JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 48, No. 1 AMERICAN WATER RESOURCES ASSOCIATION February 2012

GLACIER VARIABILITY (1967-2006) IN THE TETON RANGE, WYOMING, UNITED STATES[1]

Jake Edmunds, Glenn Tootle, Greg Kerr, Ramesh Sivanpillai, and Larry Pochop[2]

ABSTRACT: Glacier area and volume changes were quantified through the use of historical aerial photographs in Wyoming's Teton Range. Glacier area changes in the Teton Range were estimated for three glaciers using unrectified 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% during the 39-year period. The smallest glacier, Teepe, experienced the greatest area loss (60 ± 3%), whereas the largest glacier, Teton Glacier, lost 17 ± 3% of the 1967 area. For the current research, aerial photography from 1967 to 2002 was used to estimate glacier volume loss using stereoscopy techniques. The aerial photographs provide a finer resolution when compared with other datasets including satellite imagery (e.g., Landsat). Volume loss for the three glaciers was estimated to be 3.20 ± 0.46 million cubic meters over the period of 1967 to 2002. In assessing the primary climatic driver of the glacier ice loss, observed summer (June, July, and August) temperature data showed a statistically significant increase in temperatures when comparing the period of study (1968 to 2006) with historical temperatures from 1911 to 1967. When comparing spring (April 1st Snow Water Equivalent) snowpack for the period of study with historical records beginning in 1931, a significant difference in snowpack was not observed.

(KEY TERMS: glacier; Teton Range; Wyoming.)

Edmunds, Jake, Glenn Tootle, Greg Kerr, Ramesh Sivanpillai, and Larry Pochop, 2011. Glacier Variability (1967-2006) in the Teton Range, Wyoming, United States. *Journal of the American Water Resources Association* (JAWRA) 48(1): 187–196. DOI: 10.1111/j.1752-1688.2011.00607.x

INTRODUCTION

Grand Teton National Park (GTNP) and the Teton Range in northwest Wyoming is host to 10 named glaciers that have been in a period of recession since the 1850s 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 streamflow that affect fish populations in small, headwater streams) and recreational (fewer visitors to the GTNP) impacts. With the current focus on climate change and the potential impacts on glaciers, GTNP personnel expressed an interest to document changes in the Teton glaciers based on the reported loss of glacier area in the Wind River Range of Wyoming (Cheesbrough *et al.*, 2009; Thompson *et al.*, 2011). Three glaciers were selected for this study: Teton Glacier, Middle Teton Glacier, and Teepe Glacier. Teton Glacier was selected because it is the largest glacier in the range and due to its visibility to GTNP visitors. Middle Teton Glacier was selected because it is one of the larger glaciers found in the range. To provide a range of glacier sizes, a smaller glacier, Teepe Glacier, was also selected for this study. The streamflow generated from the

[1]Paper No. JAWRA-10-0126-P of the *Journal of the American Water Resources Association* (JAWRA). Received July 31, 2010; accepted August 9, 2011. **Discussions are open until six months from print publication.**

[2]Respectively, Graduate Student (Edmunds) and Professor Emeritus (Pochop), Department of Civil and Architectural Engineering, University of Wyoming, Laramie, Wyoming 82071; Associate Professor (Tootle), Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, Tennessee 37996; Director (Kerr), Office of Water Programs, University of Wyoming, Laramie, Wyoming 82071; and Associate Research Scientist (Sivanpillai), Department of Botany and Wyoming Geographic Information Science Center (WyGISC), University of Wyoming, Laramie, Wyoming 82071 (E-Mail/Tootle: gtootle@utk.edu).

glaciers directly feeds the Snake River that flows into 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. Research efforts determined that small glaciers are highly sensitive to changes in precipitation and temperature (Meier, 1984; Oerlemans *et al.*, 1998). Due to their sensitivity to precipitation and temperature, the glaciers are important indicators of regional climate change (Granshaw and Fountain, 2006).

Previous Research Efforts

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 numerous research studies and countless photographs of the glacier.

Previous studies of Teton Glacier include: Fryxell (1935); Jepson from 1949 to 1950; M.T. Millet in 1960; and John C. Reed from 1963 to 1967. Unfortunately, the results of Jepson and Millet were never published but were included in the University of Colorado master's thesis of John C. Reed, which was published (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, thus indicating for the one-year period (1963 to 1964), the glacier was decaying and in an apparent state of recession.

The purpose of this study was to provide new data to the GTNP's historical ecological inventory of the glaciers. As the glaciated regions of the 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 aims to create a database of quantitative information about the glaciers for GTNP by quantifying the glacier area change and glacier volume change for the three selected glaciers (Teepe, Middle Teton, and Teton) in the Teton Range, through the use of aerial photographs.

STUDY AREA

The Teton Range in western Wyoming (Figure 1) is an unbroken 65-km host to 10 named glaciers. 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 average elevations of Teton (latitude: 43.742; longitude: −110.791), Middle Teton (latitude: 43.742; longitude: −110.805), and Teepe Glaciers (latitude: 43.736; longitude: −110.798) were, respectively, 3,250, 3,326, and 3,454 meters. The glaciers are generally oriented to the east with average slopes ranging from 27 to 38% based on the 1967 image.

METHODS

Data

For this study, a 1-meter resolution, late-summer (when snowcover is minimal) aerial photography was selected. The 1-meter resolution was used to minimize the error associated with estimating area and volume losses. It has been reported that photointerpretation currently provides the most accurate classification (90% or higher) of temporal landscape changes (Lindgren, 1985; Jensen, 1986).

Area Estimation

The aerial photographs were obtained from the United States Geological Survey (USGS) and Wyoming Geographic Information and Science Center (WyGISC, 2009) in Laramie, Wyoming. Images were acquired for 1967, 1983, 1994, and 2002 from the USGS whereas the images for 2002 and 2006 were obtained from WyGISC. The WyGISC images were an orthorectified mosaic covering the entire county. As the WyGISC images had been orthorectified, it was the logical choice to use for georeferencing the other images. To maintain consistency, 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 fact that this is the same image acquired through the U.S. Department of Agriculture aerial imagery program that was used for creating

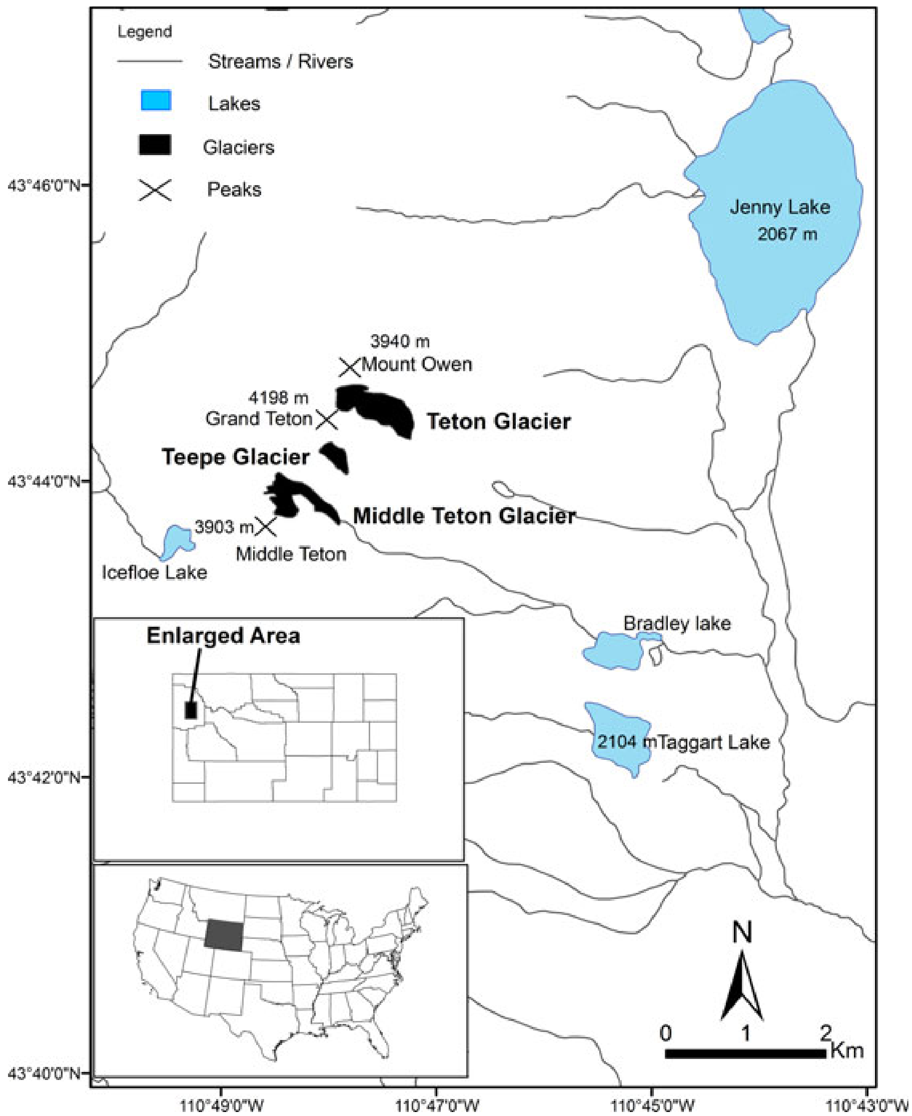

FIGURE 1. Location Map of Three Studied Glaciers in the Teton Range.

the orthorectified county mosaic. The 1967 and 1994 images were black and white. The 1983 and 2001 images were color infrared and the 2006 image was true color.

Volume Estimation

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. As the WyGISC data was a mosaic, stereo pairs could not be created and, therefore, could not 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 photographs. The reports provided flying height, fiducial coordinates, and the calibrated focal length. These reports were crucial in developing the stereo pairs (Ledwith and Lundén, 2001) to estimate volume loss and the associated error estimates.

Data Uncertainty

Uncertainty was assessed in calculating area and volume changes from aerial photographs. Each image set had to be analyzed slightly different due to the manner they were photographed. Some images were black and white, whereas others were color infrared and true color. A major challenge occurred in the area calculations. The analyst had to determine glacier ice and differentiate what was shadows, debris, and dirty ice.

There was also uncertainty in estimating the volume change. In determining ground control points (GCP) to create the stereo pairs, there were minimal roads or buildings. Therefore, trees and giant boulders were used as GCP. Although it can be assumed that the boulders have not moved during the period of the study, there is still some level of uncertainty in that assumption. 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).

Area Analysis

The images obtained from the USGS were without spatial coordinates and, therefore, had to be associated by the user. Due to the rugged terrain of the Tetons, this process became more challenging as the images also required geometric correction. We created subsets of each image to cover each glacier and also provided additional area for locating GCP. Thirty GCP were used in the process of geometrically correcting the photographs using a third-order polynomial transformation. This task was completed for each individual glacier for every year resulting in nine different images (three sets of images each for 1967, 1983, and 1994). County mosaics acquired in 2002 and 2006 were the remaining two images.

The images were exported to ArcMap 9.3 (ESRI, Inc., Redlands, CA, USA), a Geographic Information System (GIS) for analyzing the area of the glaciers. The geographic area was calculated by "heads up" digitizing of each glacier. Each glacier was digitally delineated 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 processing 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 acquired. Shadows are the primary challenge with digital processing and classification, and the manual method allows for better interpretation of the shadow influence.

Area Error Estimation

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

The total digitizing error (e_{d}) was calculated using Equation (1) (Hall *et al.*, 2003).

$$e_{\mathrm{d}} = \sqrt{r_{\mathrm{p}}^2 + r_{\mathrm{b}}^2} + e_{\mathrm{r}}, \tag{1}$$

where r_{p} is the pixel resolution of the georeferenced paper maps, r_{b} is the pixel resolution of the base map (2002 aerial photograph), and e_{r} is the registration error of the summation of the georeferenced paper map root mean-squared error (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):

$$e_{\mathrm{a}} = r_i^2 \times \left(\frac{2e_{\mathrm{d}}}{r_{\mathrm{i}}}\right), \tag{2}$$

where r_{i} is the image's pixel resolution and e_{d} is the total digitizing error calculated in Equation (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 casted 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.

$$\delta Q = \sqrt{(\delta q_1)^2 + (\delta q_2)^2 + \cdots (\delta q_n)^2}, \tag{3}$$

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

Volume Analysis

Volume change analyses were conducted in ERDAS (ERDAS, Inc., Atlanta, GA, USA) and ArcGIS software (ESRI, Inc.), which contained the algorithms used in this part of the study. After placing a pair of adjacent aerial images from the same year in ERDAS' Leica Photogrammetry Suite (LPS) module, information about the camera's calibrated focal length was entered along with the fiducial points. The fiducial points were placed individually on each photograph to an accuracy of 0.10 pixels RMSE.

Photographs were then georeferenced to known points using the 2002 color infrared photograph. As neither survey benchmarks nor anthropological structures exist in the photographs, the control and check points were placed on distinct rock formations or vegetated areas that were not subject to movement over time. Thirty points were used in creating GCP and check points with X, Y, and Z coordinates.

Georeferencing was accomplished by overlaying the 2002 photograph over a digital elevation model (DEM) obtained from the USGS. One point on the 2002 photograph providing northing, easting, and elevation was selected, then the same point was found on the other two photographs, 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 photographs with overlapping portions, which are positioned such that the parallax between the common objects allows the user to view the objects in 3D using either red/blue anaglyph stereo glasses or liquid crystal display (LCD) stereo glasses.

Each stereo pair was converted to a digital terrain model (DTM) in ERDAS LPS. The volume difference was calculated using two DTMs 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 Inc.'s (Golden, CO, USA) Surfer software. 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.

TABLE 1. Teton, Middle Teton, and Teepe Glaciers: Area With Error (km^2); Fractional Area Change (FAC) – Minimum, Average, Maximum (%); Volume Loss With Error (MCM).

	Teton		Middle		Teepe	
Year	**Area (km^2)**	**± (km^2)**	**Area (km^2)**	**± (km^2)**	**Area (km^2)**	**± (km^2)**
1967	0.259	0.005	0.212	0.003	0.055	0.002
1983	0.234	0.002	0.207	0.003	0.054	0.003
1994	0.215	0.006	0.164	0.004	0.032	0.001
2002	0.215	0.004	0.16	0.003	0.026	0.001
2006	0.215	0.004	0.158	0.007	0.022	0.001

	Fractional Area Change (%)			Fractional Area Change (%)			Fractional Area Change (%)		
Period	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**
67-83	−7	−10	−12	2	−2	−7	9	−2	−12
83-94	−5	−8	−11	−16	−21	−25	−34	−41	−47
94-02	5	0	−5	2	−2	−7	−13	−19	−24
02-06	4	0	−4	5	−1	−7	−8	−15	−22
67-06	−14	−17	−20	−21	−25	−30	−57	−60	−63

	Volume Loss		Volume Loss		Volume Loss	
Period	**(MCM)**	**± (MCM)**	**(MCM)**	**± (MCM)**	**(MCM)**	**± (MCM)**
67-83	0.36	0.05	0.30	0.05	0.23	0.03
83-94	0.70	0.10	0.74	0.10	0.19	0.03
94-02	0.22	0.03	0.29	0.05	0.16	0.02
67-02	1.29	0.18	1.34	0.20	0.57	0.08

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 the methodology below, was repeated 10,000 times through the use of a random number generator that resulted in a confidence interval (CI) of 95%.

The method involved first determining a baseline 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 million cubic meters (MCM), the area would be

$$\frac{1.29 \times 10^6 \text{meters}^3}{4.84\text{meters}} = 2.67 \times 10^5 \text{meters}^2.$$

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 0 and a standard deviation of 1. This resulted in an error between the values of negative 10 and positive 10. This value was then multiplied by the aforementioned area to create an error estimate. After repeating 10,000 times, the data were normally distributed and the CI provided the associated error estimation.

$$\text{Ve} = \text{CI of } (\text{DEM error} \times \mathit{Area} \times \text{RandomNumber}) \tag{4}$$

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

RESULTS

Glacial Area Change From 1967 to 2006

In 1967, the total surface area of Teton, Middle Teton, and Teepe Glaciers was 0.526 ± 0.010 km^2 (Table 1). The largest glacier in 1967 was Teton Glacier with a surface area of 0.259 ± 0.005 km^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 of 0.055 ± 0.002 km^2.

The total 2006 calculated surface area of the three glaciers was 0.395 ± 0.012 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 0.044 ± 0.009 km^2 of its 1967 surface area. Middle Teton Glacier experienced the greatest loss at 0.054 ± 0.010 km^2. The smallest glacier, Teepe Glacier, lost 0.033 ± 0.003 km^2.

Fractional Area Change

Similar to Granshaw and Fountain (2006), the fractional area change (FAC), the area change

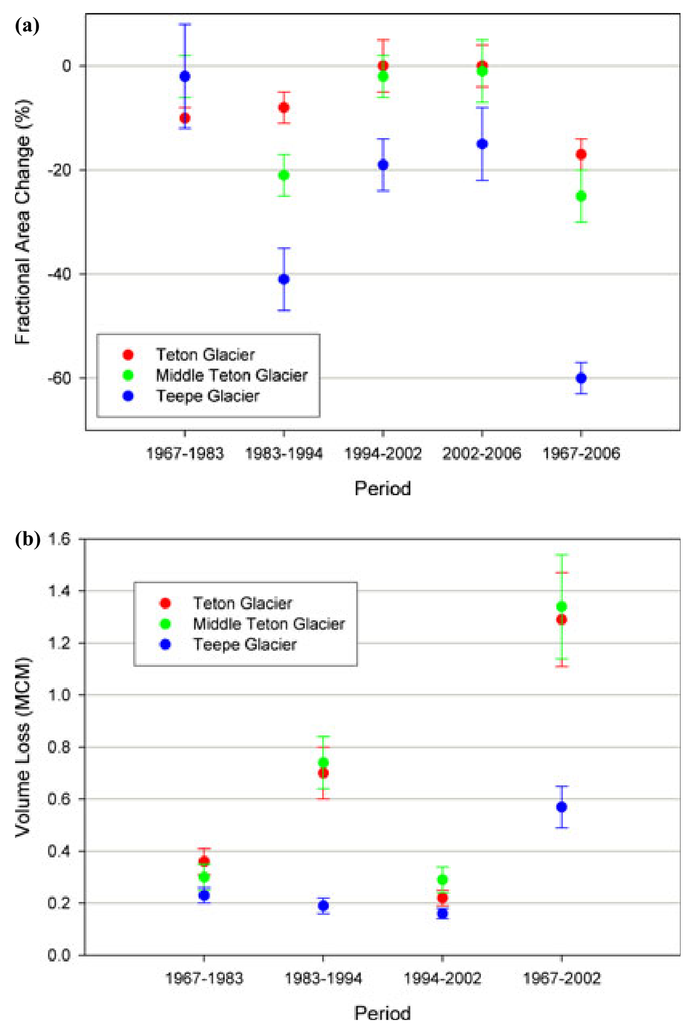

FIGURE 2. (a) Individual Glacier Fractional Area Change – FAC (%); (b) Individual Glacier Volume Loss (MCM). The “whisker” plots show the estimated error.

divided by the original area, was plotted against original area. Between the years 1967 and 2006, the FAC for Teton, Middle Teton, and Teepe Glacier were 17, 25, and 60%, respectively (Figure 2a and Table 1). The FAC was calculated for each time step (1967-1983, 1983-1994, 1994-2002, and 2002-2006) (Figure 2a and Table 1). Referring to Figure 2a, the "whisker" plots (average, maximum, and minimum FAC) show the range of uncertainty when calculating the FAC. For example, in 1967, the surface area of Teton Glacier was $0.259 \pm 0.005\ km^2$ whereas, in 2006, the surface area was $0.215 \pm 0.004\ km^2$. Therefore, the average FAC was determined by $(0.215 - 0.259)/0.259$ or −17%. The maximum FAC was determined by using the smallest estimated 2006 area ($0.215 - 0.004 = 0.211\ km^2$) minus the largest estimated 1967 area ($0.259 + 0.005 = 0.264\ km^2$) divided by the 1967 area ($0.259\ km^2$) or −20%. The minimum FAC was determined by using the largest estimated 2006 area ($0.215 + 0.004 = 0.219\ km^2$) minus the smallest estimated 1967 area ($0.259 - 0.005 = 0.254\ km^2$) divided by the 1967 area ($0.259\ km^2$) or −14%.

Glacial Volume Loss From 1967 to 2002

The glacial volume change was determined between three periods (1967-1983, 1983-1994, and 1994-2002) and for the entire period of record (1967-2002) (Figure 2b and Table 1). Combined, the three glaciers lost a total of 3.20 ± 0.46 MCM between 1967 and 2002 (Figure 3). The period of highest volume loss appears to be 1983-1994 when 1.63 ± 0.23 MCM of volume was lost, which equates to approximately 49% of the total volume lost during the 1967-2002 study period. Middle Teton Glacier lost the greatest volume, 1.34 ± 0.20 MCM.

DISCUSSION AND CONCLUSIONS

An investigation of historic climatic (Precipitation, Snowpack, Temperature) variability in the Teton Range was performed in an attempt to explain the rapid loss of glacier area and mass. Initially, research

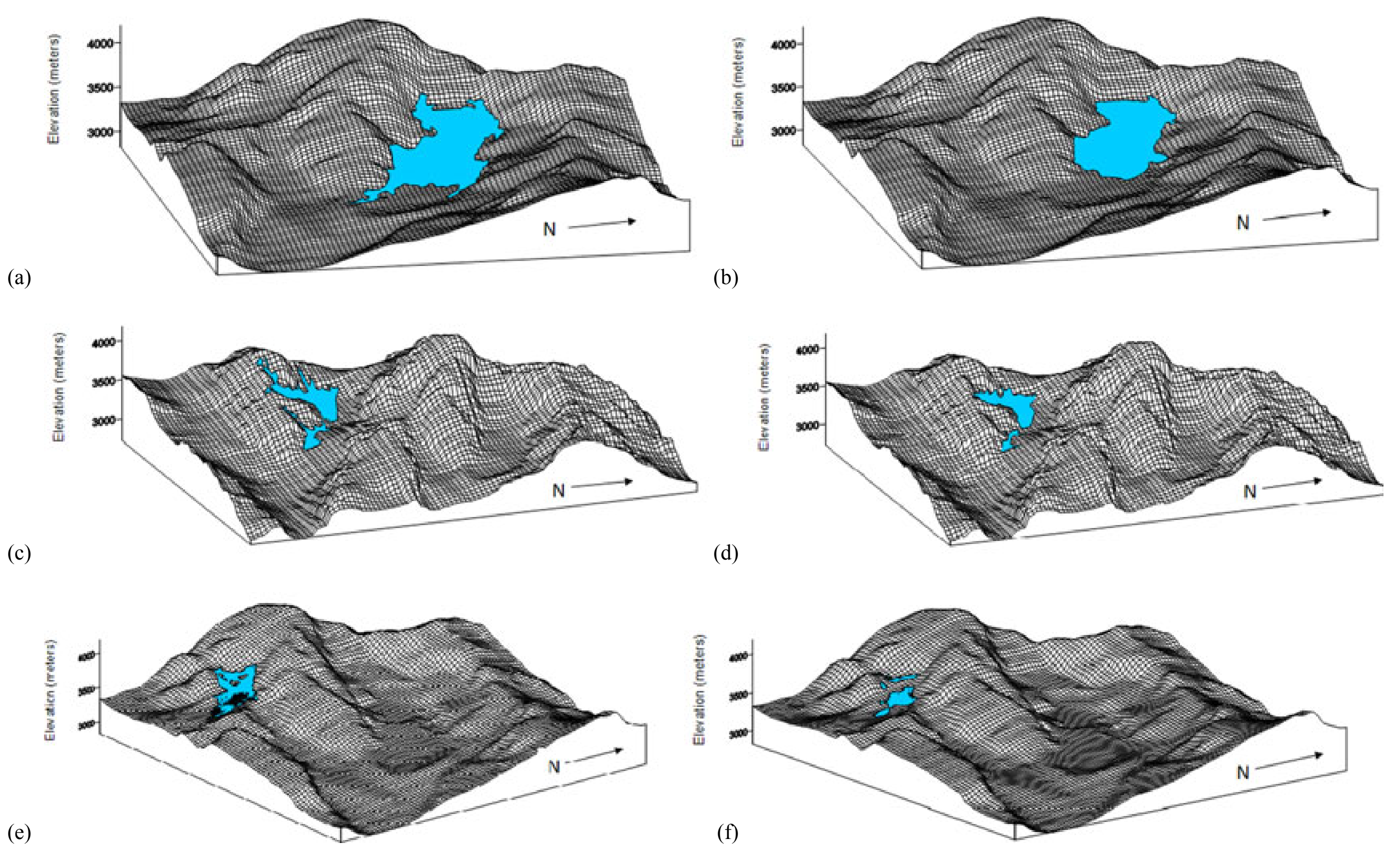

FIGURE 3. Three-Dimensional Wireframes for (a) Teton Glacier in 1967; (b) Teton Glacier in 2002; (c) Middle Teton Glacier in 1967; (d) Middle Teton Glacier in 2002; (e) Teepe Glacier in 1967; and (f) Teepe Glacier in 2002. The "blue" area represents the estimated surface of the glacier.

efforts that developed paleo reconstructions (using tree rings) were investigated. However, the paleo streamflow (Graumlich *et al.*, 2003; Watson *et al.*, 2009; Barnett *et al.*, 2010) and precipitation (Gray *et al.*, 2004a,b, 2007) studies were in regions adjacent to the Teton Range. Further investigation revealed a paleo temperature study by Naftz *et al.* (2002) in which ice cores were extracted from the Freemont Glacier in the nearby Wind River Range (Wyoming). The ice cores revealed a rapid warming since the 1960s in the Wind River Range (Naftz *et al.*, 2002).

Next, historic records of observed precipitation (snowpack) and temperature were investigated. The Natural Resource Conservation Service (NRCS) maintains an extensive data collection system (SNOwpack TELemetry or SNOTEL) in the western U.S. (http://www.wcc.nrcs.usda.gov/snow/) in which snowpack (Snow Water Equivalent – SWE) is collected. Each of the snowpack stations used in the current research had complete records from 1930 to 2006 and the April 1st SWE dataset selected has been used in previous research efforts (Hunter *et al.*, 2006; Aziz *et al.*, 2010). Four SNOTEL stations in Wyoming (Base Camp, Granite Creek, Snake River, and Lewis Lake Divide) were identified near (within approximately 50 km) the Teton glaciers (Figure 4). The yearly April 1st SWE dataset for each station was segregated into two time periods, 1930 to 1967 and 1968 to 2006 (time period of glacier study). Similar to Tootle *et al.* (2005), the nonparametric rank-sum test was performed on the two time periods, for each of the four stations, to test the difference in the medians. The method compares two independent datasets and determines if one dataset has significantly larger values than the other dataset. For each of the four stations, the rank-sum test determined that there were no significant (>90%) differences in April 1st SWE between the two time periods. Interestingly, the April 1st SWE combined average and standard deviation for the four stations from 1930 to 1967 (54.6 cm and 25.2 cm) and from 1968 to 2006 (56.2 cm and 26.3 cm) were very similar.

Finally, temperature data were retrieved from the National Weather Service (NWS) Cooperative Observer Program (COOP). The Moran, Wyoming (length of record from 1911 to 2006) and Jackson, Wyoming (length of record from 1921 to 2006) stations were selected due to the length of record and location near the Teton glaciers (Figure 4). Average monthly (June, July, and August) temperatures for the spring-summer season, when glacier melt is likely the greatest, were selected. Similar to the SNOTEL data, the time periods were segregated, for each station, for each month. For the Moran station, the dates were 1911 to 1967 and 1968 to 2006. For the Jackson station, the dates were 1921 to 1967 and 1968 to 2006. The

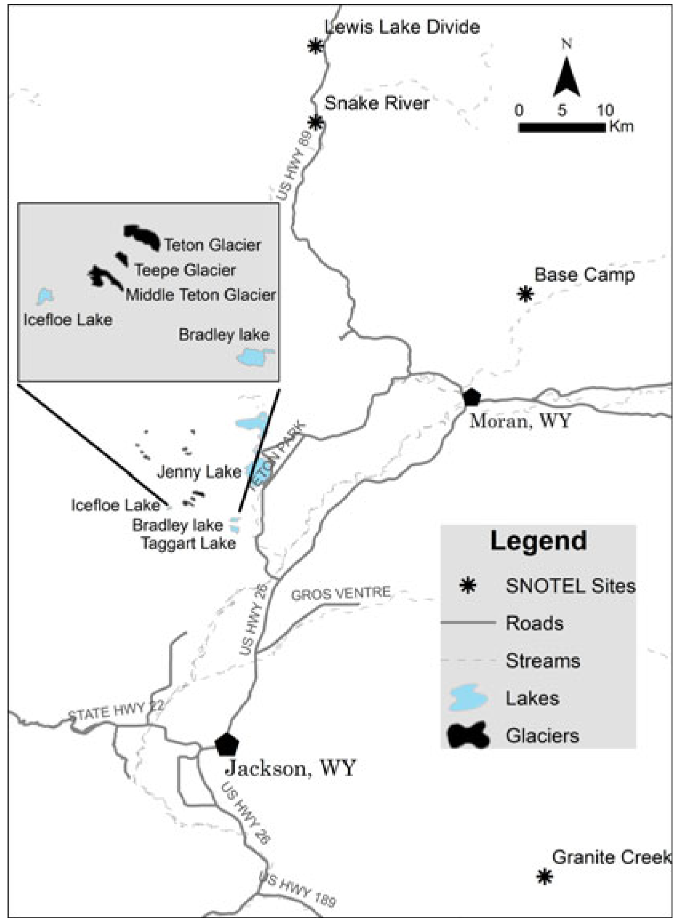

FIGURE 4. Location Map of SNOTEL Stations (Base Camp, Granite Creek, Snake River, and Lewis Lake Divide) and Temperature Stations (Jackson and Moran, Wyoming) Used in the Current Teton Glacier Research.

Moran station had missing data for July (1999 and 2002) whereas the Jackson station had missing data for June (1925, 1934, 1948, and 1996), July (1922, 1925, and 1948), and August (1943 and 1948). Six rank-sum tests were performed, three (June 1911 to June 1967 and June 1968 to June 2006; July 1911 to July 1967 and July 1968 to July 2006; August 1911 to August 1967 and August 1968 to August 2006) for the Moran station and three (June 1921 to June 1967 and June 1968 to June 2006; July 1921 to July 1967 and July 1968 to July 2006; August 1921 to August 1967 and August 1968 to August 2006) for the Jackson station. The rank-sum testing of the Moran station resulted in all three months having temperature differences (>95% significance) such that the temperatures during the time period of the glacier study were significantly higher than the time period prior to the study. The July and August months resulted in the highest (>99% significance) differences. The Moran station 1911 to 1967 temperatures (mean ± standard deviation – celsius) were: June (10.6 ± 1.5), July

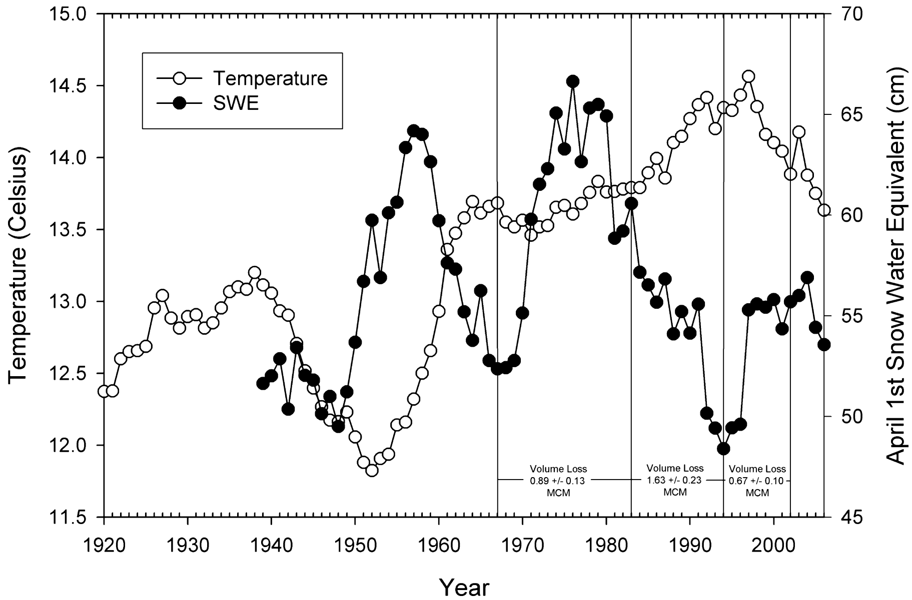

FIGURE 5. Temperature (yearly June, July, and August average – celsius) for the Moran, Wyoming Temperature Station With 10-Year (end year) Filter (1920 to 2006); April 1st Snow Water Equivalent (yearly average for Base Camp, Granite Creek, Snake River, and Lewis Lake Divide stations – centimeter) With 10-Year (end year) Filter (1939 to 2006); and Total Glacier Volume (mass) Loss (MCM) for 1967 to 1983, 1983 to 1994, and 1994 to 2002.

(14.4 ± 1.1), and August (13.3 ± 1.1), whereas the 1968 to 2006 temperatures were: June (11.6 ± 1.4), July (15.5 ± 1.3), and August (14.8 ± 1.3). The rank-sum testing of the Jackson station had similar results in that all three months had temperature differences (>90% significance) such that the temperatures during the time period of the glacier study were significantly higher than the time period prior to the study. The June and August months resulted in the highest (>95% significance) differences. The Jackson station 1921 to 1967 temperatures (mean ± standard deviation – celsius) were: June (12.2 ± 1.4), July (16.2 ± 1.1), and August (15.1 ± 1.1), whereas the 1968 to 2006 temperatures were: June (12.9 ± 1.4), July (16.6 ± 1.3), and August (15.6 ± 1.2).

The yearly (1930 to 2006) April 1st SWE (cm) for the four SNOTEL stations were averaged and a 10-year (end year) filter was applied, which resulted in a time period of 1939 to 2006 (Figure 5). Given the longer and more complete record of the Moran station, the yearly (1911 to 2006) June, July, and August temperatures (Celsius) were averaged and a 10-year (end year) filter was applied, which resulted in a time period of 1920 to 2006 (Figure 5). The estimated glacier volume loss with error (MCM) is shown for the periods of 1967 to 1983, 1983 to 1994, and 1994 to 2002 (Figure 5). The graph clearly reveals the increase in June, July, and August temperatures during the glacier period of study and, thus, confirms the Wind River Range ice core observations of Naftz *et al.* (2002) of increased temperatures from the 1960s to present. Additionally, the greatest loss of glacier mass occurred from 1983 to 1994, which coincides with a rise in temperatures and a reduction in snowpack. The snowpack variability may be associated with the Pacific Decadal Oscillation or the El Nino-Southern Oscillation (Hunter *et al.*, 2006). However, as determined by the rank-sum testing, the long-term change was not of significance.

Concurrent research efforts on the Wind River Range, using both LandSat and aerial photographs of glacier ice, confirmed the results provided in this research that glaciers in northwest Wyoming are in a period of recession (Cheesbrough *et al.*, 2009; Thompson *et al.*, 2011). Future work may include paleo (tree-ring based) reconstructions of snowpack and temperature in the Teton Range to provide insight into the observed glacier recession prior to the 1960s. The paleo reconstructions may extend back 400 years and would reveal if the summer temperatures have increased and/or if snowpack has decreased. Additional future research may utilize heavy isotopes (obtained from tree rings) that reveal changes in water sources (e.g., precipitation, glacier melt) that would help explain the glacier recession observed.

ACKNOWLEDGMENTS

This research is supported by the Rocky Mountain Cooperative Ecosystems Studies Unit and the University of Wyoming Water Research Program (funded jointly by the USGS, the Wyoming

Water Development Commission, and the University of Wyoming). Additional support was provided by the University of Tennessee, the USGS 104B program, the Oak Ridge National Laboratory Joint Directed Research and Development program, and the National Science Foundation P2C2 award AGS-1003393. The authors wish to thank the staff of the Grand Teton National Park, especially Ms. Sue Consolo-Murphy for her support. Finally, the authors thank the Editor, Associate Editor, and three anonymous reviewers for their support and helpful comments.

LITERATURE CITED

Aziz, O.A., G.A. Tootle, S.T. Gray, and T.C. Piechota, 2010. Identification of Pacific Ocean Sea Surface Temperature Influences of Upper Colorado River Basin Snowpack. Water Resources Research 46, W07536, doi: 10.1029/2009WR008053.

Barnett, F.A., S. Gray, and G. Tootle, 2010. Upper Green River Basin (United States) Streamflow Reconstructions. American Society of Civil Engineers Journal of Hydrologic Engineering 15(7):567-579.

Cheesbrough, K., J. Edmunds, G. Tootle, G. Kerr, and L. Pochop, 2009. Estimated Wind River Range (Wyoming, USA) Glacier Melt Contributions to Agriculture. Remote Sensing 1:818-828.

DeBeer, C.M. and M. Sharp, 2007. Recent Changes in Glacier Area and Volume Within the Southern Canadian Cordillera. Annals of Glaciology 46:215-221.

Devisser, M., 2008. Glaciers of Wyoming. Glaciers of the American West, Glaciers Online: http://glaciers.research.pdx.edu/states/wyoming.php, *accessed* January 15, 2010.

Fryxell, F., 1935. Glaciers of the Grand Teton National Park of Wyoming. Journal of Geology 43:381-397.

Granshaw, F.D. and A.G. Fountain, 2006. Glacier Change (1958-1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology 52(177):251-256.

Graumlich, L.J., M.F.J. Pisaric, L.A. Waggoner, J.S. Littell, and J.C. King, 2003. Upper Yellowstone River Flow and Teleconnections With Pacific Basin Climate Variability During the Past Three Centuries. Climatic Change 59(1-2):245-262.

Gray, S.T., C. Fastie, S.T. Jackson, and J.L. Betancourt, 2004a. Tree-Ring Based Reconstructions of Precipitation in the Bighorn Basin, Wyoming Since AD 1260. Journal of Climate 17:3855-3865.

Gray, S.T., L.J. Graumlich, and J.L. Betancourt, 2007. Annual Precipitation in the Yellowstone National Park Region Since AD 1173. Quaternary Research 68(1):18-27, doi: 10.1016/j.yqres.2007.02.002.

Gray, S.T., S.T. Jackson, and J.L. Betancourt, 2004b. Tree-Ring Based Reconstructions of Interannual to Decadal-Scale Precipitation Variability for Northeastern Utah. Journal of the American Water Resources Association 40:947-960.

Hall, D.K., K. Bayr, R.A. Bindschadler, and Y.L. Chien, 2003. Consideration of the Errors Inherent in Mapping Historical Glacier Positions in Austria From Ground and Space (1893-2001). Remote Sensing of Environment 86:566-577.

Hunter, T., G.A. Tootle, and T.C. Piechota, 2006. Oceanic-Atmospheric Variability and Western U.S. Snowfall. Geophysical Research Letters 33:L13706.

Jensen, J.R., 1986. Introductory Digital Image Processing. Prentice-Hall, Englewood Cliffs, New Jersey.

Ledwith, M. and B. Lundén, 2001. Digital Photogrammetry for Air-Photo-Based Construction of a Digital Elevation Model Over Snow-Covered Areas – Blamannsisen, Norway. Norsk Geografisk Tidsskrift – Norwegian Journal of Geography 55(4):267-275, doi: 10.1080/00291950152746630.

Lindgren, D.T., 1985. Land Use Planning and Remote Sensing. M. Nijhoff Publishers, Dordrecht, The Netherlands.

Marston, R.A., L.O. Pochop, G.L. Kerr, M.L. Varuska, and D.J. Veryzer, 1991. Recent Glacier Changes in the Wind River Range, Wyoming. Physical Geography 12(2):115-123.

Meier, M.F., 1984. Contribution of Small Glaciers to Global Sea Level. Science 51:49-62.

Naftz, D.L., D.D. Susong, P.F. Schuster, L.D. Cecil, M.D. Dettinger, R.L. Michel, and C. Kendall, 2002. Ice Core Evidence of Rapid Air Temperature Increases Since 1960 in Alpine Areas of the Wind River Range, Wyoming, United States. Journal of Geophysical Research (Atmospheres) 107(D13): ACL 3-1, CiteID 4171, doi: 10.1029/2001JD000621.

Oerlemans, J., B. Anderson, A. Hubbard, P. Huybrechts, T. Jóhannesson, and W.H. Knap, 1998. Modelling the Response of Glaciers to Climate Warming. Climate Dynamics 14(4):267-274.

Reed, J.C., 1964. Recent Retreat of the Teton Glacier, Grand Teton National Park, Wyoming. U.S. Geological Survey Professional Paper 501–C, pp. C147-C151.

Thompson, D., G. Tootle, G. Kerr, R. Sivanpillai, and L. Pochop, 2011. Glacier Variability in the Wind River Range, Wyoming, USA, American Society of Civil Engineers. Journal of Hydrologic Engineering, 16(10):763-770, doi: 10.1061/(ASCE)HE.1943-5584.0000384.

Tootle, G.A., T.C. Piechota, and A.K. Singh, 2005. Coupled Oceanic/Atmospheric Variability and United States Streamflow. Water Resources Research 41:W12408.

Watson, T., F.A. Barnett, S. Gray, and G. Tootle, 2009. Reconstructed Streamflow for the Headwaters of the Wind River, Wyoming USA. Journal of the American Water Resources Association 45(1):1-13.

WyGISC (Wyoming Geographic Information), 2009. Science Center WyGISC Data Server. http://partners.wygisc.uwyo.edu/website/dataserver/viewer.htm, *accessed* April 15, 2009.