Targeted Ice Sheet Conservation through Seabed Anchored Curtains

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Societal Vulnerabilities to Sea Level Rise

~1 m SLR in 2100, with no coastal protection:
- ~1 million people per year permanent forced migration
- 100-500 million people per year temporary displacements
- ~$50 trillion per year damages
- Destruction of coastal communities, small island states
- Loss of wetland ecosystems

With coastal protection:
- $20-70 billion per year spent on protection
- ~100k people per year peak forced migration
- 10's of k people per year persistent forced migration

Nicholls et al., 2008; Hinkel et al., 2014; Jevrejeva et al., 2016

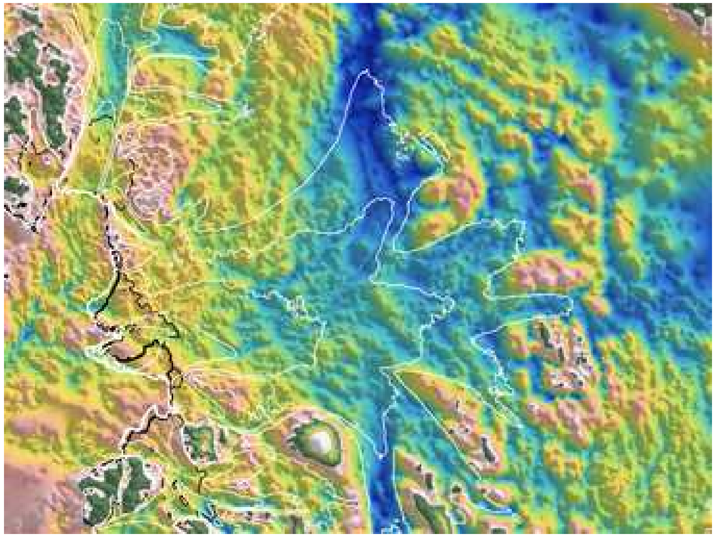
Potential for Ice Sheet Collapse: Theory

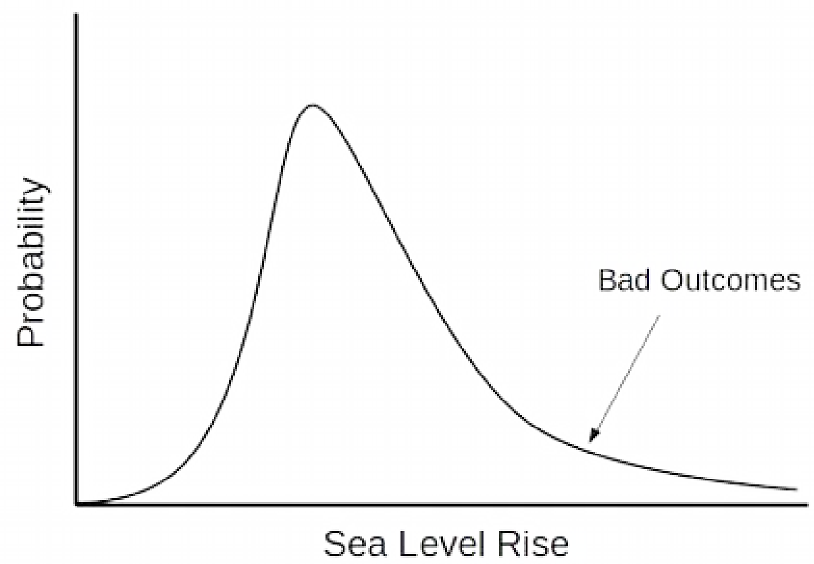
1. The Marine Ice Sheet Instability (MISI) has a long history in the glaciological literature (e.g. Hughes, 1973; Weertman, 1974; Thomas and Bentley, 1978; Schoof, 2007).
2. Some factors are known to protect against MISI, such as lateral buttressing from a confined shelf and central trough (Gudmundsson et al., 2012) or gravitational and isostatic effects (Gomez et al., 2010). However, Thwaites (the most at-risk glacier) does not have a deep stabilizing trough or a well-confined shelf.
3. During a collapse, the probability distribution of sea level rise becomes both broader (ie, more uncertain) and skewed towards higher values (Robel et al., 2019). Small perturbations early in the retreat become amplified by the instability into large differences in ice sheet geometry later in the collapse, creating a “long tail” of dangerously rapid sea level rise that cannot be ruled out.

Potential for Ice Sheet Collapse: Theory

In other words,

Thwaites basal topography



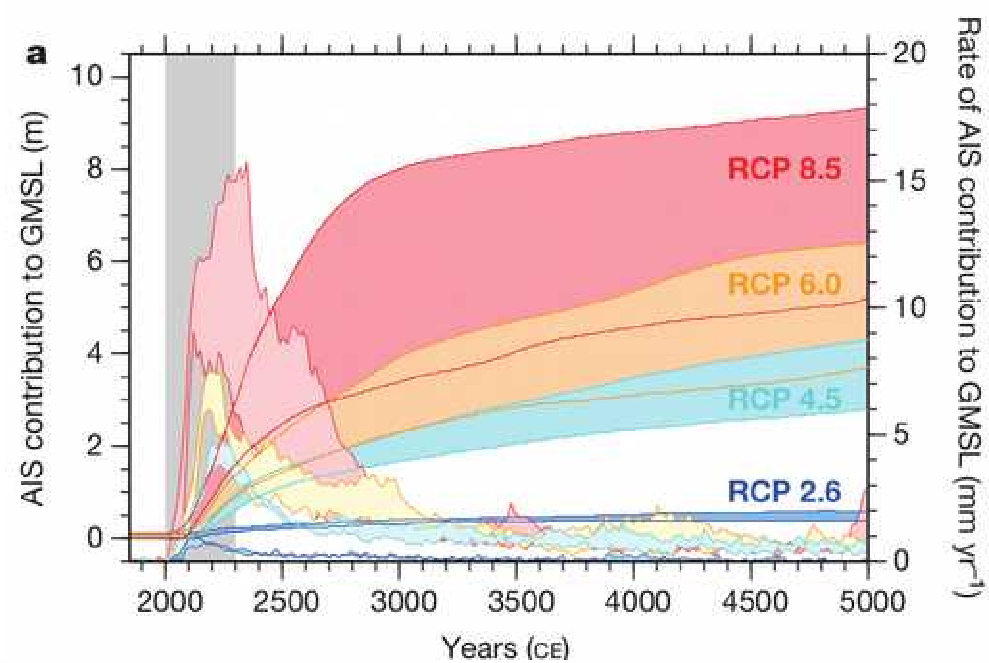


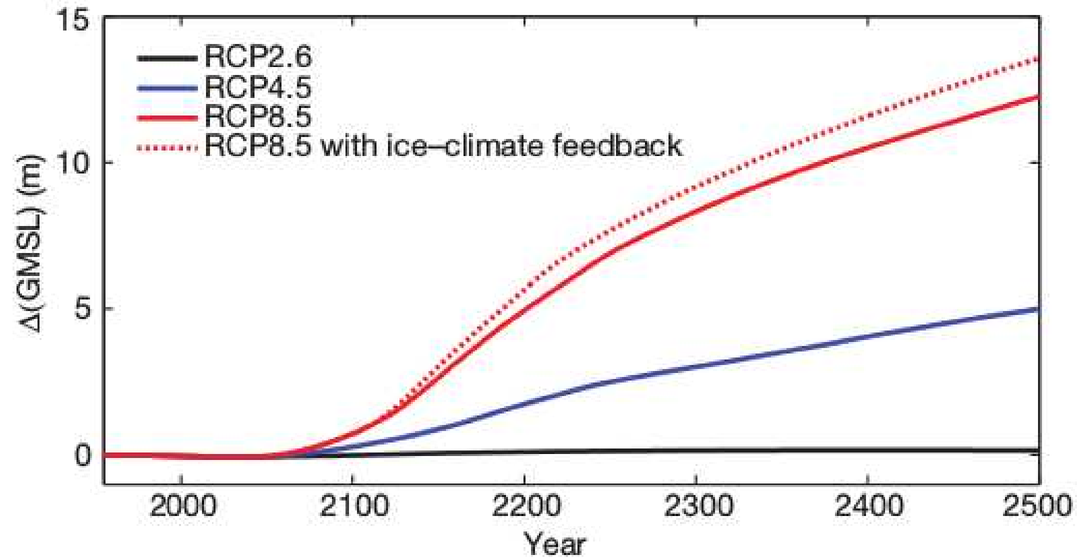
This...

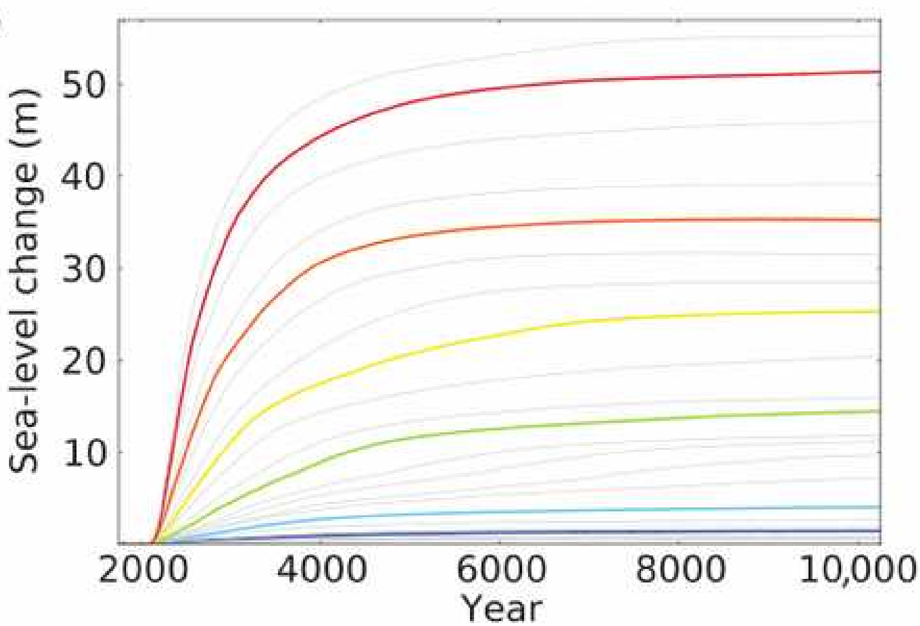
...leads to this...

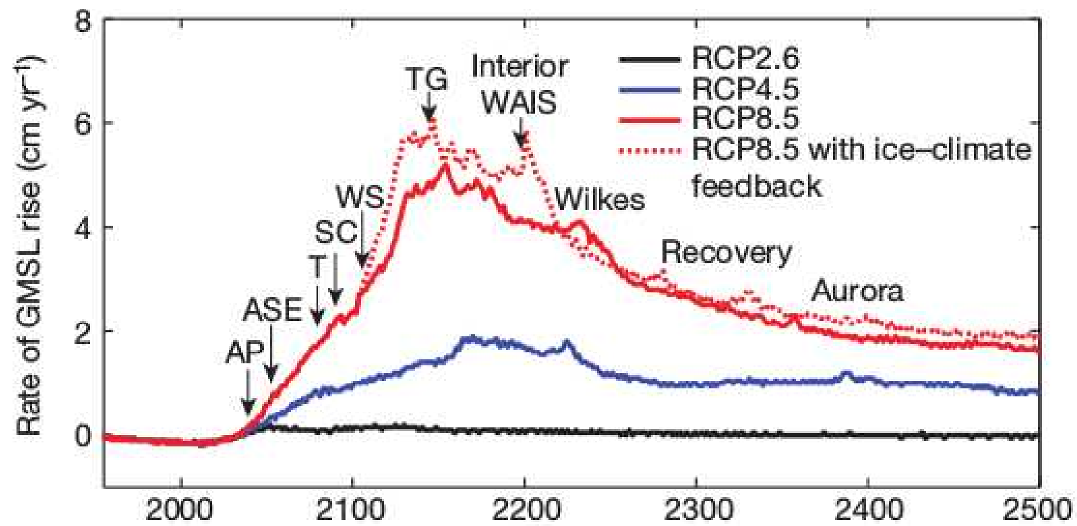
...which leads to serious societal risks that cannot be ignored

Potential for Ice Sheet Collapse: Models









Note: all of these models predict SLR rates of at least 1 m/century between 2100 and 2400

Winkelmann et al., 2015; Golledge et al., 2015; DeConto and Pollard, 2016

Potential for Ice Sheet Collapse: Present Situation

nature climate change LETTERS
PUBLISHED ONLINE: 12 JANUARY 2014 | DOI: 10.1038/NCLIMATE2094

Retreat of Pine Island Glacier controlled by marine ice-sheet instability

L. Favier[1,2], G. Durand[1,2]*, S. L. Cornford[3], G. H. Gudmundsson[4,5], O. Gagliardini[1,2,6], F. Gillet-Chaulet[1,2], T. Zwinger[7], A. J. Payne[3] and A. M. Le Brocq[8]

Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011

E. Rignot[1,2], J. Mouginot[1], M. Morlighem[1], H. Seroussi[2], and B. Scheuchl[1]

[1]Department of Earth System Science, University of California, Irvine, California, USA, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica

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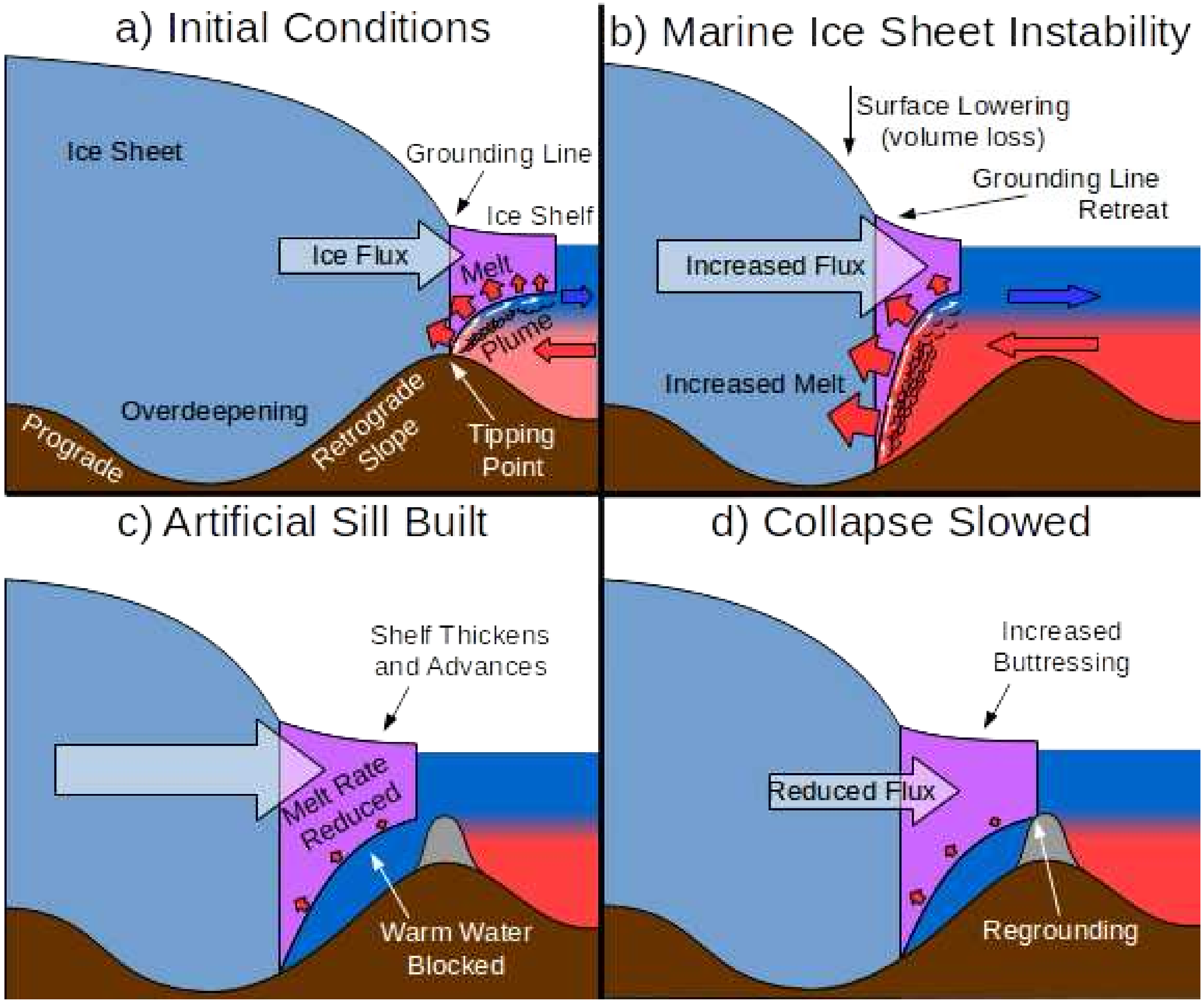
- Amundsen sector is presently retreating and losing mass
- Thwaites glacier is severely overdeepened with little lateral buttressing
- Multiple plausible papers in the literature suggest that collapse has already begun
- Even if we don't know for sure that a collapse is underway, the plausible risk is enough to justify contingency planning

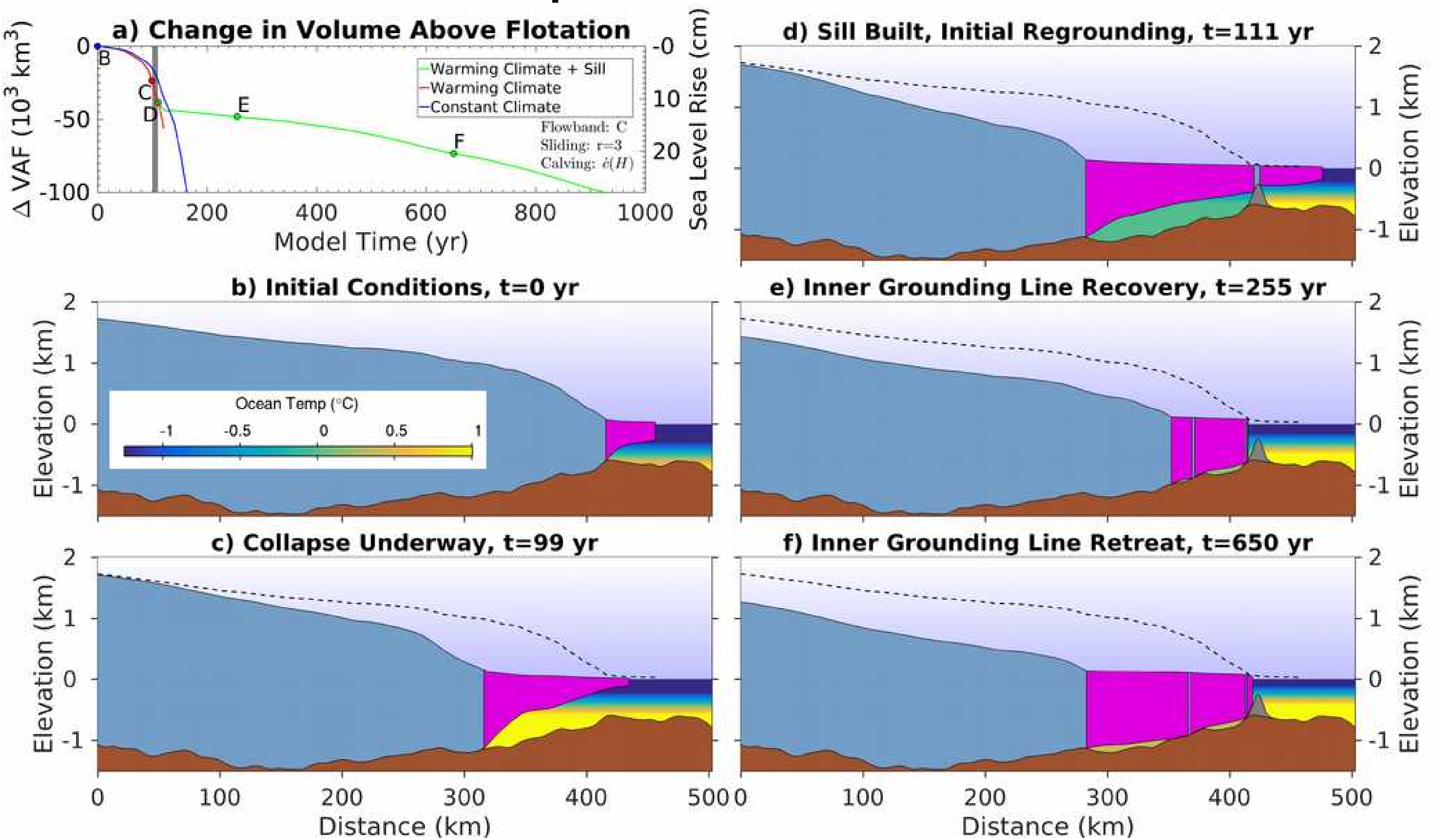
Potential Solution: Targeted Intervention?



Our first idea was for an artificial sill that would both block warm water and provide buttressing to the ice shelf

Wolovick and Moore, 2018

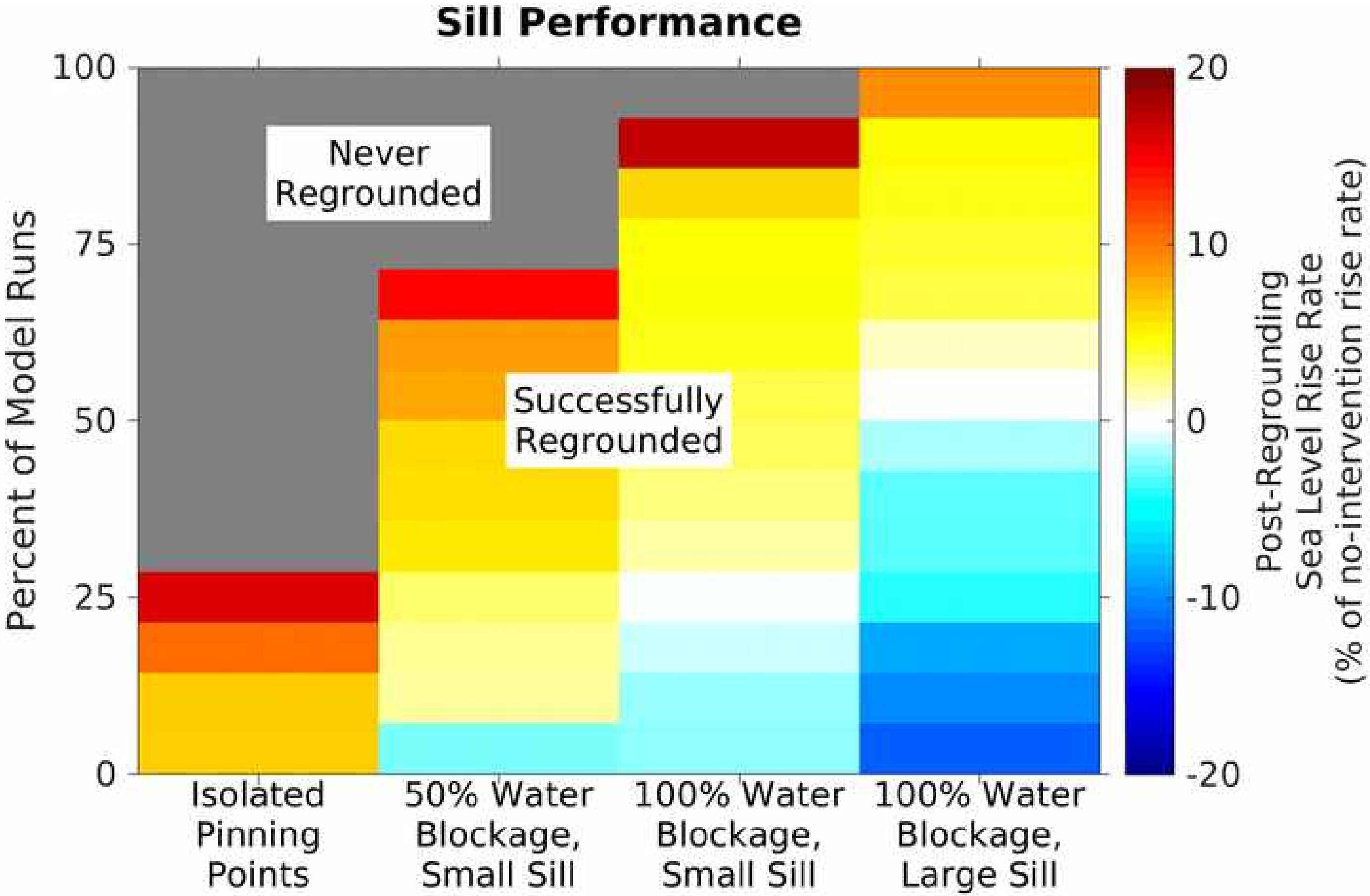
Example Model Results



A reduction in basal melt rate during retreat leads to an enlargement of the ice shelf, regrounding, buttressing, and thus a slowdown or reversal in the retreat

Wolovick and Moore, 2018

Effectiveness Summary

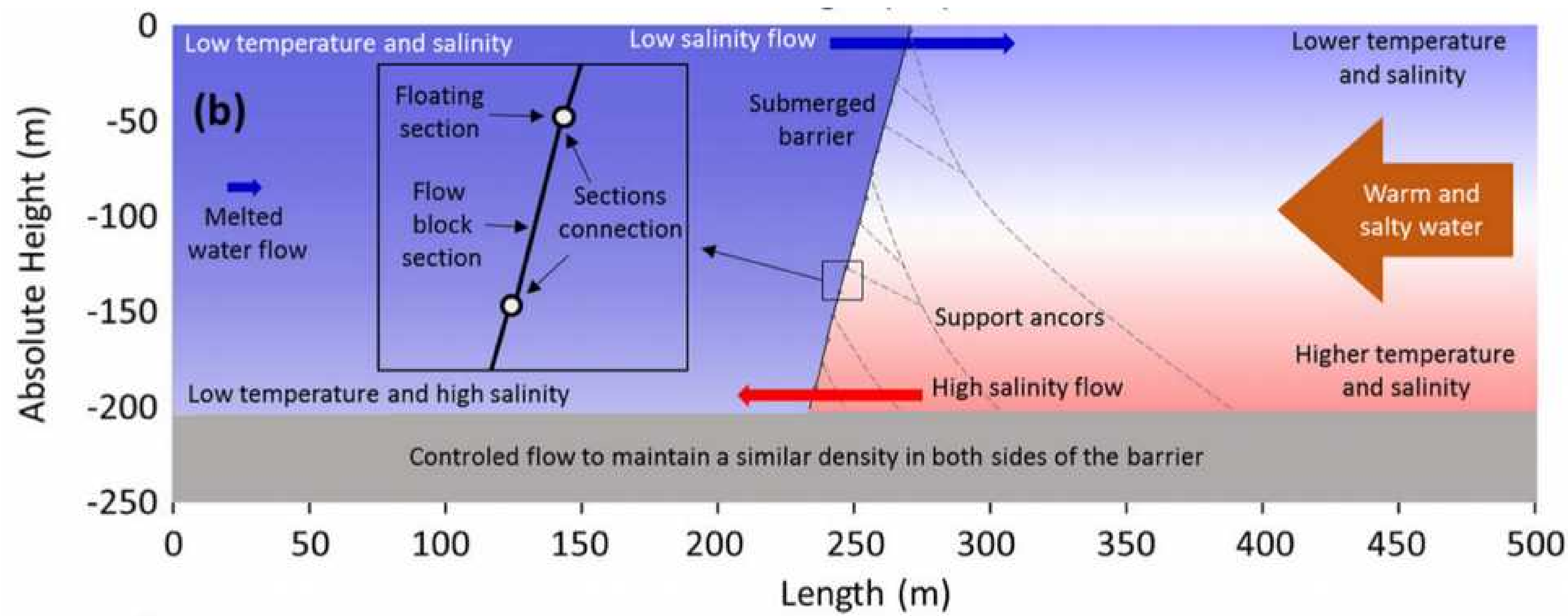


Dynamic factors favoring a successful intervention:

1. Buttressing (high bathymetry to reground on)
2. Water blocking (melt reduction)

Wolovick and Moore, 2018

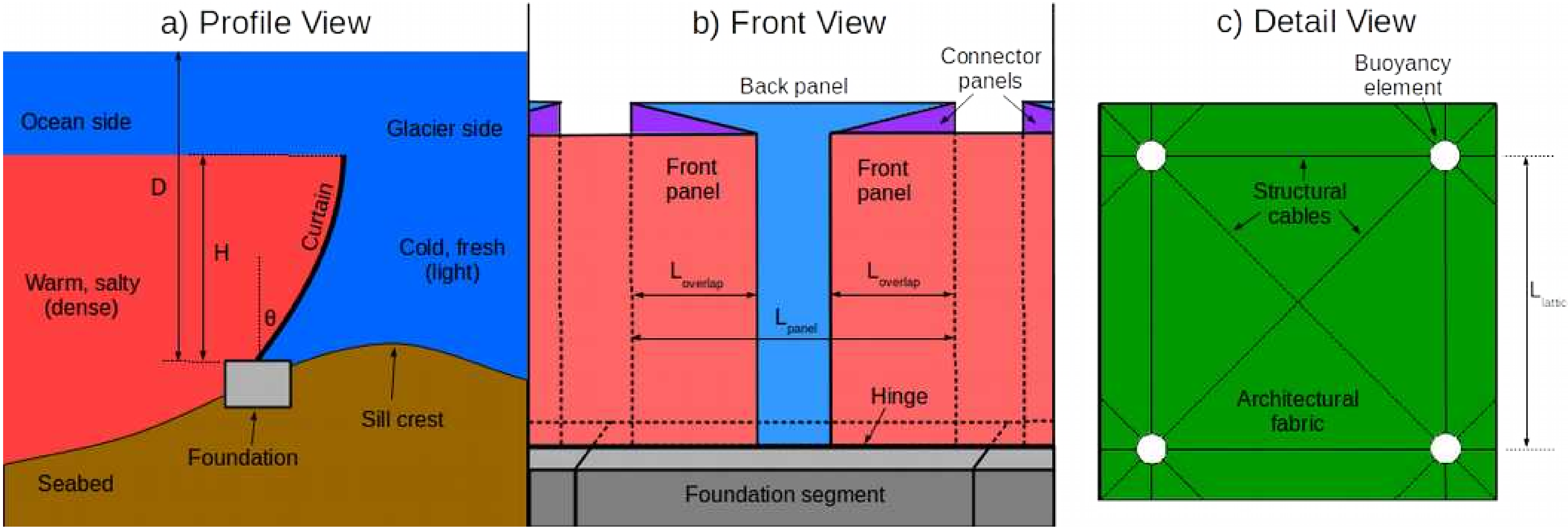
Thin Metal Barriers



- Others compared earthen dams (sills) with thin metal barriers for water blocking, and found that thin barriers are much cheaper.
- Thin barriers are also more easily removable in the event of unforeseen consequences.
- Both sills and thin barriers must still address iceberg impacts.
- Those results inspired our next design iteration...

Hunt and Byers, 2018

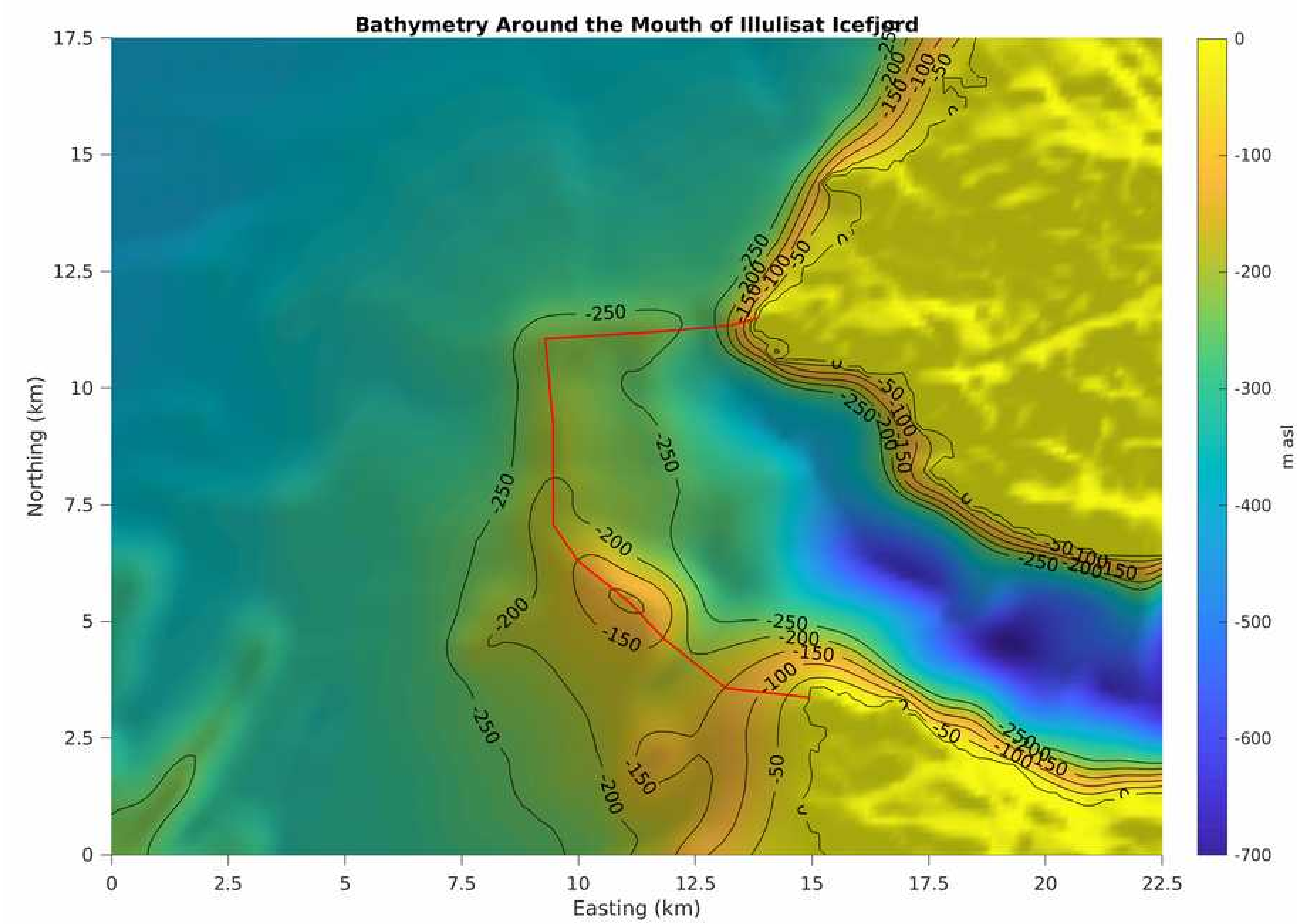
Seabed Anchored Curtains



Key Features:

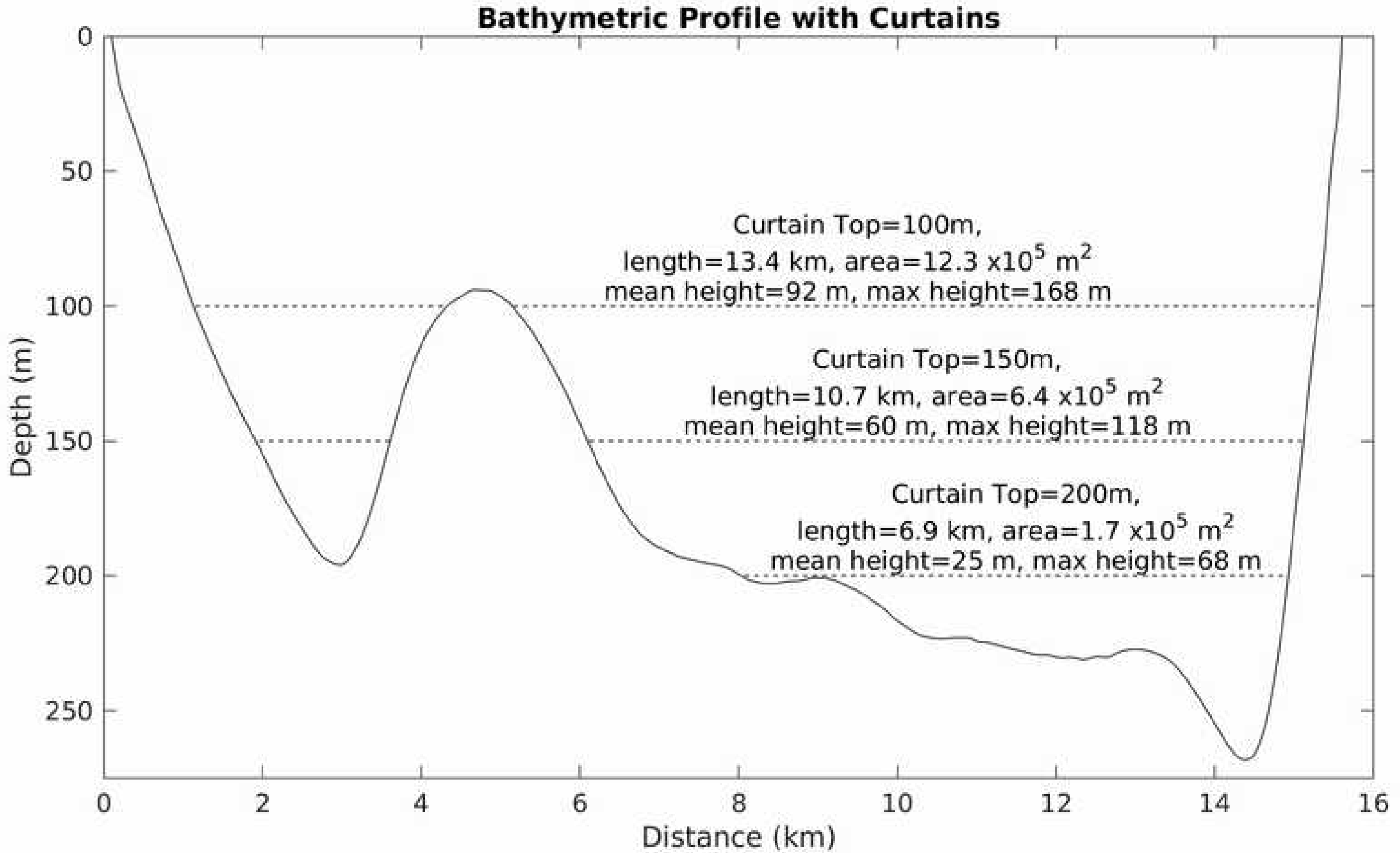
1) Flexible buoyant curtains anchored to the seabed, terminate in the thermocline
2) Equilibrium lean angle determined by balance between curtain buoyancy and ocean pressure difference
3) Flexible curtain hinges freely to allow it to accommodate iceberg impacts
4) Pleated geometry (b) allows for extra curtain area and increased deformation during iceberg encounters (with other configurations being considered)
5) Small-scale structure (c) includes buoyancy elements, structural cables, and durable tensile fabric (ex: PTFE coated glass cloth)
6) Structural loads (and therefore most components of the cost) scale with H^2

Potential Route at Ilulissat Mouth



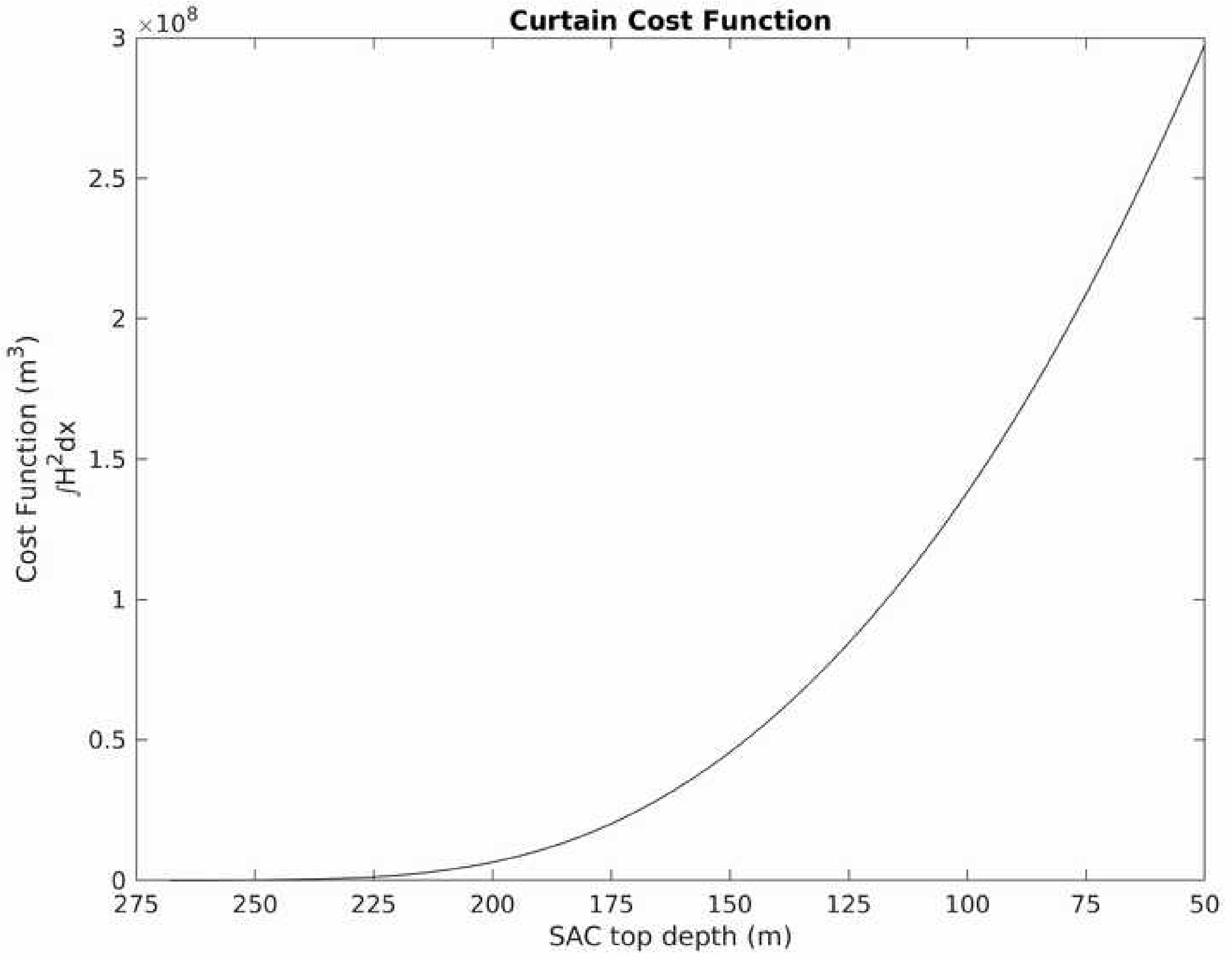
Bathymetry from Bedmachine_v3 (Morlighem et al., 2014, and updates)

Potential Route at Ilulissat Mouth



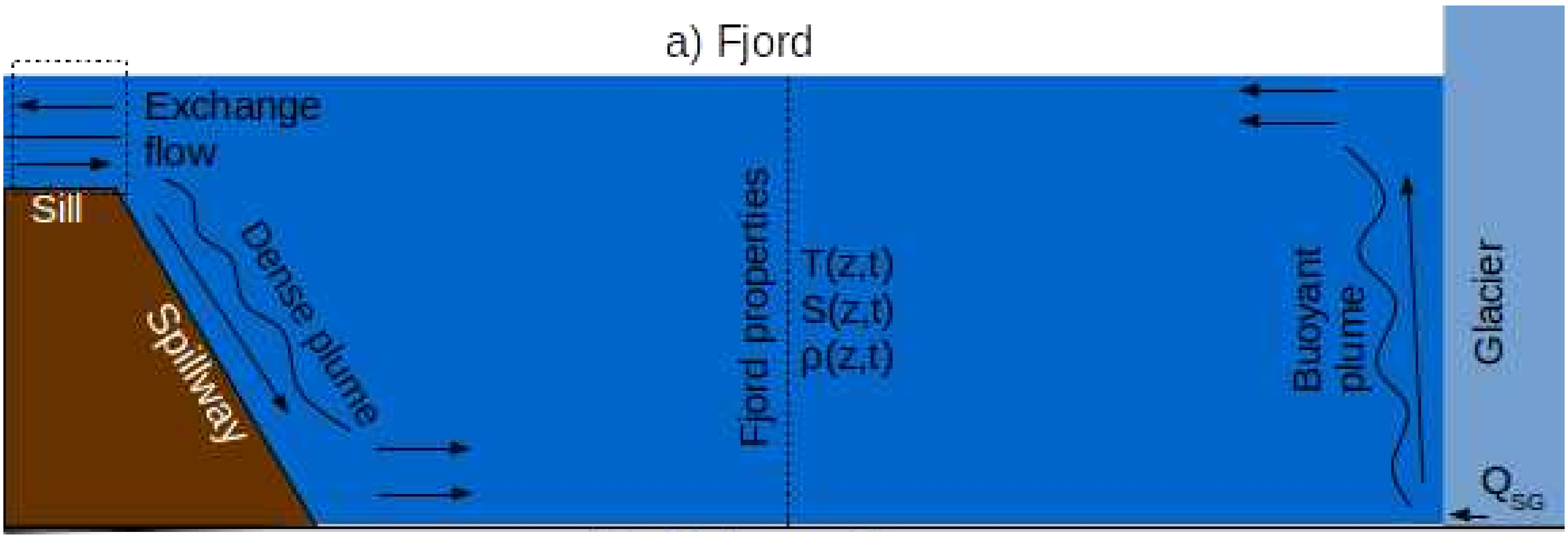
Bathymetric profile extracted along the path in the previous slide, with three potential curtain levels shown

Potential Route at Ilulissat Mouth

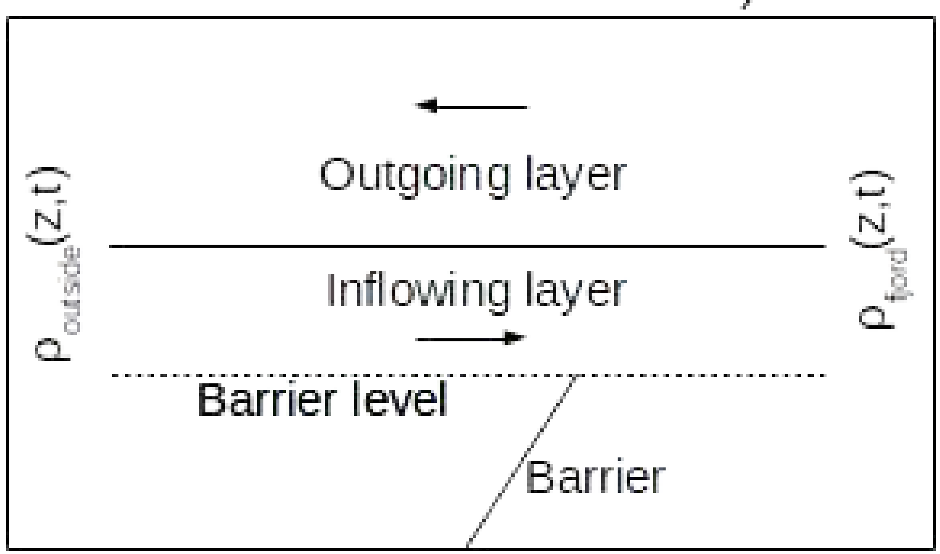


Curtain cost function defined as the integral of H^2 along the route of the curtain, because structural loads scale with H^2. Actual costs require far more analysis to estimate.

Model Description



b) Exchange Flow

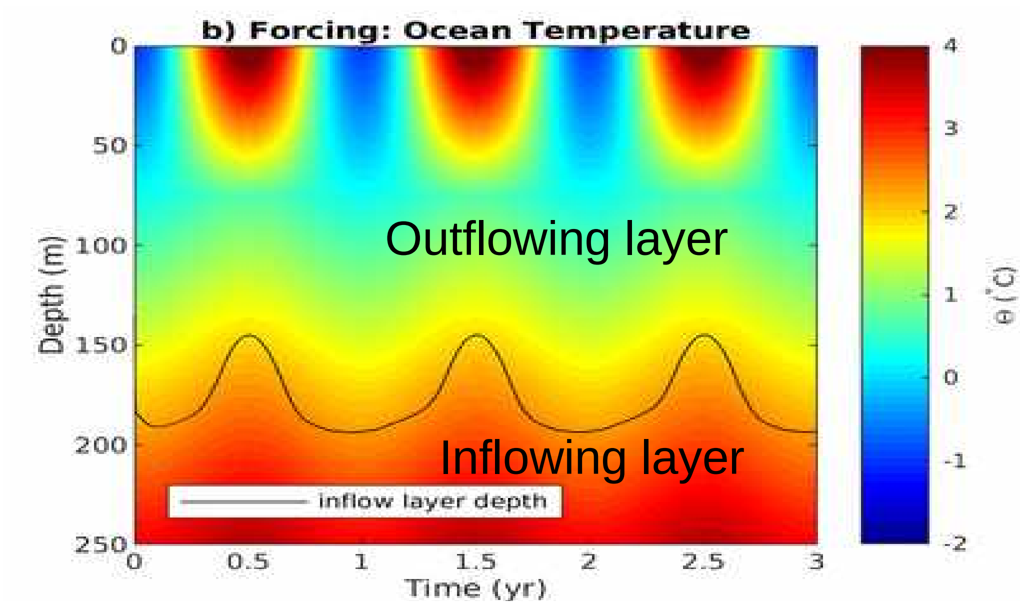


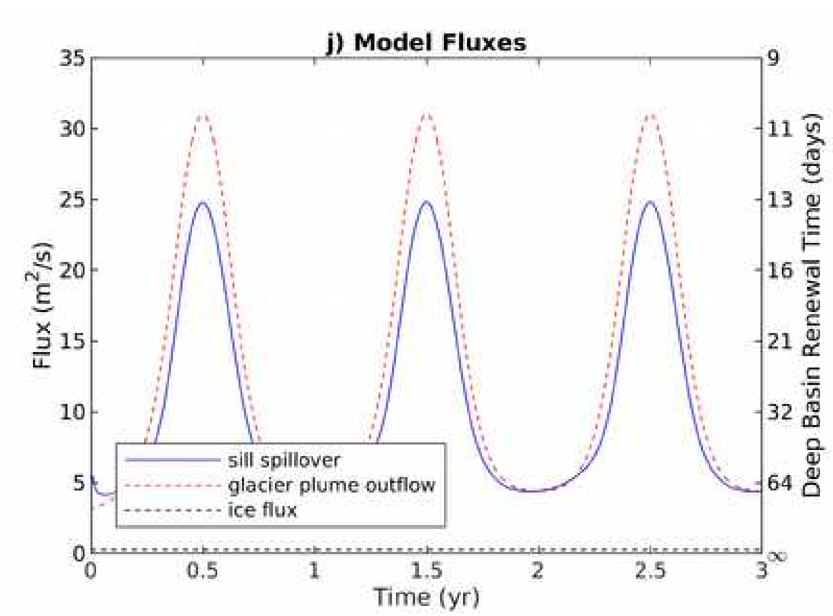
Exchange flow determined by:
1. Density difference
2. Critical flow
3. Mass balance
4. Interface depth from max exchange

Barrier lean determined by balance between barrier buoyancy and pressure difference (when barrier is allowed to lean).

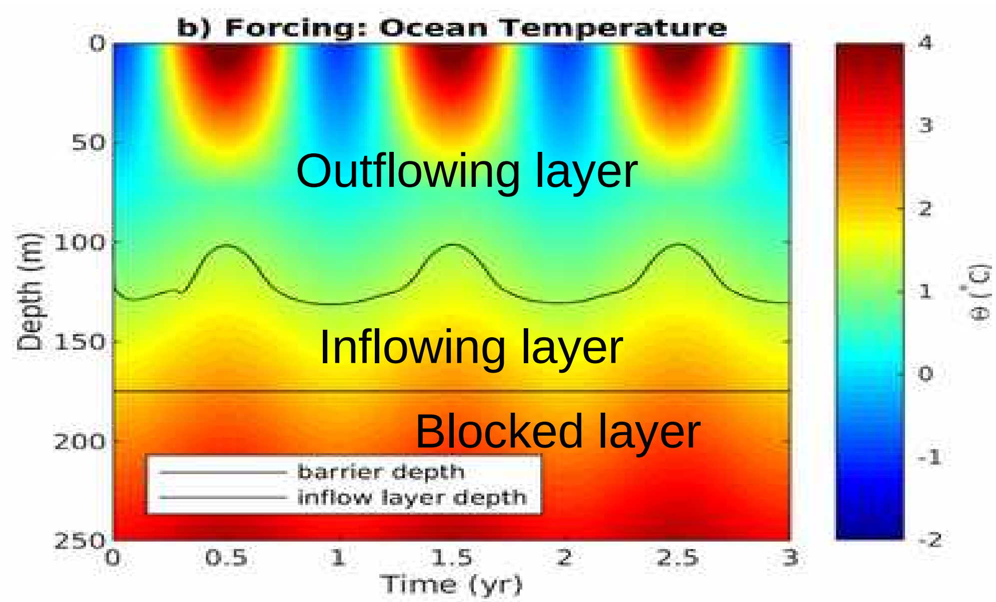
Example Model Results: Sill Exchange

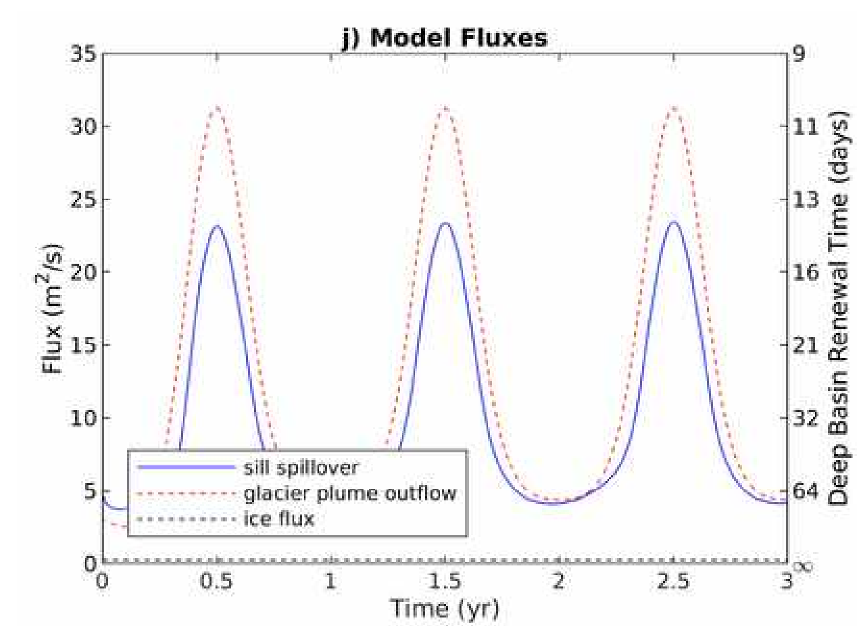
No Barrier





Barrier Top @ 175m

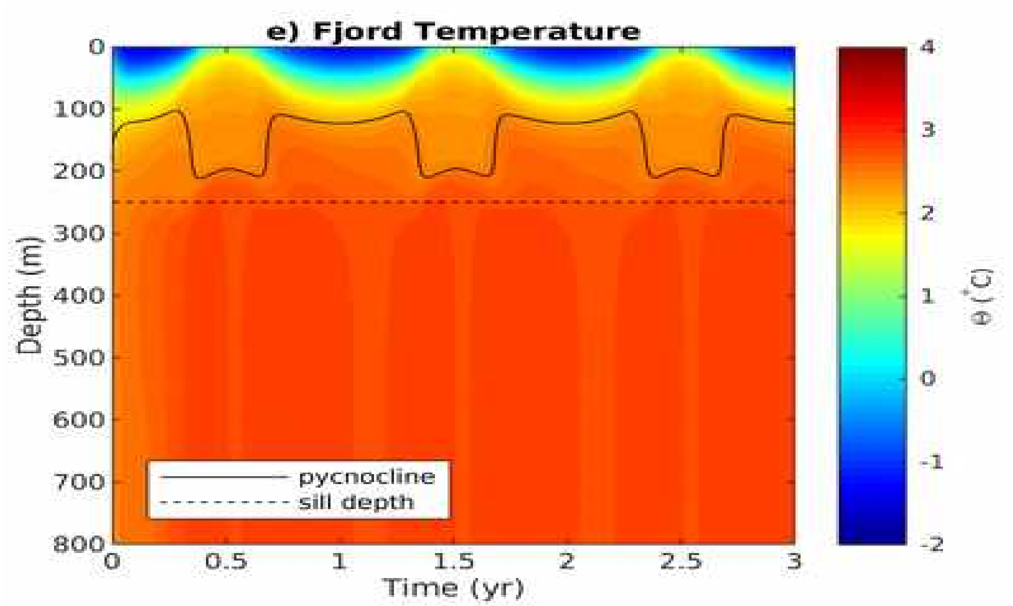


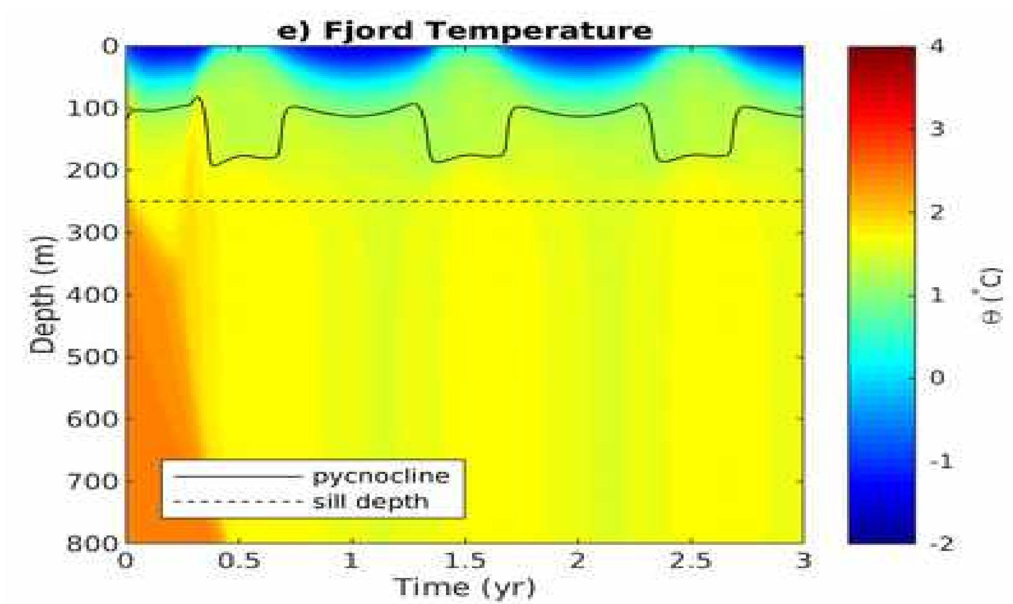


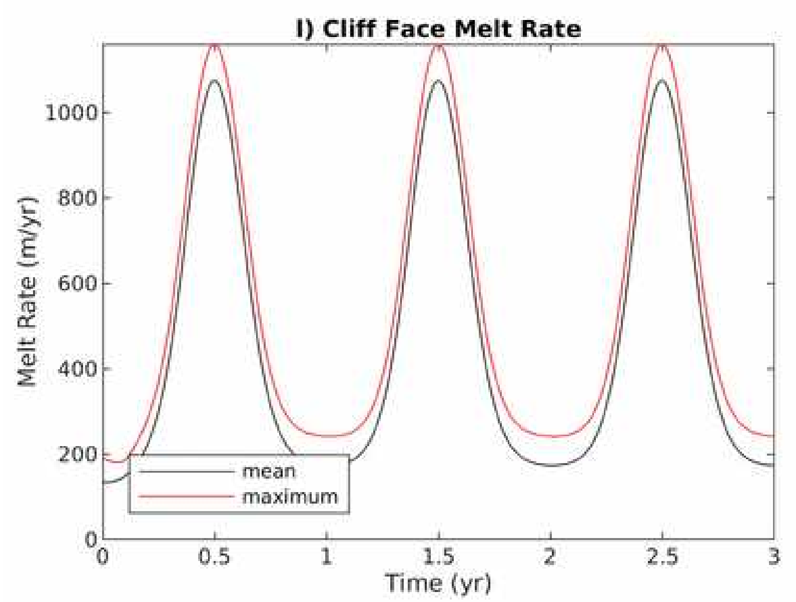
Example Model Results: Fjord, Glacier Response

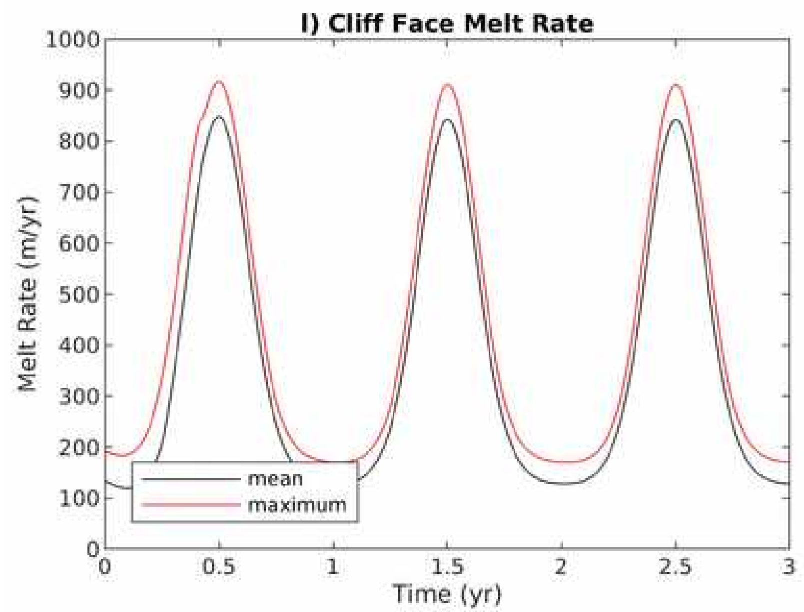
No Barrier

Barrier Top @ 175m

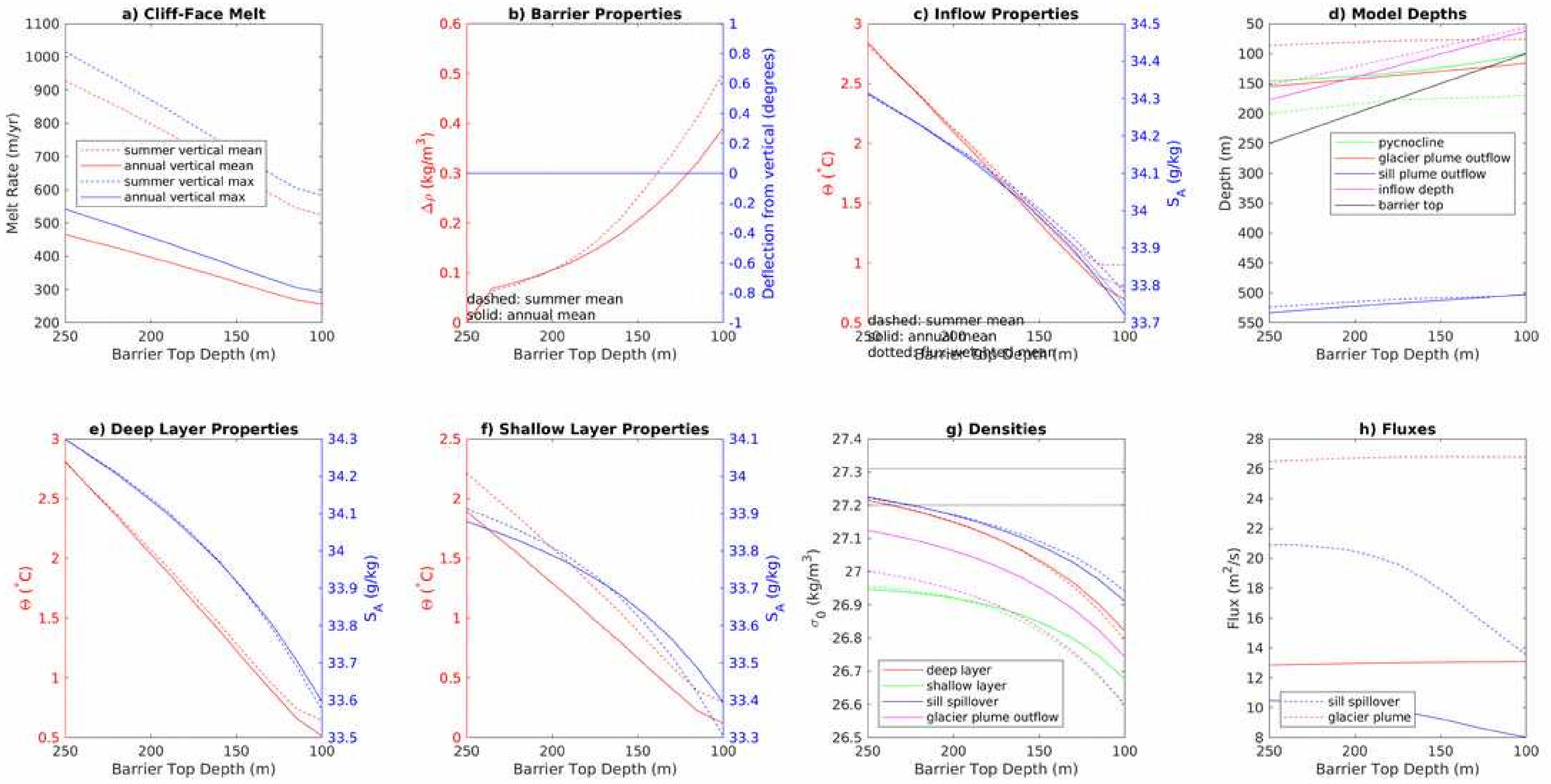






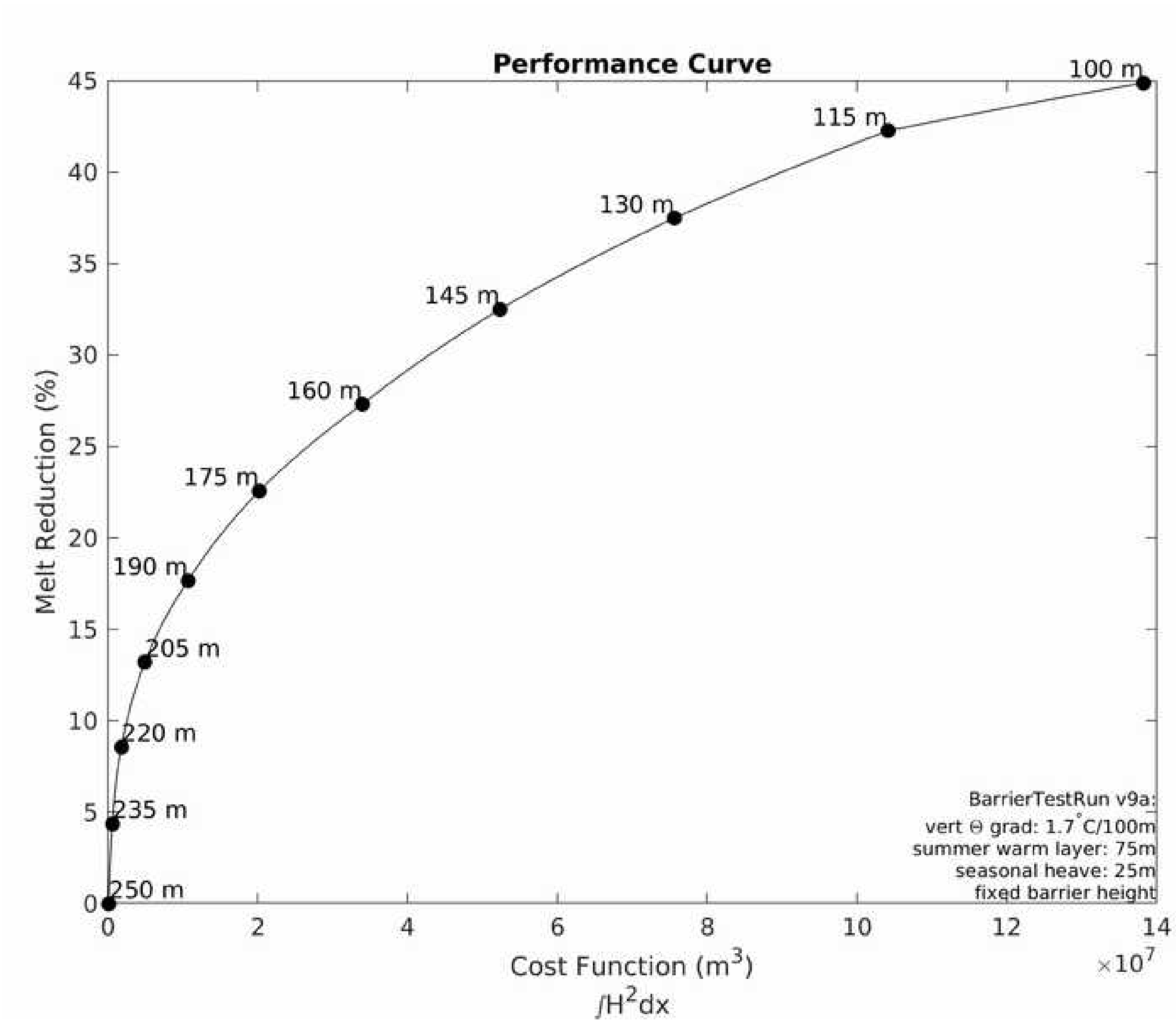


Model Results: Barrier Effectiveness



- Melt reduction closely tracks reduction in inflow temperature.
- Both deep and shallow layers of fjord get colder (should reduce iceberg melt and increase melange buttressing).
- These results show a rigid barrier; experiments with hinged barriers show broadly similar patterns.

Estimating Barrier Cost-Effectiveness from Model



We estimate the shape of the cost-effectiveness curve by combining model estimates of melt reduction with the SAC cost function estimated earlier.

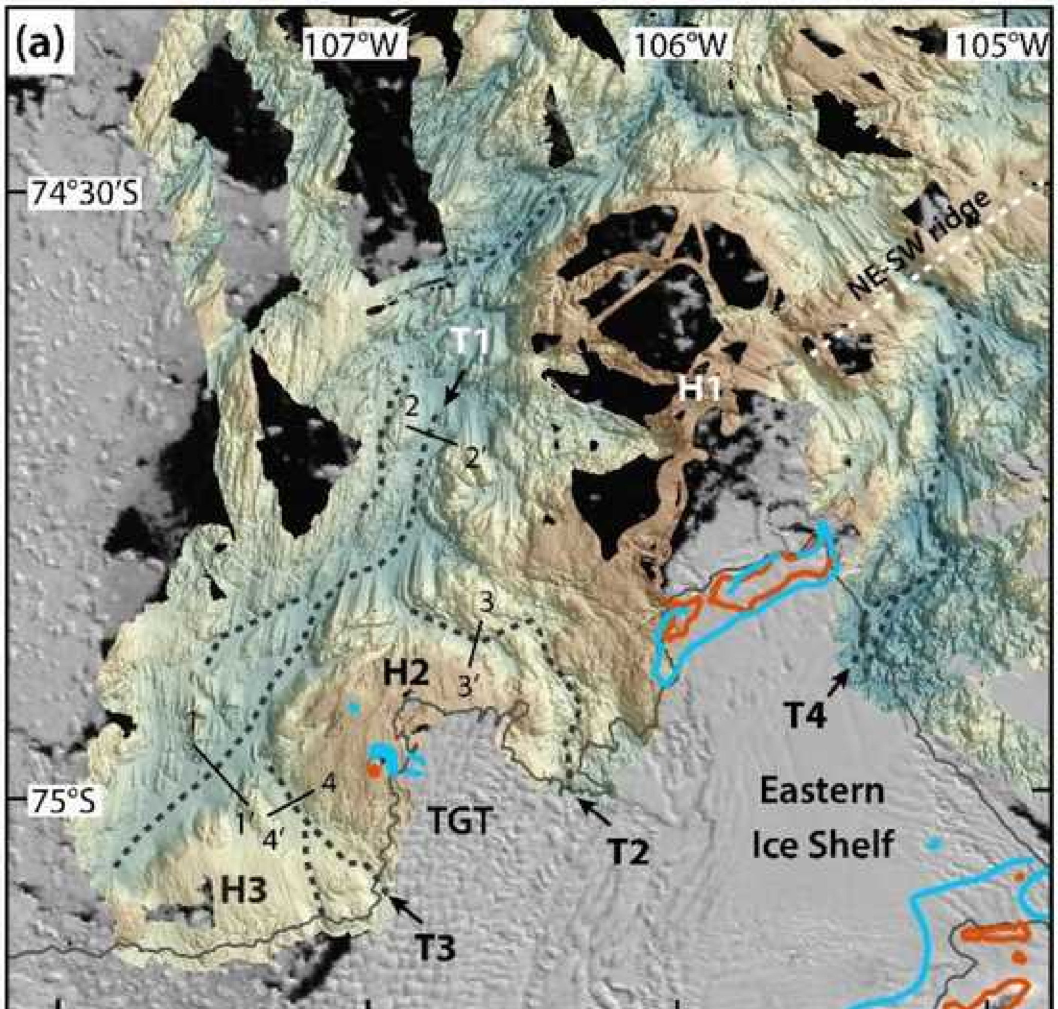
(numbers indicate curtain top depth)

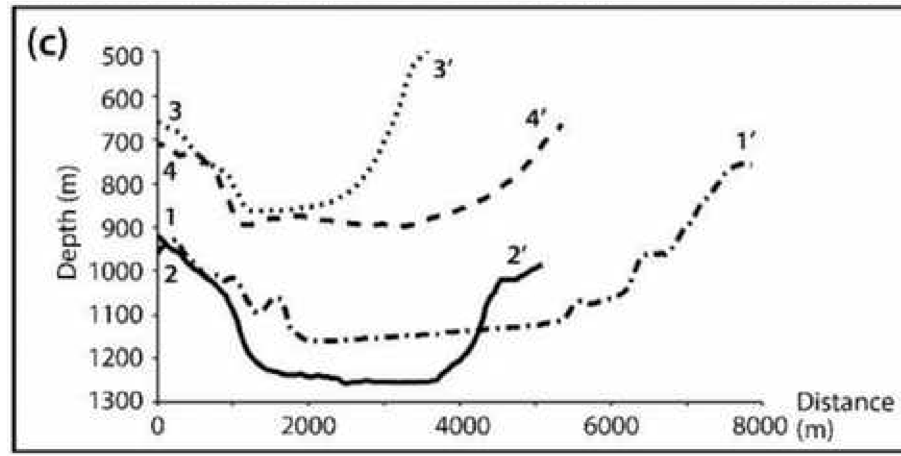
- Small curtains can achieve modest melt reductions (relatively) cheaply
- Diminishing marginal returns set in for larger curtains

Conclusions from Simple Fjord Model

1. Blocking the deeper layers over the sill forces the exchange flow to move higher in the water column, drawing in colder waters than before.
2. The deep fjord basin can get colder but is unlikely to become stagnant so long as the buoyant plume at the ice face continues to entrain and upwell deep water.
3. Substantial fjord coolings and associated melt reductions are feasible, although the exact numbers depend strongly on the forcings applied (especially the vertical temperature gradient at the sill).
4. The ice dynamic response to the SAC will depend on the connection between calving and melt (if any) and on any changes in melange buttressing in response to colder fjord temperatures.

Potential Curtain Routes at Thwaites





- Existing high points provide the buttressing, *no artificial sill required*
- SAC could block deep warm water at a handful of narrow canyons, *no need to block the whole glacier width*

Hogan et al., 2020 (in review, TC Discussion)

Overall Conclusions

1. SAC provide a cheaper, less environmentally damaging, and more easily reversible way to block deep warm water than artificial sills.
2. Using SAC for water blocking means that we must rely on natural pinning points or confining fjords to produce buttressing.
3. SAC effectiveness is strongly related to the ocean temperature gradient at the blocking location.
4. Implementation would require detailed site investigations, numerical modeling and tank testing, engineering design and costing, risk analysis and environmental impact studies, and small-scale pilot projects. IE, not any time soon...
5. ...but given the societal consequences of ice sheet collapse, and the long-tailed distribution of collapse speed, the glaciological community would be remiss not to develop contingency plans should the need arise.