Teton Glacier Study, Final Report

“Glacial Change in Grand Teton National Park”

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by

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Abstract

Glacial area and volume changes were quantified through the use of aerial photographs of Wyoming's Teton Range. Glacial area changes in the Teton Range were estimated for three glaciers using un-rectified aerial photography from 1967 to 2006. The total surface area of the three glaciers was 0.53 km^2 in 1967 and 0.40 km^2 in 2006, a decrease of 25% over the 39 year period. The smallest, Teepe Glacier, experienced the most noticeable area loss of approximately 60% while the largest, Teton Glacier, lost approximately 17%.

Aerial photography from 1967 to 2002 was used to estimate glacier volume loss using stereoscopy techniques. Volume loss for the three glaciers was estimated to be 3.2 million cubic meters (MCM) over the 35 year period. The results of the volume change were compared to estimates using Bahr's et al. (1997) area to volume conversion equation. An empirical relationship (power formula) was developed, relating volume loss to area loss for the Teton Range glaciers.

Temperature and April 1st snow water equivalent (SWE) data were analyzed in an attempt to identify a climate driving factor for glacial area and volume loss. Neither temperature nor April 1st SWE data correlated to trends of area or volume losses.

The contribution of the glaciers in the Teton Range to streamflow in the Snake River was examined. The contribution of ice melt from the three glaciers to flow in the Snake River was found to be less than one third of one percent.

The results from the Teton Range were compared to results from a similar study of the Wind River Range. Many similarities were identified.

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Chapter 1: Introduction

Grand Teton National Park (GTNP) attracts many visitors every year. One of the highlights of the park is the amazing views of the Teton glaciers. The Teton Range in northwest Wyoming (USA) is host to ten named glaciers with many climbers, hikers, and outdoor enthusiasts traveling to the park to enjoy the views from a distance or venturing to the glaciers themselves. Glaciers have been receding since the 1850's, or approximately the end of the last "Little Ice Age" (Marston et. al., 1991). The loss of glacier volume could have both environmental (decrease in critical summer stream flow that affect fish populations in small, headwaters streams) and recreational (fewer visitors to Grand Teton National Park) impacts.

Considering the potential impacts of reduced glaciers within Grand Teton National Park, personnel expressed an interest to document changes in the Teton glaciers based on the reported reduction of glacier volume in the Wind River Range of Wyoming. Three glaciers were selected for this study including Teton Glacier, Middle Teton Glacier, and Teepe Glacier. Teton Glacier was selected because it is the largest glacier in the range and can be viewed easily from the road. Middle Teton Glacier was selected because it is one of the larger glaciers found in the range. To provide a range of glacial sizes, a small glacier Teepe Glacier was also selected for this study. The stream flow generated from the glaciers directly feeds the Snake River which eventually joins the Colombia River.

The surface area of the glaciers is an important element in this study as Devisser, (2008) cites the largest glacier (Teton) as being 0.30 km^2. Previous research efforts determined that small glaciers are highly sensitive to changes in precipitation and temperature (Meier, 1984; Oerlemans and others, 1998). Due to their sensitivity to precipitation and temperature, the glaciers are important indicators of regional climate change (Granshaw and Fountain, 2006).

The purpose of this study was to add data to Grand Teton National Park's historical ecological inventory of the glaciers for GTNP. Since the glaciated regions of GTNP have not been intensely studied in the past, it is essential to understand the past behaviors of the glaciers in the region. This study was undertaken to create a database of quantitative information about the glaciers for GTNP by quantifying the glacial area change and glacial volume change for the three selected glaciers (Teepe, Middle Teton, and Teton) in the Teton Range, Wyoming (USA) through the use of aerial photographs.

The analysis also resulted in developing an empirical relationship (power equation) between glacial area loss and glacial volume loss, for the Teton Range. The equation is specific to the Teton Range and allows for future predictions of volume loss based on area change. This study also investigated climate factors impacting glacier changes.

1.1 Study Area

The Teton Range in western Wyoming is an unbroken 65 kilometer host to ten named glaciers (Figures 1 and 2). These glaciers were first identified in the summer of 1879 during the Hayden survey in which the party used field glasses to spot "living" glaciers on Mount Moran (Fryxell, 1935). The majority of the glaciers in the Teton Range have a north or east aspect, with the exception of the Falling Ice Glacier on Mount Moran, which faces southeast (Devisser, 2008). The three glaciers selected for this study are located on the east slope of the mountain range.

1.2 Background

Teton Glacier which occupies a spectacular east-facing cirque between the east ridge of Grand Teton peak and Mount Owen has been well described by Fryxell (1935). The glacier is fed in large part by avalanches from the encircling cliffs, some of which are more than 900 meters high (Reed, 1964). Teton Glacier has been one of the most studied glaciers in the Teton Range due to its accessibility. This has resulted in a number of research studies and countless photos of the glacier.

Previous studies of Teton Glacier include; Fryxell (1933 and 1935), Jepson (1949 and 1950), M.T. Millet (1960), and John C. Reed (1963 to 1967). Unfortunately the results of Jepson and Millet were never published as they were part of a master's thesis from the University of Colorado (Reed, 1964). The majority of Fryxell's work on the Tetons was focused on describing the Tetons and individual glaciers. In his 1935 publication, Fryxell describes Teton, Middle Teton, and other glaciers in great detail.

Reed's research was conducted by placing metal stakes into Teton Glacier to monitor the movement of the glacier and any change in depth. This was performed in 1963 and then repeated in 1964. By 1964, the glacier had lost over 1.5 feet in depth as the stakes that had been placed the year before were no longer in the ice.

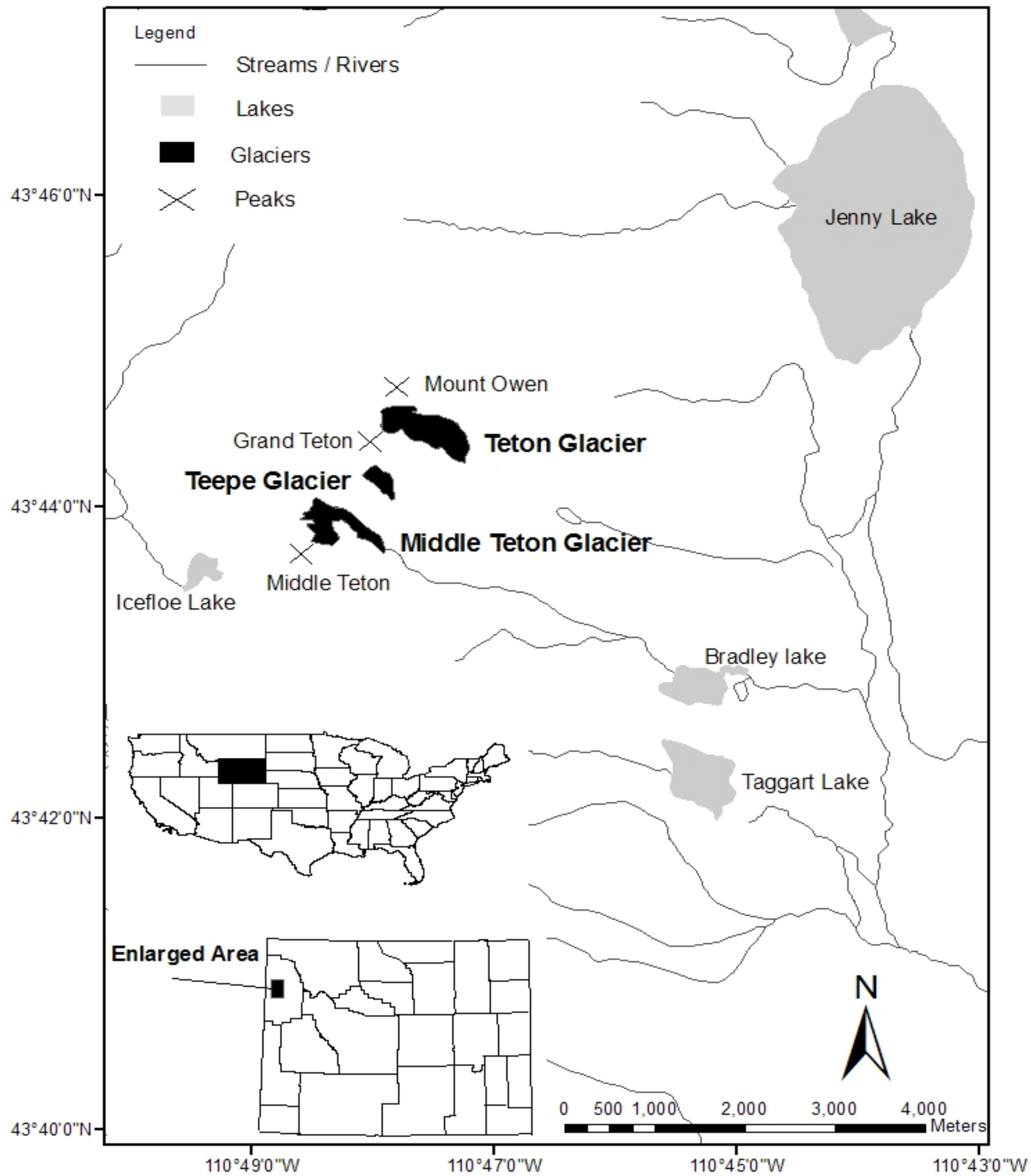

Figure 1. Glacier Location Map (Northwest Wyoming, U.S.).

Figure 2. Photos of the Teton region and glaciers.

Chapter 2: Data

Aerial photography, at one meter resolution, was used for this study (obtained in late summer months when there is minimal snow cover). The one meter resolution was used to minimize the error associated with estimating area and volume losses. It has been reported that photo-interpretation currently provides the most accurate classification (90% or higher) of temporal landscape changes (Lindgren 1985; Jensen 1986).

2.1 Area Data

The aerial photographs were obtained from the United States Geological Survey (USGS) and Wyoming Geological Information and Science Center (WyGISC) in Laramie, Wyoming (Appendix, Table A.4.1). Images were acquired for 1967, 1983, 1994, and 2002 from the USGS. The 2002 and 2006 images from WyGISC were an orthorectified mosaic covering the entire county. Since the WyGISC images had been orthorectified, they were the logical choice to use for geo-referencing the other images. To maintain consistency, and since other images were color infrared, the 2002 color infrared county mosaic was used as the reference image.

Five of the six images were used in the estimation of glacial areas. The 2002 image from USGS was not used due to the availability of the WyGISC image that was already orthorectified. The 1967 and 1994 images were black and white. The 1983 and 2001 images were color infrared and the 2006 images were true color.

2.2 Volume Data

Only four of the images were used in the estimation of glacial volume change. The 1967, 1983, 1994, and 2002 images were used because stereo pairs could be created from two images for the same year. Since the WyGISC data was a mosaic, stereo pairs could not be created and, therefore, couldn't be used for volume estimation.

Calibration reports of the images for 1967, 1983, 1994, and 2002 were obtained from the Earth Resources Observation and Science (EROS) data center in Sioux Falls, South Dakota. The calibration reports provided information on the sensor and camera used to take the photos. The reports provided flying height, fiducial coordinates, and the calibrated focal length. These reports were crucial in developing the stereo pairs to estimate volume loss and the associated error estimates.

2.3 Uncertainty

There can be much uncertainty in calculating area and volume change from aerial photographs. Each image set had to be analyzed slightly differently because of the way they were photographed. Some images were black and white, others color infrared, and still others were true color. Most of the uncertainty was in the area calculations, where the user had to determine what was glacial ice and what was not. Shadows, debris, and dirty ice made this task challenging.

There is also uncertainty in estimating volume change. In determining ground control points (GCP's) to create the stereo pairs, there was a lot of uncertainty. Due to few roads or buildings to use as GCP's, trees and giant boulders had to be used. One can easily assume that the boulders have not moved, but there is still some level of uncertainty. Trees were also used and can cause some issues because shadows can make it difficult to select the exact same point on two different images, especially if they are a different image type (black and white, color infrared, or true color).

2.4 Climate Data

Temperature data were retrieved from the National Weather Service (NWS) Cooperative Observer Program (COOP). Jackson, Moran, and Snake River stations were selected due to the length of record and location (Appendix, Tables A.4.2 – A.4.4). Jackson and Moran are just to the east of Teton Range while the Snake River station is to the northeast of the range. Snowfall data, expressed as April 1st snow water equivalent (SWE), were collected from the Natural Resources Conservation Service (NRCS) for four locations to the south and north of glacial locations. The four SNOTEL stations selected for this study were Snake River, Lewis Lake Divide, Grassy Lake, and Phillip's Bench (Appendix, Table A.4.5).

The climate data were compiled to investigate if relationships exist between glacial changes and climatic factors. The temperature and SWE data were broken into periods between the image data sets. The temperature data (1905-2006) could be extended further back than SWE, as the SWE data only went back to 1981.

Chapter 3: Methods

3.1 Area analysis

The aerial images obtained from the USGS were without spatial coordinates and, therefore, these had to be generated by the user. Due to the rugged terrain of the Tetons, this process became more challenging as the images also required geometric correction. ERDAS Imagine provided an approach to attach spatial coordinates while also geometrically correcting the image. The first step was to clip the image to a size that covered each glacier individually but also provided additional area to locate ground control points (GCP's).

Thirty GCP's were used in the process of geometrically correcting the photos using a third order transformation. This task was completed for each individual glacier for every year resulting in eleven different images (three sets of images for 1967, 1983, and 1994, and the two county mosaics in 2002 and 2006).

The images were exported to a geographic information system (GIS) and ArcMap 9.3 (ESRI, Redland, CA) was selected to analyze the area of glacial coverage. The area was calculated by "heads up" digitizing the glacier. The glacier was outlined and polygons were created in the interior of the glacier to crop out areas of bedrock leaving an "ice surface polygon" (DeBeer and Sharp, 2007).

There are numerous methods available for analyzing glaciers using manual or digital interpretation of imagery. Manual digitization requires increased time and effort, but is generally considered more accurate as the human eye can depict differences whereas digital interpretation may not. Therefore, the manual method was selected for this study as many challenges were presented with the aerial photography of the research area. The major challenge with the aerial photography is that the glaciers are either located in a "bowl like feature' or on the north side of a peak where they are shaded during the time the images were taken. Shadows are the primary challenge with digital interpretation, and the manual method allows for better interpretation of the shadow influence.

3.1.1 Area Error Estimation

The Teton Range, like other glacial locations, was found to display rugged topographic characteristics which made it challenging to access specific glaciers. Any field investigation of small glaciers, such as those in the Tetons and elsewhere in the Rocky Mountains (U.S.A), is likely to be a difficult endeavor (Fryxell, 1935). This results in few spatial points that coincide when aerial photos were taken from different years. This presents challenges in determining the associated error estimates. Due to a lack of field data, two methods were used to calculate error. Hall et al. (2003) determined that error could be determined by an equation using the aerial photo being analyzed and the base map used for georectifying.

The total digitizing error (e_d) was calculated using equation 3.1 (Hall et al., 2003).

$$e_d = \sqrt{r_p{}^2 + r_b{}^2)} + e_r \qquad \textbf{(3.1)}$$

where r_p is the pixel resolution of the georeferenced paper maps, r_b is the pixel resolution of the base map (2002 aerial photo), and e_r is the registration error of the summation of the georeferenced paper map RMSE and the 2001 base map RMSE. Once the digitizing error was determined, the area uncertainty (e_a) was measured using the following formula (Hall et al., 2003):

$$e_a = r_i^2 * \left(\frac{2e_d}{r_i}\right) \qquad \textbf{(3.2)}$$

where r_i is the image's pixel resolution and e_d is the total digitizing error calculated in equation 3.1.

The second method used was to carefully re-digitize the glacial boundaries to depict the areas that could have been omitted or incorrectly identified to find the extremes of the glacial area. In some instances, it was difficult to distinguish differences between clean ice, dirty ice, rock outcroppings, and ice covered by shadows cast from surrounding mountain peaks.

The total error (δQ) was found using a method by DeBeer and Sharp (2007) that combines the Hall method and DeBeer and Sharp methods.

$$\delta Q = \sqrt{(\delta q_1)^2 + (\delta q_2)^2 + \cdots (\delta q_n)^2}, \qquad \textbf{(3.3)}$$

where $\delta q_1, \ldots, \delta q_n$ represent each individual uncertainty in surface area occurring from the area uncertainty with the respect to georeferencing as well as the delineation process of individual glacier boundaries (Thompson, 2009).

3.2 Volume Analysis

The method of creating volume change estimates also used ERDAS and ArcMap. A pair of raw images from the same year was placed together into the ERDAS software. Information about the camera had to be manually provided, including the fiducials and calibrated focal length. The fiducials were placed individually on each photo to an accuracy of 0.10 pixels root mean squared error (RMSE).

The photos were referenced to known points using the 2002 WyGISC photo. Since neither survey benchmarks nor anthropological structures exist in the photos, the control and check points were placed on distinct rock formations or vegetated areas that were not subject to movement over time (Bell, 2009). Thirty points were used in creating GCP's and check points with X, Y and Z coordinates.

Georeferencing was accomplished by overlaying the 2002 photo over a digital elevation model (DEM) obtained from the USGS. One point on the 2002 photo providing northing, easting, and elevation was selected and then the same point was found on the other two photos and the elevation was manually entered for those points. Providing this information allowed for a stereo pair to be created for the years of 1967, 1983, 1994, and 2002. A stereo pair is a set of two or more photos with overlapping portions, which are positioned such that the parallax between the common objects allows the user to view the objects in 3-D using either red/blue anaglyph stereo glasses or LCD stereo glasses (Bell, 2009).

The ERDAS software also provided a method for converting the stereo pair into a digital terrain model (DTM). The volume difference was calculated using two DTM's from separate years and the difference was found by subtracting the lower surface (most recent year) from the upper surface (earlier year) using Golden Software's Surfer program. For example, the 1983 surface was subtracted from the 1967 surface and a volume was calculated. This resulted in the volume change from 1967 to 1983.

3.2.1 Volume Error Estimation

The error in the estimation of volume was determined through evaluating the overall elevation difference and the error associated with the DEM used in preparing the stereo pairs. A resampling approach, per methodology below, was repeated 10,000 times through the use of a random number generator which resulted in a confidence interval of 95%.

The method involved first determining a base line elevation by finding the average elevation difference between two selected years. The volume change was then divided by the average elevation to determine an area used in error calculation. For example, if the elevation difference was 4.84 meters and the corresponding volume difference was 1.29 MCM, the area would be

$$\frac{1.29 * 10^6\ meters^3}{4.84\ meters} = 266529\ meters^2$$

This was performed to determine volume change for each pairing of years (1967-1983, 1983-1994, 1994-2002) for all three glaciers.

The second step was to multiply the DEM error (10 meters) by a random number with a mean of zero and a standard deviation of one. This resulted in an error between the values of negative ten and positive ten. This value was then multiplied by the aforementioned area to create an error estimation. After repeating 10,000 times, the data was normally distributed and the confidence interval provided the associated error estimation.

$$Ve = CI\ of\ (DEM\ error * Area * Random\ Number) \qquad \textbf{(3.4)}$$

The above equation represents one iteration of 10,000 iterations performed. Volume estimation (Ve) was measured in MCM for one iteration and the confidence interval (CI) was found after 10,000 iterations were calculated with a 95% confidence level.

Chapter 4: Results and Discussion

4.1 Glacial Area Change from 1967 to 2006

The average elevations of Teton, Middle Teton, and Teepe Glaciers were respectively 3250, 3326, and 3454 meters (Table 1). The glaciers were all generally oriented to the east with an average slope of 17°. The slope and aspect were only calculated for the base year of 1967, as these were not subject to change over time.

Table 1**.** Teton, Middle Teton, and Teepe Glacier characteristics for 1967.

					Elevation (meters)		
Glacier Name	**Latitude**	**Longitude**	**Aspect (°)**	**Slope (%)**	**Min**	**Max**	**Mean**
Teton	43.742	-110.791	100.5	26.8	3129	3537	3250
Middle Teton	43.732	-110.805	79.00	30.7	3129	3705	3326
Teepe	43.736	-110.798	158.30	38.4	3390	3704	3454

Based on the high resolution aerial photographs, the largest glacier in 1967 was Teton Glacier with a surface area of 0.259 ± 0.005 km^2 (Table 2). Middle Teton Glacier was the second largest with a surface area of 0.212 ± 0.003 km^2. The smallest glacier studied was Teepe Glacier with a surface area 0.055 ± 0.002 km^2. The total 1967 surface area of Teton, Middle Teton, and Teepe Glaciers was 0.526 ± 0.010 km^2 The total 2006 calculated surface area of the three glaciers was 0.396 ± 0.011 km^2. This was a decrease of 0.131 ± 0.021 km^2 which equates to a loss of approximately 25% of the total surface area since 1967. Teton Glacier lost 0.043 ± 0.009 km^2 or 17% of its 1967 surface area. Middle Teton Glacier experienced the greatest loss, 0.054 ± 0.010 km^2, or a 25% decrease. The smallest glacier, Teepe Glacier, lost the highest percentage of area, 0.033 ± 0.002 km^2 or a 60% decrease.

Table 2. Glacier Areas and associated errors (1967, 1983, 1994, 2002, and 2006).

Glacier	Year	Area (km^2)	Error (km^2)
Teton	1967	0.259	0.005
	1983	0.234	0.002
	1994	0.215	0.006
	2002	0.215	0.004
	2006	0.215	0.004
Middle Teton	1967	0.212	0.003
	1983	0.207	0.003
	1994	0.164	0.004
	2002	0.160	0.003
	2006	0.158	0.007
Teepe	1967	0.055	0.002
	1983	0.054	0.003
	1994	0.032	0.001
	2002	0.026	0.001
	2006	0.022	0.001

4.1.1 Fractional Area Change

The fractional area change (FAC) was determined per Granshaw and Fountain's formula (2006), which is the area losses divided by the initial area. For Teton, Middle Teton, and Teepe Glacier, for the 1967-2006 period, the percentage losses were 17%, 25%, and 60%, respectfully. The FAC was calculated for each time step as well (1967-1983, 1983-1994, 1994-2002, and 2002-2006). The base area for the earliest year (x-axis) was plotted against the FAC (Figures 3a-3e).

With the exception of one data point (1967-1983), the smaller the glacial area the higher the FAC. Teton Glacier was the largest glacier and had the lowest FAC, as opposed to Teepe Glacier which was the smallest glacier in the study and had the highest FAC. In a companion study of the Wind River Range, the smaller glaciers (1966 area <0.5 km^2) displayed a greater FAC and appear to be receding at a greater rate than the larger (1966 area >0.5 km^2) glaciers (Thompson, 2009).

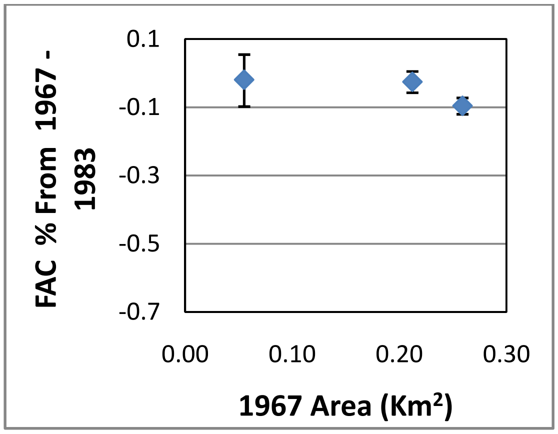

Figure 3a. FAC 1967-1983

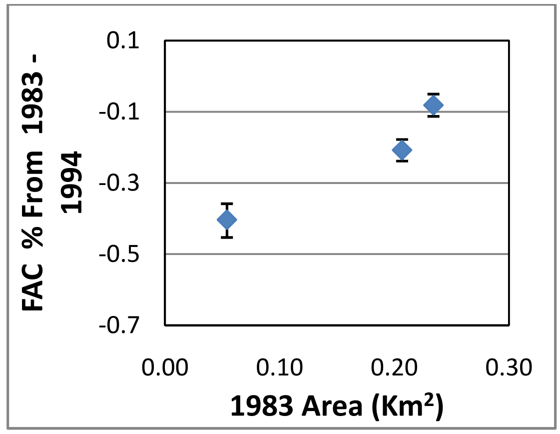

Figure 3b. FAC 1983-1994

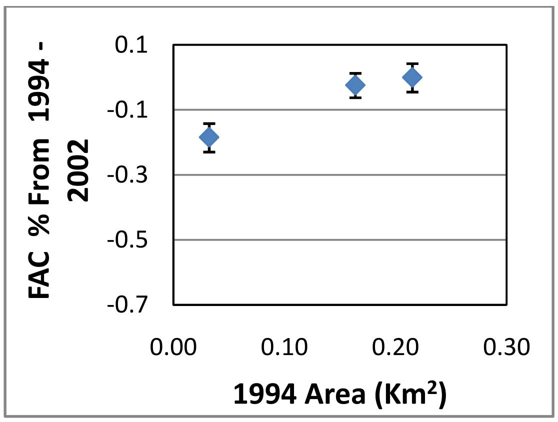

Figure 3c. FAC 1994-2002

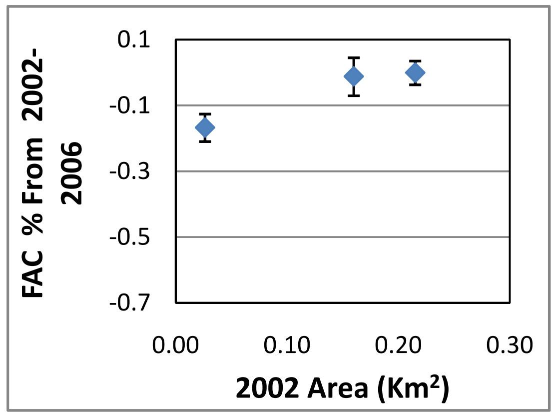

Figure 3d. FAC 2002-2006

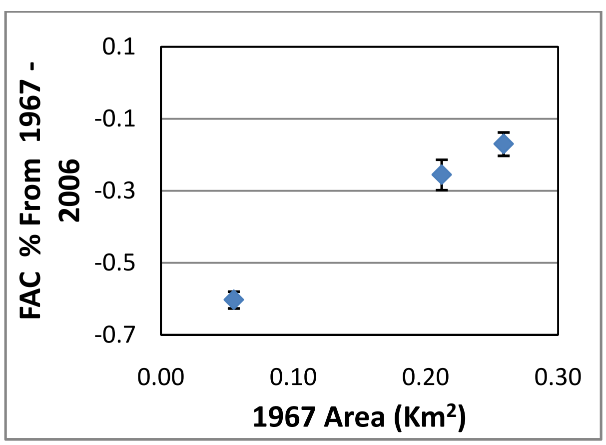

Figure 3e. FAC 1967-2006

4.2 Glacial Volume Change from 1967 to 2002

The glacial volume changes were determined directly from aerial photos between three periods 1967-1983, 1983-1994, and 1994-2002 (Table 3 and Figures 4-6). Combined, the three glaciers lost a total 3.2 ± 0.40 MCM between 1967 and 2002. Middle Teton Glacier lost the most volume, 1.34 ± 0.16 MCM. The highest period of loss was between the 1983-1994 period when 1.64 ± 0.20 MCM of volume was lost for the three glaicers. This was 51% of the total volume lost during the 1967-2002 study period.

Table 3. Glacial volume changes and associated errors between three study periods (1967-1983, 1983-1994, and 1994-2002) and between end points (1967-2002).

Glacier	Year	Direct Measurements of change in volume (MCM)	Estimated error in volume (MCM)
Teton			
	1967-1983	0.36	0.05
	1983-1994	0.70	0.10
	1994-2002	0.22	0.03
	1967-2002	1.29	0.18
Middle Teton			
	1967-1983	0.30	0.05
	1983-1994	0.74	0.10
	1994-2002	0.29	0.05
	1967-2002	1.34	0.20
Teepe			
	1967-1983	0.23	0.03
	1983-1994	0.19	0.03
	1994-2002	0.16	0.02
	1967-2002	0.57	0.08

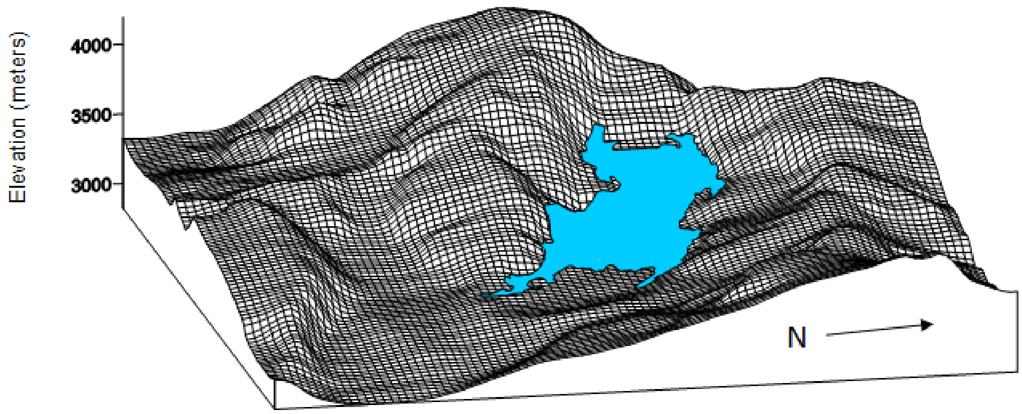

Figure 4a. 1967 Teton Glacier wireframe.

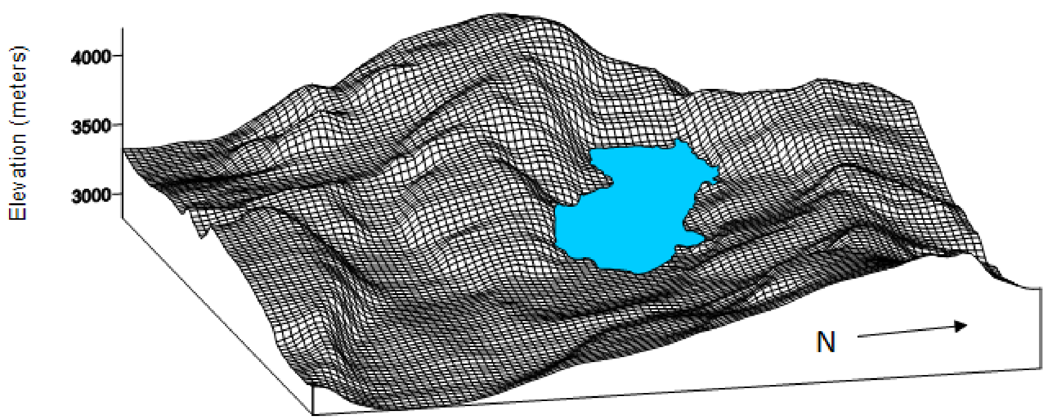

Figure 4b. 2002 Teton Glacier wireframe.

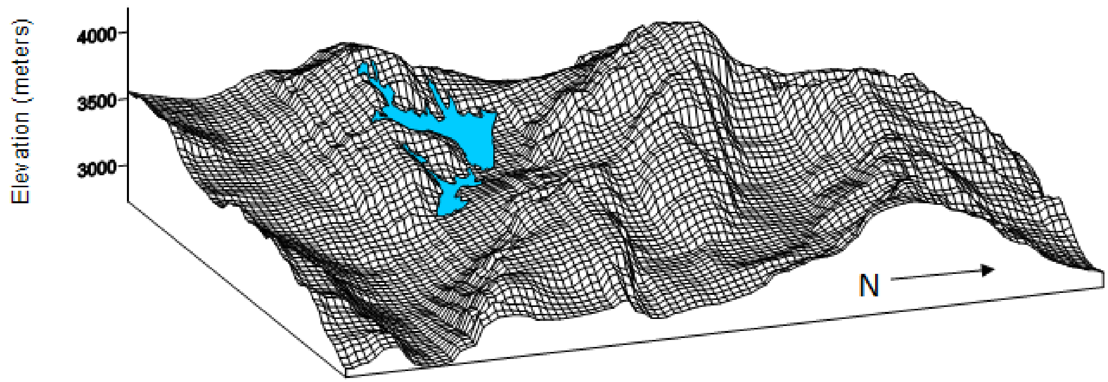

Figure 5a. 1967 Middle Teton Glacier wireframe.

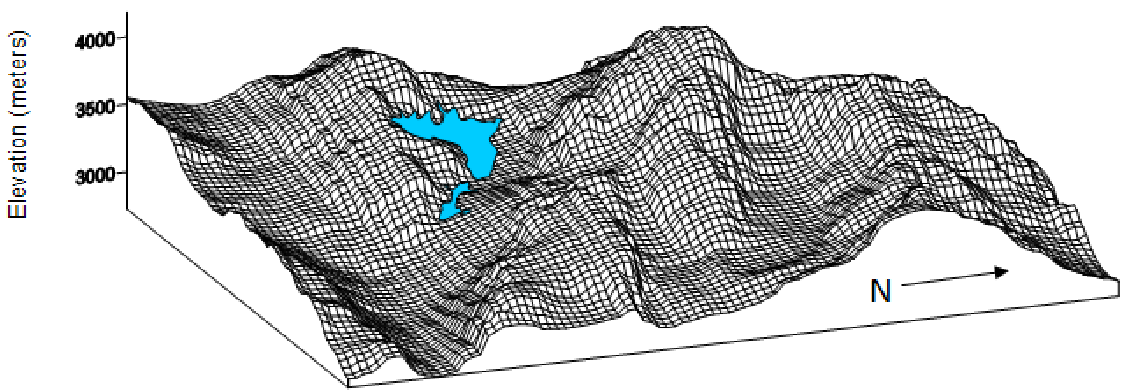

Figure 5b. 2002 Middle Teton Glacier wireframe.

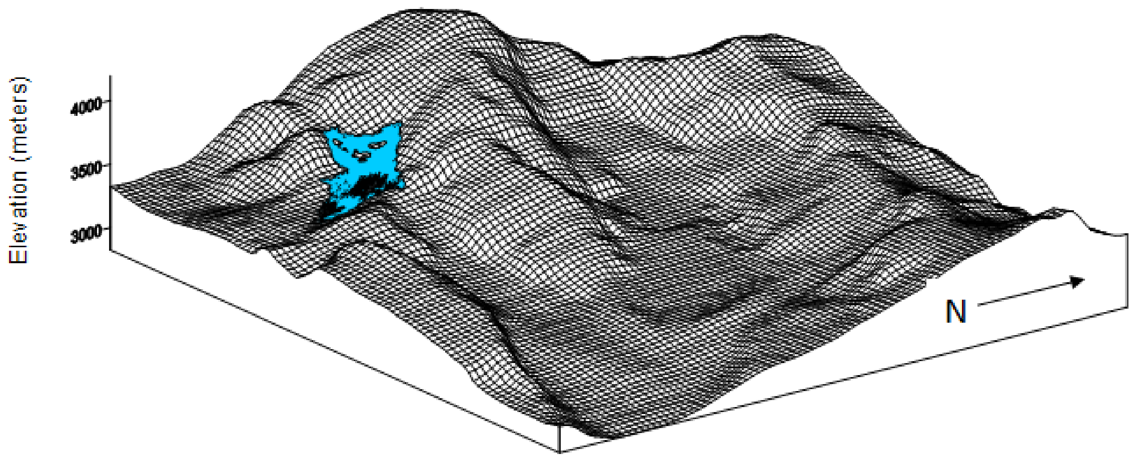

Figure 6a. 1967 Teepe Glacier wireframe.

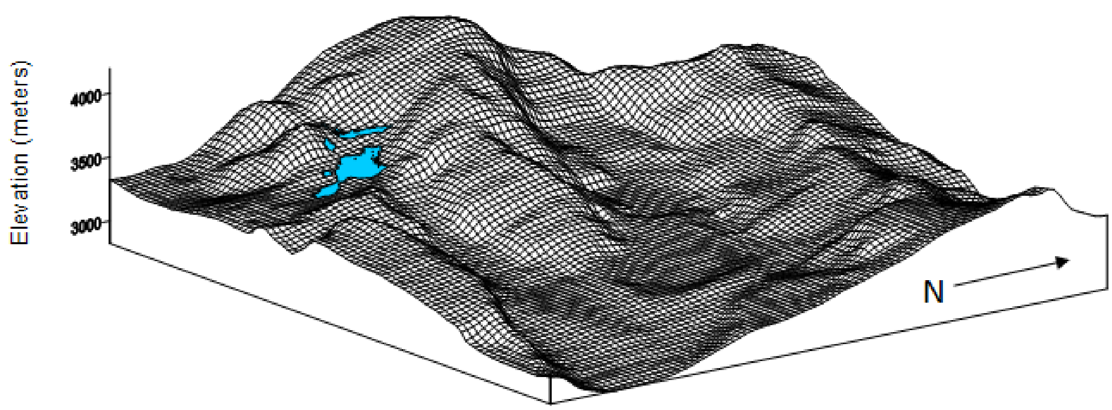

Figure 6b. 2002 Teepe Glacier wireframe.

The results from direct measurement of volume losses were compared to volume losses estimated using Bahr's et al. (1997) area to volume relationship (Table 4). The glacial areas, as estimated in Section 4.1, were used in Bahr's equation to estimate glacial volumes. The estimated volumes were then used to estimate volume changes. Bahr's equation used for comparison, with area in square meters and volume in cubic meters, was

$$Volume = 0.175 * Area^{1.36} \qquad \textbf{(3.5)}$$

Results show that for the three glaciers combined, the overall volume changes using Bahr's area to volume conversion were 30.3% lower than the volume changes obtained by direct measurements from aerial photos.

Table 4. Comparison of direct measurements of change in volume for the Teton Range and estimates from Bahr equation area to volume conversions.

Glacier	Year	Direct Measurements of change in volume (MCM)	Bahr Equation Change in volume (MCM)	Difference (MCM)	% Difference
Teton					
	1967-1983	0.36	0.52	-0.15	-42.0%
	1983-1994	0.70	0.42	0.28	40.0%
	1994-2002	0.22	0.00	0.22	100%
	1967-2002	1.29	0.94	0.35	27.2%
Middle Teton					
	1967-1983	0.30	0.11	0.19	64.6%
	1983-1994	0.74	0.80	-0.06	-7.9%
	1994-2002	0.29	0.07	0.22	75.9%
	1967-2002	1.34	0.98	0.36	26.7%
Teepe					
	1967-1983	0.23	0.01	0.22	94.4%
	1983-1994	0.19	0.24	-0.05	-27.0%
	1994-2002	0.16	0.06	0.10	63.2%
	1967-2002	0.57	0.31	0.26	45.8%
Total	1967-2002	3.20	2.23	0.97	30.3%

4.3 Relating Area Change to Volume Change

Similar to Bahr et al. (1997), an empirical equation (power formula) was developed for the Teton Glaciers. Besides using a different data set, the major difference between Bahr's work and this study is Bahr calculates volume as a function of area whereas the equation derived herein calculates volume change as a function of area change. The topography underneath the glacier is not considered for the equation derived herein, only the topography in the upper part of the glacier that is exposed between two study years.

To determine the empirical equation, the area change (x-axis) was plotted against the volume change (y-axis) for each glacier (Teton, Middle Teton, and Teepe) for each period evaluated (1967-1983, 1983-1994, and 1994-2002). This resulted in nine points (Figure 7). The additional nine points came from combinations of different time steps (1967-1994, 1983-2002, and 1967-2002).

$$Volume\ Change = 1.95 * Area\ Change^{1.22} \quad \textbf{(3.6)}$$

Area change is input in square meters and the volume change is determined in cubic meters. The data fit the equation with an R^2 of 0.94.

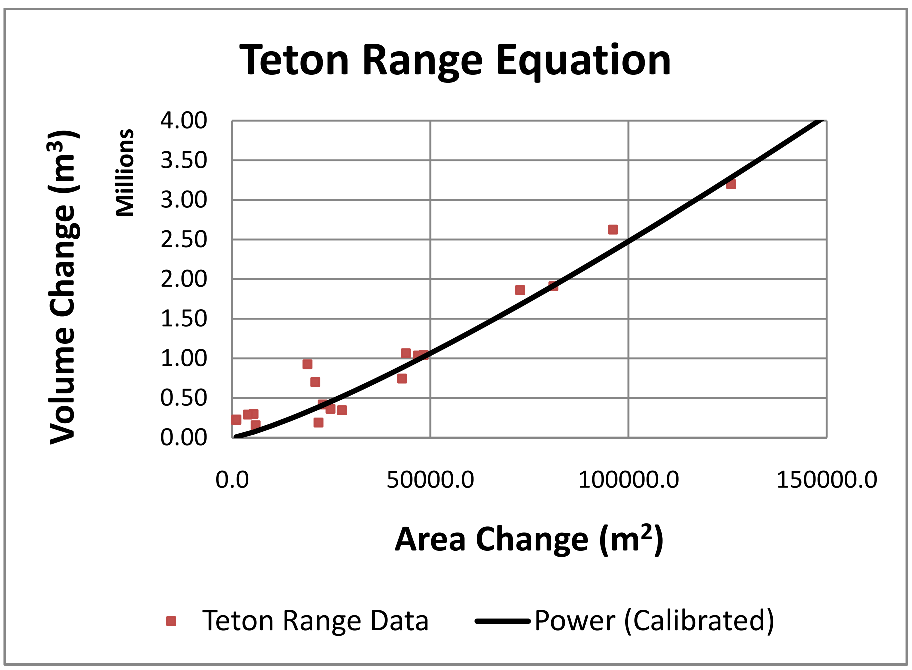

Figure 7. Derived Teton Range equation plotted as area change (x-axis) for select period and volume change (y-axis) for same time period.

4.4 Glacial Changes vs Climate Factors

4.4.1 Temperature

Temperature data were compiled from three COOP stations (Jackson, Moran, and Snake River) dating as far back as 1905 (Appendix 4, Tables A.4.2 – A.4.4). Jackson and Moran are just to the east of Teton Range while the Snake River station is to the northeast of the range. Temperatures from the late summer months (June, July, August, and September) were selected as this is when, on average, the highest temperatures occur. The average temperature from 1905 to 1966 for June, July, August, and September was 12.3°C and during the study period (1967-2006) the average temperature was 12.8°C.

In an attempt to find a correlation between temperature and the area and volume losses, the temperature data were considered for the same four periods as area and volume changes were estimated (1967-1983, 1983-1994, 1994-2002, and 2002-2006). The period of 1983-1994 had the greatest rate of area loss per year, more than four times as much as any other period (Table 5). The same was the case for the rate of volume loss per year, as the 1983-1994 period had approximately twice the rate of loss per year as any other period (Table 6). The warmest period during July, August, and September (JAS) was between the years of 1994-2002 (Table 7 and Figures 8 and 9). The 1983-1994 period showed the lowest average temperature. This didn't relate to rates of loss found during the same time periods.

The period of June through September was analyzed to investigate if any one month's temperature could be driving the glacial retreat. The only indication of a temperature driver, although very weak at best, was that the average temperature for the higher ice-melt period (1983-1994) for June was 12°C (Figures 10 and 11). This temperature is higher than for the other periods, as the June average for 1967-1983 was 11.3°C and the 1994-2002 and 2002-2006 June temperatures averaged 11.6°C (Table 7).

Table 5. Average rate of area loss shown as % per year between four study periods.

	Total Area of Three Galciers	Area Loss Between Listed Dates	Number of Years between Dates	Average Rate of Area Loss Between Dates*
Year	**km^2**	**%**		**%/Yr**
1967	0.526			
1983	0.495	-5.9	16	-0.37
1994	0.411	-17.0	11	-1.54
2002	0.401	-2.4	8	-0.30
2006	0.395	-1.5	4	-0.37

*i.e., the slope of the area loss curve

Table 6. Average rate of volume loss shown as MCM/year between three study periods.

	Direct Measurement Volume Change of Combined Three Glaciers	Bahr Equation Volume Change of Combined Three Glaciers	Average Rate of Change Per Year*	
			Direct Measurement	Bahr Equation
Period	**(MCM)**		**(MCM/Yr)**	
67-83	0.89	0.64	0.06	0.04
83-94	1.63	1.46	0.15	0.13
94-02	0.67	0.13	0.08	0.02

*I.e., the slope of the volume loss curve

Table 7. Average monthly temperatures for June-September for the four study periods (1967-1983, 1983-1994, 1994-2002, and 2002-2006).

	Average temperature ˚C			
Period	June	July	August	September
67-83	11.3	15.3	14.5	9.4
83-94	12.0	15.0	14.5	9.5
94-02	11.6	15.8	14.9	10.3
2002-06	11.6	16.5	14.3	9.4

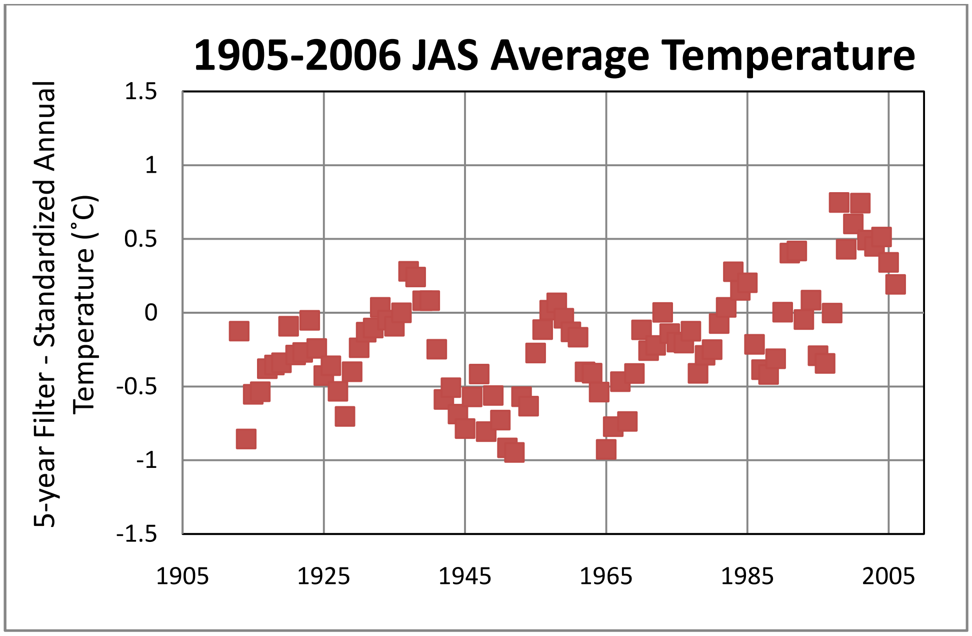

Figure 8. July, August, and September average standardized temperature 1905-2006 for three COOP stations (Jackson, Snake River, and Moran).

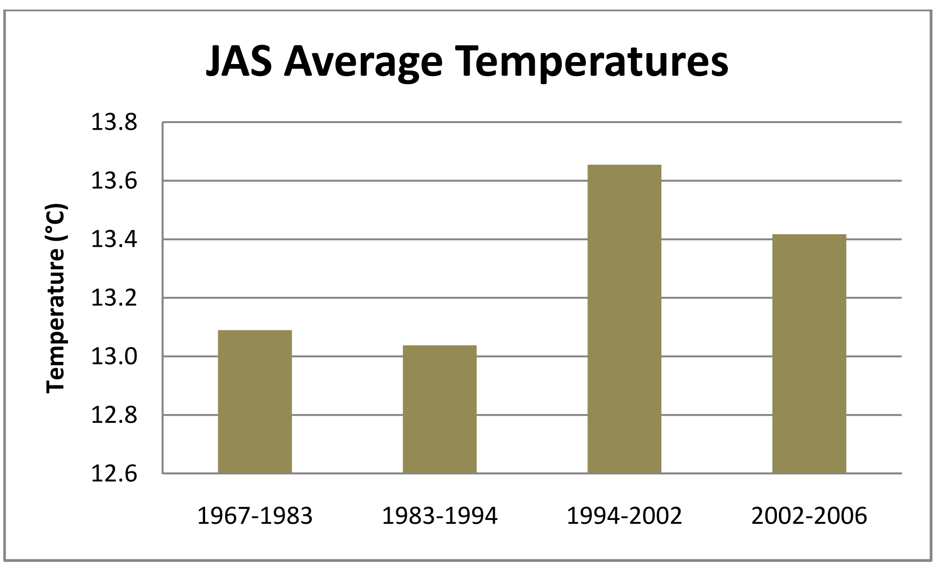

Figure 9. July, August, September (JAS) average temperatures by period for three COOP stations (Jackson, Snake River, and Moran).

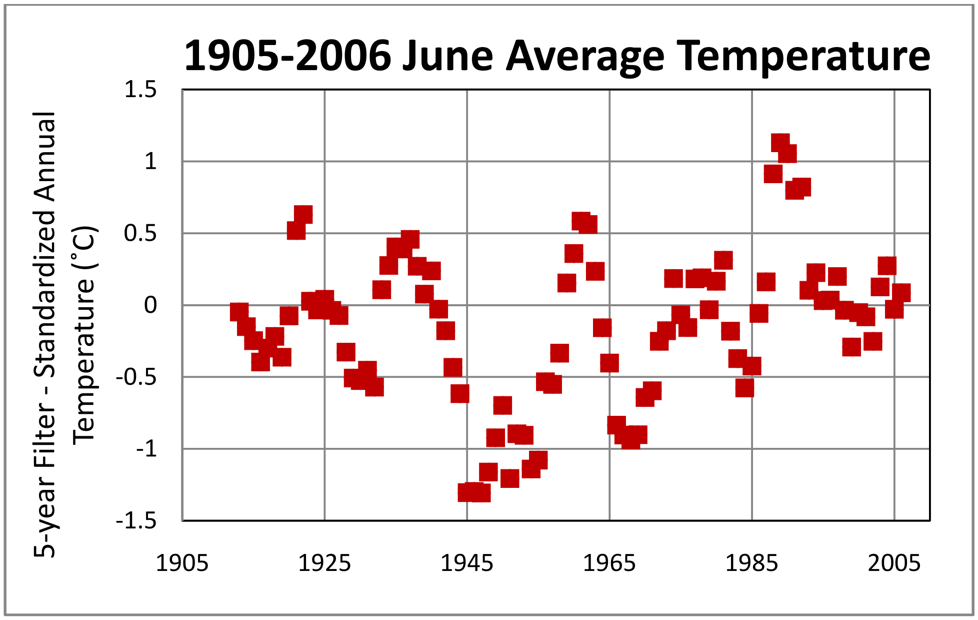

Figure 10. June average standardized temperature 1905-2006 for three COOP stations (Jackson, Snake River, and Moran).

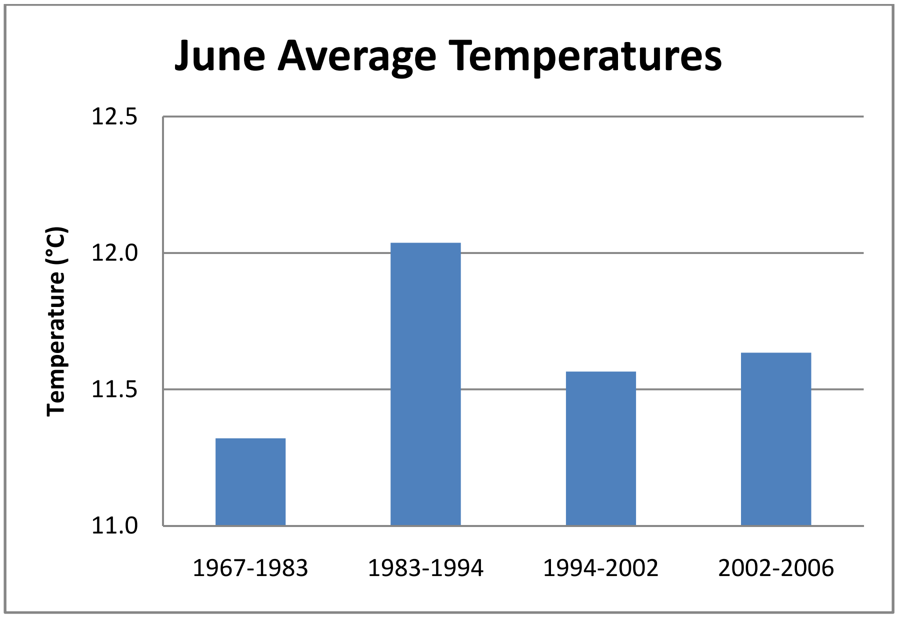

Figure 11. June average temperatures by period for three COOP stations (Jackson, Snake River, and Moran).

4.4.2 April 1st Snow Water Equivalent

April 1st snow water equivalent (SWE) data were obtained for four stations (Snake River, Lewis Lake Divide, Grassy Lake, and Phillip's Bench) near the glaciers (Appendix, Table A.4.5). These stations reported similar values and it was assumed that the trends in these data might be similar to the trends of SWE at the glacier locations.

The lowest SWE was between the period of 2002 and 2006 with an average of 66 cm. The highest SWE was between 1994 and 2002 with an average of 72 cm (Figure 12), while the overall average from 1983 to 2006 was 71 cm. Comparing the values to the rates of area and volume losses (Tables 5 and 6), the April 1st SWE data and the rates of loss do not seem to be related. During the period of the highest SWE (1994-2002) there was little glacial area or volume loss. The lowest period of SWE (2002-2006) reflected approximately the same loss rate as the 1994-2002 period.

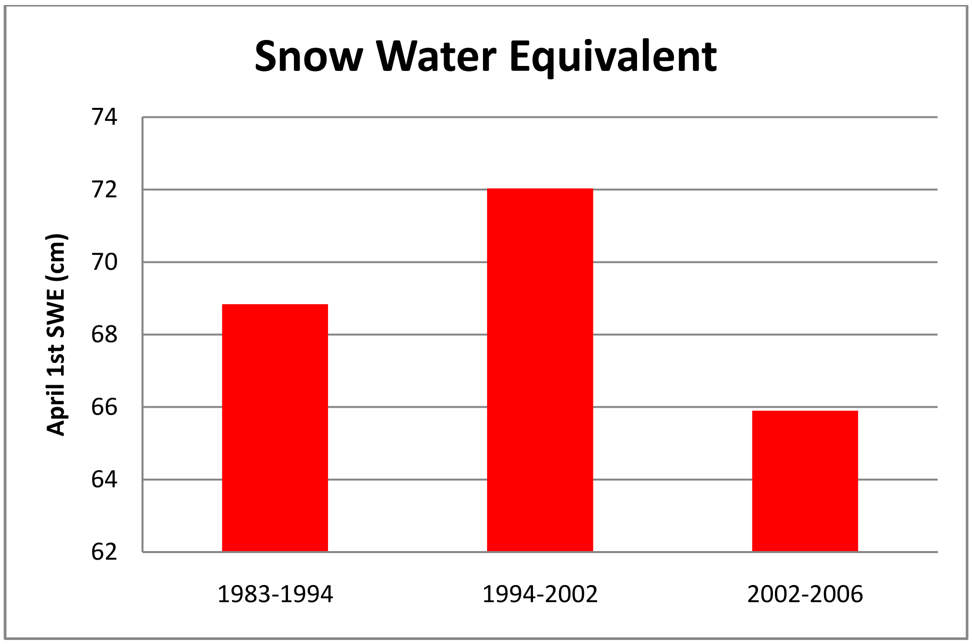

Figure 12. SNOTEL data by period for four stations (Snake River, Lewis Lake Divide, Grassy Lake, and Phillip's Bench).

4.5 Glacial Melt Contribution to the Snake River

Snake River stream flow data were analyzed between 1967 and 2006 (Table 8). The total flow annually and for JAS months was determined in MCM and compared to the estimated volume of glacier ice lost (assuming all ten glaciers lost volume at the same rate that Teton, Middle Teton, and Teepe Glaciers lost) during the same time periods. Even assuming that all the volume lost makes it directly to the Snake River and occurs during the months July through September, the contribution of the ice melt to Snake River streamflow is minimal.

An analysis of the annual stream flow displays the highest percentage of Snake River stream flow contributed from the glaciers was 0.17%. The highest found during JAS months was 0.21%. The average over the entire period was 0.05%. Thus, most of the impact of the Teton glacial ice melt is on local streams. However, stream flow records for the local streams are not available. Observations during the field trip to Teton Glacier confirmed that many of the small streams flowing during late summer originated at the glaciers.

Table 8. Total stream flow at Snake River near Moran Junction stream gage #13011000.

	Total stream flow (MCM)			
Year	Annual	July	August	September
1967	1,314	256	263	137
1968	1,195	208	247	175
1969	1,264	189	208	178
1970	1,306	233	201	195
1971	1,817	335	259	175
1972	1,713	232	240	211
1973	1,050	195	173	131
1974	1,842	312	258	137
1975	1,407	157	292	148
1976	1,559	154	304	117
1977	1,000	282	163	75
1978	1,006	155	150	76
1979	1,181	184	117	50
1980	1,124	178	135	60
1981	1,058	102	75	77
1982	1,657	349	152	141
1983	1,496	395	193	118
1984	1,851	419	205	386
1985	1,373	108	139	93
1986	1,915	250	190	191
1987	910	141	125	102
1988	849	125	127	91

1989	613	75	202	188
1990	1,050	147	164	206
1991	1,109	127	159	156
1992	1,506	359	322	170
1993	658	82	189	182
1994	1,191	191	366	161
1995	1,115	253	193	163
1996	1,890	234	189	167
1997	2,275	235	202	198
1998	1,637	248	203	239
1999	1,598	175	180	180
2000	1,107	136	129	107
2001	1,418	267	324	221
2002	1,001	220	268	256
2003	1,229	315	392	286
2004	1,181	191	189	173
2005	693	132	129	124
2006	948	148	136	132

4.6 Comparison to Wind River Range Glaciers

From a similar study, for the Wind River Range, during a 1966-2006 study period, the ice melt rate was greater during the second portion (1989 to 2006) of the period (Thompson, 2009). The rate of loss exhibited in the Teton Range was similar to WRR, especially when comparing the 1983-1994 period for the Tetons and the 1989-2006 period for the WRR. For these periods, the Teton glaciers exhibited an average rate of area loss of 1.5% per year while the WRR glacial area loss averaged between 1.9% and 1.6% per year (Table 9).

The comparison of direct volume change measurements to volume changes based on the Bahr area to volume conversion yielded similar results for the WRR and Tetons, especially during the 1989-2002 period. On average the difference between Bahr and direct volume change measurements in the WRR was approximately 32% (Table 10) and the Teton Glaciers averaged a 30.3% difference.

The climate data impacts were comparable to the results in the WRR, as the JAS average temperatures had no distinct correlation to average rate of ice losses per year. In two of the WRR COOP stations, the 1966-1989 average temperatures were warmer than the 1989-2006 average temperatures and vice versa (Table 11). The Teton Range temperature data were also inconclusive.

The data for the April 1st SWE was the only climate difference between the Teton Range and the WRR. In general, the increased WRR ice melt rates during the 1989-2006 portion of the 1966-2006 study were consistent with lower snow water equivalent values and lower stream flows during the 1989-2006 period as compared to the 1966-1989 period (Thompson 2009). The seven SNOTEL stations were consistent in that the April 1st SWE was lower during the 1989 to 2006 period as opposed to the 1966 to 1989 period (Table 12).

Table 9. Wind River Range average rate of area loss expressed as %/yr between 1966 and 2006.

		Total area of all glaciers in watershed	Area loss between listed dates	Average rate of area loss between dates*
Watershed	Year	(km^2)	%	%/Yr
Green River	66	7.9		
	89	6.5	17.6	0.8
	2006	4.8	27.1	1.6
Green River	66	12.5		
	89	10.6	15.3	1.2
	2006	7.9	25.2	1.9
Dinwoody	66	14.4		
	89	12.8	11.1	0.9
	2006	10.0	22.0	1.7

*I.e., the slope of the area loss curve

Table 10. Wind River Range direct volume change estimates compared to Bahr equation.

	Period	Direct measurements of change in volume (MCM)	Average rate of loss (MCM/ Yr)	Bahr equation change in volume (MCM)	Bahr average rate of loss (MCM/ Yr)	% difference between Bahr and direct measurement of volume change difference
Bull Lake Watershed	89-02/06*	135.0	10.4	102.0	6.0	24.4
Green River Watershed	89-02/06*	95.7	7.4	58.0	3.4	39.4

*Direct measurements were to 2001 whereas area-volume were to 2006

Table 11. Wind River Range JAS average temperatures for four COOP stations.

	JAS average temperature ˚C for four COOP stations			
Period	Dubois	Diversion Dam	Pinedale	Burris
66-89	13.9	18.1	12.9	16.2
89-06	14.3	17.3	13.2	15.9

Table 12. Wind River Range SNOTEL average April 1st snow water equivalent (SWE) for 7 stations.

	WRR SNOTEL average April 1st SWE (cm)						
Period	Elkhart Park	New Fork Lake	Kendall	Big Sandy Opening	Little Warm	Cold Springs	Hobbs Park
66-89	35.1	28.4	36.8	37.8	29.7	23.9	38.4
89-06	31.8	26.9	32.5	34.0	26.9	17.8	34.0

4.7 Predicting Glacial Changes

Realistically, it may be impossible to predict future activity of the Teton Range glaciers, since glacial changes are climate dependent. Historically, glaciers have gone through cycles of assimilation and recession in response to climate cycles. For the WRR, Kelsey (Wyoming's Wind River Range, American Geographic Publishing, 1988) hypothesizes that the WRR glaciers may have completely disappeared during a warming period 7500 to 5000 years ago. Thus, the glaciers that exist today are probably the result of advances that have occurred since that period. Kelsey also states that earlier in history, a WRR glacier extended 50 miles down the Green River Valley nearly to the site of U.S. 189/191, as evidenced by glacial erosion and deposition. Although documentation could not be found, since many of the factors that can be compared are similar for the WRR and Teton glaciers, the Teton glaciers may have gone through similar cycles to those of the WRR.

Since predicting future climate trends is difficult, if not impossible, the scenario of assuming glacial recession rates remain as during the period of this study, i.e. 1967-2006 was theorized. Thus, Figures 13a-13c are not predictions of expected conditions, but rather projections of glacial trends assuming climate conditions remain unchanged, which is unlikely. The glacial change trends of the past 40 years were projected into the future to estimate the approximate time when the glaciers would disappear based on the assumption of the unlikely continuation of recent trends (Figures 13a-13c). The projections were performed for the three glaciers studied (Teton, Middle Teton, and Teepe). As the glaciers become smaller, the rate of losses could increase assuming similar climate conditions.

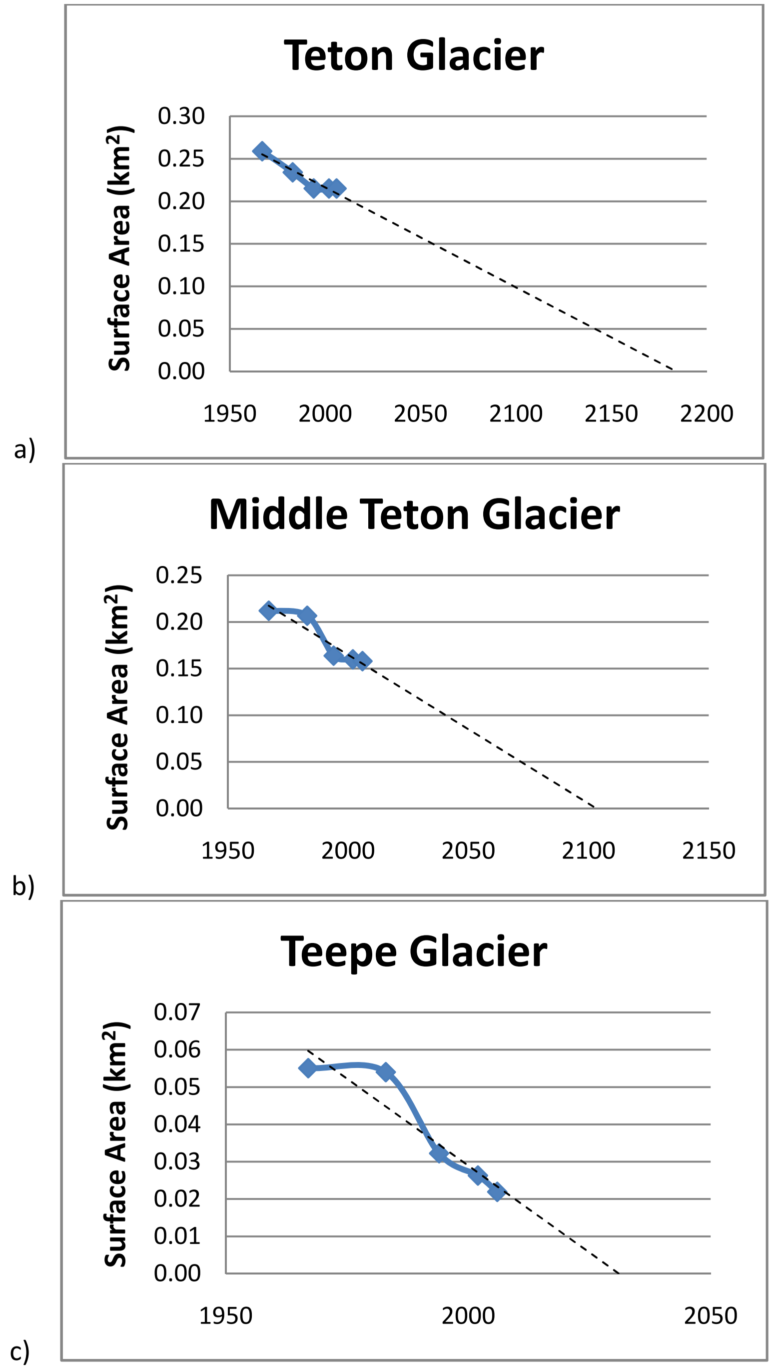

Figure 13. Theorized projected glacial trends for Teton, Middle Teton, and Teepe Glaciers in the Teton Range (theorized, based on the unlikely assumption that glacial trends continue as during the period of this study).

4.8 Field Observations of Teton Glacier

A field trip was taken to Teton Glaicer on August 29, 2009 for field observations (Figures 14a and 14b). Teton Glacier sits in a cirque just between the peaks of Grand Teton and Mount Owen. The trip was important in direct observation of the land and type of features that had only previously been seen from aerial photographs.

The trip started in the Lupine Meadows parking lot and traversed through many switchbacks until finally reaching Surprise and Amphitheater Lakes. From this point, the trail followed upward along the ridge leading to Grand Teton peak. The last and hardest part of the trek was traversing across the boulder fields to the moraine of Teton Glacier. The last stop was directly on the surface of the glacier where the observations continued.

The steepness of the surrounding cliffs and size of the glacier was breath-taking. Numerous digital photos were taken to compare the findings to aerial photos of Teton Glacier. Some areas, which were unclear in aerial photos were observed and photographed for future analyses of the glacial area. The focus was particularly on areas where it could not be discerned if the surface was dirty ice or bare ground. Many superglacial streams were found near the bottom of the glacier. Most streams were small, less than 15 cm deep and about as wide. One main stream at the bottom of the glacier was estimated to be 0.5 meters wide and 0.25 meters deep. The flow from the glacier wound down the slope and eventually fed Delta Lake. Field observations confirmed that much of the impact of the glaciers is on local environmental factors such as the small streams originating at the base of the glaciers.

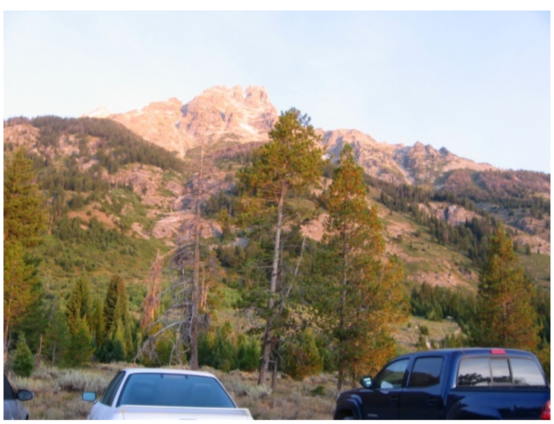

Figure 14a. Example of photos taken during field trip to Teton Glacier.

Figure 14b. Example of photos taken during field trip to Teton Glacier.

Chapter 5: Summary

Analyses of the magnitude and changes of glaciers (Teton, Middle Teton, and Teepe) in the Teton Range have been performed. The surface area of the glaciers was quantified (1967-2006) as well as the change in volume (1967-2002) for the three glaciers in this study. The directly measured volume changes estimated in this study were compared to estimates using Bahr's et al. (1997) area to volume conversion. The climate data was studied in this region in an attempt to isolate climate factors directly related to the change in glacial area and volume. Stream flow data was compiled to estimate the approximate additional stream flow in the Snake River from glaciers in the Teton Range. The results from this study were compared to those of the Wind River Range (WRR).

The three glaciers studied (Teton, Middle Teton, and Teepe) decreased from a total surface area of 0.526 km^2 in 1967 to a total surface area of 0.395 km^2 in 2006, a reduction in surface area of 0.131 km^2 or 25% during the 1967-2006 period. Middle Teton Glacier lost the most area with 0.054 km^2, while Teepe lost the highest percentage of area at 60%. The highest rate of area loss was found between the 1983 and 1994 time period, with a loss of 1.54 %/yr.

The glaciers lost a volume of 3.20 million cubic meters (MCM) between 1967 and 2002, determined directly by the comparison of stereo pairs created from one meter resolution aerial photographs. Middle Teton Glacier lost the most at 1.34 MCM. As was the case for area, the highest rate of volume loss, 0.15 MCM/yr, was during the 1983 to 1994 time period. An empirical (power equation) was derived, relating area change to volume, to estimate future volume changes based on measured change in area.

This study analyzed climate factors that might be driving the area and volume losses. Neither temperature nor April 1st SWE variations were observed to be consistent with variations in the retreat rates of glaciers in the Teton Range. The only possible relationship found, though not very strong, was the elevated June temperatures during the 1983 to 1994 period. The April 1st SWE data failed to be related to glacial area or volume losses in the Teton Range. When rates of ice loss were the highest, the SWE was greater than during other time periods, which is opposite of what would be expected.

The stream flow data from the Snake River was analyzed to determine the approximate contribution from the glaciers in the Teton Range. Assuming all ice melt reached the Snake River, the contribution from the glacier loss was less than a third of a percent even during the time period when the rate of loss was at its peak measurement.

The results from this study were compared to the results of a study of the WRR glaciers. The results from the WRR glacier study were very comparable to those found in the Teton Range study. The rates of area losses were almost identical, especially during the 1983-1994 period in the Teton Range and the 1989-2006 period in the WRR. The Teton Range had an average rate of area loss of 1.5 %/yr and the WRR experienced a loss of 1.6 %/yr. The Teton Range direct volume loss estimates compared to the loss estimates from the Bahr method in much the same manner as the WRR results. The Teton Range measurements yielded a difference between Bahr and direct volume measurements of 30% and the WRR for two different watersheds was 24%

and 39% respectively. The climate data impacts for the Teton study was similar to the WRR data, as the changes in temperature data failed to correlate with area and volume losses. The difference between the Teton Range study and the WRR data was the April 1st SWE. The findings in the WRR indicated that April 1st SWE was lower during the period of a higher rate of area and volume losses.

The glaciers in the Teton Range create a majestic view and remain to be one of the defining features of the Tetons. Accurate monitoring of the changes in the area and volume of the glaciers is crucial to understanding the potential impact of the variability of the glaciers in the future.

Appendix 1: References

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Appendix 2: Acknowledgements

This research was supported by the Grand Teton National Park Service and the University of Wyoming Office of Water Programs. This report is a revised version of the following documented thesis by Jake Edmunds:

Edmunds, Jake F., 2010. Glacier Variability (1967-2006) in the Teton Range, Wyoming, U.S.A., M.S. Thesis, Department of Civil and Architectural Engineering, University of Wyoming, Laramie.

The authors wish to express their appreciation to Ramesh Sivanpillai, Larry Pochop, Jameson Bell, and Derrick Thompson for their assistance throughout this study. Further thanks to Larry Pochop for his assistance in preparing this report.

Appendix 3: Project Coordination: Meetings/Data Sharing

Meetings were held monthly with the glacier project team in Laramie, Wyoming. Project objectives and results were discussed. The meetings helped keep the project on schedule and constantly introduced ideas on improving the work being done. Other coordination efforts/meetings included:

- Thompson, D., J. Bell, J. Edmunds, G. Tootle and G. Kerr, 2009. "Glacier Variability in Wyoming's Wind River Range and Teton Range". Presentation at *American Water Resources Association* 2009 Spring Specialty Conference, May 4-6, 2009. Anchorage, Alaska.
- Presentation at UW-NPS Research Center. AMK Ranch. July 16th, 2009.
- Teton Range Glacier Study meeting. Met with Sue Consolo-Murphy (Chief of Science and Resources Management) discussing continuation of work to be completed on the glacier project. July 16th, 2009.
- Teton Range Glacier Study meeting. Meeting with Kathryn Mellander (GIS specialist for Grand Teton National Park) about GIS work and aerial photos of the Teton Range. July 17th, 2009.
- Discussion of glacier projects and Teton Glacier trip coordination with Hazel Reynolds Reynolds (graduate student at Idaho State University). August 12, 2009.
- Field observation trip to Teton Glacier with Hazel on August 29, 2009.
- Presented an update on glacier project at UW-NPS Research Center. AMK Ranch. September 4, 2009.
- J. Edmunds, G. Tootle and G. Kerr, 2010. "Glacier Variability in the Teton Range, Wyoming". Poster Presentation at *American Water Resources Association* 2010 Spring Specialty Conference, March 29-31, 2010. Orlando, Florida.

Appendix 4: Project Data

Table A.4.1. Aerial Photography Characteristics.

Year	Source	Project	Roll	RMSE	Date Taken
1967	USGS	VBRW00	1	2.58	17-Aug-67
1983	USGS	NHAP82	383	2.50	15-Sep-83
1994	USGS	NAPPW	7824	2.50	25-Aug-94
2002	USDA	NAIP	County Mosaic	4.19	2-Sep-06
2006	USDA	NAIP	County Mosaic	4.19	2-Sep-06

Table A.4.2. Jackson COOP Average Monthly Temperature 1905-2006.

	Average Monthly Temperatures (˚C)					
Year	April	May	June	July	August	September
1905	3.6	6.9	11.0	14.8	14.9	10.2
1906	1.4	7.0	7.7	15.2	14.7	10.1
1907	3.4	7.4	10.2	14.4	-----	-----
1908	-----	-----	-----	-----	-----	-----
1909	-----	-----	-----	-----	-----	-----
1910	-----	-----	-----	-----	-----	-----
1911	-----	-----	-----	-----	-----	-----
1912	-----	-----	-----	-----	-----	-----
1913	-----	-----	-----	-----	-----	-----
1914	-----	-----	-----	-----	-----	-----
1915	-----	-----	-----	-----	-----	-----
1916	-----	-----	-----	-----	12.5	9.5
1917	0.0	6.2	-----	16.6	14.1	11.8
1918	1.5	6.9	15.4	15.6	-----	11.6
1919	-----	-----	-----	-----	-----	-----
1920	-----	-----	-----	-----	16.0	-----
1921	2.3	9.4	15.3	17.3	15.8	9.7
1922	0.5	6.8	12.9	-----	17.0	11.6
1923	1.4	8.6	11.4	18.0	15.5	11.6
1924	2.3	-----	13.4	15.6	15.3	12.3
1925	-----	-----	-----	-----	15.5	15.5
1926	5.0	10.2	14.3	16.9	14.9	11.0
1927	1.5	9.1	13.5	16.5	14.6	9.3
1928	-1.8	9.5	10.2	16.1	14.8	11.6
1929	1.5	7.0	12.3	17.6	17.6	8.4
1930	6.1	7.2	11.6	16.6	15.9	10.4
1931	3.1	7.1	14.0	17.4	15.5	10.1
1932	3.2	8.2	11.8	16.1	14.4	10.3
1933	1.8	5.9	14.8	17.2	14.3	10.9
1934	6.3	12.9	-----	18.0	17.1	11.0
1935	2.9	6.8	13.7	16.2	16.1	11.7
1936	2.7	9.4	14.2	18.0	15.5	9.2
1937	0.0	9.2	12.4	16.7	16.2	12.0

1938	2.8	7.2	13.0	15.2	14.0	11.7
1939	-----	-----	10.7	14.9	13.8	11.9
1940	-----	9.7	13.2	15.2	14.4	10.9
1941	3.6	9.0	12.4	15.7	14.7	8.2
1942	4.4	6.7	10.2	15.3	14.6	10.2
1943	6.8	4.9	10.7	15.2	-----	-----
1944	2.7	8.0	10.5	13.9	13.9	9.9
1945	0.8	8.0	9.9	19.0	16.9	8.9
1946	5.6	6.7	12.4	17.5	16.0	9.7
1947	3.3	9.7	10.7	16.1	14.0	11.7
1948	-----	-----	-----	-----	-----	11.2
1949	4.9	9.4	12.3	15.2	14.8	11.2
1950	3.8	5.9	10.9	15.0	13.6	10.4
1951	4.1	8.5	9.9	15.5	14.4	10.3
1952	3.0	8.7	12.9	15.0	14.7	12.1
1953	1.6	5.4	11.8	16.6	15.1	11.9
1954	4.8	9.2	10.6	16.6	14.4	10.8
1955	1.6	7.7	11.4	15.9	16.4	11.3
1956	4.0	9.8	13.1	16.1	13.9	11.7
1957	3.0	9.0	12.6	16.2	15.7	11.3
1958	2.1	10.4	14.2	15.7	17.2	11.7
1959	4.4	6.4	13.7	15.8	15.0	10.3
1960	4.3	7.8	12.5	16.2	13.7	11.0
1961	3.1	8.9	14.4	17.0	16.2	7.6
1962	4.2	8.5	11.9	14.6	13.8	10.6
1963	2.2	9.0	11.7	15.3	14.8	12.7
1964	1.9	7.7	11.0	16.3	12.9	8.9
1965	3.7	6.1	10.7	15.1	13.8	7.0
1966	2.2	8.4	11.1	15.8	14.2	11.6
1967	1.5	7.4	11.6	16.1	15.1	11.7
1968	1.2	6.3	11.2	16.3	13.3	9.3
1969	4.3	9.7	11.2	15.7	16.3	11.2
1970	0.0	7.6	12.7	16.1	16.1	8.2
1971	2.7	8.1	12.3	15.6	16.8	7.8
1972	3.0	7.5	12.9	15.2	14.9	8.4
1973	0.9	8.1	12.2	16.0	15.6	9.5
1974	3.4	6.9	14.6	17.1	14.2	10.2
1975	-0.1	6.1	11.5	17.7	13.4	10.0

1976	2.6	9.9	11.7	16.2	14.5	11.4
1977	4.8	7.5	15.1	16.0	14.7	10.7
1978	4.7	7.6	12.0	15.8	13.5	10.3
1979	3.2	8.4	12.0	15.4	15.3	11.5
1980	4.0	8.8	12.1	16.2	14.3	11.3
1981	5.2	8.5	13.1	16.4	16.1	12.0
1982	2.2	7.6	12.2	16.1	17.2	10.5
1983	1.2	6.1	11.5	16.5	17.1	11.3
1984	-----	10.3	11.3	16.7	16.2	9.4
1985	4.5	9.1	13.3	17.1	14.3	8.9
1986	3.3	6.5	15.0	15.0	15.0	8.6
1987	5.9	9.3	13.2	15.7	14.3	10.5
1988	5.4	8.1	16.3	17.6	16.6	9.9
1989	5.2	8.7	12.6	18.6	14.7	10.6
1990	5.4	7.4	12.7	16.9	15.5	13.3
1991	3.7	7.9	13.3	16.4	16.8	10.7
1992	6.1	10.5	13.7	15.1	16.1	10.9
1993	2.6	8.9	11.5	12.3	14.3	10.7
1994	5.1	10.5	13.8	16.7	16.9	11.2
1995	3.8	7.0	11.5	15.4	15.5	11.0
1996	3.6	7.4	-----	17.6	16.1	10.7
1997	2.8	9.7	15.4	15.9	16.5	13.1
1998	3.4	8.9	10.4	18.3	16.7	13.9
1999	2.9	7.7	12.7	16.3	16.9	10.8
2000	7.1	10.6	13.9	17.5	17.2	11.2
2001	4.5	10.1	13.7	16.8	16.4	12.1
2002	5.7	8.5	13.9	18.5	14.9	11.8
2003	5.9	10.4	13.5	19.6	18.4	10.9
2004	7.3	10.3	14.7	17.6	16.4	12.4
2005	5.0	9.3	11.5	17.1	15.2	10.2
2006	6.4	11.2	14.9	19.0	15.5	10.8

Table A.4.3. Snake River COOP Average Monthly Temperatures 1905-2006.

	Average Monthly Temperatures (˚C)					
Year	April	May	June	July	August	September
1905	-----	-----	11.2	13.6	14.1	9.5
1906	2.3	4.8	8.4	13.4	12.4	8.7
1907	-----	-----	-----	14.5	12.6	8.0
1908	-----	5.4	7.7	14.2	12.6	9.0
1909	-2.9	3.0	11.9	14.0	14.3	8.8
1910	2.8	5.7	11.4	15.3	11.8	9.6
1911	1.6	4.9	11.9	13.1	12.2	8.5
1912	-0.8	3.8	10.6	13.9	12.6	6.4
1913	1.2	5.9	10.6	10.9	13.5	10.3
1914	2.1	6.7	9.4	-----	-----	-----
1915	-----	-----	-----	17.5	19.8	11.1
1916	2.7	-----	-----	-----	16.8	-----
1917	-----	-----	-----	15.7	12.6	7.9
1918	-1.3	-----	-----	-----	-----	-----
1919	-----	-----	-----	-----	-----	12.6
1920	-0.1	4.5	8.7	14.2	13.3	7.8
1921	-1.2	6.2	11.6	13.3	12.6	5.9
1922	-3.6	3.4	11.6	13.1	14.0	8.5
1923	-0.8	5.0	8.8	14.9	11.1	9.0
1924	0.1	6.6	10.3	13.5	11.8	7.7
1925	1.9	7.1	10.6	12.7	-----	7.6
1926	2.9	8.2	11.2	14.7	13.6	5.7
1927	0.7	3.5	-----	14.0	11.3	8.4
1928	-2.6	7.0	6.9	13.4	12.3	9.1
1929	-1.5	3.2	9.6	15.2	14.8	-----
1930	3.8	5.7	10.3	14.8	14.3	8.3
1931	0.7	6.0	12.5	15.8	13.6	8.5
1932	-0.5	6.0	10.5	13.4	12.8	8.4
1933	-1.2	4.0	12.3	15.7	13.5	8.6
1934	4.5	10.1	10.6	15.5	14.7	7.2
1935	-0.2	4.3	9.7	15.1	12.7	8.8
1936	-0.1	7.3	12.0	17.4	14.3	8.9
1937	-0.7	6.9	11.4	15.6	13.9	10.4

1938	1.0	4.7	11.5	14.2	13.1	11.0
1939	2.6	7.1	-----	14.5	13.5	9.3
1940	1.7	7.8	12.1	14.8	14.7	11.0
1941	1.3	7.3	11.0	14.9	13.7	6.0
1942	1.7	4.0	-----	-----	-----	10.6
1943	-----	-----	-----	14.3	13.7	10.1
1944	1.0	6.7	9.3	13.3	12.3	8.7
1945	-2.1	5.5	8.0	14.0	13.7	7.0
1946	2.8	4.9	10.8	15.5	13.8	7.8
1947	0.2	6.8	9.0	14.7	12.6	9.1
1948	-----	-----	-----	-----	13.3	9.2
1949	1.7	7.1	10.3	14.3	15.2	9.7
1950	0.1	2.7	9.4	12.9	13.7	8.8
1951	3.0	7.2	7.8	14.5	13.0	8.1
1952	2.1	6.6	10.8	13.6	13.7	10.3
1953	-1.6	3.8	10.2	15.7	13.8	9.6
1954	1.6	6.8	9.0	15.5	12.6	8.8
1955	-1.0	5.2	9.5	14.5	14.7	8.8
1956	1.0	7.1	11.0	14.7	12.7	8.8
1957	0.7	6.6	10.0	14.3	13.7	8.6
1958	-----	-----	-----	-----	-----	-----
1959	-----	-----	-----	-----	-----	-----
1960	-----	-----	-----	-----	-----	-----
1961	-----	-----	-----	-----	-----	-----
1962	-----	-----	-----	-----	-----	-----
1963	-----	-----	-----	-----	-----	-----
1964	-----	-----	-----	-----	-----	-----
1965	-----	-----	-----	-----	-----	-----
1966	-----	-----	-----	-----	-----	-----
1967	-----	-----	-----	-----	-----	-----
1968	-----	-----	-----	-----	-----	-----
1969	2.4	7.6	10.2	14.1	14.6	10.2
1970	-2.5	5.3	10.5	15.1	14.9	6.7
1971	-2.1	5.9	10.0	14.3	16.8	6.7
1972	0.4	5.8	11.1	13.5	14.7	7.1
1973	-1.8	5.9	10.6	14.6	14.1	-----
1974	-0.6	4.1	11.8	15.7	12.8	8.0
1975	-3.3	2.4	8.8	15.4	10.8	7.4

1976	-0.1	5.9	9.0	14.5	11.3	8.9
1977	1.7	5.4	13.0	14.2	12.9	6.8
1978	1.2	4.3	10.1	14.4	11.6	7.5
1979	-0.6	4.8	10.3	14.4	13.5	10.0
1980	0.4	6.3	10.2	13.8	11.6	8.1
1981	1.9	5.6	9.7	13.3	14.6	9.8
1982	-3.2	3.5	9.8	13.3	14.3	7.8
1983	-1.9	3.6	8.5	13.4	14.9	7.5
1984	-----	4.6	8.7	14.3	13.9	6.4
1985	1.2	6.9	11.1	15.3	11.4	-----
1986	0.4	4.4	12.7	12.0	13.3	5.7
1987	3.1	8.2	11.3	12.8	11.4	9.1
1988	1.0	6.4	13.2	14.4	12.0	6.3
1989	0.5	5.4	10.2	15.2	12.2	7.7
1990	2.5	4.3	10.4	14.6	13.4	11.4
1991	-1.0	4.6	10.5	13.7	14.3	8.3
1992	2.6	8.4	10.6	11.6	12.6	6.7
1993	-0.5	6.8	9.0	9.4	11.1	7.2
1994	1.0	7.3	10.5	14.1	13.8	8.9
1995	-0.6	3.9	8.8	12.3	11.7	7.4
1996	-0.5	3.9	10.6	15.1	13.1	6.8
1997	-2.4	5.5	11.7	13.0	13.4	-----
1998	0.3	6.3	7.4	14.4	11.2	11.5
1999	-0.8	3.8	9.3	13.0	13.9	6.8
2000	2.3	6.3	10.0	14.6	14.0	7.5
2001	-0.1	6.9	10.5	15.2	14.7	9.8
2002	0.6	5.0	11.1	16.2	12.1	8.3
2003	2.0	6.1	10.2	16.3	15.2	7.7
2004	2.6	5.3	10.3	13.8	12.2	7.6
2005	0.2	5.9	9.0	14.4	13.0	7.5
2006	1.8	6.3	11.5	16.1	12.4	8.4

Table A.4.4. Moran COOP Average Monthly Temperatures 1911-2006

	Average Monthly Temperatures (˚C)					
Year	April	May	June	July	August	September
1905	-----	-----	-----	-----	-----	-----
1906	-----	-----	-----	-----	-----	-----
1907	-----	-----	-----	-----	-----	-----
1908	-----	-----	-----	-----	-----	-----
1909	-----	-----	-----	-----	-----	-----
1910	-----	-----	-----	-----	-----	-----
1911	-1.4	5.8	12.7	14.0	14.0	7.4
1912	-1.4	4.0	10.9	11.1	11.9	5.9
1913	1.4	6.3	11.0	13.0	14.2	8.8
1914	3.3	6.9	10.1	13.9	12.6	7.7
1915	5.1	5.8	8.4	12.3	13.6	7.8
1916	1.0	3.0	8.2	13.8	12.1	7.6
1917	-4.0	4.3	8.4	15.8	12.5	9.6
1918	-1.2	4.7	13.5	13.4	12.2	9.2
1919	0.8	7.0	12.2	14.2	13.2	9.3
1920	-0.6	5.4	9.7	14.6	13.7	9.4
1921	-0.3	7.1	12.4	14.5	13.9	7.3
1922	-0.3	6.3	11.9	13.3	15.4	10.2
1923	0.7	6.8	10.2	16.3	13.2	9.6
1924	1.1	6.9	10.7	13.8	12.3	8.4
1925	1.9	6.2	9.1	14.0	12.1	9.9
1926	4.3	8.4	12.5	15.8	13.8	7.0
1927	-0.1	5.4	12.0	14.9	12.4	8.4
1928	-3.5	7.9	9.0	14.0	11.4	9.0
1929	-1.5	4.2	9.2	13.6	14.7	7.2
1930	4.1	6.3	10.0	15.4	15.0	9.4
1931	0.8	6.0	12.6	15.1	13.5	8.4
1932	-1.0	5.4	10.6	14.3	12.9	8.3
1933	-2.0	4.5	12.5	15.3	13.0	9.3
1934	4.7	9.7	10.8	15.1	14.0	7.5
1935	0.6	5.0	10.9	14.4	13.3	10.0
1936	0.3	7.8	12.5	16.7	13.9	8.3
1937	-1.9	6.9	10.2	15.0	13.6	10.1

1938	0.4	5.5	11.6	13.9	12.4	10.7
1939	2.2	7.2	8.8	13.8	12.3	9.1
1940	1.3	7.6	11.4	13.8	13.5	9.8
1941	0.6	7.2	10.2	14.2	13.1	7.0
1942	1.6	4.9	9.1	14.1	13.7	8.9
1943	3.5	4.8	8.6	13.5	12.8	9.7
1944	0.2	6.7	9.3	12.9	12.0	8.6
1945	-2.9	5.9	8.0	13.8	13.2	7.4
1946	2.6	5.7	10.7	15.1	13.4	8.2
1947	0.2	7.7	8.9	14.2	12.9	10.0
1948	0.4	6.4	11.4	13.5	12.7	9.2
1949	1.5	7.6	10.6	13.9	12.4	9.3
1950	-0.6	3.5	9.4	12.4	11.7	8.1
1951	0.5	6.6	7.4	13.2	11.6	8.0
1952	0.4	6.4	10.2	12.4	12.6	9.4
1953	-2.1	4.2	10.2	14.4	12.8	9.0
1954	1.2	7.3	8.9	14.5	11.7	8.3
1955	-1.0	5.6	10.1	15.5	15.5	9.9
1956	1.2	7.9	11.9	14.9	13.0	9.9
1957	0.5	6.9	11.0	15.3	14.5	10.0
1958	-0.1	9.6	12.7	14.3	16.0	9.6
1959	1.2	4.7	12.6	15.2	13.8	8.8
1960	1.9	6.5	11.8	16.5	13.4	11.1
1961	0.3	7.1	13.8	15.7	15.6	6.3
1962	1.9	7.1	11.3	13.9	13.4	9.9
1963	0.1	7.4	10.7	15.1	14.8	11.6
1964	0.5	6.0	9.9	15.9	12.7	8.6
1965	2.2	5.5	10.2	14.7	13.8	6.1
1966	0.3	8.2	11.1	15.9	14.2	11.4
1967	0.2	5.9	10.7	15.5	15.3	11.6
1968	-0.9	5.4	10.7	15.4	12.9	9.1
1969	3.1	8.9	10.2	14.8	15.6	11.2
1970	-1.8	5.4	11.8	15.5	15.8	7.4
1971	0.4	6.9	10.6	14.6	16.8	7.4
1972	1.2	6.5	11.6	13.9	14.8	8.0
1973	-1.2	6.3	11.1	14.9	14.9	9.4
1974	1.5	5.5	12.6	16.6	13.1	9.5
1975	-2.3	4.0	9.7	16.7	12.7	9.3

1976	0.7	7.1	10.4	15.6	13.4	10.7
1977	3.0	6.6	14.3	15.5	13.9	9.4
1978	2.9	6.5	12.0	16.1	13.2	8.5
1979	1.3	6.9	12.1	15.6	15.2	11.8
1980	2.1	7.4	11.6	15.6	13.7	10.5
1981	3.1	7.0	11.4	15.1	15.6	11.2
1982	-2.2	4.8	10.6	14.4	15.8	9.5
1983	-0.9	4.8	10.4	14.8	16.0	10.0
1984	-0.6	5.9	10.5	16.1	15.7	8.3
1985	2.3	7.8	12.4	16.6	13.2	7.2
1986	2.2	6.3	13.7	13.4	15.3	7.4
1987	4.1	8.9	12.4	14.3	12.9	10.4
1988	2.5	7.4	15.8	17.2	15.7	10.2
1989	2.2	7.1	11.9	18.0	14.3	10.4
1990	4.3	6.5	12.2	16.5	15.9	13.8
1991	0.8	6.3	12.5	15.9	16.6	10.8
1992	5.1	10.5	13.1	13.9	15.3	9.7
1993	1.2	8.2	10.4	11.2	13.1	10.2
1994	3.3	9.9	12.9	16.9	16.9	12.3
1995	1.5	6.3	11.2	14.9	15.5	10.9
1996	1.7	6.4	13.1	16.9	15.6	9.4
1997	0.4	7.7	13.2	15.0	15.3	11.6
1998	1.8	7.3	8.8	17.6	16.0	12.8
1999	0.4	5.3	10.5	-----	15.1	8.6
2000	3.6	7.5	11.9	16.0	15.0	9.3
2001	1.2	7.4	12.0	15.6	15.6	11.0
2002	1.3	6.4	11.8	-----	13.2	9.5
2003	1.5	6.4	10.4	16.7	16.4	9.3
2004	2.5	5.8	10.4	14.3	13.0	8.8
2005	1.7	6.1	9.2	15.1	13.5	8.6
2006	2.2	6.7	12.1	16.9	13.1	8.6

Table A.4.5. SNOTEL April 1st SWE 1981-2006.

SNOTEL APRIL 1st SWE (cm)				
Year	Snake River	Lewis Lake Divide	Grassy Lake	Phillip's Bench
1981	-----	47.0	59.2	40.4
1982	-----	137.2	135.4	111.8
1983	-----	95.3	102.9	89.7
1984	-----	73.4	86.1	62.2
1985	-----	82.8	79.8	57.9
1986	-----	117.1	100.8	96.0
1987	-----	46.5	47.2	43.9
1988	-----	74.7	71.9	57.4
1989	-----	113.3	104.4	93.2
1990	37.3	69.1	69.6	56.4
1991	39.4	73.7	74.9	58.2
1992	26.7	57.9	54.9	42.4
1993	41.4	74.2	80.8	70.4
1994	33.3	53.3	62.7	49.5
1995	51.6	104.1	100.3	73.7
1996	54.1	122.7	96.3	84.8
1997	73.9	134.6	117.1	109.2
1998	42.7	76.7	78.2	67.6
1999	57.4	103.6	109.5	83.1
2000	43.9	67.8	82.6	58.9
2001	25.9	42.4	52.3	41.4
2002	35.3	75.2	71.9	55.4
2003	37.3	85.9	80.0	64.0
2004	39.6	73.7	87.1	59.9
2005	30.0	59.4	62.7	57.4
2006	54.4	104.4	97.3	87.1