# (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.

Test edit - JK

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's iconic landscape of jagged peaks and classic U-shaped valleys has been carved out of stone by glaciers over many thousands of years. The range is the defining feature of Grand Teton National Park, which lies just south of Yellowstone in the north-western corner of Wyoming. This study investigates the change in extent and volume of the park's 11 named glaciers from the Little Ice Age to 2021.

Isotopic dating has been used on the moraine 1. Little Ice Age While most of the sculptural work was completed over the last two ice ages ==cite==, the Little Ice Age (1300-1850), a period of cooling in the northern hemisphere, left its mark on the landscape. Terminal and lateral moraines delineate the park's remaining glaciers, which subsist on and in north and east facing walls and valleys scattered throughout the park.

- 2. Glacial change 1950-present day
- natural climate cycle
- anthropogenic influences
- climate vs topography
- 3. Distinguishing

Relevance - impact

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. Little Ice Age 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. 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 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? dozens? of permanent snow and icefields. About forty miles long and ten miles across, the mountain range is an (ecological? geological?) continuation of the Rockies that lies northwest of the Wind River Range within the Greater Yellowstone Ecosystem

Since the end of the Little Ice Age (~1850-1870) CITE, glaciers in this range have retreated or disappeared entirely. 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, onto the glacier surface, and protect the glacier from wind scouring.

While nearby glaciers have been documented and studied (CITE- GNP, Wind River, Rockies), the Teton range glaciers have been generally overlooked. This work aims 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 2014 LiDAR imagery (CITE) 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 since 2015/6. These include surface elevation surveys, ablation stake installation and monitoring, accumulation surveys through snow pits and snow probe surveys, and most recently, ground-penetrating radar. While most of the focus of the glacier monitoring program in the Tetons is on Middle Teton Glacier, timelapse cameras and air temperature sensors were also installed at four other sites across the park.

## **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. Surveyors followed a pre-determined grid (add point spacing) as closely as possible, with slight deviations for crevassing and rockfall hazard. The data was processed using ### Ablation Stake Surveys Ablation stakes are deployed yearly on Middle Teton Glacier. One-meter sections of PVC pipe are pre-cut, labeled with the site identifier, year, and stake section number, and connected via accesssory 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 [doi? 10.1111/j.0435-3676.1999.00088.x] 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 Trimble (CITE). Most sites were revisited twice throughout the season to measure ablation and take a GPS reading. Sites were visited in subsequent seasons if they were able to be located. The locations of the stakes can be found in Figure 1, and the surface velocities and ablation measurements are in Figure 2. ### Accumulation surveys To estimate seasonal accumulation, a team took snow probe measurements across the glacier and dug xx 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 0.5m depth to the bottom of the pit using a 500cc density cutter and a scale. ### Seasonal timelapse imagery and air temperature sensors Timelapse cameras and air temperature sensors are installed seasonally at five of the eleven glaciers: Middle Teton, Teton Glacier, Falling Ice Glacier, Peterson Glacier, and Schoolroom Glacier. Repeat photos of these glaciers are also taken every summer season at set locations. Additional photos are taken every year of Glacier Peak and Teepe glaciers. Skillet and the three Triple glaciers are not actively monitored by the park. ### Ground-penetrating radar

# Ice-slab model to generate approximate ice thicknesses

Resu	lts
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## **Conclusions**

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The rest of this document is a full list of formatting elements/features supported by Manubot. Compare the input (.md files in the /content directory) to the output you see below.

## **Basic formatting**

	_

Semi-bold text

**Bold text** 

Centered text

Right-aligned text

Italic text

Combined italics and bold

### Strikethrough

- 1. Ordered list item
- 2. Ordered list item
  - a. Sub-item

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

subscript: H<sub>2</sub>O is a liquid

superscript: 2<sup>10</sup> is 1024.

unicode superscripts<sup>0123456789</sup>

unicode subscripts<sub>0123456789</sub>

A long paragraph of text. Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum.

Putting each sentence on its own line has numerous benefits with regard to <u>editing</u> and <u>version</u> <u>control</u>.

Line break without starting a new paragraph by putting two spaces at end of line.

## **Document organization**

Document section headings:

# **Heading 1**

## **Heading 2**

**Heading 3** 

**Heading 4** 

**Heading 5** 

**Heading 6** 



#### Horizontal rule:

Heading 1's are recommended to be reserved for the title of the manuscript.

Heading 2's are recommended for broad sections such as Abstract, Methods, Conclusion, etc.

Heading 3's and Heading 4's are recommended for sub-sections.

## Links

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Link with text

Link with hover text

Link by reference

## **Citations**

Citation by DOI [7].

Citation by PubMed Central ID [8].

Citation by PubMed ID [9].

Citation by Wikidata ID [10].

Citation by ISBN [11].

Citation by URL [12].

Citation by alias [13].

Multiple citations can be put inside the same set of brackets [7,11,13]. Manubot plugins provide easier, more convenient visualization of and navigation between citations [8,9,13,14].

Citation tags (i.e. aliases) can be defined in their own paragraphs using Markdown's reference link syntax:

# 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:

```
from manubot.cite.doi import expand_short_doi

def test_expand_short_doi():
    doi = expand_short_doi("10/c3bp")
    # a string too long to fit within page:
    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-
        konstruktsiyah"
```

Code block with no syntax highlighting:

```
Exporting HTML manuscript
Exporting DOCX manuscript
Exporting PDF manuscript
```

## **Figures**



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



**Figure 2:** An image too wide to fit within page at full size. Loaded from a specific (hashed) version of the image on GitHub.



Figure 3: A tall image with a specified height. Loaded from a specific (hashed) version of the image on GitHub.



**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
е	2.71828182845904523 536028747135266	24977572470936999 5957496696762772	40766303535475945 7138217852516642	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:

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

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

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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.