Glacier Variability in the Wind River Range, Wyoming

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Abstract: Variability in surface area for 44 glaciers in Wyoming's Wind River Range was estimated through a comparison of historic aerial photography from 1966 to 2006. The total surface area of the 44 glaciers was estimated to be 45.9 ± 1.6 km^2 in 1966 and 28.6 ± 0.4 km^2 in 2006, a decrease of 38%. Glacial surface area was also estimated utilizing resampled aerial photography to assess the relationship between area and measurement scale. Aerial photographs were resampled to resolutions of 10 m, 15 m, 22.5 m, and 30 m to represent other satellite image resolutions used for evaluating glacier boundaries. The results show a linear decrease of total glacier area as resolution decreases. When comparing 1-m resolution to the resampled 30-m resolution for 1966 and 2006 photos, an average area difference of 5% was observed. Additionally, the current research was compared to previous research efforts that utilized Landsat imagery to detect glacier area change from 1985 to 2005. We concluded that fine spatial resolution remotely sensed imagery remains the preferred and most accurate source for measuring glacier characteristics. **DOI: 10.1061/(ASCE)HE.1943-5584.0000384.** © *2011 American Society of Civil Engineers.*

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Introduction

Glaciers and ice caps cover approximately 10–11% of the earth's surface (Gleick 1996) and store approximately 75% of the world's freshwater (Bates et al. 2008). With the recent studies in the Northern and Central Rocky Mountains of North America and the findings that glaciers are retreating as a response to the regional climate warming (Marston et al. 1991), the western United States has seen large variations in summer streamflows. These critical summer streamflows replenish reservoirs and provide water for irrigation. Hence, there is a renewed interest in assessing how their surface area changes as a result of climate warming.

Alpine glaciers make up approximately 4% of the worlds land ice area (Dyurgerov and Meier 1997, 2000) and are often located in remote locations. However, research shows these alpine glaciers are important regional climate-change indicators because of their high sensitivity to temperature and precipitation changes (Meier 1984; Oerlemans et al. 1998; Granshaw and Fountain 2006). Over the past century, annual air temperatures have risen by $0.74° \pm 0.18$°C globally (Solomon et al. 2007). During the twentieth century, this increase in temperature has been associated with a continuous retreat of smaller alpine glaciers (Dyurgerov and Meier 2000). The shrinkage of these alpine glaciers has a direct impact on the hydrologic cycle, including freshwater supply, agriculture outputs, hydroelectric power, flooding, and habitat loss (Haeberli and Beniston 1998; Theurillat and Guisan 2001).

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Glaciers serve as valuable frozen freshwater reservoirs, storing water in the winter and releasing it during the warmer summer months (Marston 1989). This storage and releasing effect of water is important for hydroelectric power generation, flood control, sea level fluctuations, glacier dynamics, sediment transport, and formation of landforms (Jansson et al. 2003). Most studies (e.g., Dyson 1952; Mears 1972; Meier 1951) indicate that the glaciers in the Wind River Range have been retreating since the 1850s, the approximate end of the Little Ice Age (Marston et al. 1991). The melt water from these glaciers is thought to be important during the warmer summer and fall months to supplement flows needed for irrigation, fisheries, and the fulfillment of interstate water compacts (Barry Lawrence, personal communication, August 12, 2009). As a result, the management and prediction of future flows from glaciers has become important to water planners in the region (Hutson 2003).

Remote sensing is useful in monitoring and detecting changes in earth surface features, such as glaciers across large areas. The availability of imagery data for inaccessible areas and advances in their processing techniques have resulted in opportunities for monitoring glacier changes across large geographic areas. The motivation of this research is to determine the extent of glacier area changes within the Wind River Range through the use of remote sensing techniques, specifically expanding upon the research conducted by Cheesbrough et al. (2009) on the Wind River Range glaciers. Cheesbrough et al. (2009) studied area changes for 42 glaciers using Landsat imagery (30-m resolution) from 1985 to 2005. This research will extend the study period (1966–2006) by using fine spatial resolution (1-m) aerial photography and compare the results obtained from aerial photos to that of Landsat images for calculating the surface area of glaciers. Higher spatial resolution data improved detection of small water bodies in the Powder River Basin, Wyoming (Sivanpillai and Miller 2010). The specific objectives of the study are to

1. Use aerial photography to detect surface-area changes for 44 glaciers located in the Wind River Range, Wyoming, between 1966 and 1989, between 1989 and 2006, and between 1966 and 2006;
2. Calculate glacier surface area by using resampled aerial photography at multiple resolutions (10 m, 15 m, 22.5 m, and 30 m)

to assess the relationship between area and measurement scale for the years 1966 and 2006; and
3. Compare the results from this study to previous work that used Landsat imagery for measuring changes in glacier surface area.

Study Area

Wind River Range, Wyoming

The Wind River Range, the largest discrete mountain mass in Wyoming, is an unbroken 160-km mountain range that extends from west-central Wyoming to northwestern Wyoming (Marston et al. 1989). Approximately 63 glaciers are located in the Wind River Range, including seven of the 10 largest glaciers in the American Rocky Mountains (Bonney 1987). These glaciers occur in the highest parts of the Wind River Range throughout most of its length, with the greatest concentration located within the Fremont Peak quadrangle along the east slope of the Continental Divide (Pochop et al. 1990). This easterly orientation is associated with decreased solar radiation and predominantly westerly winds (Fryxell 1935). The majority of these glaciers are cirque glaciers, but three of the largest are valley glaciers (Meier 1951). Today's glaciers are thought to be small remnants of the Little Ice Age, a period that occurred sometime between 1400 and 1850 (Marston et al. 1991; Krimmel 2002), but Thompson and Love (1998) cited evidence that the glaciers may date back as far as the Audubon advance (3000 years ago).

The glaciers are located within a minimum and maximum elevation of 3,113–4,205 m, with a mean elevation of 3,536 m (Devisser 2008). The highest elevations of the Wind River Range form part of the Continental Divide, which also acts as the boundary between Fremont and Sublette Counties in Wyoming. Because these glaciers straddle the Continental Divide, the runoff flows into two separate drainage systems. The western slope contributes to the Colorado River Basin, whereas the eastern slope contributes to the Missouri River Basin (Pochop et al. 1990). According to Pochop et al. (1989), the Wind River Range glaciers are considered a vital water

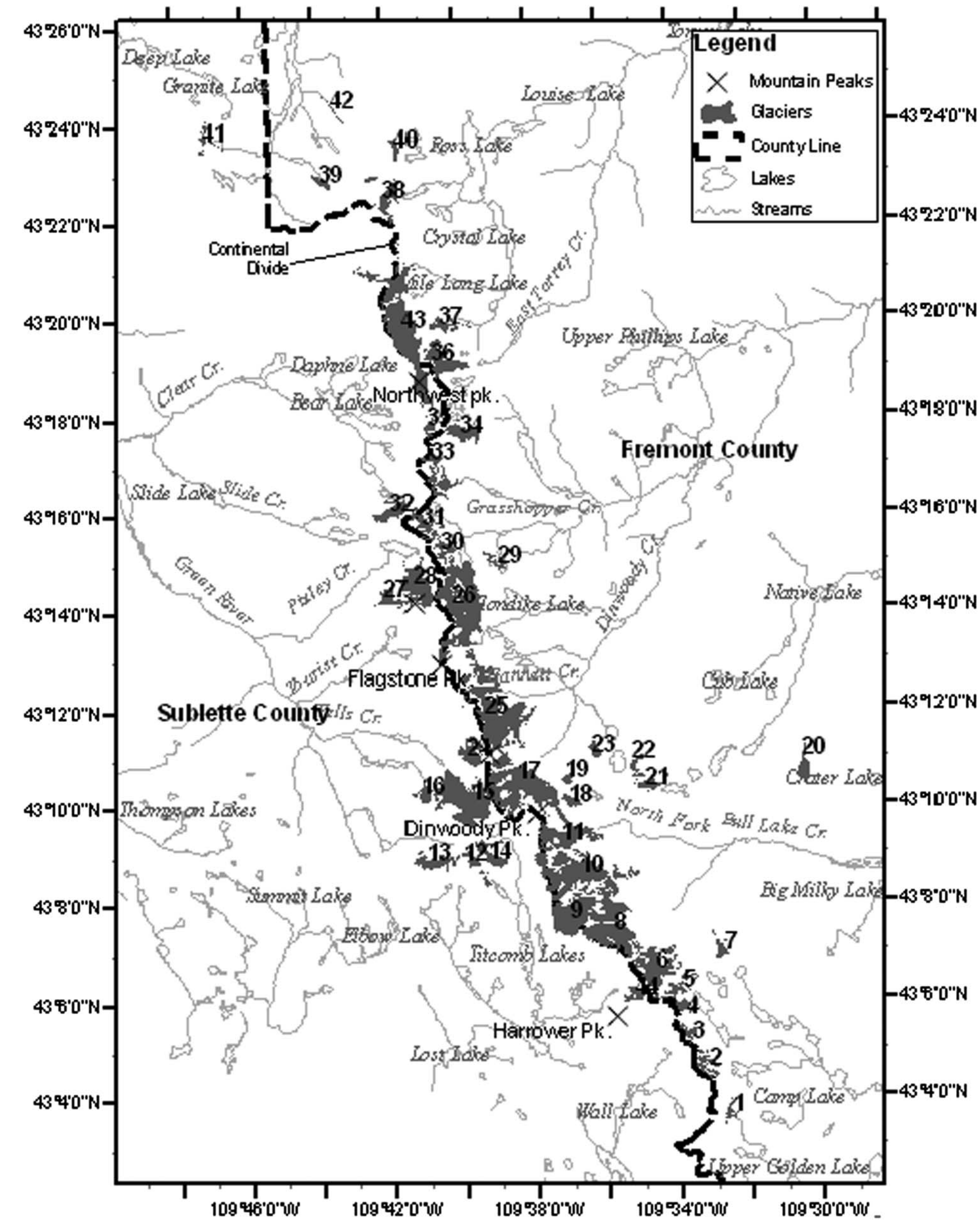

Fig. 1. Location map of 44 studied glaciers (ID provided) in the Wind River Range

source to western Wyoming during dry summer months and years of low precipitation.

The average annual precipitation from 1971 to 2000 at the higher elevations of the Fremont Peak area of the Wind River Range Mountains is 1,143 mm/year (Curtis and Grimes 2004), with most of this precipitation occurring during the winter months as snow (Martner 1986). The average annual snowfall from 1961 to 1990 in this area ranges between 6,324 mm and 20,116 mm (Curtis and Grimes 2004). This large range contributed to the quantity of snow and climatic conditions present at the time of measurement.

Data and Methods

A primary group of 44 glaciers (Fig. 1; Table 1) in the Wind River Range was examined by interpreting aerial photographs to identify spatial trends occurring between the years 1966 and 2006.

Table 1. Wind River Range Glacier Identification Number (ID), Name, and Characteristics [Aspect, Slope, and Elevation per 2001 Digital Elevation Model (DEM)]

						Elevation (m)		
Site ID	Glacier names	Latitude	Longitude	Aspect (°)	Slope (%)	Min	Max	Mean
1	NN	43.0613	−109.5441	144.9	17.1	3545	3724	3629
2	NN	43.0758	−109.5546	115.1	26.8	3349	3917	3658
3	NN	43.0865	−109.5648	148.3	36.2	3508	3899	3717
4	NN	43.0965	−109.5678	119.9	33.5	3550	3895	3728
5	NN	43.1029	−109.5710	138.5	28.3	3481	3945	3756
6	Knife Point Glacier	43.1117	−109.5797	109.0	22.3	3359	3947	3592
7	NN	43.1165	−109.5478	93.8	28.6	3403	3867	3560
8	Bull Lake Glacier	43.1225	−109.5995	122.7	24.9	3507	4118	3789
9	Upper Fremont	43.1314	−109.6143	120.6	17.7	3676	4178	3966
10	Sacagawea Glacier	43.1439	−109.6124	114.4	19.6	3397	4125	3716
11	Helen Glacier	43.1566	−109.6192	103.8	23.2	3418	4147	3712
12	NN	43.1451	−109.6593	124.3	21.1	3417	3848	3590
13	Stroud Glacier	43.1481	−109.6788	132.1	28.8	3425	3910	3610
14	Twins Glacier	43.1499	−109.6532	89.2	22.5	3345	3838	3557
15	Mammoth Glacier	43.1684	−109.6671	188.3	19.1	3386	4016	3680
16	Baby Glacier	43.1704	−109.6843	176.0	28.3	3423	3908	3609
17	Dinwoody Glacier	43.1716	−109.6385	146.8	22.3	3390	4147	3687
18	NN	43.1671	−109.6154	97.4	23.3	3742	4017	3829
19	Heap Steep Glacier	43.1749	−109.6179	69.1	36.5	3459	3959	3656
20	NN	43.1780	−109.5070	77.3	16.6	3508	3761	3669
21	NN	43.1720	−109.5799	130.4	29.7	3509	3953	3728
22	NN	43.1776	−109.5851	91.1	29.7	3667	4012	3757
23	NN	43.1849	−109.6059	125.7	17.0	3803	4000	3862
24	Minor Glacier	43.1856	−109.6626	205.0	24.8	3495	4054	3696
25	Gannett Glacier	43.1992	−109.6520	102.0	21.2	3343	4199	3768
26	Grasshopper Glacier	43.2355	−109.6659	130.8	14.6	3345	4087	3704
27	J Glacier	43.2368	−109.6945	198.4	26.0	3532	3991	3771
28	Sourdough Glacier	43.2430	−109.6865	167.0	16.8	3581	3942	3691
29	NN	43.2500	−109.6490	79.0	28.1	3432	3734	3612
30	NN	43.2543	−109.6747	63.5	23.6	3378	3754	3559
31	NN	43.2635	−109.6832	118.9	15.2	3502	3898	3766
32	Connie Glacier	43.2682	−109.6972	150.1	24.2	3522	3884	3708
33	NN	43.2823	−109.6791	132.1	18.4	3472	3975	3772
34	Downs Glacier	43.2959	−109.6645	90.1	23.6	3392	3937	3677
35	NN	43.2983	−109.6809	185.3	26.2	3646	3943	3812
36	NN	43.3196	−109.6727	96.1	18.7	3545	4027	3742
37	NN	43.3304	−109.6712	65.3	28.0	3298	3875	3696
38	NN	43.3755	−109.6986	88.5	11.1	3568	3757	3658
39	NN	43.3808	−109.7282	157.7	13.2	3509	3637	3600
40	NN	43.3919	−109.6939	94.4	4.7	3560	3597	3573
41	NN	43.3949	−109.7831	80.2	23.4	3276	3524	3422
42	NN	43.4062	−109.7227	259.2	13.9	3244	3487	3363
43	Continental Glacier	43.3313	−109.6903	97.3	12.7	3291	4028	3814
44	Harrower Glacier	43.1015	−109.5889	225.6	23.2	3496	3794	3634

Note: see Table 2 for current research. NN denotes glaciers with no name.

Additionally, trends were examined for a subset of 10 of the 44 glaciers using resampled (simulated data in other spatial resolutions) aerial photography at resolutions of 10 m, 15 m, 22.5 m, and 30 m for the 1966 and 2006 images. The resampled images were used to assess the relationship between area and measurement scale (pixel resolution) and to corroborate the results from the aerial analysis.

Surface-Area Analysis with Aerial Photographs

A total of 44 glaciers were selected in the Wind River Range to represent a comprehensive range of size, aspect, and elevation. The investigation of glacier area changes of the primary 44 glaciers was accomplished by using remotely sensed images and geographic information systems (GIS). Detecting change of a feature by using aerial photography is generally considered time-consuming and cumbersome (Lindgren 1985). While challenging, aerial photos were used because of their extremely fine resolution (approximately 1 m), allowing both large and small glaciers to be examined thoroughly. Additionally, photointerpretation currently provides the most accurate classification (90% or higher) of temporal landscape changes (Lindgren 1985; Jensen 1986). The aerial photographs for this research were taken during the late summer/early fall months, when snowpack had disappeared and the glacier terminus was clearly visible.

The aerial photos were obtained from the Wyoming Geographic Information Science Center (WyGISC) and the University of Wyoming Geology Library, both in Laramie, Wyoming (Table 2). The images include aerial photographs for the years 1966, 1989, and 2006 at a scale of 1:40,000. The aerial photos obtained from the University of Wyoming Geology Library were in the form of paper photographs, whereas each image from WyGisc was georeferenced and available in digital format. Each paper photograph was scanned at 600 dpi (dots per square inch) with a fine resolution EPSON GT-15000 flatbed photo scanner and was saved as a TIF image.

The georeferencing process involved assigning spatial coordinates to each nonreferenced paper photo. This process was completed using ERDAS Imagine 9.3, an image processing and GIS software package (ERDAS, Inc., Georgia). Unknown spatial coordinates were estimated by digitally registering the 1966 and 1989 photos to the 2001 Fremont County compressed county mosaic (CCM) aerial photo (which was used as the base) to enable calculation of area change between years. All photos were georeferenced to the Universal Transverse Mercator (UTM) zone 12-coordinate system and are tied to the North American Datum 1983 (NAD83) units. Although it is challenging to georeference photos of mountainous terrain, the scanned image was projected using a 2–4 polynomial transformation and nearest neighbor, resampling until the root mean square error (RMSE) of the control points equaled 0.1 or less. The lack of surveyed benchmarks and field data for the entirety of the study area resulted in the identification of ground control points (GCPs) for each photo. The number of GCPs placed on prominent and permanent topographical features ranged between seven and 50 GCPs for each photo. They included rock outcrops, mountain summits, lake edges, trail intersections, and identifiable changes in vegetation on each map.

Once RMSE was calculated for each individual georeferenced paper photo, the RMSE was summed together with the base photo's (2001 CCM) state average RMSE of 2.5 m. For the 1966 photos, this resulted in an average RMSE of 2.57 pixels (2.57 m); for 1989, we calculated an average RMSE of 2.55 pixels (2.55 m). The 2006 Fremont County mosaic was generated by the U.S. Department of Agriculture (USDA) by rectifying individual color aerial photos with a calculated RMSE value of 4.19 m (WyGISC 2009).

Once the 1966 photos were digitized and georeferenced, the photos were imported into ArcGIS 9.3 (ESRI 2008), and the boundaries of the glaciers were interpreted manually. Although on-screen digitizing by manual delineation of glacier ice is time-consuming and labor intensive, it is still widely used (Raup et al. 2000; Khalsa et al. 2004; Khromova et al. 2006). All photos were interpreted by the same analyst to minimize interpretation error between years. According to Krimmel (2002), a practical problem in identifying individual glaciers is that it is nearly impossible to record every small mass of snow and ice that fits the glacier definition. Of the 63 glaciers in the Wind River Range, a primary group of 44 glaciers was analyzed on the basis of recognition elements (i.e., shape, size, pattern) described by Avery and Berlin (1992). Glaciers sharing a common boundary, such as the Bull Lake Complex, were separated based on the ice-flow direction and land topography. Glaciers were identified and digitized by their glacier ice boundary, ice extents, and stagnant ice (ice that is non-flowing or physically separated from the main glacier body). After all 44 glaciers were digitized, the surface area was calculated using the ArcGIS *calculate area geometry* function (ESRI 2008).

Table 2. Aerial Photography and DEM Used for Glacier Area Changes from 1966 to 2006

Year	Source	Project	Contents	Comments	Data obtained from	URL
1966	USGS	VBMB	Black-and-white paper photos	Paper photos that were scanned and georeferenced; flown in September 1966	University of Wyoming Geology Library, Laramie, Wyoming	
1989	USGS	NAPP	Black-and-white paper photos	Paper photos that were scanned and georeferenced; flown in August 1989	University of Wyoming Geology Library, Laramie, Wyoming	
2001	USGS	NAPP	Color-infrared aerial photo mosaic	Fremont County Compressed County Mosaic; flown in September 2001	WyGISC, Laramie, Wyoming	http://wygl.wygisc.org/ImageryServer/
2006	USDA	NAIP	True-color aerial photo mosaic	Fremont County Compressed County Mosaic; flown in September 2006	WyGISC, Laramie, Wyoming	http://wygl.wygisc.org/ImageryServer/
2001 DEM	USGS	1/3 arc-second resolutions (approx. 10 m)	WyGISC, Laramie, Wyoming	http://wygl.wygisc.org/DataServer/		

Errors Associated with Calculating Area and Area Change

The methods used for digitization and delineation of glacier boundaries and the calculation of area are relatively straightforward; however, positional and interpreter errors are potential uncertainties that are still present.

Positional Error

Error may result from the digitization and georeferencing of the original georeferenced photos or the registration to the base image. Originally, the accuracy of the paper photos used for 1966 and 1989 was estimated by adopting the national mapping standards determined by the U.S. Geological Survey (USGS). However, the lack of field data and the question of how well national mapping standards apply to maps of mountainous areas (Granshaw and Fountain 2006) resulted in the estimation of georeferencing area error by using a method developed from Hall et al. (2003).

The total digitizing error (e_d) was calculated using Eq. (1) (Hall et al. 2003):

$$e_d = \sqrt{(r_p^2 + r_b^2)} + e_r \tag{1}$$

in which r_p = pixel resolution of the georeferenced paper photos, r_b = pixel resolution of the base map (2001 aerial photo), and e_r = registration error of the summation of the georeferenced paper photo RMSE and the 2001 base map RMSE. Once we determined the digitizing error, we measured the area uncertainty (e_a) by using the following formula (Hall et al. 2003):

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

in which r_i = image's pixel resolution, and e_d = total digitizing error calculated in Eq. (1).

Interpreter Error

The presence of shadows at the end of the glaciers, debris, and rock outcroppings in the photographs posed some challenges to the accurate determination of the boundary of each glacier. In some instances, ice was also covered by shadows cast from surrounding mountain peaks, which also made it difficult to delineate the glacier boundary. Debeer and Sharp (2007) proposed a technique in which researchers repeated measured the surface-area changes for the entire glacier population over the study period. Measurements were made to determine the uncertainty associated with the manual delineation and interpretation of the glacier boundaries. Glacier ice boundaries were repeatedly delineated to determine both the maximum and minimum change in area for each individual glacier. On the basis of the results from the differences in area change as a result of interpreter boundary delineation, the overall uncertainty was estimated for the area measurements of the entire study glacier population.

Total Error Associated with Glacier Surface Area

We calculated the total error (δQ) for each individual glacier's surface area by using Eq. (3) (Debeer and Sharp 2007) for the years 1966, 1989, and 2006:

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

in which $\delta q_1, \ldots, \delta q_n$ = each individual uncertainty present in the calculation of surface area. These individual uncertainties occur from the area uncertainty with respect to registration error and the error associated with the delineation process (interpreter error) of each individual glacier boundaries.

Surface-Area Analysis with Resampled Images

In order to analyze the relationship between area and measurement scale, we measured the surface area of 10 glaciers at different spatial resolutions. The 1966 and 2006 photographs were resampled to resolutions of 10 m, 15 m, 22.5 m, and 30 m by using the nearest-neighbor resampling method in ERDAS Imagine. These spatial resolutions match the spatial resolution of data collected by Satellite Pour l'Observation de la Terre (SPOT; 10 m), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; 15 m), Indian Remote Sensing Satellite-Linear Imaging Self-Scanned Sensor (IRS-LISS; 22.5 m), and Landsat images (30 m). The nearest-neighbor resampling method is computationally the most efficient and simplest method for resampling an image (Kovalick 1983). The nearest-neighbor method assigns each corrected pixel the value from the nearest uncorrected pixel. It transfers the original data values without averaging them as the other methods do (Jensen 1996).

Errors Associated with Resampled Photos

Challenges associated with the interpretation of glacier boundaries were apparent in both the 1966 and 2006 aerial photos. The 1966 aerial photos were captured in black and white, whereas the 2006 photos were in true color. Although both forms have their own advantages and disadvantages, the true-color photographs had a significant advantage over black-and-white photographs because of better contrast and tonal differences among various features. It was more difficult to delineate glacier boundaries in black-and-white photographs as a result of the presence of shadows, especially as the resolution became coarser. As black-and-white photographs were resampled, the individual pixels with varying gray tones were mixed, making it difficult to determine the differences between glacier ice, shadows, rocks, or debris-covered glacier ice. True-color photos experienced similar errors; however, it was much easier to differentiate the features surrounding the glaciers. This challenge in delineating glacier boundaries with the black-and-white or true-color photographs could have contributed to additional uncertainty in the resampled glacier surface areas.

Results

Glacier Area Change from 1966 to 2006

In 1966, a total surface area of 45.9 ± 1.6 km^2 was calculated by using fine-resolution unrectified aerial photography for 44 glaciers in the Wind River Range. NN was the smallest glacier (Site ID 42), with an area of 0.09 ± 0.02 km^2, and Gannett Glacier (Site ID 25) was the largest at 4.80 ± 0.15 km^2. Glaciers ≤ 0.5 km^2 accounted for 50% (22 glaciers) of the glacier population, whereas glaciers ≥ 1.0 km^2 accounted for only 27% (12 glaciers) of the total glacier population. In 1989, researchers calculated the total surface area to be 39.7 ± 0.7 km^2, a reduction of 6.2 ± 0.9 km^2 (13%) from 1966. For 2006, the total calculated surface area equaled 28.6 ± 0.4 km^2, a reduction of 11.2 ± 0.2 km^2 (28%) from 1989 and 17.3 ± 1.2 km^2 (38%) from 1966. The glaciers ≤ 0.5 km^2 in 2006 accounted for 70% (31 glaciers) of the glacier population, whereas glaciers ≥ 1.0 km^2 accounted for only 20% (9 glaciers) of the total glacier population.

Table 3. Satellite Imagery Used in the Analysis of Glacier Area Changes for 42 Glacial Complexes from 1985 to 2005 (data from Cheesbrough et al. 2009)

Image ID	Date	Platform
5037030008522010	Aug. 8, 1985	Landsat 5
5037030008924710	Sep. 4, 1989	Landsat 5
5037030009422910	Aug. 17, 1994	Landsat 5
7037030009925150	Sep. 8, 1999	Landsat 7
5037030000524310	Aug. 31, 2005	Landsat 5

Fractional Area Change

As in Granshaw and Fountain (2006), the fractional area change (FAC), the area change divided by the original (either 1966 or 1989) area, was plotted against original area. Between the years 1966 and 1989, the FAC for individual glaciers ranged from $+27$ to -53%, with an average of -14% [Fig. 2(a)]. Seven of these glaciers have a positive FAC, meaning that they readvanced between 1966 and 1989. This was consistent with the findings of Cheesbrough (2007), who identified an increase in 1989 glacier area by using Landsat images (Table 3). The remaining 37 glaciers had a negative FAC and decreased in overall area. For the FAC plot between the years 1989 and 2006, an average FAC of -34% was calculated, with no glaciers readvancing [Fig. 2(b)]. After analyzing the 41-year period from 1966 to 2006, the FAC plot [Fig. 2(c)] illustrates that the entire glacier population in the Wind River Range has receded. During this period, the FAC ranged from -3% to -93%, with an average of -43%. Similar to the observations of Granshaw and Fountain (2006) in the North Cascades National Park Complex, the smaller glaciers (1966 area < 0.5 km^2) of the Wind River Range exhibit a greater FAC and are receding at a greater rate than the larger glaciers. Referring to Fig. 2, the whisker plots (average, maximum, and minimum FAC) show the range of uncertainty when calculating the FAC.

Resampled Glacier Area Change

Of the 10 glaciers analyzed, the total glacier surface area calculated for 1966 by using 1-m resolution aerial photos was 7.8 ± 0.24 km^2. The smallest glacier had an area of 0.15 ± 0.01 km^2; the largest, 3.4 ± 0.06 km^2, with an average of 0.8 ± 0.02 km^2. When delineating the glacier boundary using 30-m resolution photos, the total surface area was 7.4 ± 0.28 km^2, with the smallest having an area of 0.13 ± 0.00 km^2; the largest, 3.1 ± 0.08 km^2, with an overall average of 0.7 ± 0.03 km^2. This was a surface-area decrease of 0.4 ± 0.04 km^2 (5%) between the 1-m resolution and the 30-m resolution photos for 1966. When evaluating 10 m, 15 m, and 22.5 m, there appears to be a linear decreasing trend when relating total area to pixel resolution (Fig. 3). Coarser resolution of the image being used to delineate the glacier boundary results in a smaller calculated total surface area. This was likely the result of the resolution becoming coarser, and thus, it was more difficult to identify the ice extents and stagnant ice extending from the glacier and to distinguish debris-covered ice from moraines. In addition, when glaciers consisted of dirty snow and ice, the coarser images would make it difficult to differentiate between what is glacier ice and what might be rock or debris-covered glacial ice. In 2006, the 30-m resolution photo calculated the total surface area to be 4.6 ± 0.24 km^2, a decrease of 2.7 ± 0.04 km^2 (37.1%) from 1966. This is similar (0.3% difference) to the calculated area change from 1966 to 2006 when using 1-m resolution photos. The results confirm the glacier area change calculated by using 1-m aerial photographs. Of the 10 glaciers analyzed, we found that all were retreating from 1966 to 2006 for resolutions of 10 m, 15 m, 22.5 m, and 30 m.

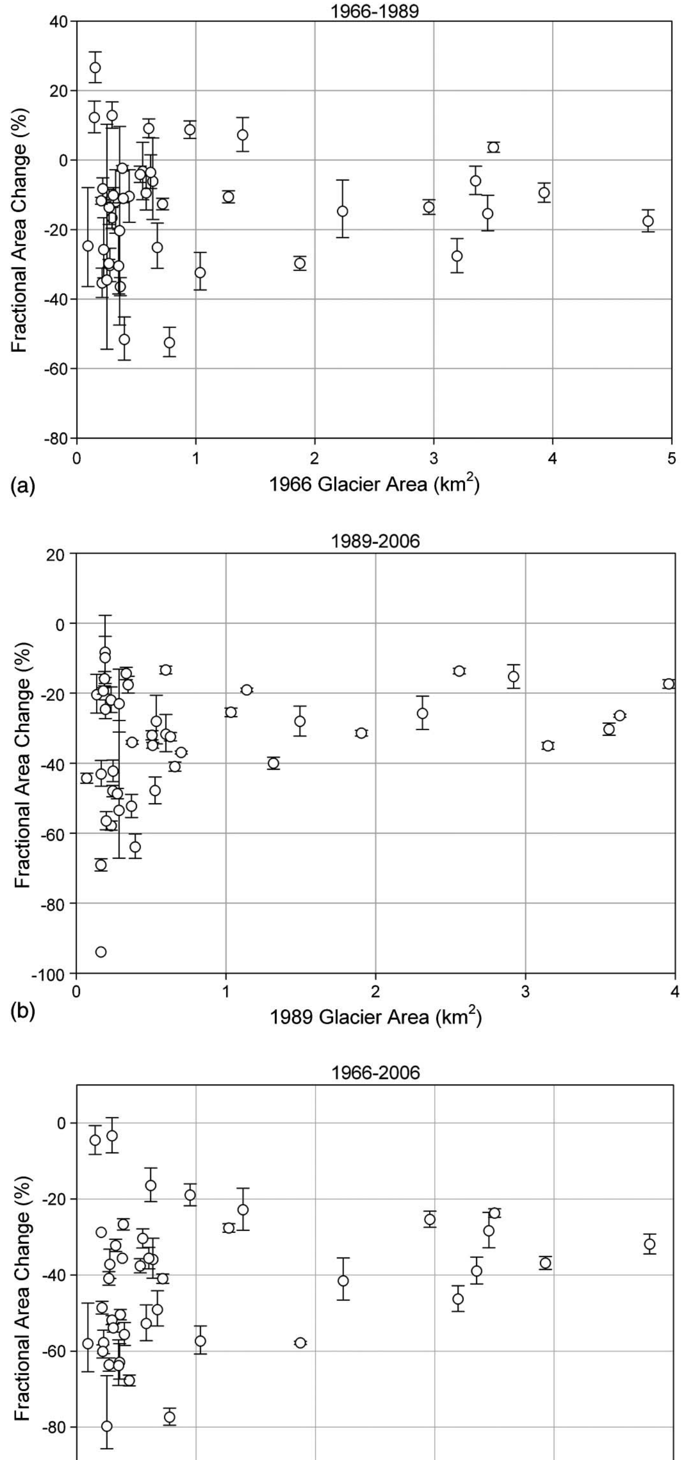

Fig. 2. Individual glacier fractional area change (%) versus original area (km^2) for (a) 1966 to 1989; (b) 1989 to 2006; (c) 1966 to 2006

Discussion

Alpine glaciers across the globe are rapidly receding in apparent response to the pronounced warming of the last century (Plummer 2004). Of the 44 glaciers analyzed, each has receded during the 1966 to 2006 period. This pattern of glacier recession is similar to those calculated in Rocky Mountain National Park in the

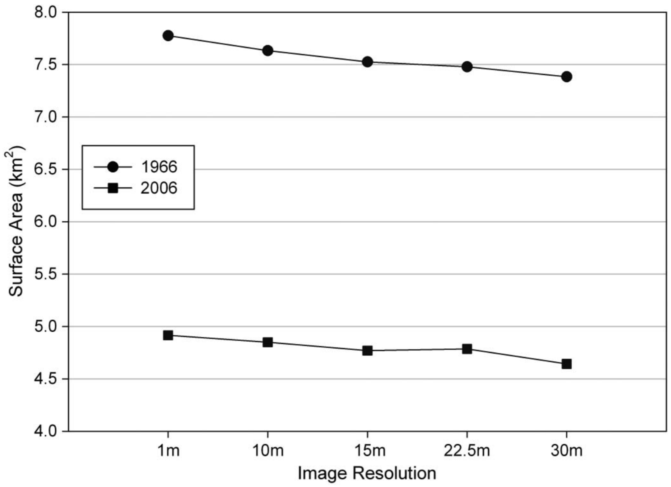

Fig. 3. Resampled resolution (1 m, 10 m, 15 m, 22.5 m, and 30 m) versus average surface area (km^2) for 10 selected glaciers (1966 and 2006)

northern Front Range of Colorado and the glaciers found in the Teton Range of Wyoming. The Rocky Mountain National Park's glaciers actually increased in size from 1953 to 1990 (an increase of 12%) but then decreased from 1990 to 2001 (a decrease of 22%), for an overall decrease of 10% between 1953 and 2001 (Hoffman et al. 2007). The recession of three glaciers (Teton Glacier, Middle Teton Glacier, and Teepe Glacier) in the neighboring Teton Range was similar to the Wind River Range glaciers, in that they decreased 25% from 1967 to 2006 (Edmunds 2009). Because of the similar regional climate and topographical location, the three study areas experienced similar results.

Comparing area change results to the study conducted by Cheesbrough et al. (2009) using Landsat images yields the following results. Cheesbrough et al. (2009) calculated that in 1985, the 42 glaciers covered an area of 41.2 ± 11.7 km^2 and in 2005, an area of 30.8 ± 8.2 km^2. This is an overall decrease in glacier area from 1985 to 2005 of approximately 25%. Cheesbrough et al. (2009) evaluated 42 glaciers, with several of these glaciers (Bull Lake Glacier, Upper Fremont Glacier, Sacagawea Glacier, and Helen Glacier) grouped into what they refer to as the Bull Lake Complex. Therefore, the glaciers studied by the current research are similar in scope to those studied in Cheesbrough et al. (2009). Considering the results previously discussed, using aerial photography, the areas for 1989 and 2006 were 39.7 ± 0.7 km^2 and 28.6 ± 0.4 km^2, respectively. This was a decrease of approximately 28% from 1989 to 2006 by using aerial photography (Table 4).

When calculating area change, we found Landsat images to slightly underestimate the overall total area of the glaciers when compared to areas calculated with aerial photos. This could be dependent of the resolution of the image from which the boundary was delineated or simply differences in interpretation. The results from the glacier areas calculated using resampled aerial photographs show that when glacier boundaries are delineated by the 30-m (resolution equivalent of a Landsat image) photo, the glacier area is underestimated slightly compared to areas calculated with 1-m aerial photos. By calculating glacier surface area with aerial photos, we can estimate a more accurate representation of area change. The resolution of the image is also important when calculating volume change and glacier meltwater contributions to streamflow when volume-area scaling techniques are used, given that these techniques are directly dependent on the estimated area of the glacier.

Table 4. Comparison of Glacier Area Change [Cheesbrough et al. (2009) and Current Research]

Study	Number of glaciers analyzed	Years	Total surface area (km^2)	Area change (%)
Cheesbrough et al. (2009)	42	1985	41.2 ± 11.7	25
		2005	30.8 ± 8.2	
Current research	44	1989	39.7 ± 0.7	28
		2006	28.6 ± 0.4	

Conclusion

We investigated Wind River Range glaciers to expand on previous work and determine the extent of glacier area changes between 1966 and 2006. The total surface area of the 44 glaciers was estimated to be 45.9 ± 1.6 km^2 in 1966 and 28.6 ± 0.4 km^2 in 2006, a decrease of 42%. This research concludes that high-resolution aerial photography remains the preferred method for measuring glacier characteristics. However, fine-to-moderate spatial resolution images (SPOT, ASTER, IRS-LISS, and Landsat images) may also provide useful information to support the assessment of glaciers. When evaluating resampled images at 10 m, 15 m, 22.5 m, and 30 m resolutions, the coarser the resolution, the more overestimated the individual glacier FAC and underestimated the total glacier area.

It is very difficult, if not impossible, to predict when or if glaciers will disappear completely. However, the loss of glaciers and glacier runoff could be detrimental to downstream water users, and future monitoring of these glaciers could prove to be important to Wyoming's future water planning.

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