

Tidewater Glaciers: McCarthy 2018 Notes

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What makes water terminating glaciers special?

In a 'normal' glacier surface mass balance is always close to zero. That is, by the time ice arrives at the terminus of the glacier, there is not much ice left. In a water-terminating glacier, however, the surface mass balance can be very positive, and there can be significant ice fluxes at the terminus. This can result in some interesting behavior.

First, let's define a few terms:

- **Frontal ablation:** All loss of ice that occurs at the glacier front (F)
- **Calving:** Ice that is lost from the glacier front by mechanically breaking off (C)
- **Frontal melt:** Ice that is lost at the glacier front by melting (M)
- **Sub-shelf melt:** Ice that is lost through melt at the bottom of a floating tongue or ice shelf

The average rate of change of glacier front position dL/dt is given by the difference in average ice flow v and average frontal ablation f :

$$\frac{dL}{dt} = v - f \quad (1)$$

Many tidewater glaciers have very high rates of near-terminus ice flow as well as frontal ablation (order 10 m/d or 4 km/yr). Depending on the relative rate of frontal ablation and ice flow, such glaciers thus have the capacity to advance or retreat rapidly. Factors, such as proglacial bathymetry, water temperature, and water circulation in a glacial fjord can all play a role, and we therefore often encounter widely differing behavior amongst neighboring tidewater glaciers.

Some of the interesting behaviors of tidewater glaciers are:

- Some tidewater glaciers can retreat extremely rapidly (1 km/yr or more for many years). Examples are Columbia Glacier (> 20 km in 20 years); Glacier Bay (150 km in about 200 years); Jakobshavn Isbræ (15 km in 2-3 years), etc.
- Some tidewater glaciers advance in a regionally warming climate (Hubbard Glacier, Taku Glacier, etc).

- Both behaviors pose great challenges for assessments of future glacier change.
- Tidewater glaciers are among the most rapidly flowing glaciers in the world (> 40 m/d at Jakobshavn Isbræ)
- Rapidly changing tidewater glaciers exhibit a great influence on the physical oceanography of fjords and on fjord ecosystems, with important feedbacks

In summary, tidewater glaciers are spectacular, change rapidly, and are difficult to predict.

These notes will first address how rapid flow and ice retreat are connected, explain the tidewater glacier cycle, and touch on the importance of subaqueous melt.

The marine instability hypothesis

Many tidewater (and land terminating) glaciers have glacier beds that are overdeepened, that is, the base of the glacier is at a lower elevation upglacier from the terminus. This leads to interesting behavior, particularly for water-terminating glaciers. Retreat into deeper water can lead to increased ice flux, thinning, and further retreat. This positive feedback is known as the marine instability hypothesis (Weertman) or simply rapid tidewater glacier retreat (Austin Post). Many believe that the marine instability mechanism is already underway in parts of West Antarctica (particularly Thwaites and Pine Island Glaciers). In non-polar areas it has been observed in many places; the best documented is Columbia Glacier in Alaska.

The simultaneous occurrence of rapid retreat, thinning, and acceleration might appear non-intuitive. Shouldn't flow acceleration lead to a glacier advance?

Ice thinning can have two different consequences: On the one hand thinner ice is expected to deform less and therefore lead to glacier slow down; on the other hand thinner ice leads to smaller effective pressure at the glacier bed, which leads to an increase in basal motion and therefore glacier acceleration. The relationship between effective pressure and basal motion is generally believed to be very non-linear as effective pressures become very close to zero. For such glaciers, thinning will lead to acceleration, retreat (mechanical instability) and further thinning (because of the high ice fluxes).

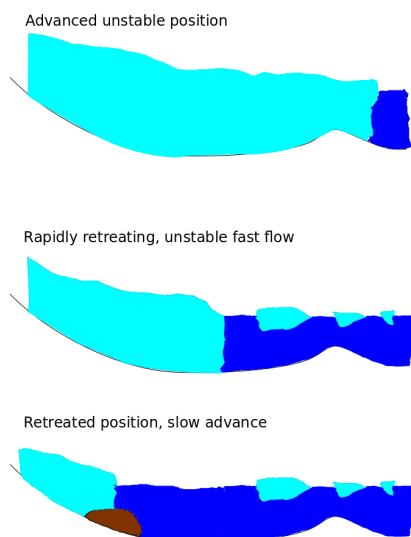
Pfeffer (2007, JGR) introduced a stability parameter that determines whether a glacier will react to an ice thickness change in a stable or unstable manner. The parameter is given by $\frac{\partial q}{\partial h}$ (q is the ice flux and h ice thickness), which can be evaluated with some assumptions about basal motion.

Take home point: A glacier in the 'right' (or wrong!) geometrical configuration can be subject to a positive feedback involving thinning, acceleration, and retreat

Such a feedback might only be stopped as a glacier reaches a pinning point (lateral constriction) or retreats onto land.

The tidewater glacier cycle

The marine instability leads to the idea of the tidewater glacier cycle, which goes back to Austin Post. It involves the idea of a cyclical behavior, much of which occurs independently of current climate.



- In the advanced unstable position the glacier rests on a shallow sill and the surface mass balance is very nearly zero. At this stage, the glacier is susceptible to changes in either frontal ablation or surface mass balance.
- Once retreat is underway, the glacier is subject to the marine instability mechanism, until it reaches a sufficiently shallow or constricted area
- Glacier advance becomes possible when the glacier produces sufficient sediment to build a shoal that protects the terminus from large rates of frontal ablation.

For non-polar tidewater glaciers, typical time scales for retreat are decades to centuries. Advances can be an order of magnitude slower.

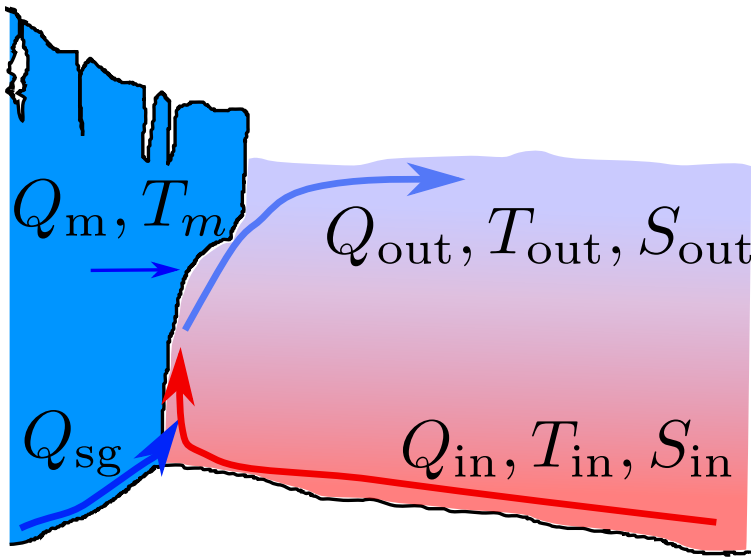
Subaqueous melting and the importance of water temperature

An important finding of the last decade or two is that, in many instances, frontal ablation is dominated by subaqueous melt, which is driven by both ocean temperature and freshwater discharge driven ocean circulation. That is, mechanical calving is often like the proverbial tip of the iceberg: much of the action happens with submerged ice. Many questions remain, such as:

- Even if ocean melting is large, is it driving glacier change?
- What are the relative roles of glacier dynamic adjustments versus ocean-forced retreat?
- Can warming oceans serve as a trigger for rapid tidewater glacier change?
- What does it take to stop or reverse a tidewater glacier in rapid retreat?

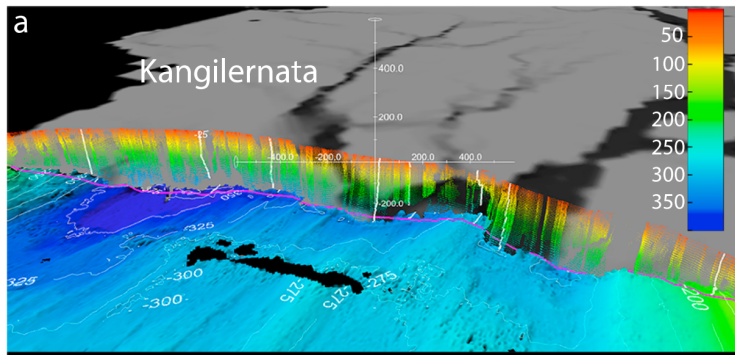
Temperate tidewater glaciers without floating tongues

Most temperate tidewater glaciers do not have floating tongues, or only for short times. Ocean-driven melt is determined by water temperature and freshwater discharge induced fjord circulation:



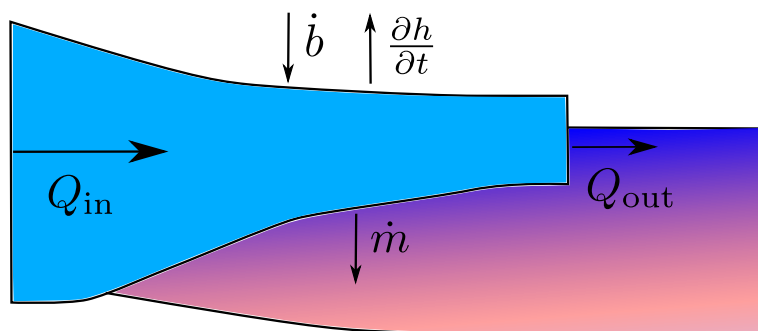
Motyka et al. (2003, Ann. Glac.) pioneered this method at LeConte Glacier and variations have been applied in many places since, finding area-averaged melt rates of up to 10 m/d; often a large proportion of the total ice flux.

This is a very active field of research. A current highlight is the capability to image the ice face with multibeam methods (e.g. Rignot et al., GRL, 2015), revealing large subglacial channels and overhanging ice faces:



It is an open research question to what degree mechanical calving is simply a reaction to undercutting.

Floating shelves or ice tongues



Melt rates under ice shelves can be derived from mass balance methods. In some settings they can reach very high values (> 200 m/yr at Jakobshavn Isbræ before its break-up). Such floating tongues appear very vulnerable to ocean warming. It is generally believed that warmer ocean water led to the breakup of many floating ice tongues in Greenland.

Take home points

- Tidewater glaciers flow fast, change rapidly, and often in unexpected ways.
- Tidewater glaciers are subject to instabilities, involving rapid retreat, flow acceleration and thinning. In extreme cases this can lead to the disappearance of entire glacier systems
- Tidewater glaciers can be subject to cyclical behavior that is modulated by climatic conditions. Sediment dynamics are an integral part of this cyclicity.
- Ocean-ice interactions play a crucial role: Ocean dynamics determines ice melting, subglacial discharge drives ocean circulation, and marine ecosystems are heavily influenced by the glacier-ocean interaction.