ESS 203 - Glaciers and Global Change

Wednesday February 24, 2021.

Outline for today

- Today's highlights on Friday – *Alex Kissel*
- Highlights of last Monday – *Justice Correa-West*

Oerlemans paper

– 20^{th}C global warming inferred from glacier retreat

- Scalings
- Thermometers
- Update into C21

Canvas ➔ Files ➔ Lecture Slides ➔ ESS203_day_21.pdf

Mid-term #2, Wednesday March 3

Study questions are posted;
3 of these will form the actual test.

- Read the notes on the TESTS page “Writing a test”.
- Meet with classmates, and talk with your classmates to compare and develop your ideas and trial answers.

Assignment for Friday February 26:

Please read the *Nature Geoscience* article by Gerard Roe et al., "Centennial glacier retreat as categorical evidence of regional climate change".

It is posted on the class web site (READINGS tab),

https://courses.washington.edu/ess203/RESOURCES/READING/reading_index.shtml

and under the Files tab on Canvas:

https://canvas.uw.edu/courses/1434502/files/folder/HomeWork?preview=74049110

Don't knock yourself out with details. Just read deeply enough to answer our standard 3 questions in a paragraph or two.

1) What Question are Roe et al. asking?
1) What is their answer to The Question?
3) What points in the paper are still unclear to you? (Definitely look at Figure 4.)

Please have the paper available during class on Friday.

Highway Traffic

Q is flux of cars on the road (Cars per minute passing a counter).

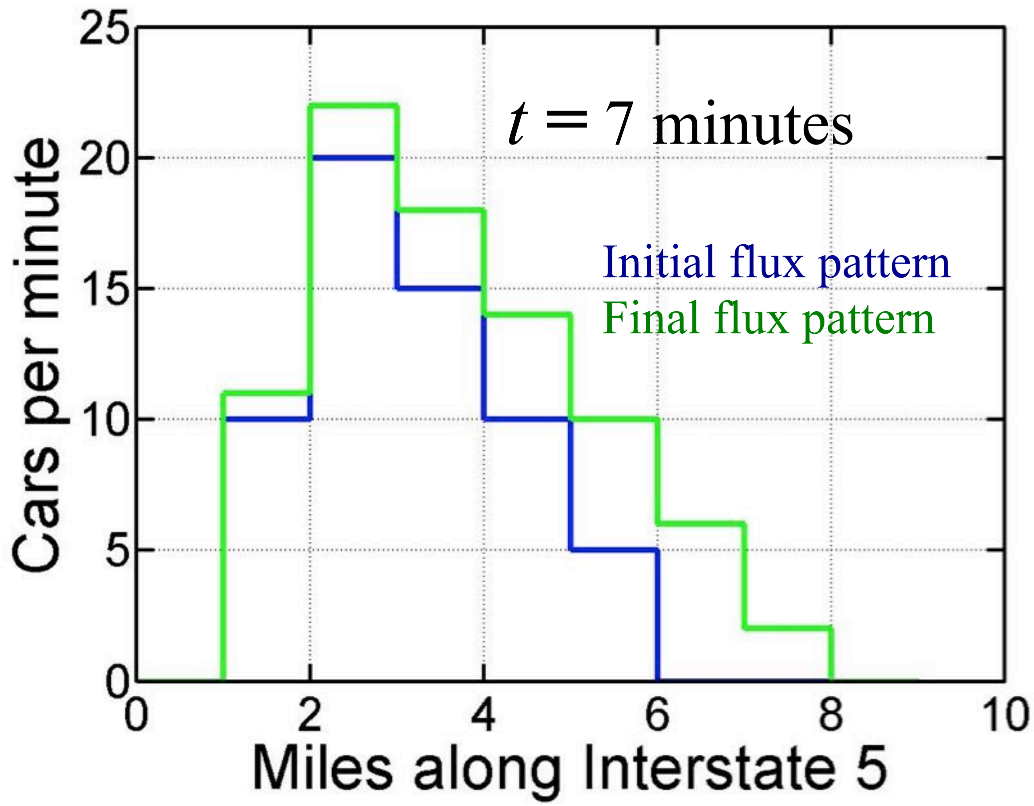
Let's see how that flux changes with time at each point along I-5.

Let's find how many minutes it takes for I-5 to adjust to heavier traffic, as Husky fans (and even a few Couger fans) begin to park in Montlake for the Apple Cup.

Time to Fill up I-5

- b_{term} = number of cars that left I-5 at last off-ramp (-5 cars/minute) .

- H = cars per mile initially on the highway at "Equilibrium Line" (20 cars).



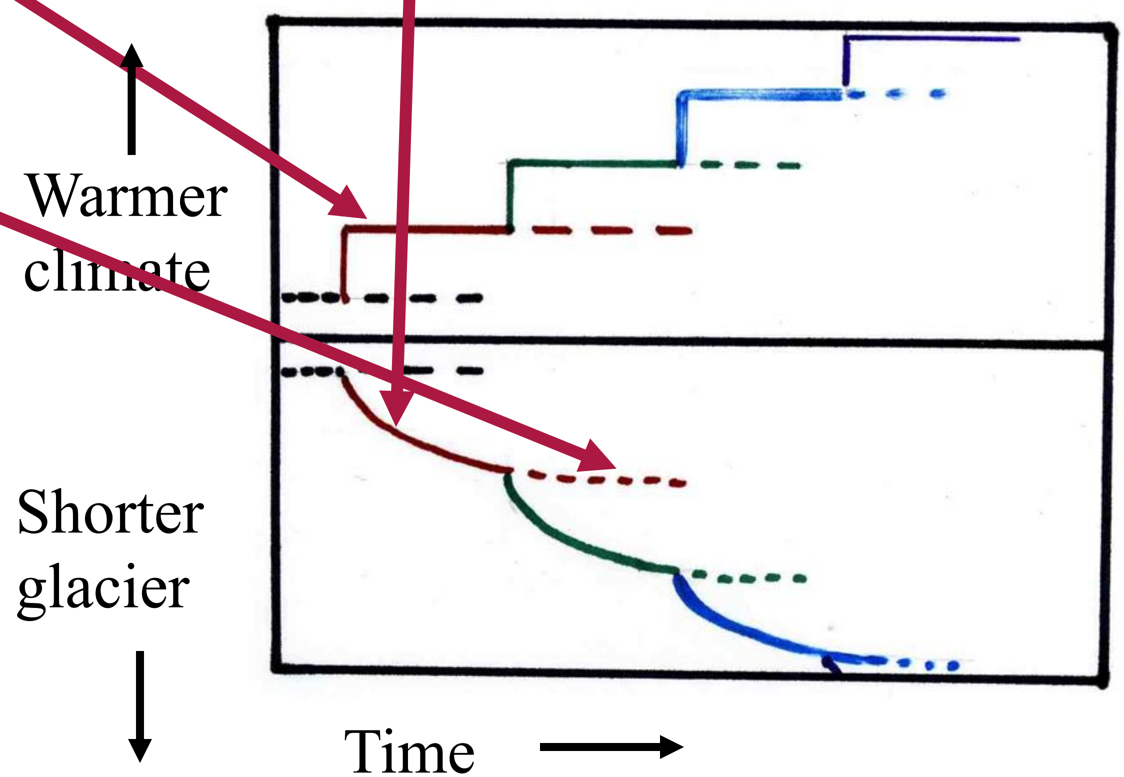
Initial flux pattern
Final flux pattern

- We can figure out long it takes for cars to start reaching Husky Stadium.

$$\text{Time} = \frac{H}{-b_{\text{term}}} = \frac{20\,\text{cars}}{5\,\text{cars}/\text{minute}} = 4\,\text{minutes}$$

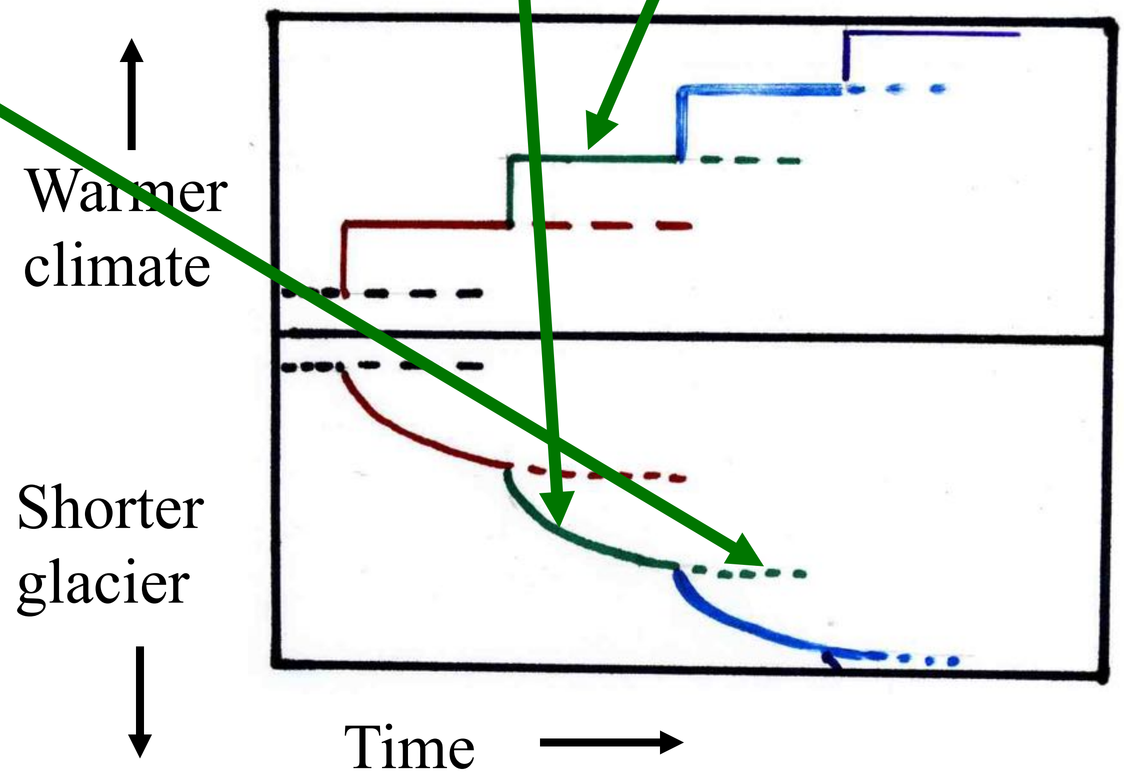
Superposition of Climate Changes

- The climate changes abruptly to a warmer and drier state.
  - glacier retreats, rapidly at first.
- Then slower and slower as it approaches its new reduced steady size.



Just as retreat slows down, climate changes again.

- Climate becomes even warmer and drier.
- This speeds up the retreat again.
- The retreat slows down, as the terminus approaches the new steady position for this latest climate.

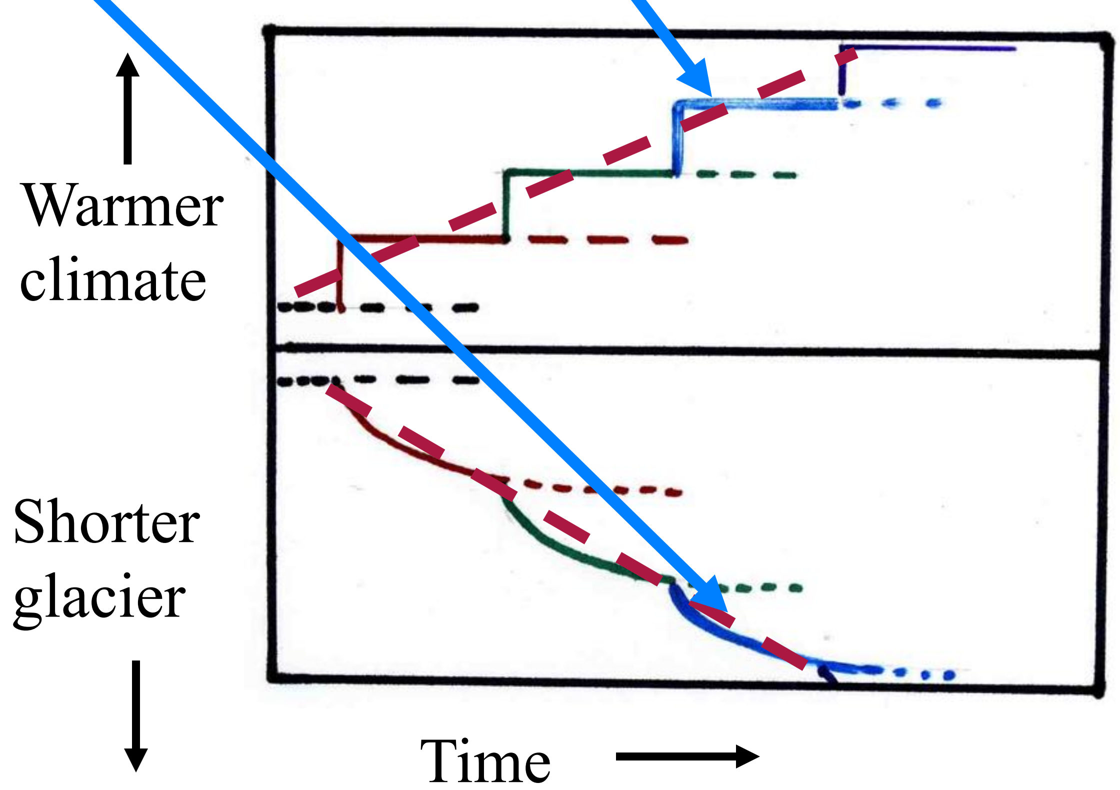


Climate Change Continues

- Yet again, the climate warms.
- The terminus retreats faster again.

What just happened?

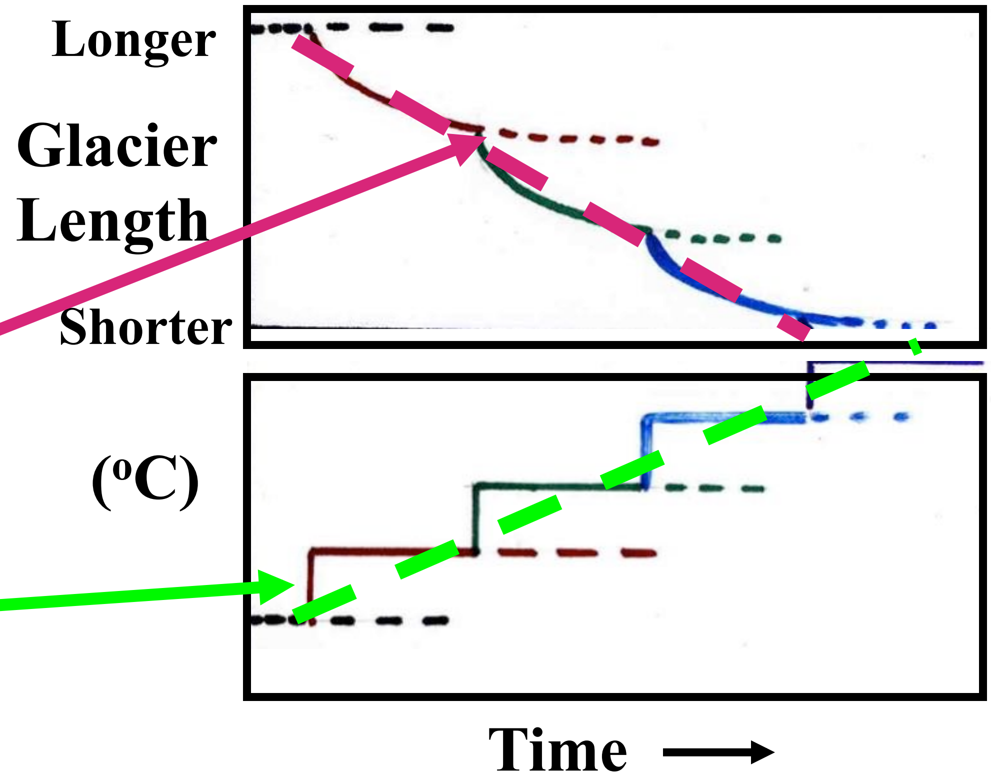
- We just used our knowledge of glacier response to a climate jump in order to estimate response to a continuous gradual change!



Superposition of Climate Changes

A constantly retreating glacier terminus may be a sign of a constantly warming climate.

(Anon.)



Curious Scientists predict glacier changes

For glaciers, small to gigantic ···

Glacier	Length L	Terminus Width W	Thickness at ELA H	Terminus climate b_{term}	Climate change db
#1	2 km	0.2 km	100 m	-4 m/yr	0.02 m/yr
#2	100 km	1 km	1000 m	-1 m/yr	0.02 m/yr
#3	1000 km	20 km	3000 m	-0.5 m/yr	0.02 m/yr

They all see the same climate change.

Let's estimate

- how far each glacier will advance
- the time scale for that advance to happen.

Curious Scientists predict glacier changes

Length change $$dL = \frac{A \times db}{-W_{term} \times b_{term}}$$

Response time $$\tau = \frac{H}{-b_{term}}$$

Glacier	Length L (km)	Width W (km)	Area $A=L\times W$ (km^2)	Terminus Width W_{term}(km)	Thickness at ELA H (km)	Terminus climate b_{term}(m/yr)	Climate change db (m/yr)	Advance dL (km)	Time Scale τ (ka)
#1	2.0	0.2	0.4	0.2	0.1	-4	**0.02**	0.01	**0.025**
#2	100	1	100	1	1.0	-1	0.02	2.0	1.0
#3	1,000	20	20,000	20	3.0	**-0.5**	0.02	**40**	**6.0**
#1b	2.0	0.2	0.4	0.2	0.1	-4	**0.04**	**0.02**	**0.025**
#3b	1,000	20	20,000	20	3.0	**-0.25**	0.02	**80**	**12.0**

Glaciers and Global Warming

Oerlemans, J. 1994. Quantifying global warming from the retreat of glaciers. *Science* 264, 243-245.

Topics today

- How can glaciers measure global-temperature change?
- How do glaciers stack up against a bunch of thermometers?
- What else do we know about 20th C warming?

Plenary Questions (and your homework)

- What is the question that Oerlemans is asking?
- What is his answer to the question?
- What points (if any) are still unclear to you?

Group Questions for Curious Scientists

Q-1

- What is the general trend of glacier terminus positions worldwide in the past century?
- What is it about the glacier terminus-position observations that makes them an appealing data set for this climate-change question?

Q-2

- Why is Oerlemans concerned about the time scales for the glaciers to adjust to instantaneous climate shifts that we analyzed?

Q-3

- How does the climate change that Oerlemans is looking for differ from the instantaneous shift from one steady-state climate to another that we analyzed earlier in class?
- How would you use concepts from our previous analysis to estimate what a glacier would do if the climate just kept warming up continually?

https://docs.google.com/document/d/1sZESjlg1q7a55qlZzf1_2k7rxULMiRgQJpR7lfwZU1o/edit

Some more Questions about the paper…

- Oerlemans uses 2 scalings to convert actual retreat rate to the retreat rate that a "standard glacier" would have experienced at every location. Why does he do that?
- What ***is*** this scaling based on glacier slope?
- What ***is*** this scaling based on total precipitation?
- What is "Climate Sensitivity"?
- Why not just read a whole bunch of thermometers?

We will try to answer these questions by examining the paper today.

Why Scaling?

Oerlemans wants to compare "apples to apples".

If 2 glaciers retreat at different rates for the same amount of warming, how can you infer a unique rate of warming?

- You can't, without knowing more about how glaciers work.

Oerlemans solves this problem by using what he knows about glaciers to figure out how fast a "standard glacier" would be retreating if it was in the valley next to each of these real (and widely diverse) glaciers.

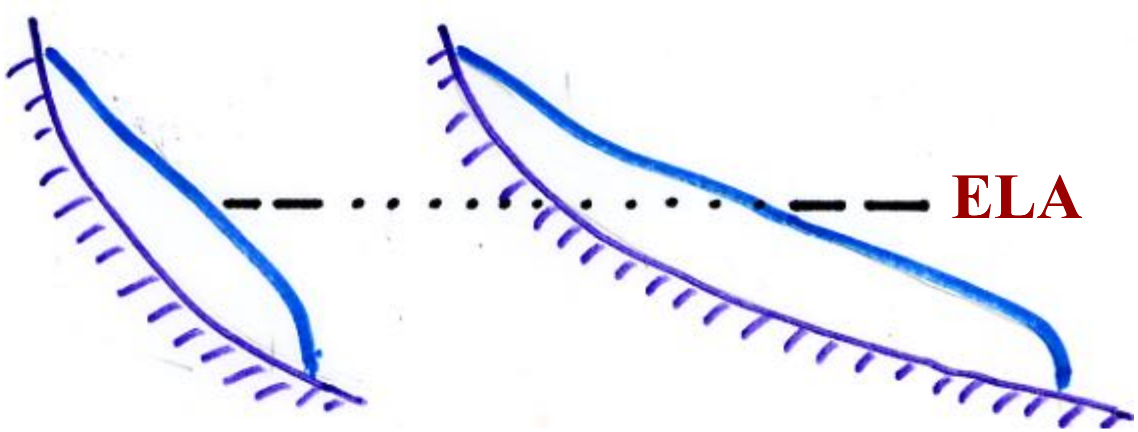
- All "standard glaciers" have the same slope, length, precipitation rate, and climate sensitivity.

Scaling based on glacier slope

ELA is roughly tied to a level in the atmosphere where the temperature is cold enough to preserve snow through the summer.

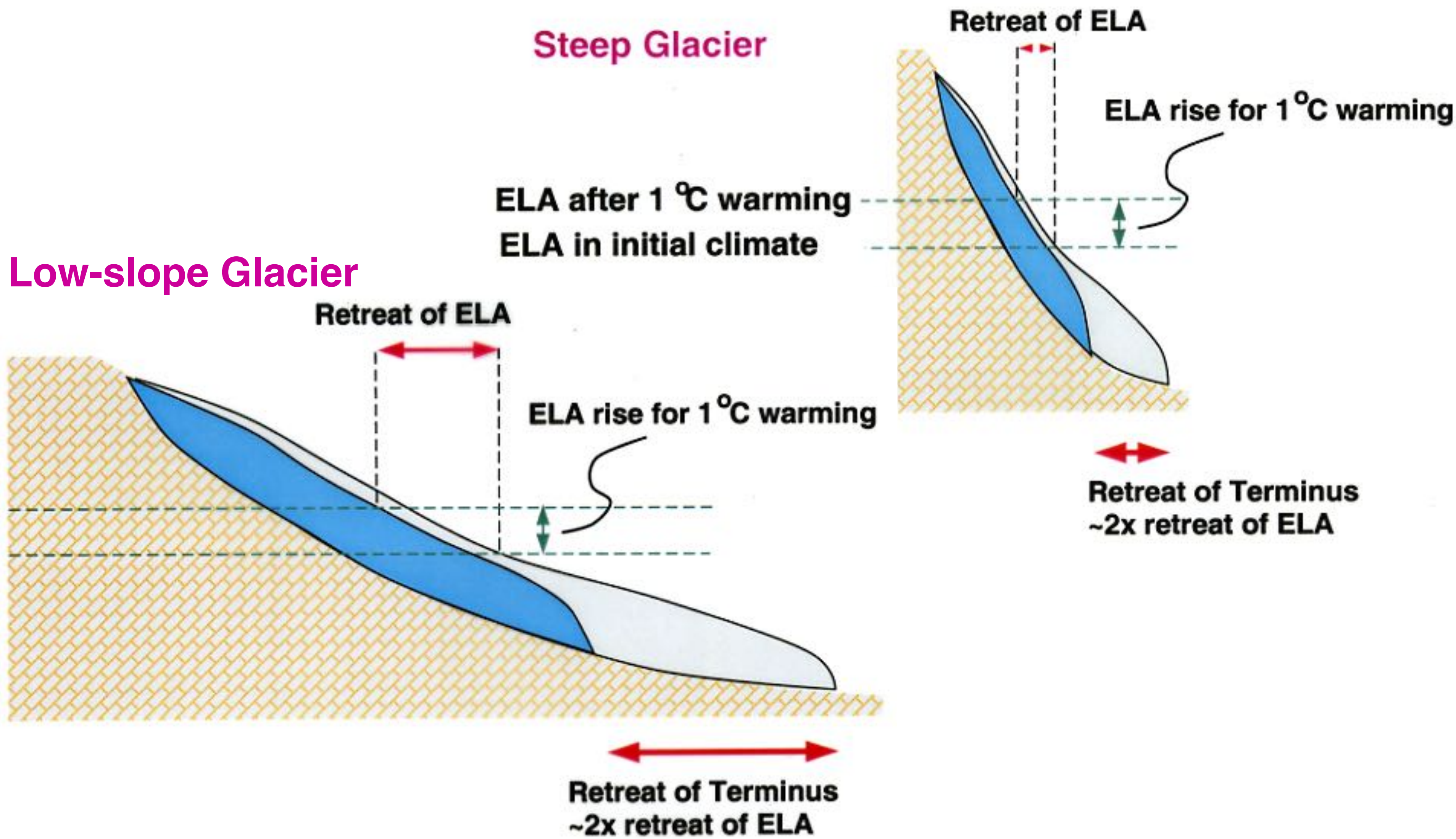
- Can you estimate how far the ELA rises for a 1°C warming? (What do you know about lapse rates?)

- Now think of a glacier with a gentle slope, and right beside it a glacier with a very steep slope. The 2 glaciers have the same ELA.



- Which one might retreat farther if ELA rises?

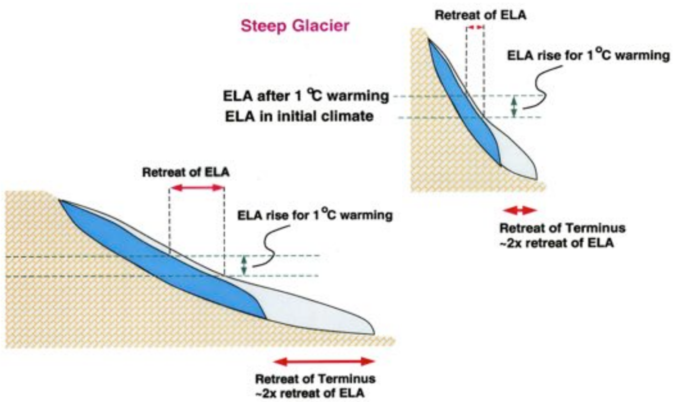
Scaling based on glacier slope



Scaling based on glacier slope

The ELA has risen by the same amount for both glaciers.

- On which glacier does this climate change remove more square meters from the accumulation area?
- On which glacier does the climate change add more ablation area?
- Which glacier retreats faster as the climate warms?



$$\boxed{t^* = \frac{t \times s}{\bar{s}}}$$

s = slope of real glacier.

s = average slope of all his glaciers, or slope of his "standard glacier".

t = retreat rate (m/year) observed on real glacier.

*t** = retreat rate that a "standard" glacier would have experienced.

Retreat time *t** of Standard companion to a steep glacier (with retreat rate *t*, slope *s*) is faster than glacier with a steep slope *s* (because it must retreat farther.

Curious Scientists –
Scaling based on total precipitation (rain + snow)

1. If climate gets warmer, some precipitation that used to fall as snow, will now fall as rain.

- What change will this have on the net amount of snow remaining in the accumulation area at the end of summer?
- What change will this have on the net amount of ice melted in the ablation area by the end of summer?

This change in glacier mass balance each year plays a role like "**d*b***" that we used to assess glacier responses to one-time sudden changes in climate.

Curious Scientists – Scaling based on total precipitation (rain + snow)

2. Think of 2 different glaciers that have the same size and shape:
One has a small accumulation rate and small ablation rate (e.g. a glacier in the Canadian Arctic).
One has a high rate of snow accumulation and a high rate of melting (e.g. Blue Glacier).

- Which glacier is more likely to be having precipitation on any given day in winter when it might be unexpectedly mild due to global warming?
- Which glacier is more likely to be having heavy precipitation?
- So, which of these two is likely to suffer the greater loss of winter snowfall in an absolute sense (and glacier mass) by conversion of snow to rain, if the temperature is getting warmer?
- Which glacier is probably going to retreat faster as the climate warms?

Climate Sensitivity

C = change in mass balance (e.g. db) of real glacier, in response to a 1°C warming (dT), i.e. db/dT

$\overline{C}$ = average climate sensitivity of all glaciers in the study, or sensitivity of the "standard glacier".

t^* = retreat rate of a glacier with slope of standard glacier at site in question, but non-standard climate sensitivity.

t^{**} = retreat rate of standard glacier at site in question.

$$\boxed{t^{**} = \frac{t^* \times \overline{C}}{C}}$$

Standard glacier (with sensitivity $\overline{C}$) retreats slower than glacier with higher-than-average sensitivity C.

Climate Sensitivity

Recall that retreat rate for glacier with "standard" slope $\bar{s}$, but nonstandard sensitivity C, was

$$t^* = \frac{t \times s}{\bar{s}}$$

So …

$$t^{**} = \frac{t^* \times \bar{C}}{C} = \frac{t \times s \times \bar{C}}{\bar{s} \times C}$$

- Glaciers that retreat fast because they have low slopes (s) or large sensitivities (C) have a "standard" companion that is slowed down by the scaling.
- Amount of slow-down is calculated from known glacier physics.
- Oerlemans can then compare all those imaginary standard companions.

Climate Sensitivity

Glaciers that retreat fast because they have low slopes (*s*) or large sensitivities (*C)* have a "standard" companion that is slowed down by the scaling.

- And *vice versa*
- Oerlemans then compared all those ***imaginary standard companions***.

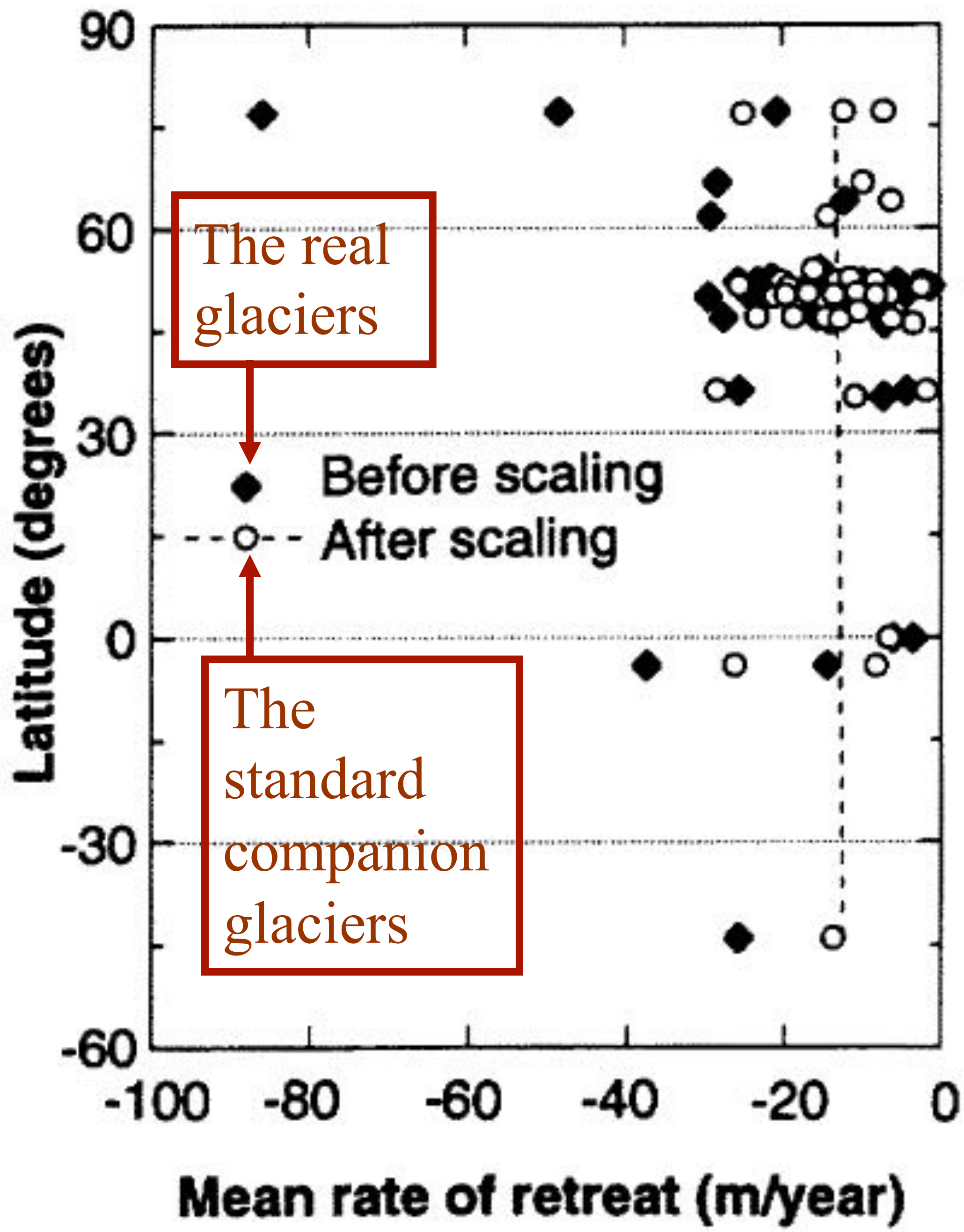
He is not arbitrarily "cherry-picking" or "massaging" the data to make it show what he wants.

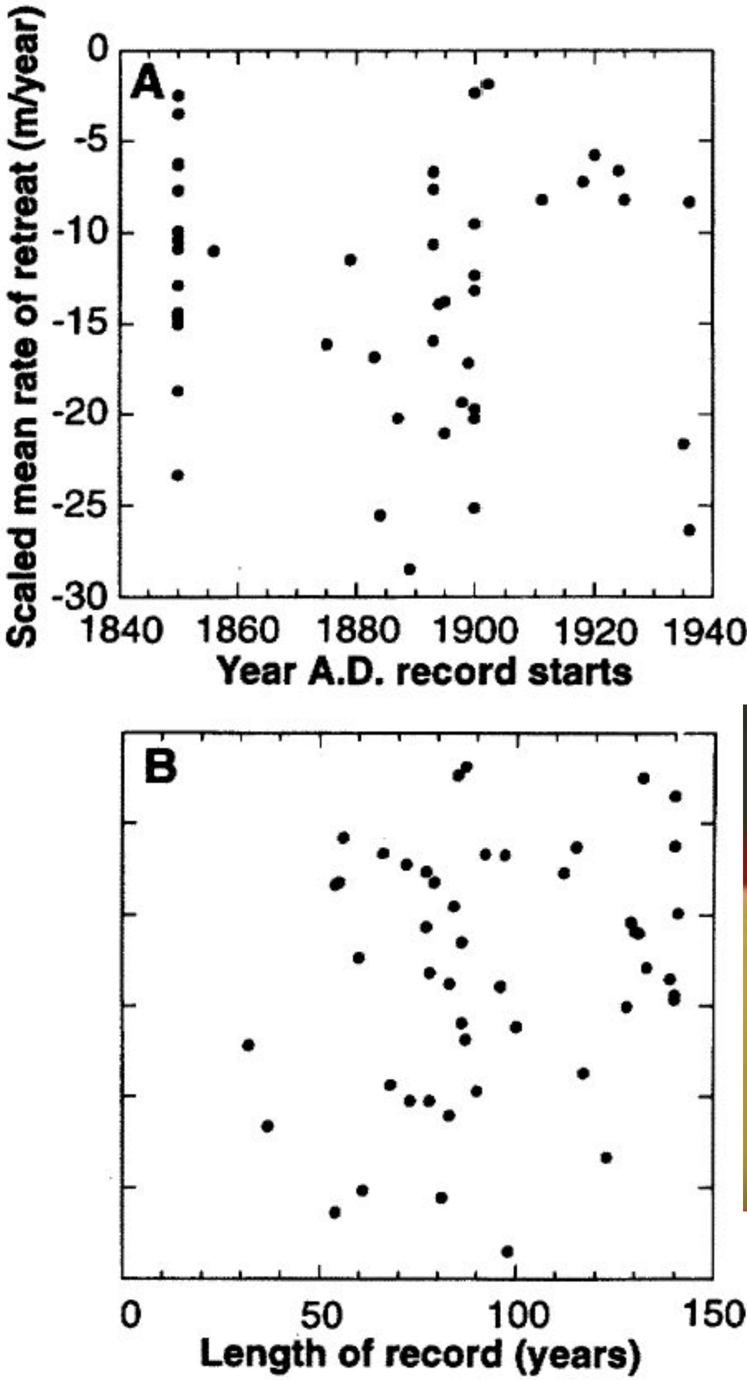
- The scalings are based on known physical concepts about how glaciers work.
- They could have worsened the agreement on retreat rates, but they didn't. The scalings improved it.

Retreat Rates after Scaling (*t***)

After accounting for differences in how glaciers with different slopes and differences in precipitation should respond, Oerlemans finds that glaciers around the world are all telling a similar story.

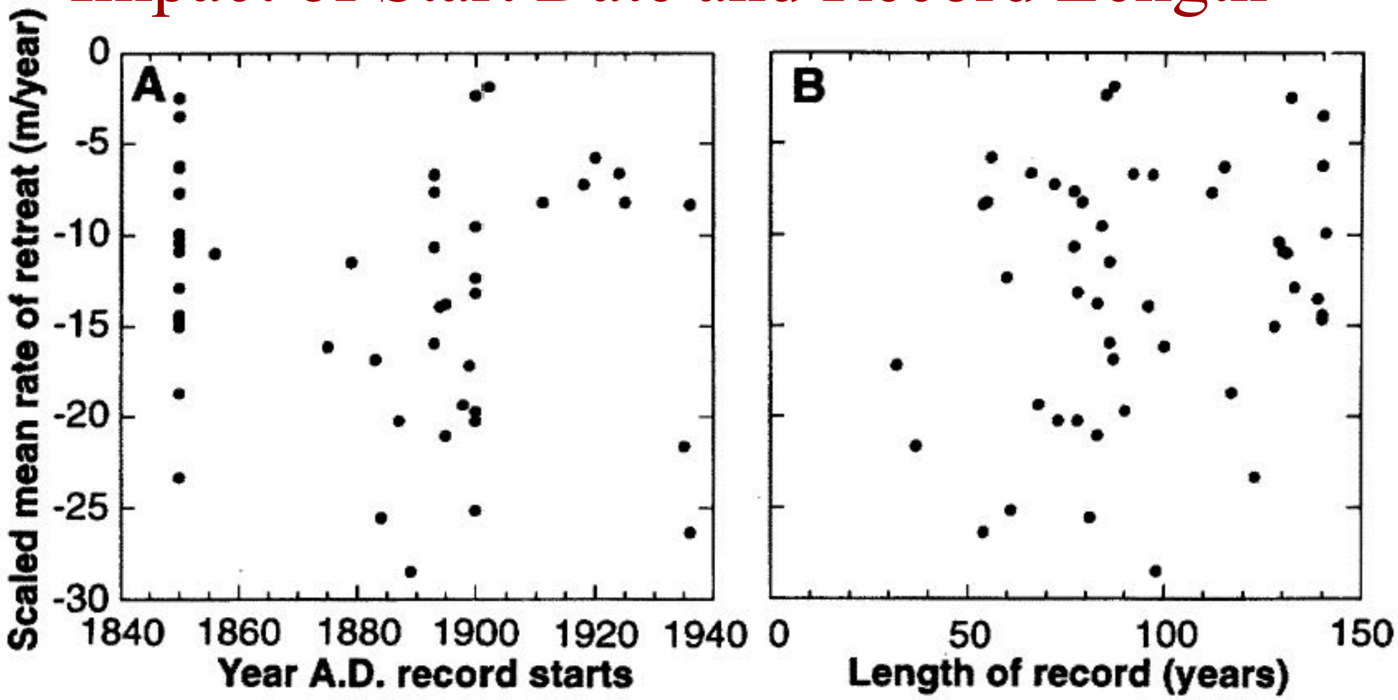
- A "standard glacier" in every area would be suffering a similar retreat rate.




A
B
Scaled mean rate of retreat (m/year)
0
-5
-10
-15
-20
-25
-30
1840 1860 1880 1900 1920 1940
Year A.D. record starts
0 50 100 150
Length of record (years)

What’s up, doc?!

Impact of Start Date and Record Length



Why are these graphs included in the paper?

- Do you see any obvious patterns?
- Is that good or bad?

That's **good**!

The scaled retreat rates are **not** an artifact of when data were collected.

Glaciers as Recorders of Global Warming

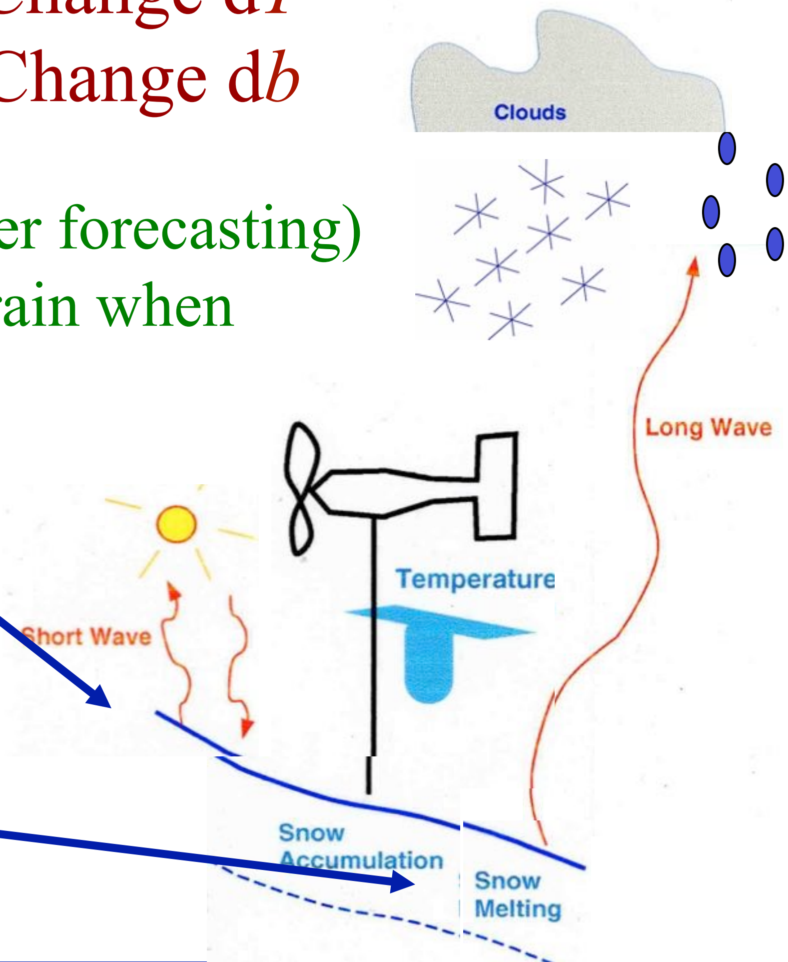
Observed retreat rates varied from 1.3 to 86 m/year.

- By carrying out 2 rescalings, Oerlemans estimated the retreat rates that would be seen if a "***standard glacier***" existed at each site.
- Scaled rates showed much less scatter.
- Average retreat rate of scaled glaciers was 13 m/year.

But Oerlemans still doesn't know how fast the Earth is getting warmer.

- How does he then figure out how much the temperature must have changed in the previous 100 years to cause this rate of glacier retreat?

Relating Temperature Change dT to Mass Balance Change db



Accumulation

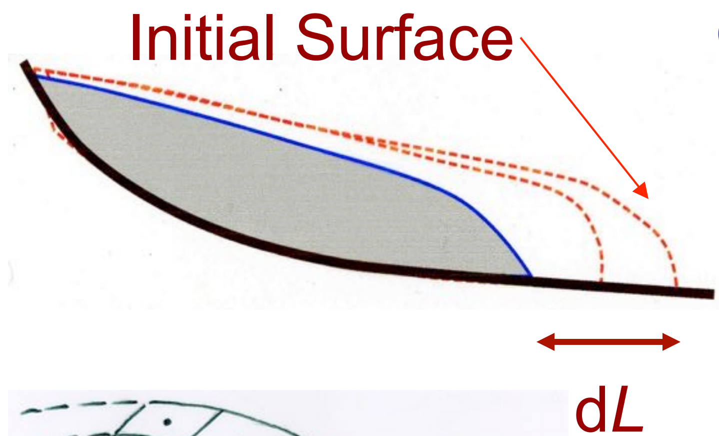
- Regional climate model (like weather forecasting) predicts new amounts of snow and rain when temperature rises by 1°C.

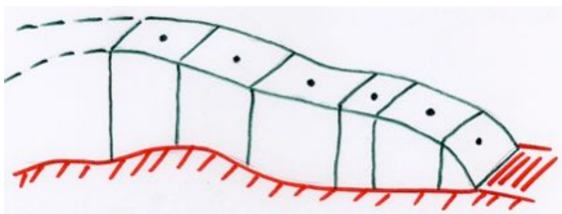
Ablation

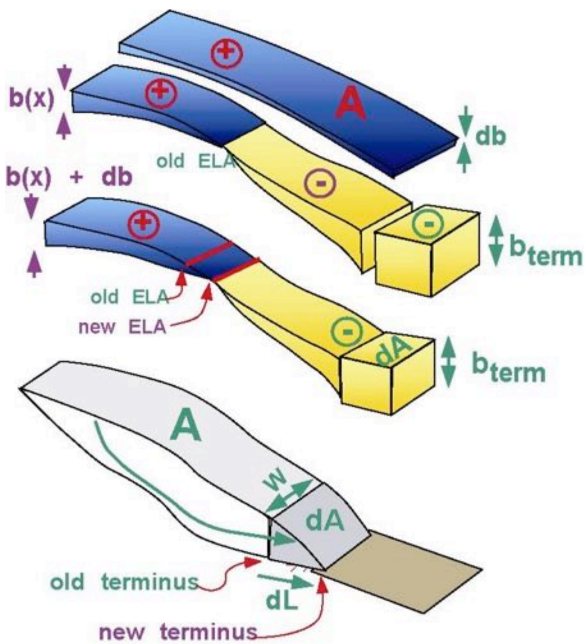
- Local energy-balance model calculates new melting rate when temperature rises by 1°C.

Combining these 2 calculations gives db/dT, estimate of net mass-balance change db in response to temperature change of dT = 1°C

Relating Length Change d*L* to Mass-balance Change d*b*







Glacier Response

- Knowing d*b* for 1°C warming, we must find distance "d*L*" that a ***standard glacier*** retreats in response to climate change d*b*.

We could do that in several ways …

- Use a multi-box computer model driven by climate change d*b*, to watch glacier change through time.
- Use our simple approximation

$$\boxed{dL = -\,A \times db / (W_{term}\ b_{term})}$$

How Far does Standard Glacier retreat for 1^{o}C?

When climate warms by dT=1^{o}C,

- mass balance on standard glacier decreases by db.
- "standard glacier" retreats distance dL.

We want to find dL/dT, i.e. how far standard glacier retreats when climate warms by dT=1^{o}C.

$$\frac{dL}{dT} = \left(\frac{dL}{dT}\right) \times \underbrace{\left(\frac{db}{db}\right)}_{=1} = \left({dL}/{db}\right) \times \left({db}/{dT}\right)$$

We know

- (dL/db) from glacier-response model applied to standard glacier.
- (db/dT) from climate/energy balance model.

The result:

$$\boxed{\frac{dL}{dT} = \left({dL}/{db}\right) \times \left({db}/{dT}\right) = 2\ \mathrm{km}/^{o}\mathrm{C}}$$

How Fast is Earth Warming?

When climate warms by $dT = 1^oC$,

- "Standard glacier" retreats distance $dL = 2$ km.

$$dL/dT = 2 \text{ km}/^oC$$

Oerlemans' data set from World Glacier Monitoring Service (WGMS) shows that

- Standard glaciers around the world are all "observed" to be retreating at the rate

$$dL/dt = 13 \text{ m/year}$$

Now, finally, we are ready to find rate of global warming (dT/dt)

Now we can find rate of global warming, (dT/dt)

$$\frac{dT}{dt} = \left(\frac{dT}{dt}\right) \times \underbrace{\left(\frac{dL}{dL}\right)}_{=1} = \left(\frac{dL}{dt}\right) \times \left(\frac{dT}{dL}\right)$$

$$= \left(\frac{dL}{dt}\right) \times \cancel{\left(\frac{dT}{dL}\right)} \times \left(\frac{\cancel{\left(dL/dT\right)}^{=1}}{\left(dL/dT\right)}\right) = \left(\frac{\left(dL/dt\right)}{\left(dL/dT\right)}\right)$$

dL/dt = 13 m/year (derived from WGMS Data)
dL/dT = 2 km/°C (model result for standard glacier)

$$\boxed{\frac{dT}{dt} = \frac{13\,\text{m}/\text{year}}{2000\,\text{m}/{}^{\circ}\text{C}} \cong \frac{0.0066\ {}^{\circ}\text{C}}{\text{year}} = \frac{0.66\ {}^{\circ}\text{C}}{\text{century}}}$$

Thermometer Networks

Isn't it simpler to just measure global warming with some thermometers?

Hansen and Lebedeff did exactly that in 1987.

- They collected tens or hundreds of thousands of air temperature measurements from weather stations all over the world.
- They then averaged all those measurements year by year to infer a global temperature rise.