

# Water-terminating glaciers

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Introduction

Calving

Thinning-retreat-acceleration

Tidewater glacier cycle

Sub-aqueous melting

Relevance of submarine melting (Conclusion)

# Outline

## Introduction

## Calving

## Thinning-retreat-acceleration

## Tidewater glacier cycle

## Sub-aqueous melting

## Relevance of submarine melting (Conclusion)

# What makes water-terminating glaciers important?

- ▶ They are very common (This is a particular feature of the way glacier erosion works)
- ▶ They can behave seemingly erratic (advancing when all others are retreating, or vice versa)
- ▶ This makes all global assessments of glacier change challenging

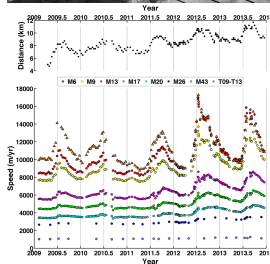
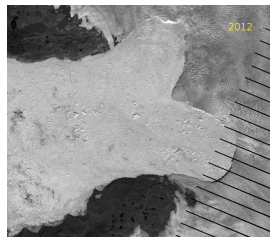
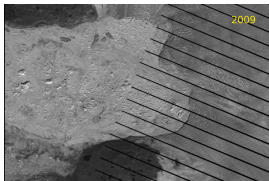
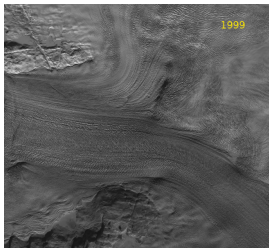


# What makes water-terminating glaciers interesting?

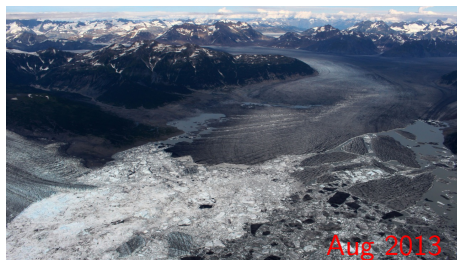
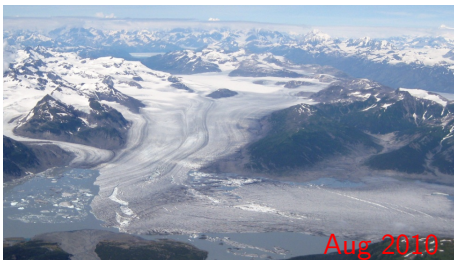
- ▶ They are spectacular
- ▶ They flow fast
- ▶ They change a lot
- ▶ Their behavior can be asynchronous with climate



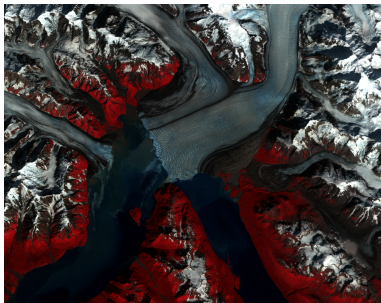
# Example: Jakobshavn Isbræ



# Example: Yakutat Glacier retreat



# Example: Hubbard Glacier

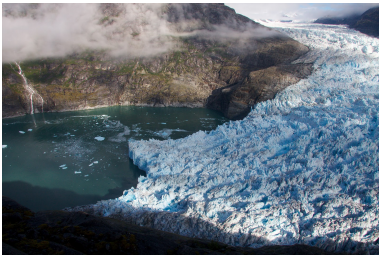


1986



2013

# Tidewater vs lake-calving



Similar water depths, but very different morphology, ice flux, etc

# Lecture goals

- ▶ Understand the *tidewater glacier cycle*
- ▶ Understand why a glacier can simultaneously thin, accelerate and retreat
- ▶ Think about the importance of sub-aqueous melting and how that can explain different morphologies of water-terminating glaciers

# Mass budget of tidewater and outlet glaciers

- ▶ Glaciers ending in water have a non-zero flux across their termini
- ▶ The magnitude of this flux can change rapidly
- ▶ In many situations the mass loss through discharge into the ocean is as important as surface melting and sometimes it dominates surface melting entirely.





Ice flux at Le Conte Glacier, SE Alaska



## Reason for variability

- ▶ The glacier front is a free boundary
- ▶ If ice supply is given by  $u$  and the calving velocity  $u_c$ , then the length of the glacier  $L$  is given by  $dL/dt = u - u_c$
- ▶ Generally, the length change of a glacier is one to two orders of magnitude smaller than either  $u$  or  $u_c$ .
- ▶ This indicates that ice velocity and calving fluxes are not independent of each other.
- ▶ But there are important exceptions to this, such as rapid collapses of floating ice



## Retreat of Columbia Glacier, Alaska

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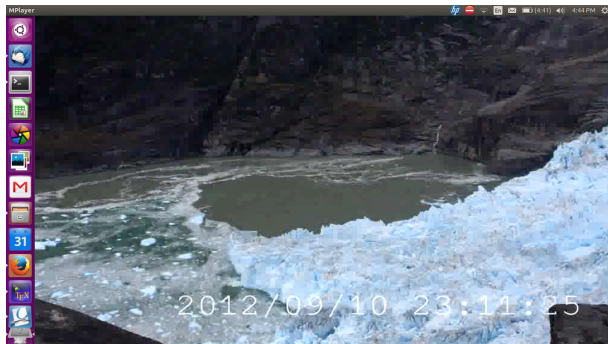
Tidewater glacier cycle

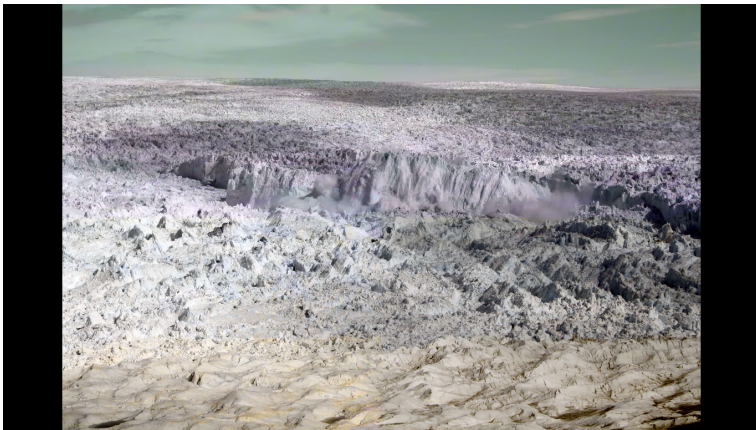
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Relevance of submarine melting (Conclusion)

# Calving

- ▶ Ice discharge consists of mechanical break-up and melting
- ▶ The combination of both is known as *Frontal ablation*
- ▶ Calving occurs at all sizes (power law?)





Whole thickness calving (Jakobshavn Isbrae, Greenland)

# Calving mechanisms

- ▶ Fracture mechanics
- ▶ Damage mechanics
- ▶ Empirical laws



# Calving mechanisms

## Linear Elastic Fracture Mechanics (LEFM)

- ▶ Crevasses open when tensile stress exceeds the fracture toughness (Mode I failure)
- ▶ The weight of the ice counteracts the tensile stress
- ▶ Water in crevasses helps opening crevasses
- ▶ Conclusion: Crevasses can propagate through the entire ice column, if sufficient water is present

# The Benn calving law

- ▶ If crevasses reach to the bottom of the ice the glacier calves
- ▶ Crevasse depth depends on strain rate and ice thickness
- ▶ Water helps crevasse penetration
- ▶ Benn postulate: If a crevasse reaches sea level, the glacier calves

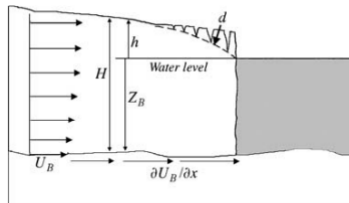


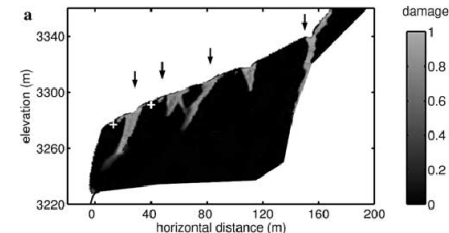
Fig. 12. Schematic illustration of first-order calving in response to longitudinal stretching. Surface crevasses propagate downward to a depth  $d$  in response to the velocity gradient  $\partial U_B / \partial x$ . Calving is assumed to occur when  $d = h$  (after Benn et al., in press).

Benn et al., 2007



# Damage mechanics

- ▶ Papers by Antoine Pralong (ETH Zürich)
- ▶ Introduce a new variable for damage  $\omega \in [0, 1]$ , where  $\omega = 0$  signifies total damage, i.e. a crevasse
- ▶ This has been used to model dry-calving at hanging glaciers
- ▶ There are efforts to introduce a damage variable into shallow shelf models



Pralong and Funk, 2007

# Empirical laws: Water depth

- Observation: Calving rate depends on height of water column
- This does not seem to work well on a rapidly retreating glacier

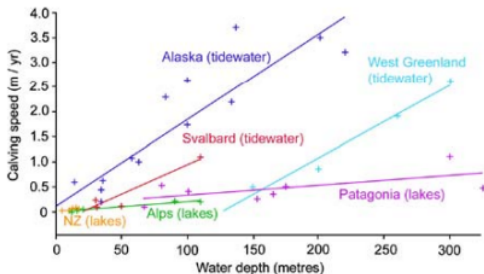


Fig. 2. Variation of calving rate with water depth for tidewater and freshwater calving glaciers in different regions. From Haresign (2004).

Benn et al., 2007

# Empirical laws: Floatation criterion

- ▶ Calving rate is such that a certain cliff height above floatation is maintained
- ▶ Works quite well for grounded tidewater glaciers, but does not allow floating tongues to develop
- ▶ Physical justification: Well grounded ice bergs do not easily calve, even if full thickness fracture has occurred.



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# Causes for changes in calving flux

- ▶ Break-up of ice shelves leads to large changes in ice flux
- ▶ This is known as the buttressing effect
- ▶ Examples: Larsen B Ice Shelf, floating tongues in Greenland

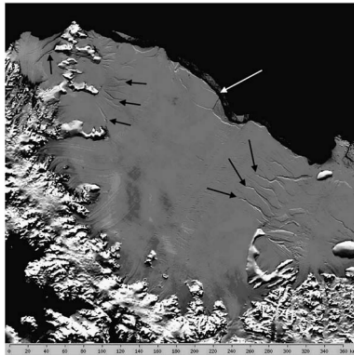
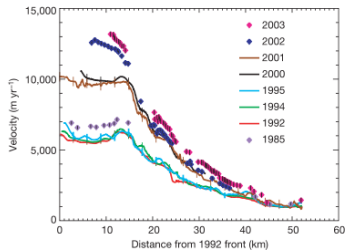


Fig. 7. MODIS image of Larsen ice shelf, Antarctic Peninsula. Prominent rifts (indicated by black arrows) occur in areas of high extending flow. Rift growth is in the process of isolating a large tabular berg (white arrow). Image from <http://nsidc.org> (Haran et al., 2005).

Benn et al., 2007

# Thinning and acceleration

- ▶ Basal motion is dependent on the effective pressure:  $p_{\text{eff}} = p_{\text{ice}} - p_{\text{water}}$
- ▶ Water pressure at the base of a tidewater glacier is determined by sealevel
- ▶ Thinning ice leads to lower overburden pressure, hence lower effective pressure, and therefore higher rates of basal motion
- ▶ Higher velocities lead to increased ice discharge and surface lowering
- ▶ This can lead to the disintegration of entire icefields.



**Figure 2** Profiles of speckle-tracked (see Methods), Landsat, airborne feature-tracked speed from along the line shown in Fig. 1a and as a function of distance from the approximate position of the 1992 calving front. One-sigma error bars are shown at several-kilometre intervals. The 1985 (ref. 6), 2002 and 2003 data sets were sparsely sampled, so only individual point measurements are plotted. The data were acquired over the periods from February to March 1992, December 1993 to March 1994, November 1995, October to November 2000, May 2001, July to September 2002, and March to May 2003.

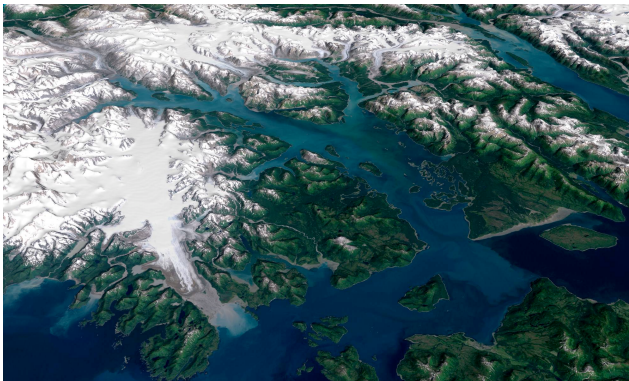
Joughin et al., 2004

## Flux vs thickness relations

- ▶ Pfeffer (2007, *A simple mechanism for irreversible glacier retreat*) derived a stability index for tidewater glaciers
- ▶ Ice flux depends on ice thickness in two ways: thinner ice decreases ice deformation, but it also reduces effective pressure leading to higher rates of sliding
- ▶ This can be formalized in a stability index by calculating  $\partial q / \partial h$
- ▶  $\partial q / \partial h < 0$  indicates unstable behavior

## Inland effects

Tidewater glacier retreat can lead to the disappearance of entire icefields.



Chris Larsen, UAF



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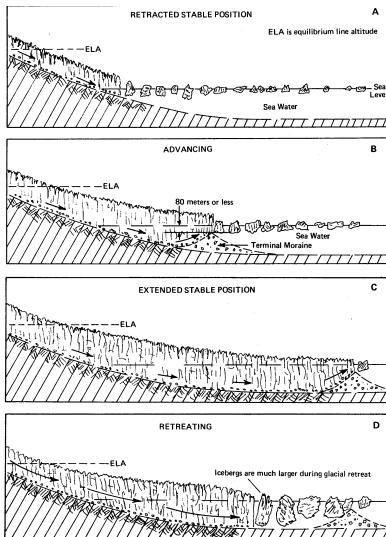
# The tidewater glacier cycle

The large dynamic influence of the ocean geometry can lead to glacier behavior that is sometimes de-coupled from climate and leads to the **tidewater glacier cycle**

- ▶ A tidewater glacier in retreat will continue retreat until calving stabilizes (shallow water or narrow fjord)
- ▶ At this point, the surface balance is often very positive
- ▶ The glacier starts advancing by protecting itself from deep water by pushing a terminal moraine
- ▶ The glacier reaches a state where the surface balance becomes near zero
- ▶ A period of warmer climate can now trigger a retreat
- ▶ This cycle can take decades or centuries.

# The tidewater glacier cycle

- Note that the AAR is *not* a good indicator of glacier health



## Glacier advance: Taku Glacier



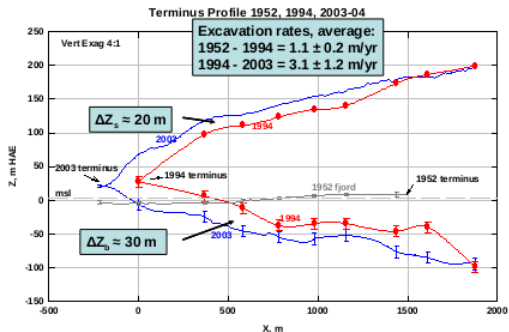
1905



1929

# Glacial erosion

- ▶ Proglacial moraines make glacier advance possible
- ▶ Advancing glaciers override and then excavate till
- ▶ This happens at rapid rates (up to meters per year)



*An integral part of the tidewater glacier cycle is bedrock evolution*

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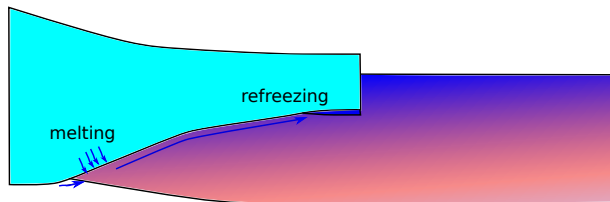
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# Thermodynamics

- ▶ Energy content of water (**temperature**): Water has a large specific heat
- ▶ Density structure of water (**temperature, salinity**) determines convection patterns and fluxes
- ▶ Polar oceans and fjords are density dominated by salinity, not temperature (cold fresh water overlies warm saline water)

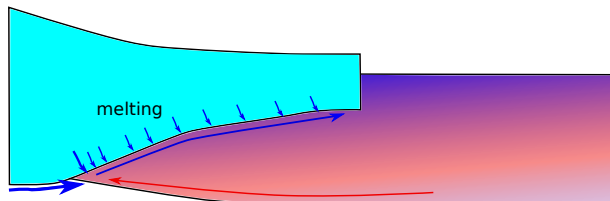
## Ocean terminating, floating tongue, cold



- ▶ Subglacial discharge is small
- ▶ Subshelf convection is primarily driven by buoyant meltwater
- ▶ Supercooled meltwater can lead to refreezing
- ▶ Example: Pine Island Glacier (melt rates  $10\text{--}20 \text{ m yr}^{-1}$  in channels, temp forcing  $1.5 \text{ K}$ , *Stanton et al., 2013, Science*)

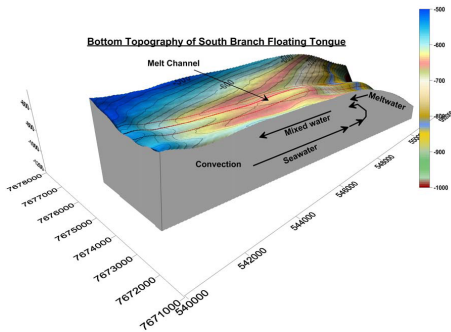


# Ocean terminating, floating tongue, warmer



- ▶ Subglacial discharge is larger
- ▶ Subshelf convection is primarily driven by subglacial freshwater exiting at the grounding line

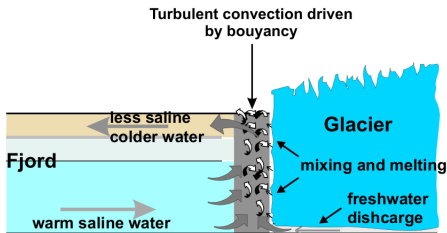
## Example: Jakobshavn Isbræ



- ▶ Meltrates exceeded  $200 \text{ m yr}^{-1}$  when floating tongue was seemingly stable (based on topography and velocity measurements from mid 1980s)
- ▶ An increase in temperature forcing by about 1 K led to an additional 70 m of thinning and break-up of the floating tongue
- ▶ This was followed by a doubling of ice flux

Motyka et al., 2011, JGR

# Ocean, grounded, warm



- ▶ Meltrates exceed  $10 \text{ m d}^{-1}$  and vary seasonally
- ▶ Temperature forcing is large (up to 10 K)
- ▶ Subglacial discharge is large

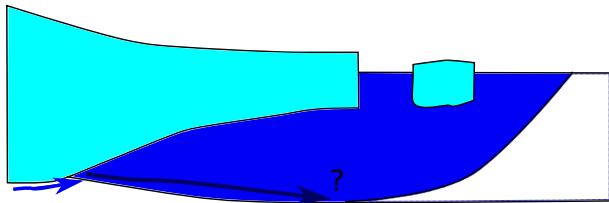
Motyka et al., 2003, 2013

## Example: LeConte Glacier, Alaska



Large discharge and strong currents

## Cold lakes



- ▶ Subglacial discharge can be large
- ▶ But: lake is cold and subglacial freshwater does not induce strong subshelf currents
- ▶ Example Yakutat Glacier: Lake temperature less than  $1^{\circ}\text{C}$ , thinning of tongue mainly by surface ablation; Trüssel et al., 2013
- ▶ Thinning is dominated by surface mass balance

## Bigger and warmer lakes

- ▶ Bigger lakes are likely to be warmer due to a large dark surface
- ▶ Bottom water is very likely to be  $4^{\circ}\text{C}$
- ▶ Subglacial discharge would be buoyant and temperature forcing significant
- ▶ Such lake terminating glacier should look more like tidewater glacier with less extreme forcing (Patagonia)

# Summary

- ▶ The difference in observed meltrates can be explained by differences in forcing (ambient water temperature, salinity and amount of freshwater discharge).
- ▶ This explains different morphologies of glacier termini.
- ▶ Ice temperature does play a role (greater structural integrity of a cold floating tongue)

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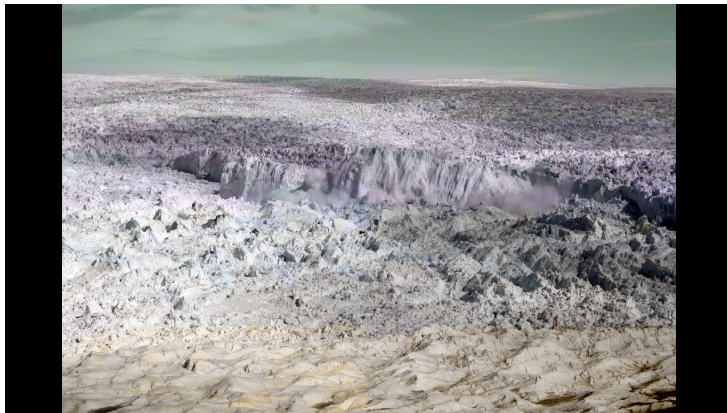
# Ocean, floating tongue

- ▶ Melting can occur along a large fraction of the ice underside
- ▶ Changes in forcing can have a large cumulative effect
- ▶ This can lead to a large scale destabilization of the floating ice
- ▶ Example: Jakobshavn Isbræ. This is possibly ongoing in the Amundson Sea Embayment (Thwaites Glacier has already lost floating ice, Pine Island might do so)
- ▶ Some ice shelves appear more stable at the moment (Ronne-Filchner, Ross)

## Ocean terminating and grounded

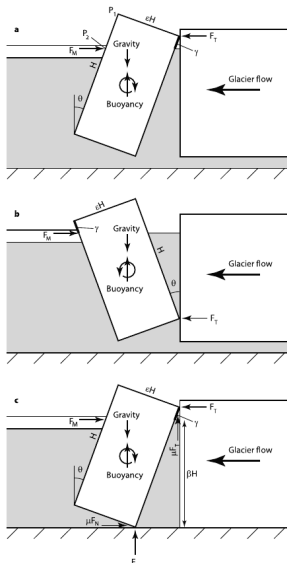
- ▶ Melting occurs over small area only (calving face)
- ▶ Melt rates are often very high (10s of m/d), but so are ice fluxes
- ▶ In some, but not all cases melting appears to be the dominant mechanism of frontal ablation (Motyka et al., 2003, 2013; Bartholomaeus et al., 2013)
- ▶ An indication is the amount of calving submarine ice

# Jakobshavn Isbrae



Ice velocity: 40 m/d, submarine melting: perhaps 1 m/d, melting is not directly relevant

# Jakobshavn Isbræ: The ice mélange



- ▶ Submarine melt does not appear to be directly relevant to calving (order of magnitude too small)
- ▶ However, strength of the proglacial mélange does appear to be relevant, and can inhibit calving (Amundson et al., 2010, JGR)
- ▶ Ocean conditions and melt thus exhibit an indirect influence on calving and ice flux

## Example: LeConte Glacier, Alaska

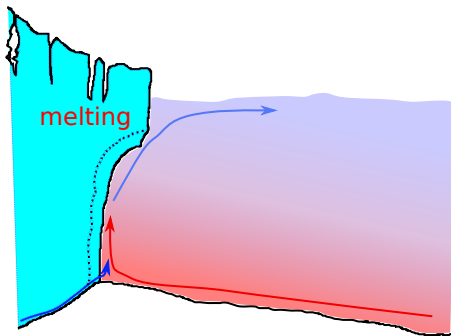


Ice flux and submarine melting are of similar magnitude, no evidence for submarine calving events (at certain times)

## Lake calving glacier

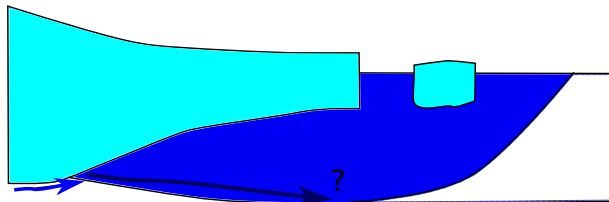
- ▶ For cold lakes, surface mass balance determines thinning and disintegration of floating ice (e.g. Trüssel et al., 2013)
- ▶ Glaciers calving into warmer lakes with  $4^{\circ}\text{C}$  bottom water might behave more like tidewater glaciers

## Temperate tidewater glaciers



- ▶ If a small floating tongue is formed, it will quickly melt and disintegrate
- ▶ This leads to large stresses and deformation rates in the terminus area
- ▶ Fast flow and high calving rates are the consequence

# Cold lakes



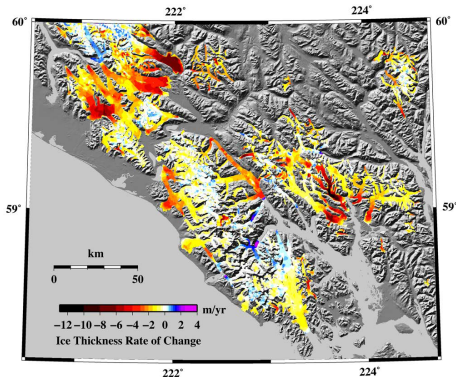
- ▶ Floating tongue can form
- ▶ Thickness gradients are smaller, decreasing strain rates and stresses
- ▶ There is less crevassing, slower flow, lower calving rates



## Some additional remarks: Fluxes at a terminus

- ▶ Terminus position change = Ice flux - Frontal ablation ( $\dot{L} = Q - F$ )
- ▶ These terms can be different by two orders of magnitude
- ▶ Example: Hubbard Glacier:  $\dot{L} \ll Q \approx F$ . This implies that ice flux and frontal ablation are not independent mechanisms
- ▶ Example: Jakobshavn winter advance:  $\dot{L} \approx Q \gg F$
- ▶ Example: Jakobshavn spring break up:  $\dot{L} \approx F \gg Q$
- ▶ This shows that various controls operate at different glaciers and at different times. This pertains to the master-slave discussion of Benn et al.

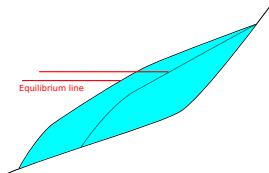
## Some more remarks: Sensitivity to change



Larsen et al., 2007

- ▶ Lake calving and tidewater glaciers can show large volume change signals
- ▶ But: many lake-calving glaciers have calving rates that are not very significant compared to surface ablation
- ▶ This can be understood in terms of 'macroscopic glacier theory' (e.g. Harrison, 2001, 2013; Lüthi, 2009)

# High sensitivity glaciers



- ▶ Retreat has two effects: loss of low altitude ice (negative feedback) and lowering of surface (positive feedback)
- ▶ Negative feedback is suppressed when the bed slope at the terminus is zero or negative
- ▶ Water terminating glaciers can react sensitively to changes (both positive and negative) in addition to the sensitivity imposed by calving