

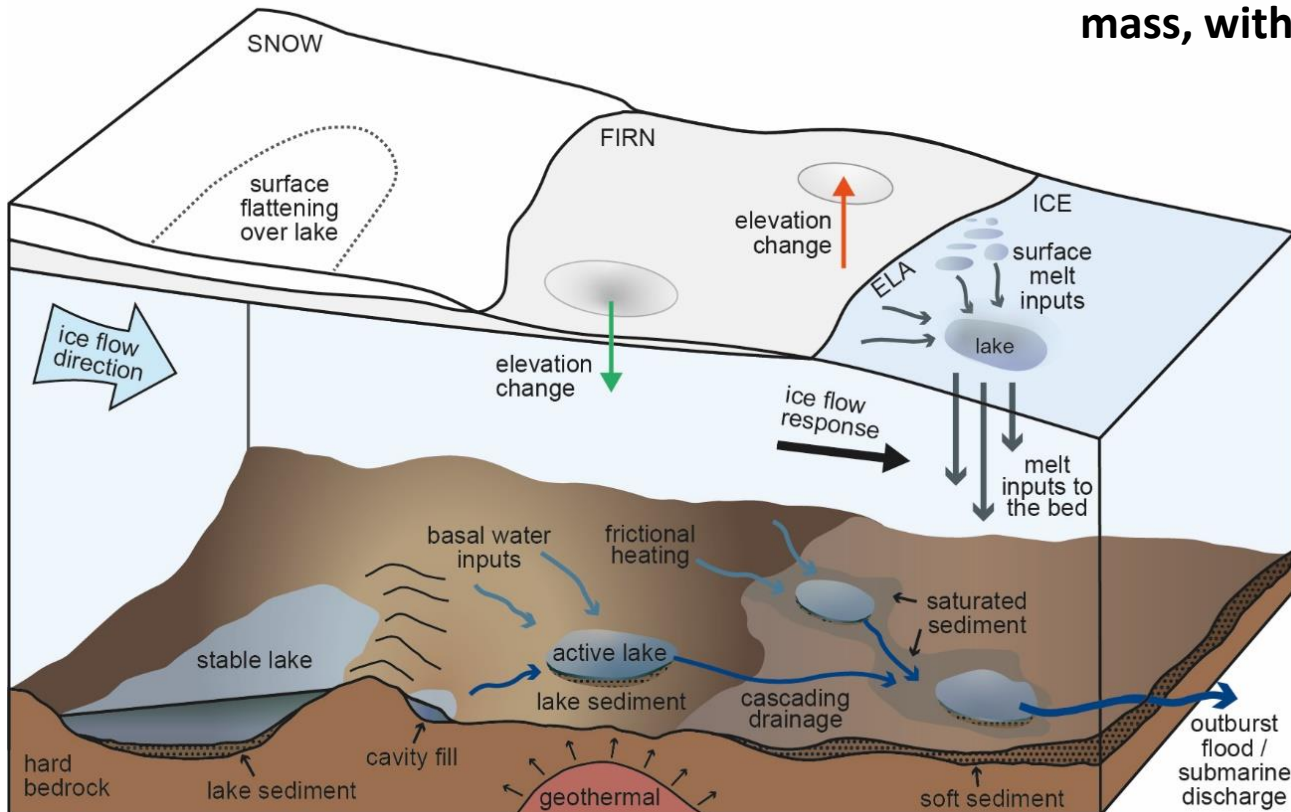
Subglacial lakes and their changing role in a warming climate

Stephen J. Livingstone¹, Yan Li², Anja Rutishauser³, Rebecca J. Sanderson^{4,5}, Kate Winter⁵, Jill Mikucki⁶, Helgi Björnsson⁷, Jade S. Bowling⁸, Winnie Chu⁹, Christine Dow¹⁰, Helen A. Fricker¹¹, Malcolm McMillan⁸, Felix Ng¹, Neil Ross⁴, Martin J. Siegert¹², Matthew Siegfried¹³, Andrew J. Sole¹.

¹Univ. Sheffield | ²Chinese Academy of Sciences | ³Univ. Texas | ⁴Newcastle Univ. | ⁵Northumbria Univ. | ⁶Univ. Tennessee | ⁷Univ. Iceland | ⁸Lancaster Univ. | ⁹Georgia Institute of Technology | ¹⁰Univ. Waterloo | ¹¹Scripps Institute of Oceanography | ¹²Grantham Institute | ¹³Colorado School of Mines

 @living_stephen

 s.j.livingstone@sheffield.ac.uk



Subglacial lake: any discrete water body at the base of an ice mass, without presuming a minimum area or depth.

- Small (~ 1 m) bodies in basal cavities
- Large (>100 km) lakes that influence overlying ice dynamics
- Shallow ($<\sim 1$ cm) water patches connected by saturated sediments
- Deep (~ 100 s m) water bodies with their own internal circulation

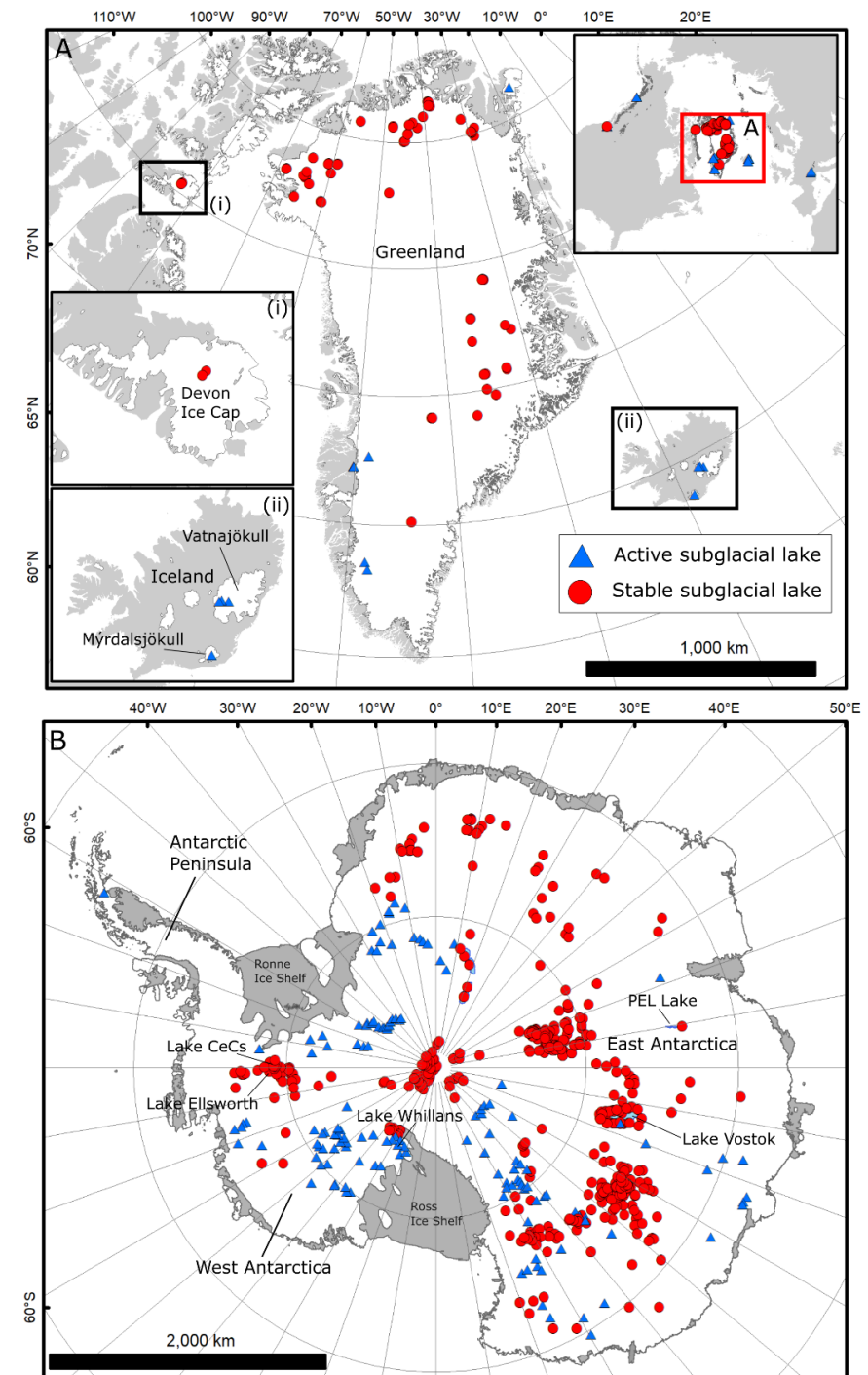
AIMS

1. Compile a global inventory of subglacial lakes
2. Use the inventory to evaluate subglacial lake environments, dynamics, and their wider impact on ice flow and sediment transport
3. Predict how lakes may change in the future using space-time substitution

Different settings of subglacial lakes and their links with other parts of the hydrological system of an ice sheet or a glacier.

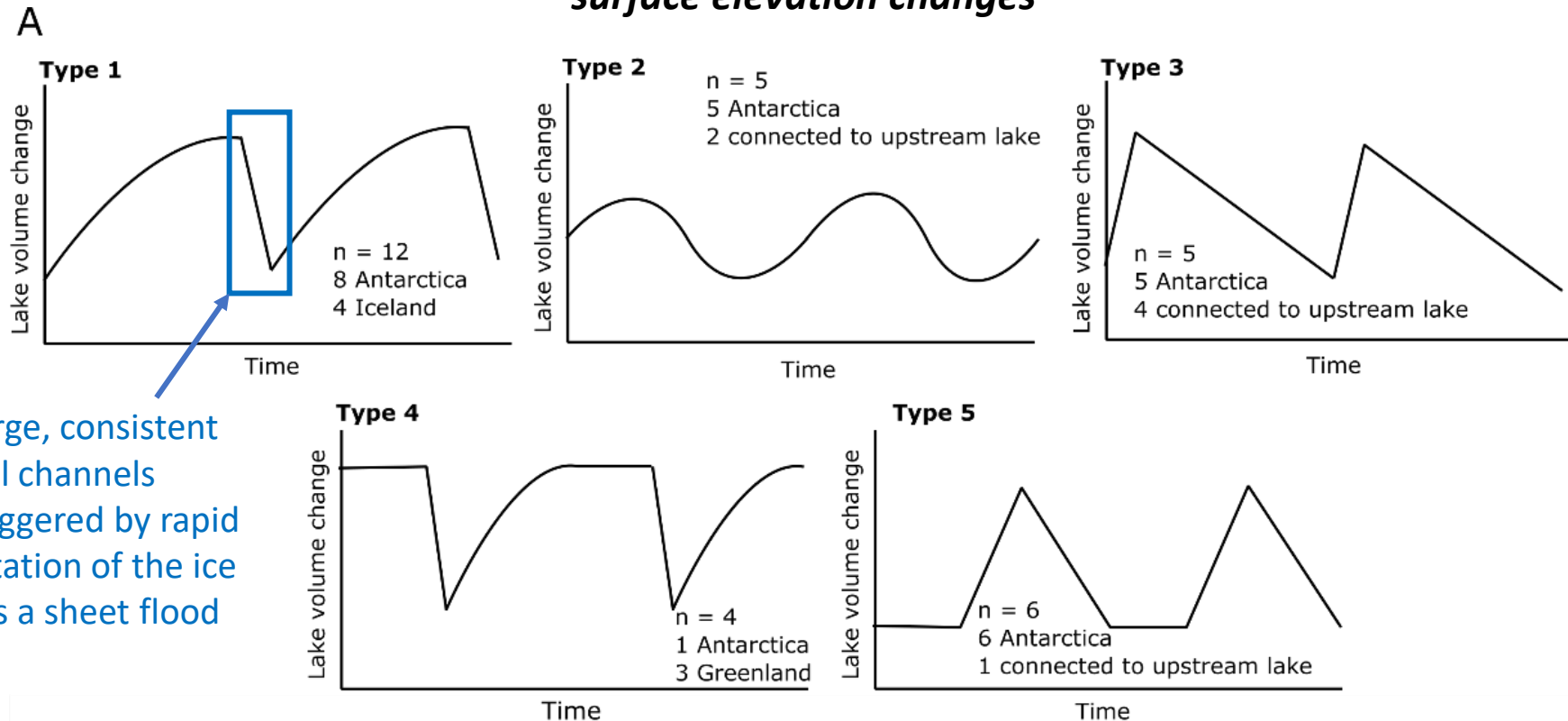
Distribution & Dynamics

- New global inventory of 757 subglacial lakes
 - Antarctic: 675 (incl. 59 newly identified)
 - Greenland: 64
 - Iceland: 8
 - Devon Ice Cap: 2
 - Valley Glaciers: 8
- ~80% increase in the number of Antarctic lakes since the last inventory
- Majority currently found beneath Antarctica (but some bias)
- >80% lakes are not observed to fill or drain (stable)



Distribution & Dynamics

Schematic of five main fill-drain cycle types of subglacial lakes identified from ice-surface elevation changes

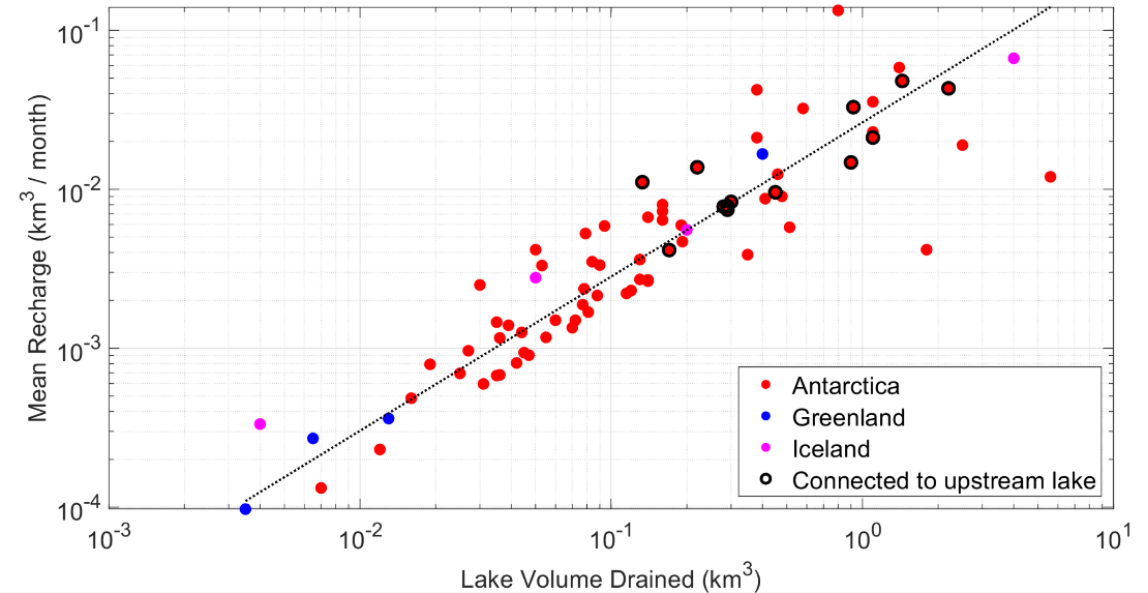
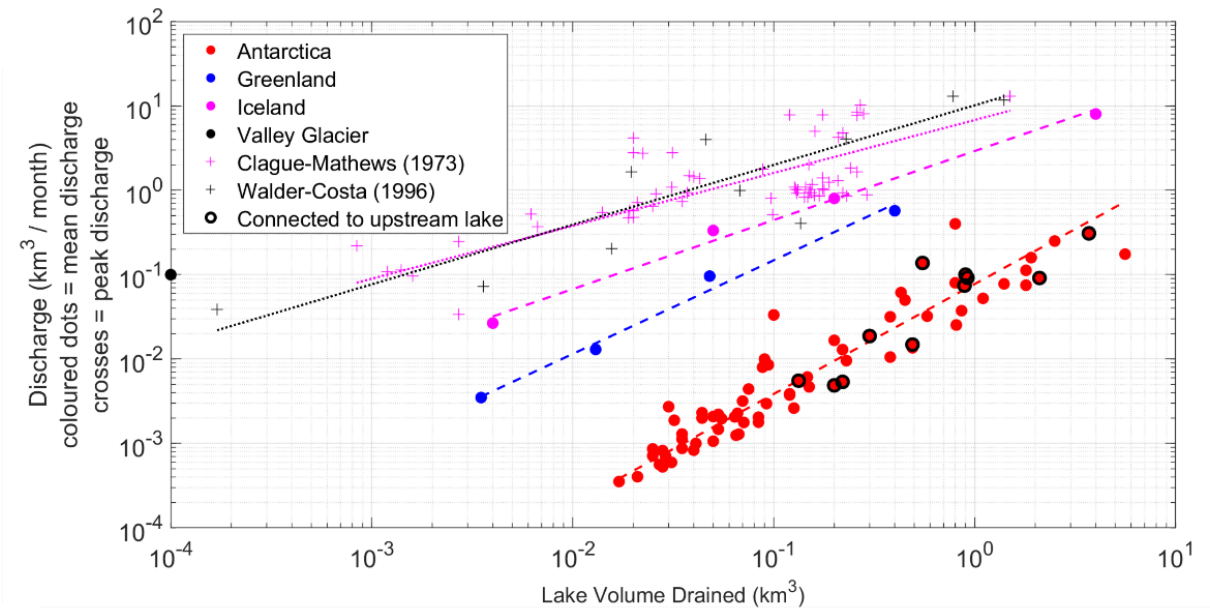


- (i) Exponentially rising discharge, consistent with drainage via subglacial channels
- (ii) Linearly rising discharge triggered by rapid subglacial lake refilling, flotation of the ice dam, and initial drainage as a sheet flood

For lakes with at least one complete fill-drain cycle on record
(relatively rare)

Distribution & Dynamics

- Active subglacial lakes of Iceland, Antarctica and Greenland exhibit **consistent power-law relationships between mean discharge and lake volume across drainage events**
- Antarctic lakes take tens of months to drain
- Greenland and Iceland lakes drain in days to weeks (= higher mean discharge for a given lake volume)
- Consistent with jökulhlaup theory - higher hydraulic gradients (steeper ice-surface slopes) in Iceland & Greenland produce greater subglacial lake discharges of shorter duration compared to Antarctica
- **Larger lakes recharge at a faster rate than smaller lakes.** Relationship not fully understood, but indicates an underlying control on lake refilling associated directly or indirectly with the lake size.



Mean water discharge versus total water volume drained, for drainage events from subglacial lakes and ice-marginal lakes

Distribution & Dynamics

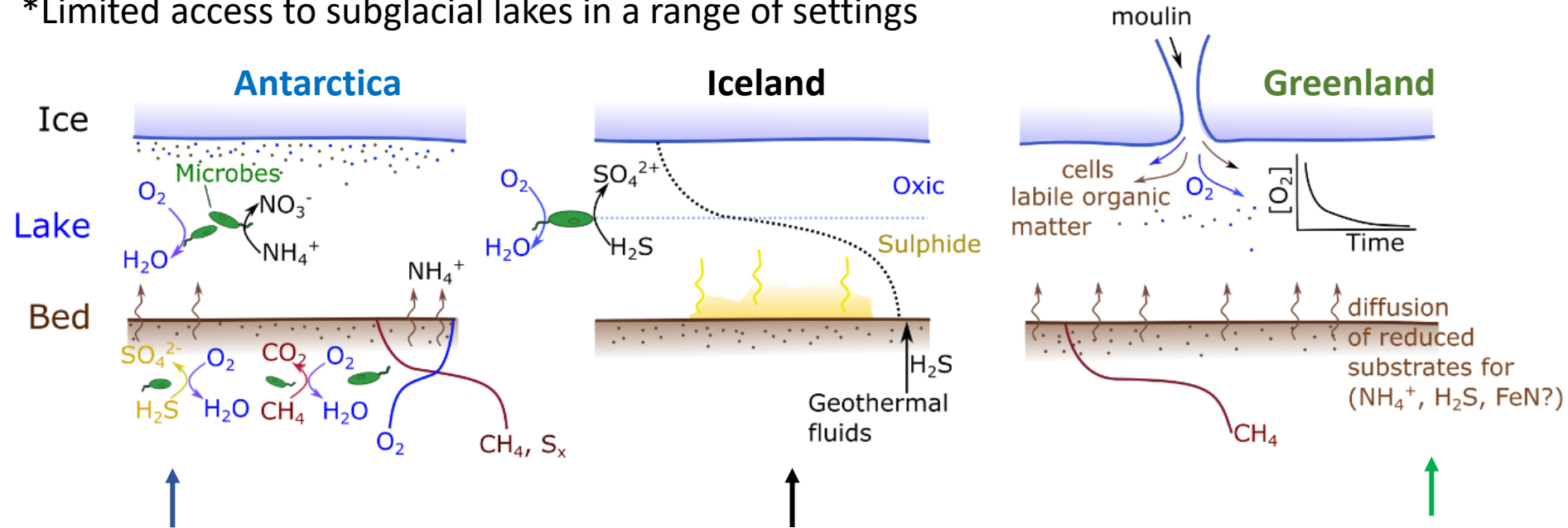
Spectrum of types identified

- 1) Isolated, stable lakes with a large size range beneath Devon Ice Cap and interiors of Antarctica and Greenland
- 2) Large (median: 0.12 km^3) but slowly cascading lake drainage beneath Antarctic ice streams
- 3) Order of magnitude smaller subglacial lakes that produce higher discharges (for a given lake volume) of shorter duration (days to weeks)
- 4) Small pockets of water (on the order of 0.0001 km^3) beneath valley glaciers that drain rapidly (<hour to days)

Subglacial Ecosystems

*Generalized examples of microbial redox reactions across a range of lake settings**

*Limited access to subglacial lakes in a range of settings



- (i) Basal ice interacts with the surface water column
- (ii) Lack surface connectivity - restricts oxygen resupply & delivery of photosynthetically derived nutrients within glacial melt.

- (i) Melting of oxygenated ice and flux of sulfidic geothermal fluid - chemically and thermally stratified water column
- (ii) At the chemocline, sulphur oxidizing microbes dominate.

- (i) Moulins - deliver supraglacial materials
- (ii) In sediments - redox transitions influenced by oxygen availability

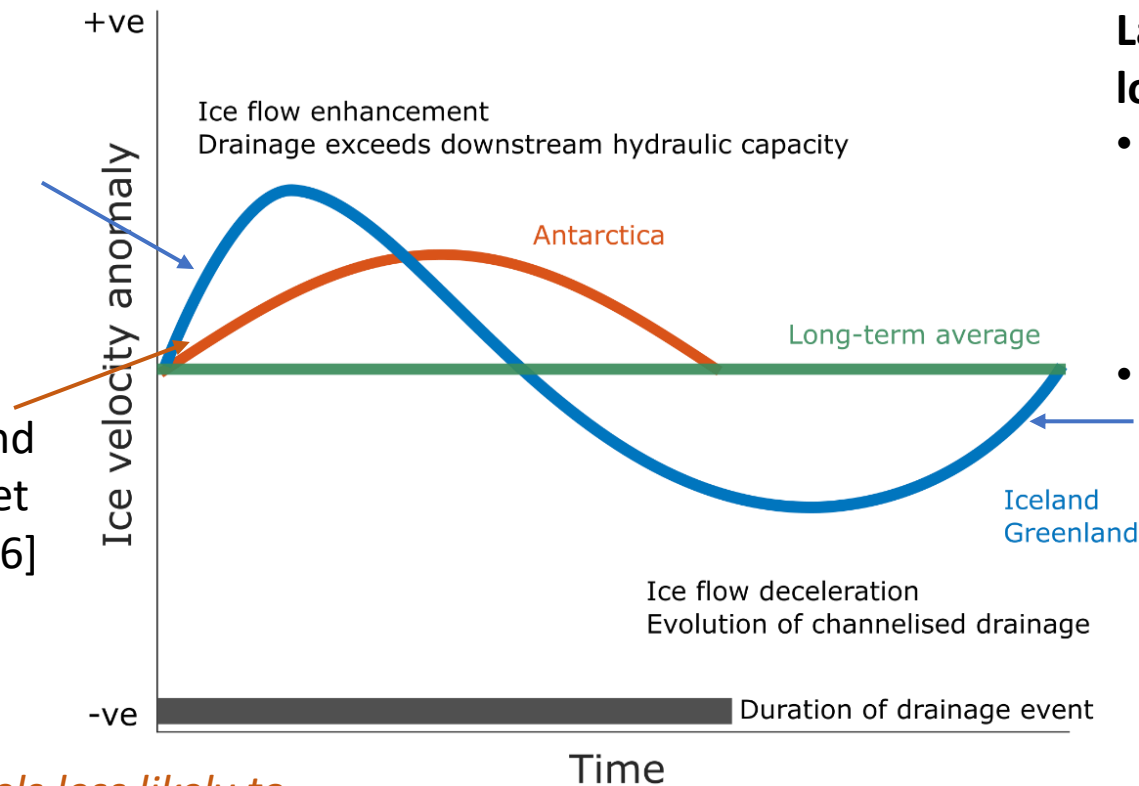
Impact on Ice Dynamics

*Conceptual model of the influence of subglacial lake activity on ice flow
(although based on limited observations)*

e.g., Thwaites Glacier - muted 2% increase followed by a ~3% deceleration over 6 months [Hoffman et al., 2020]

Multi-year but more muted (<10%) ice flow enhancement

- e.g., Byrd Glacier, Whillans and Mercer ice streams [Stearns et al., 2008; Siegfried et al., 2016]



Large initial acceleration followed by longer-term deceleration

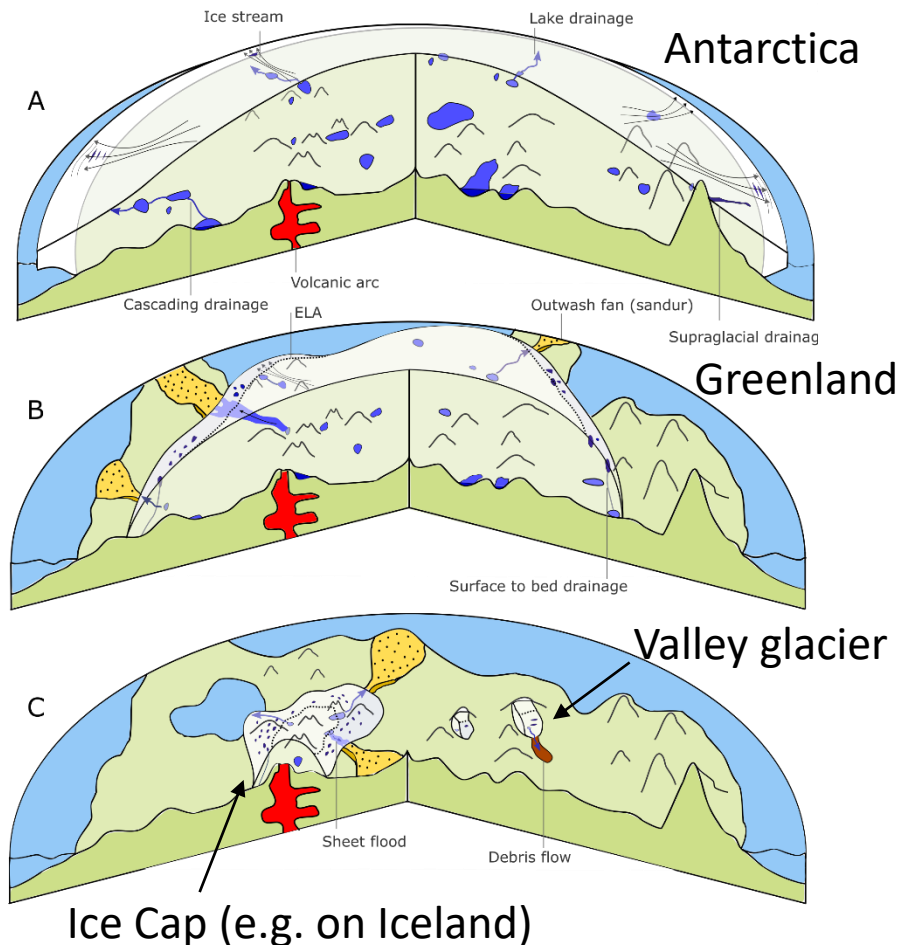
- e.g., Grimsvotn, Iceland – 200% increase followed by 50% reduction that took 4-yrs to recover [Magnússon et al., 2007, 2010]
- e.g., 25% decrease over a month following drainage under Isunguata Sermia, Greenland [Livingstone et al., 2019]

Lower mean discharges, channels less likely to form and more rapidly shut down (shallow hydraulic potential gradient and thick ice)

Relatively thin ice with steeper hydraulic potential gradients enable channels to form

Future evolution of subglacial lakes

As ice masses shrink and warm, ice-surfaces steepen and melting intensifies and expands further inland



- Lakes likely to get smaller and cover a smaller proportion of the bed (*modulated by roughness, thermal regime, geothermal heat flux*)
- Drainage likely to produce higher discharge drainages of shorter duration.
- Coupling to surface melt and rainfall inputs will modulate fill-drain cycles, increase the potential for catastrophic drainages, and seasonally enhance oxic processes.
- Impact on lake biogeochemical activity uncertain - likely to modify melt-refreeze patterns at the ice-lake interface and enhance the local downstream flux of sediment, solute and nutrients.
- Transient ice-flow enhancement followed by a slowdown as channels develop.
- More likely that a fill-drain cycle of a subglacial lake leads to a net reduction in ice flow.

Potential impacts of climate warming on the distribution, geometry and activity of subglacial lakes.

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