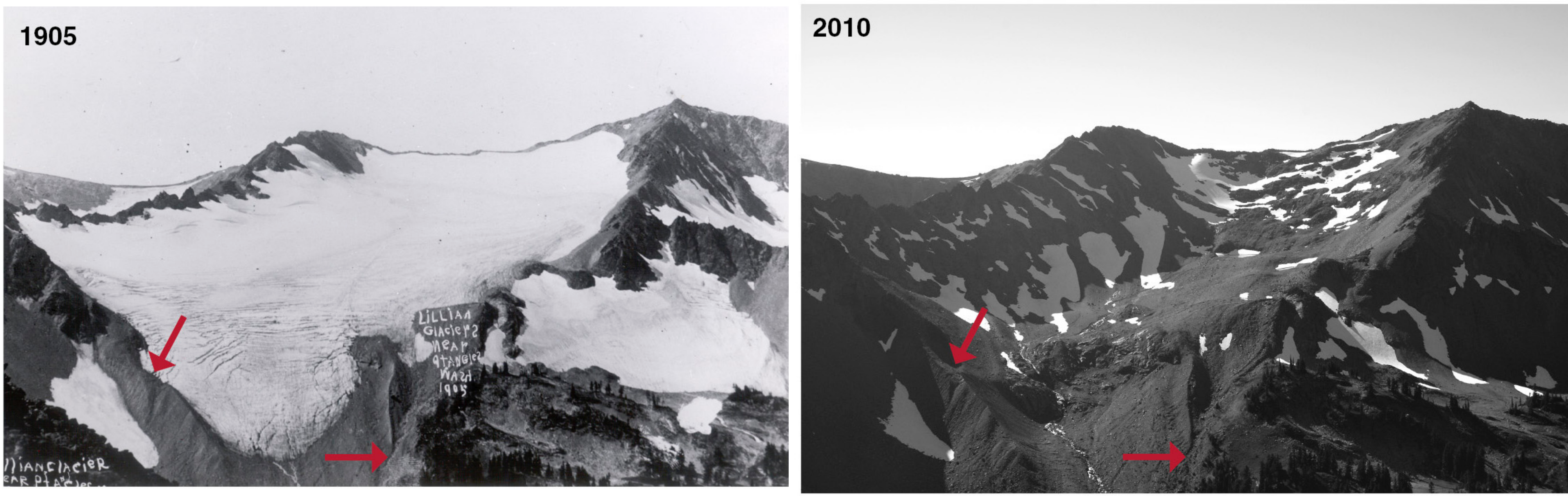
Mountain glacier responses to climate

ESS 431• Oct. 29 2018

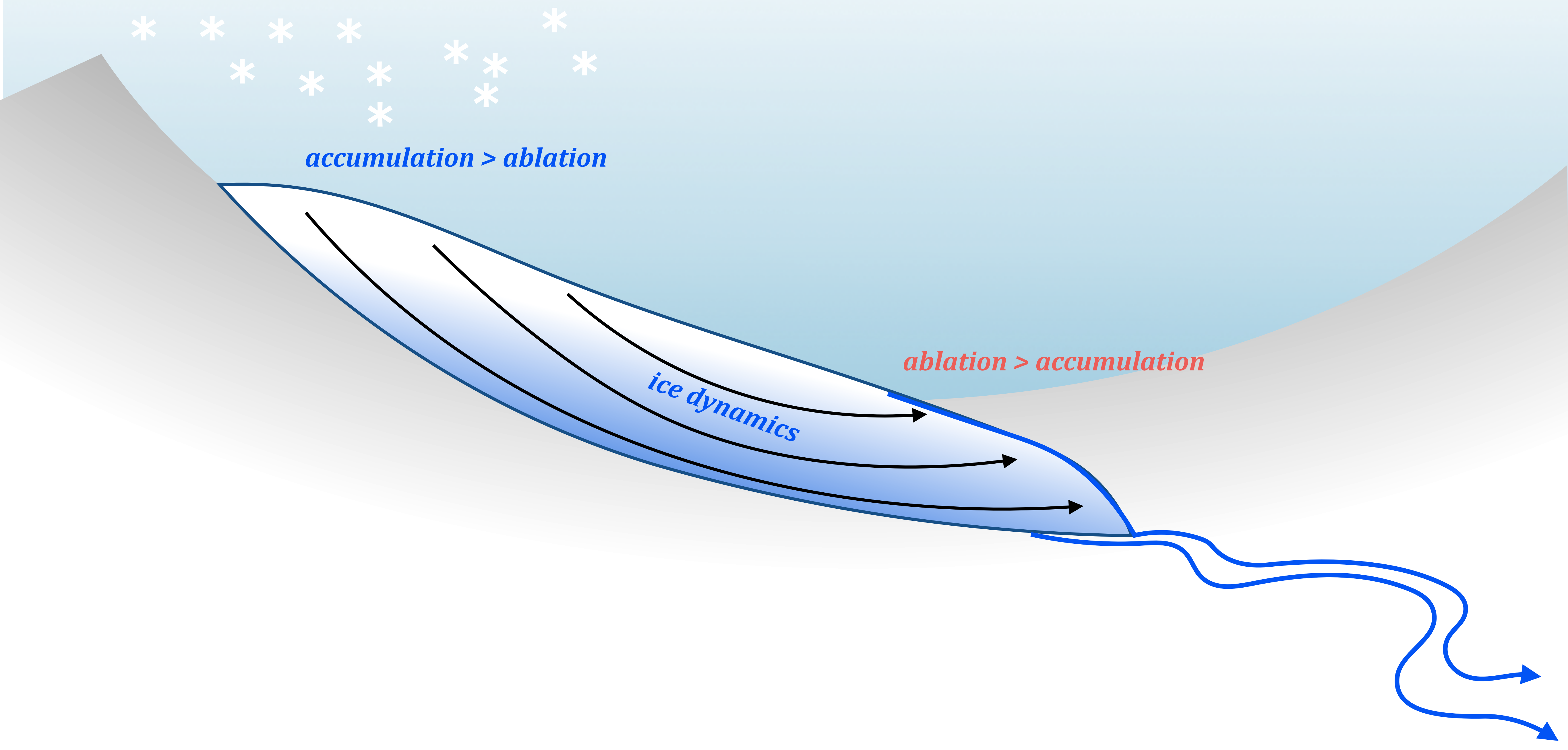
John Christian (*jemc2 at uw.edu*)

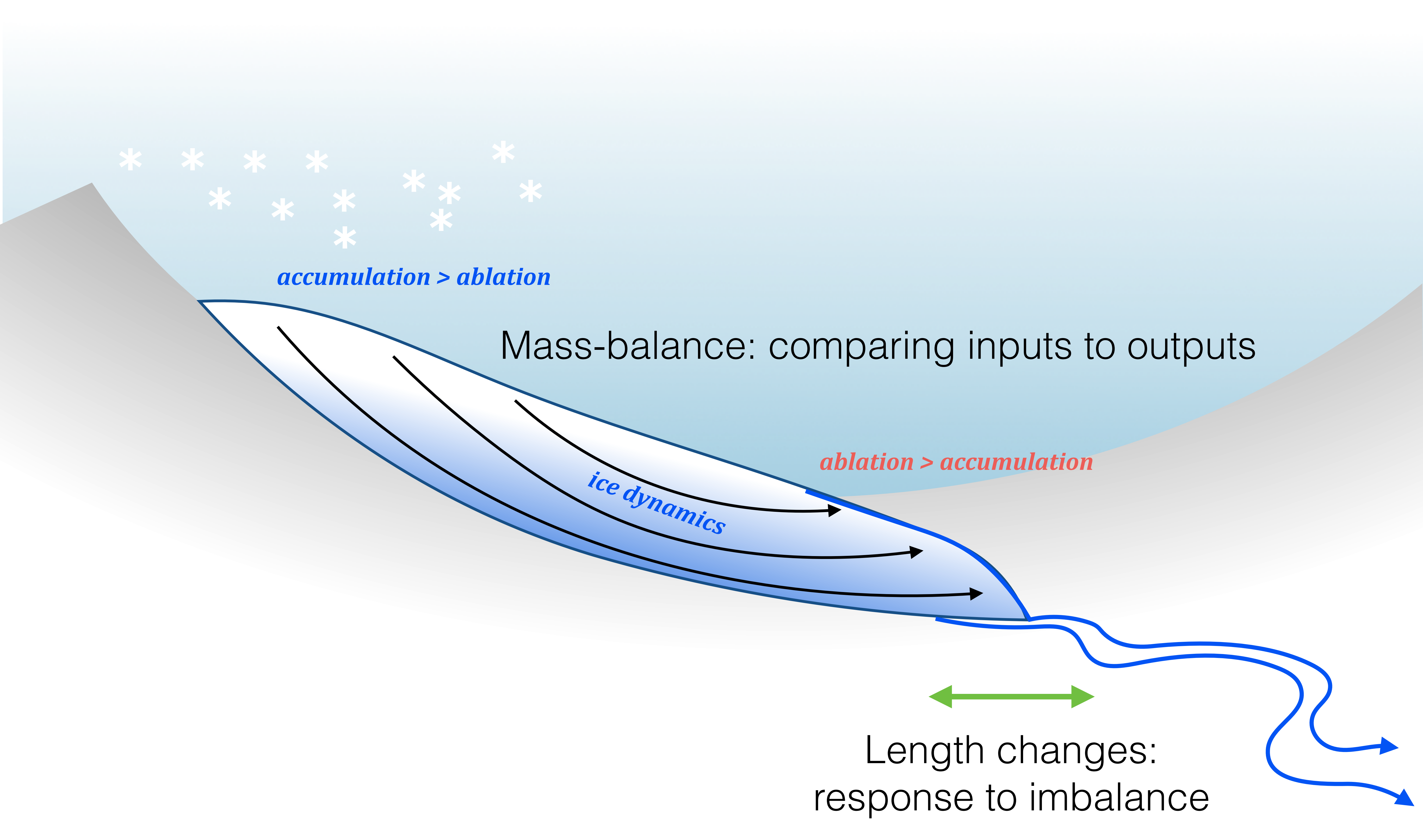


Lillian Glacier, Olympic National Park

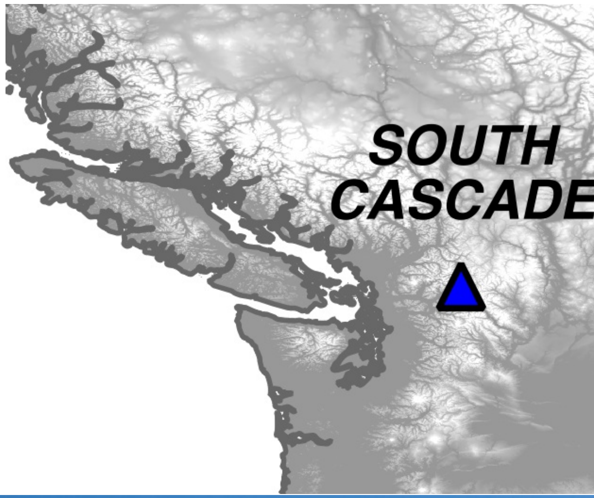
http://www.nps.gov/olym/learn/nature/glaciers.htm

- what happened here?
- how fast?
- how is the story alike/different for other glaciers?
- *what are some simple tools we can apply to these questions?*


accumulation > ablation
ice dynamics
ablation > accumulation

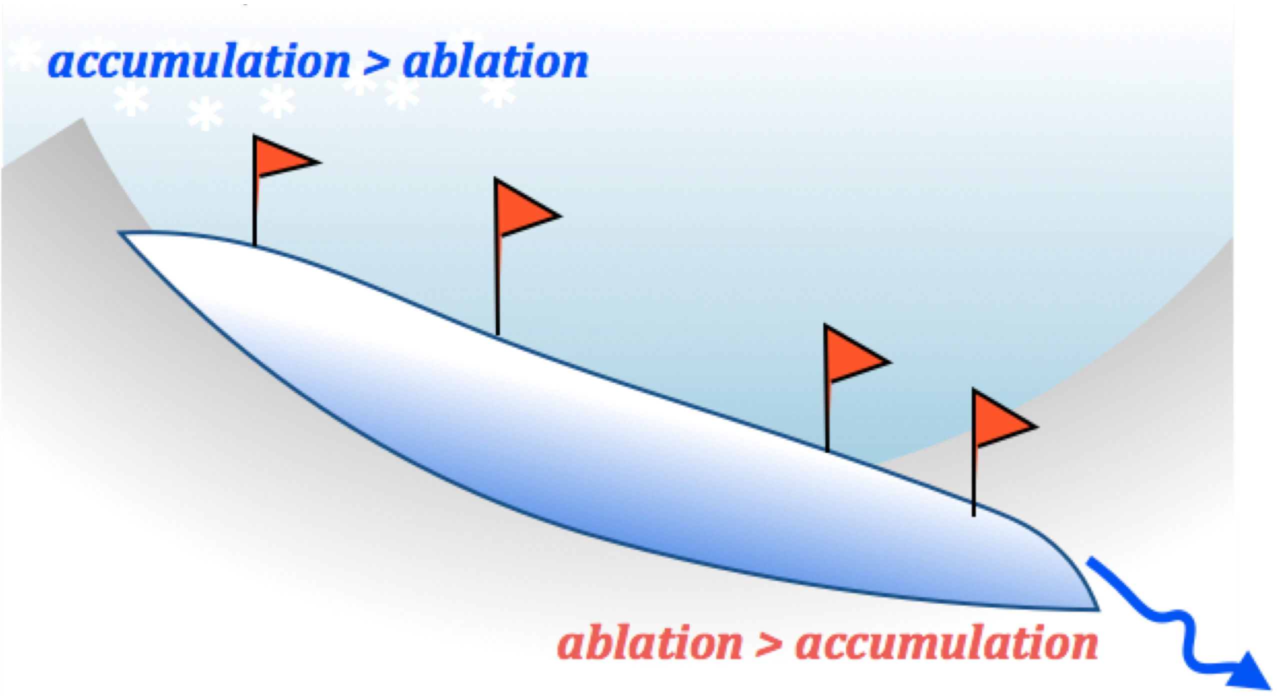

accumulation > ablation
Mass-balance: comparing inputs to outputs
ice dynamics
ablation > accumulation
Length changes:
response to imbalance

Measuring mass balance



Traditionally done with boots on the ground

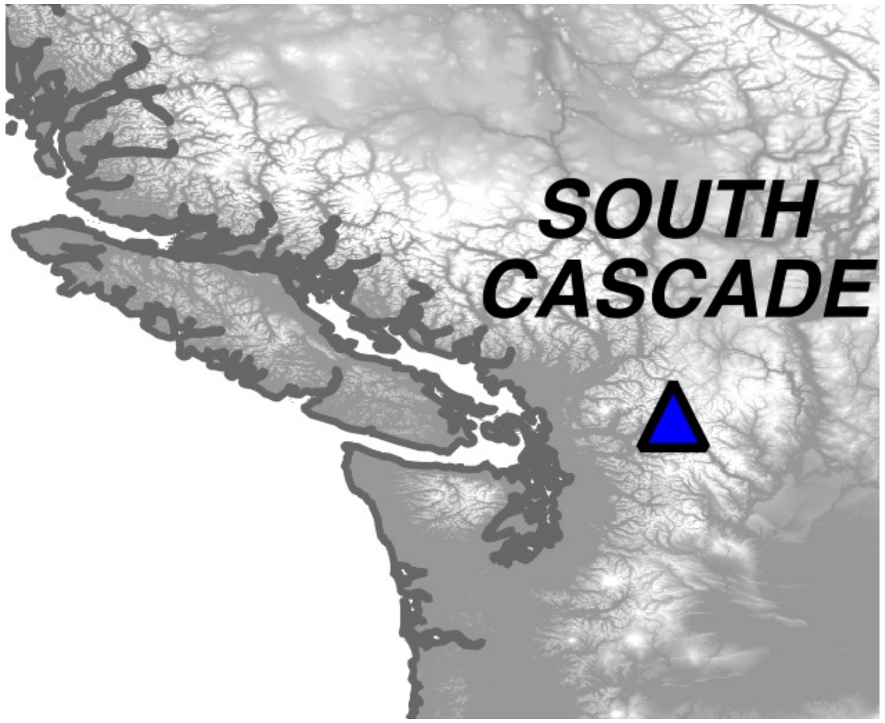
- Mass balance over some time period is measured in a few places and extrapolated to whole glacier
- Assume surface processes dominate (snowfall, surface melt)

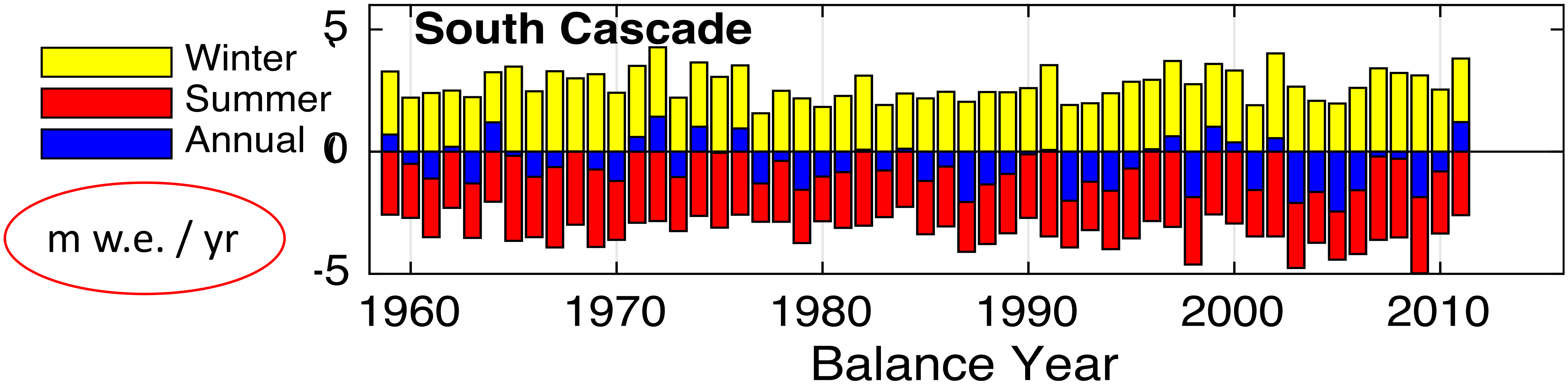


Typically, a single glacier-wide value is reported

- Units: meters water equivalent / year

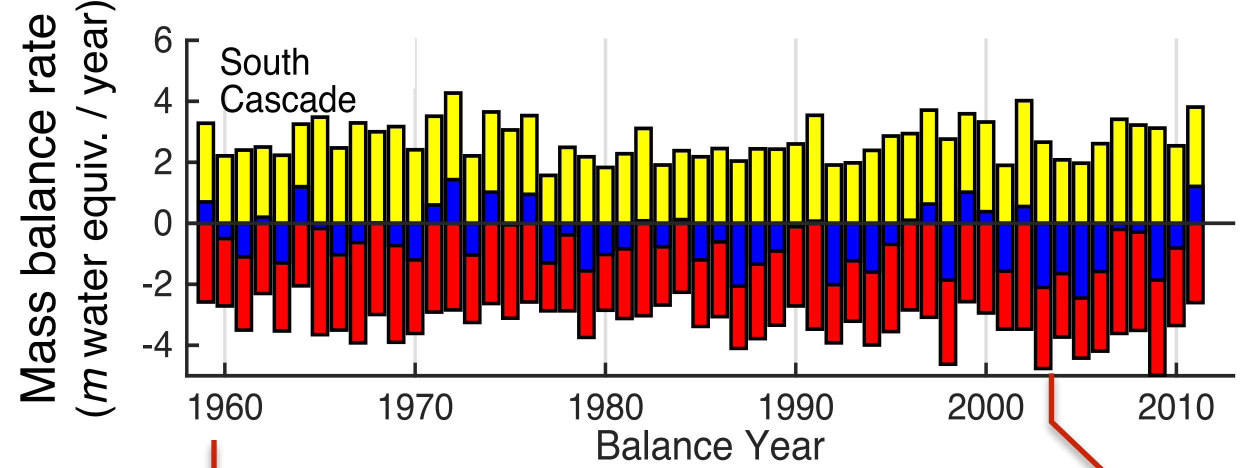
Longest mass balance record in North America (Thanks USGS!)





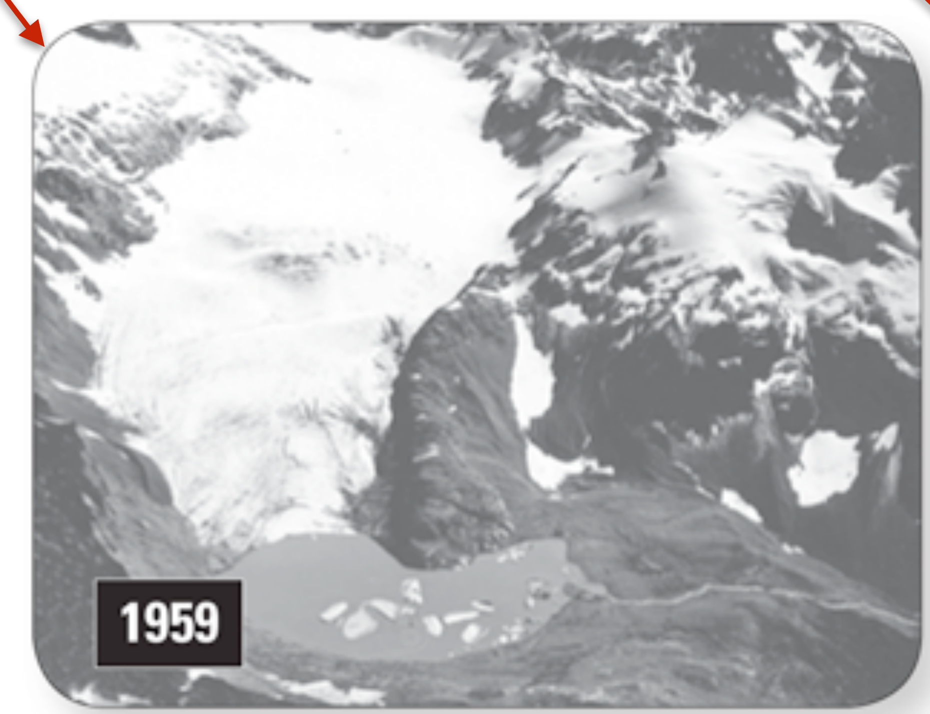
Annual balance = Winter balance - Summer balance

Mass-balance:



USGS photos: https://pubs.usgs.gov/fs/2009/3046/

Length:



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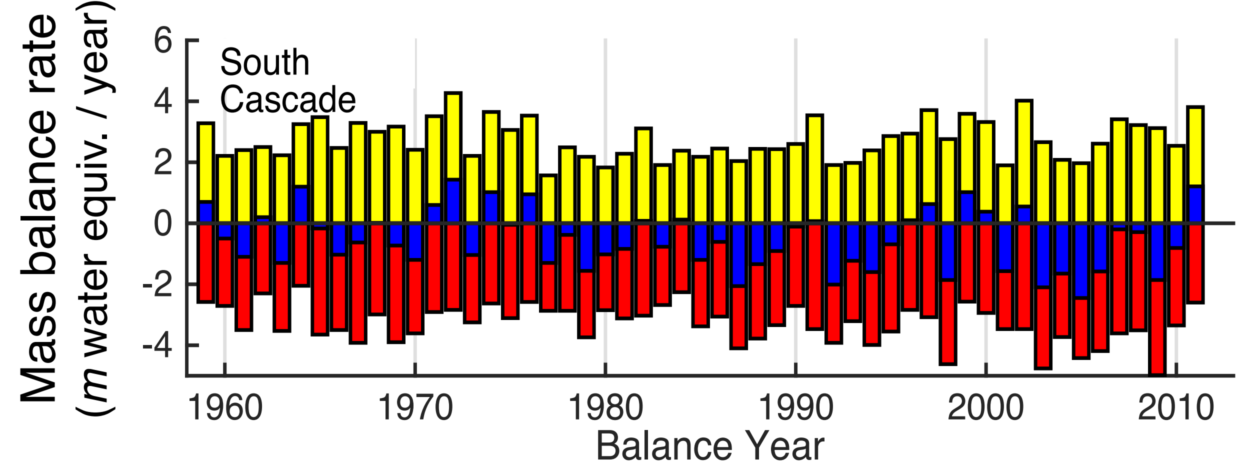
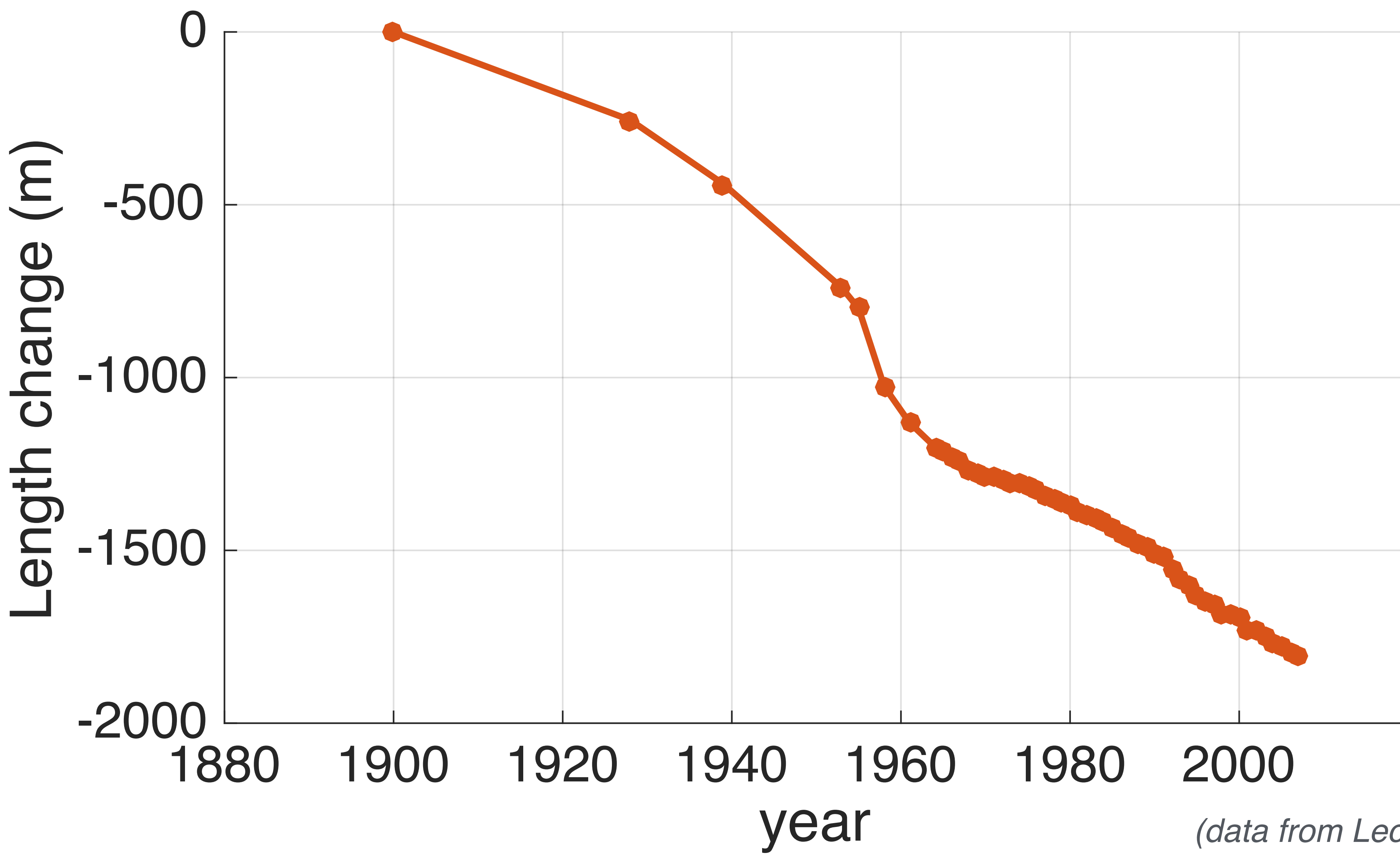


Length:

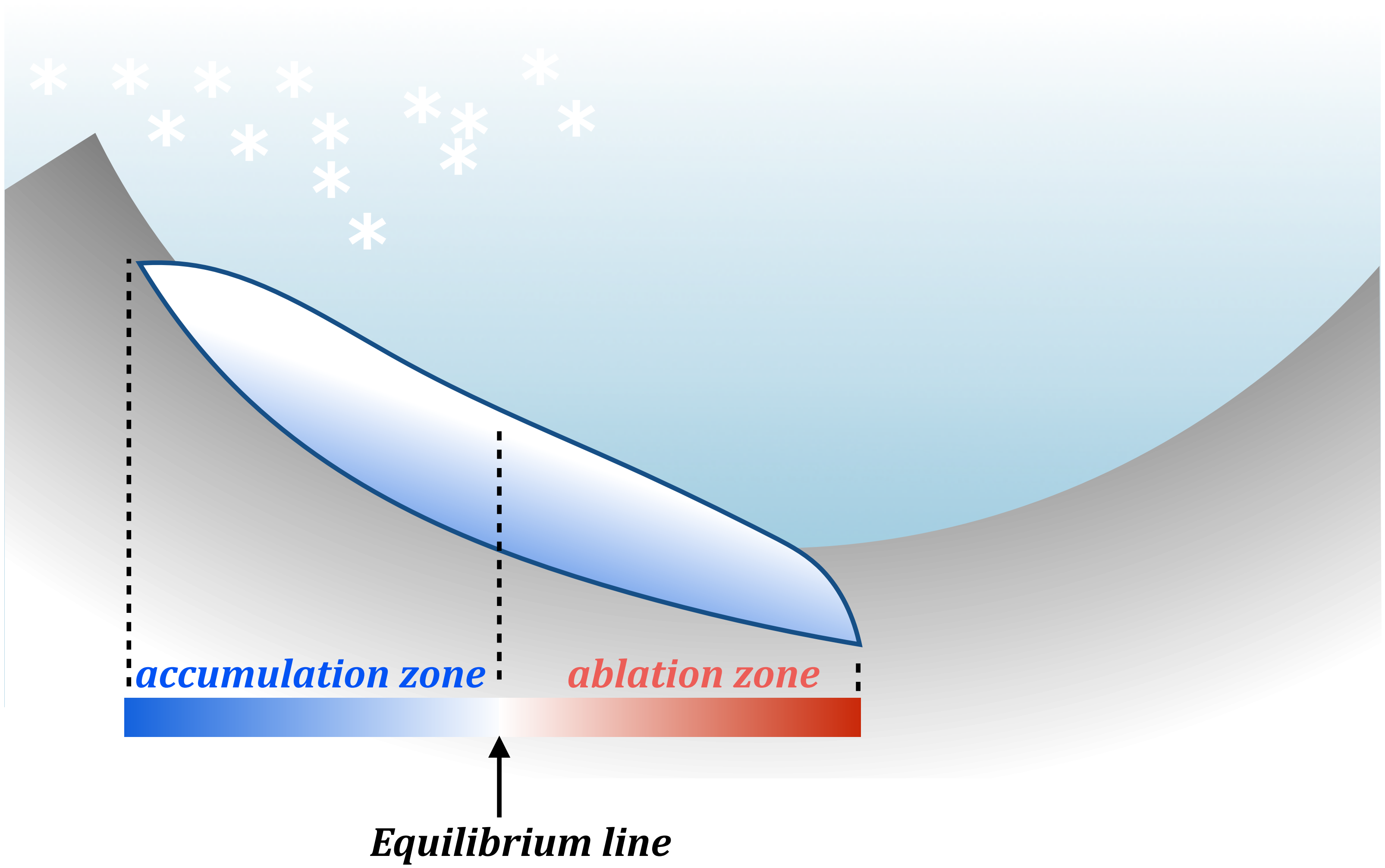
Why do these records look so different?



(data from Leclercq et al., 2014)

Basic glacier length response

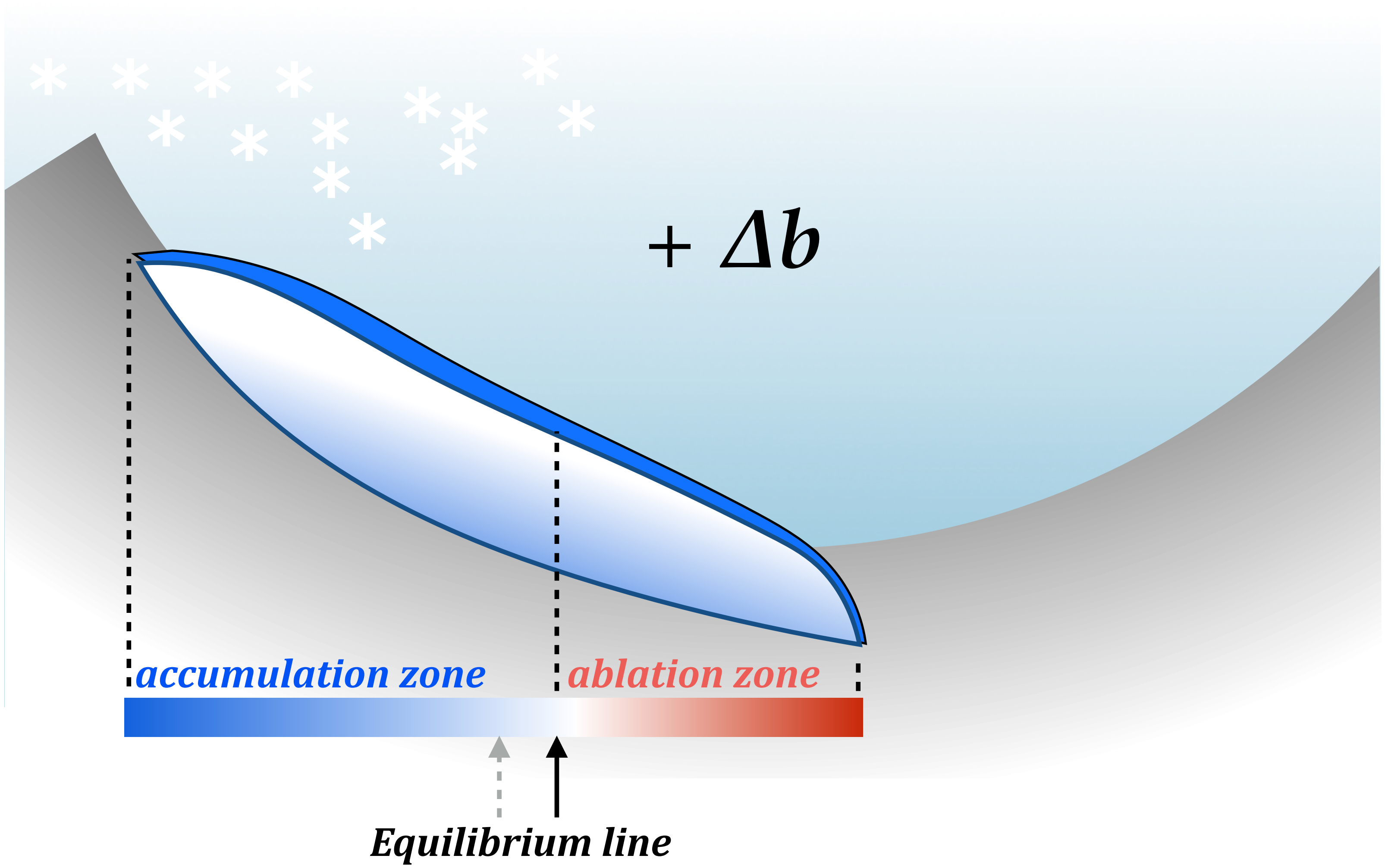
Initial state: in equilibrium



$$\int_A b \, \mathrm{d}a = 0$$

Basic glacier length response

Positive change in mass balance
- now we're out of balance (gaining mass)

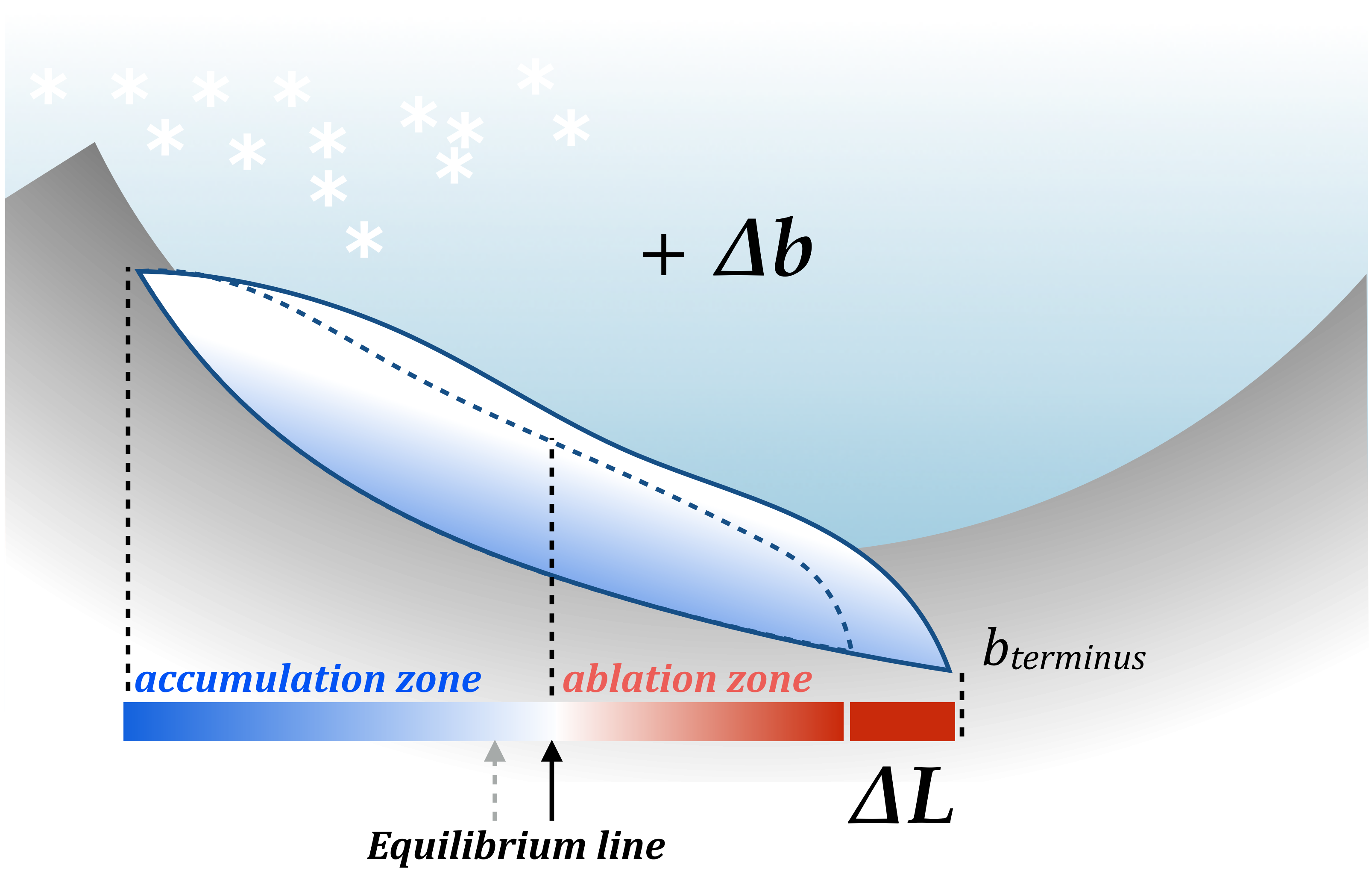


$$\int_A (b + \Delta b)\, \mathrm{d}a \neq 0$$

NOTE we're defining this to be a persistent change; not seasonal or yearly anomaly

Basic glacier length response

Positive change in mass balance
- Glacier advances, adding to ablation area

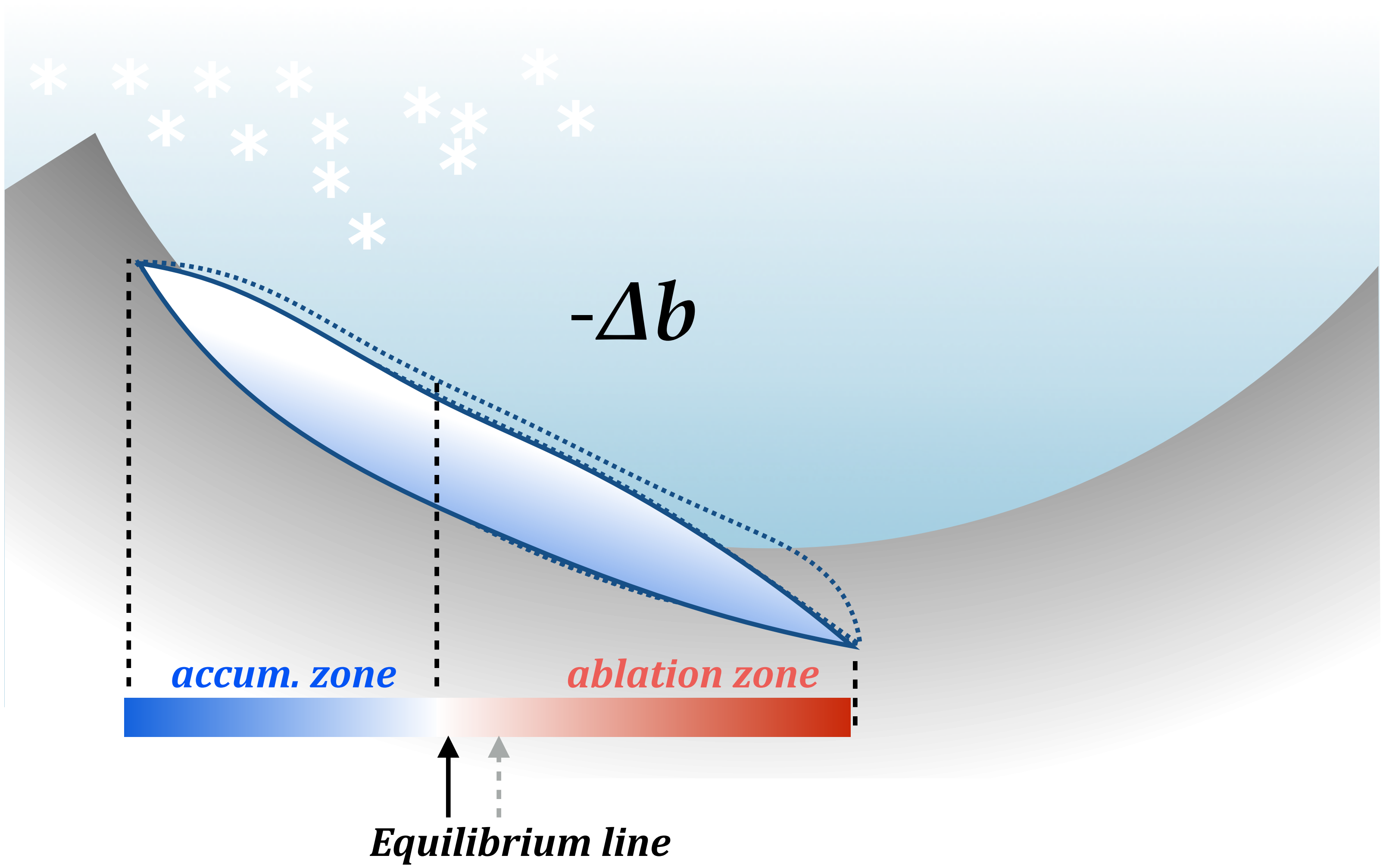


Balance is restored when $\Delta b \times L = -\Delta L \times b_{terminus}$

$$\int_{A+\Delta A} (b + \Delta b)\, \mathrm{d}a = 0$$

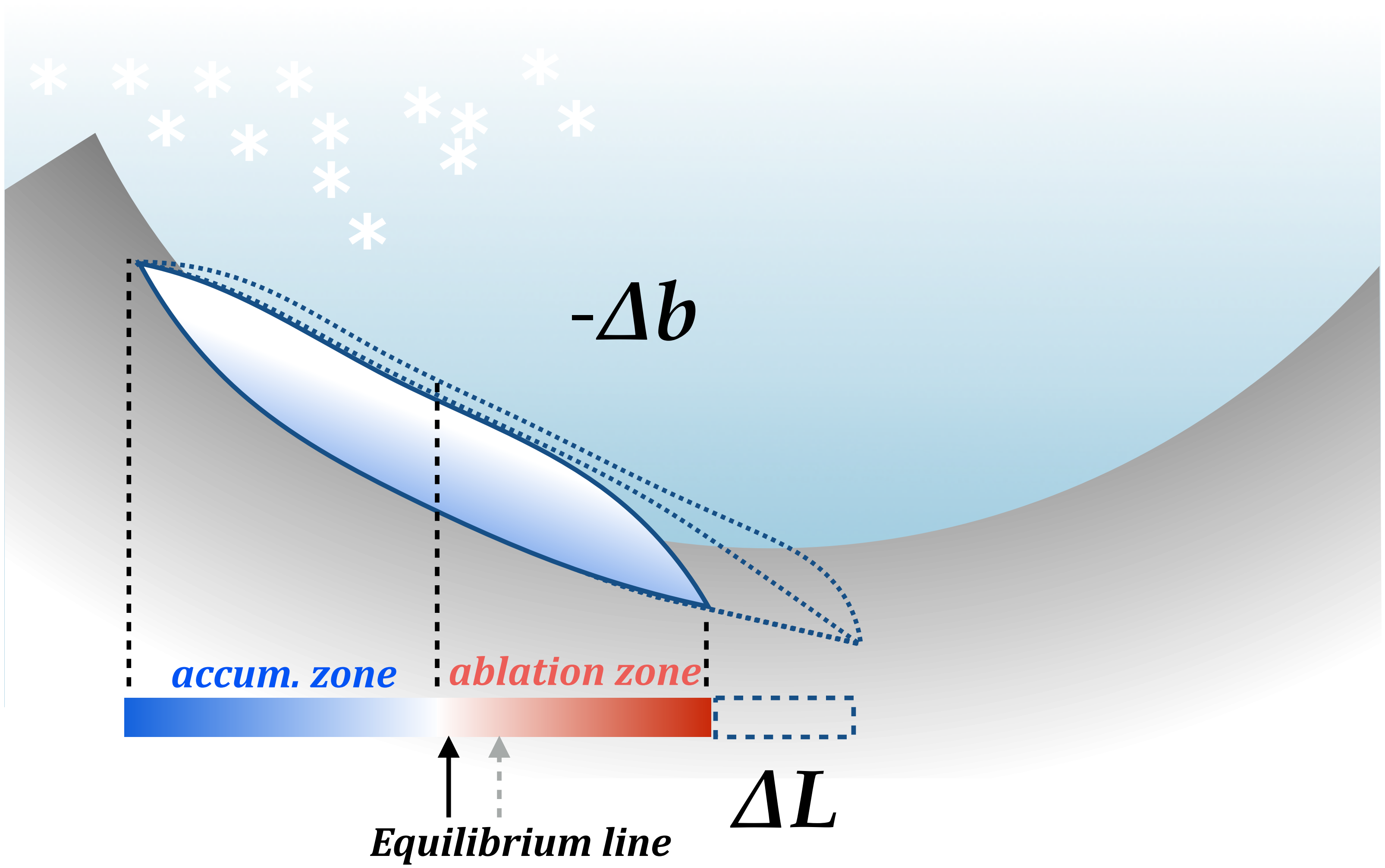
Basic glacier length response

Negative change in mass balance
-(losing mass)

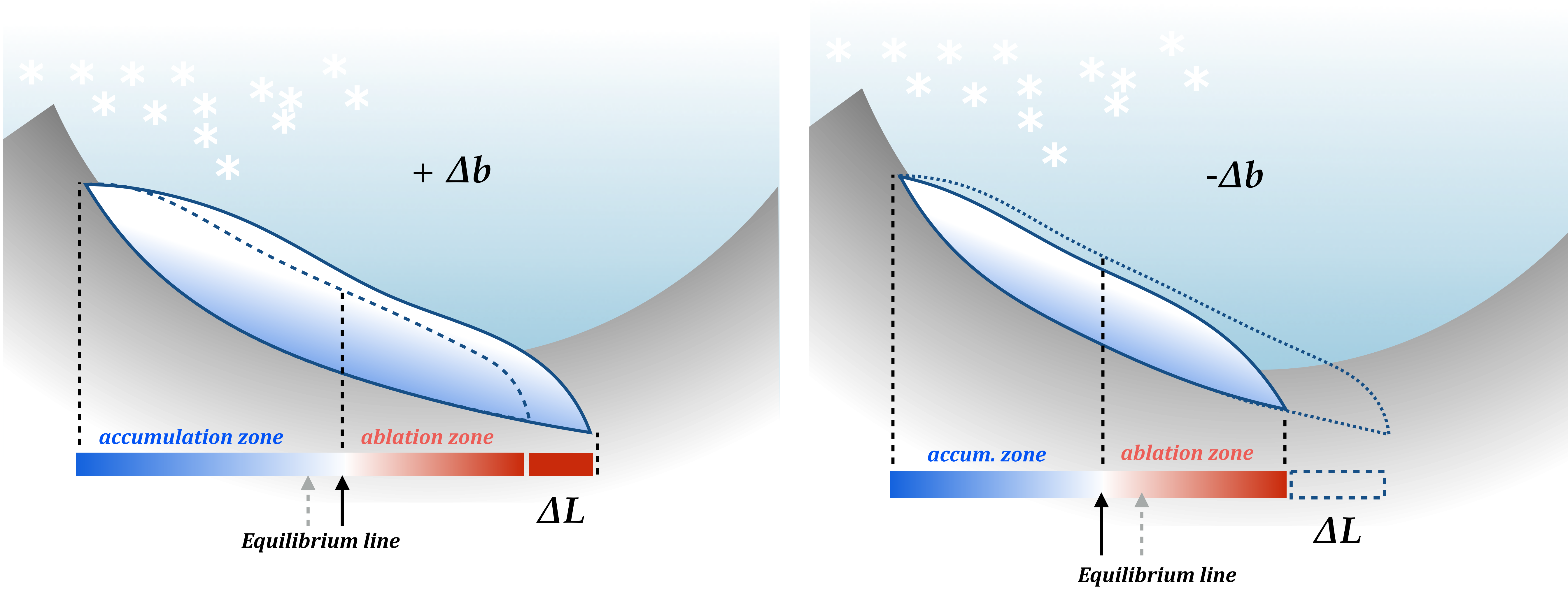


Basic glacier length response

Negative change in mass balance
- glacier retreats, reducing ablation zone



glacier's *equilibrium* sensitivity: $\Delta L / \Delta b$



That is, how much must ablation area grow or shrink to restore mass balance?

$$\Delta b \times L = \Delta L \times b_{terminus}$$

$$\int_{A+\Delta A} (b + \Delta b)\, \mathrm{d}a = 0$$

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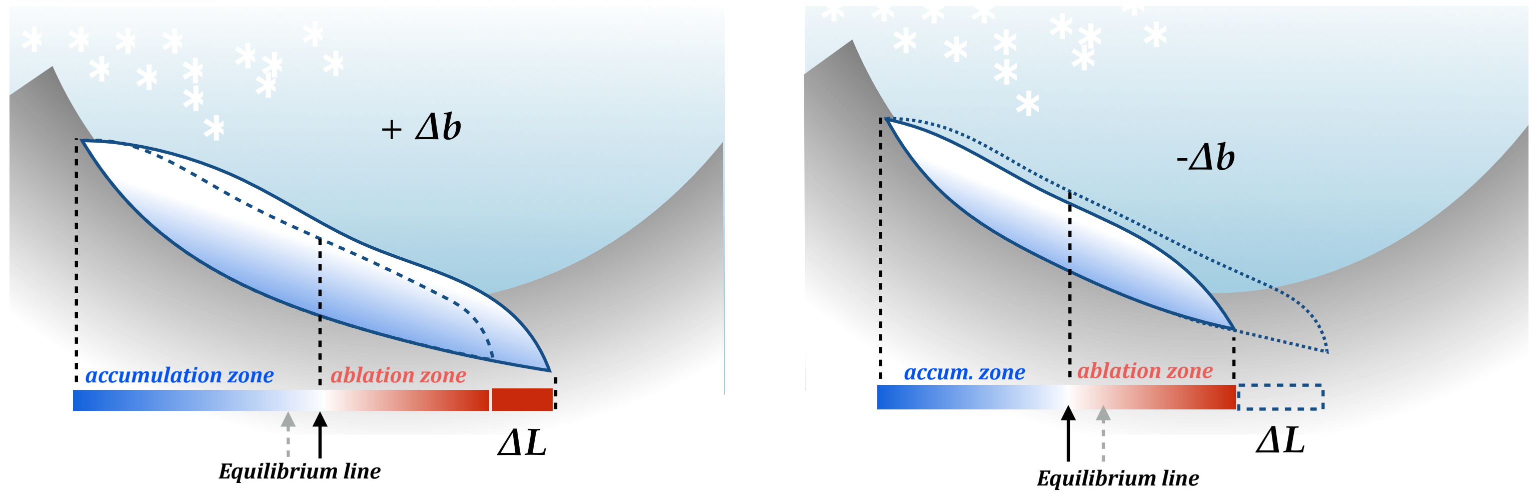

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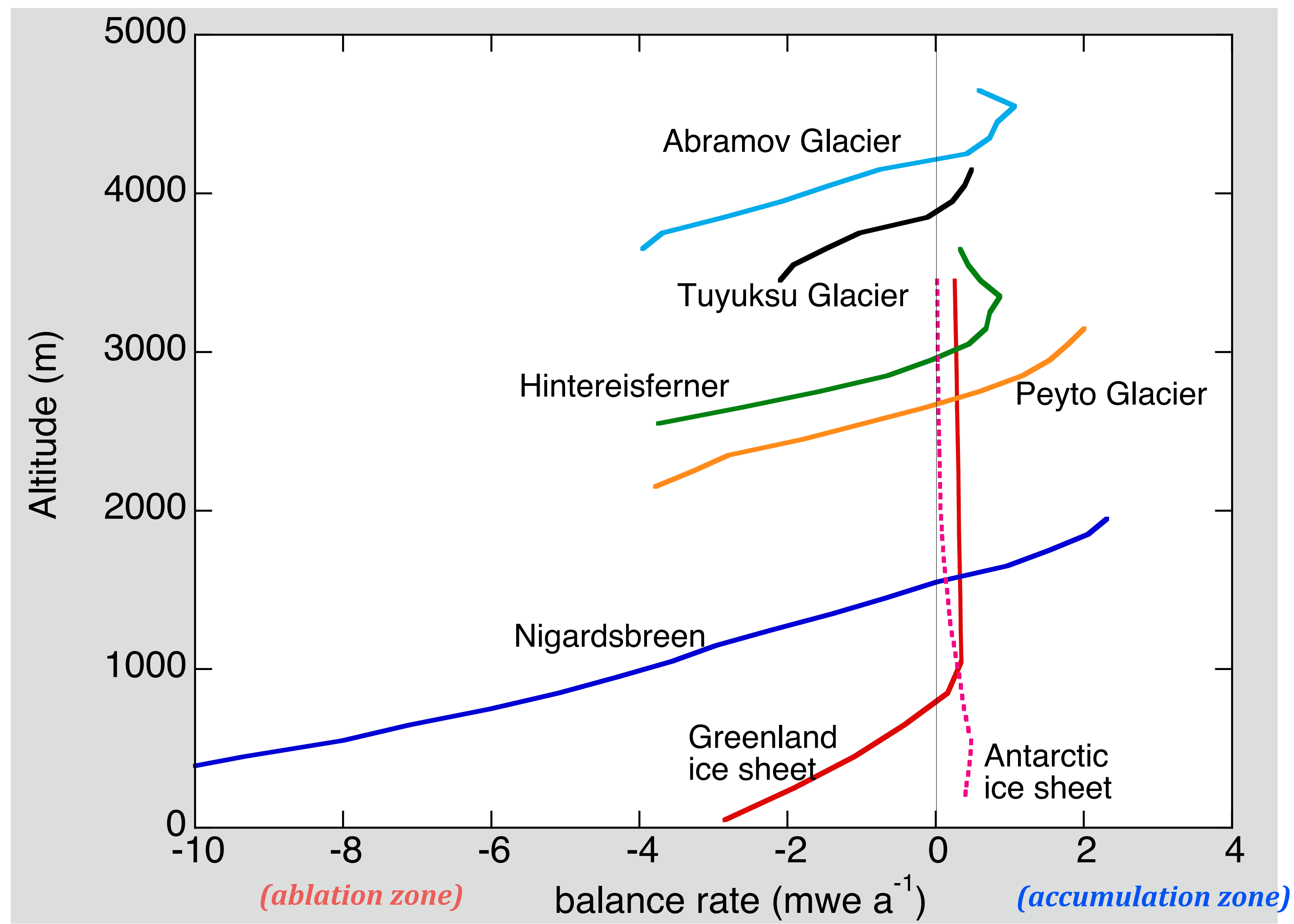
this depends on:

- **mass balance gradient**



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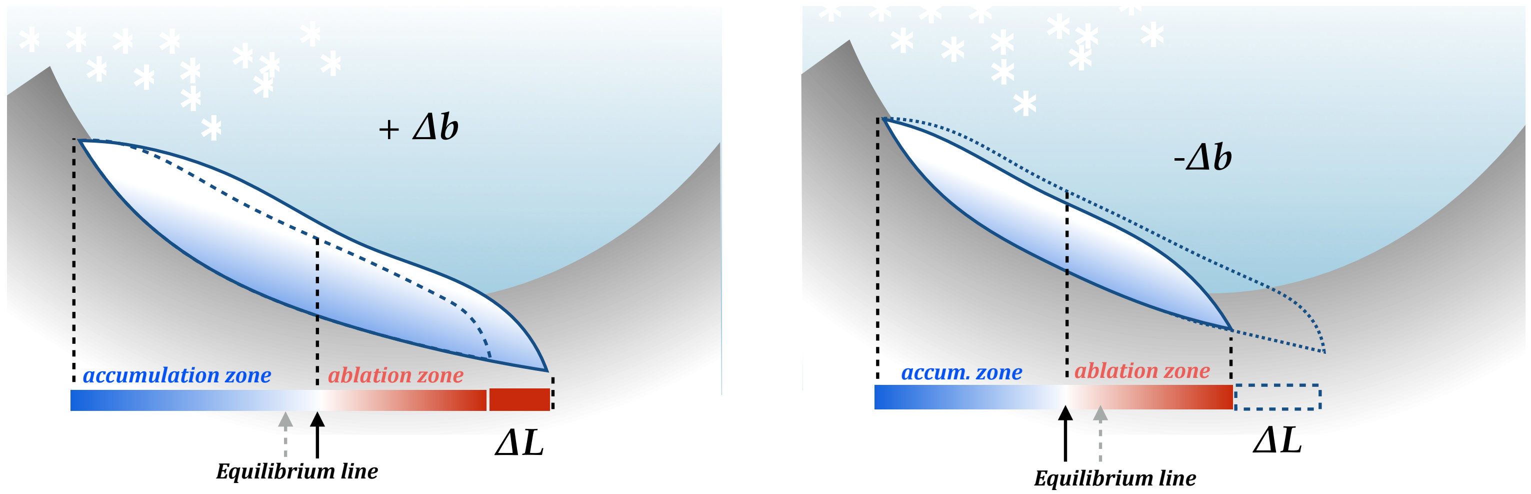

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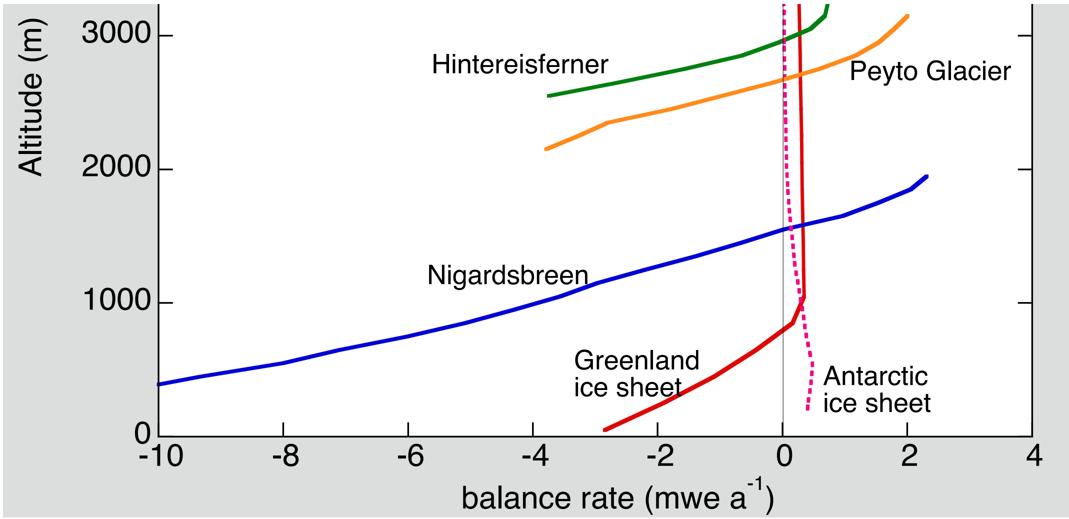
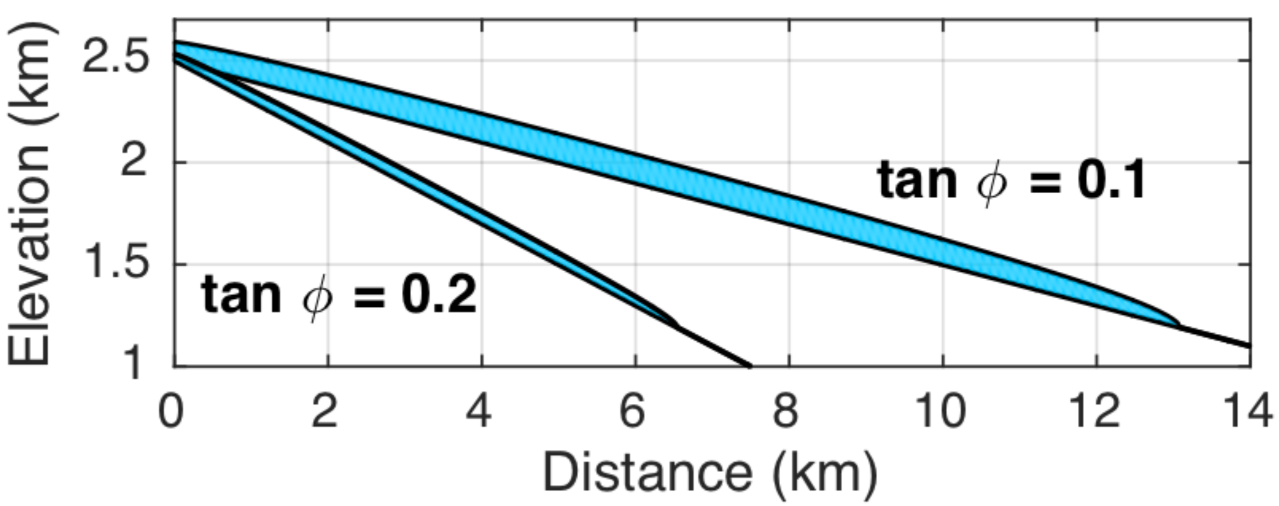


this depends on:

- mass balance gradient

- **Glacier geometry (especially slope)**

(how much advance is needed to reach down into high ablation rates?)



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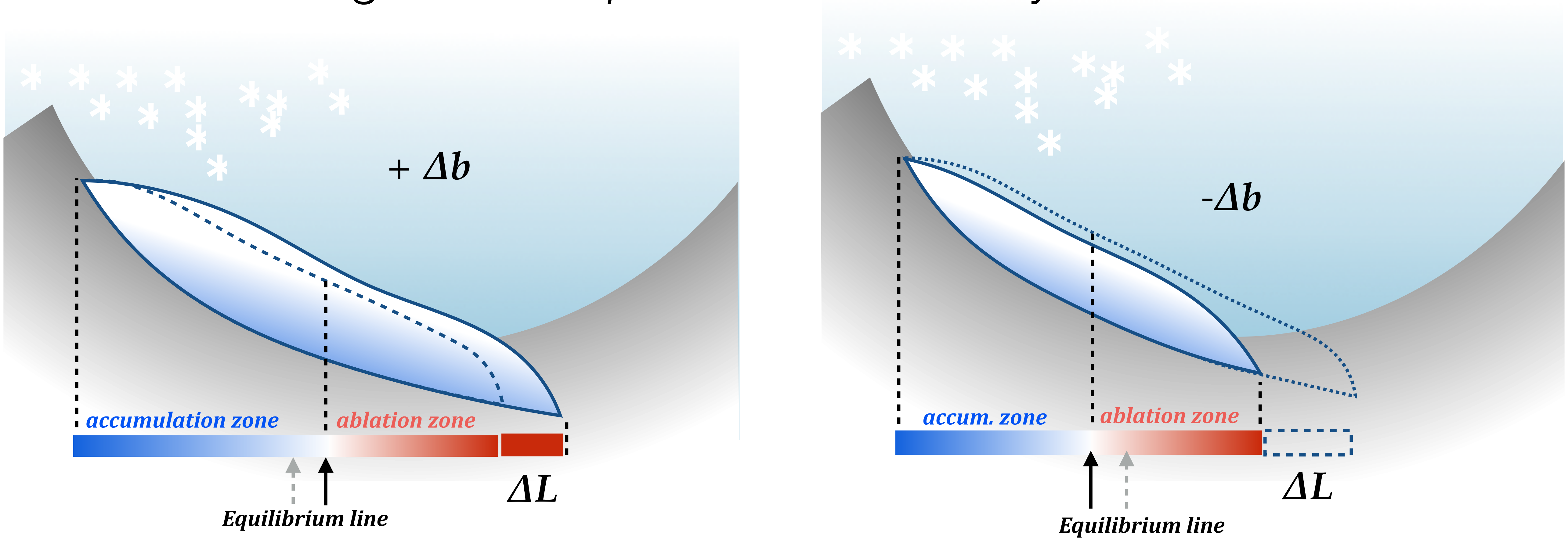
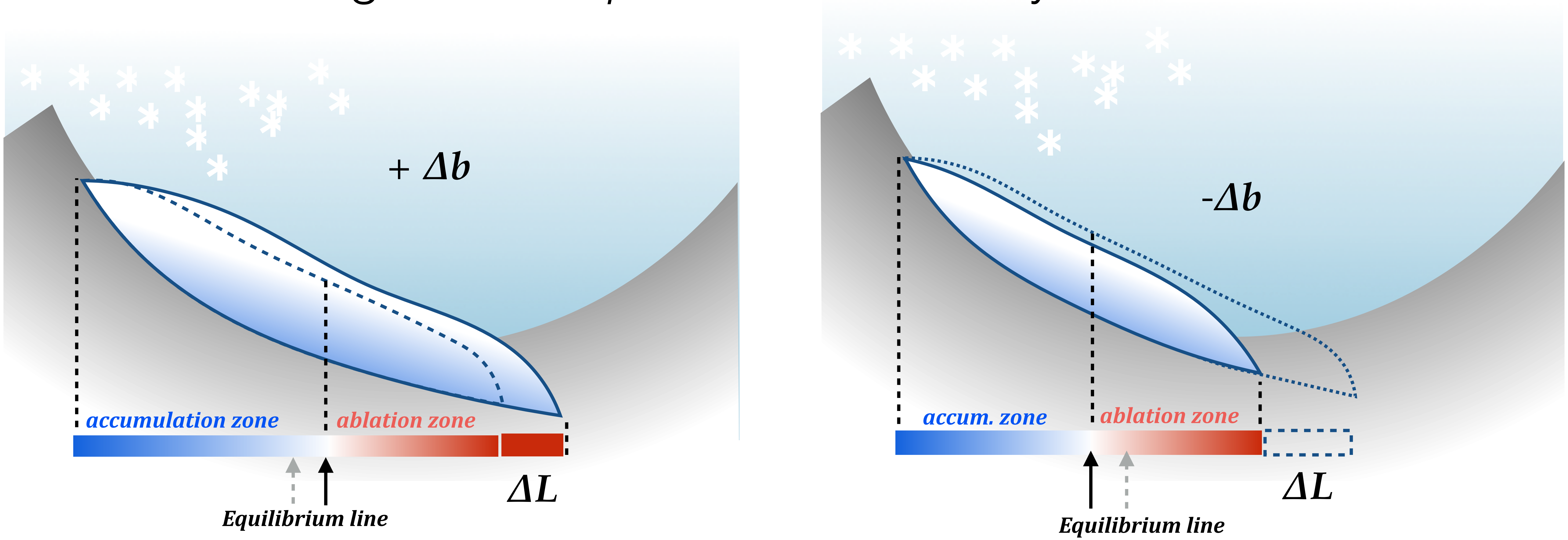


Equilibrium response to climate variations can be largely constrained by geometry

(how does glacier drape itself over the landscape and sample the local climate?)

Ok, easy enough, but how do these adjustments happen in time?

glacier's *equilibrium* sensitivity: $\Delta L / \Delta b$



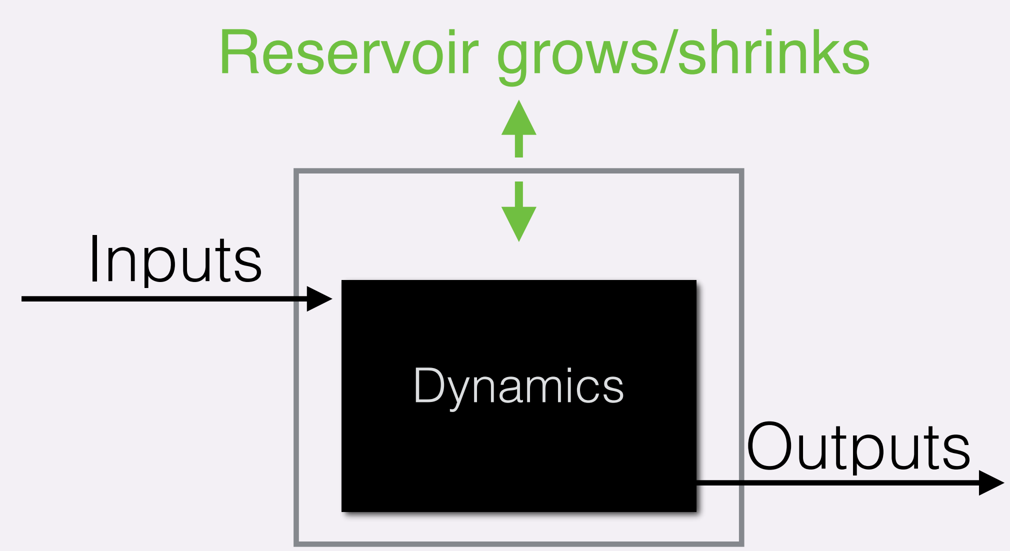
Equilibrium response to climate variations can be largely constrained by geometry

(how does glacier drape itself over the landscape and sample the local climate?)

Ok, easy enough, but how do these adjustments happen in time?

How simply can we start?

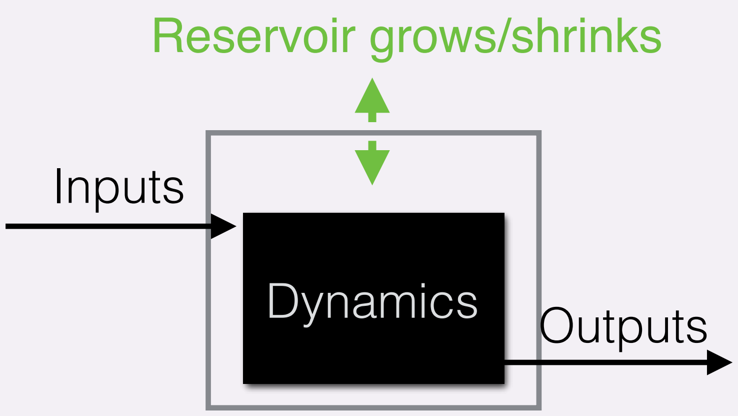
What would we want to know about the reservoir?



Typical mountain glaciers have ~decade — century "memories"

Johanneson-Raymond-Waddington timescale (1989): $\tau = -H/b_t$

- valley geometry, climate, and ice dynamics are represented in H and b_t



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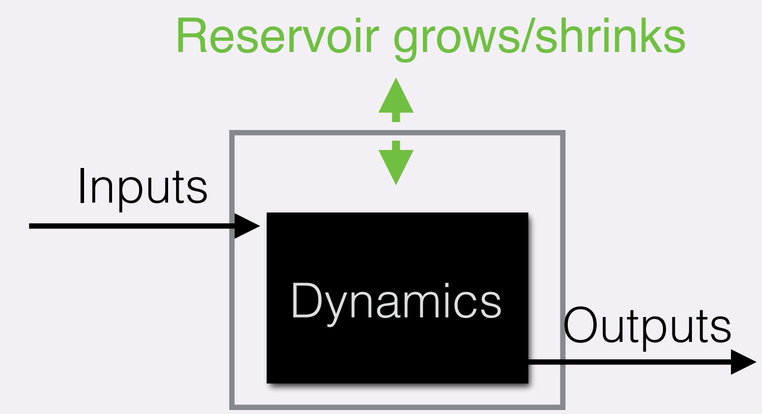
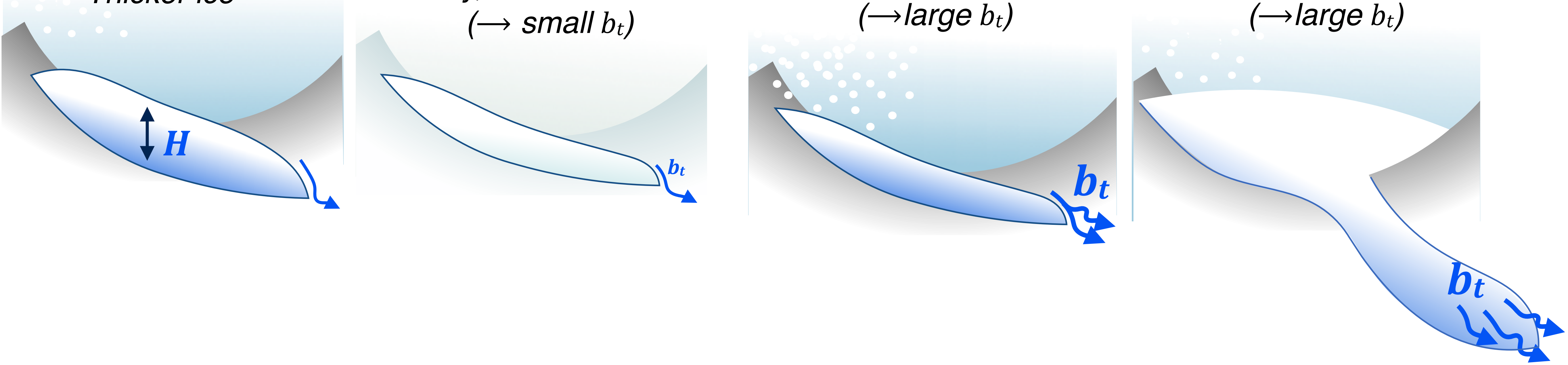


Longer response times | **Shorter response times**

Thicker ice | *Dry, cold climates (⟶ small b_t)* | *High accumulation rates (⟶large b_t)* | *Large elevation spans (⟶large b_t)*



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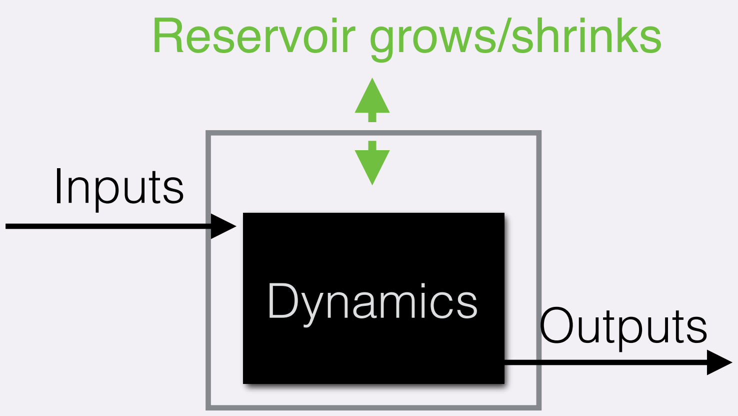
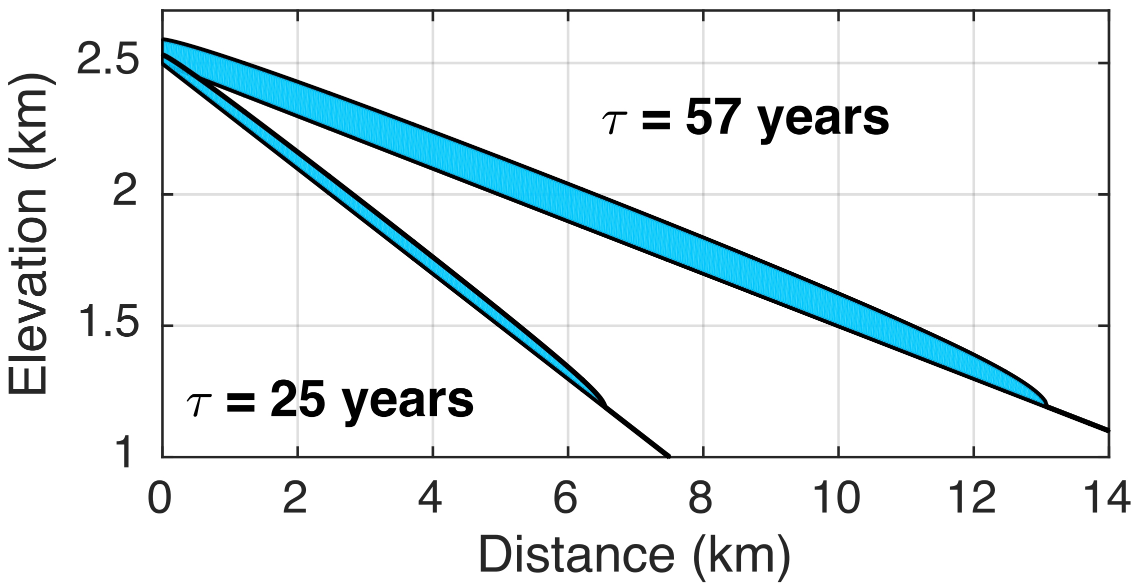


What other natural systems have characteristic time scales?

Illustrating response times with idealized glaciers

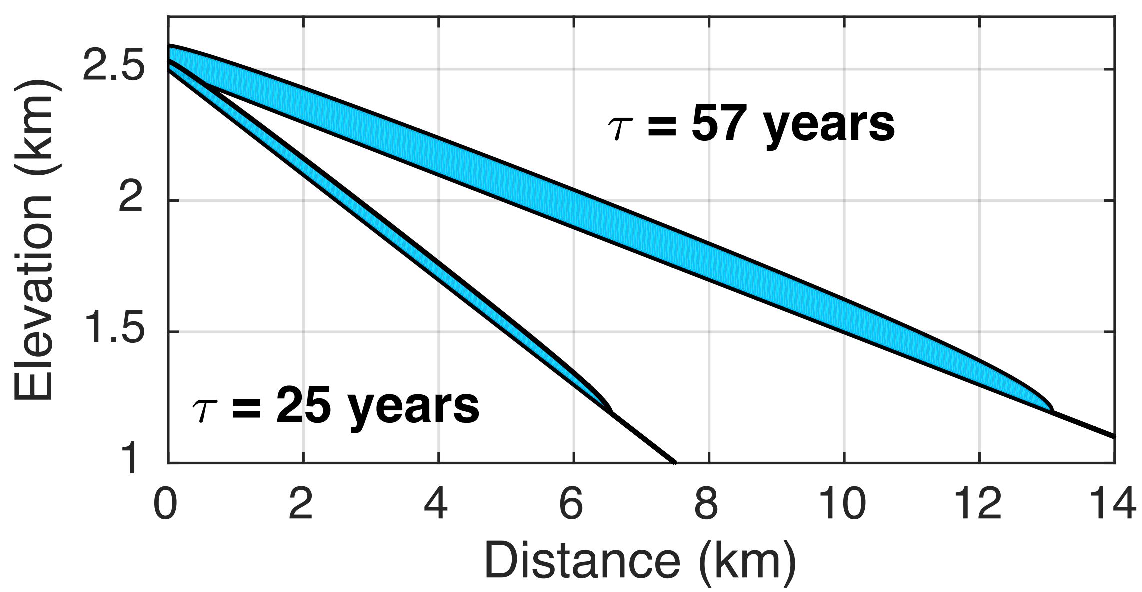


- Constant width
- Constant bed slope
- Simple climate-mass balance relationship
  - linear increase with elevation
  - changes in climate (*T* or *P*) produce uniform mass balance anomalies over the glacier

$$\Delta b = \Delta P - \boldsymbol{\mu}(\Delta T)$$

melt factor (0.5 m / yr / °C)

Illustrating response times with idealized glaciers



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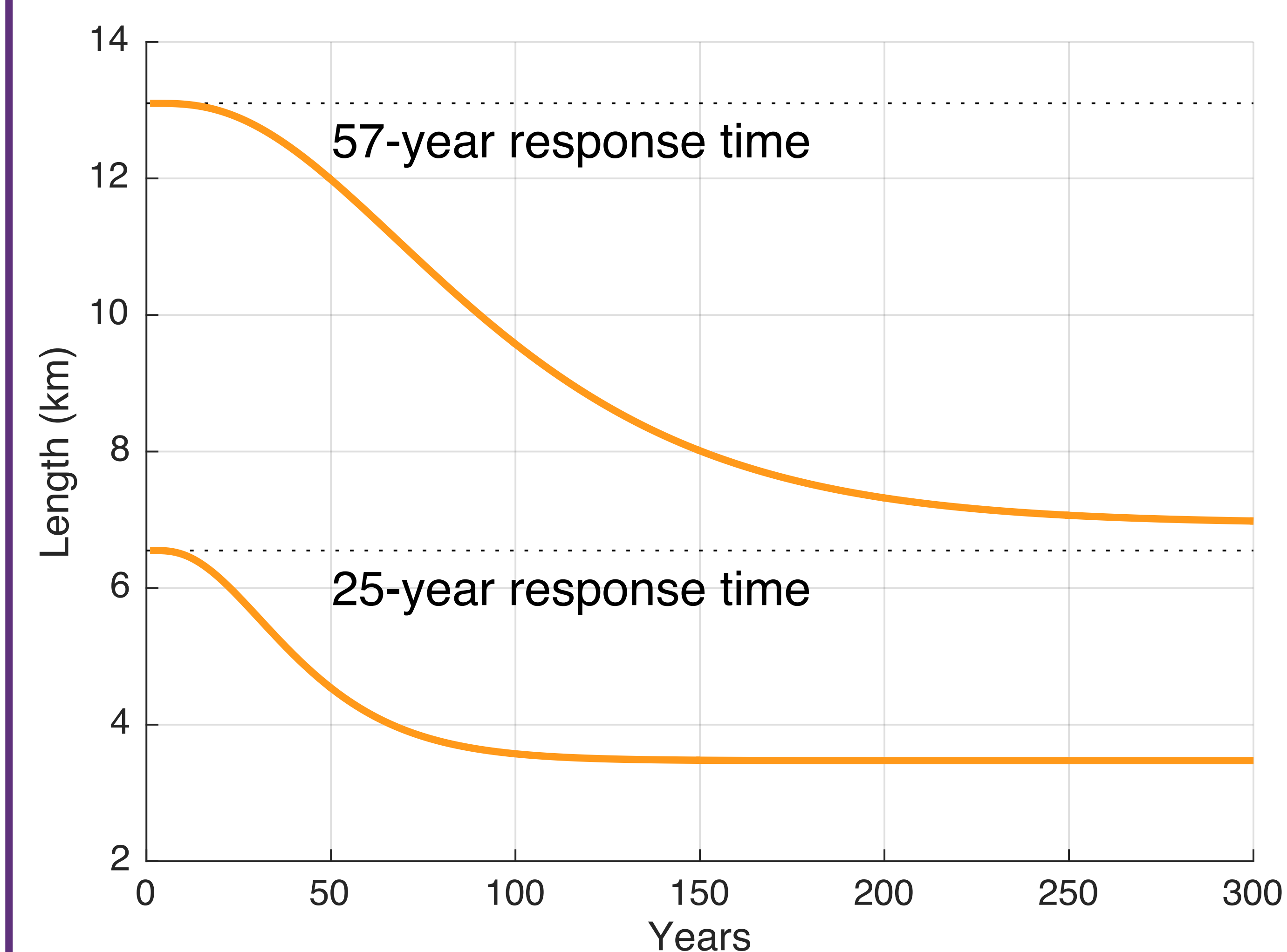
$$\Delta b = \Delta P - \mu(\Delta T)$$

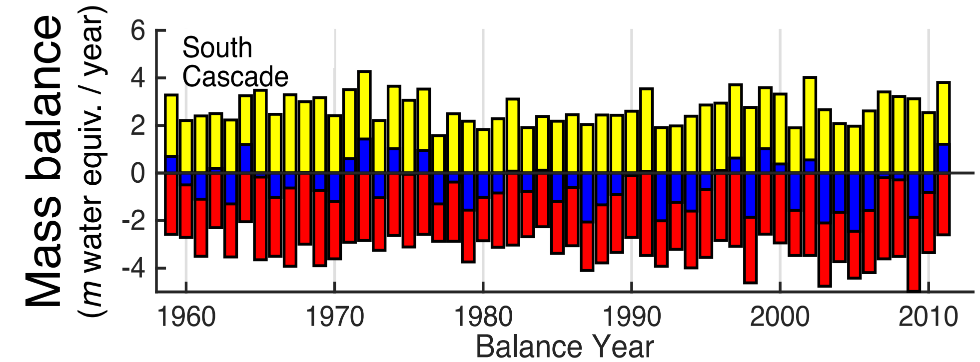
- Consider a step change in climate: (instant 2°C warming at year zero)
- Both glaciers approach new equilibrium, but at different rates
- Also note different total sensitivity!

  (why?)

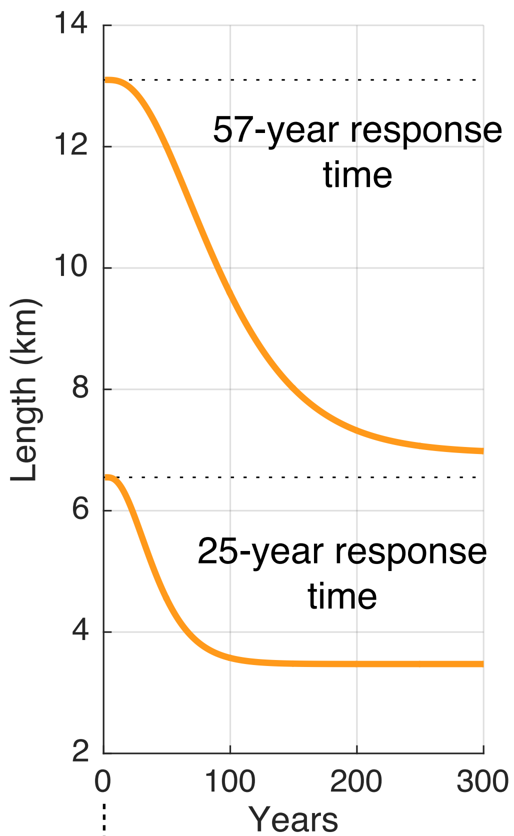


Illustrating response times with idealized glaciers

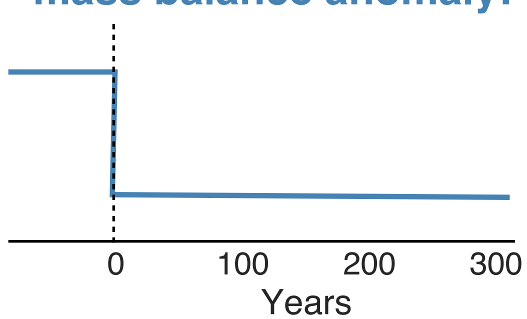
- Ok, but we know climate doesn't behave like that
- What does a glacier do with year-to-year variability?



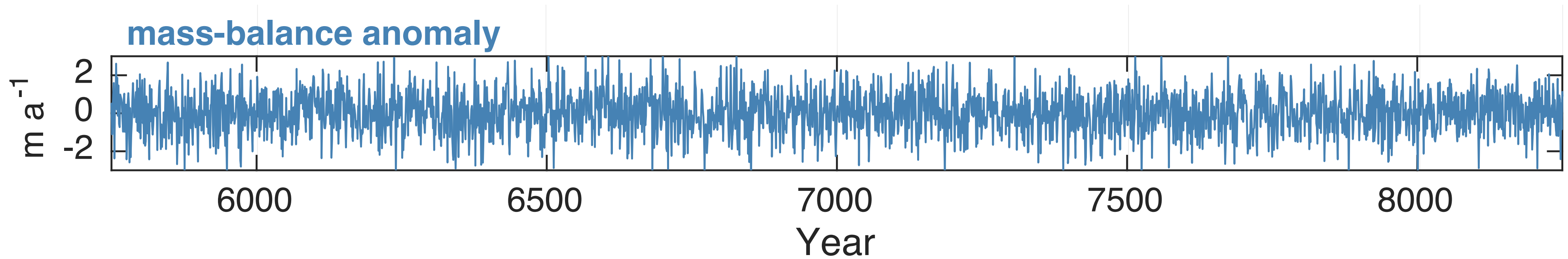
2 °C step-change



mass balance anomaly:



Random variability in Temperature and Precipitation:



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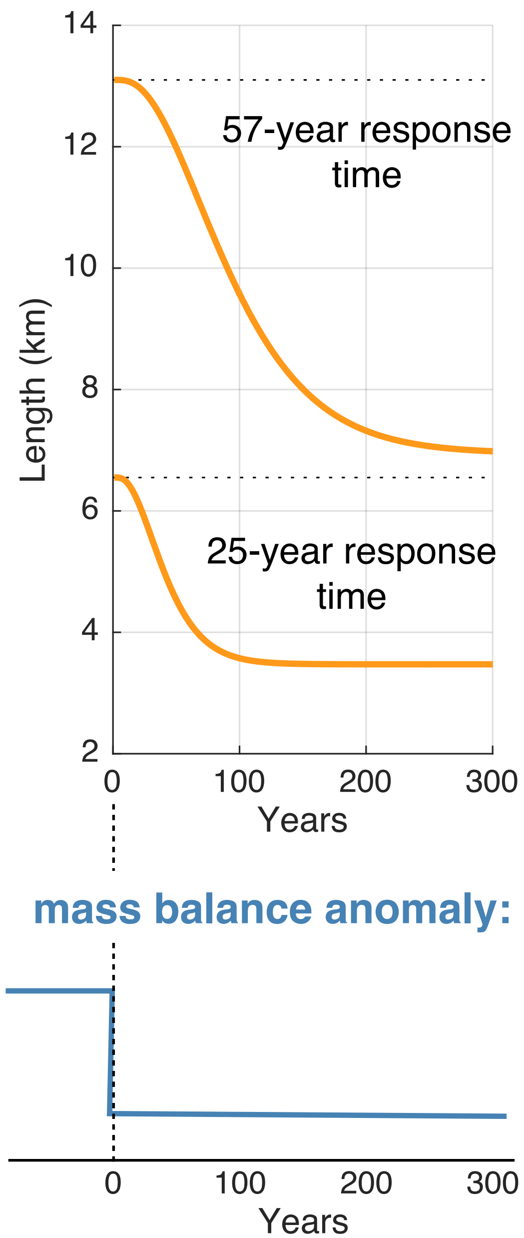

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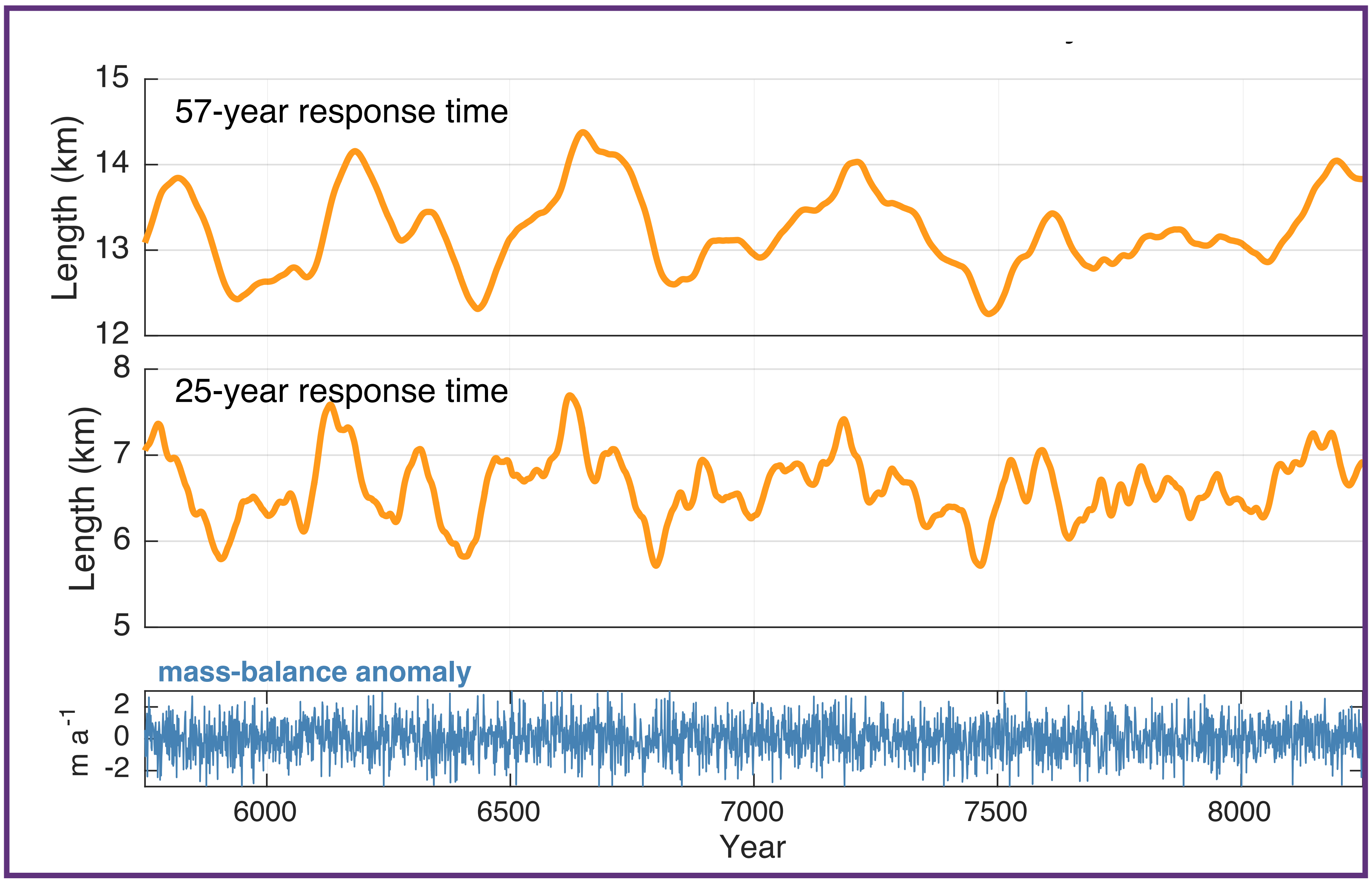
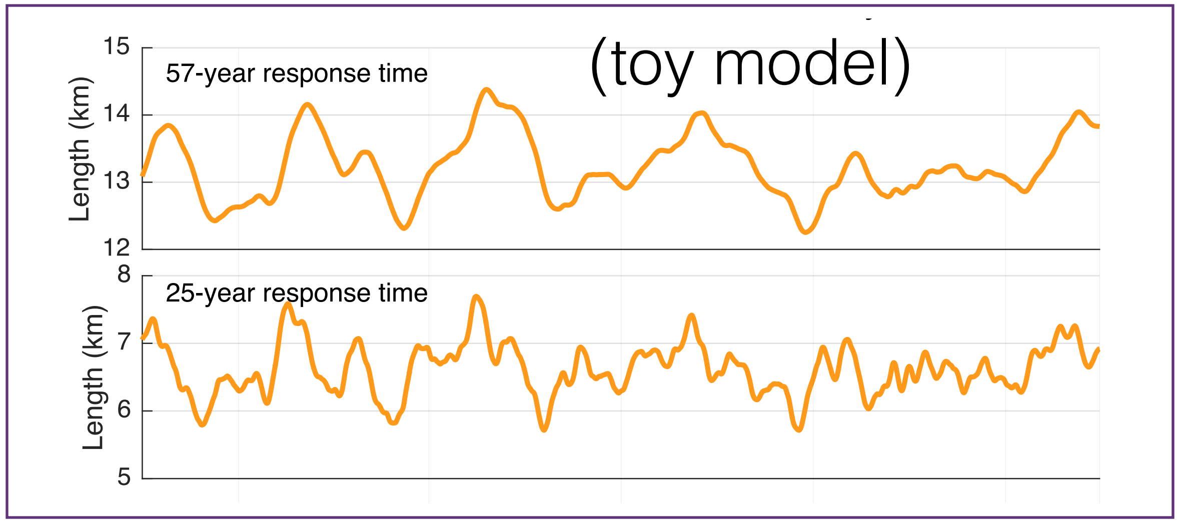
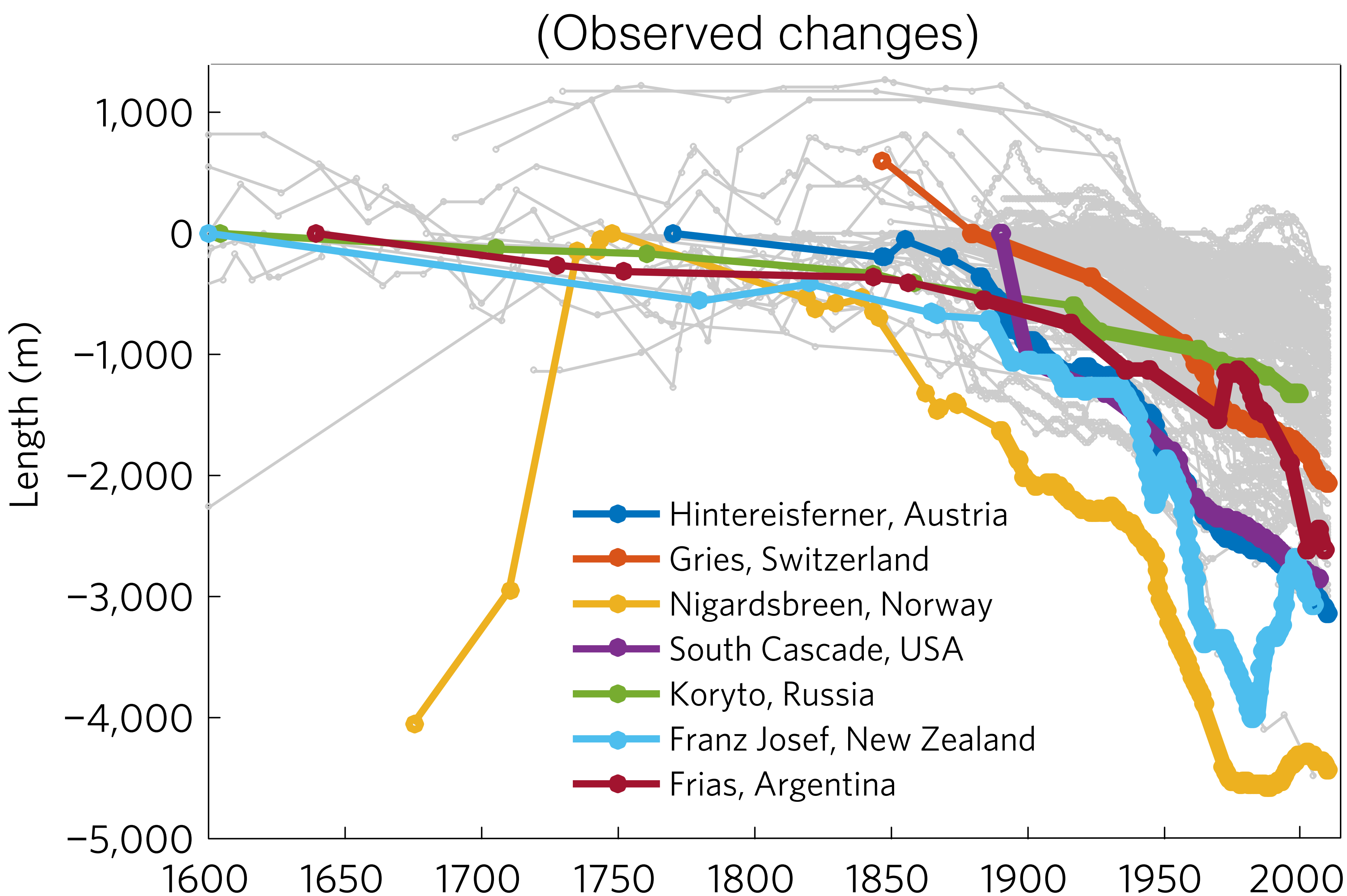




Glaciers have been responding to natural variability and an anthropogenic trend



(From Roe et al., 2016; see also Leclercq et al., 2014)

nature geoscience
ARTICLES
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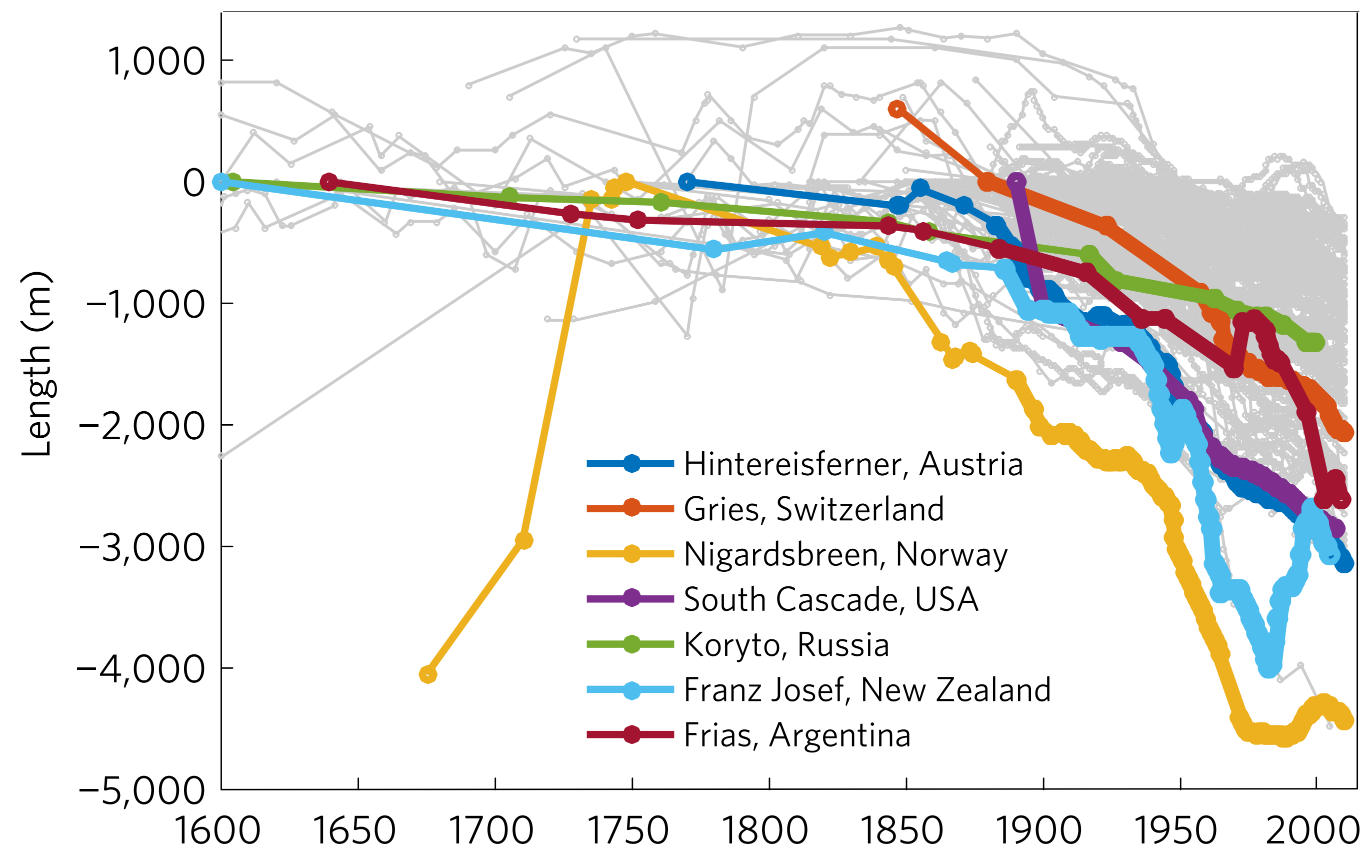
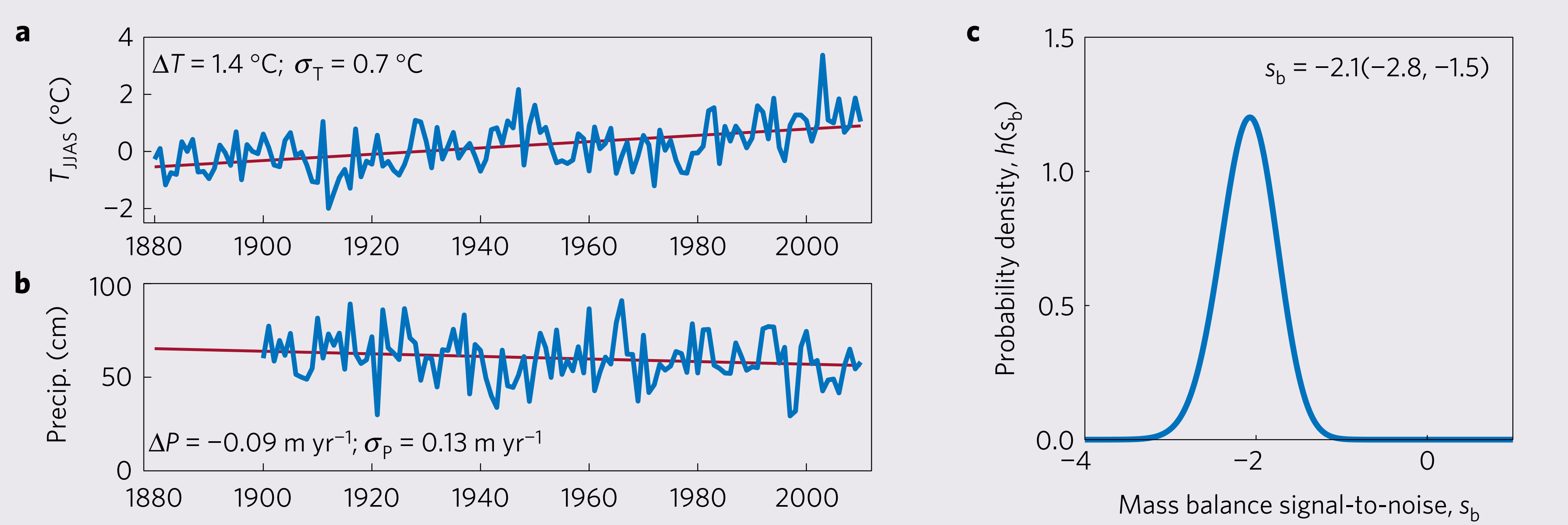
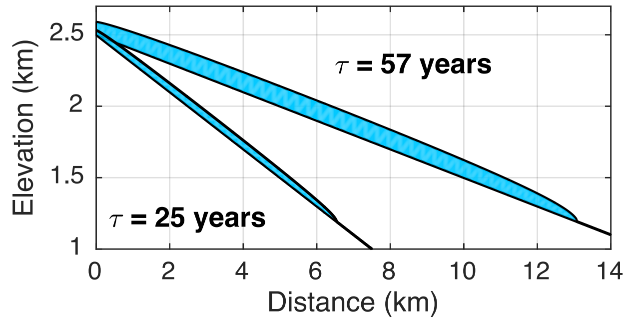
Centennial glacier retreat as categorical evidence of regional climate change

Gerard H. Roe[1]*, Marcia B. Baker[1] and Florian Herla[2]



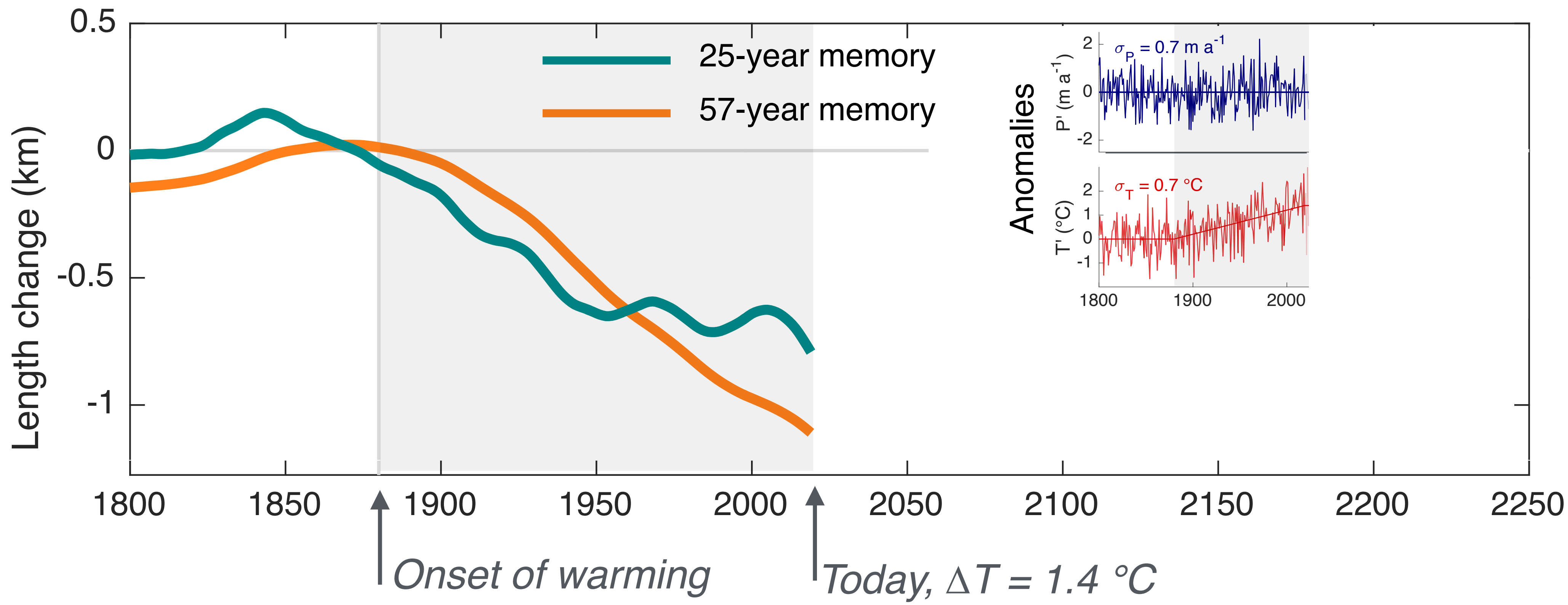
mass balance signal (Hintereisferner)





Back to toy model: warming signal + variability

- trend of 1°C per century, no trend in snowfall
- NOT simulating a specific glacier, but these are plausible values



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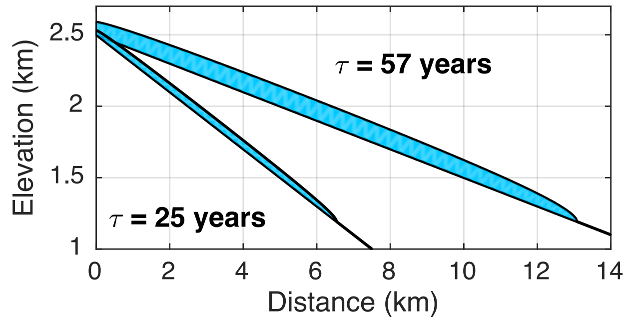
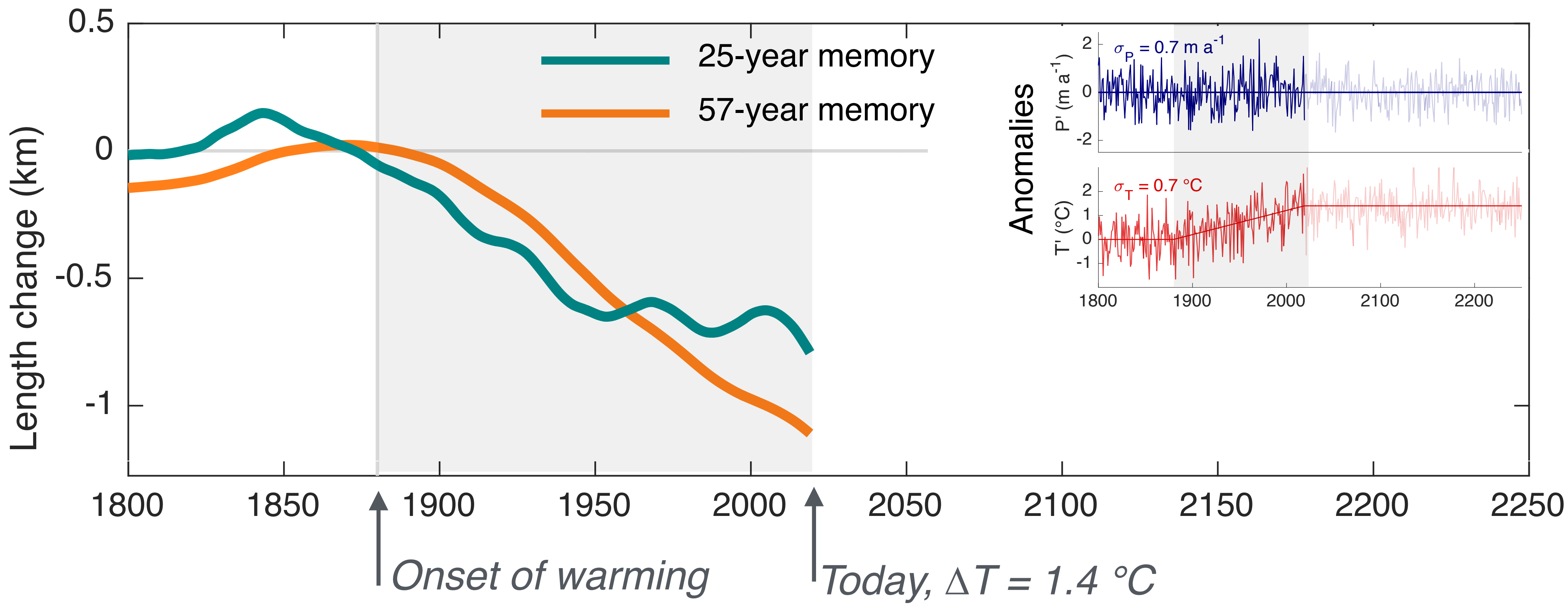
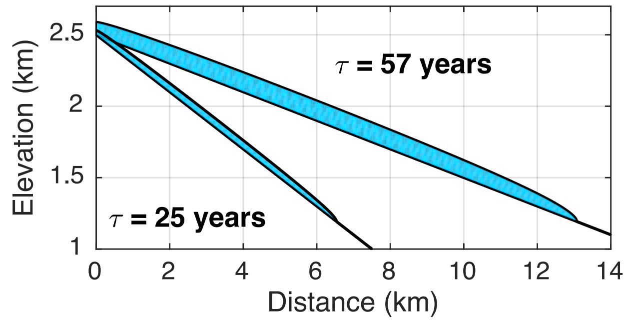




Thought experiment: what would happen if we stopped warming today?



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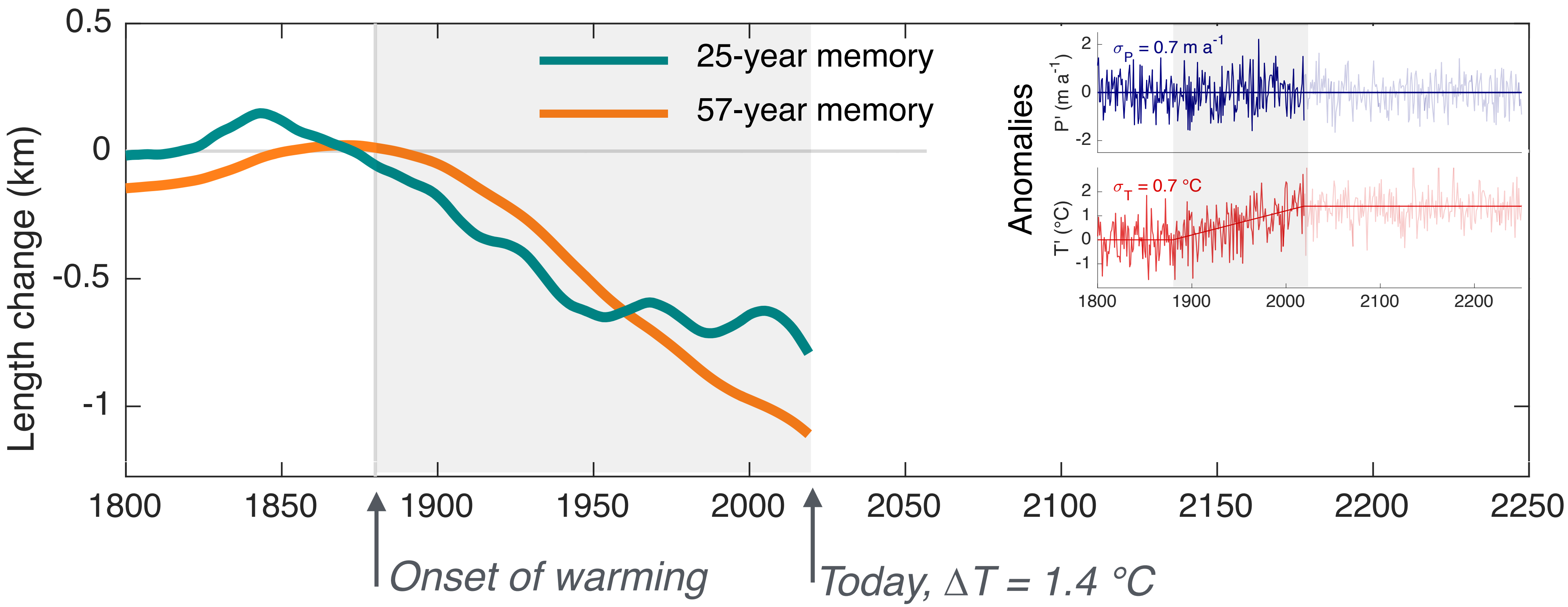

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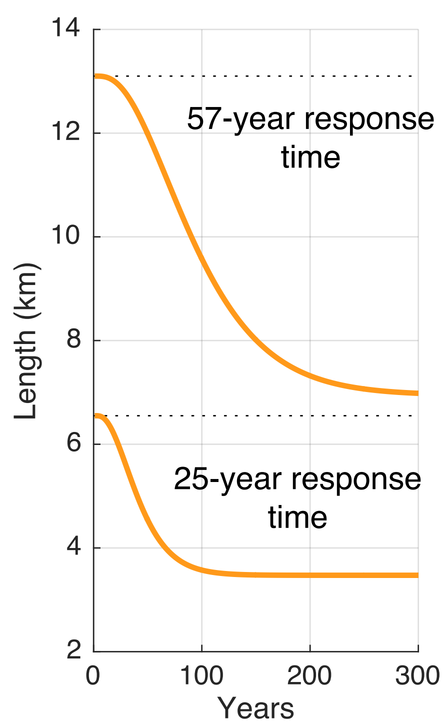
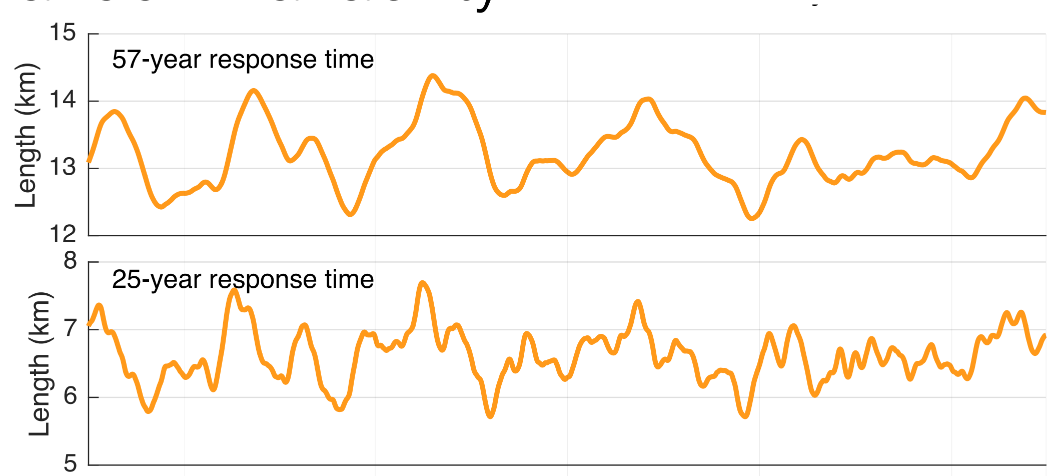
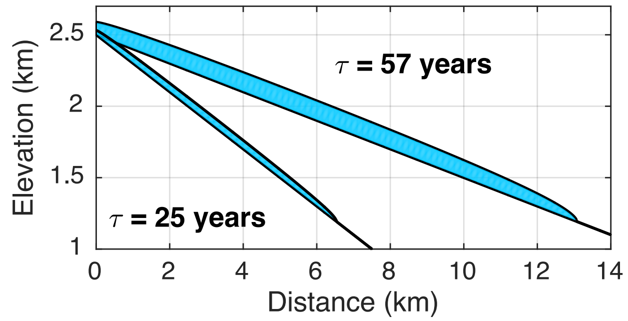
Step change:



Random variability:





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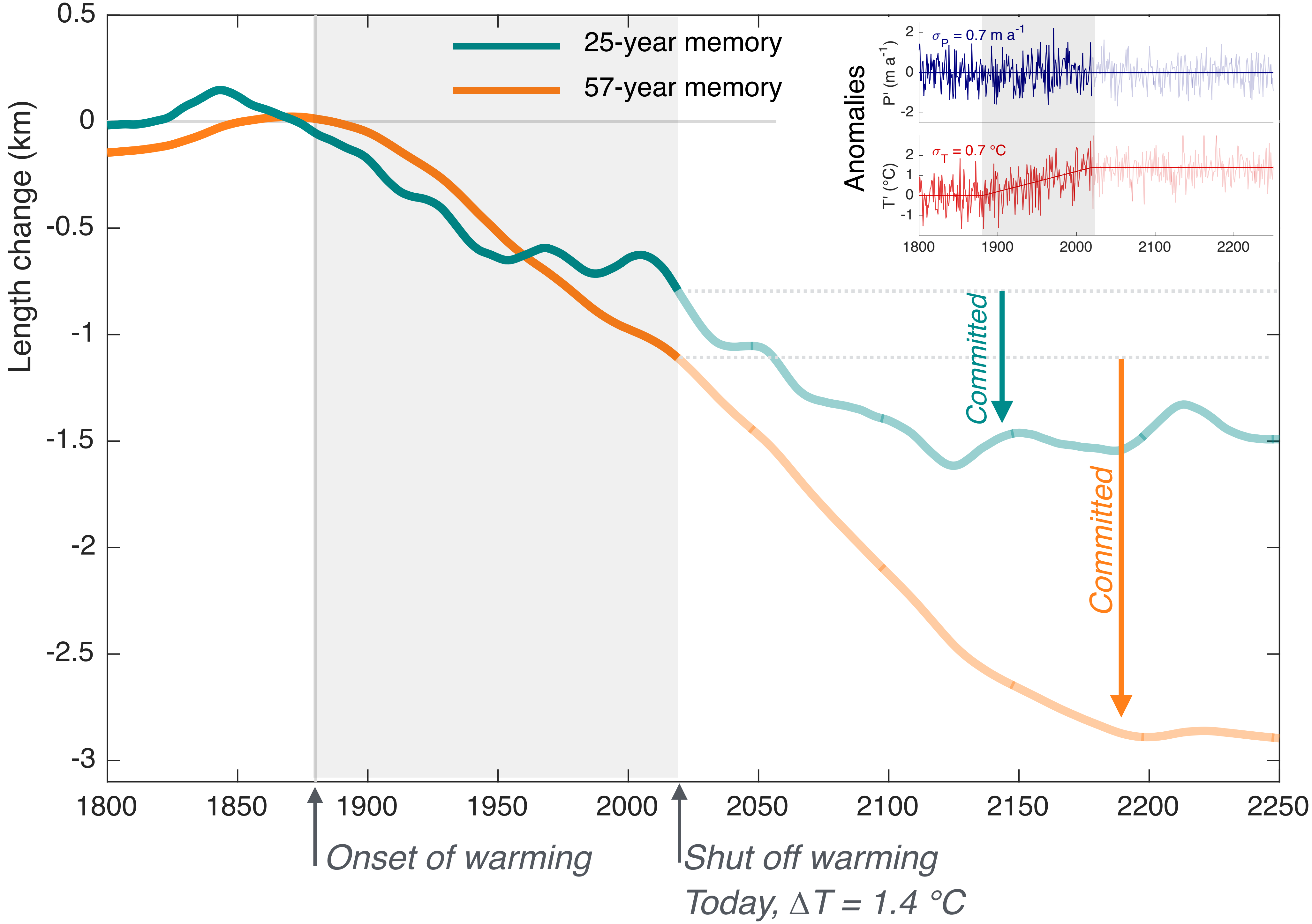
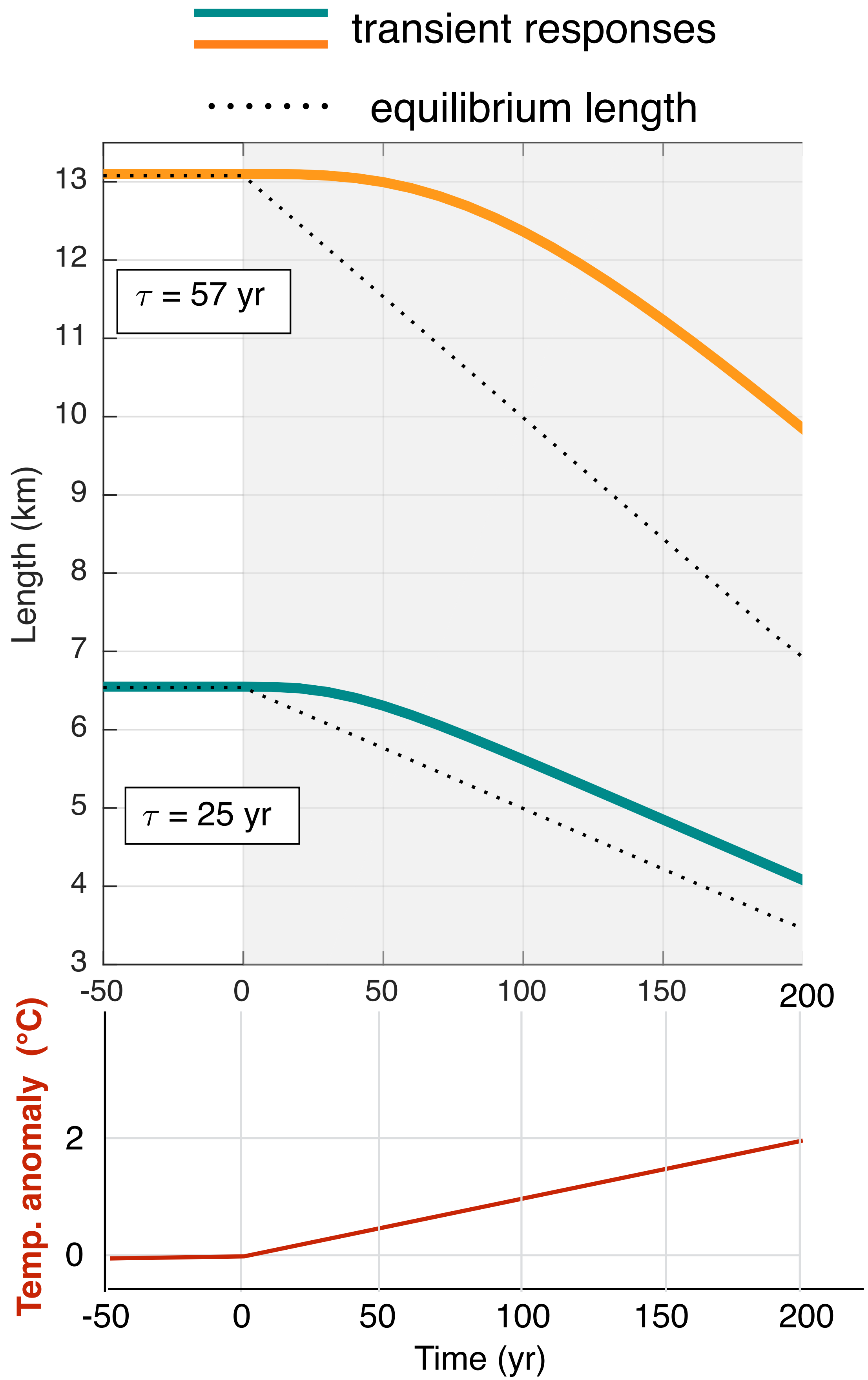
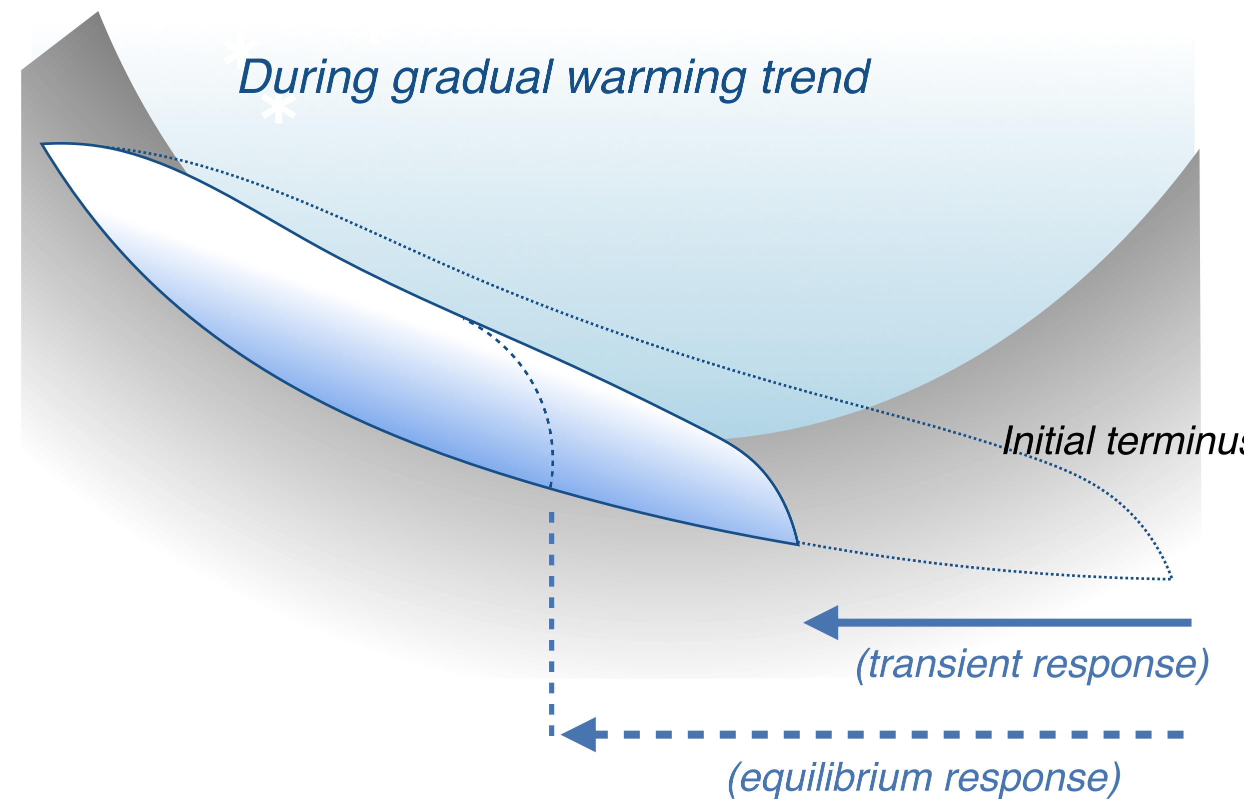
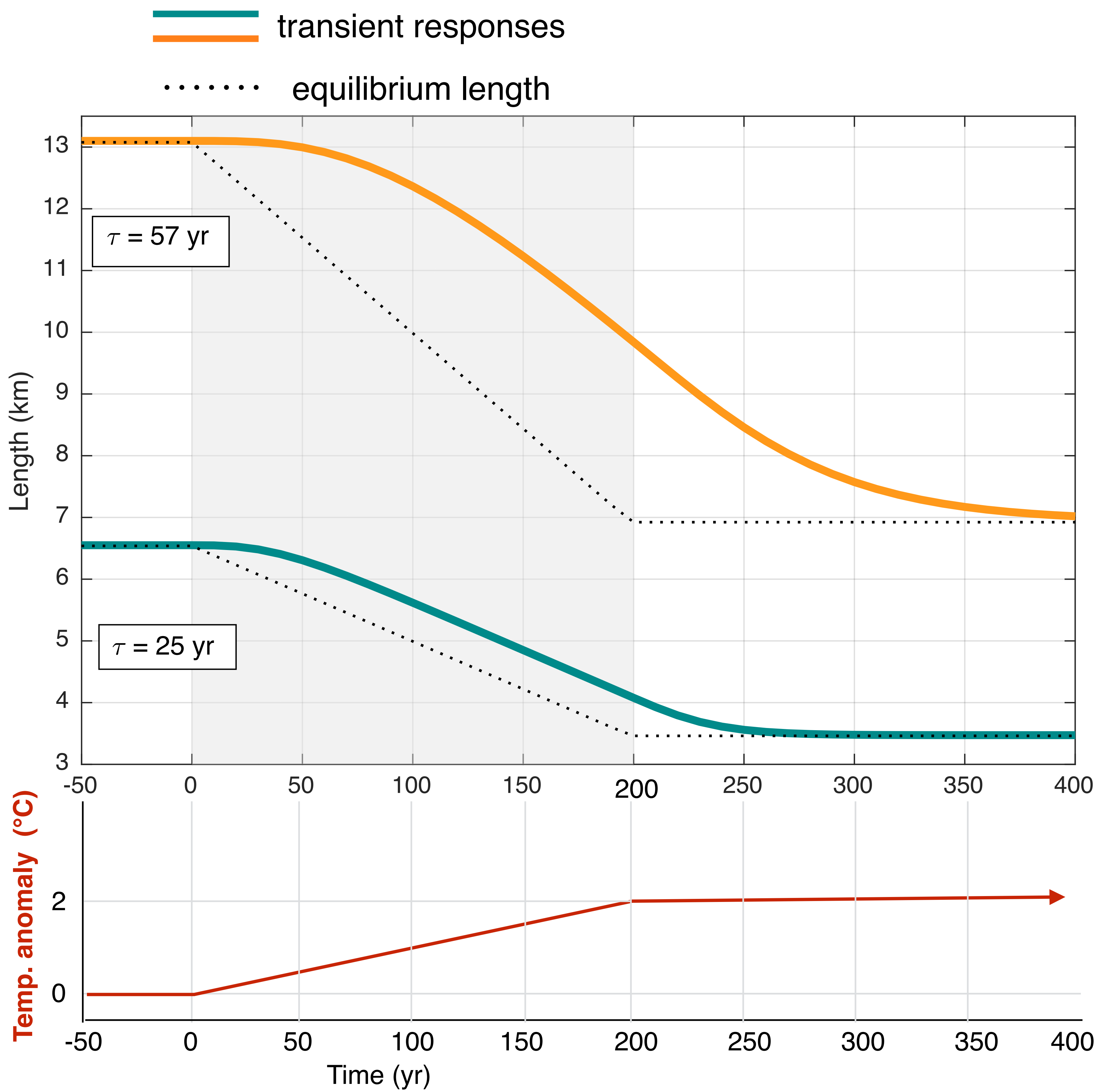


Many glaciers are committed to additional retreat, even with no further warming





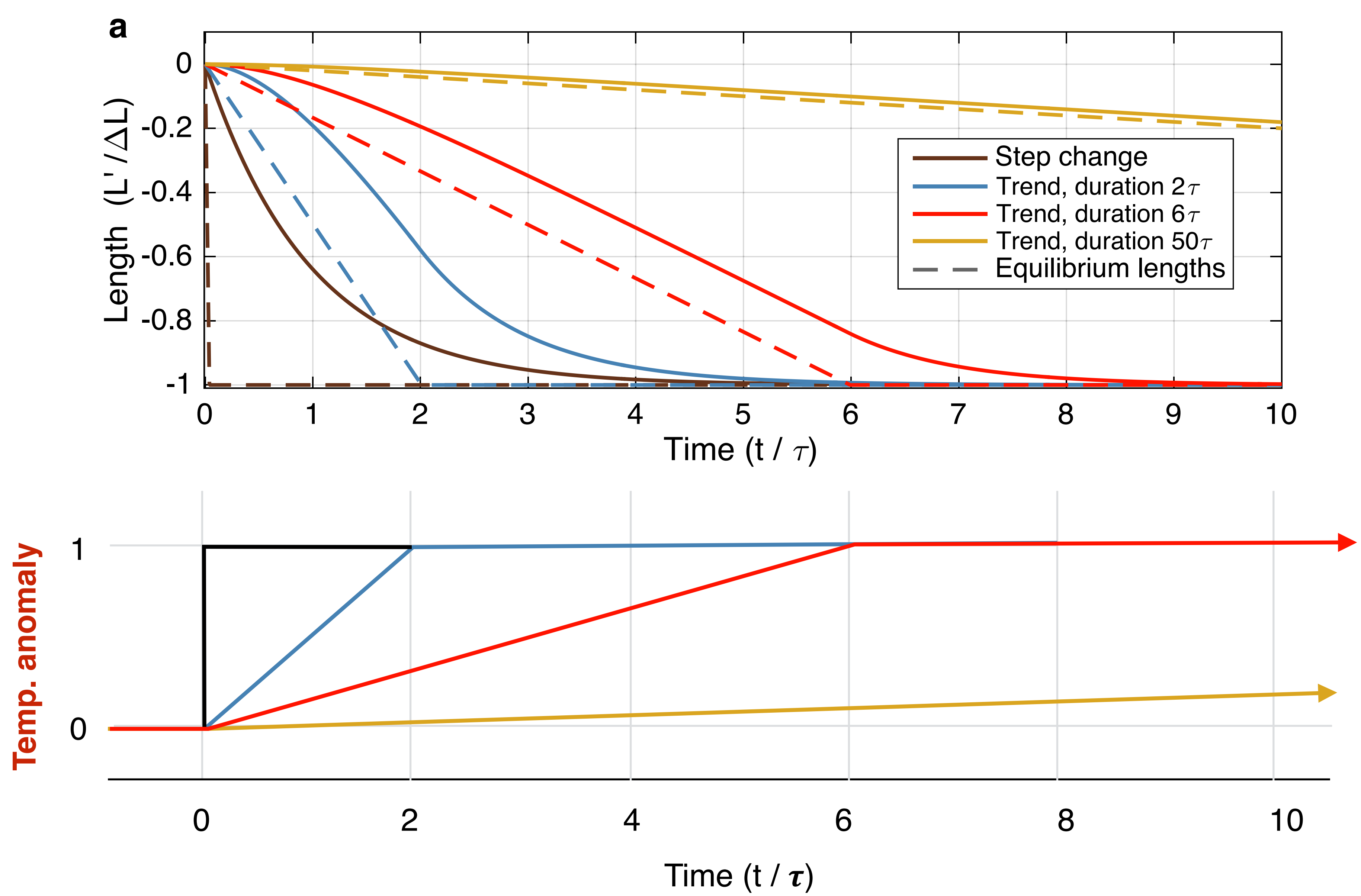
- multi-decade memory means that glaciers lag a warming trend
- difference between actual state and equilibrium depends on response time



- Glacier can’t catch up until warming stops…

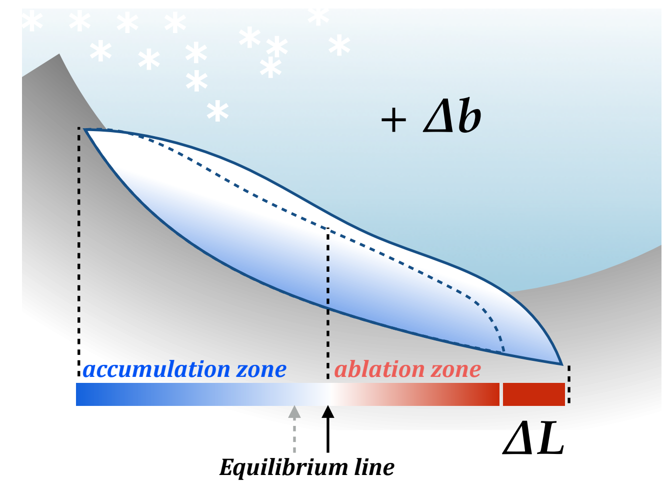
Lagging equilibrium response as a general principle

- Basic response of any system with memory
- This lag gets interesting when the trend hasn't lasted much longer than the memory
- Glaciers responding to ~a century of warming are in this sweet spot



Takeaways

- Glaciers respond to mass-balance changes by adjusting length to restore equilibrium:



- The timescale for these changes is ~decades for most mountain glaciers

$$\tau = -H/b_t$$

- Glaciers respond with slow fluctuations to natural variability…

- … and lagged responses to gradual trends

- Glaciers have “felt” anthropogenic warming, but are also committed to additional retreat