Mountain glaciers

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/
‘Before and after’ Glacier images

https://www.reddit.com/r/pics/comments/3t1j5p/columbia_glacier_alaska_august_28_2009_columbia/

Left photograph by James Balog, right photograph by Matthew Kennedy © Earth Vision Institute

nationalgeographic.com/
Stein Glacier, Switzerland, has retreated by 550 m between 2006 and 2015; James Balog and the extreme ice survey
‘Before and after’ Glacier images


Qori Kalis Glacier in Peru has retreated by 1.14 km between 1978 and 2016; Lonnie Thompson
Thrift Glacier, Switzerland, has retreated by 1.17 km between 2006 and 2015; James Balog and the extreme ice survey

Workshop 1 a, b (leave c for HW)

Glacier lengths records
Chapter 1. Introduction

It depends on the ocean temperature and why the magnitude of hurricanes may be expected to increase in a warmer climate. We also analyze the observed record, and examine the many uncertainty factors involved in the projection of future hurricane magnitude.

Figure 1.4: Records of glacier length for a few mountain glaciers, relative to their length in 1960.
All glacier length time series

Figure 11.1: Glacier length time series for 879 records, relative to their position in 1960.

Figure 11.3: Showing all glaciers with observed edge location time series, marking the 791 glaciers with negative trends in red, and the 29 with positive trends in blue. The blue symbols are drawn on top of the red ones, assuring that the few locations with positive trends are clearly highlighted.
Averaged/binned length records

Figure 11.2: (a) A bin-average of the glacier length records seen in Fig. 11.1. (b) The number of observations per bin.
Are glaciers retreating due to end of little ice age?

https://en.wikipedia.org/wiki/Little_Ice_Age
Are glaciers retreating due to end of little ice age?

Erik Thorvaldsson (c.950 – c.1003), known as Erik the Red, was a Norse explorer, described in medieval and Icelandic saga sources as having founded the first settlement in Greenland.

https://en.wikipedia.org/wiki/Erik_the_Red

“The Norse colonies in Greenland starved and vanished by the early 15th century, as crops failed and livestock could not be maintained through increasingly harsh winters. Greenland was largely cut off by ice from 1410 to the 1720s.”

(https://en.wikipedia.org/wiki/Little_Ice_Age)
Are glaciers retreating due to end of little ice age?

The last written records of the Norse Greenlanders are from a 1408 marriage at Hvalsey Church, now the best-preserved of the Norse ruins.

Erik Thorvaldsson (c.950 – c.1003), known as Erik the Red, was a Norse explorer, described in medieval and Icelandic saga sources as having founded the first settlement in Greenland.

“"The Norse colonies in Greenland starved and vanished by the early 15th century, as crops failed and livestock could not be maintained through increasingly harsh winters. Greenland was largely cut off by ice from 1410 to the 1720s.”

https://en.wikipedia.org/wiki/Erik_the_Red

https://en.wikipedia.org/wiki/Little_Ice_Age
Are glaciers retreating due to end of little ice age?

The Frozen Thames, 1677

https://en.wikipedia.org/wiki/Little_Ice_Age
Are glaciers retreating due to end of little ice age?

The Frozen Thames, 1677

Winter skating on the main canal of Pompenburg, Rotterdam in 1825, shortly before the minimum, by Bartholomeus Johannes van Hove

https://en.wikipedia.org/wiki/Little_Ice_Age
Are glaciers retreating due to end of little ice age?

The Frozen Thames, 1677

Winter landscape with iceskaters, c. 1608, Hendrick Avercamp

Winter skating on the main canal of Pompenburg, Rotterdam in 1825, shortly before the minimum, by Bartholomeus Johannes van Hove

https://en.wikipedia.org/wiki/Little_Ice_Age
Are glaciers retreating due to end of little ice age?

First line of evidence: Last-exposure dates from recovered plants
Last-exposure dates from recovered plants

**Fig. 2.** Glacier retreat as documented in the Peruvian Andes. (A) Retreat of Qori Kalis from 1963 to 2005. (B) Retreat records for Qori Kalis and six other Andean glaciers. (C) The photos document the expansion of the proglacial lake from 1991 to 2005 as Qori Kalis retreated.

**Abrupt tropical climate change: Past and present**

Lonnie G. Thompson*†‡, Ellen Mosley-Thompson*§, Henry Brecher*, Mary Davis*, Blanca León*, Don Les, Ping-Nan Lin*, Tracy Mashiotta*, and Keith Mountain**

PNAS, 2006
Last-exposure dates from recovered plants

Table 1 Sample locations and $^{14}$C ages

<table>
<thead>
<tr>
<th>Site #</th>
<th>Sample ID</th>
<th>$^{14}$C age (yr)</th>
<th>$^{14}$C ± 1σ (yr)</th>
<th>Cal age (yr)</th>
<th>±1σ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M13-B002v</td>
<td>&gt;43,300</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>M13-B005v</td>
<td>&gt;48,370</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>M13-B007v</td>
<td>&gt;45,277</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>M13-B011v</td>
<td>43,770</td>
<td>4670</td>
<td>45,443</td>
<td>+4557/-1177</td>
</tr>
<tr>
<td>5</td>
<td>M14-B101v</td>
<td>&gt;46,320</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>M14-B028v</td>
<td>&gt;45,277</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>M14-B045v</td>
<td>&gt;49,990</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>M14-B051v</td>
<td>&gt;45,277</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>M14-B064v</td>
<td>41,800</td>
<td>3250</td>
<td>45,171</td>
<td>+2893/-2420</td>
</tr>
<tr>
<td>10</td>
<td>M13-B066v</td>
<td>45,830</td>
<td>1770</td>
<td>48,199</td>
<td>+1801/-520</td>
</tr>
<tr>
<td>11</td>
<td>M13-B069v</td>
<td>&gt;47,800</td>
<td>-</td>
<td>-</td>
<td>+1509/-390</td>
</tr>
<tr>
<td>12</td>
<td>M13-B091v</td>
<td>45,240</td>
<td>2570</td>
<td>48,491</td>
<td>+2551/-730</td>
</tr>
<tr>
<td>13</td>
<td>M14-B091v</td>
<td>&gt;45,277</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>M14-B258v</td>
<td>34,300</td>
<td>3600</td>
<td>38,214</td>
<td>+3662/-3200</td>
</tr>
<tr>
<td>15</td>
<td>M14-B258v</td>
<td>39,740</td>
<td>950</td>
<td>43,550</td>
<td>+689/-810</td>
</tr>
<tr>
<td>16</td>
<td>M10-B258v</td>
<td>37,510</td>
<td>490</td>
<td>41,880</td>
<td>+380/-320</td>
</tr>
<tr>
<td>17</td>
<td>M10-B104v</td>
<td>&gt;45,277</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>M10-B104v</td>
<td>29,100</td>
<td>1500</td>
<td>33,094</td>
<td>+1265/-1600</td>
</tr>
<tr>
<td>19</td>
<td>M10-B231v</td>
<td>44,300</td>
<td>1300</td>
<td>47,570</td>
<td>+1306/-1280</td>
</tr>
<tr>
<td>20</td>
<td>M10-B231v</td>
<td>23,920</td>
<td>100</td>
<td>27,959</td>
<td>+977/-150</td>
</tr>
<tr>
<td>21</td>
<td>M10-B232v</td>
<td>37,500</td>
<td>3600</td>
<td>41,194</td>
<td>+3738/-3110</td>
</tr>
<tr>
<td>22</td>
<td>M10-B196v</td>
<td>52,120</td>
<td>3860</td>
<td>48,226</td>
<td>+1774/-460</td>
</tr>
<tr>
<td>23</td>
<td>M10-B196v</td>
<td>42,100</td>
<td>1270</td>
<td>45,545</td>
<td>+1080/-1280</td>
</tr>
<tr>
<td>24</td>
<td>M10-B201v</td>
<td>50,300</td>
<td>3080</td>
<td>48,419</td>
<td>+1581/-410</td>
</tr>
<tr>
<td>25</td>
<td>M14-B020v</td>
<td>&gt;45,650</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>M14-B085v</td>
<td>39,280</td>
<td>1230</td>
<td>43,228</td>
<td>+910/-980</td>
</tr>
<tr>
<td>27</td>
<td>M14-B107v</td>
<td>&gt;46,320</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>M14-B113v</td>
<td>&gt;46,320</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>29</td>
<td>M14-B143v</td>
<td>&gt;46,320</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>M14-B154v</td>
<td>&gt;45,980</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>31</td>
<td>M14-B158v</td>
<td>&gt;46,320</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>32</td>
<td>M14-B163v</td>
<td>&gt;46,380</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>33</td>
<td>M14-B164v</td>
<td>&gt;45,220</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>34</td>
<td>M14-B165v</td>
<td>46,120</td>
<td>2870</td>
<td>47,592</td>
<td>+2408/-690</td>
</tr>
<tr>
<td>35</td>
<td>M14-B183v</td>
<td>45,780</td>
<td>2750</td>
<td>47,549</td>
<td>+2451/-700</td>
</tr>
<tr>
<td>36</td>
<td>M14-B184v</td>
<td>&gt;46,320</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>37</td>
<td>M15-B047v</td>
<td>&gt;47,000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>38</td>
<td>M15-B048v</td>
<td>&gt;44,400</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>39</td>
<td>M10-B247v</td>
<td>45,600</td>
<td>2500</td>
<td>47,636</td>
<td>+2364/-680</td>
</tr>
<tr>
<td>40</td>
<td>M10-B255v</td>
<td>43,200</td>
<td>2700</td>
<td>46,338</td>
<td>+2541/-1830</td>
</tr>
<tr>
<td>41</td>
<td>M10-B256v</td>
<td>50,700</td>
<td>3100</td>
<td>48,468</td>
<td>+1532/-390</td>
</tr>
<tr>
<td>42</td>
<td>M14-B009v</td>
<td>44,200</td>
<td>1850</td>
<td>47,303</td>
<td>+1842/-1370</td>
</tr>
<tr>
<td>43</td>
<td>M14-B046v</td>
<td>&gt;50,143</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>44</td>
<td>M14-B161v</td>
<td>&gt;50,768</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

All plant samples were collected between 2010 and 2015 (year of collection denoted by sample ID prefix, M10-, M13-, etc.). Samples with > are minimum limiting ages and indistinguishable from the organic measurement blank. All other samples are also reported in calibrated years BP using IntCal 2013 and OxCal 4.2.4.23. For sample metadata see Supplementary Table 1.

From Miller et al., 1

Rapidly receding Arctic Canada glaciers revealing landscapes continuously ice-covered for more than 40,000 years

Simon L. Pendleton et al, 2019, Nature communications
Regeneration of Little Ice Age bryophytes emerging from a polar glacier with implications of totipotency in extreme environments, 2013, PNAS
Catherine La Farge\textsuperscript{a,1}, Krista H. Williams\textsuperscript{a}, and John H. England\textsuperscript{b}
Last-exposure dates from recovered plants

Fig. 1. Location of study site. (A) Map of the Canadian High Arctic and northwest Greenland with ice cover in white. Teardrop Glacier, Sverdrup Pass, Ellesmere Island, Nunavut, is indicated by a red arrow. (B) Oblique aerial view (from the north) of Teardrop Glacier, July 2009. Light-toned perimeter (white arrows) marks the trimline at the limit of the LIA advance. Subglacial samples were collected between the Xs (red) within 10 m of glacial margin.

Fig. 2. Subglacial LIA bryophyte populations emerging from Teardrop Glacier margin. (A) Intact population of P. alpinum at glacier margin. (Scale bar, 10 cm.) (B) Corresponding detail of same P. alpinum population (red arrow). (C) Populations of A. turgidum < 1 m from glacier margin. (Scale bar, 20 cm). (D) Corresponding detail of same of A. turgidum (red arrow) showing intact stems and leaves.

Regeneration of Little Ice Age bryophytes emerging from a polar glacier with implications of totipotency in extreme environments, 2013, PNAS

Catherine La Farge,†, Krista H. Williams, and John H. England
Regeneration of Little Ice Age bryophytes emerging from a polar glacier with implications of totipotency in extreme environments, 2013, PNAS

Catherine La Fargea,1, Krista H. Williamsa, and John H. Englandb
Are glaciers retreating due to end of little ice age?

Second line of evidence: Relation between temperature and glacier extent, glacier adjustment time scale.
Notes section 11.2.1

(1) Basics: Accumulation & ablation zones, equilibrium line
(2) SMB, PDD
(3) Reconstructing temperature from glacier extent
Workshop #2:

Temperature and glacier length
Temperature reconstructed from glacier length

Figure 11.5: Relating temperature to glacier length. (a) Globally and annually averaged surface temperature (blue) and its smoothed version used for the analysis of glacier length and global temperature (red). (b) The binned-average glacier length from Fig. 11.2a, interpolated to 1-year resolution (blue) and smoothed (red). (c) The optimal solution for the global mean surface temperature calculated from the binned glacier extent using eqn (11.3) is shown in red, together with the observed smoothed temperature redrawn from panel a, and with the equilibrium temperature with the glacier length (dash, see text for details).

\[
\frac{dL'(t)}{dt} = -\frac{1}{\tau} (L'(t) + cT'(t)).
\]

\[
L'(t) = (L'_0 + cT'_0)e^{-t/\tau} - cT'_0,
\]
The worldwide retreat of many glaciers during the past few decades is frequently mentioned as a clear and unambiguous sign of global warming. The reconstructed warming in the first half of the 20th century is about 1.5 kelvin. This warming was notably coherent over the globe. There is a strong bias toward the European Alps, where a wealth of documents exists still in place today. However, records based on information from moraines dated by lithostratigraphy or fossil wood without any additional evidence have not been used in the most temperature reconstructions of the late Holocene climate, glacier records are not included and most information comes from tree rings (including Storglaciären, Sweden) but only in the second half of the 20th century. The problems involved in the interpretation of glacier length records from different parts of the world. Each dot represents a data point. Data points are scarce before 1900; after 1900 a considerable number of records have annual resolution.

Oerleman, Extracting a Climate Signal from 169 Glacier Records; SCIENCE, VOL 308, 29 APRIL 2005
Temperature reconstructed from glacier length

Fig. 1. Examples of glacier length records from different parts of the world. Each dot represents a data point. Data points are scarce before 1900; after 1900 a considerable number of records have annual resolution.

Fig. 2. (A) Number of records for the last 300 years. The decline after 1990 is due to a large delay in the reporting and publishing of data in a suitable form. (B) Stacked records of glacier length. Irregularities occur when a glacier with a large length change is added. However, this does not necessarily involve a large change in climatic conditions because glaciers exhibiting large changes are normally those that have a large climate sensitivity (and thus respond in a more pronounced way to, for instance, a temperature change). After 1900, the irregularities disappear because the number of glaciers in the sample increases strongly.
Temperature reconstructed from glacier length

Fig. 1. Examples of glacier length records from different parts of the world. Each dot represents a data point. Data points are scarce before 1900; after 1900 a considerable number of records have annual resolution.

Fig. 2. (A) Number of records for the last 300 years. The decline after 1990 is due to a large delay in the reporting and publishing of data in a suitable form. (B) Stacked records of glacier length. Irregularities occur when a glacier with a large length change is added. However, this does not necessarily involve a large change in climatic conditions because glaciers exhibiting large changes are normally those that have a large climate sensitivity (and thus respond in a more pronounced way to, for instance, a temperature change). After 1900, the irregularities disappear because the number of glaciers in the sample increases strongly.

Fig. 3. (A) Temperature reconstruction for various regions. The black curve shows an estimated global mean value, obtained by giving weights of 0.5 to the Southern Hemisphere (SH), 0.1 to Northwest America, 0.15 to the Atlantic sector, 0.1 to the Alps, and 0.15 to Asia. Year (B) Best estimate of the global mean temperature obtained by combining the weighted global mean temperature from 1834 with the stacked temperature record before 1834. The band indicates the estimated standard deviation.

Oerleman, Extracting a Climate Signal from 169 Glacier Records; SCIENCE, VOL 308, 29 APRIL 2005
Are glaciers retreating due to end of little ice age?

Third line of evidence:
Isotopic cores from mountain glaciers, including signs of unusual recent melt events
Notes section 11.2.2

glacier ice cores: isotopic and melt records
Workshop 4
Isotopic records from Quelccaya ice cores
Figure 11.6: Isotopic records from the Quelccaya Ice Cap in the Andes, Peru (latitude 13S). (a) Two high-resolution shallow ice cores showing the presence of a seasonal cycle in 1976 (blue) and its elimination by surface melting and percolation of melt water by the time the 2016 core was drilled (red). (b) A decadal bin-average of a long record from the Quelccaya Summit Ice core. The cyan shading indicates plus and minus one standard deviation for each decade.
Are glaciers retreating due to end of little ice age?

Fourth line of evidence:
Mountain glaciers adjustment time
Notes section 11.4

Glacier dynamics
Workshop 3:

Idealized glacier-length adjustment scenarios
Figure 11.4: Two idealized adjustment scenarios of glacier length based on solution (11.2), assuming $\tau = 15$ years, and based on the initial lengths and perturbation temperatures indicated.
The slow final states of the equilibration seen in this simulation (years 40–100 in Fig. 11.8) are in marked contrast to the observed global glacier retreat which seem to have actually accelerated in the past 20–30 years (Fig. 11.2). This again suggests that this recent accelerated retreat is unlikely to be a response to the termination of the little ice age in the nineteenth century, as we should have been in the slow final adjustment to that change, by now.

The results in Figs. 11.7 and 11.8 were obtained by solving what is known as the “shallow ice approximation” (SIA) for glacier or ice sheet flow, based on the assumption that the ice thickness is significantly smaller than its horizontal extent.

Figure 11.7: (a) Surface mass balance for two scenarios (solid blue vs dash red), showing also the corresponding Equilibrium Line Altitudes (horizontal dash lines). (b) The steady solution of the Shallow Ice Approximation for glacier height for the two scenarios.

Figure 11.7: (a) Surface mass balance for two scenarios (solid blue vs dash red), showing also the corresponding Equilibrium Line Altitudes (horizontal dash lines). (b) The steady solution of the Shallow Ice Approximation for glacier height for the two scenarios.
Figure 11.8: The time-dependent transition between the blue and red solutions in Fig. 11.7b. (a) Glacier thickness as function of horizontal thickness for different times after the ELA changed from the blue to the red lines in Fig. 11.7a. Progressing times are denoted by changing color of the thin lines from blue to green to red. (b) Glacier length as function of time during the transition.
Mountain glaciers: summary
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
  - Carbon-dated exposed plants of many 100s-1000s yrs ago, long before start of little ice age.
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
  - Carbon-dated exposed plants of many 100s-1000s yrs ago, long before start of little ice age.
  - Glacier length similar to global temperature: recent glacier trends as unusual as recent warming observed independently.
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
  - Carbon-dated exposed plants of many 100s-1000s yrs ago, long before start of little ice age.
  - Glacier length similar to global temperature: recent glacier trends as unusual as recent warming observed independently.
  - Accelerating retreat in recent decades is in contrast to expected slowdown of response to little ice age 150 years ago.
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
  - Carbon-dated exposed plants of many 100s-1000s yrs ago, long before start of little ice age.
  - Glacier length similar to global temperature: recent glacier trends as unusual as recent warming observed independently.
  - Accelerating retreat in recent decades is in contrast to expected slowdown of response to little ice age 150 years ago.
  - Adjustment time calculated for most glaciers is 10-50 yrs, so any adjustment to the exit from the little ice age is long over.
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
  - Carbon-dated exposed plants of many 100s-1000s yrs ago, long before start of little ice age.
  - Glacier length similar to global temperature: recent glacier trends as unusual as recent warming observed independently.
  - Accelerating retreat in recent decades is in contrast to expected slowdown of response to little ice age 150 years ago.
  - Adjustment time calculated for most glaciers is 10-50 yrs, so any adjustment to the exit from the little ice age is long over.
  - Isotopic ice core records as a temperature proxy suggests that the 20th century is unusual within the past 1500 years or so.
Mountain glaciers: summary

- A dramatic retreat, accelerating over past decades.
- Plenty of evidence that this is not a natural response to exit from little ice age:
  - Carbon-dated exposed plants of many 100s-1000s yrs ago, long before start of little ice age.
  - Glacier length similar to global temperature: recent glacier trends as unusual as recent warming observed independently.
  - Accelerating retreat in recent decades is in contrast to expected slowdown of response to little ice age 150 years ago.
  - Adjustment time calculated for most glaciers is 10-50 yrs, so any adjustment to the exit from the little ice age is long over.
  - Isotopic ice core records as a temperature proxy suggests that the 20th century is unusual within the past 1500 years or so.
  - Surface melting seen in tropical ice cores in the 21st century have not occurred in the previous many 100s-1000s yrs.
The End