(WIP) Glaciation in Grand Teton National Park: Little Ice Age to 2021

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Abstract

Glaciers are responsible for some of the Teton Range's most iconic features, and remain important for both visitor recreation and as integral components of the alpine ecosystem. Much work remains to be done to document glacial change in the Teton range over the course of the last two centuries, from the end of the Little Ice Age (LIA) to the present day. Here we present: the first database of LIA glacial geology in the Teton Range, a series of remotely sensed change in aerial and volume extent from 1955-present day extended from Reynolds 2011 and Edmunds et al. 2012 [1], in situ data of Middle Teton surface elevation change and velocity from National Park Service-led efforts, preliminary GPR results from the first campaign in May 2021, and a slab model estimating ice thickness and volume across the range. These observations will help inform efforts to understand the future of ice in the Tetons as well as the Greater Yellowstone Ecosystem, from impacts on the alpine ecosystem to changing natural hazards for visitors.

Another edit, this time its on my local machine in a branch of the original repo (i.e. not a forked version). I made the branch in the github website.

Introduction.{page_break_before}

The Teton Range is the defining feature of Grand Teton National Park (GRTE), which lies just south of Yellowstone in the north-western corner of Wyoming. The 50-mile-long range runs approximately north to south, with elevations ranging from 6,400 feet in Jackson Valley to ~13,700 feet at the top of the Grand Teton. Its iconic landscape, of jagged peaks and gentle valleys, has been sculpted by glaciers over hundreds of thousands of years. Since the end of the Little Ice Age, Teton ice has rapidly disappeared. This study investigates the change in extent and volume of the park's glaciers from the Little Ice Age to 2021.

These glaciers were first noted in western scientific publications between 1870 and the early 1930s, mapped by the U.S. Geological and Geographical Survey of the Territories (also known as the Hayden Survey) and later in more detail by mountaineer and geologist Frithof Fryxell ([**doi?**]: doi.org/10.1086/624317). The park currently recognizes 11 named glaciers, although some debate remains whether some of these were, or still are, large enough bodies of ice to be classified glaciologically as glaciers. In this paper, we discuss the size and estimated volume of these glaciers, but for ease of understanding, will refer to all bodies of ice as glaciers unless otherwise explicitly noted.

The eleven glaciers in GRTE - Middle Teton, Teton, Teepe, Schoolroom, Petersen, Skillet, Falling Ice, West Triple, Middle Triple, East Triple, and Glacier Peak – subsist on and in north- and east-facing walls and valleys scattered throughout the park, protected by steep terrain that shades the ice surface from sun and provides extra accumulation through avalanching and wind-blown snow. Terminal and lateral moraines produced during the Little Ice Age (1300-1850, cite) delineate these glaciers, as well as trace the ghosts of those that have melted into ice fields, rock glaciers, and rock strewn landscapes. These moraines can give us an estimate of ice volume at the peak of the Little Ice Age, around 1850 == (cite)== Initial retreat of glaciers in nearby ranges has been attributed to natural climactic recovery from the LIA ([**doi?**]: https://doi.org/10.1080/15230430.2019.1634443). Since then, glacial change has been attributed to anthropogenic climate change ([**doi?**]: https://doi.org/10.1126/science.1254702) and topographical influences ([**doi?**]: https://doi.org/10.5194/tc-12-2109-2018)

Compared to their neighbors in the north (Glacier National Park and Yellowstone National Park), south (the Rockies), and east (Wind River Range), Teton glaciers have been far less studied. As significant members of the visual, recreational, ecological, and geological systems of the Teton Range, as well as a connective geographical link between the better studied Rocky Mountain, Wind River, and Glacier National Park glaciers, an understanding of glacial change in the Tetons can help us understand past events and future implications throughout the park and beyond. This work publishes for the first time a record of: Little Ice Age glacial geological records, a time series of aerial and volumetric change for all eleven glaciers from 1950-2021, and in-situ observations of Middle Teton Glacier from 2016-2021.

This paper combines remotely sensed, in situ, and modeled data and outputs to comprehensively examine the changes in Teton glaciation since the Little Ice Age. LIA moraines and trimlines provide an estimate of ice volume and extent. Aerial and satellite imagery produce a timeseries of aerial change between 1950-2021, and are used to generate digital elevation models to estimate ice volume loss across seven decades. Among other work,*in-situ* data collection has generated high resolution surface elevation changes of Middle Teton Glacier over the last seven years, providing a benchmark for future glacier work. Finally, two simple models (ice slab, VOLTA) allow us to estimate past and current ice volume in the landscape.

- [[31.study-area]]
- [[32.LIA-mapping]]
- [[33.aerial-change]]
- [[34.dem-generation]]
- [[35.in-situ-data]]
- [[36.ice-slab-model]]
- [[37.topography-vs-cliamte]]

The Teton Range in northwest Wyoming is home to 11 named glaciers and a handful of permanent snow and icefields. About 40 miles long and 10 miles across, the short and narrow high mountain range is a geological continuation of the Rocky Mountains that extends into the Greater Yellowstone Ecosystem. The range is bordered by other mountain ranges: Absaroka Range to the northwest, Wind River Range to the southeast, and the Wyoming Range to the south. Additionally, the Teton Range is flanked by flat-floored valleys, with Jackson Hole to the east and by Teton Basin to the west. The highest peaks of the Teton Range lie near the eastern edge of the fault-block mountain range, while broader and gentler slopes gradually decline into Idaho farmland.

Since the end of the Little Ice Age (~1850-1870), glaciers in this range have retreated or disappeared entirely [**doi?** https://doi.org/10.1080/02723646.1991.10642421]. Geologic remnants of these glaciers, in the form of moraines and trimlines, can be mapped throughout the park. The surviving glaciers have primarily east- and north-facing aspects, and are, for the most part, topographically protected by large rock walls. These walls provide both steep surfaces for snow to accumulate and avalanche from, and protect the glacier from wind scouring.

While changes to nearby glaciers have been studied and well documented [**doi?** https://doi.org/10.3133/fs20193068,**doi?** https://doi.org/10.1080/02723646.1991.10642421,**doi?** https://doi.org/10.1016/S1040-6182(96)00026-2], the Teton Range glaciers have been relatively understudied. This builds on surveys by Fryxell (cite), Reed (cite), Reynolds et al. (cite), and Edwards et al. (cite), aiming to qualitatively and quantitatively record glacial change in the Tetons over the last 150-170 years, from the end of the LIA to 2021.

Little Ice Age Glacier Identification

LIA moraines were digitized primarily from 1m resolution LiDAR imagery (CITE, 2014) with a hillshade applied (QGIS). These data were corroborated and augmented by ==year== National Agricultural Inventory Program (NAIP) aerial imagery and ==add data refs==. Little Ice Age moraines are found far upvalley of dated moraines from the Last Glacial Maximum [2]. LGM deglaciation began around 13.8ka and finished by 11.5ka according to lake sediment records [3]. No cosmogenic dating of LIA moraines exist in the literature. We initially followed the methods outlined in Martin-Mikle 2019 [4], delimiting the LIA location and size of glaciers from the presence of a terminal moraine, the presence of lateral moraines, and a size requirement of 0.01 km^2. However, not all of the 11 named glaciers fit this criteria; these are outlined in light red in Figure 1. Because of their relevance to park history and visitation, they are included here but with the caveat that their size may limit the relevance of our analysis. Trimelines were only visible for… We estimated minimum and maximum extent using the GlaRe [5] package in ArcGIS Pro to reconstruct ice extent in the LIA.

==add note about trimlines, etc==

> The criteria used for identifying the former size and location of glaciers were (1) the presence of a terminal moraine; (2) the presence of lateral moraines; and (3) whether the identified glacier area exceeded 0.01 km2. A potential glacier was not omitted if it failed to meet both of the first two criteria (i.e., a LIA glacier that terminated at a cliff with well-defined lateral moraines but no discernible terminal moraine). [[**martin-mikleGlacierRecessionLittle2019?**]]

VOLTA[6], which employs an augmented slab model, was used to remove ice to determine full extent… corroborated by comparing ice thickness between glaciers that have completely disappeared and those that remain…

Change in Aerial Extent

Digital Elevation Model timeseries

Digital Elevation Models were generated using HIPP and HSFM (CITE).

In-Situ Data

To better understand the change in ice volume and extent, surveys have been conducted at Middle Teton glacier (MTG) since 2016. MTG was chosen as the benchmark glacier for the Tetons in 2016 owing to its size (second largest) and ease of access, accessible from the trail to the Lower Saddle, where the most popular routes to climb the Grand Teton begin.

Surveys taken across MTG include accumulation surveys through snow pits and snow probe surveys, ablation stake installation and monitoring, and most recently, ground-penetrating radar. Additionally, park scientists and climbing rangers perform annual fall surface elevation surveys of MTG. While most of the focus of the glacier monitoring program in the Tetons is on Middle Teton Glacier, timelapse cameras and air temperature sensors are also installed at sites near four other glaciers across the park.

Accumulation surveys

To estimate seasonal accumulation, the park collected snow probe measurements and digs two snow pits at the end of the accumulation season (late May - early June) in 2019, 2020, and 2021. Snow probe measurements are taken at 25 m spacing along lines perpendicular to glacier flow/steepness; lines were separated by ~50m as conditions allowed. Surveyors noted the type of transition as either firn or glacial ice. In addition, two snow pits are dug down to the previous year’s summer surface at the location of the highest and lowest ablation stakes. Snow density is sampled every 0.5 m depth to the bottom of the pit using a 500cc density cutter and a scale.

Ablation Stake Surveys

Ablation stakes are deployed yearly at the same time as the accumulation surveys on Middle Teton Glacier. One-meter sections of PVC pipe are pre-cut, labeled with the site identifier, year, depth, and stake section number, then connected via accessory cord. The appropriate length for an ablation stake was site-specific, determined by adding the amount of accumulation measured by snow probe to the maximum estimated ice ablation and an additional two meters for anchoring; most stakes were 10-13 m in length. A Heucke steam drill [7] was used to drill the hole for installing the stakes. Stakes were installed in late May/early June in 2019, 2020, and 2021 to measure surface ablation and surface velocity and their locations were marked using a handheld Trimble Geo 7X (CITE). Most sites were revisited twice throughout the season to measure ablation and take a GPS reading. Sites were visited in subsequent seasons if stakes were located.

The locations of the stakes can be found in Figure 1, and the surface velocities and ablation measurements are in Figure 2. (ADD how surface velocities are calculated). Meltwater equivalent from snow and ice is derived from the ablation stake readings and the accumulation survey. The difference in stake readings between site visits provide a melt depth since last visit, while snow probe measurements provide depth of snow and depth to firn/glacial ice. Using snow and ice depths and their respective densities (i.e., measured snow pit density or glacial ice density), melt depth can be converted to meltwater equivalent (mwe).

Ground-penetrating radar

[**dan?**]

Surface Elevation Surveys

At the end of the ablation season (usually early September) a team of park scientists and climbing rangers conducts a surface elevation survey and terminus survey to measure high resolution changes in surface height and terminus location. The first surface elevation survey was conducted in 2015 with 63 ungridded points; these are excluded from our analysis. Between 2016 and 2021, the survey expanded to cover a majority of Middle Teton Glacier.

On-glacier surveyors followed pre-determined 10-meter grids for steeper, higher elevations and 20-meter grids for gentler, lower elevations as closely as possible; slight deviations in the surveyed gridpoints avoid crevassing and rockfall hazards. Each gridpoint is measured using a handheld Trimble Geo 7X connected to external Frontier Precision G8 GNSS or Zephyr 2 antennae, both of which are attached to a survey rod. Four team members participate in the survey; two at higher elevations and two at lower elevations.

Post collection, the surface elevation data is processed in GPS Pathfinder Office. A real-time differential correction is applied to the data using the National Geodetic Survey site in Driggs, ID (IDDR) for 2016-2018 and 2020-2021. For the 2019 survey data, we used the National Geodetic Survey site in Kelly, WY (TSWY) as data from IDDR was not available. All GPS data uses the UTM 12 North NAD 1983 coordinate reference system unless otherwise specified.

==(note this paragraph may change: updating protocol to re-process in Matlab)==

Seasonal timelapse imagery and repeat photo points

Timelapse cameras (cite) are installed seasonally at five of the eleven glaciers: Middle Teton, Teton Glacier, Falling Ice Glacier, Peterson Glacier, and Schoolroom Glacier. Cameras are mounted on boulders or trees using pitons and/or webbing at the beginning of the summer season, usually in June the melting snowpack clears trails for travel. They are set to record four images per day at 1100, 1130, 1200, and 1230. Cameras are recovered at the end of the ablation season. Images are then selected to maximize visibility of the terminus and snowline while minimizing shadow and shadow movement. If possible, images from the same sun angle are chosen throughout the summer. Usually this means images near the beginning of the season are selected from 1230 or 1200, and images from later in the season are chosen from 1100 or 1130. If weather or other elements obscure the image, an image from a different (preferably, neighboring) time is chosen instead. Timelapse videos are compiled using Windows Movie Maker.

Repeat photos of Middle Teton, Teton Glacier, Falling Ice Glacier, Peterson Glacier, Schoolroom Glacier, Teepe Glacier, and Glacier Peak are also taken every summer season at set locations (FIGURE?) using a camera, tablet, or smartphone. These photos are used to capture a different angle from the timelapse cameras or to track glaciers where no timelapse imagery is available.

Skillet and the three Triple Glaciers are not actively monitored by the park.

Annual air temperature sensors

Air temperature sensors (HOBO Pendant Temperature Data Logger) are installed yearly at five glaciers (Middle Teton, Teton Glacier, Falling Ice Glacier, Peterson Glacier, and Schoolroom Glacier) as well as in non-glaciated canyons and along sites at the base of the range (FIGURE?). The air temperature sensors are calibrated yearly to a National Institute of Standards and Technology (NIST) certified device in both room-temperature and ice baths to verify that the loggers remained within +/- 0.53°C to the NIST device reading from 0° to 50°C. The loggers are programmed to record data once an hour pre-deployment and mounted on trunks 10-15 feet above the ground within tree stands with solar radiation shielding following Holden and others (2013) [**doi?** 10.1016/j.agrformet.2013.06.011].

Ice-slab model to generate approximate ice thicknesses

Following Nye (1965) and Florentine et al. (2019), we use a simple slab model to estimate the ice thickness,

$$h = \frac{\tau}{f \rho g sin \alpha},$$

where h is the thickness of the glacier, τ is the basal shear stress, f is a shape factor ([8]), ρ is the density of ice (917 kg m^{-2}), and α is the surface slope of the glacier.

This relationship assumes that the driving and yield stress are equal. If this is true, ice surfaces with low surface angles must have large driving stresses, e.g. be very thick. But once a glacier thins substantially and stops flowing, which occurs near the terminus of many Teton glaciers - this relationship fails to hold. While this model is used widely as a simple tool for estimating the ice thickness of alpine glaciers [9], this caveat is an important one. As alpine glaciers continue to thin, this issue will only become more pronounced.

This model was extended to account for simplified topography ([8]), side drag ([10]), and variable basal shear stresses ([**doi10.3189/S0260305500015834?**]).

Results

Surface Elevation Surveys

Figure {[fig?]: MTG201621}a shows the surface elevation change between 2016 and 2021, using the boundary of the 2016 survey.

We use a simple slab model to estimate glacier thickness, using Nye's 1952 formulation. Since the 1950s, this shear-stress-based model has been expanded to include variable basal shear stress, valley-wall drag, a shape factor, and so on.

Instead of absolute ice thickness estimates, we aim to investigate change in ice thickness. Lacking surface mass balance measurements (few measurements taken, except, as outlined above, between 2016 and the present day), surface velocity (these glaciers are, in general, too small for most satellite data to be used to track surface features, so the only measured velocity data is from ablation stakes left on Middle Teton Glacier between 2019 and the present day), and weather data or reanalysis (sparse measurements in the Tetons likely do not reflect the surface mass additions of avalanching and wind-blown snow), we are left with glacial outlines and DEMs (LiDAR and HSFM, see Sections XX and XX respectively) as the only source of information for our models. The simplest approach to generating ice thickness estimates of alpine glaciers is an area-scaling approach (see Bahr 2015 for a review). With digital elevation models from HSFM and LiDAR, we can go further with information about surface slope and the surrounding topography. In Nye 1952, we obtain the approach used in this paper, which assumes a perfectly plastic model with no topographical influence. Farinotti et al. (2017) showed in their intercomparison project that the inclusion of more data (e.g. surface velocities, SMB measurements) did not, on average, improve modeled glacier thickness estimates. The models that performed the best and only used OL and DEM information included Farinotti et al. 2009 (the ITEM model), Huss and Farinotti 2014 (HF-model), Linsbauer et al. (2014), and Frey et al. (2014), two mass-conserving-based and two shear-stress-based approaches respectively. Huss and Farinotti (2014) and Frey et al. (2014) extend their counterparts without fundamentally changing the physics, so we considered these two possible approaches.

Conclusions

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    b. Sub-item
        i. Sub-sub-item
3. Ordered list item
    a. Sub-item

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Line break without starting a new paragraph by putting
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Referencing figures, tables, equations

Figure 1

Figure 2

Figure 3

Figure 4

Table 1

Equation 1

Equation 2

Quotes and code

> Quoted text

> Quoted block of text
>
> Two roads diverged in a wood, and I—
> I took the one less traveled by,
> And that has made all the difference.

Code `in the middle` of normal text, aka `inline code`.

Code block with Python syntax highlighting:

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    assert doi == "10.25313/2524-2695-2018-3-vliyanie-enhansera-copia-i-
        insulyatora-gypsy-na-sintez-ernk-modifikatsii-hromatina-i-
        svyazyvanie-insulyatornyh-belkov-vtransfetsirovannyh-geneticheskih-
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Figures

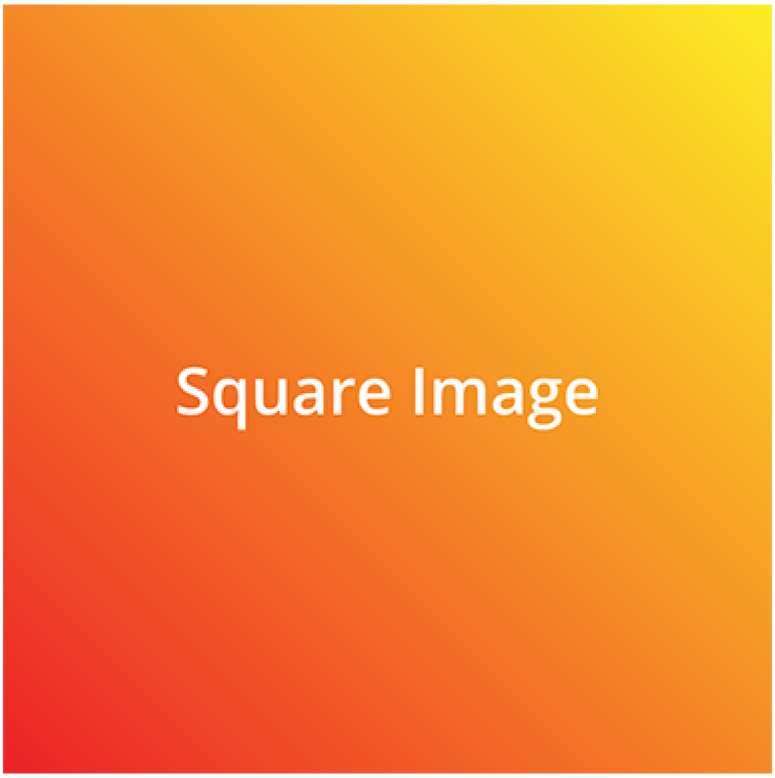

Figure 1: A square image at actual size and with a bottom caption. Loaded from the latest version of image on GitHub.

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Figure 4: A vector `.svg` image loaded from GitHub. The parameter `sanitize=true` is necessary to properly load SVGs hosted via GitHub URLs. White background specified to serve as a backdrop for transparent sections of the image.

Tables

Table 1: A table with a top caption and specified relative column widths.

Bowling Scores	**Jane**	**John**	**Alice**	**Bob**
Game 1	150	187	210	105
Game 2	98	202	197	102
Game 3	123	180	238	134

Table 2: A table too wide to fit within page.

	Digits 1-33	**Digits 34-66**	**Digits 67-99**	**Ref.**
pi	3.14159265358979323 846264338327950	28841971693993751 0582097494459230	78164062862089986 2803482534211706	[`piday.org`](piday.org)
e	2.71828182845904523 536028747135266	24977572470936999 5957496696762772	40766303535475945 7138217852516642	[`nasa.gov`](nasa.gov)

Table 3: A table with merged cells using the `attributes` plugin.

	Colors	
Size	**Text Color**	**Background Color**
big	blue	orange
small	black	white

Equations

A LaTeX equation:

$$\int_0^\infty e^{-x^2} dx = \frac{\sqrt{\pi}}{2} \tag{1}$$

An equation too long to fit within page:

$$x = a + b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z + 1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9 \tag{2}$$

Special

⚠ WARNING *The following features are only supported and intended for `.html` and `.pdf` exports. Journals are not likely to support them, and they may not display correctly when converted to other formats such as `.docx`.*

LINK STYLED AS A BUTTON

Adding arbitrary HTML attributes to an element using Pandoc's attribute syntax:

> Manubot Manubot Manubot Manubot Manubot. Manubot Manubot Manubot Manubot. Manubot Manubot Manubot. Manubot Manubot. Manubot.

Adding arbitrary HTML attributes to an element with the Manubot `attributes` plugin (more flexible than Pandoc's method in terms of which elements you can add attributes to):

> Manubot Manubot Manubot Manubot Manubot. Manubot Manubot Manubot Manubot. Manubot Manubot Manubot. Manubot Manubot. Manubot.

Available background colors for text, images, code, banners, etc:

`white` `lightgrey` `grey` `darkgrey` `black` `lightred` `lightyellow` `lightgreen` `lightblue` `lightpurple` `red` `orange` `yellow` `green` `blue` `purple`

Using the [Font Awesome](https://fontawesome.com/) icon set:

✔ ? ★ 🔔 ⊗ ⋯

Light Grey Banner
useful for *general information* - manubot.org

Blue Banner
useful for *important information* - manubot.org

Light Red Banner
useful for *warnings* - manubot.org

creating file for folks to learn how to comment, fork, make changes.

adding text in forked repo on main branch.

note that even though i added it in the forked repo, i had to fetch upstream.

now i am deliberately creating a new branch within the forked repo.