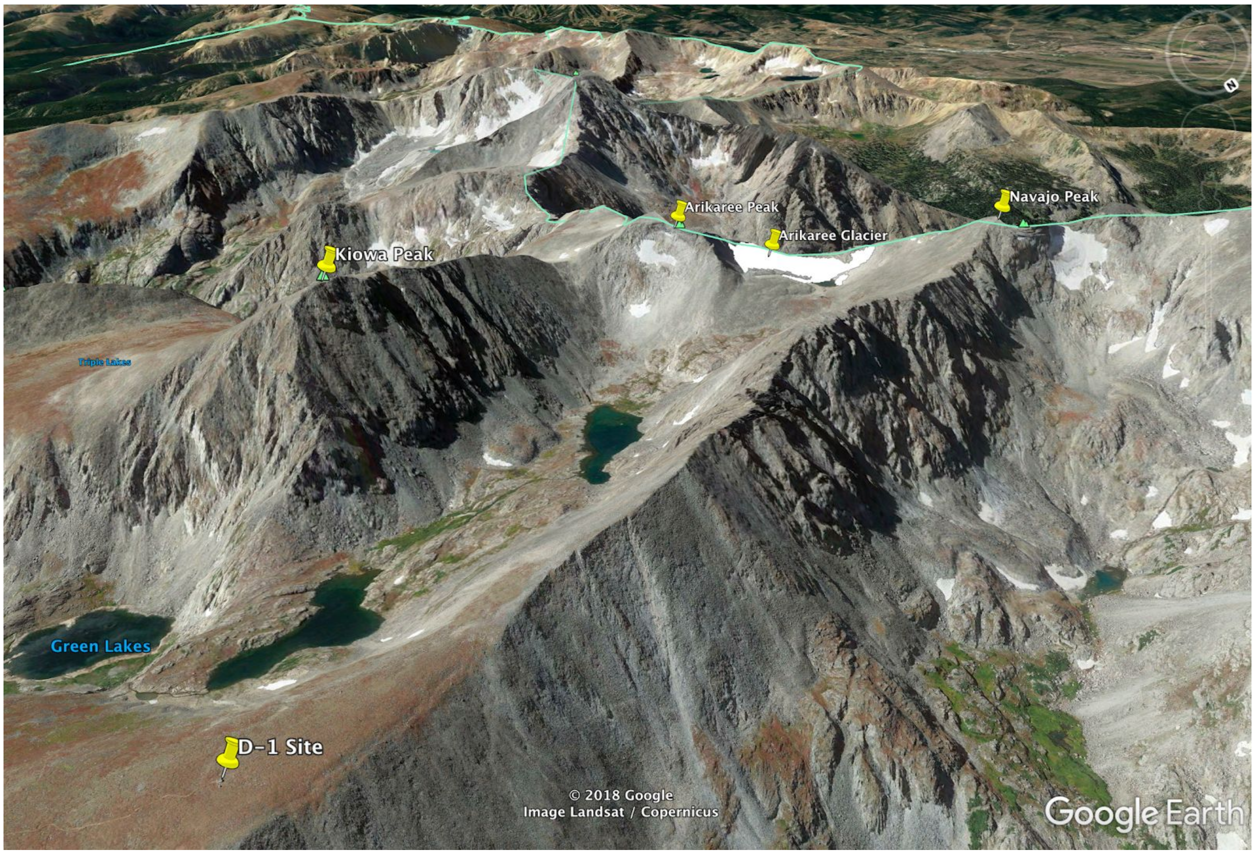

Figure 2. Oblique aerial Google Earth image of the Arikaree Glacier and surrounding Green Lakes Valley. The Arikaree Glacier sits at the head of the Green Lakes Valley beneath the north side of Arikaree Peak. Image is viewed looking southwest. Green line indicates Continental Divide.

METHODS

Temperature and Precipitation

Data collection in order to determine the mass balance of the glacier involved field measurements on the glacier as well as data from the Niwot Ridge LTER website. This data is part of the LTER program through the Institute for Arctic and Alpine Research (INSTAAR) and the University of Colorado.

Temperature data for the D-1 site on Niwot Ridge was used to evaluate temperature trends (Losleben, 2006a). This data was used to assess temperature changes on Niwot Ridge since the completion of Barreto's study in 1993. Air temperature at the D-1 site was analyzed from November 1, 1993 to present. The data used in this study was selected to start on November 1, 1993 in order to correspond with the start of the next glacial accumulation-ablation season following the completion of the study of Barreto (1994). By downloading the air temperature data from the Niwot Ridge website, the data was sorted out to only obtain the data from November 1, 1993 to the present. Days with 'no data' were filtered out and then a scatter plot was made (Fig. 3). By obtaining a trendline, a slope was obtained in order to calculate the temperature change at D-1 from the end of Barreto's study to the present. The D-1 site has temperature and precipitation measurements that are representative to those of the Arikaree Glacier despite being further east and lower in elevation.

There already has been data collected for precipitation on Niwot Ridge (Losleben, 2006b). For recent precipitation tends, precipitation data was collected at the D-1 site and sorted to obtain days that recorded a value for precipitation. In other words, the dates with 'no data' or a '0' were filtered out. Next, the data was broken up into winter months (October-May), assuming that all of this precipitation fell as snow and contributed to accumulation on the glacier. The values were summed for each winter to give a precipitation total for that season. Lastly, a scatter plot was made to evaluate for any trend in precipitation at the D-1 site over the course of 24 years (Fig. 4).

Accumulation

For accumulation data on the Arikaree Glacier, a snow pit was dug on the east side of the glacier near the moraine and glacial pool. The total snow depth as well as snow density were measured in order to calculate the snow water equivalent. As part of the annual Snow Survey, conducted at peak SWE, around 500 other point samples (some on the glacier) were recorded throughout Green Lakes Valley to help with estimating the depth of snow on the glacier for the winter year accumulation. For each year, the snow depth measurements and coordinates were put into the ArcGIS program. I ran the Inverse Distance Weighting tool to help estimate the different snow accumulation totals on different parts of the glacier. The Inverse Distance Weighting (IDW) tool was confined to the Green Lakes Valley barrier to get the snow depth across the entire basin. By downloading the outline of the Arikaree Glacier, the spatial snow depths from the IDW tool were then clipped to the outline of the Arikaree Glacier using the Clip tool. From here, the Raster to Point tool was used to convert the spatial snow depth raster into points in order to calculate an average. Once the raster was a set of points, the average was obtained by looking up the mean of the depth within the field statistics in the attribute table. This was done in order to estimate the snow depth across the entire glacier surface because snow accumulation is not a consistent depth across the entire glacier. Some areas are much deeper than others due to snow redistribution from wind (Barreto, 1994). The calculated accumulation based on the average from the field statistics was then multiplied by the measured density of the Arikaree snow pit for each year based off the Snow Survey. Snow water equivalent data and snowpack model data were downloaded from the Niwot Ridge website ("Geospatial Data Layers for Niwot Ridge LTER," 1997; Williams, 1993a, 1993b).

Some years could not be run under the IDW tool due to the fact that there was no 'depth' or 'snow depth' identification to be used as an input for the tool. Instead, these years (2002, 2004, 2006, and 2010-2014) were estimated based off the average IDW accumulation for the other years and the average snow water equivalent for each snow pit dug at the Arikaree site during the Snow Survey. Some years also did not have densities measured for the Arikaree snow pit, so the average of the other years was used (391 kg/m^3).

Ablation

A degree day method was used to estimate summertime ablation for each season based on the average air temperature values. Temperature index degree day methods are a very common way of measuring ablation due to the wide availability of air temperature data, relatively easy interpolation and forecasting possibilities of air temperature, generally good model performance despite simplicity, and the simplicity of computation (Hock, 2003). Some temperature index degree day methods have had a 0.96 correlation coefficient with true ablation (Hock, 2003) indicating the reliability of this method to estimate ablation on glaciers. Temperature index degree day methods have a high correlation with air temperature because both sensible and latent heat fluxes are heavily affected by air temperature.

To utilize the temperature degree day methods, the air temperature data from site D-1 was used with a -1.7 °C offset to get the average temperature at the Arikaree Glacier. This is because the Arikaree Glacier is 1.7 °C colder than site D-1 on average (Barreto, 1994) despite only being ~50 m higher in elevation. The data was then sorted to remove days with 'no data' and then sorted again to obtain values that have positive air temperatures (greater than 0 °C). Days above 0 °C are assumed to have melting occurring. The positive air temperature days were then summed up for each ablation season and then multiplied by a degree day factor. The degree day factor is a coefficient that the days above 0 °C sum is multiplied by and is based on a range of factors including latitude, humidity, maritime or continental climate, etc. For the sum, each temperature above zero is summed for the total ablation. For example, if there are temperatures of 5, 2, and 3 °C for three days, then the sum would be 5+2+3 for a total of 10. For the Arikaree Glacier, a degree day factor coefficient of 5.6 was used. This value was chosen because it is in between the degree day factors for the Alps and the Himalayas based on Table 1 in Hock (2003) for snow melt and at roughly the same latitudes and elevations.

Mass Balance

Once there were accumulation and ablation estimates for the glacier, the annual mass balance was calculated by subtracting the total ablation from the total accumulation (accumulation - ablation). If this value was positive, then the glacier gained mass for the year. If the value was negative, then the glacier lost mass for the year. By doing this over the course of the study (years 1997-2017), one of three different scenarios could be concluded: either the glacier is gaining size overall, losing size overall, or the mass balance varies from year to year and there is no overall trend in the data. Based on the results and analysis of previous mass balance studies, the overall health of the Arikaree Glacier can be determined.

RESULTS

Over the study period, a linear regression shows a -0.0002 °C/day slope in the air temperature at the D-1 site, suggesting that the average air temperature is actually getting colder in the alpine environment on Niwot Ridge (Fig. 3). Over the course of the data collection from 11/1/1993 to 12/31/2017, there was a -1.77 °C temperature change. Precipitation data revealed that there is an increase in winter precipitation at site D-1 by an amount of 1.94 mm per year (Fig. 4).

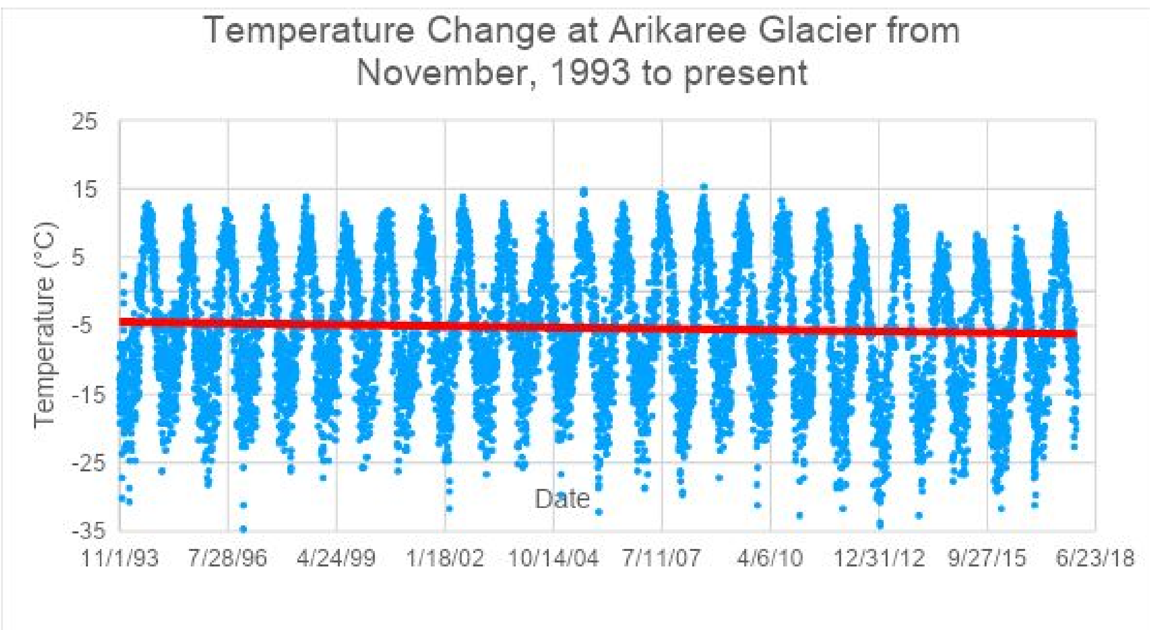

Figure 3. Air temperature data for the Arikaree Glacier, 11/1/1993 to 12/31/2017. There is an overall decrease in the average temperature from 1993-2017, resulting in an average temperature change of -1.77 °C over the course of the study. Days that consisted of 'no data' were removed from the study.

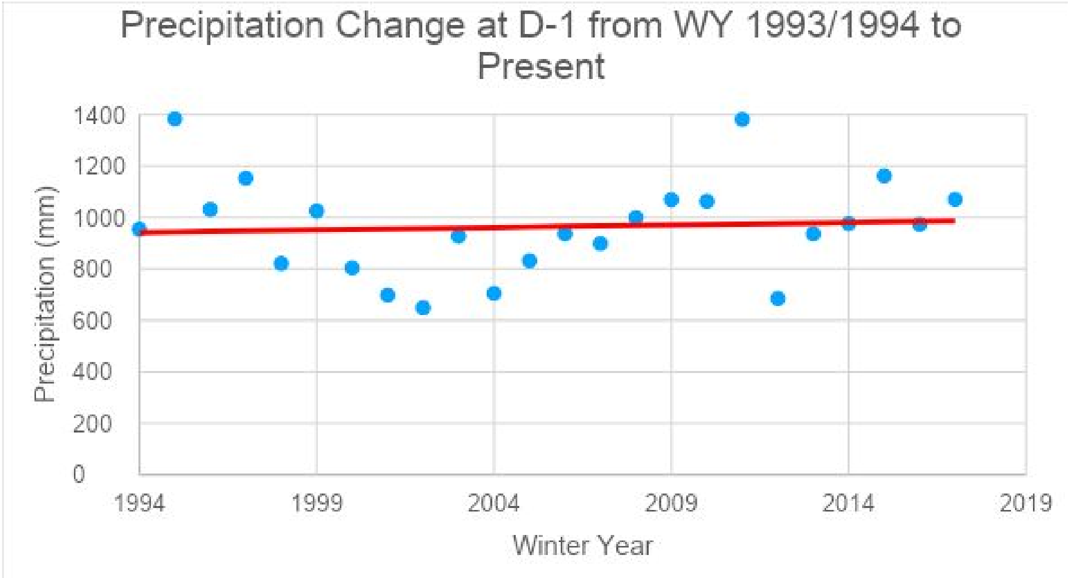

Figure 4. Precipitation data at site D-1 from winter year 1993-1994 to winter year 2016-2017. There is an overall increase in the annual precipitation across the study period. Days that consisted of 'no data' were removed from the study. Precipitation totals for the Arikaree Glacier are assumed to be greater than site D-1 due to being at a higher elevation and closer proximity to the Continental Divide, but the overall trend is assumed to be the same.

Accumulation estimates on the Arikaree Glacier vary significantly from year to year (Table 1, Fig. 5). The average snow accumulation for a given year was about 3.90 meters. The highest estimate of accumulation occurred in 1997 with almost 6 meters of snow accumulation. The lowest snow accumulation occurred in 2016 with 2.24 meters of snow accumulation. However, once multiplied by the density of the Arikaree snow pit for each year in order to obtain the snow water equivalent, the accumulations vary substantially less (Fig. 5). The year 1998 saw the greatest amount of water equivalent accumulation with 2.5 meters. The lowest water equivalent accumulation year occurred in 2016 with only 0.7 meters. A statistical t-test revealed that there is a significant trend in the negative direction of snow water equivalent accumulation.

Table 1. Accumulation data for the Arikaree Glacier from 1997-2017. Results were calculated using GIS tools based off of snow depth measurements taken at the annual Snow Survey. Years 2002, 2004, 2006, and 2010-2014 were estimated.

Year	Amount (cm)	Amount (m)	Density	Density (%)	Accumulation (m w.e.)
1997	599	5.99	332	0.332	2.0

1998	482	4.82	511	0.511	2.5
1999	504	5.04	391	0.391	2.0
2000	495	4.95	391	0.391	1.9
2001	358	3.58	391	0.391	1.4
*2002	319	3.19	386	0.386	1.2
2003	440	4.40	365	0.365	1.6
*2004	393	3.93	455	0.455	1.8
2005	406	4.06	391	0.391	1.6
*2006	414	4.14	365	0.365	1.5
2007	234	2.34	383	0.383	0.9
2008	334	3.34	391	0.391	1.3
2009	472	4.72	441	0.441	2.1
*2010	338	3.38	348	0.348	1.2
*2011	398	3.98	348	0.348	1.4
*2012	425	4.25	440	0.440	1.9
*2013	381	3.81	416	0.416	1.6
*2014	357	3.57	315	0.315	1.1
2015	324	3.24	386	0.386	1.3
2016	224	2.24	317	0.317	0.7
2017	310	3.10	447	0.447	1.4

Total ablation for years 1997-2017 yielded an average of 3.9 meters of water equivalent (w.e.) being melted each year (Table 2, Fig. 6). The highest year of ablation was 2007 with over 6 meters of water equivalent being lost, while the lowest year of melting occurred in 2014 with only 1.5 meters of water equivalent being lost. After conducting a t-test for snow water equivalent ablation, I found that there is also a significant negative trend.

Table 2. Results for total ablation using a Degree Day Method for years 1997-2017. Ablation Melt was calculated by taking the sum of days above 0 °C multiplied by the Degree Day Factor of 5.6.

Ablation Year	Sum of days above 0 degrees Celsius	Ablation Melt (mm w.e.)	Ablation Melt (m w.e.)
1994	905.8	5072	5.1
1995	565.1	3165	3.2
1996	780.6	4371	4.4
1997	749.6	4198	4.2
1998	745.7	4176	4.2
1999	670.4	3754	3.8

2000	836.1	4682	4.7
2001	789.8	4423	4.4
2002	833.5	4668	4.7
2003	727.5	4074	4.1
2004	517.8	2900	2.9
2005	759.5	4253	4.3
2006	703.8	3941	3.9
2007	1085.9	6081	6.1
2008	930.4	5210	5.2
2009	887	4967	5.0
2010	861.4	4824	4.8
2011	628.7	3521	3.5
2012	400.6	2243	2.2
2013	765.1	4285	4.3
2014	259.2	1452	1.5
2015	315	1764	1.8
2016	337.1	1888	1.9
2017	650.6	3643	3.6

Each year of the study yielded a negative mass balance (Table 3, Fig. 7). However, the negative value for net balance varied considerably from year to year. Some years were very close to reaching equilibrium while other years were largely negative. The largest negative year occurred in 2007 with over 5 meters of water equivalent loss and the smallest negative year occurred in 2014 with a 0.3 meter loss in water equivalent. A t-test showed that the positive trend in net balance is significant.

Table 3. Net Mass Balance for the Arikaree Glacier from 1997 to 2017. Net Mass Balance was calculated by subtracting the ablation from the accumulation. Positive values suggest that the glacier gained mass for the year, while negative values suggest that the glacier lost mass for the year.

Year	Accumulation	Ablation	Net Balance (m w.e.)
1997	2.0	4.2	-2.2
1998	2.5	4.2	-1.7
1999	2.0	3.8	-1.8
2000	1.9	4.7	-2.7
2001	1.4	4.4	-3.0
2002	1.2	4.7	-3.4
2003	1.6	4.1	-2.5
2004	1.8	2.9	-1.1
2005	1.6	4.3	-2.7

2006	1.5	3.9	-2.4
2007	0.9	6.1	-5.2
2008	1.3	5.2	-3.9
2009	2.1	5.0	-2.9
2010	1.2	4.8	-3.6
2011	1.4	3.5	-2.1
2012	1.9	2.2	-0.4
2013	1.6	4.3	-2.7
2014	1.1	1.5	-0.3
2015	1.3	1.8	-0.5
2016	0.7	1.9	-1.2
2017	1.4	3.6	-2.3

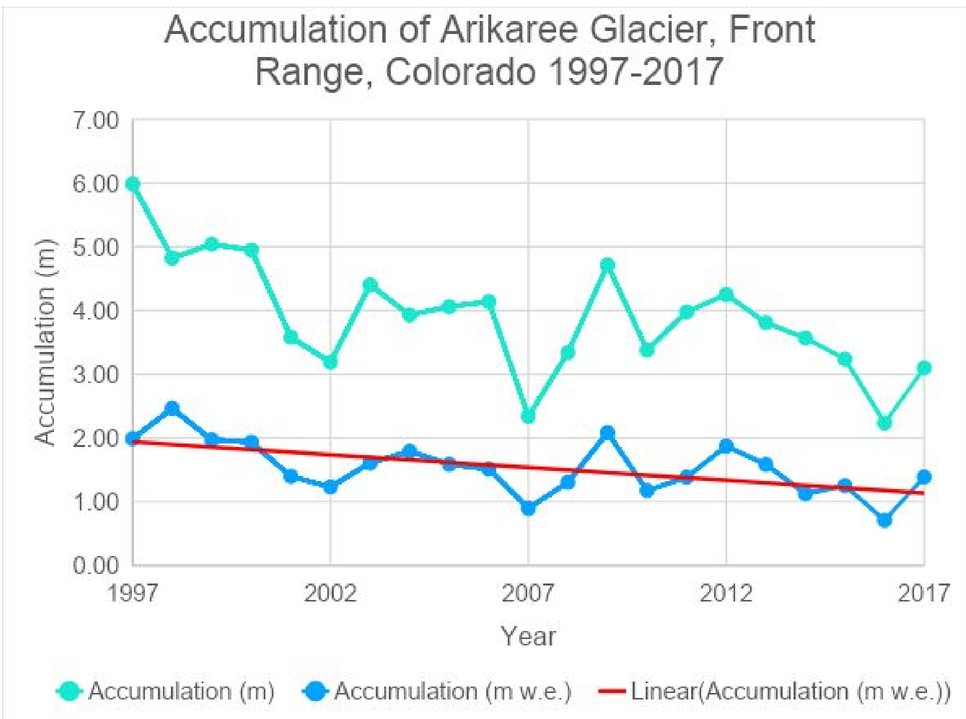

Figure 5. Graph showing accumulation data for the Arikaree Glacier from 1997-2017. Accumulation was estimated from ArcGIS program. Water equivalent accumulation (Table 1) was calculated by taking accumulation and multiplying by the density of the snow at the Arikaree Glacier site during annual Snow Survey.

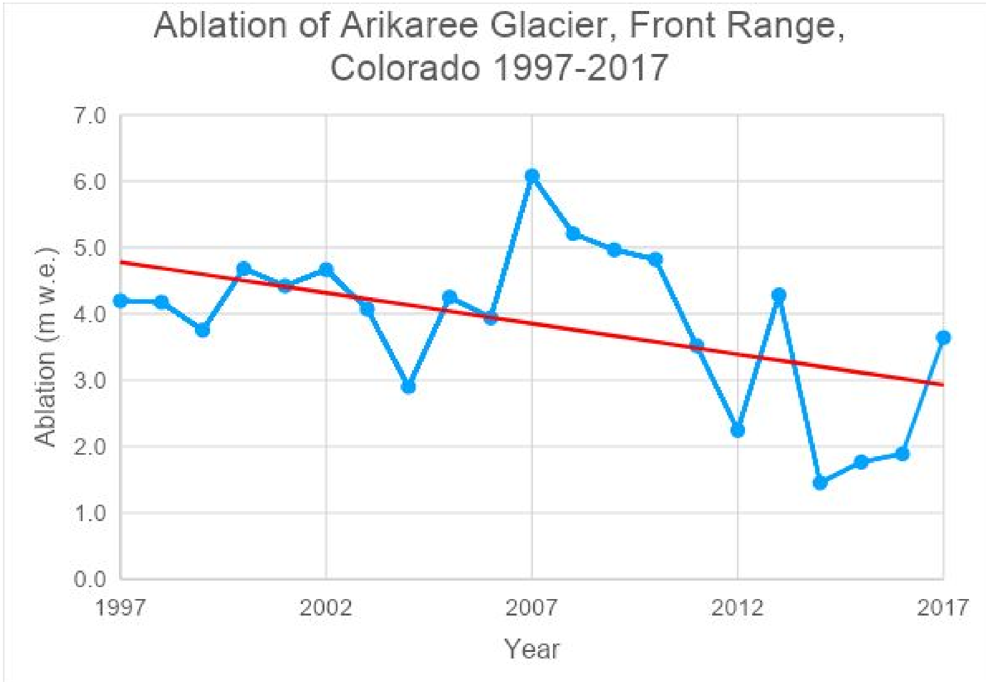

Figure 6. Graph showing ablation for the Arikaree Glacier from 1997-2017. Ablation data was calculated by using degree day methods based off of air temperatures from nearby weather station site D-1.

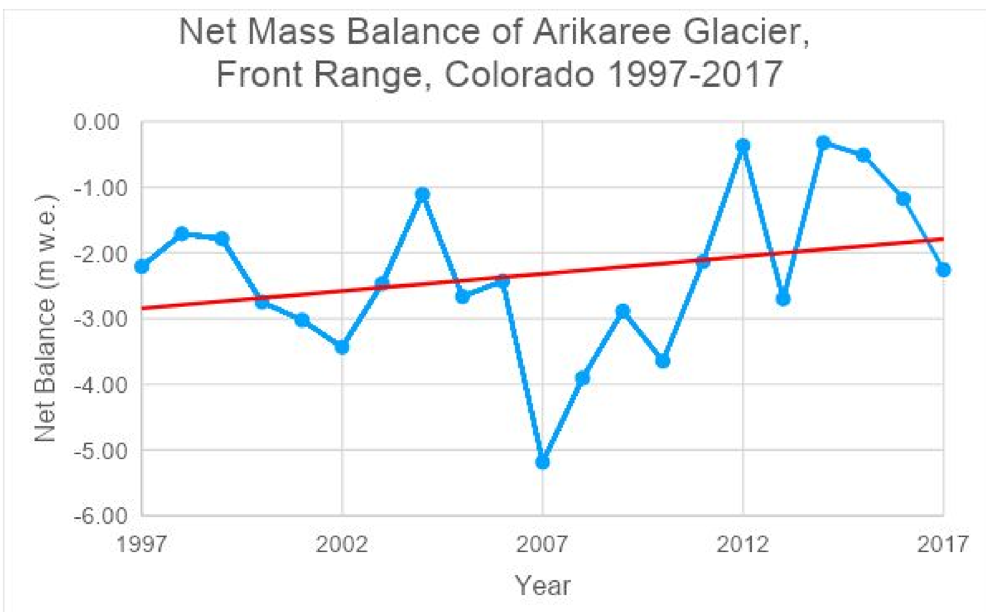

Figure 7. Graph showing net mass balance for the Arikaree Glacier from 1997-2017. There has been a negative net mass balance each year; however, in recent years, the net mass balance has been nearing equilibrium. Most notable is the large negative year in 2007 which had over 5 meters of water equivalent loss.

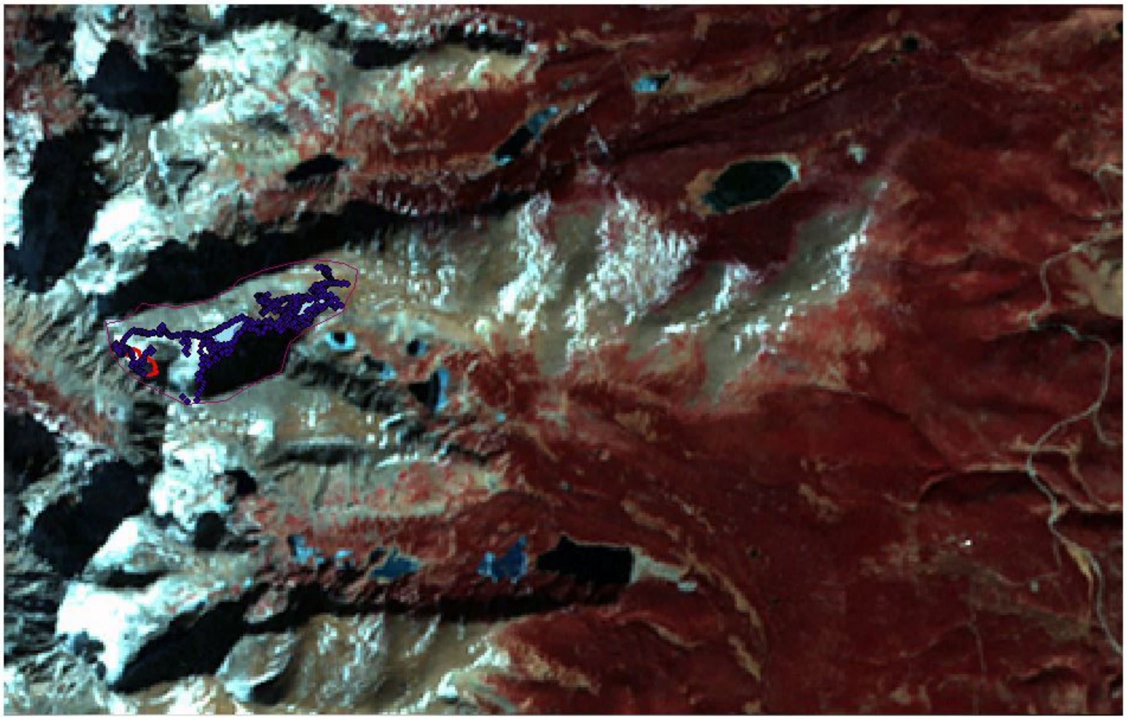

Figure 8. LandSat imagery of Green Lakes Valley (left center) and Vicinity. Blue dots represent points taken during the 2017 Snow Survey. Purple line resembles outline of Green Lakes Valley. Red outline represents Arikaree Glacier boundary.

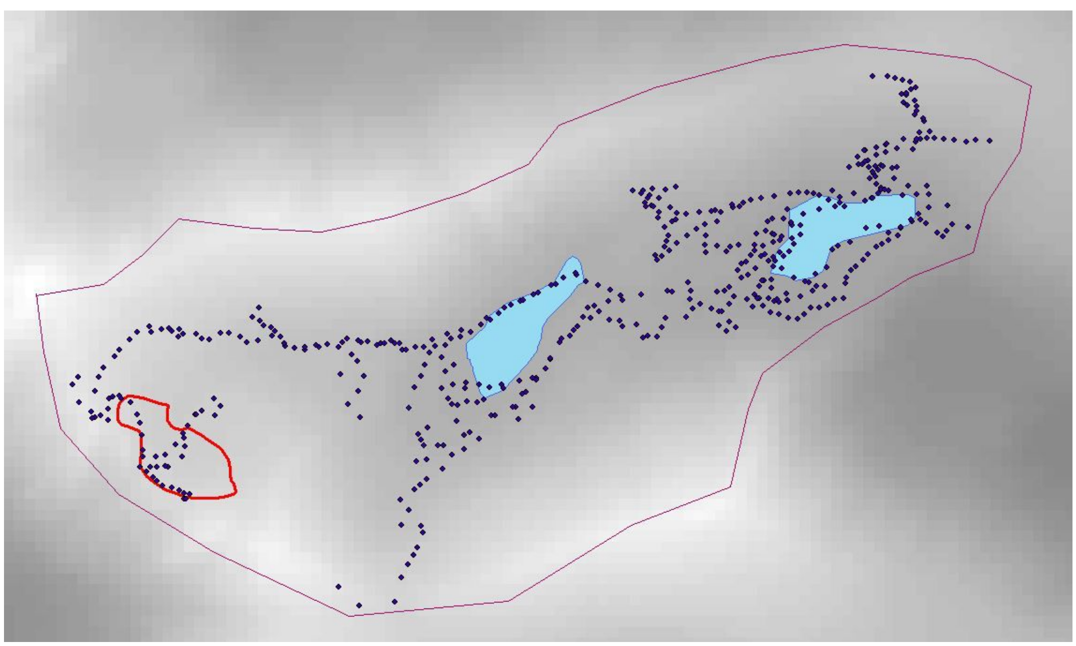

Figure 9. Green Lakes Valley Boundary (purple) against Digital Elevation Model (DEM) (black and white background). Blue dots represent snow depth points taken during the 2017 Snow Survey. Light blue polygons represent Green Lakes 4 and 5. Red outline represents the boundary of the Arikaree Glacier.

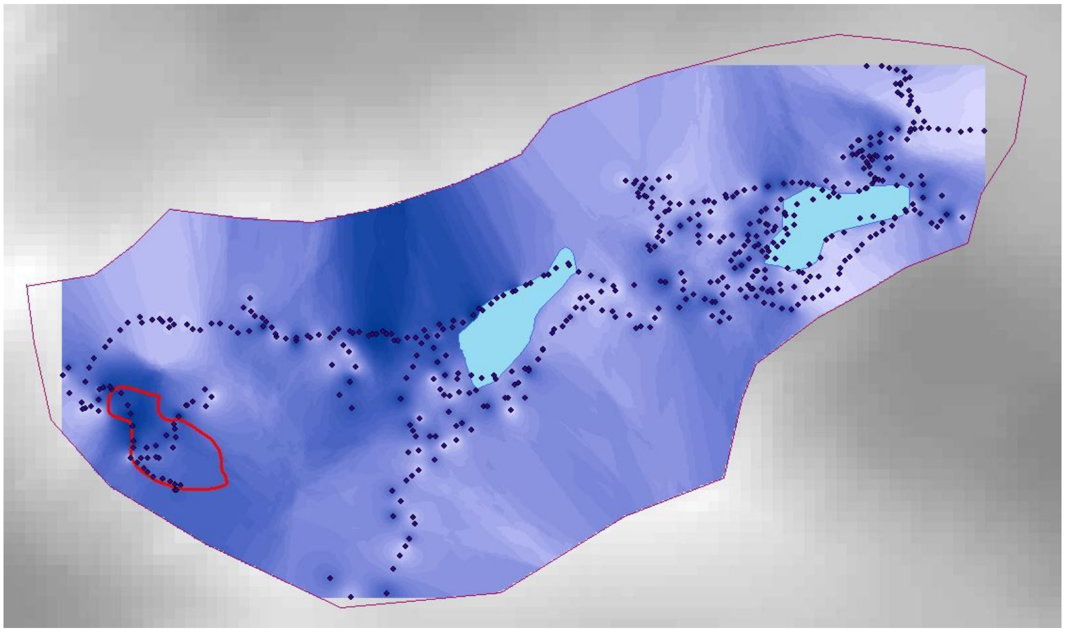

Figure 10. Inverse Distance Weighting estimation of snow depth for 2017 in Green Lakes Valley using ArcGIS. Darker blue color represents deeper snow depth while lighter blue represents shallower snow depth.

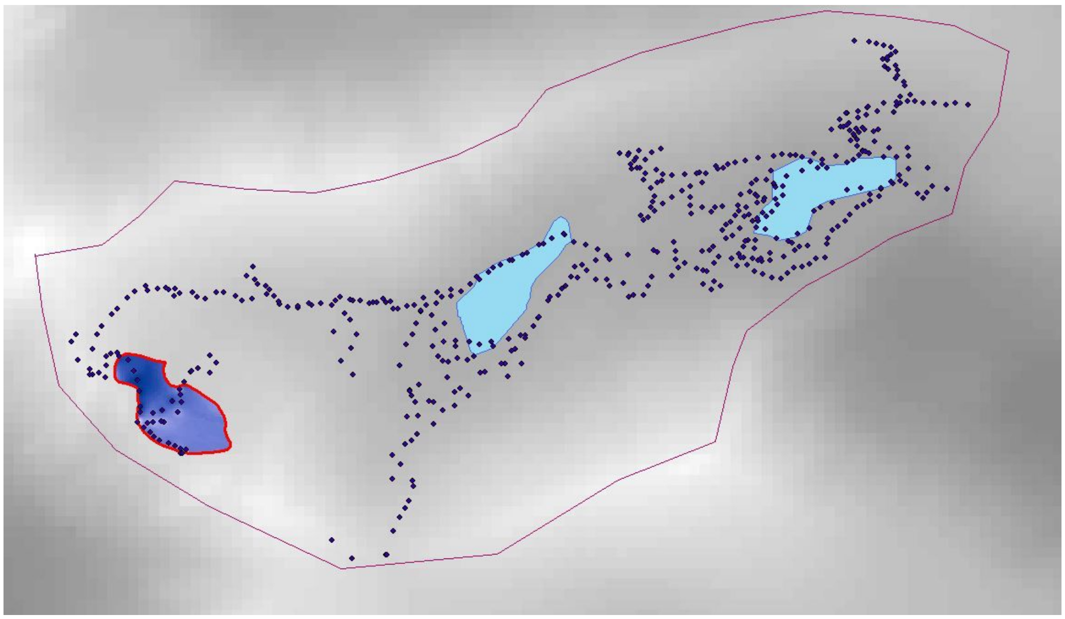

Figure 11. Inverse Distance Weighting estimation of snow depth for 2017 in Green Lakes Valley clipped to the Arikaree Glacier boundary using ArcGIS. Darker blue color represents deeper snow depth while lighter blue represents shallower snow depth.

DISCUSSION

Despite an increase in global mean temperatures, the Arikaree Glacier is actually getting colder. Believed to be due to shifts in wind patterns, this change is also favoring increased precipitation levels (Kittel et al., 2015). Both of these factors provide evidence for favorable conditions for glacier growth or positive mass balances.

When analyzing the accumulation data, the Snow Survey data only provided snow depths for some of the years of the study. Years 2002, 2004, 2006, and 2010-2014 could not obtain snow depths within the point measurements in order to use the Inverse Distance Weighting tool. As a result, accumulation could not be measured and had to be estimated by using averages from other measurements from the other years in which data was obtainable. The greatest accumulation of snow occurred in 1997 with almost six meters measured before being multiplied by the density of the snowpack. However, this result is questionable due to the lack of points measured during the 1997 Snow Survey; the accumulation on the glacier was biased by a few of the deeper point measurements.

It can be concluded that the mass balance of each year is heavily determined by the ablation season. The winter year of 2016-2017 was considered to be a large snow year for Colorado statewide, yet the mass balance was still negative due to a large ablation season. The same pattern can be seen in the year 2009. Despite over 4 meters of snow accumulation and over 2 meters of snow water equivalent, there was a heavy ablation season to also give a negative mass balance for the year. The most notable year on the Arikaree Glacier over the course of the study was in 2007. The year 2007 saw the largest negative mass balance with over 5 meters of water equivalent loss.

Averages for accumulation and ablation were 1.5 and 3.9 meters w.e. respectively for the 21-year period. This is not consistent with what would be expected with the trends of temperature and precipitation. However, when graphing the net balance data over the course of the study, there is a slight positive trend in the data showing that the Arikaree Glacier is getting closer to equilibrium in recent years. When looking at the ablation data over the course of the study, the years 2014-2016 have significantly lower summer temperatures than all of the other years of the study. Some of the daily temperatures in the other years are over 10 °C warmer than some of the warmest days in 2014-2016. When comparing these temperatures with the temperatures at the Niwot Ridge Saddle site (further east and lower in elevation than site D-1), the same dip in temperatures occurs for the summer months of 2014-2016 at the Saddle. Further research could be done to identify any possibilities of why this dip in summer temperatures occurred.

The strong variations in net mass balance of the Arikaree Glacier can likely be attributed to shifts of the El Nino Southern Oscillation. El Nino and La Nina events can alter the amount of snowfall heavily in regions of the world. Although not as extreme in Colorado, these oscillations can still affect annual snowfall in the state. El Nino years cause warmer waters in the Eastern Pacific Ocean to provide more moisture flow to the southwestern United States and mountain areas (Christopherson, 2012). This increase in moisture results in larger than normal precipitation years in Colorado. La Nina events result in colder water in the Eastern Pacific Ocean and less moisture to flow into Colorado, resulting in lower than normal precipitation years (Christopherson, 2012). This can be seen in the groupings of slightly negative mass balances in the late 1990s being attributed to favorable El Nino years towards a grouping of larger magnitude negative mass balances in 2007 and 2010, resembling La Nina years.

Despite the overall positive trend in the net mass balance toward equilibrium, the overall health of the Arikaree Glacier is poor since every year of the study produced a negative net mass balance. The temperature and precipitation conditions are favorable for a positive net mass balance, but heavy ablation during the summer months are prohibiting this result, especially when certain years contain large ablation factors, such as the one seen in 2007. This could be attributed to decreased cloud cover in summer months allowing for more direct incoming sunlight to hit the glacier and/or impurities such as dust and soot deposition lowering the albedo of the surface and resulting in faster melting.

Further research will require more detailed monitoring of accumulation and ablation in order to evaluate for the overall long-term health of the Arikaree Glacier. The Snow Survey measurements underestimate accumulation data due to the difficulties of knowing if the stake is hitting ground or a tough ice lens. To get a more accurate accumulation on the Arikaree Glacier, a separate survey could be done containing more points to measure snow depth and to have these points taken solely on the glacier. Based on the accumulation maps of the glacier in Johnson (1979) and Barreto (1994), there should be larger accumulations along the southern part of the glacier against the cirque. However, the majority of the measurements taken during the Snow Survey are not at this part of the glacier. Instead, they are taken on the shallower parts of the glacier and, therefore, underestimate accumulation data in another way. The ablation data could also be monitored through a stake method or through highly accurate GPS data to see if the ablation estimates from a degree day method are accurate. By using the stake method and possibly other forms of data, a more accurate degree day factor could also be achieved.

Other research priorities would be to monitor other glaciers in the Colorado Front Range to see if they are experiencing the same results as the Arikaree Glacier. Some notable glaciers to monitor are the Arapaho Glacier, Isabelle Glacier, and the Fair Glacier, all within a few miles of the Arikaree. Each one is similar to the Arikaree Glacier in terms of being a small mid-latitude alpine glacier, but each also has a different factor to suggest it may have different results. The Arapaho and Isabelle Glaciers both have larger cirque walls than the Arikaree to limit greater amounts of ablation. The Fair Glacier also has a larger cirque wall than the Arikaree, but is also on the windward side of the Continental Divide that could possibly allow it to differ in accumulation when compared to the Arikaree Glacier. Future research could also be done to see if there are other areas around the world that may be experiencing favorable glacier growth conditions despite increasing global mean temperatures.

Regardless, glaciers around the world need to be monitored and studied more in depth, particularly for their importance in water availability for many people. If the storage of glaciers is decreasing, then there will ultimately be less water in streams in the long run, resulting in water scarcity as population continues to increase.

CONCLUSION

The overall health of glaciers around the world is being threatened by climate change. However, due to micro-climate variability and changes in precipitation and wind patterns, there is evidence to believe that some glaciers may be experiencing positive mass balances. My study calculated the net mass balance for the Arikaree Glacier, Front Range, Colorado, USA to assess the overall health of the glacier over the course of 21 years. I gathered snow depth and snow density data gathered at the annual Snow Survey in Green Lakes Valley from the Niwot Ridge LTER website and used the ArcGIS program to estimate the accumulation on the glacier. For ablation data, I used the air temperature data from nearby site D-1 and conducted a degree day method for each year. Over the course of 21 years, the Arikaree Glacier has had a negative mass balance each year, but the negative value varies considerably from year to year. These data provide incentive for further research of the Arikaree Glacier in order to achieve a more detailed and accurate study of the mass balance as well as further research of other high alpine, mid-latitude glaciers in order to see if they are experiencing similar results as the Arikaree Glacier.

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