Mountain glaciers

Global Warming Science, EPS101

Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

‘Before and after’ Glacier images

Columbia Glacier, Alaska, August 28, 2009. Columbia Glacier, Alaska, June 22, 2015

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/

‘Before and after’ Glacier images

Stein Glacier, Switzerland, has retreated by 550 m between 2006 and 2015

James Balog and the extreme ice survey

https://newatlas.com/before-after-photos-glaciers-climate-change/49143/

‘Before and after’ Glacier images

Qori Kalis Glacier in Peru has retreated by 1.14 km between 1978 and 2016

Lonnie Thompson

https://newatlas.com/before-after-photos-glaciers-climate-change/49143/

‘Before and after’ Glacier images

Thrift Glacier, Switzerland, has retreated by 1.17 km between 2006 and 2015

James Balog and the extreme ice survey

https://newatlas.com/before-after-photos-glaciers-climate-change/49143/

Videos

Climate Change Shrinking Mountain WA Glaciers
https://www.youtube.com/watch?v=ct-FptrxO-8

Africa's First Mountains To Lose Their Glaciers
https://www.thestoryinstitute.com/rwenzori-mountains

Half of All Mountain Glaciers Are Expected to Disappear by 2100/Glacial floods
https://www.scientificamerican.com/article/half-of-all-mountain-glaciers-are-expected-to-disappear-by-2100/

Workshop 1 a, b (leave c for HW)

Glacier lengths records

Example glacier length records

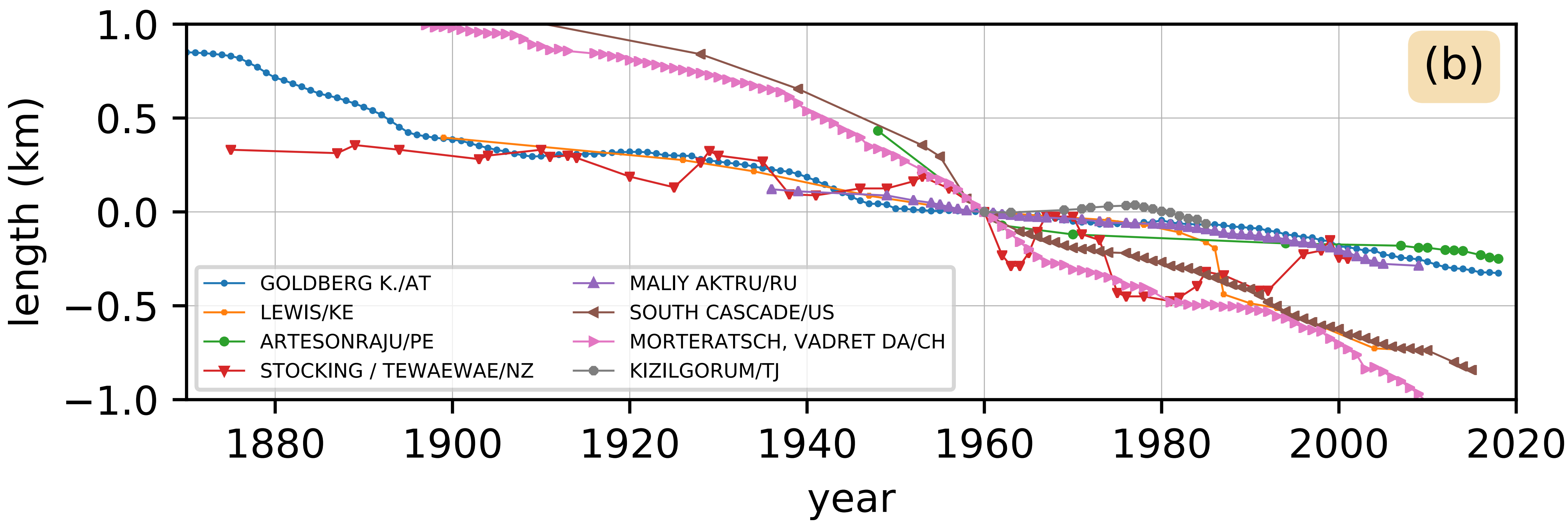
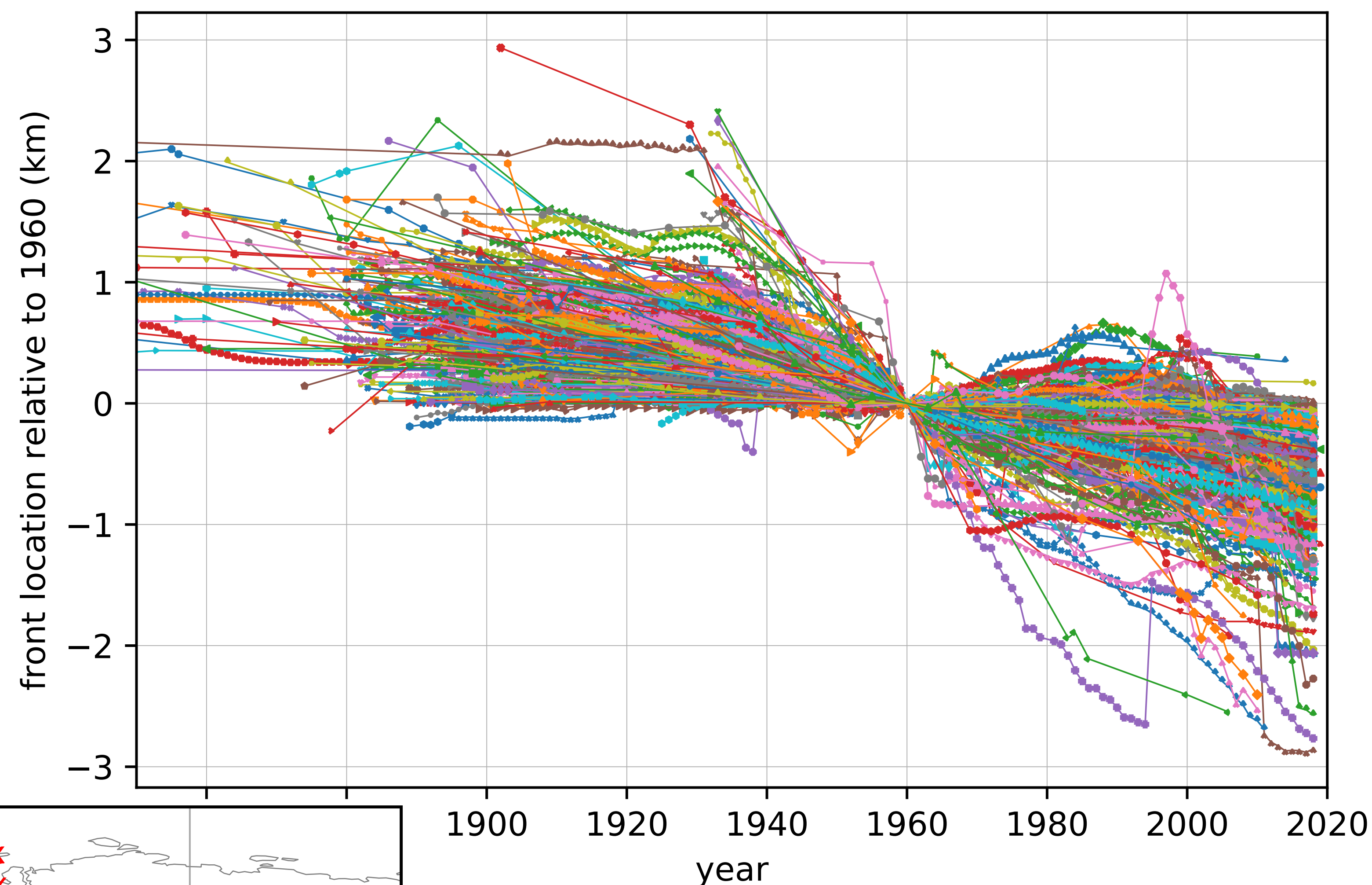


Figure 1.4: Records of glacier length for a few mountain glaciers, relative to their length in 1960.

All glacier length time series

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



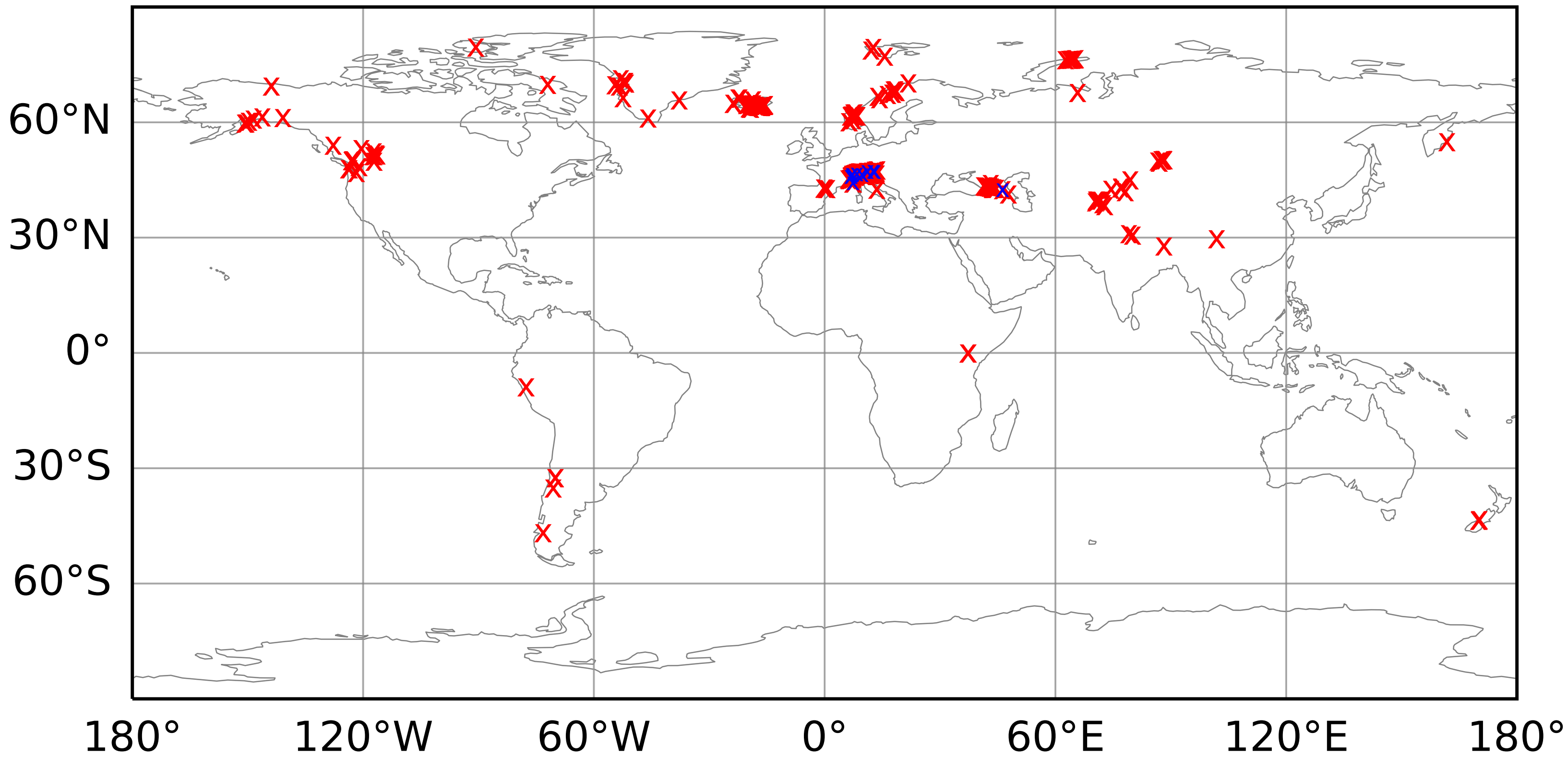


Figure 11.3: Showing all glaciers with observed edge location time series, marking the 791 glaciers with negative trends in red, and the 29 with positive trends in blue. The blue symbols are drawn on top of the red ones, assuring that the few locations with positive trends are clearly highlighted.

Averaged/binned length records

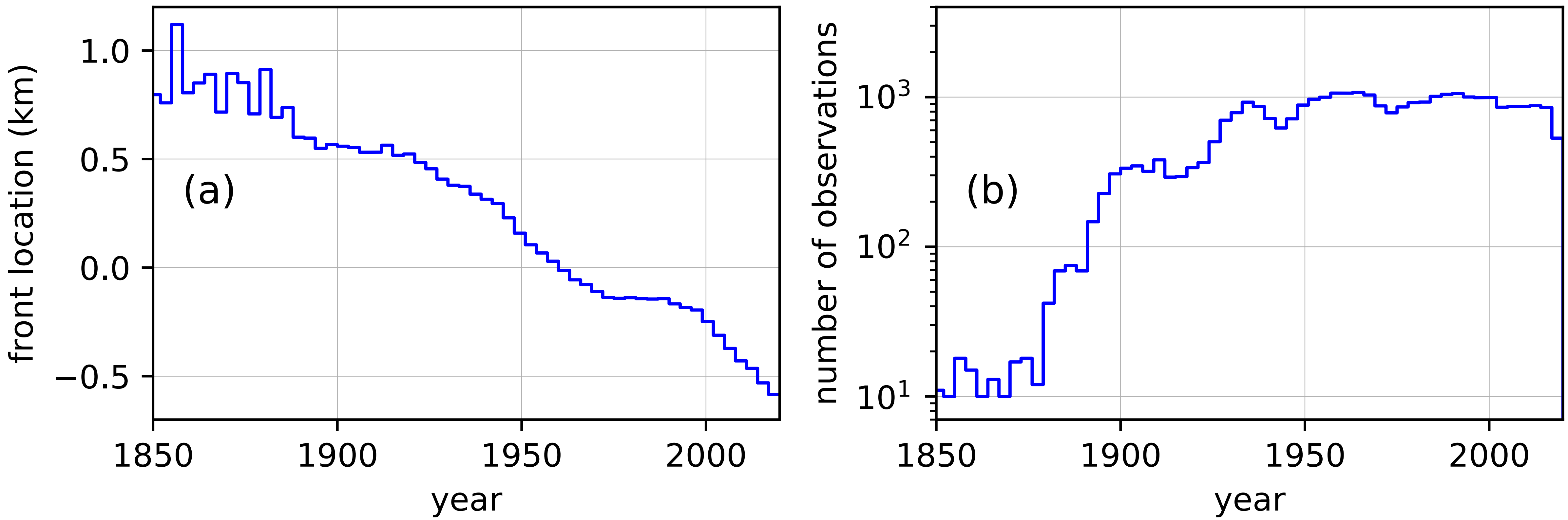
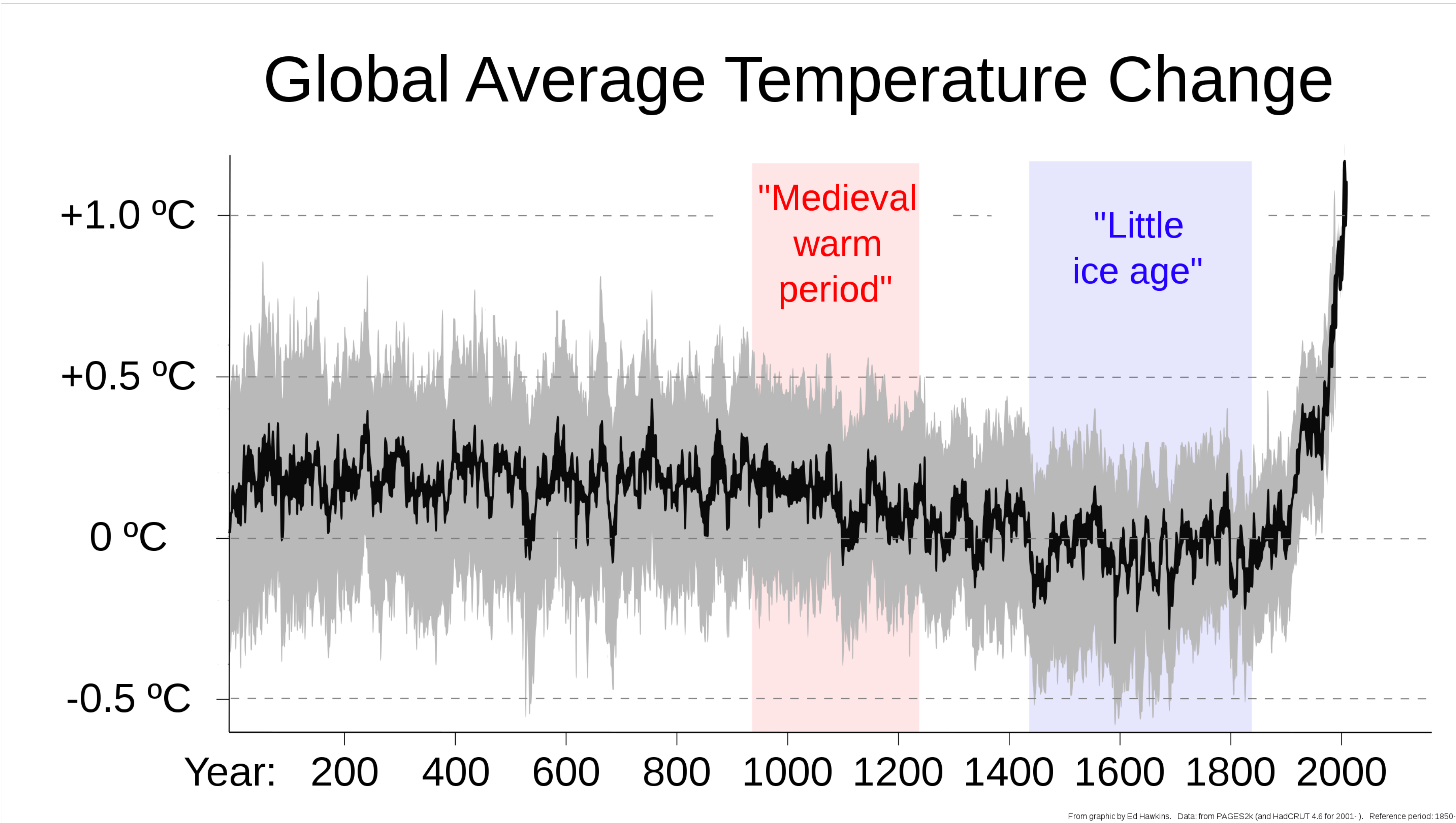


Figure 11.2: (a) A bin-average of the glacier length records seen in Fig. 11.1. (b) The number of observations per bin.

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

“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.”

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The Frozen Thames, 1677

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

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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

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Consider four lines of evidence that the observed glacier retreat during recent decades is **not** due to the end of the little ice age:

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3. Ice cores: Glacier isotopic records and recent melt events.
4. Mountain glaciers' flow and adjustment time scale to temperature/Surface Mass Balance (SMB) changes.

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

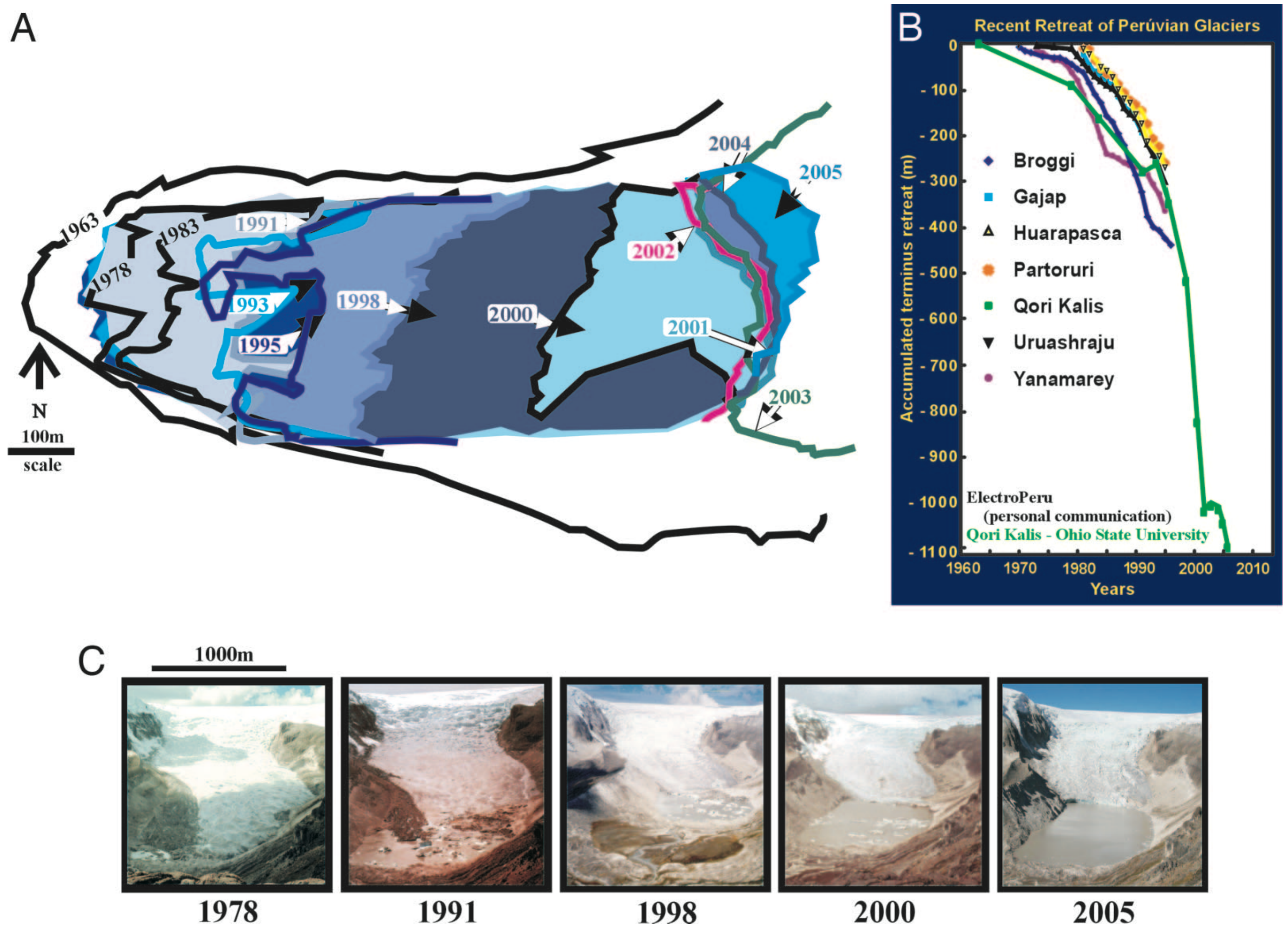


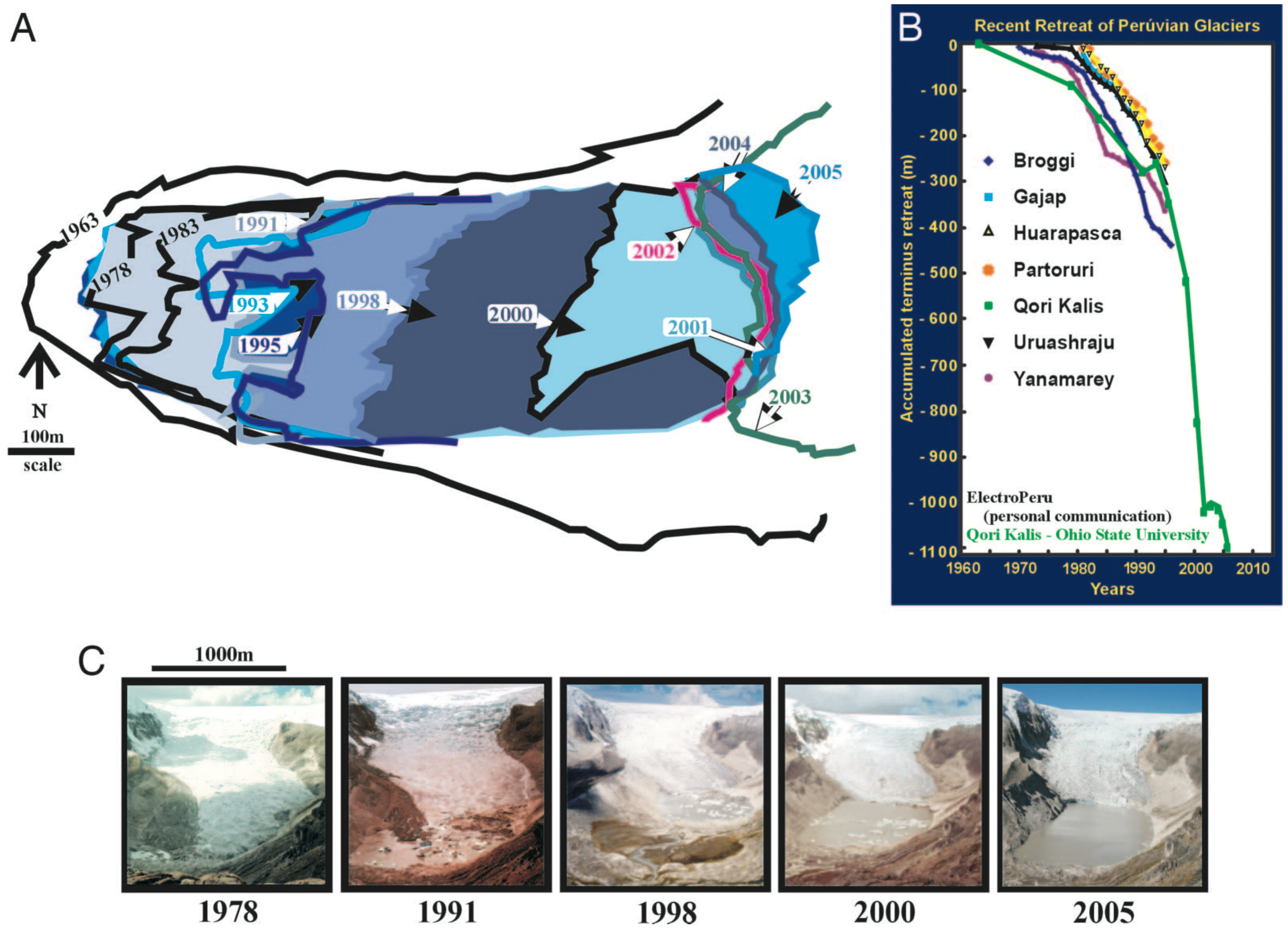
Fig. 2. Glacier retreat as documented in the Peruvian Andes. (A) Retreat of Qori Kalis from 1963 to 2005. (B) Retreat records for Qori Kalis and six other Andean glaciers. (C) The photos document the expansion of the proglacial lake from 1991 to 2005 as Qori Kalis retreated.

Abrupt tropical climate change: Past and present

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

PNAS, 2006

Last-exposure dates from recovered plants



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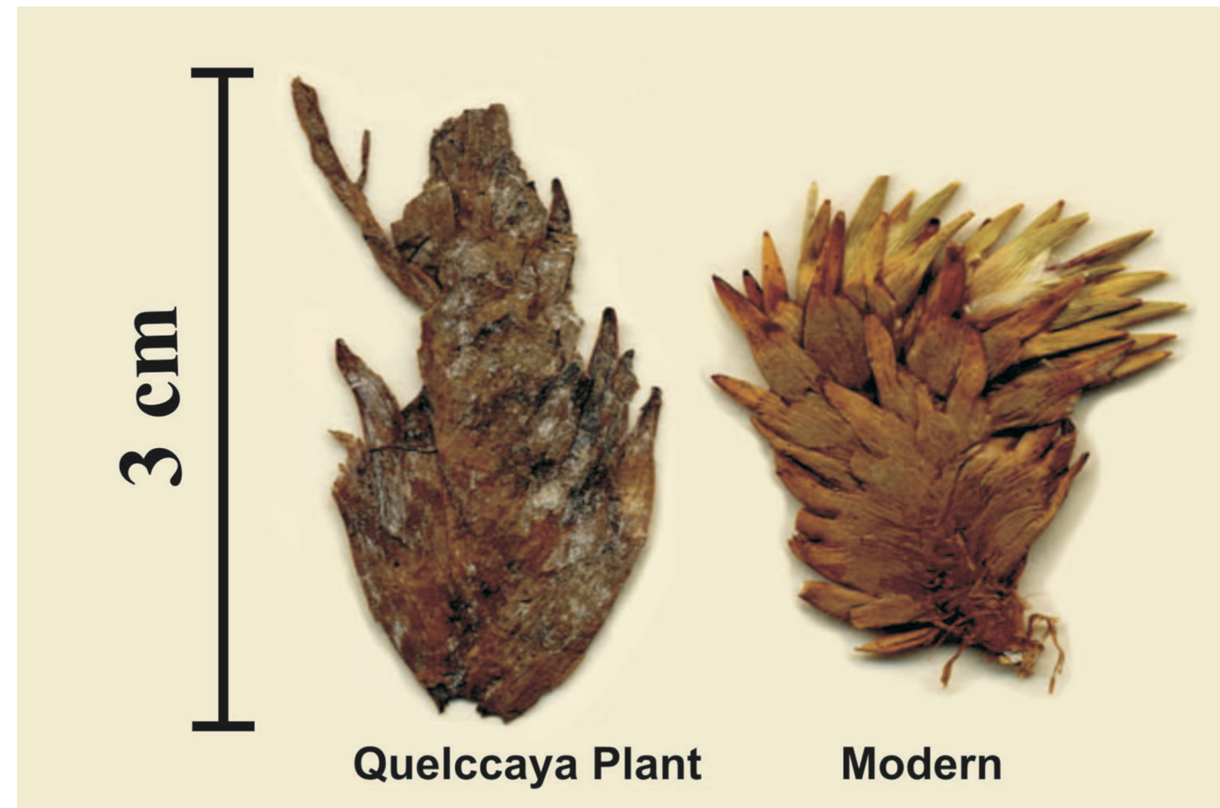

Fig. 7. The plant Distichia muscoides (**5,138±45 yr B.P.**) collected at the retreating margin of the Quelccaya ice cap in August of 2002 is compared with the modern plant (see Table 1 for dates on this and other plants).

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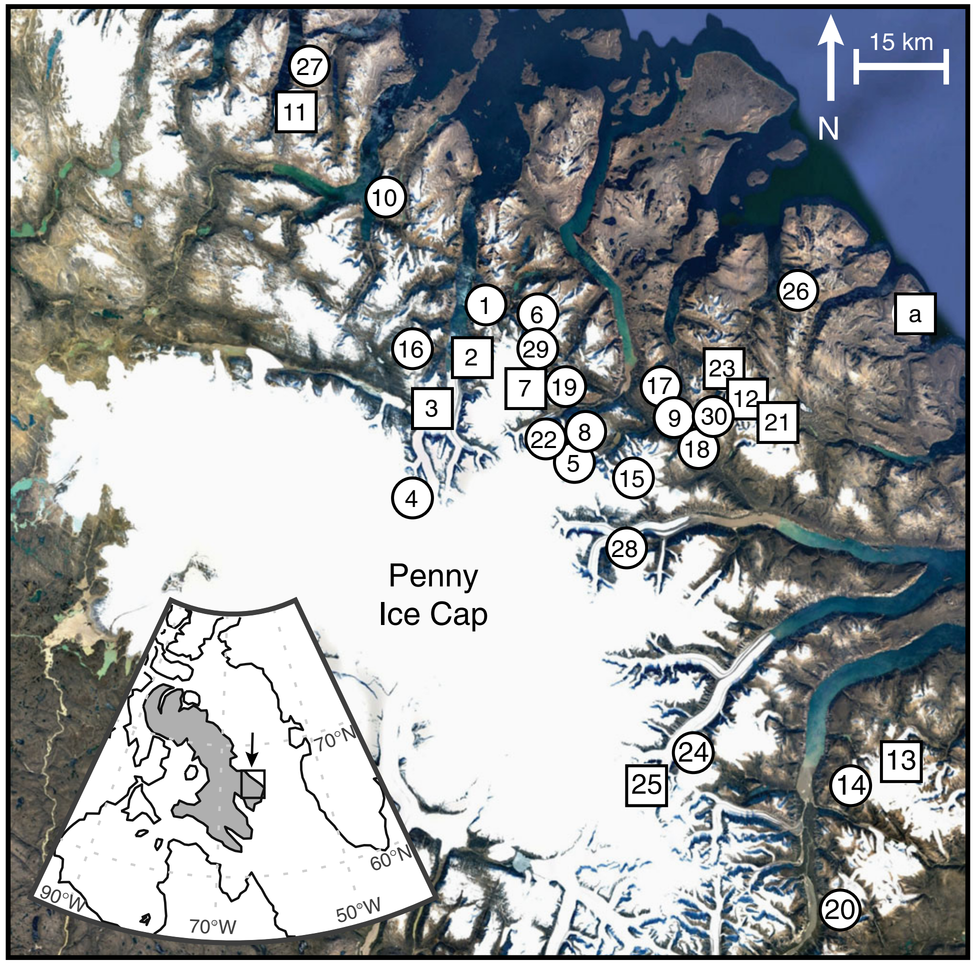

Fig. 1 Map showing sample localities on eastern Baffin Island. White circles indicate locations of plant samples, squares indicate locations with both plant and rock (in situ cosmogenic ^{14}C) samples. Site a is an unglaciated steep-sided summit where only rock was sampled (imagery: Google Earth: Image IBCAO, Landsat/Copernicus)

Table 1 Sample locations and ^{14}C ages

Site #	Sample ID	^{14}C age (yr)	$^{14}C \pm 1\sigma$ (yr)	Cal age (yr)	±1σ (yr)
1	M13-B002v	>43,300	-	-	-
2	M13-B005v	>48,370	-	-	-
2	M13-B007v	>45,277	-	-	-
3	M13-B011v	43,770	4670	45,443	+4557/−1177
3	M14-B101v	>46,320	-	-	-
4	M13-B018v	>45,277	-	-	-
5	M13-B028v	>45,277	-	-	-
6	M13-B045v	>49,990	-	-	-
7	M13-B051v	>45,277	-	-	-
7	M13-B052v	>47,000	-	-	-
7	M14-B139v	>44,940	-	-	-
8	M13-B055v	>45,277	-	-	-
9	M13-B064v	41,800	3250	45,171	+2893/−2420
10	M13-B066v	45,830	1770	48,199	+1801/-520
10	M13-B069v	>47,800	-	-	-
11	M13-B094v	48,850	2570	48,491	+1509/−390
11	M13-B091v	45,240	2570	47,449	+2551/−730
11[ab]	M10-B258v	34,300	3600	38,214	+3662/−3200
11[ab]	M10-B258v	39,740	950	43,550	+689/−810
11[ab]	M10-B258v	37,510	490	41,880	+380/−320
12	M13-B104v	>45,277	-	-	-
12[ab]	M10-B231v	29,100	1500	33,094	+1265/−1600
12[ab]	M10-B231v	44,300	1300	47,570	+1306/−1280
12[ab]	M10-B231v	23,920	100	27,959	+97/−150
12[ab]	M10-B232v	37,500	3600	41,194	+3738/−3110
13	M13-B195v	52,120	3860	48,226	+1774/−460
13	M13-B196v	42,100	1270	45,545	+1080/-1280
14	M13-B201v	50,300	3080	48,419	+1581/−410
15	M14-B020v	>45,650	-	-	-
16	M14-B085v	39,280	1230	43,228	+910/-980
17	M14-B107v	>46,320	-	-	-
18	M14-B113v	>46,320	-	-	-
19	M14-B143v	>46,320	-	-	-
20	M14-B154v	>45,980	-	-	-
21	M14-B158v	>46,320	-	-	-
22	M14-B163v	>46,380	-	-	-
23	M14-B164v	>45,220	-	-	-
23	M14-B165V	46,120	2870	47,592	+2408/-690
24	M14-B183v	45,780	2750	47,549	+2451/-700
24	M14-B184v	>46,320	-	-	-
25	M15-B047v	>47,000	-	-	-
25	M15-B048v	>44,400	-	-	-
26[ab]	M10-B247v	45,600	2500	47,636	+2364/−680
27[ab]	M10-B255v	43,200	2700	46,338	+2541/−1830
27[ab]	M10-B256v	50,700	3100	48,468	+1532/−390
28	M14-B009v	44,200	1850	47,303	+1842/−1370
29	M13-B046v	>50,143	-	-	−
30	M14-B161v	>50,768	-	-	-

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[50,51]. For sample metadata see Supplementary Table 1
[a]From Miller et al.[7]
[b]Received only deionized water pretreatment

Rapidly receding Arctic Canada glaciers revealing landscapes continuously ice-covered for **more than 40,000 years** (Pendleton et al, 2019)

Last-exposure dates from recovered plants

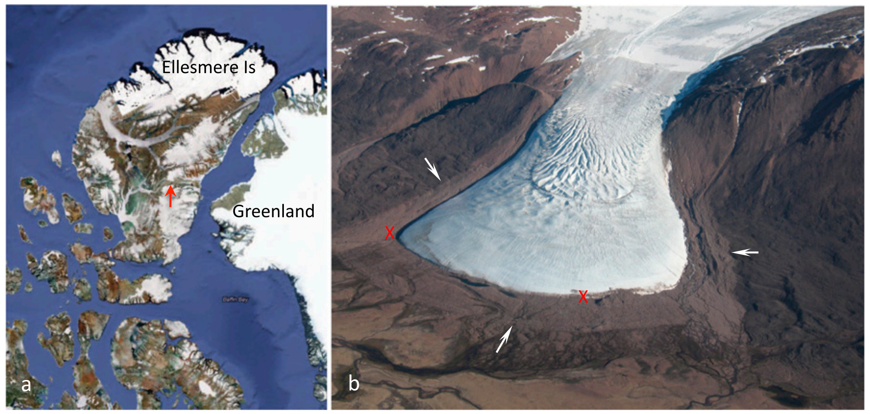

Fig. 1. Location of study site. (A) Map of the Canadian High Arctic and northwest Greenland with ice cover in white. Teardrop Glacier, Sverdrup Pass, Ellesmere Island, Nunavut, is indicated by a red arrow. (B) Oblique aerial view (from the north) of Teardrop Glacier, July 2009. Light-toned perimeter (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.

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

Catherine La Farge[a,1], Krista H. Williams[a], and John H. England[b]

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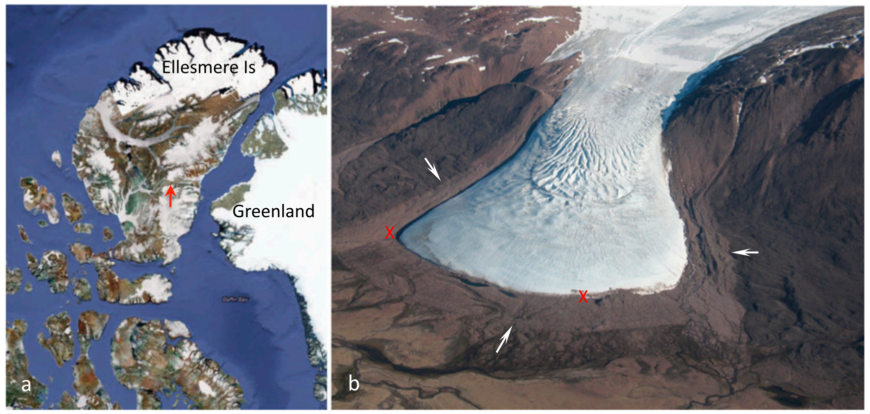

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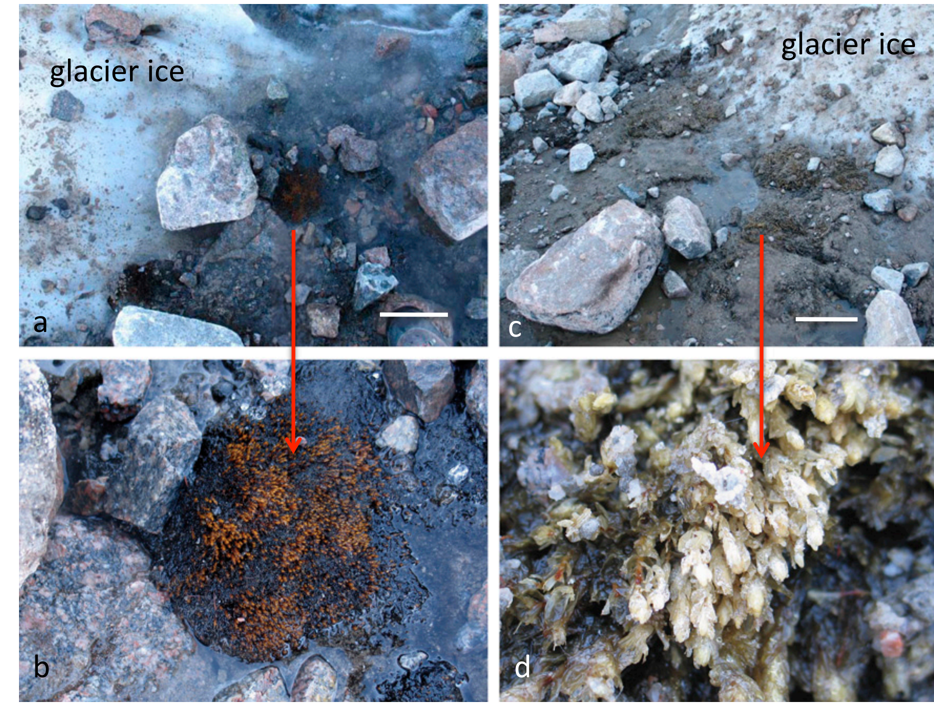

Fig. 2. Subglacial LIA bryophyte populations emerging from Teardrop Glacier margin. (A) Intact population of P. alpinum at glacier margin. (Scale bar, 10 cm.) (B) Corresponding detail of same P. alpinum population (red arrow). (C) Populations of A. turgidum < 1 m from glacier margin. (Scale bar, 20 cm).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

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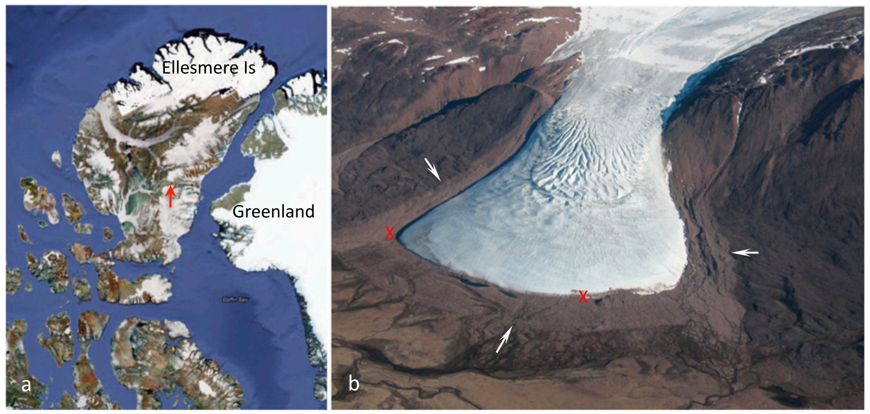

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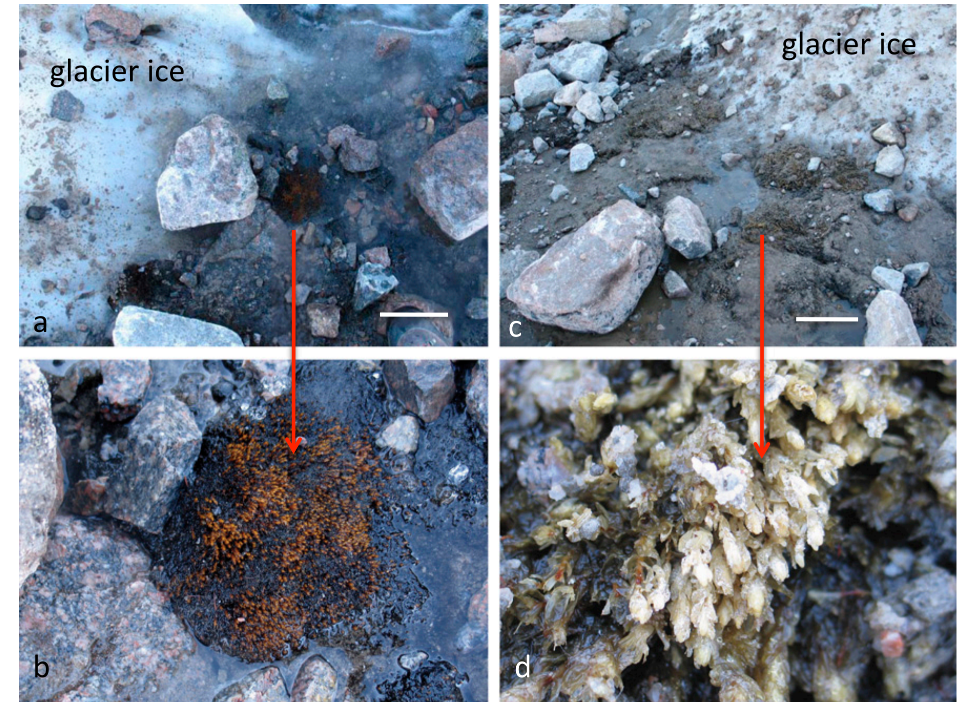

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Fig 4. Examples of extant, pioneer species growing on exhumed LIA plant material. (A) Extensive populations of LIA A. turgidum used as a colonizing substrate for P. cavifolium (a common weedy species) ~6 m from glacier margin. (B) P. cavifolium growing on blackened mats of LIA populations ~10 m from glacier margin.

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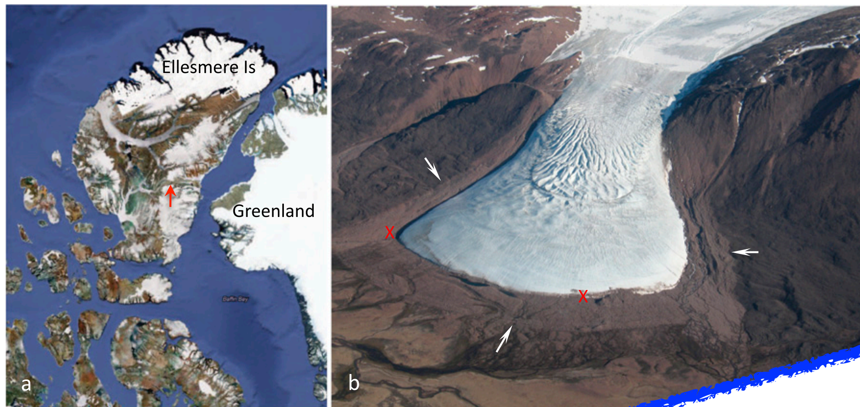

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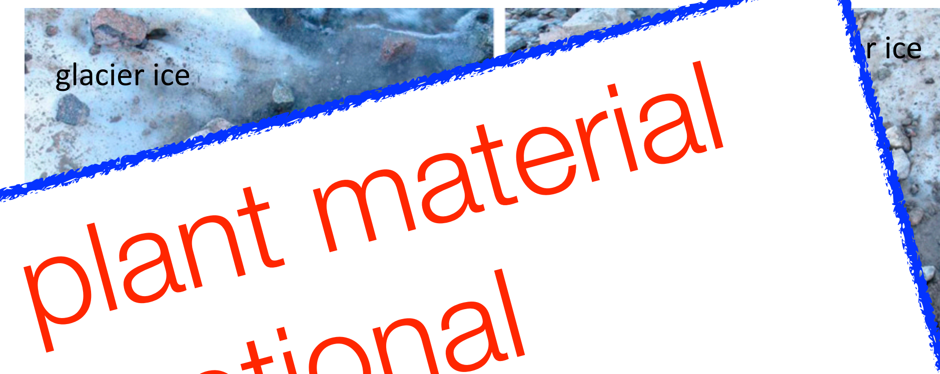

Conclusion: dates of exposed plant material indicate that glacier retreat is exceptional relative to the past 2000+ years. Glaciers are not merely retreating after briefly expanding during the little ice age a few hundred years ago.

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…n from
…). (D) Corresponding
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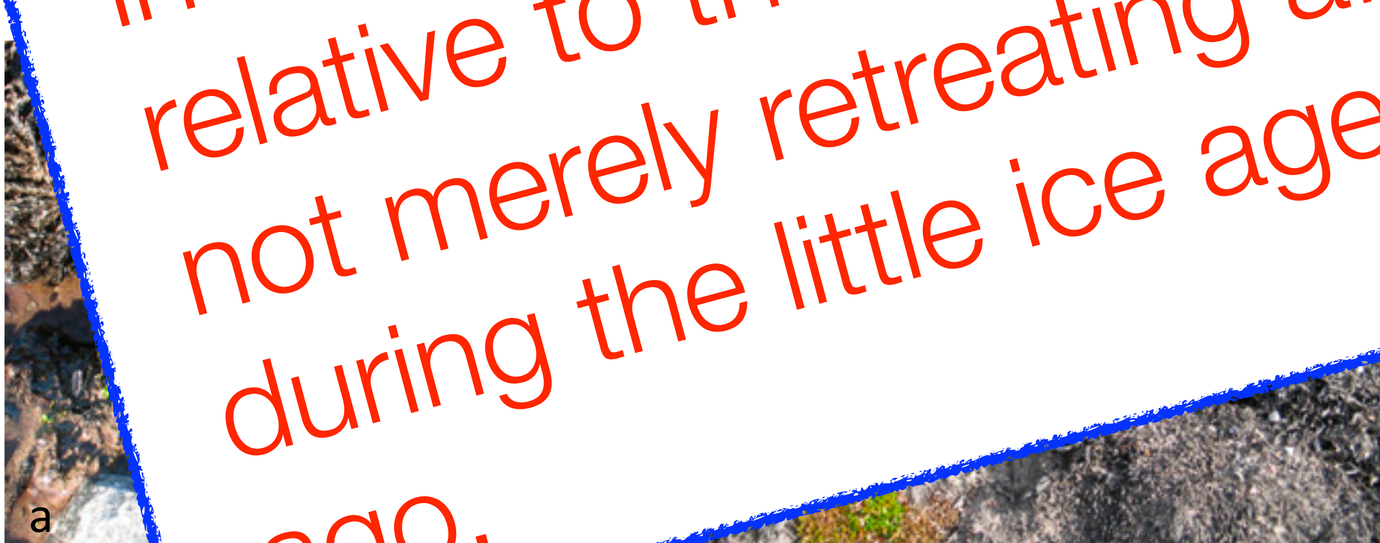

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Are glaciers retreating due to end of little ice age?

Second line of evidence:

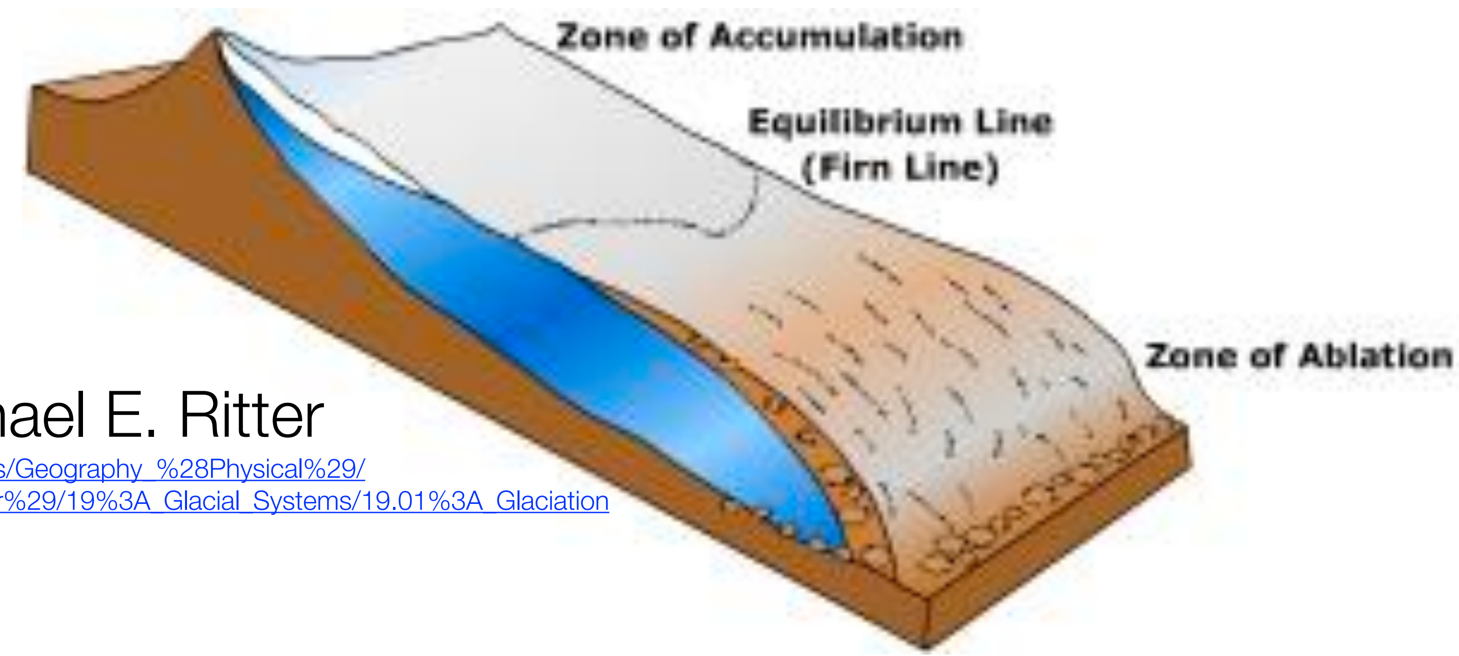
Relation between temperature and glacier extent and glacier adjustment time scale.

Notes section 11.2.1

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

use following slides

Accumulation & ablation zones, equilibrium line



Glaciation, Michael E. Ritter

https://geo.libretexts.org/Bookshelves/Geography_%28Physical%29/The_Physical_Environment_%28Ritter%29/19%3A_Glacial_Systems/19.01%3A_Glaciation

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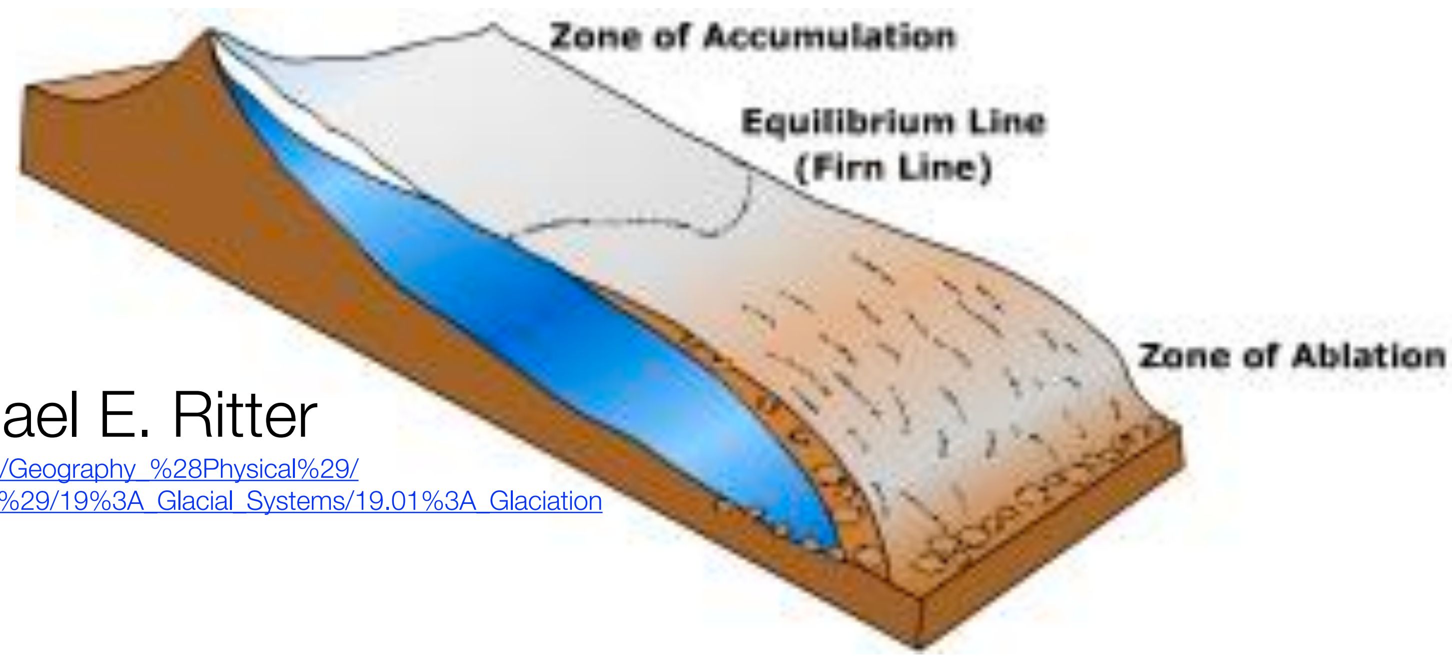

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SMB: Surface Mass Balance: rate of snow accumulation minus surface melting/ ablation.

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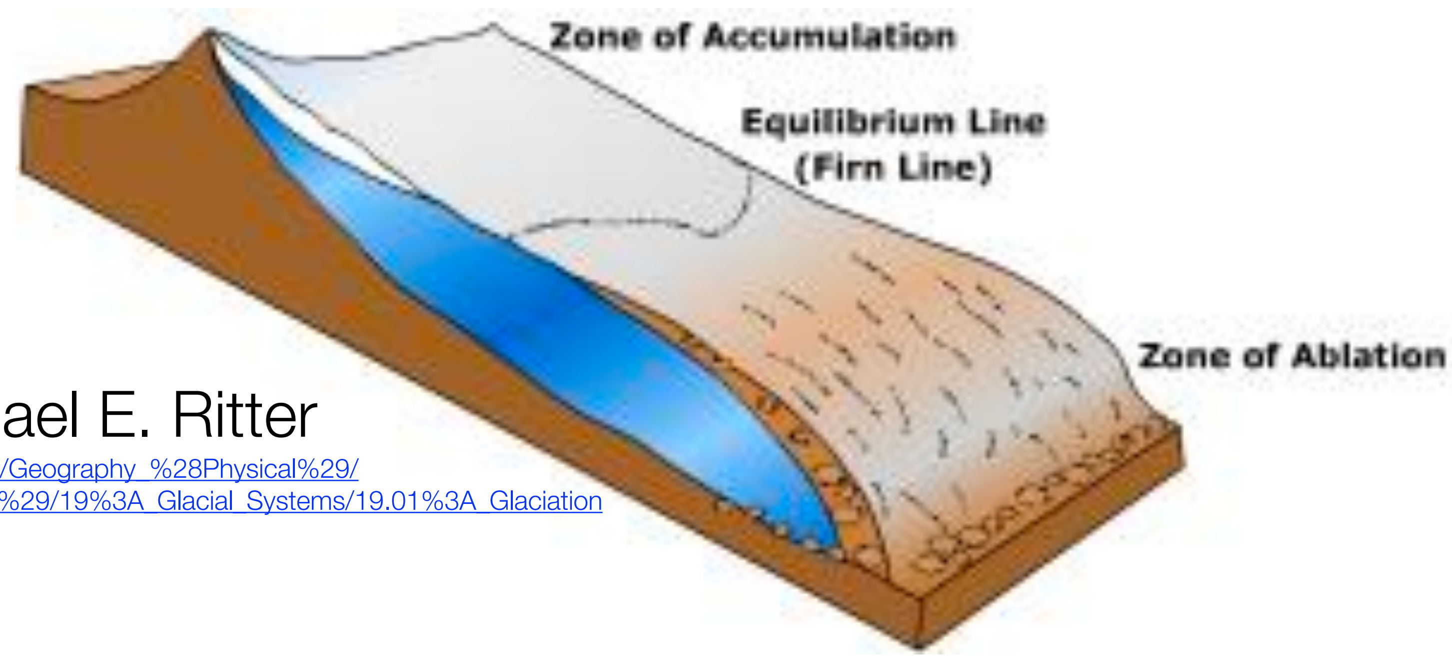

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SMB: Surface Mass Balance: rate of snow accumulation minus surface melting/ ablation.

PDD: positive degree days: an empirical measure of surface melting rate: $PDD = \sum_{\text{days (i)}} (T_i - T_{\text{melt}})\mathscr{H}(T_i - T_{\text{melt}})$

Reconstructing temperature from glacier extent

Let the lacier length anomaly be L'; & local temperature anomaly be T'.
Assuming a simple linear relation between length & temperature

$$L' = -cT'.$$

[Oerleman, 2005]

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If the temperature changes too quickly to allow glacier lengths to equilibrate at any given time, the glacier length continuously adjusts toward its equilibrium with the changing atmospheric temperature, with a typical timescale τ,

$$\frac{dL'(t)}{dt} = -\frac{1}{\tau}\left(L'(t) + cT'(t)\right)$$

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This suggests,

$$T'(t) = -\frac{1}{c}\left(L'(t) + \tau\frac{dL'(t)}{dt}\right)$$

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This suggests,

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If the temperature changed abruptly to T'_0 and then remained constant, the differential equation may be solved,

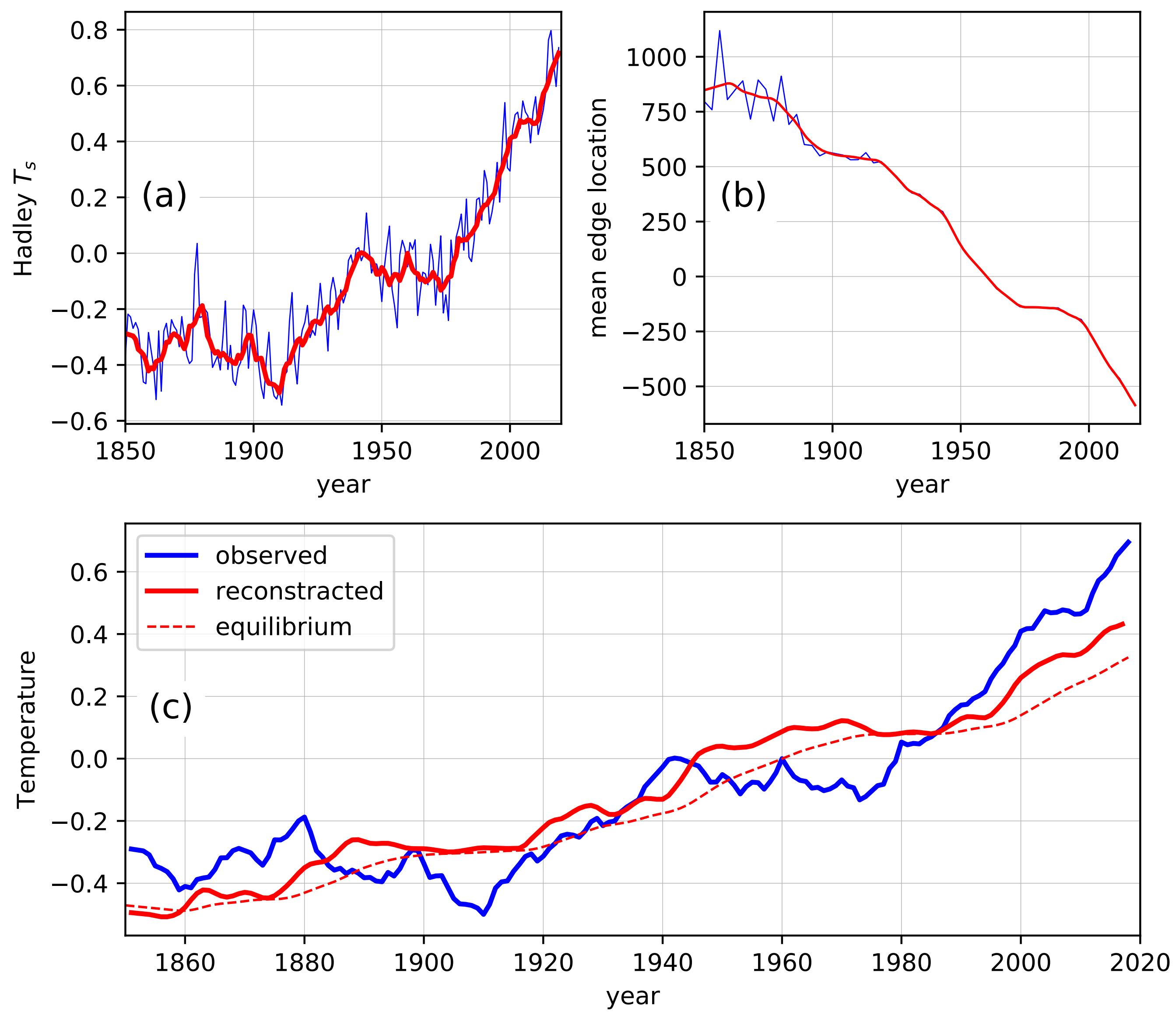
$$L'(t) = (L'_0 + cT'_0)e^{-t/\tau} - cT'_0$$

[Oerleman, 2005]

Workshop #2:

Temperature and glacier length

Temperature reconstructed from glacier length



$$\frac{dL'(t)}{dt} = -\frac{1}{\tau}\left(L'(t) + cT'(t)\right).$$

And, if $T(t) = T_0 =$ constant:

$$L'(t) = (L'_0 + cT'_0)e^{-t/\tau} - cT'_0,$$

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).

[Oerleman, 2005]

Temperature reconstructed from glacier length

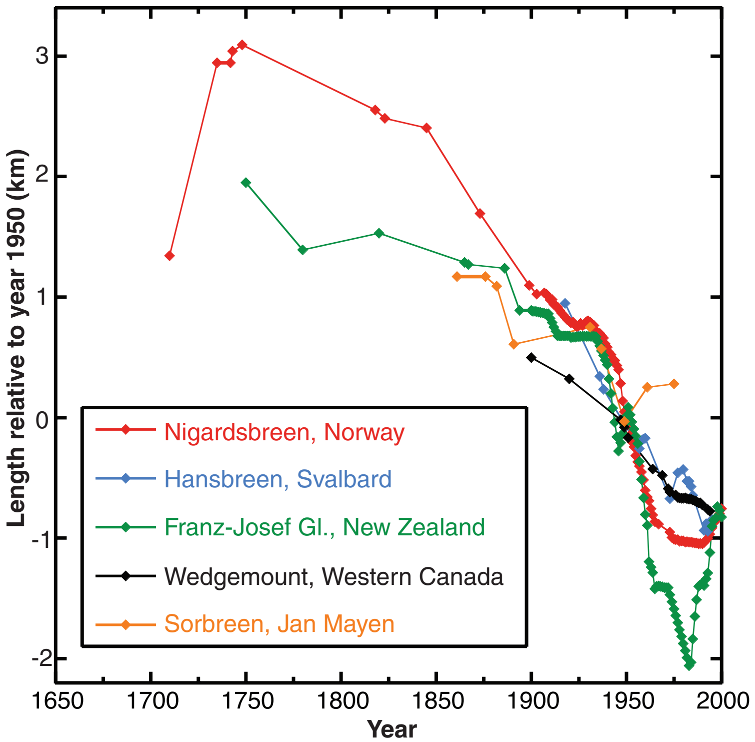


Fig. 1. Examples of glacier length records from different parts of the world. Each dot represents a data point. Data points are scarce before 1900; after 1900 a considerable number of records have annual resolution.

Oerleman, Extracting a Climate Signal from 169 Glacier Records; 2005

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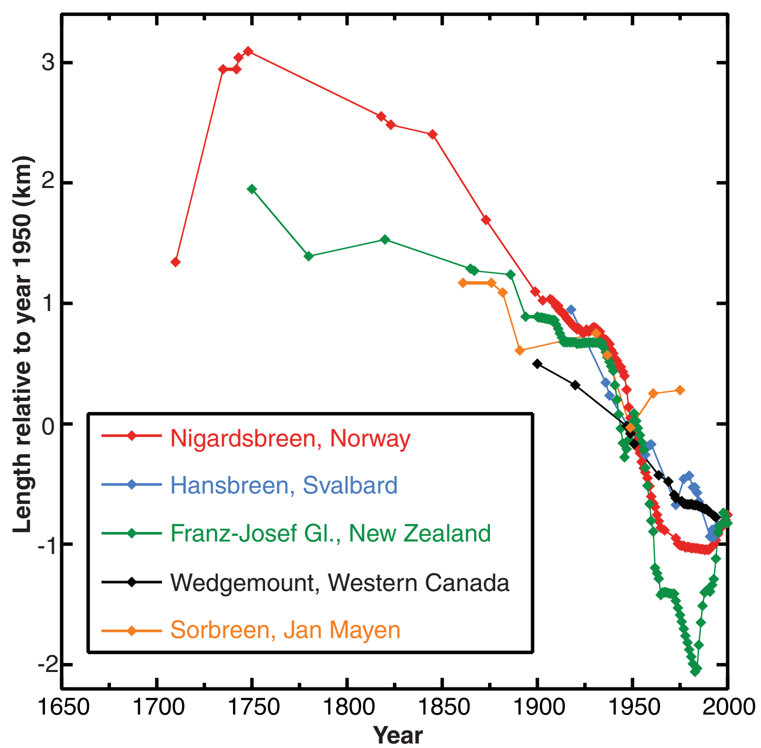

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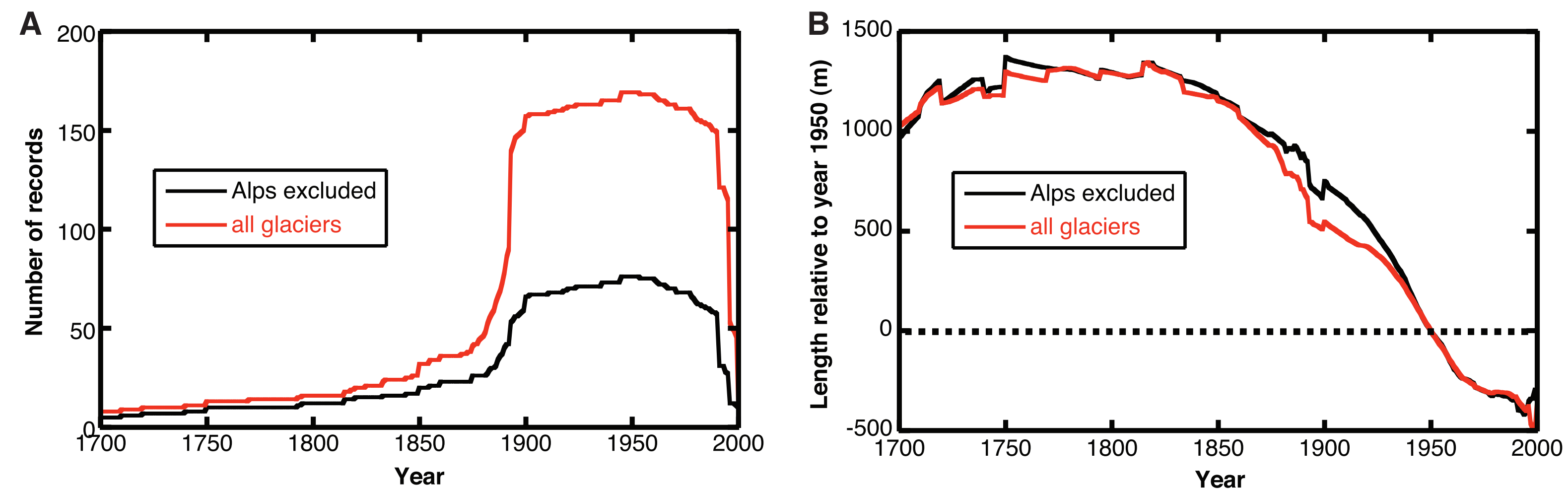
Fig. 2. (A) Number of records for the last 300 years. The decline after 1990 is due to a large delay in the reporting and publishing of data in a suitable form. (B) Stacked records of glacier length. Irregularities occur when a glacier with a large length change is added. However, this does not necessarily 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.



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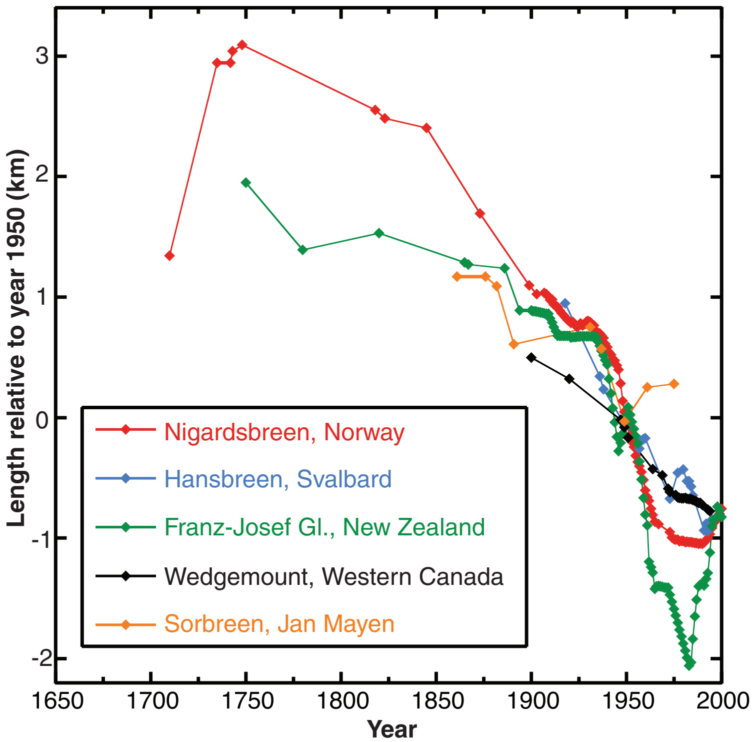

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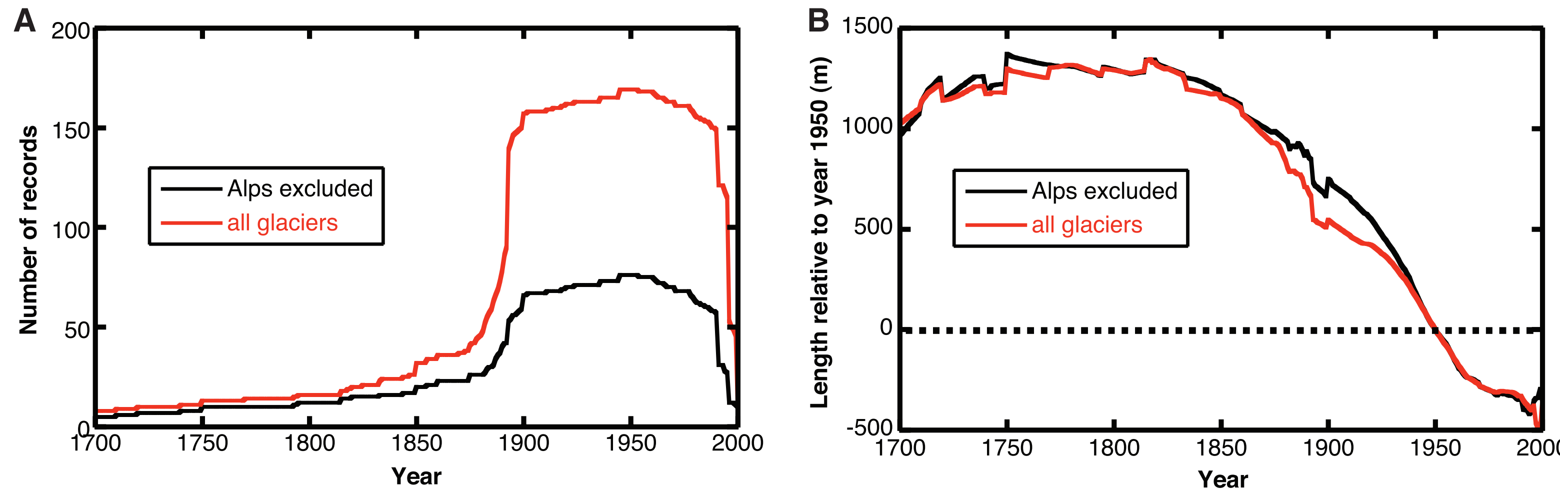

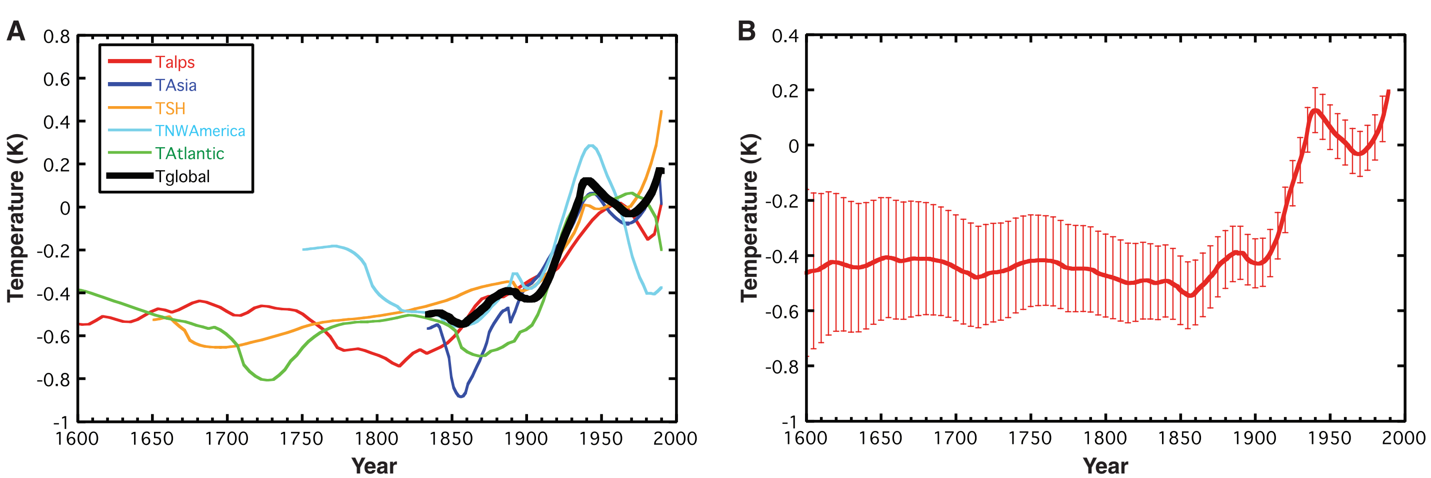

Fig. 3. (A) Temperature reconstruction for various regions. The black curve shows an estimated global mean value, obtained by giving weights of 0.5 to the Southern Hemisphere (SH), 0.1 to Northwest America, 0.15 to the Atlantic sector, 0.1 to the Alps, and 0.15 to Asia. Year (B) Best estimate of the 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; 2005

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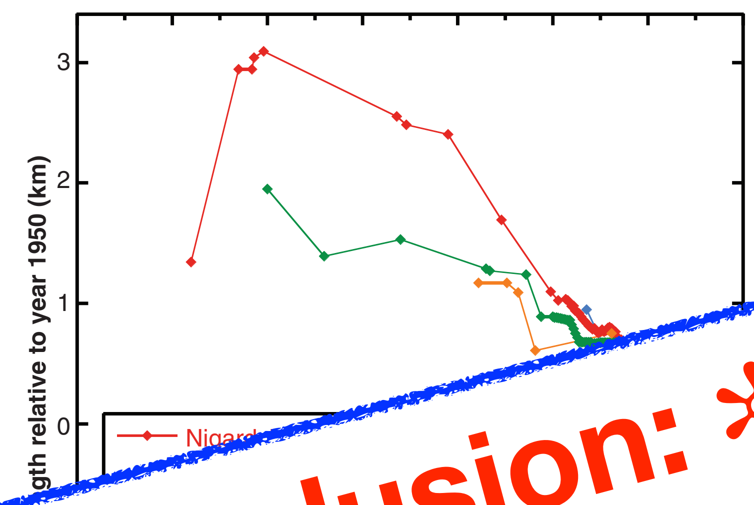

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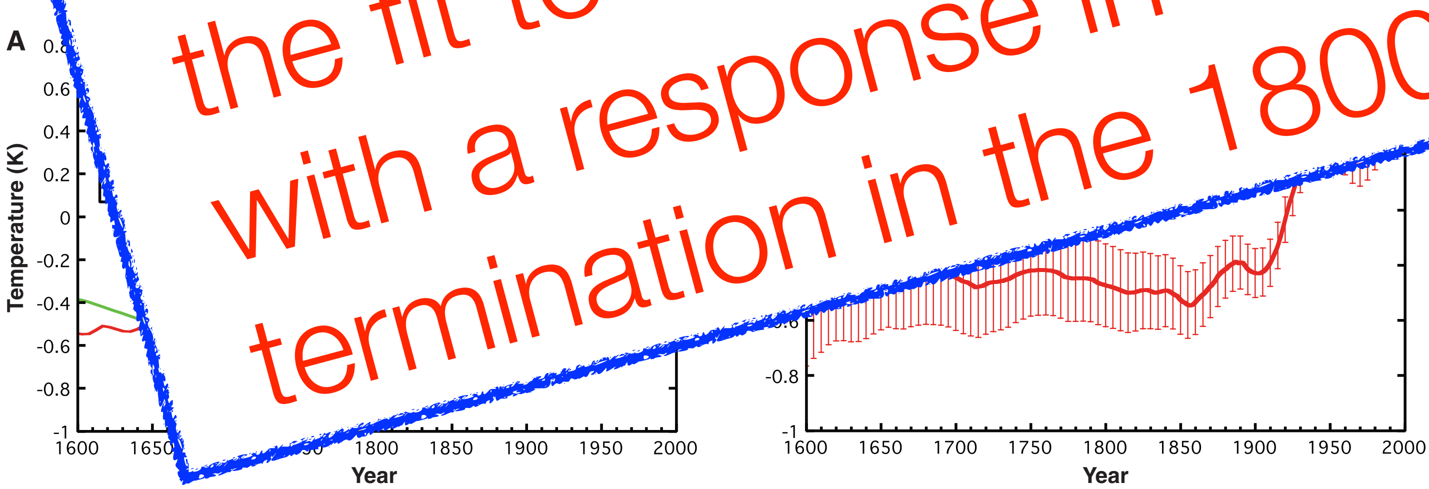
Conclusion: * The close relation between glacier extent and global temperature indicates that glaciers are affected by recent warming.
* Their response time scale calculated from the fit to GMST is too short to be consistent with a response in the 2000s to little ice age termination in the 1800s.



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Are glaciers retreating due to end of little ice age?

Third line of evidence:

Glacier isotopic records and recent melt events

Notes section 11.2.2
glacier ice cores: isotopic and melt records

Workshop 4
Isotopic records from Quelccaya ice cores

Glacier ice cores: isotopic records

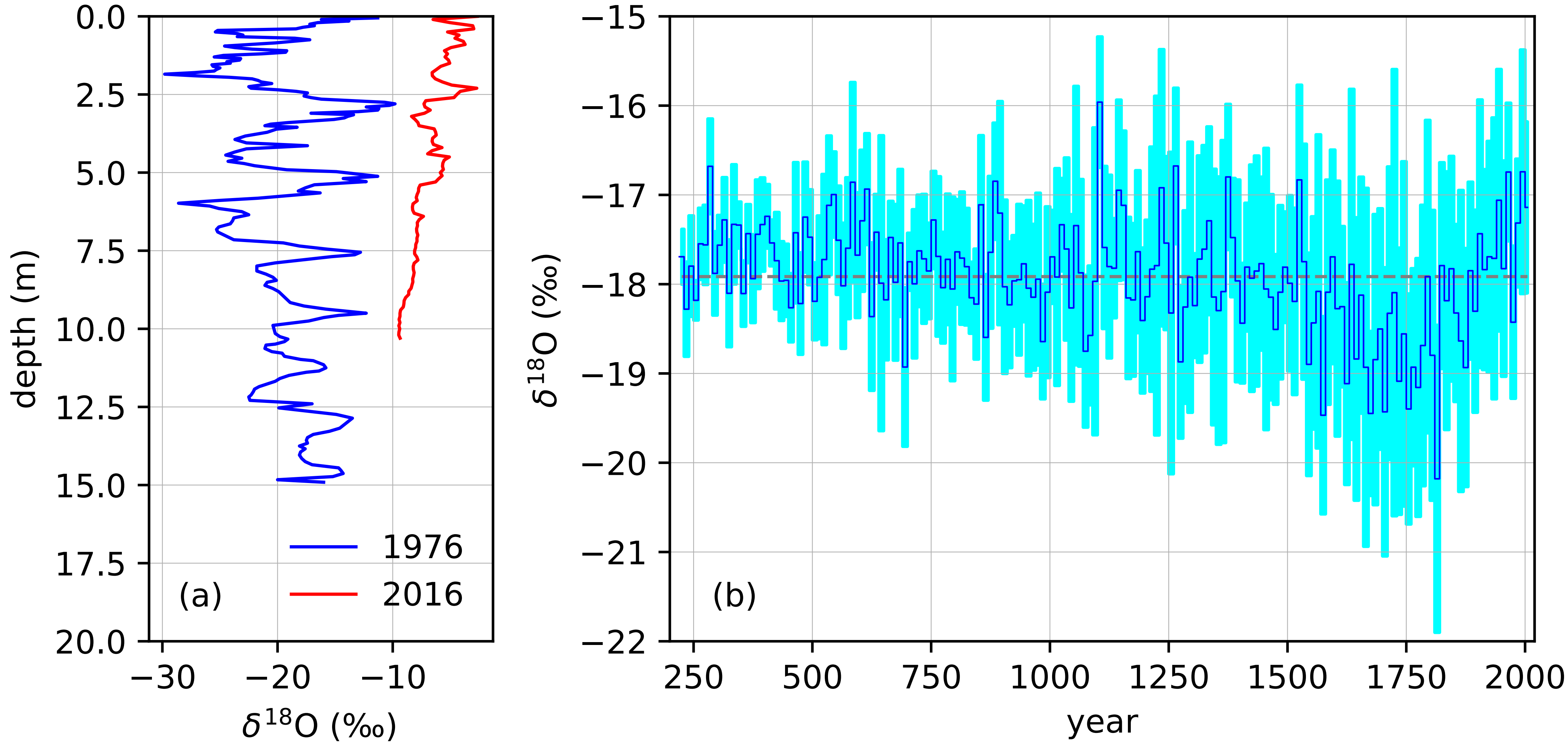
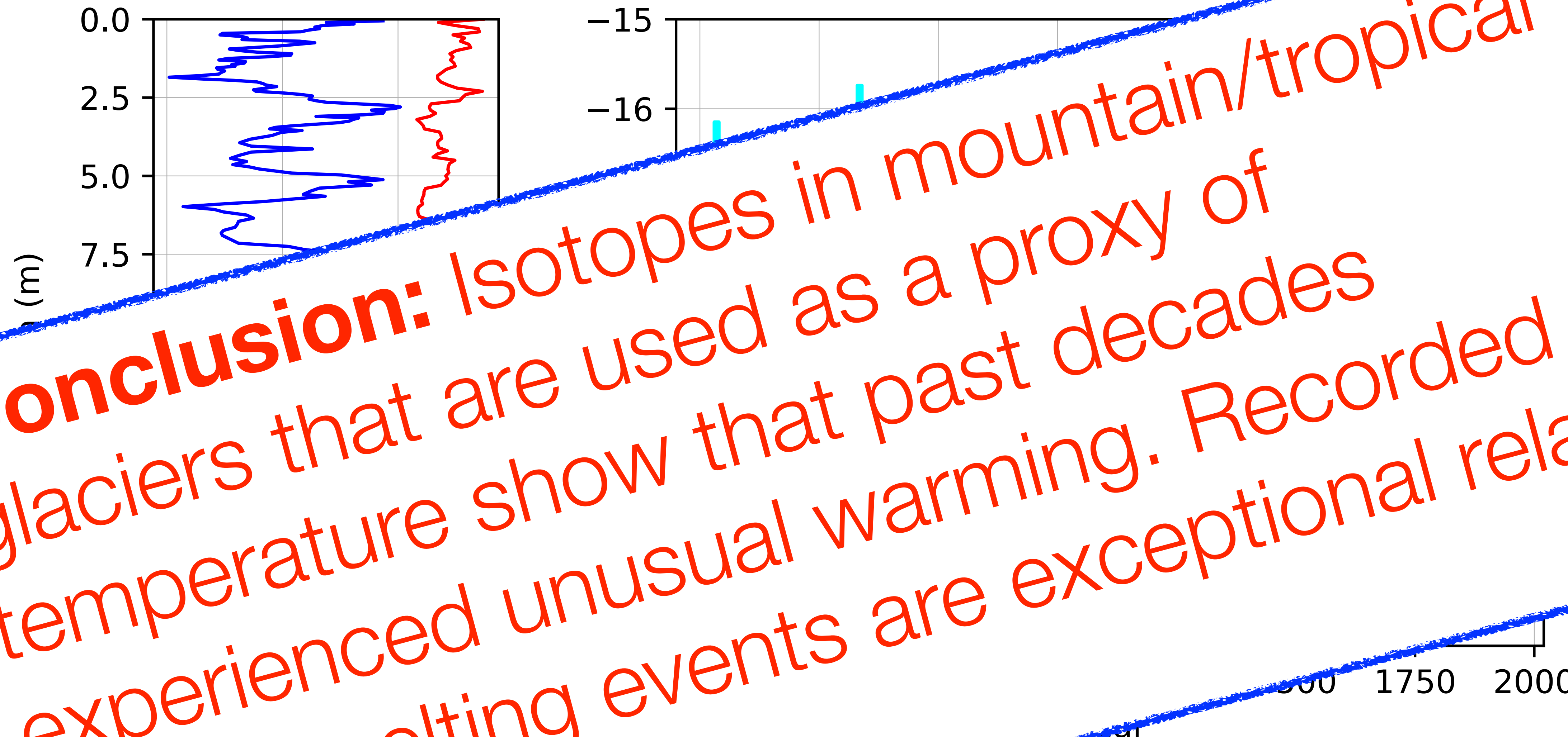


Figure 11.6: Isotopic records from the Quelccaya Ice Cap in the Andes, Peru (latitude 13S). (a) Two high-resolution shallow ice cores showing the presence of a seasonal cycle in 1976 (blue) and its elimination by surface melting and percolation of melt water by the time the 2016 core was drilled (red). (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.

[Data from Thompson et al., 2013; Thompson et al., 2017]

Glacier ice cores: isotopic records



Conclusion: Isotopes in mountain/tropical glaciers that are used as a proxy of temperature show that past decades experienced unusual warming. Recorded recent melting events are exceptional relative to previous decades.

[illegible] Quelccaya Ice Cap in the Andes, Peru [illegible] resolution shallow ice cores showing the presence of [illegible] in 1976 (blue) and its elimination by surface melting and [illegible] 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.

[Data from Thompson et al., 2013; Thompson et al., 2017]

Are glaciers retreating due to end of little ice age?

Fourth line of evidence:

Mountain glacier flow and adjustment time to temperature/SMB changes

Glacier flow

AK-05 Mendhenhall Glacier 2007-2017

https://vimeo.com/168243535

[Extreme Ice Survey]()

Glacier flow

GL-05 Ilulissat Glacier June 2007 - August 2017

https://vimeo.com/168243534

[Extreme Ice Survey]

Notes section 11.4

Glacier dynamics

Workshop 3:

Idealized glacier-length adjustment scenarios

Idealized glacier-length adjustment scenarios

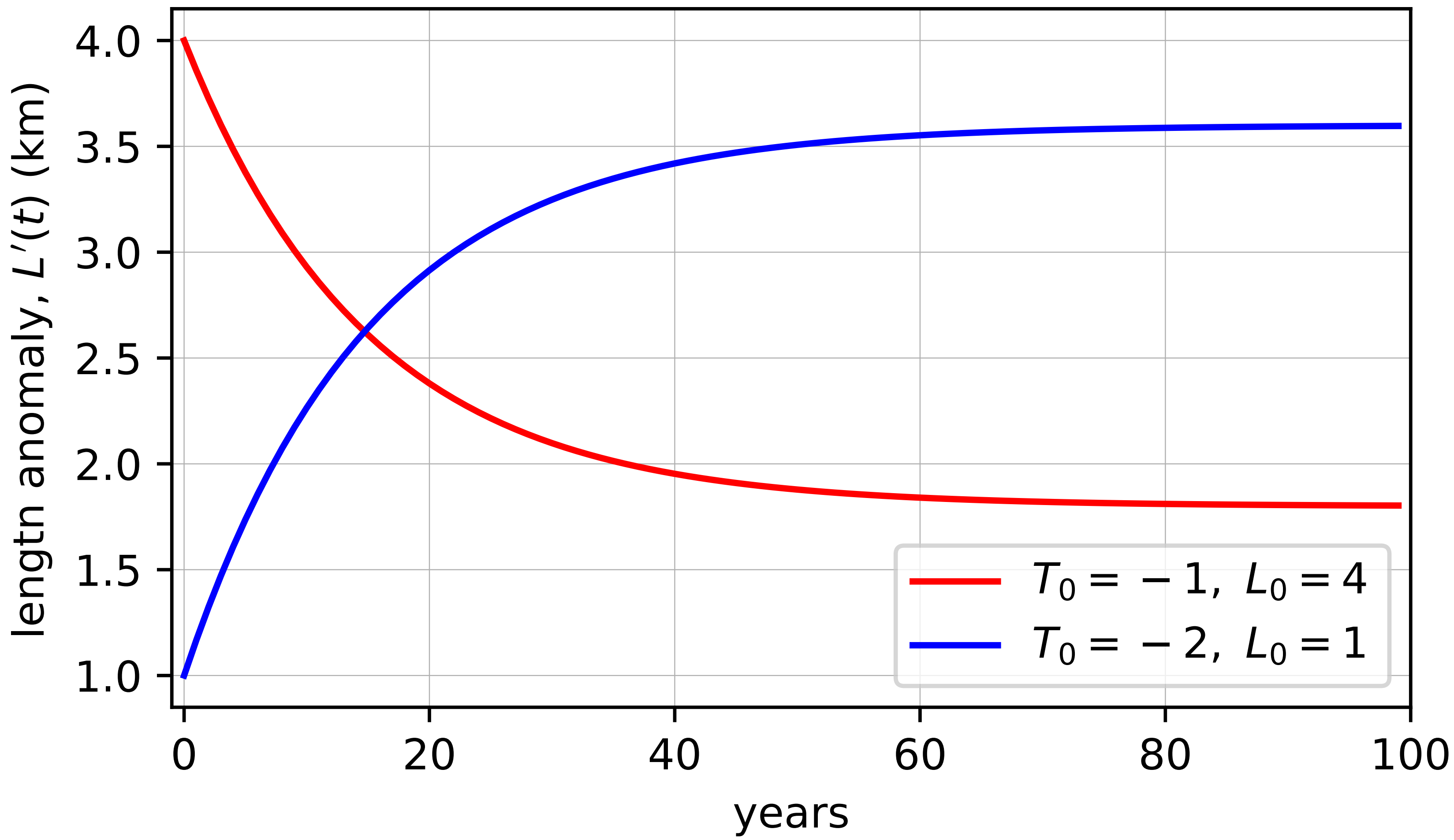


Figure 11.4: Two idealized adjustment scenarios of glacier length based on solution (11.2), assuming τ = 15 years, and based on the initial lengths and perturbation temperatures indicated.

Glacier flow: steady response to two SMBs

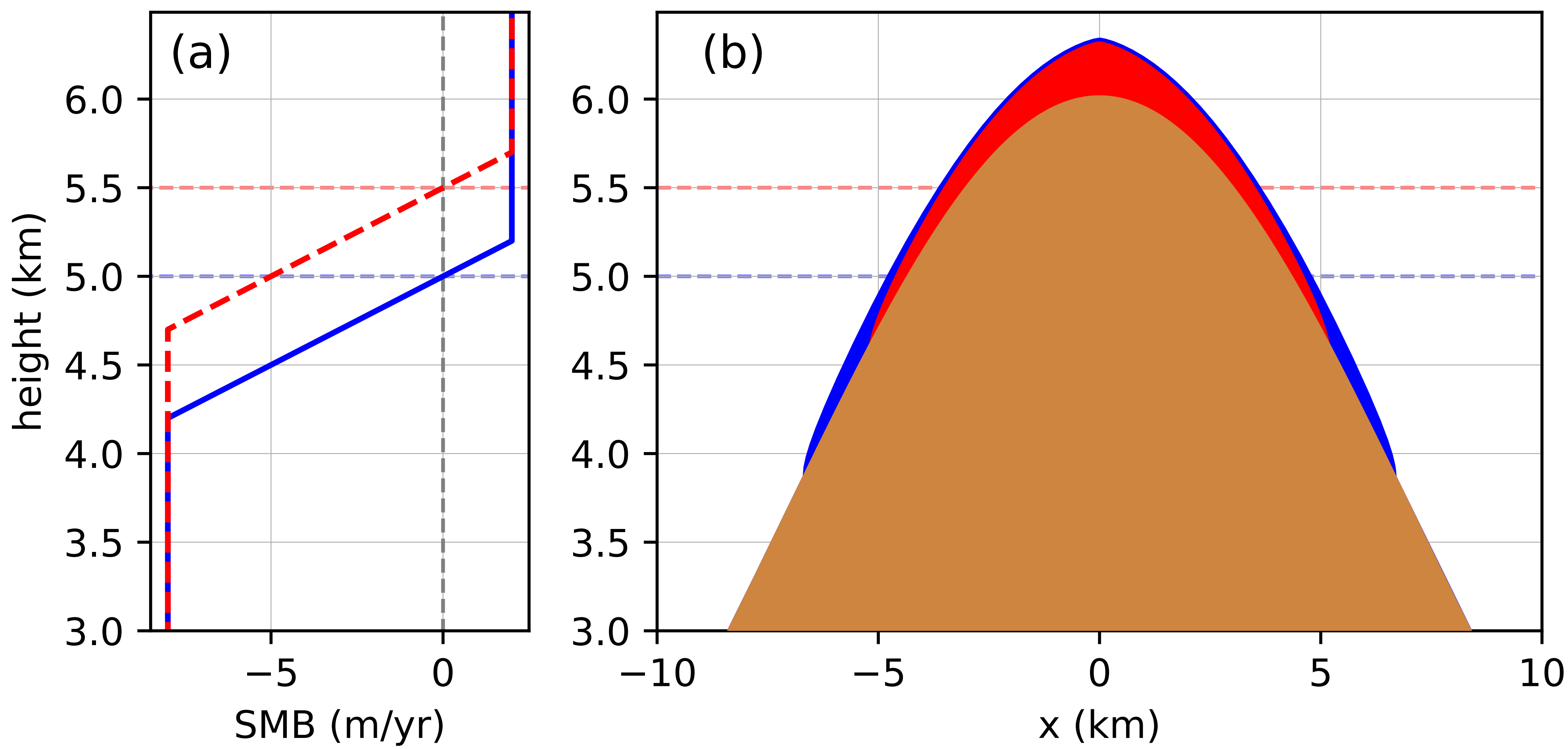


Figure 11.7: (a) Surface mass balance for two scenarios (solid blue vs dash red), showing also the corresponding Equilibrium Line Altitudes (horizontal dash lines). (b) The steady solution of the Shallow Ice Approximation for glacier height for the two scenarios.

(Calculated using an ice flow code by Bueler, 2021)

Glacier flow: time dependent adjustment to 2 SMBs

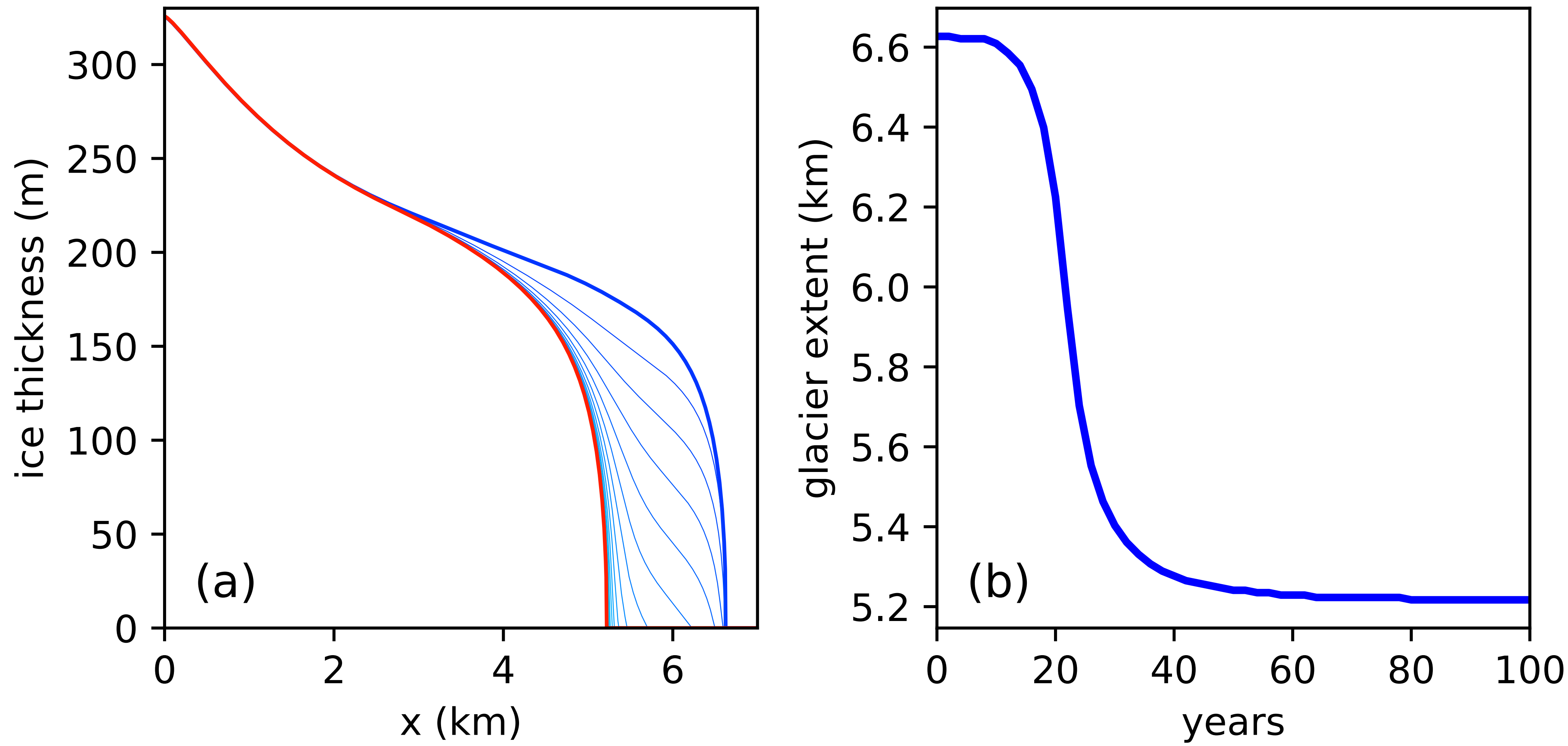


Figure 11.8: The time-dependent transition between the blue and red solutions in Fig. 11.7b. (a) Glacier thickness as function of horizontal thickness for different times after the ELA changed from the blue to the red lines in Fig. 11.7a. Progressing times are denoted by changing color of the thin lines from blue to green to red. (b) Glacier length as function of time during the transition.

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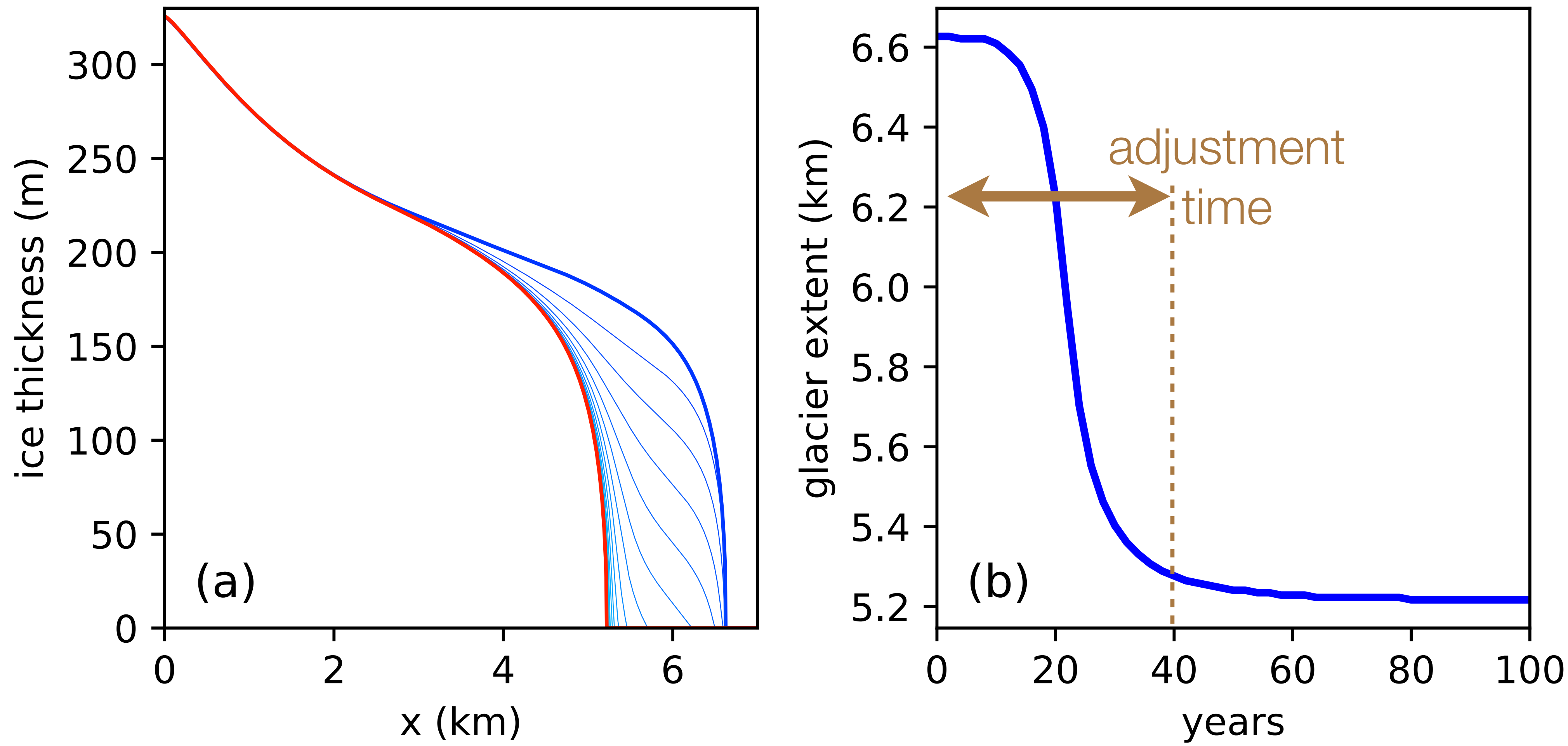

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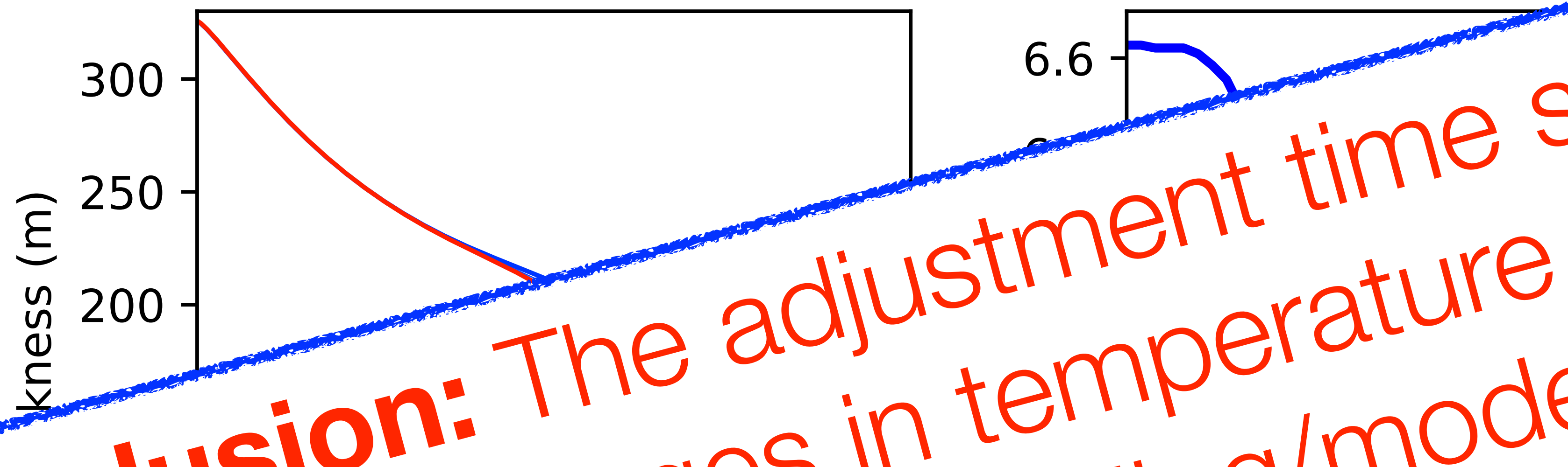

Conclusion: The adjustment time scale of glaciers to changes in temperature (deduced here from the understanding/modeling of glacier ice flow) is too short to be consistent with a retreat in the 2000s in response to the warming that ended around 1850.

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Mountain glaciers: summary

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  - Surface melting seen in tropical ice cores in the 21st century have not occurred in the previous many 100s–1000s yrs

The End