Ice sheets

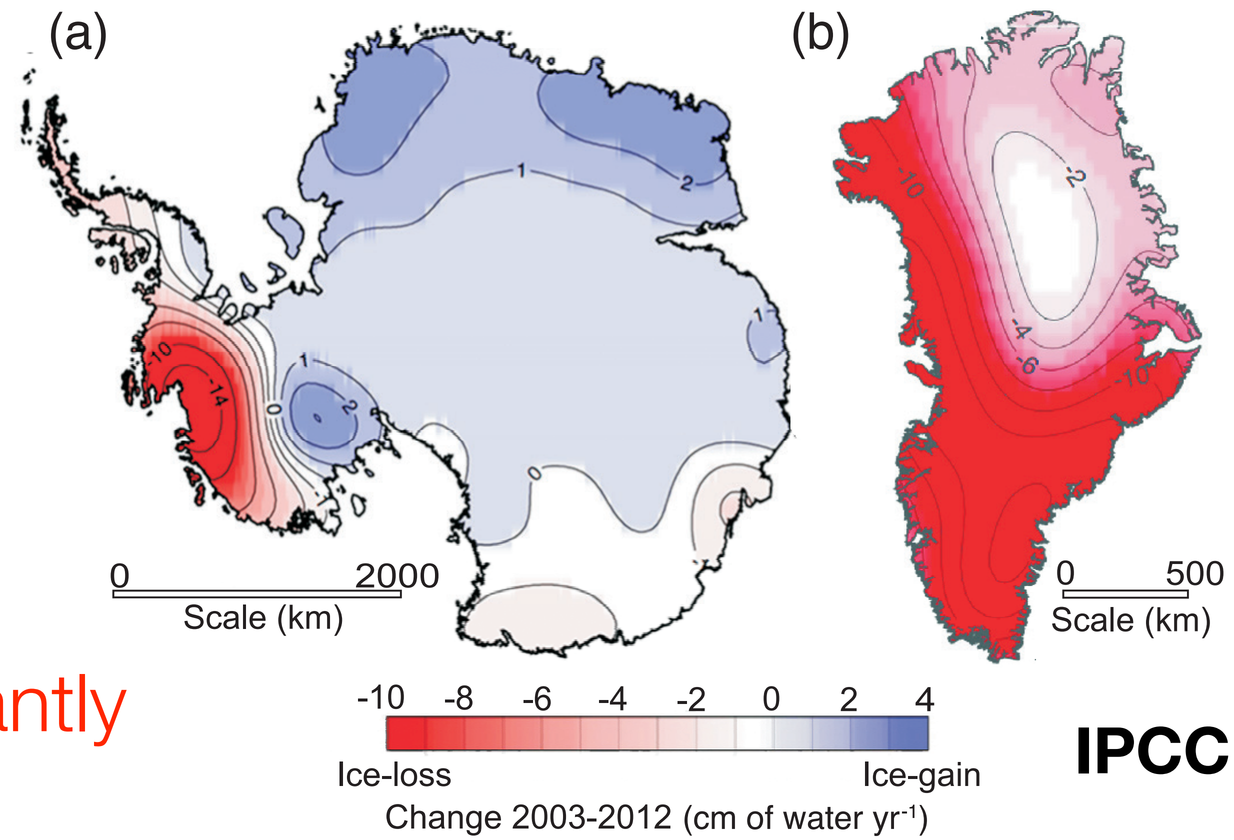
Global Warming Science, EPS101

Wanying Kang and Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

Ice sheets: why we care

Greenland & Antarctica significantly contribute to sea level rise



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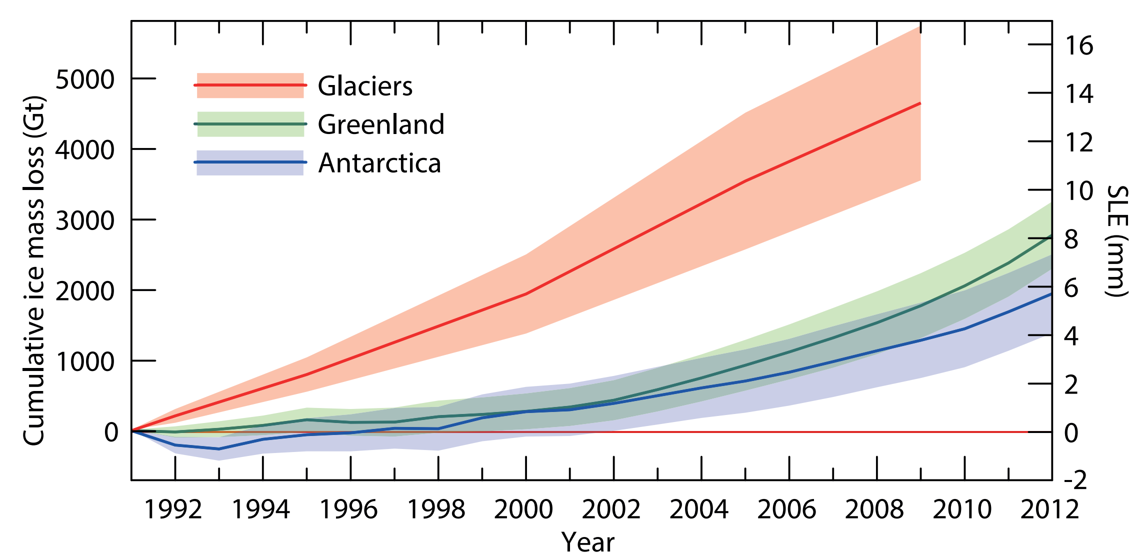

Figure TS.3 | (Upper) Distribution of ice loss from Gravity Recovery and Climate Experiment (GRACE) time-variable gravity for (a) Antarctica and (b) Greenland, shown in cm of water per year for the period 2003–2012. (Lower) The assessment of the total loss of ice from glaciers and ice sheets in terms of mass (Gt) and sea level equivalent (mm). The contribution from glaciers excludes those on the periphery of the ice sheets.

Ice sheets: why we care

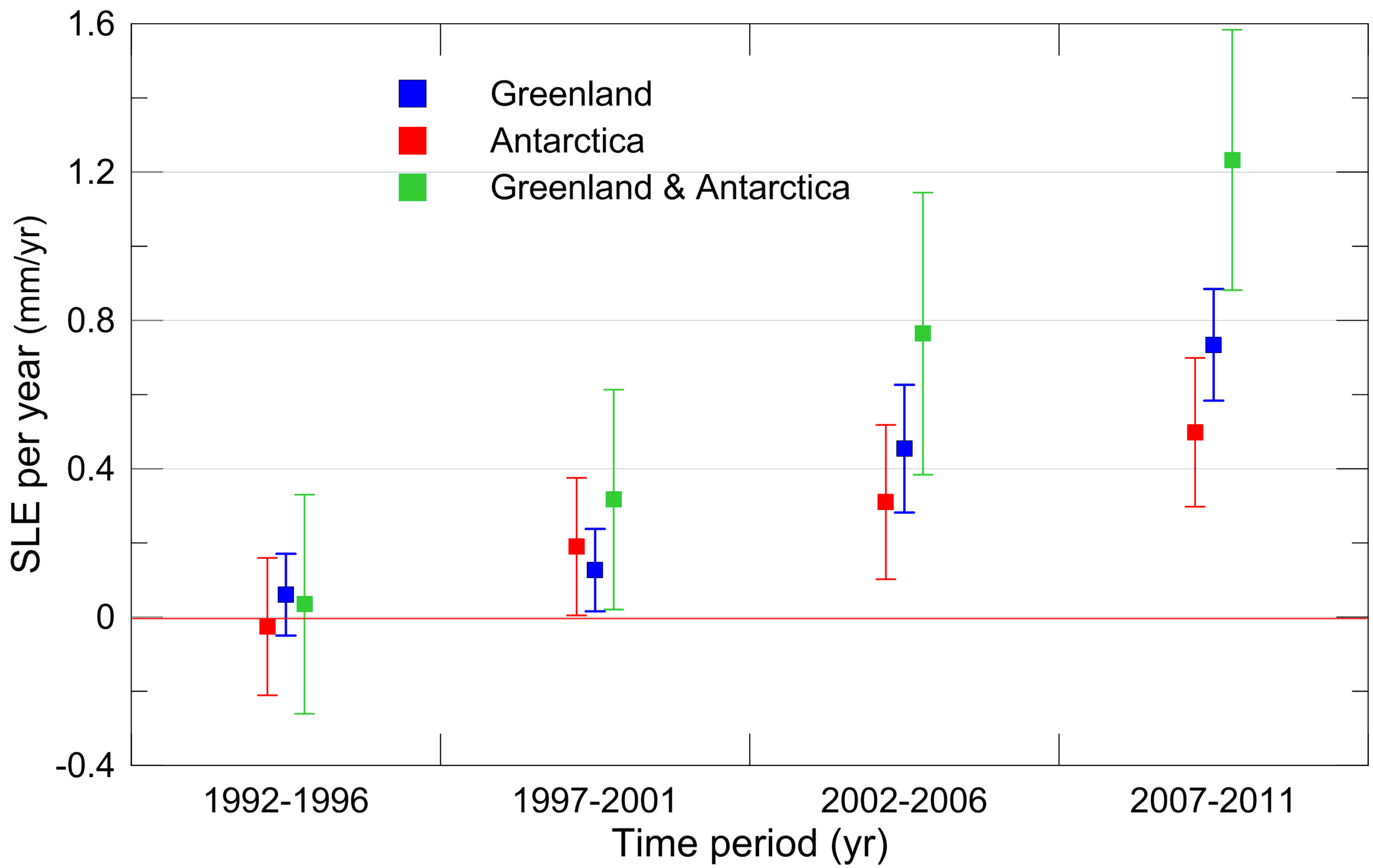

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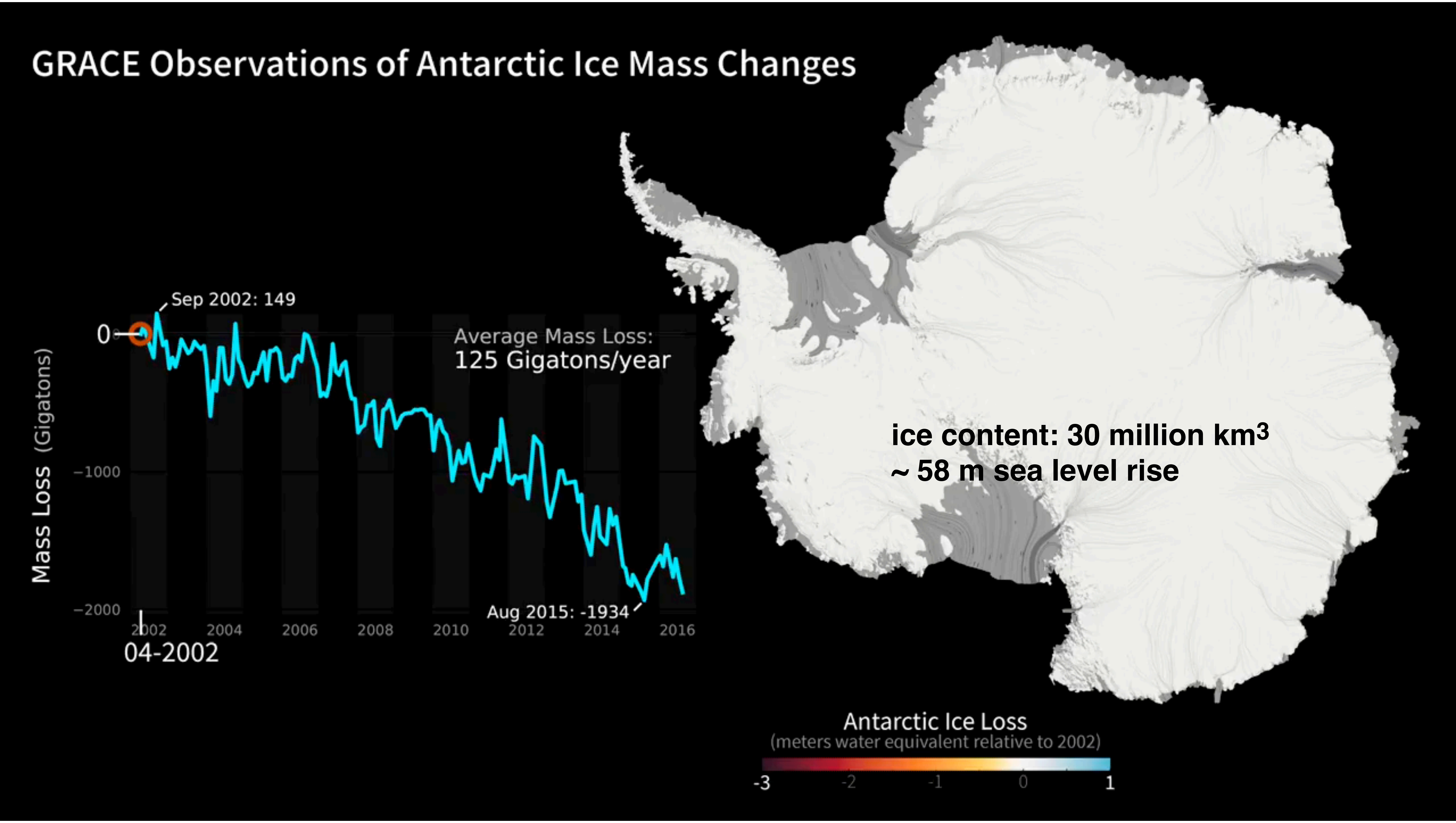
Figure 4.17 | Rate of ice sheet loss in sea level equivalent averaged over 5-year periods between 1992 and 2011. These estimates are derived from the data in Figures 4.15 and 4.16.

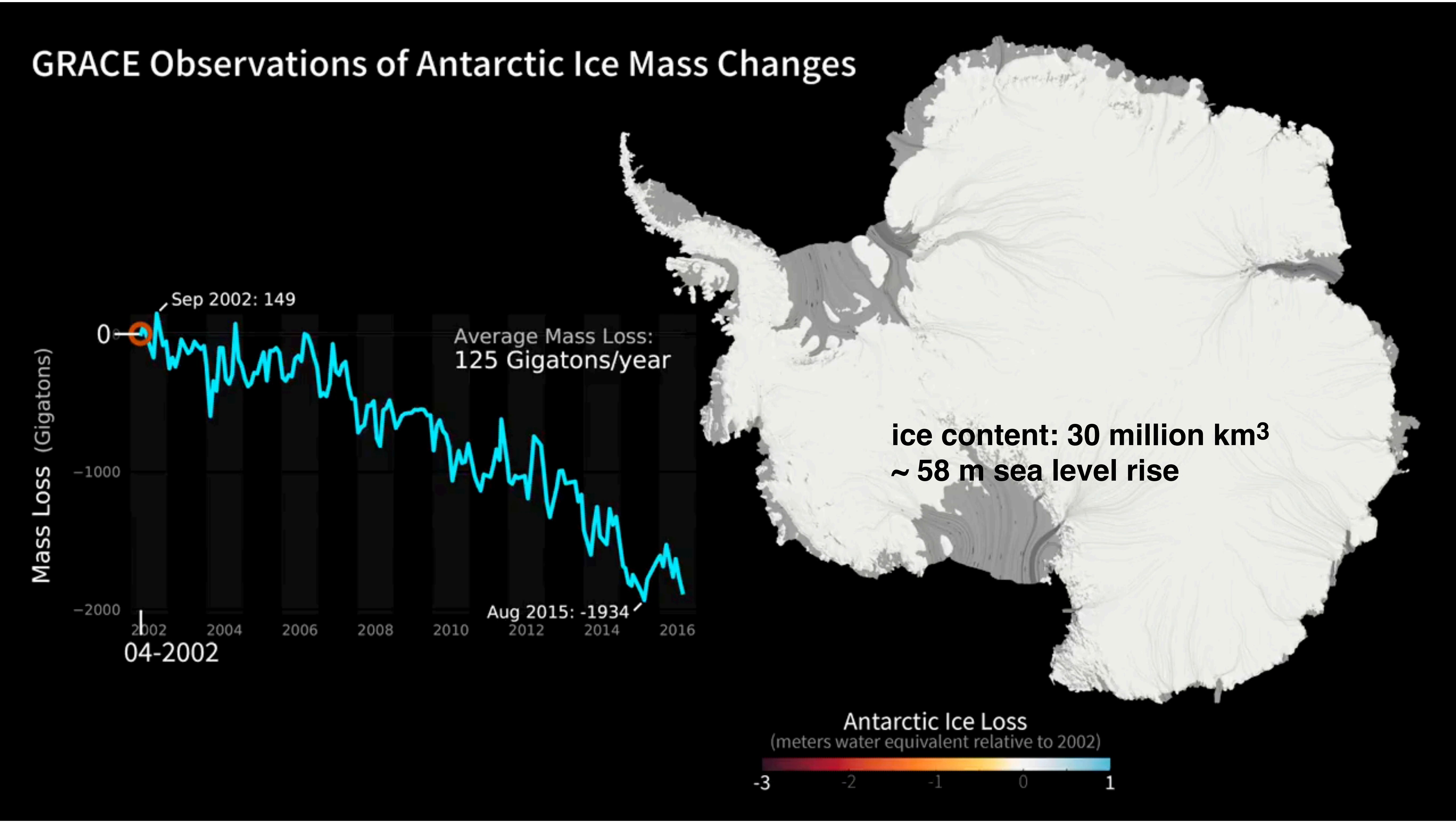
Greenland & Antarctica contributions to GMSL **accelerate**

Antarctic ice mass loss observations



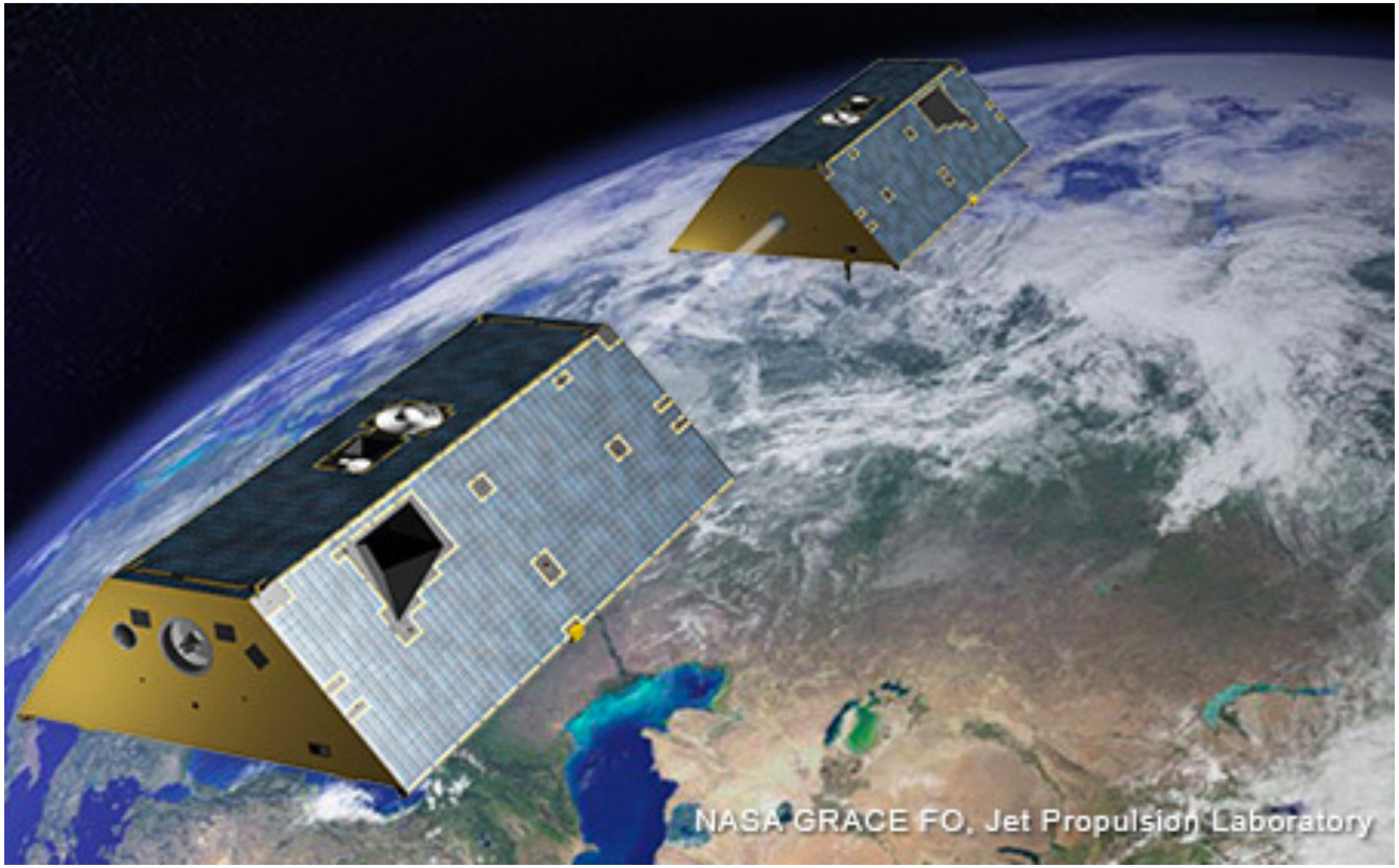
https://grace.jpl.nasa.gov/resources/31/antarctic-ice-loss-2002-2016/

Antarctic ice mass loss observations



https://grace.jpl.nasa.gov/resources/31/antarctic-ice-loss-2002-2016/

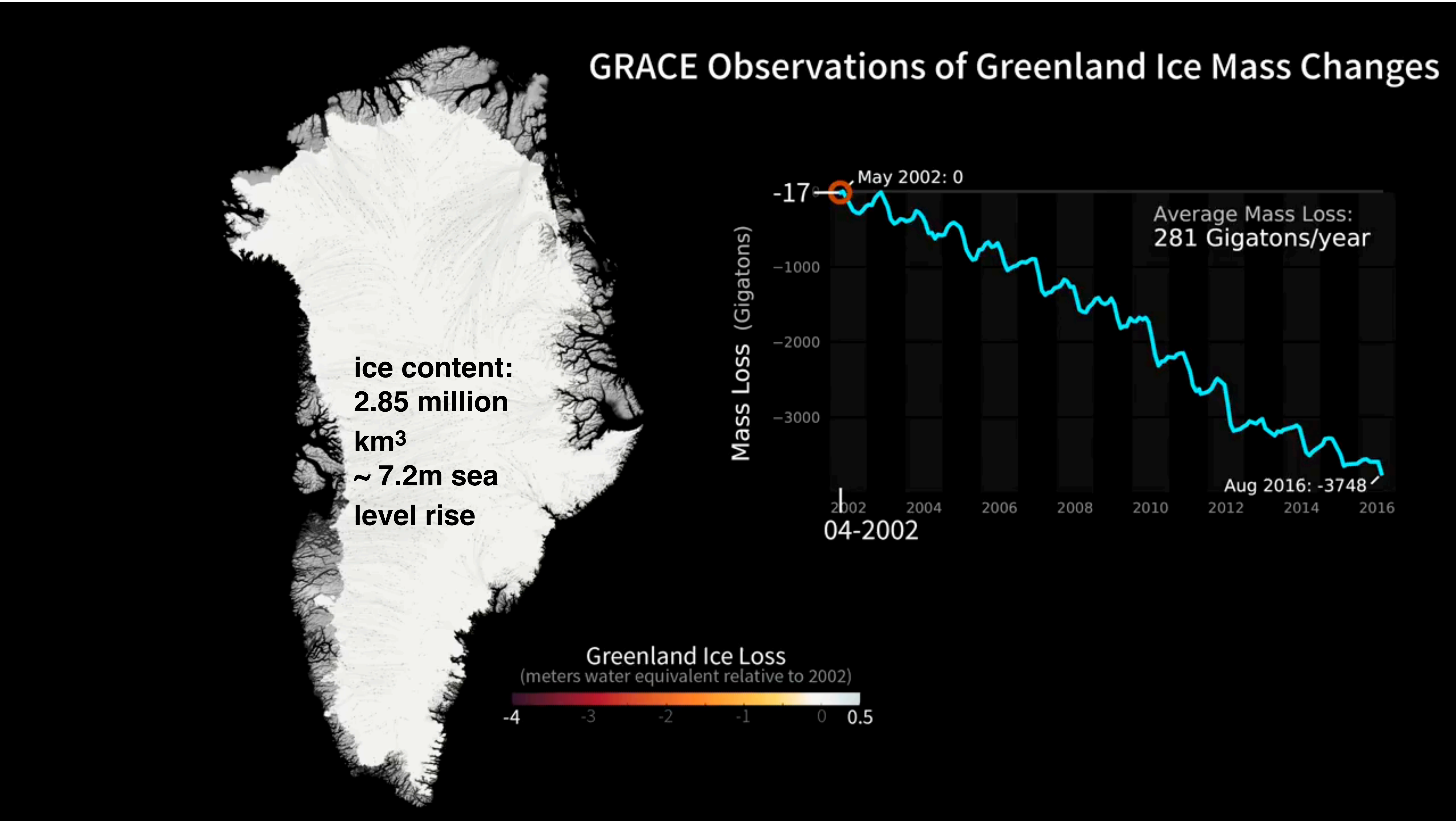
Measuring the ice mass of Greenland & Antarctica from space: GRACE



The twin GRACE-FO satellites follow each other in orbit around the Earth, separated by about 220 km.

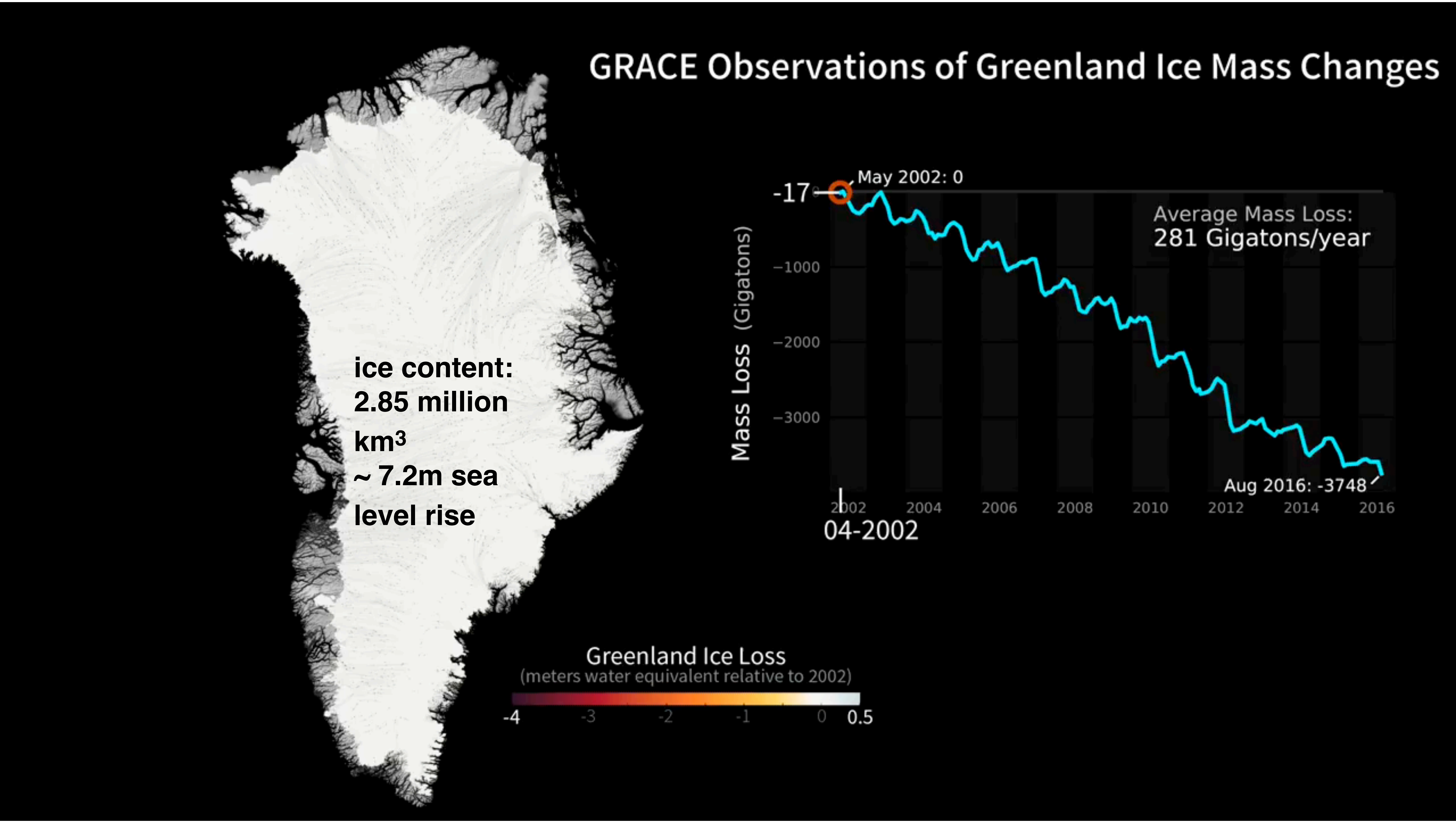
https://grace.jpl.nasa.gov/mission/grace-fo/

Greenland ice loss observations



https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/

Greenland ice loss observations



https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/

Greenland Calving event, “Chasing ice” film

https://www.youtube.com/watch?v=hC3VTgIPoGU

Greenland Calving event, "Chasing ice" film

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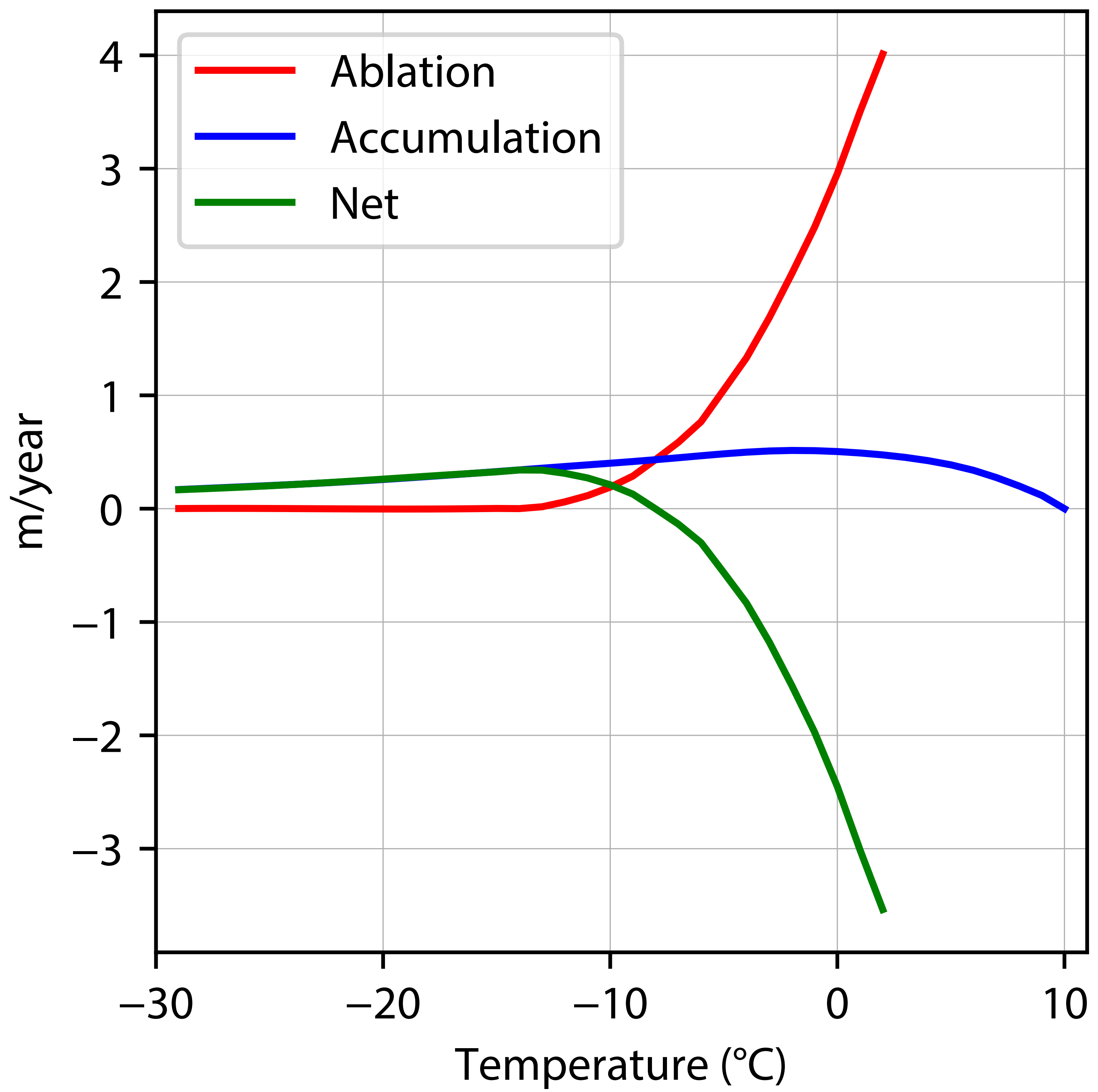
workshop #1:
Observations and projections

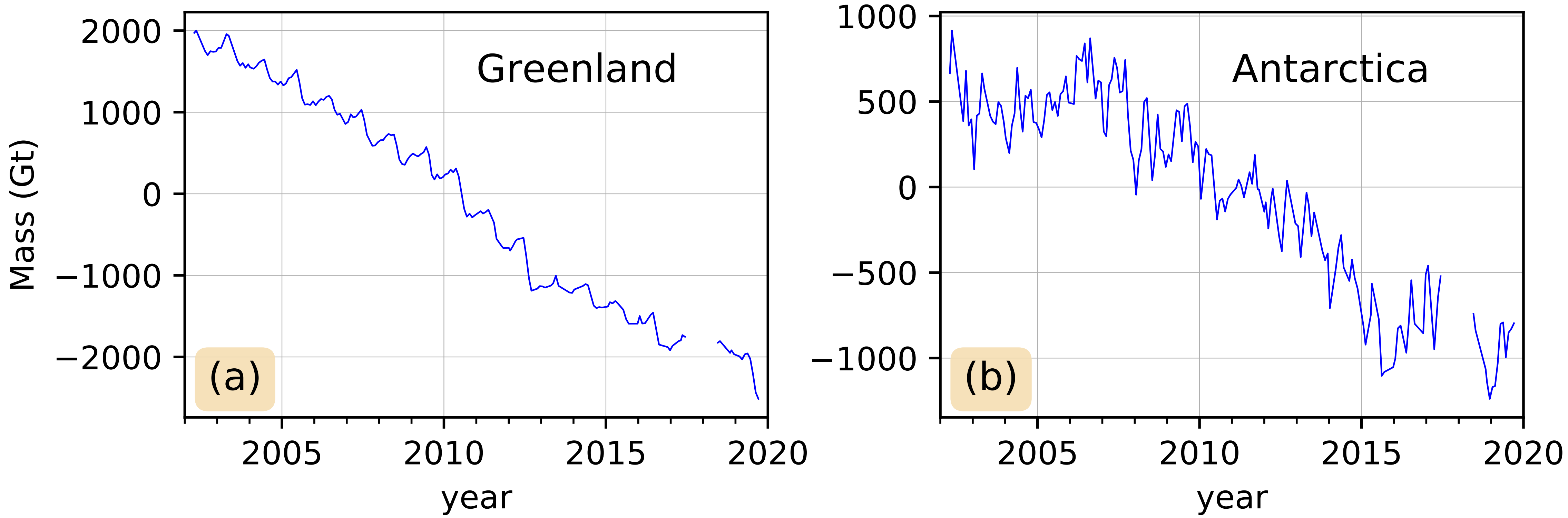
Ice sheet SMB regimes:



Surface mass balance versus temperature.
Schematic of accumulation (blue), surface ablation (red), and net surface mass balance (green) as a function of surface atmospheric temperature. After Oerleman 1992.

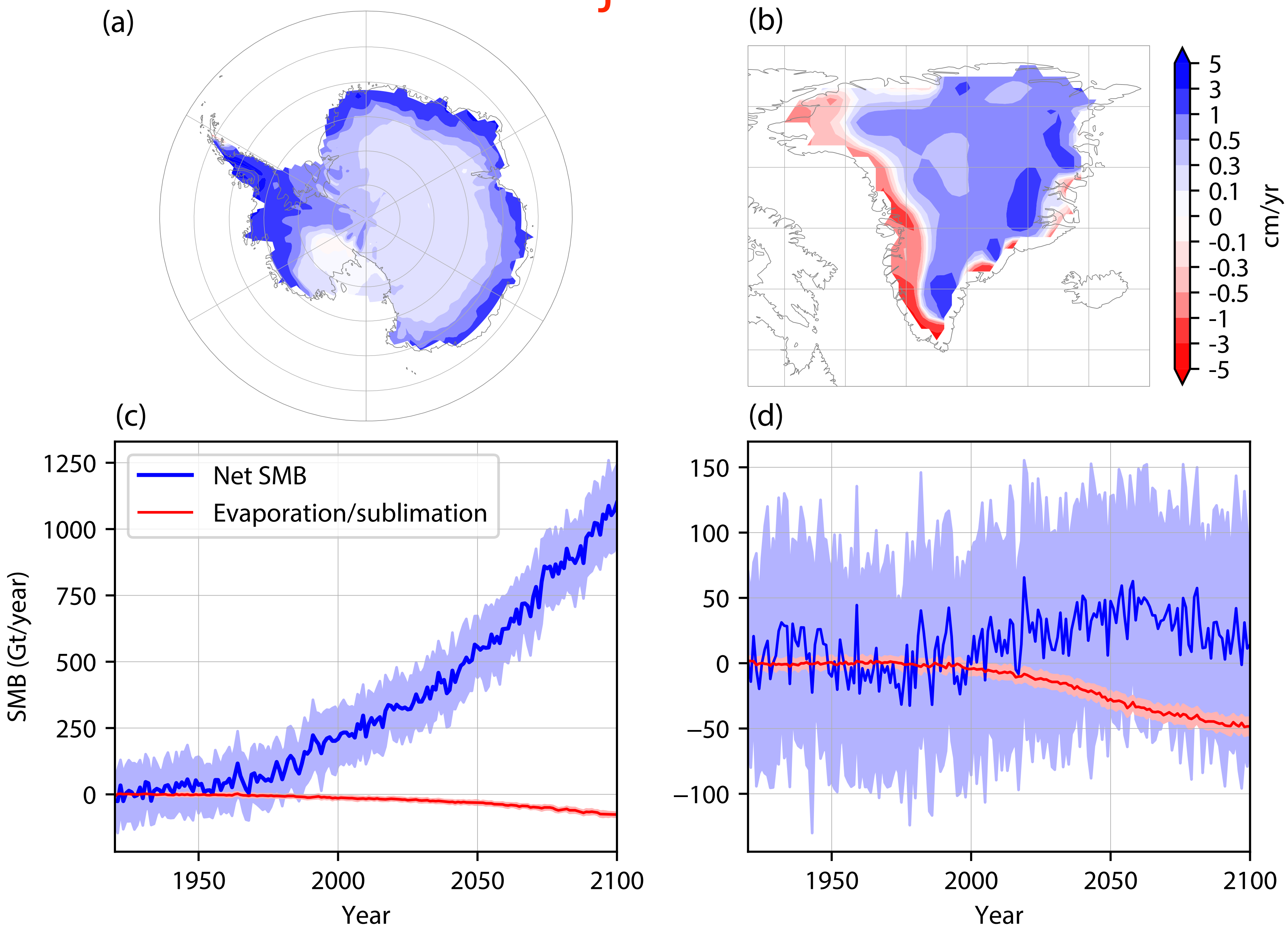
Notes section 10.3:
observed trends and projections

Present observations



Both Greenland and Antarctica show mass loss, although it is not clear to what degree this is due to natural variability, and the prediction for Antarctica suggests mass gain, at least via SMB, in the next few decades

Projections

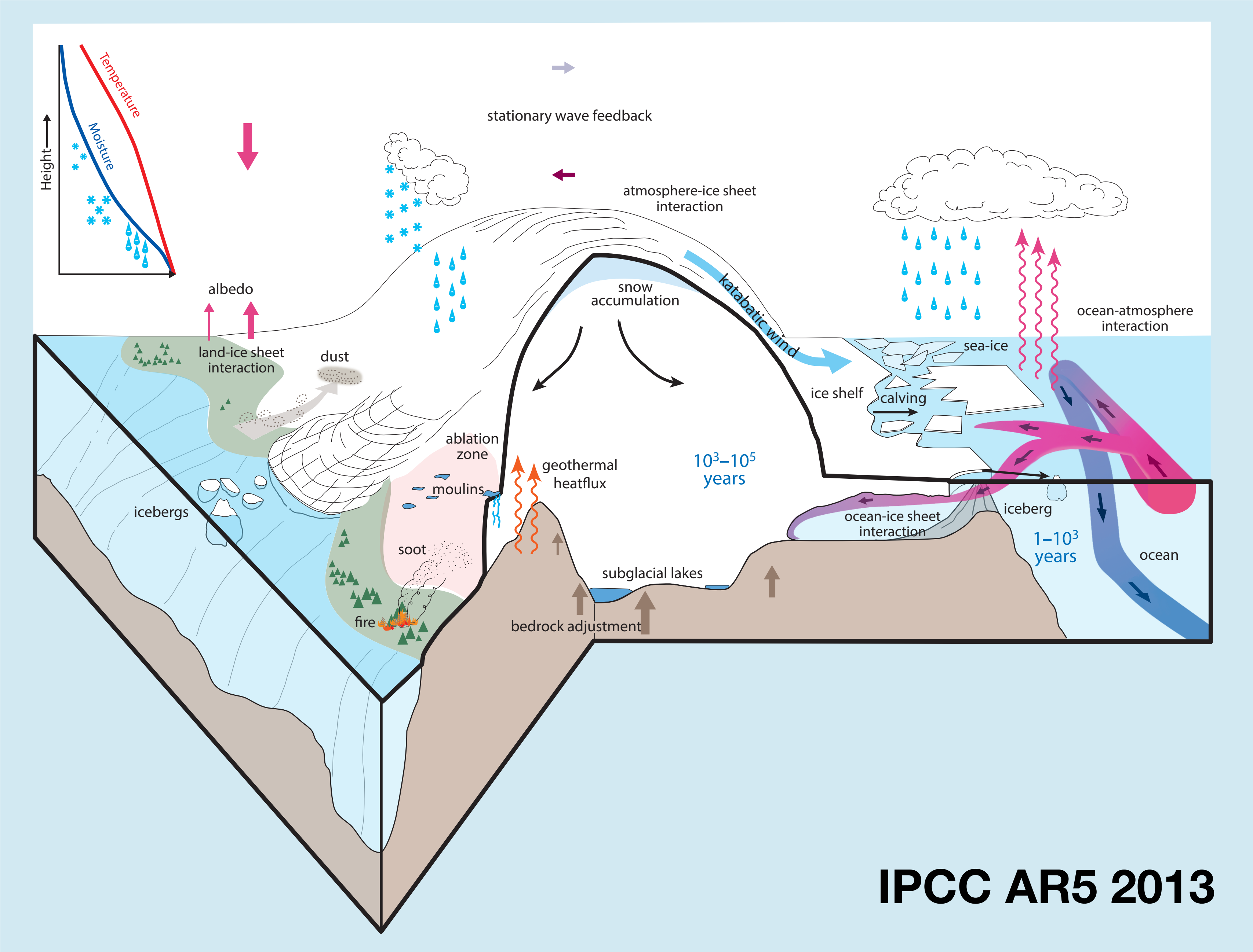


RCP8.5 projections of surface mass balance changes over Greenland & Antarctica. (a) net SMB change from 1920 to 2100, cm/yr, averaged over 30 model ensemble members. calculated as change in snow accumulation minus in sublimation rate. blue shades: a gain in SMB. (b) Same, for Greenland. (c) blue line: time series of net SMB for AIS, Gt/yr, avg over 30 members. light-blue shading: 1 std over members. red line & shading: sublimation. (d) Same, for Greenland.

Notes section 10.2
Physical processes determining the ice mass balance

Physical processes determining the ice mass balance

- Accumulation
- Ablation:
  - Albedo
  - surface melting
  - calving
  - ice flow
  - basal hydrology

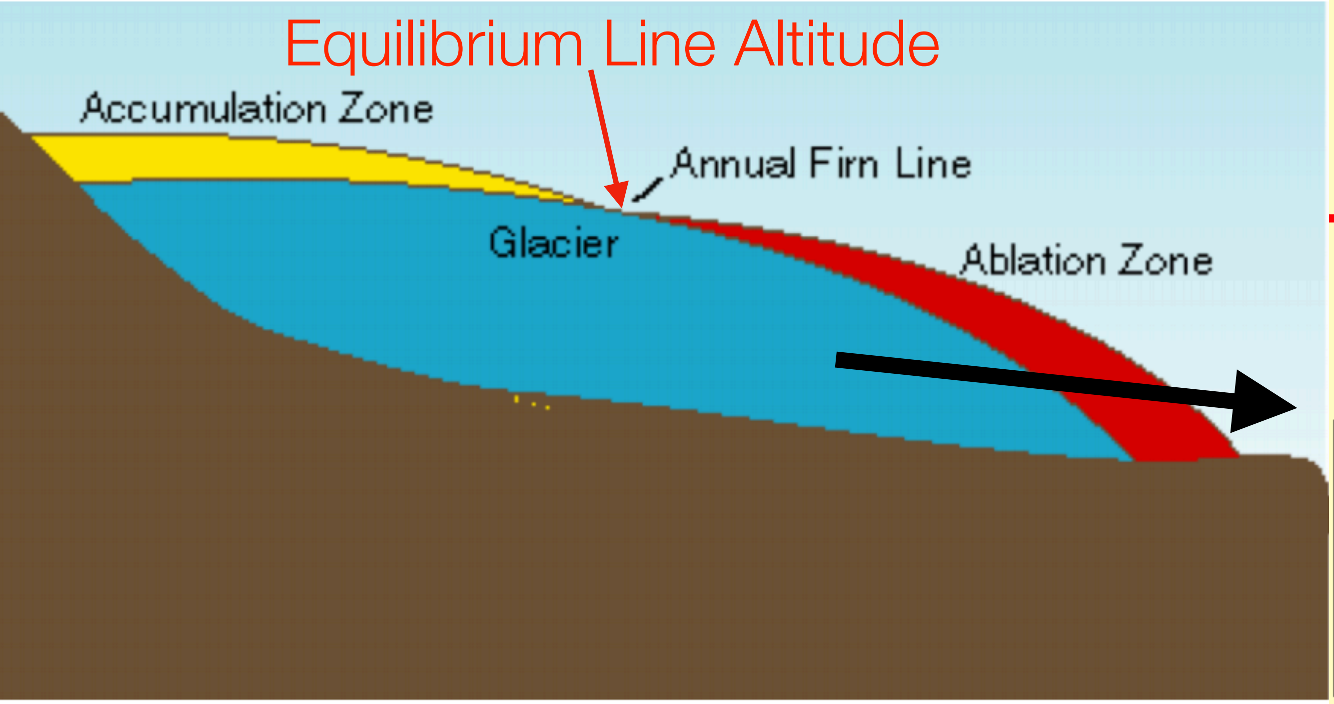


Box 5.2, Figure 1 | Schematic illustration of multiple interactions between ice sheets, solid earth and the climate system which can drive internal variability and affect the coupled ice sheet–climate response to external forcings on time scales of months to millions of years. The inlay figure represents a typical height profile of atmospheric temperature and moisture in the troposphere.

Accumulation

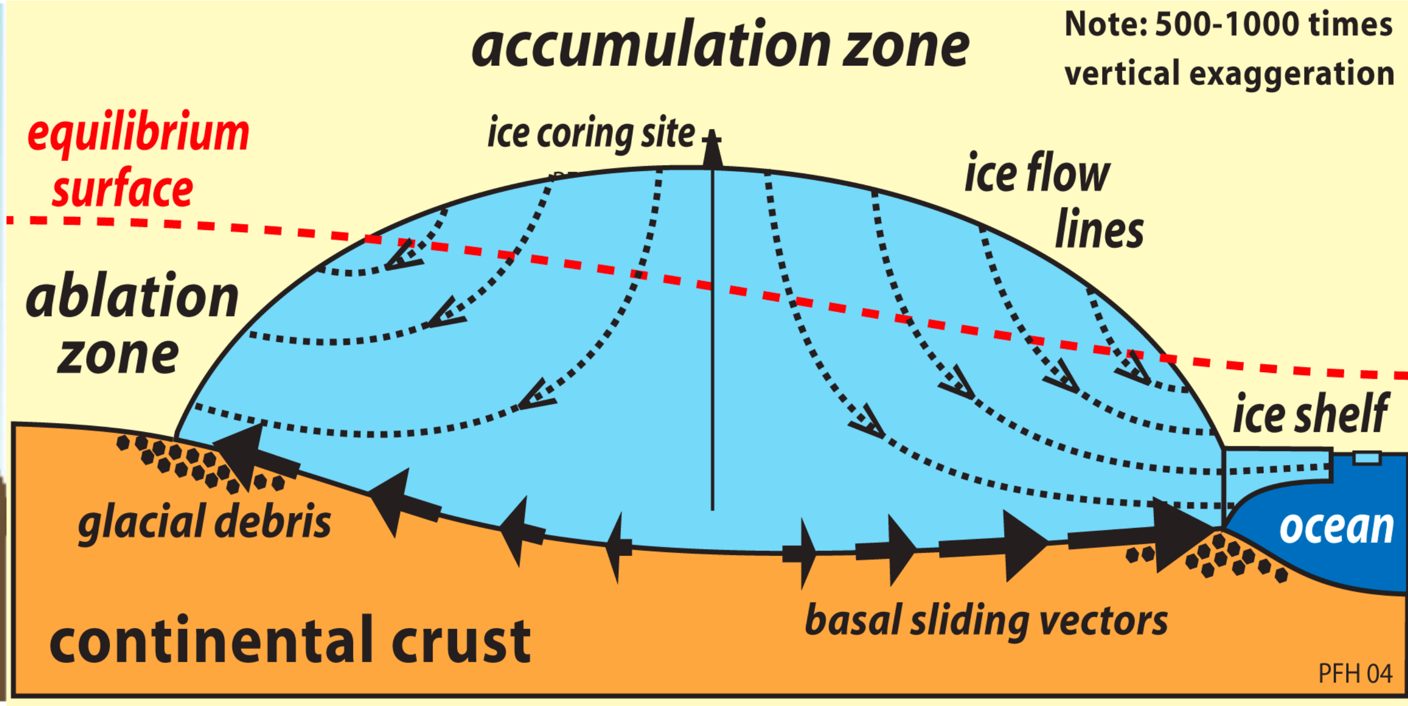
accumulation & ablation zones on ice sheets/ glaciers

Glacier



https://atmos.washington.edu/~bitz/514_2013/lecture_may2.pdf

Ice Sheet



http://www.snowballearth.org/slides/Ch10-7.gif

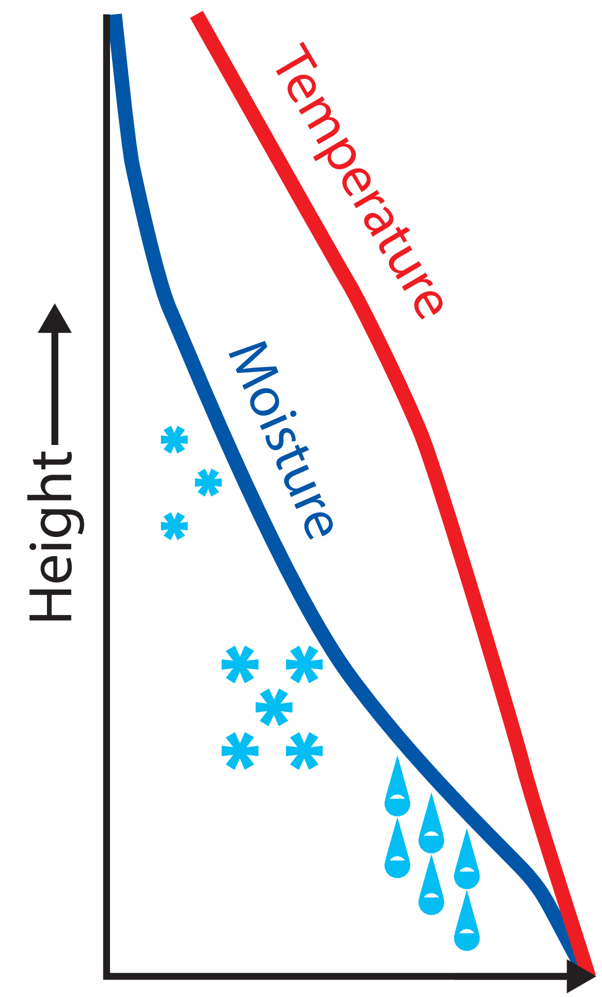
The accumulation zone and ablation zone are separated by the Equilibrium Line Altitude (ELA), or so-called firn line (Firn is old snow).
[left: from lecture slides of ATMS 514 in UW; right: snowballearth.org]

Accumulation

Snow accumulation rate depends on elevation

https://tc.copernicus.org/articles/13/943/2019/

Figure 3(a) Comparison between CloudSat (blue dots with 2σ standard deviation bars) and MRR (red solid line with shaded area representing a 95 % confidence interval) for the 17 February 2016 precipitation event at the DDU station. **(b)** Same as panel **(a)** for the 20 March 2016 event at the DDU station.



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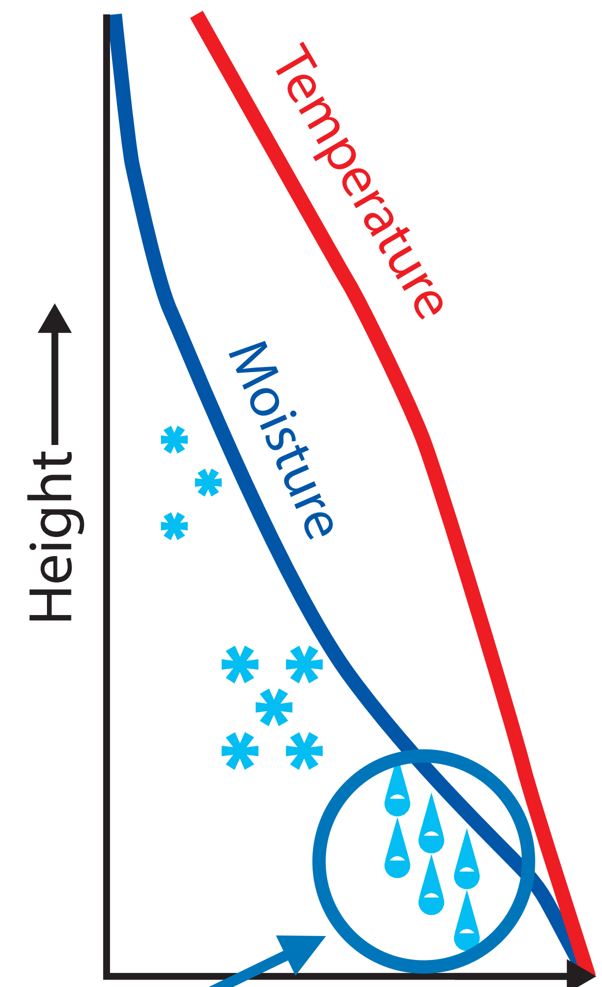
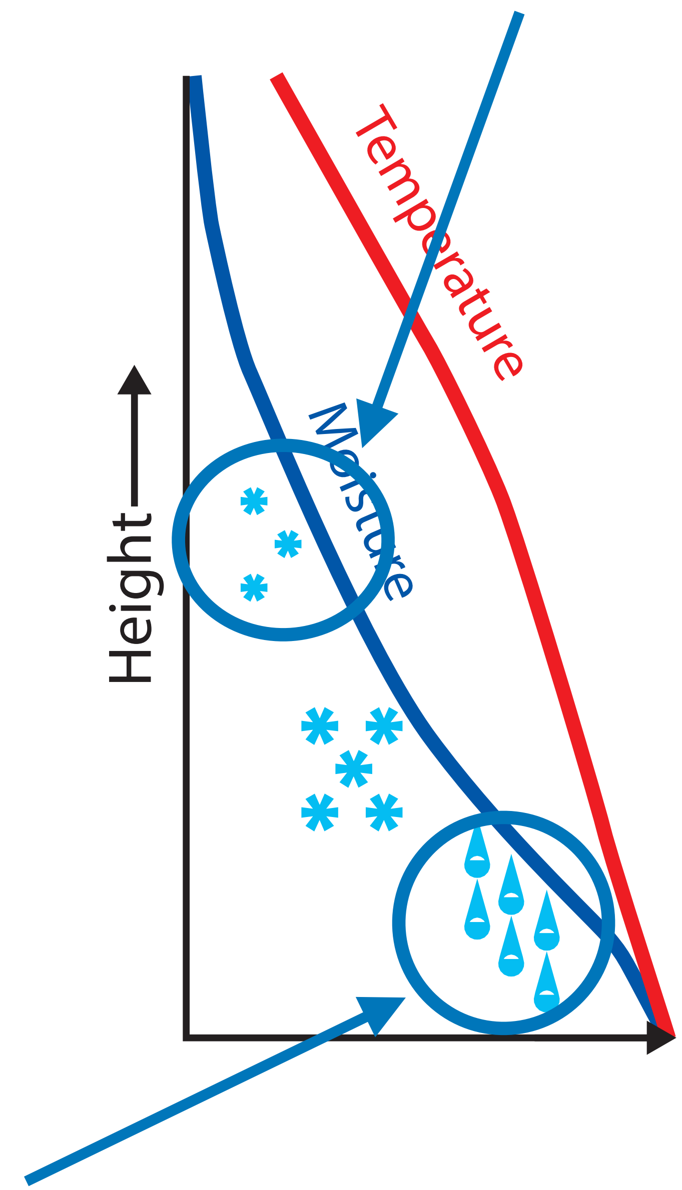


Below snow line,
rain instead of snow

Accumulation

Snow accumulation rate depends on elevation

The elevation-desert effect



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Accumulation

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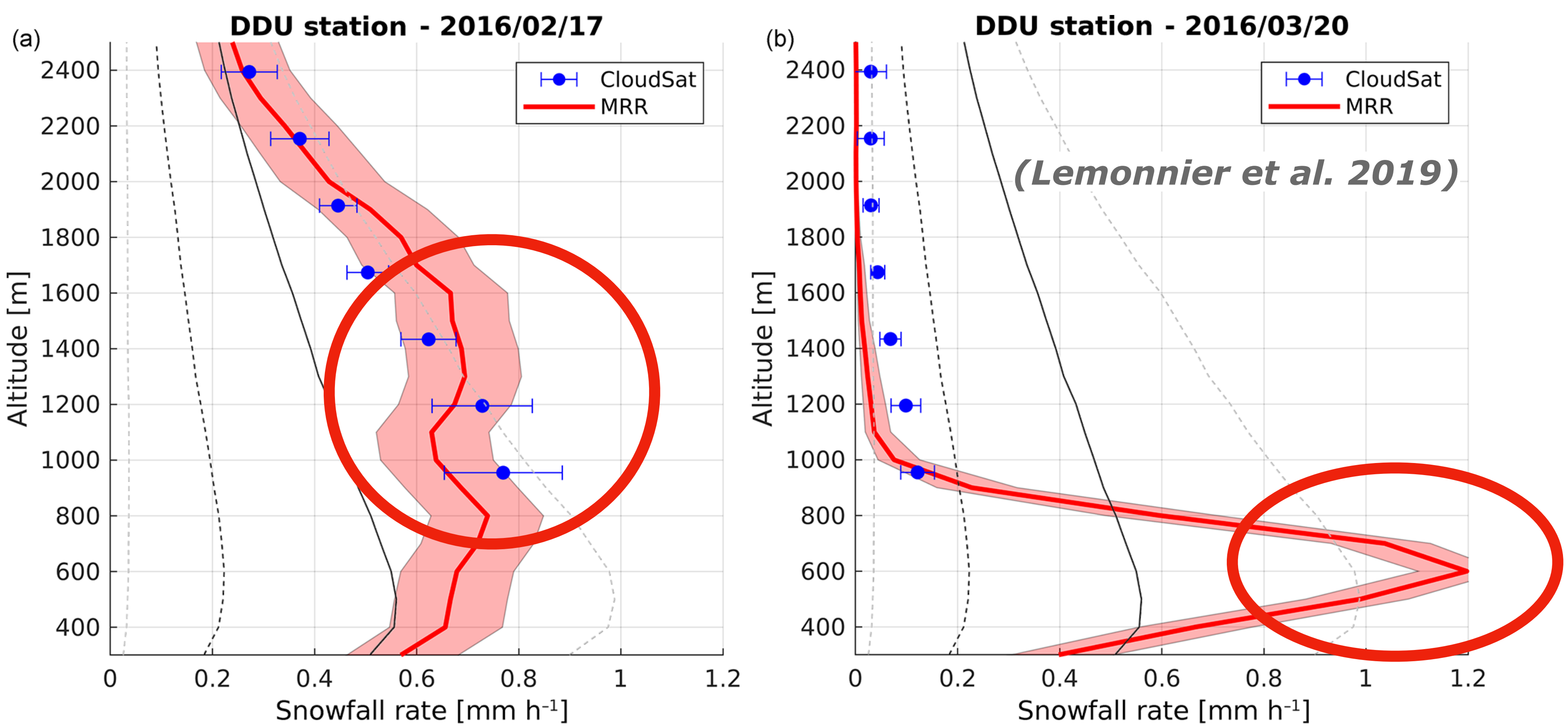

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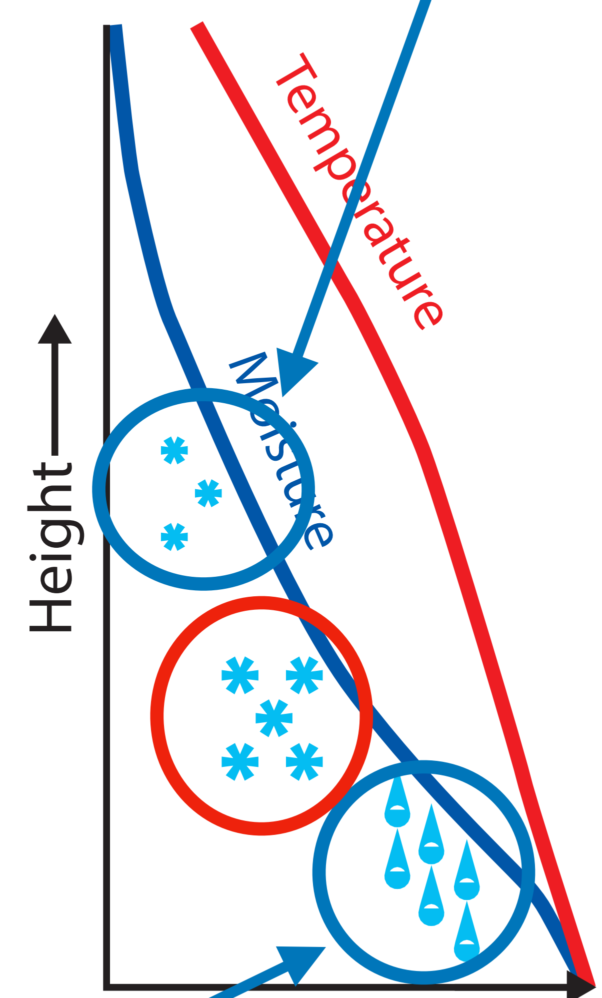
The elevation-desert effect



Below snow line, rain instead of snow

Maximum snow accumulation occurs at intermediate heights

Accumulation

temperature-precipitation feedback

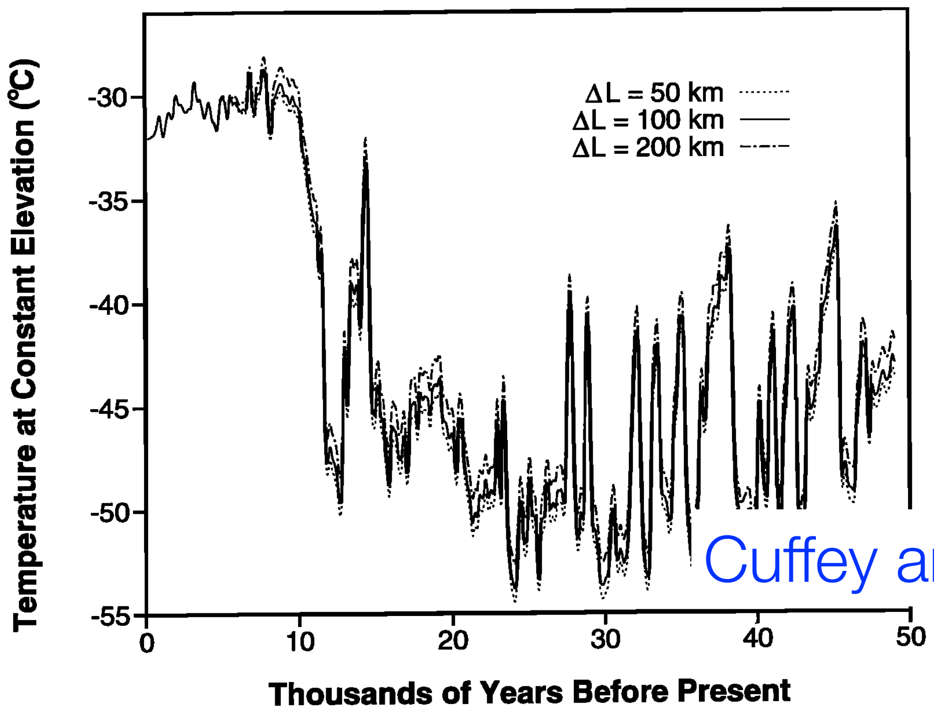


Figure 3. Temperature history according to calibrated isotope curve, corrected for elevation changes. The data have been smoothed with a 250-year triangular filter so that the effect of different elevation corrections, corresponding to different marginal retreat distances, can be seen.

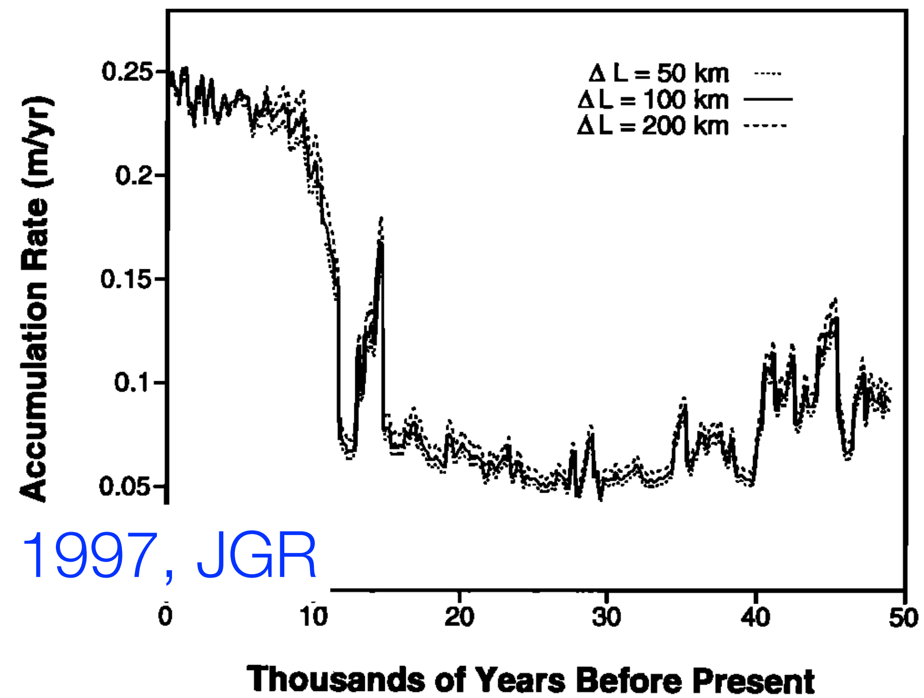
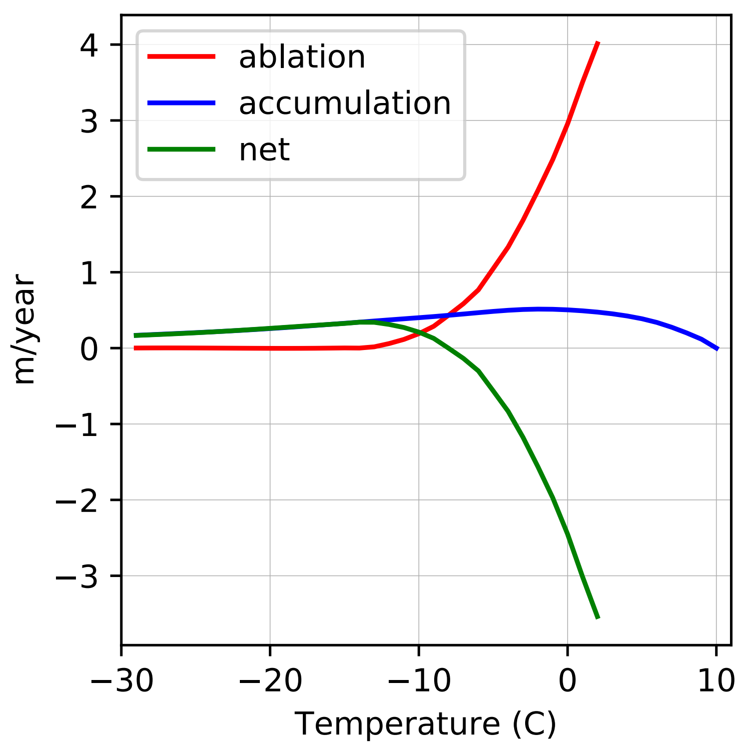


Figure 5. Accumulation rate histories for different marginal retreat distances.

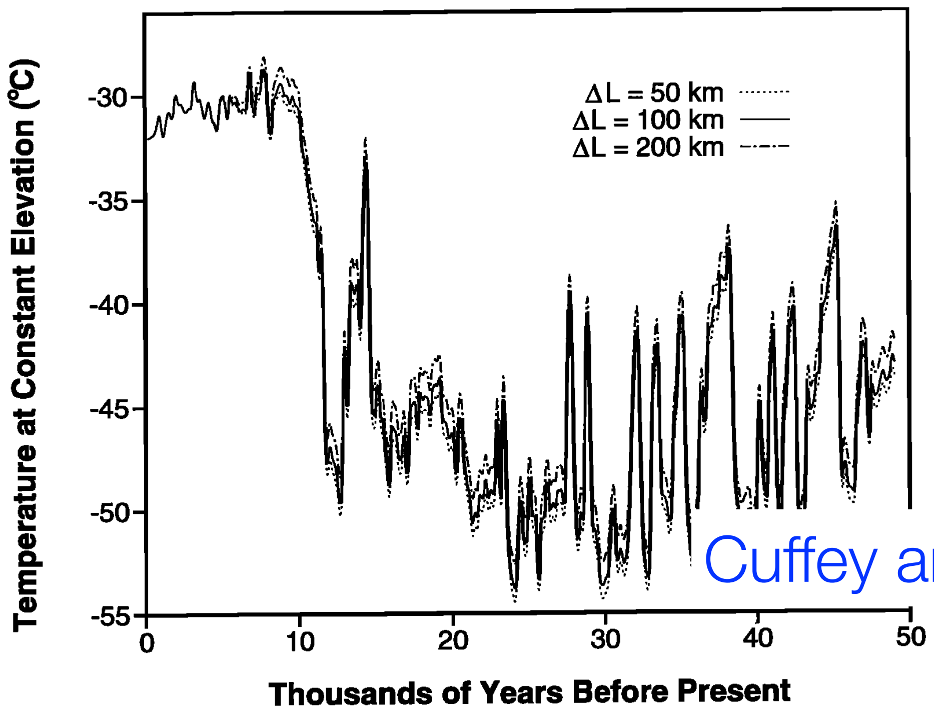
Cuffey and Clow 1997, JGR



higher accumulation rate in warmer climates

Accumulation

temperature-precipitation feedback



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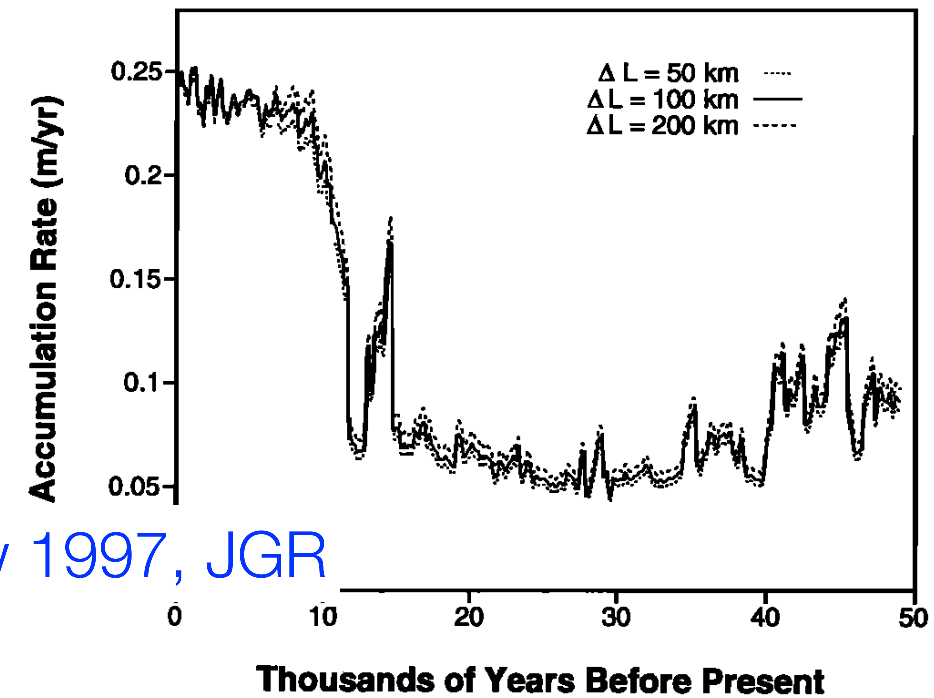

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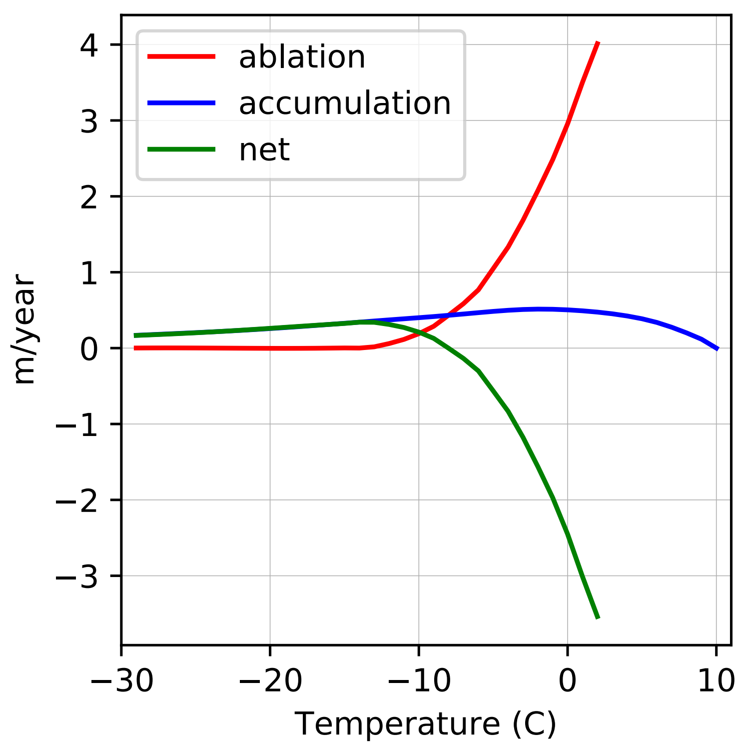

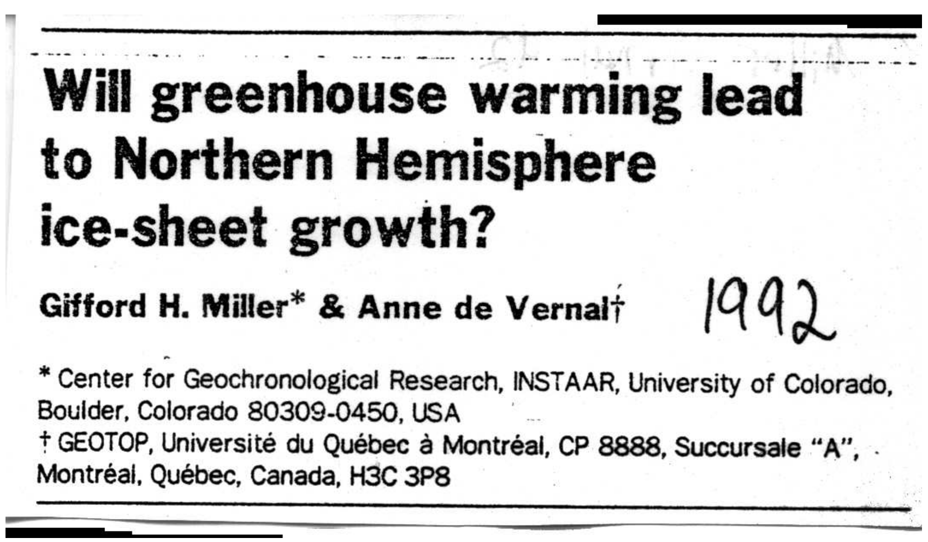

Will greenhouse warming lead to Northern Hemisphere ice-sheet growth?

Gifford H. Miller* & Anne de Vernal† 1992

* Center for Geochronological Research, INSTAAR, University of Colorado, Boulder, Colorado 80309-0450, USA
† GEOTOP, Université du Québec à Montréal, CP 8888, Succursale "A", Montréal, Québec, Canada, H3C 3P8

higher accumulation rate in warmer climates

Ablation, ice flow
Antarctic ice streams

https://www.jpl.nasa.gov/video/details.php?id=1015

Ablation, ice flow

Antarctic ice streams

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Ablation, ice flow
Greenland ice streams

NASA video: https://www.youtube.com/watch?v=GDXq8Oa5d5Q

Ablation, ice flow
Greenland ice streams

NASA video: https://www.youtube.com/watch?v=GDXq8Oa5d5Q

workshop 2:
Ice stream acceleration

Ablation

Surface melting/ sublimation/ **positive degree days**

Melting and sublimation occur mostly during summer, when the **surface air temperature** is higher than the melting temperature

The **positive degree day** empirical fit to surface melting provides a simple way to estimate total melting over a year:

Melting (m/year) = (factor) x (sum of daily mean surface air temperatures above 0, over one year)

PDD

$$\mathrm{PDD} = \sum_i (T_i - T_m)\mathscr{H}(T_i - T_m)$$

Sum over all days in a year

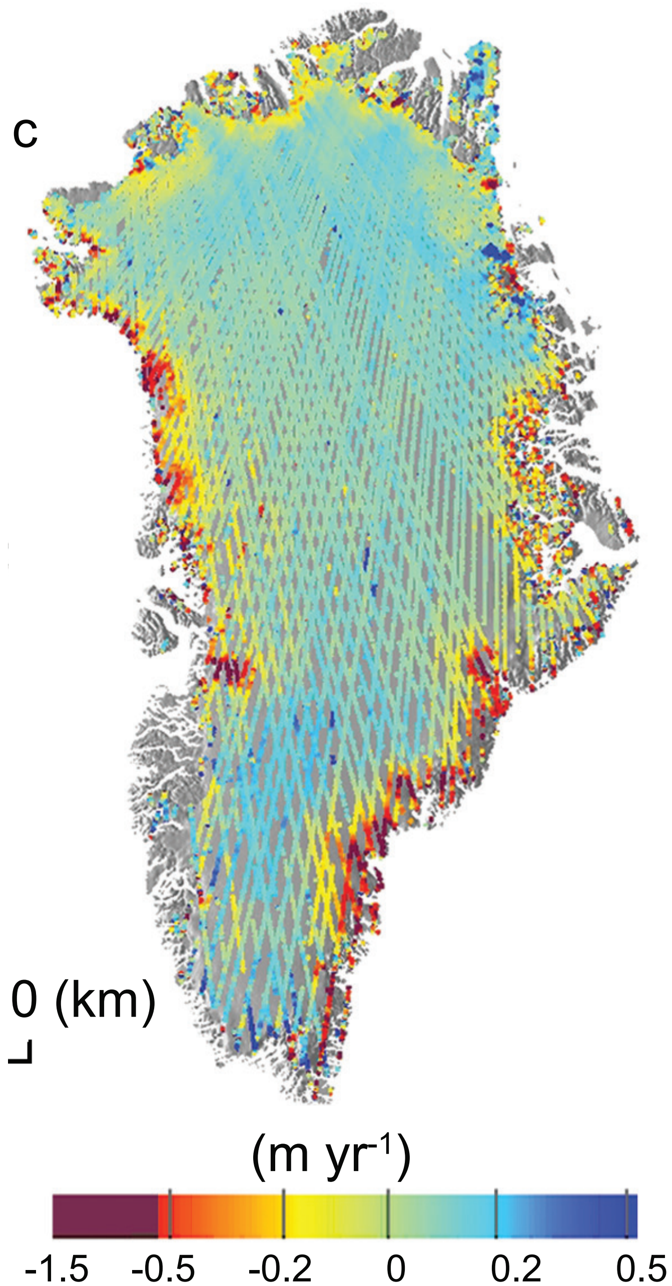
Temperature at day *i*

Melting temperature

Heaviside function [H(x)=0 for x<0, 1 otherwise]

Example: daily temperatures=[–5, 2, 4] ⇒ PDD=6

Ablation: surface mass balance



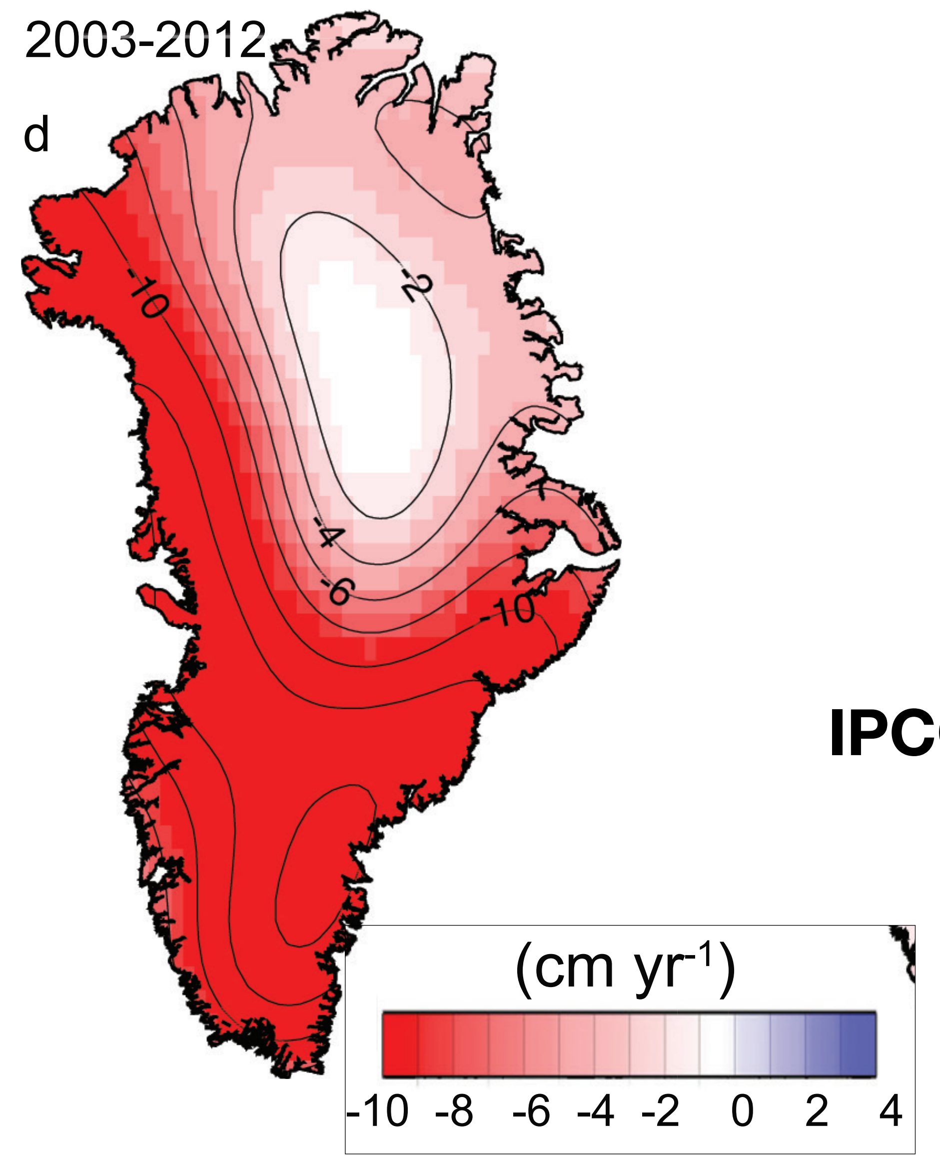


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Figure 4.13 | Key variable related to the determination of the Greenland ice sheet mass changes. (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year for 2003–2012, color coded red (loss) to blue (gain) (Velicogna, 2009).

Ablation: surface mass balance

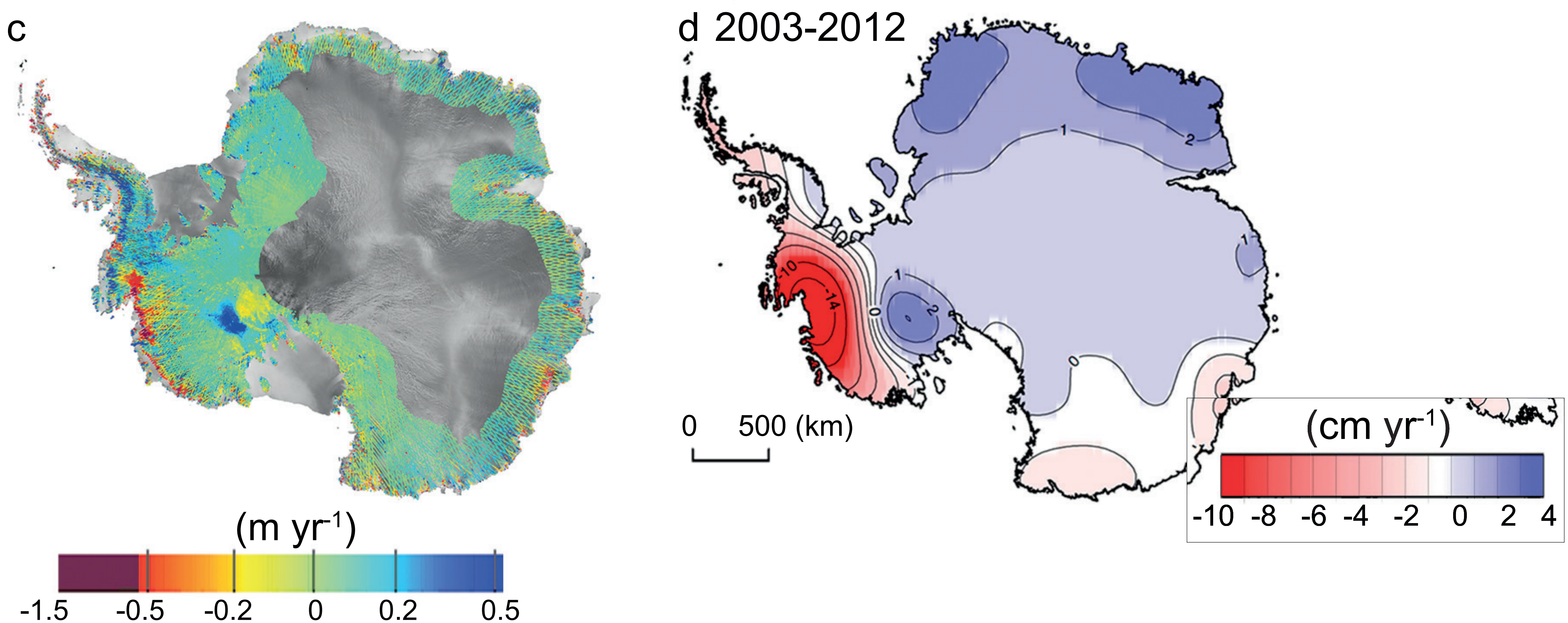

Figure 4.14 | Key fields relating to the determination of Antarctica ice sheet mass changes. **(c)** Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). **(d)** Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year for 2003–2012, color coded red (loss) to blue (gain) (Velicogna, 2009).

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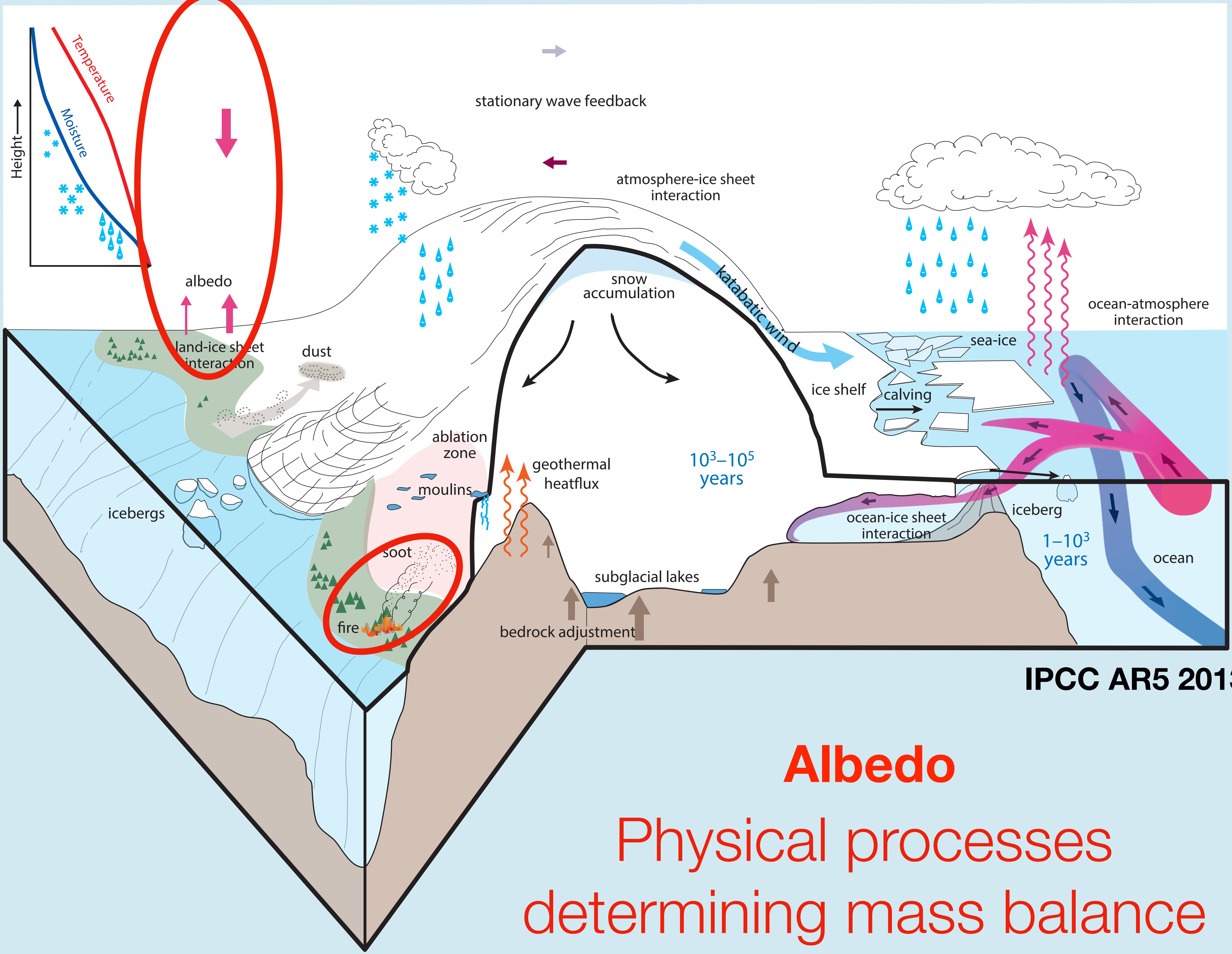
workshop 3:
Positive Degree Days



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Albedo

Physical processes determining mass balance

Ablation

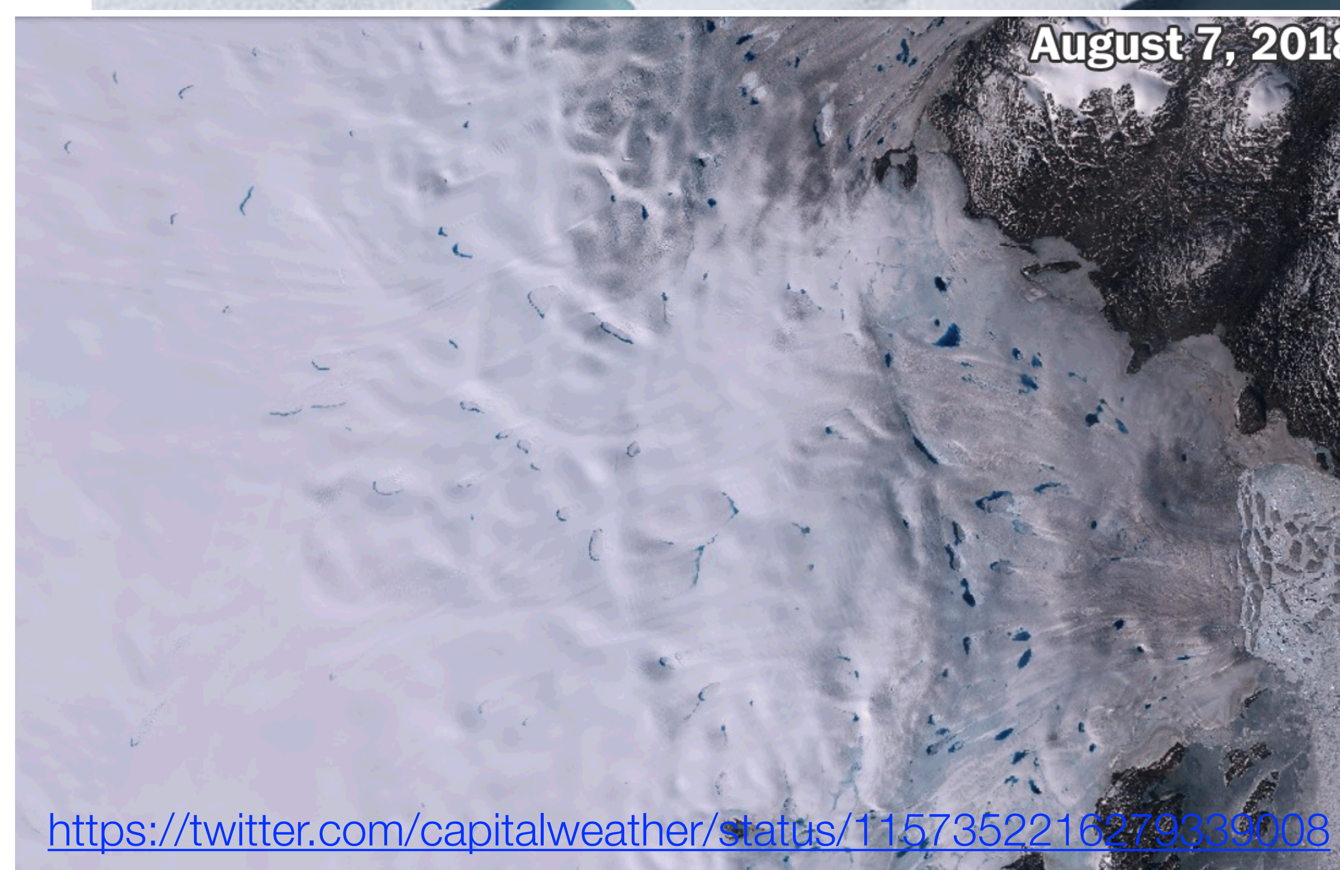
surface melting: albedo feedbacks

The surface temperature is largely controlled by the **albedo** (the surface reflectivity of sunlight).

Positive melting-albedo feedback: The low albedo of melting ponds leads to more sunlight absorption, higher surface temperature, and enhanced melting.

Biological albedo feedback: Algae in melting ponds can further darken the ice and reduce the albedo. Remote forest fires result in soot over the ice and albedo change.

Scientists retrieving samples from the Arctic Ocean in July, 2011. NASA/REUTERS. https://www.newsweek.com/ancient-ocean-temperatures-wrong-unparalleled-climate-change-694434



https://twitter.com/capitalweather/status/1157352216279339008

Ablation

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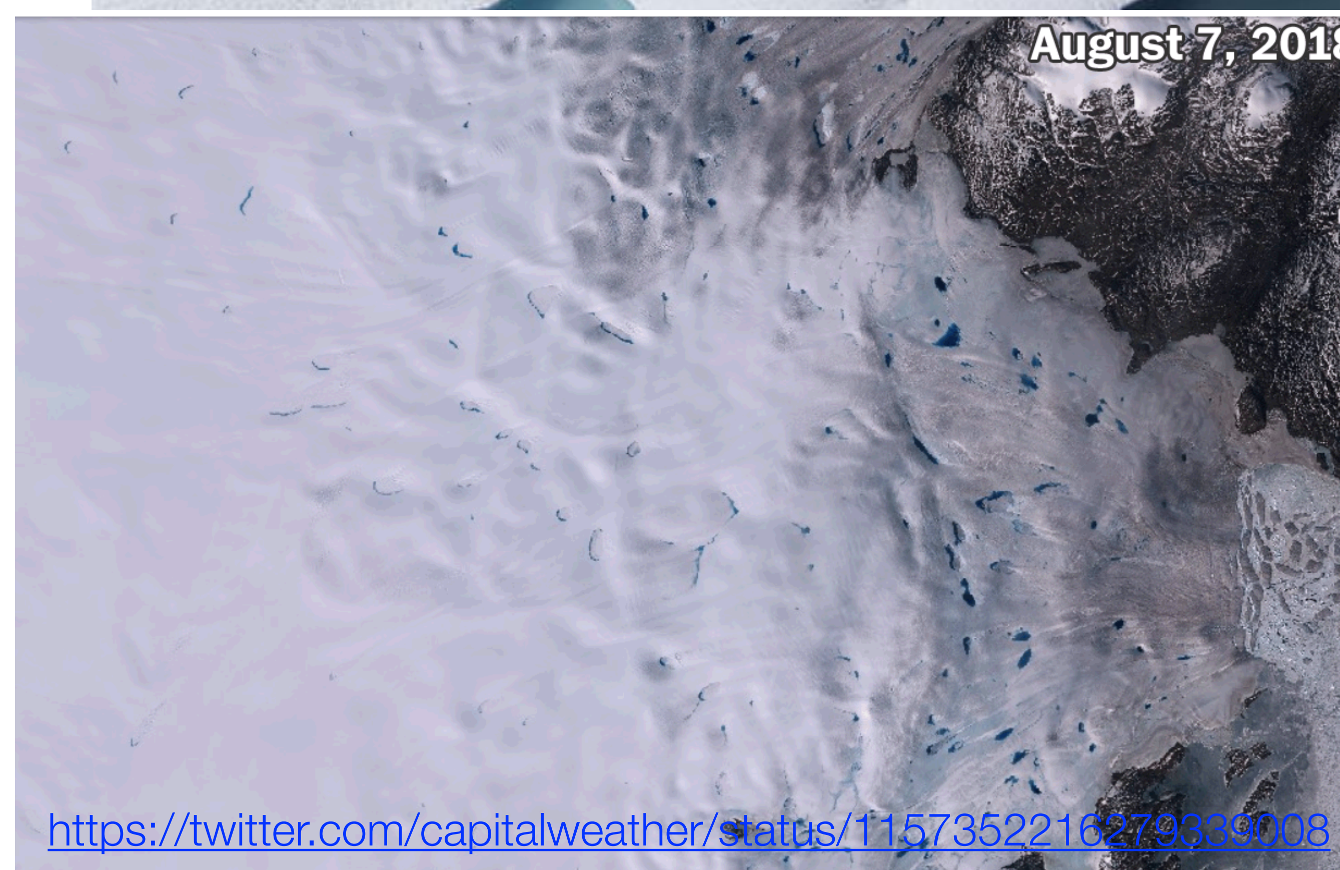

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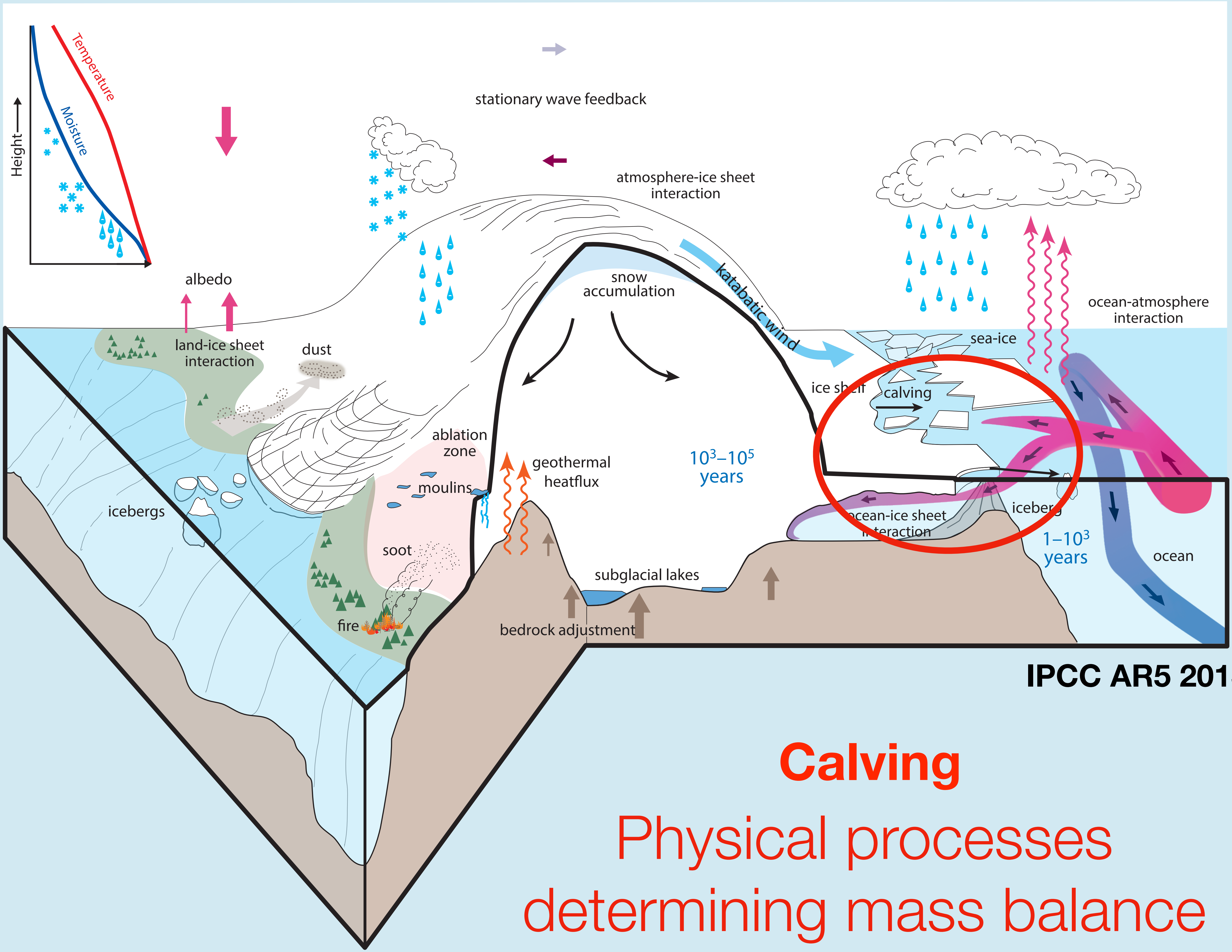

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Calving

Physical processes determining mass balance

Ablation: Calving

break-up of ice into ocean at edge of ice sheet

A giant piece of ice breaks off the Perito Moreno Glacier in Patagonia, Argentina

Credit: iStock; https://www.commercialriskonline.com/wp-content/uploads/2018/10/0_ice-calving-climate-change_iStock-694728278.jpg

Stretching and compression create crevasses

Ablation

A Massive Glacier **Calving** in 2013

https://www.youtube.com/watch?v=1s5-lvHVDqg

Ablation

A Massive Glacier **Calving** in 2013

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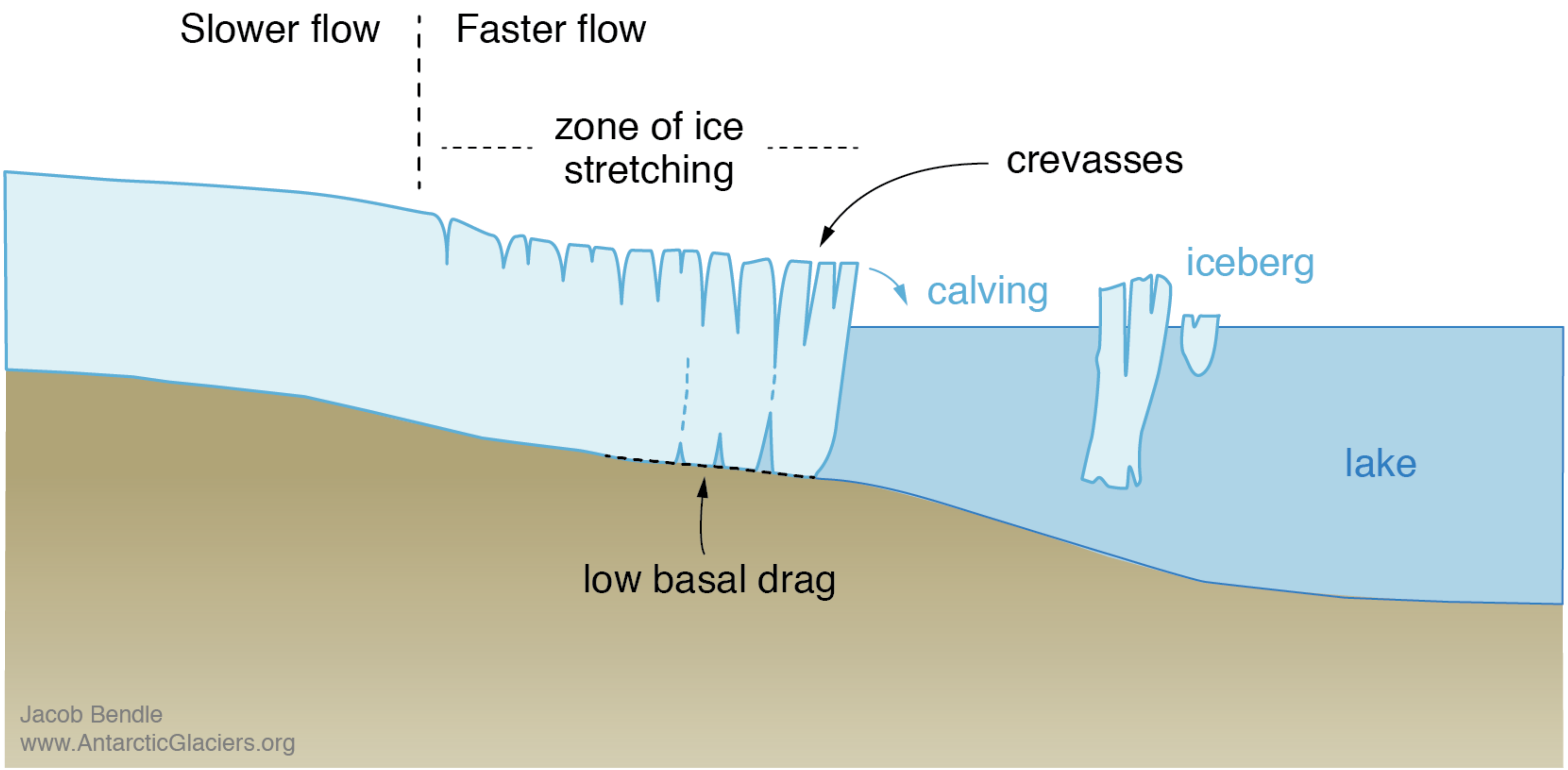
Ablation: Calving

break-up of ice into ocean at edge of ice sheet

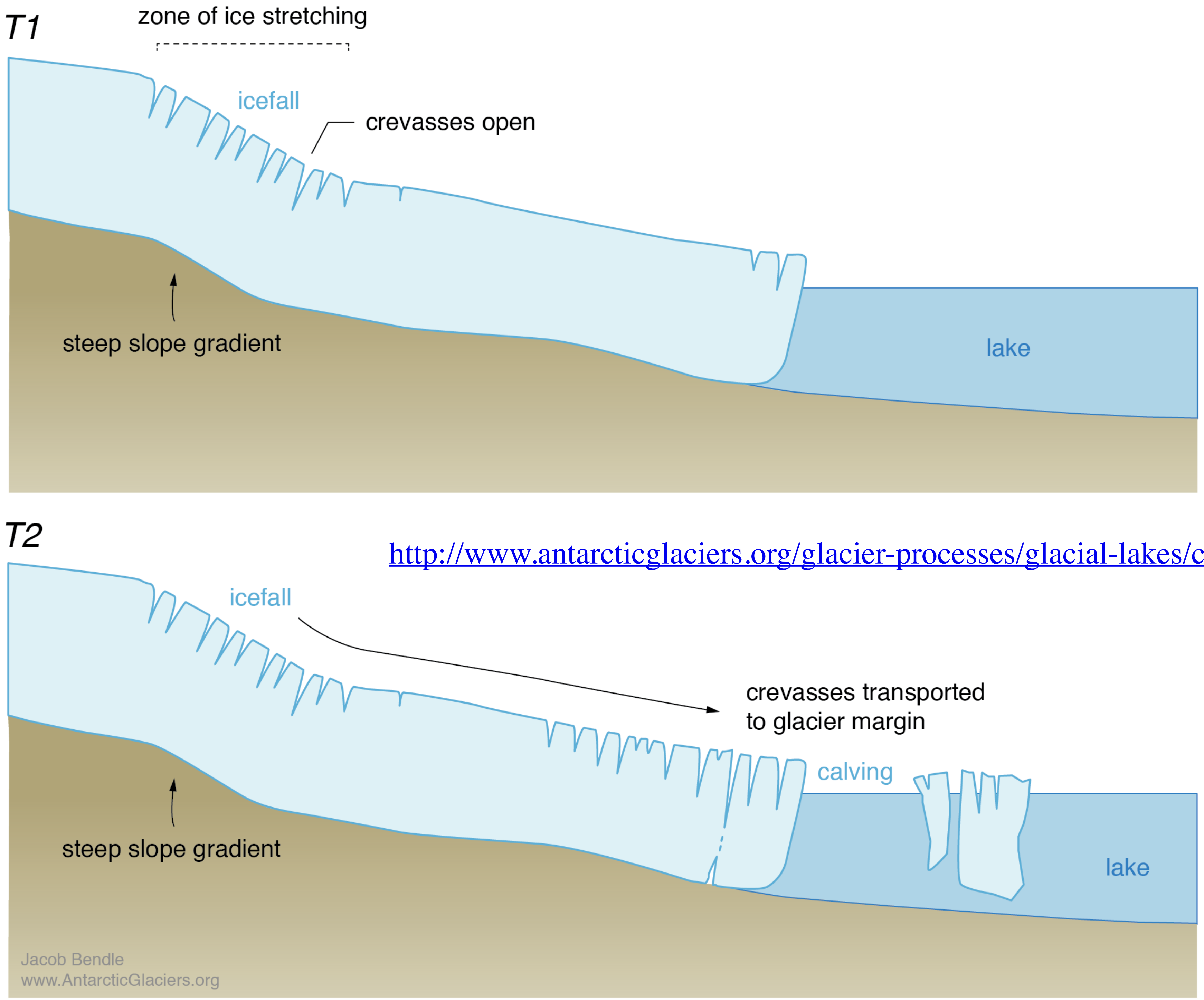


http://www.antarcticglaciers.org/glacier-processes/glacial-lakes/calving-of-freshwater-glaciers/

basal & lateral drag stretch ice sheet, creating crevasses

Ablation: Calving

break-up of ice into ocean at edge of ice sheet

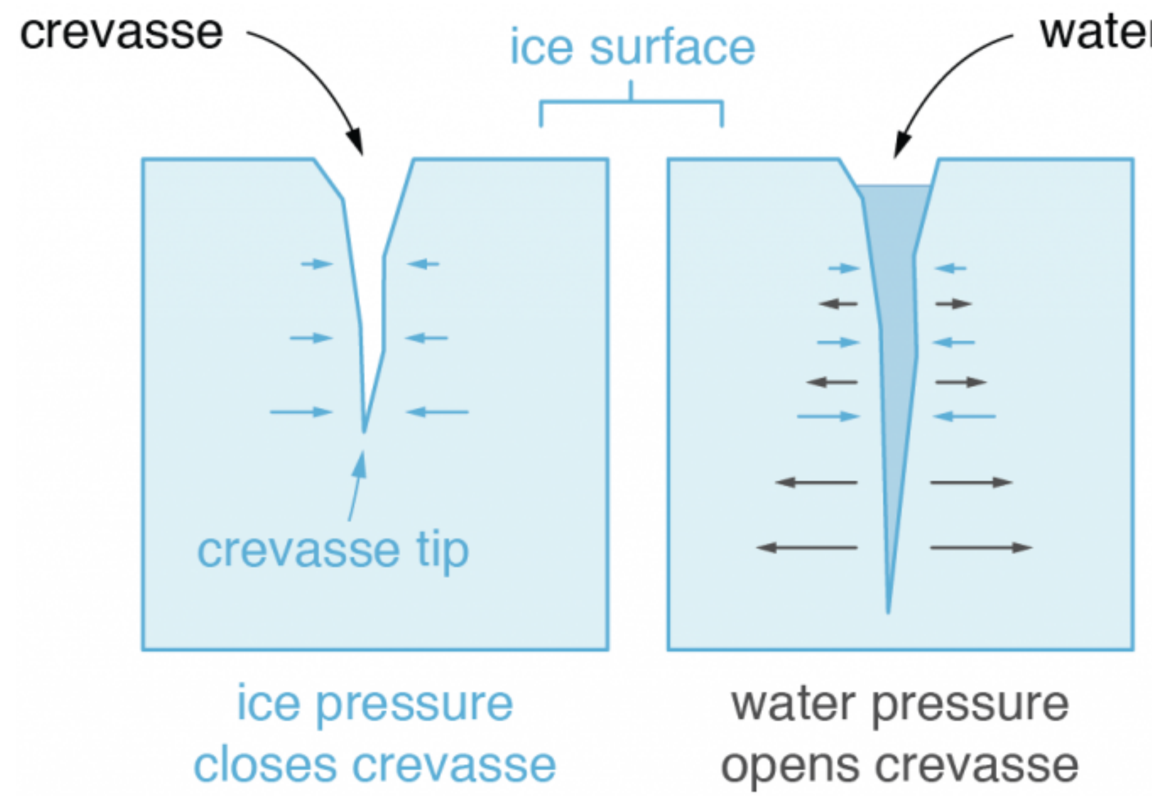


http://www.antarcticglaciers.org/glacier-processes/glacial-lakes/calving-of-freshwater-glaciers/

steep landscape also causes crevasses

Ablation

Calving due to hydro-fracturing



Calving may start once the crevasses reach sea level, as buoyancy forces may overcome yield stress (Benn et al. 2007)

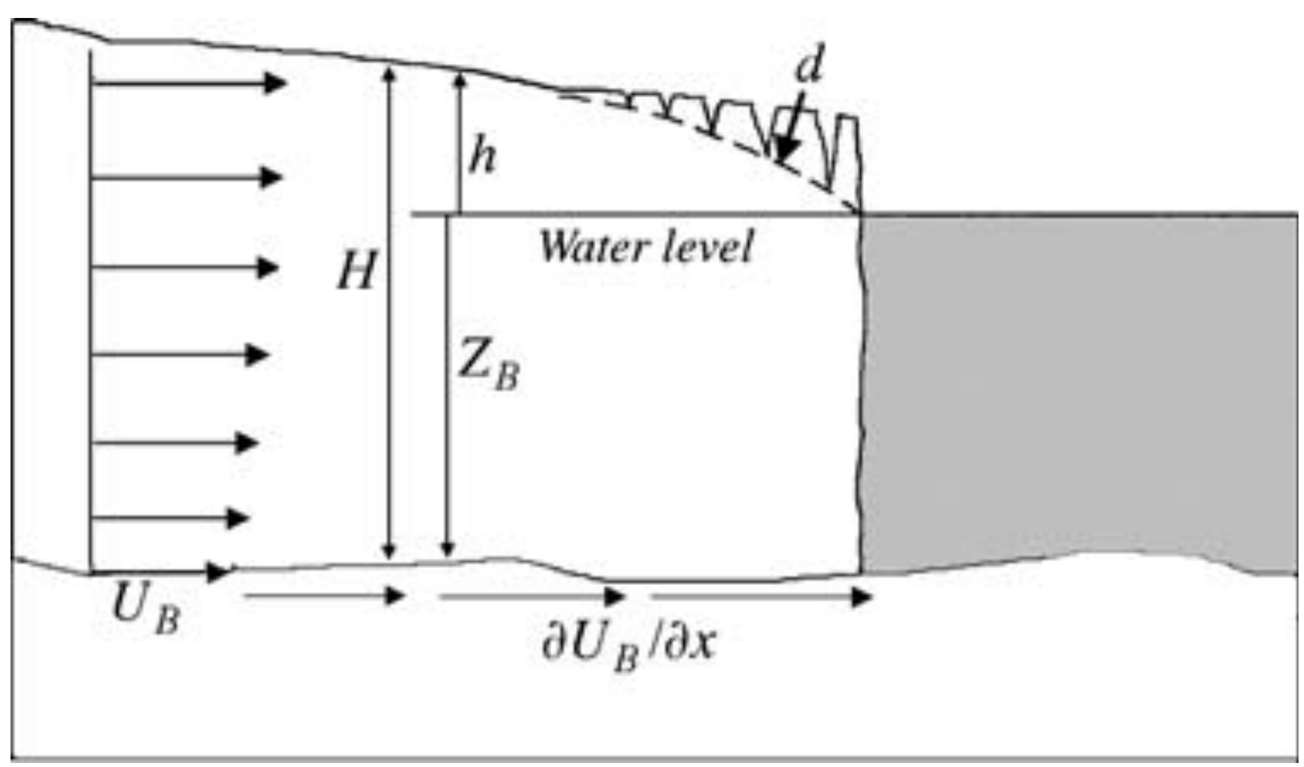
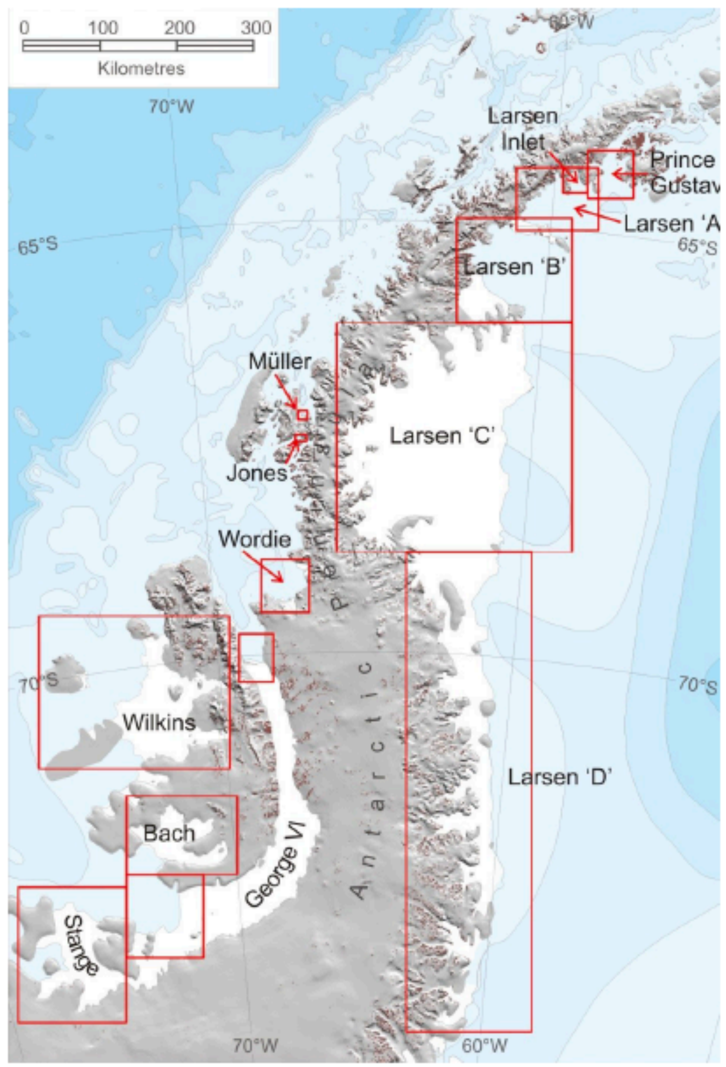


Fig. 12. Schematic illustration of first-order calving in response to longitudinal stretching. Surface crevasses propagate downward to a depth d in response to the velocity gradient $\partial U_B/\partial x$. Calving is assumed to occur when $d=h$ (after Benn et al., in press). ***Benn et al. 2007***

Ablation

Calving due to hydro-fracturing: **Larsen B ice shelf**

https://en.wikipedia-on-ipfs.org/wiki/List_of_Antarctic_and_sub-Antarctic_islands.html



https://commons.wikimedia.org/wiki/File:Antarctic-Peninsula-Ice-Shelves.png

Animation of MODIS data by Alex Forman

From 31 January 2002 to March 2002 the **Larsen B sector** partially collapsed and parts broke up, 3,250 squared km of ice 220 m thick, an area comparable to the US state of Rhode Island.

Ablation

Calving due to hydro-fracturing: **Larsen B ice shelf**

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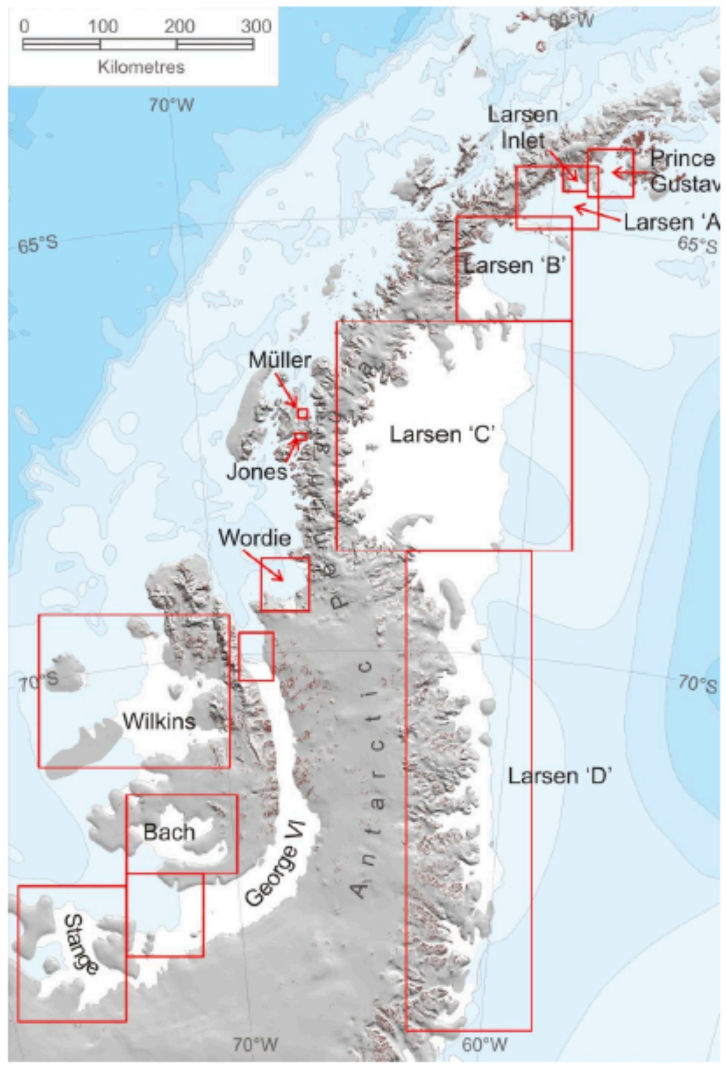

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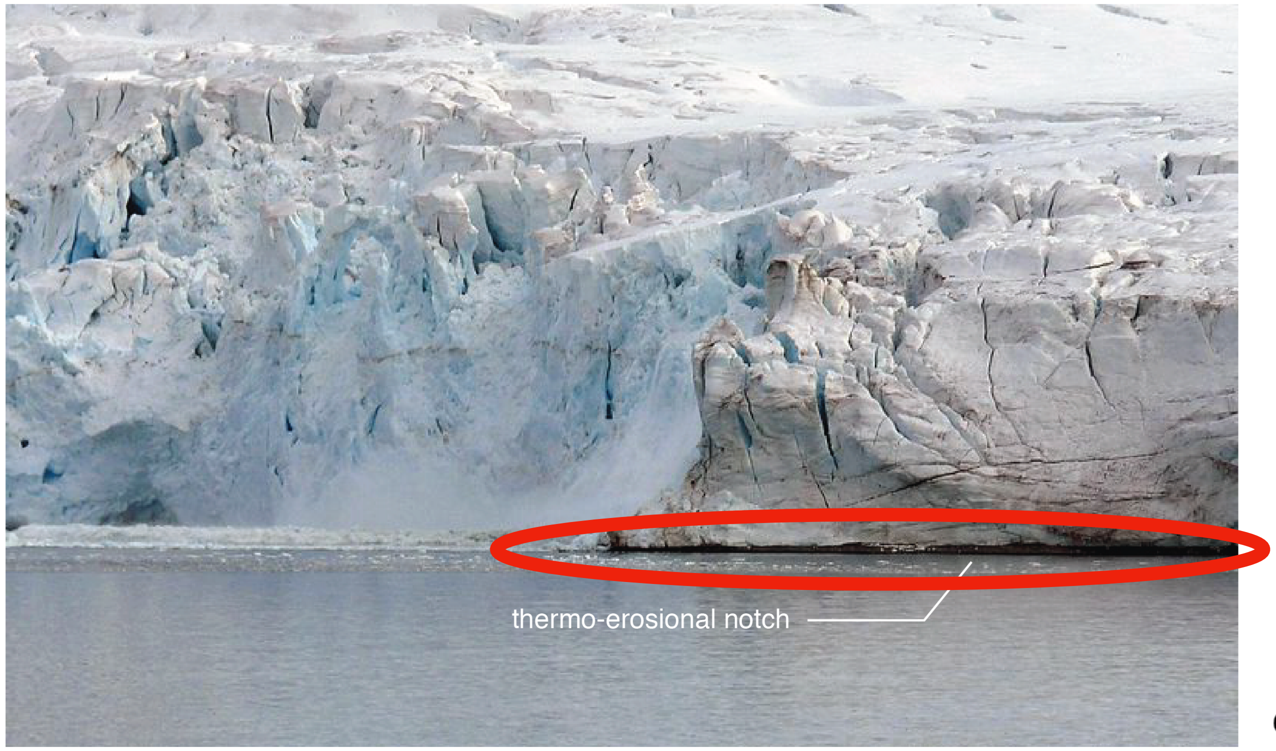
Animation of MODIS data by Alex Forman

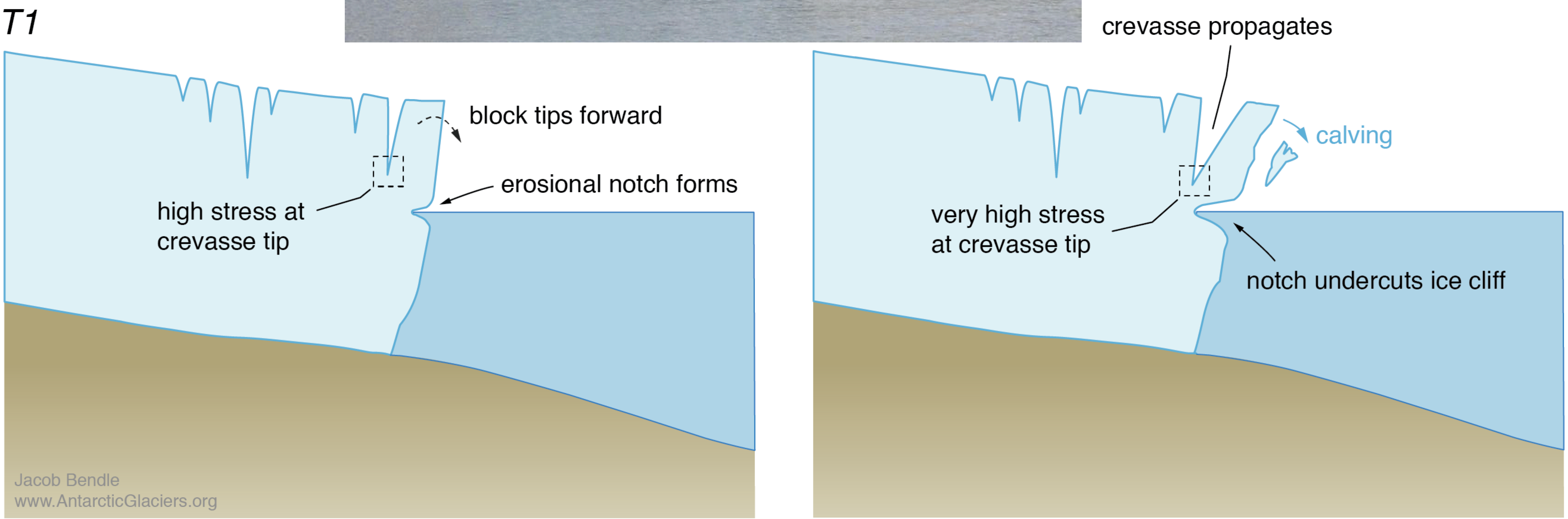
From 31 January 2002 to March 2002 the **Larsen B sector** partially collapsed and parts broke up, 3,250 squared km of ice 220 m thick, an area comparable to the US state of Rhode Island.

Ablation

Calving due to melting at waterline

http://www.antarcticglaciers.org/glacier-processes/glacial-lakes/calving-of-freshwater-glaciers/therm-erosional-notch/

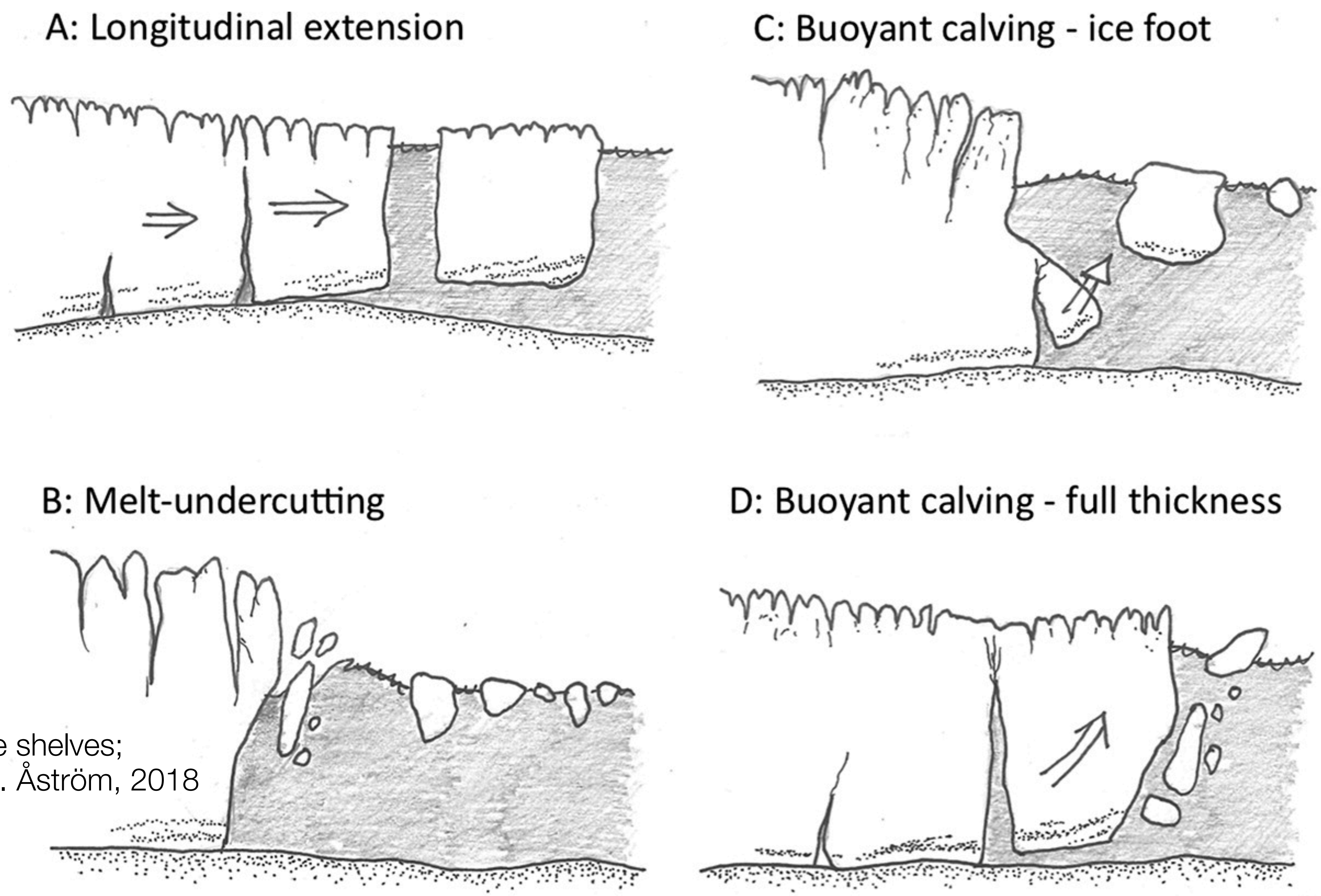




http://www.antarcticglaciers.org/glacier-processes/glacial-lakes/calving-of-freshwater-glaciers/

Ablation

Calving: role of buoyancy forces

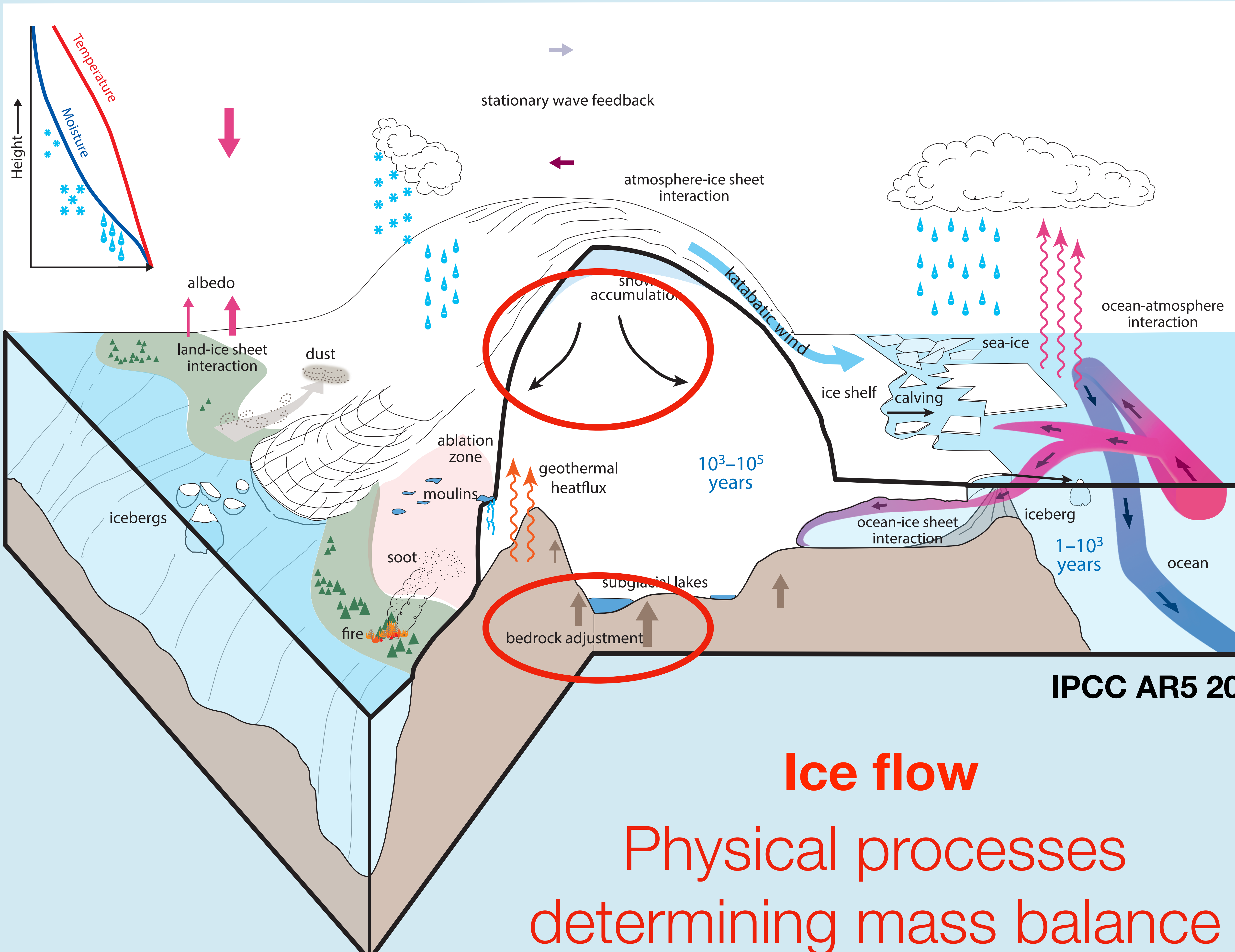


Calving glaciers and ice shelves;
Douglas I. Benn, Jan A. Åström, 2018

Figure 2. A selection of key calving styles: **(a)** rifting due to longitudinal extension, **(b)** collapse of overhang following undercutting by subaqueous melt, **(c)** buoyant calving: release of a protruding 'ice foot' below the waterline and **(d)** buoyant calving: uplift of a super-buoyant glacier tongue.

Notes section 10.2.3
Calving

workshop #4
Calving



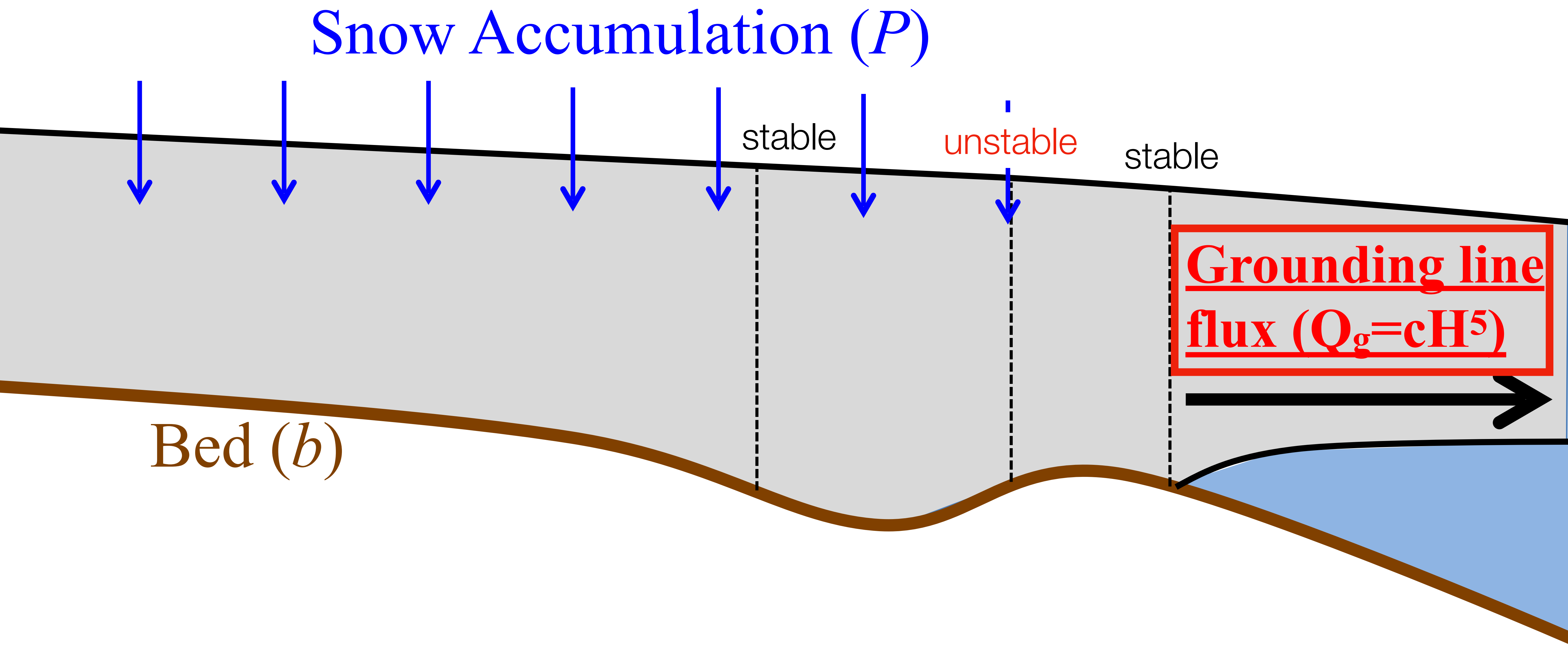
IPCC AR5 2013

Ice flow

Physical processes determining mass balance

notes section 10.2.4
Ice flow, MISI (use following slides)

Ice flow: Marine Ice Sheet Instability (MISI)

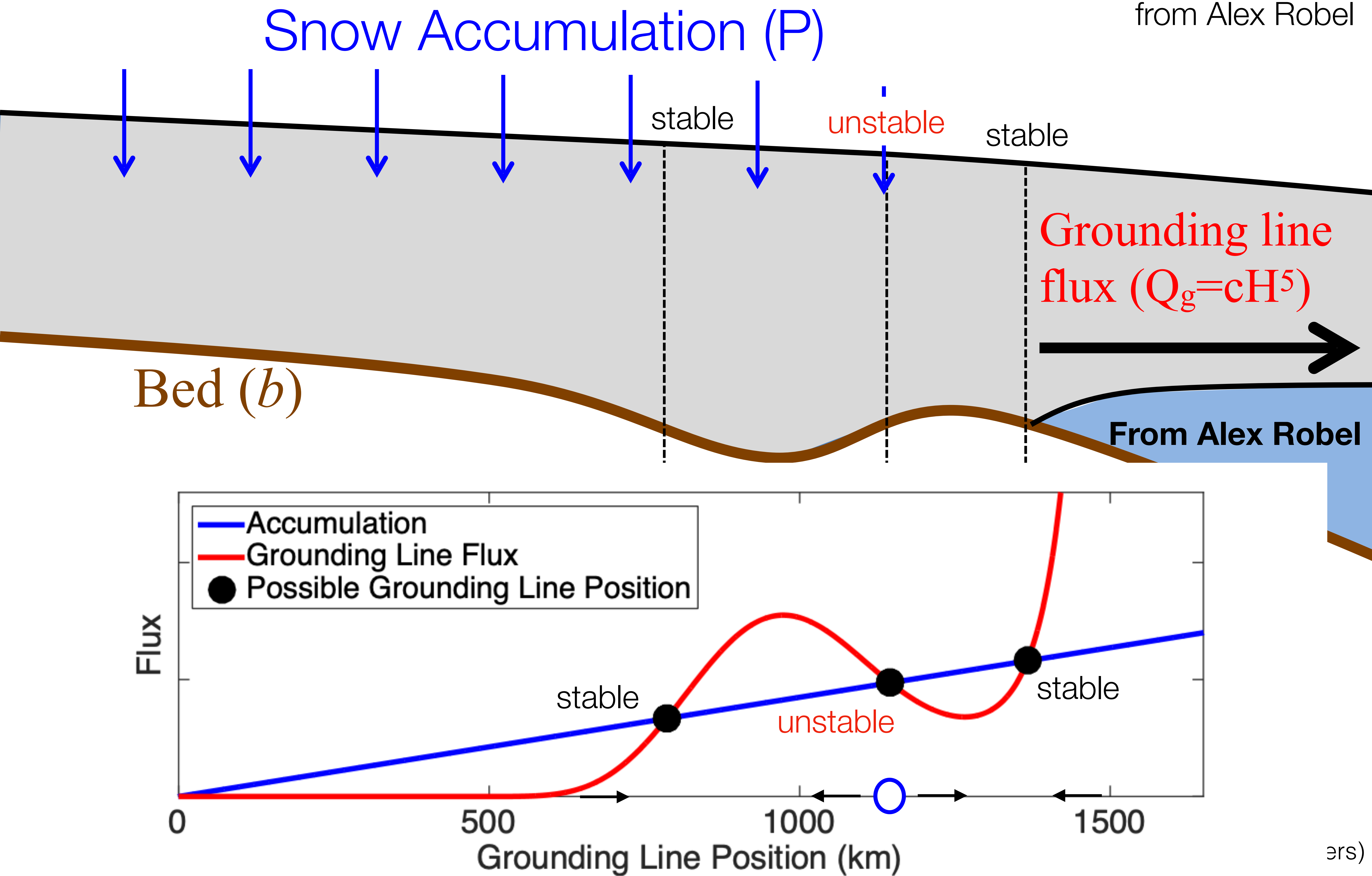


From Alex Robel

Ice transport is larger when the grounding line ice is thicker.

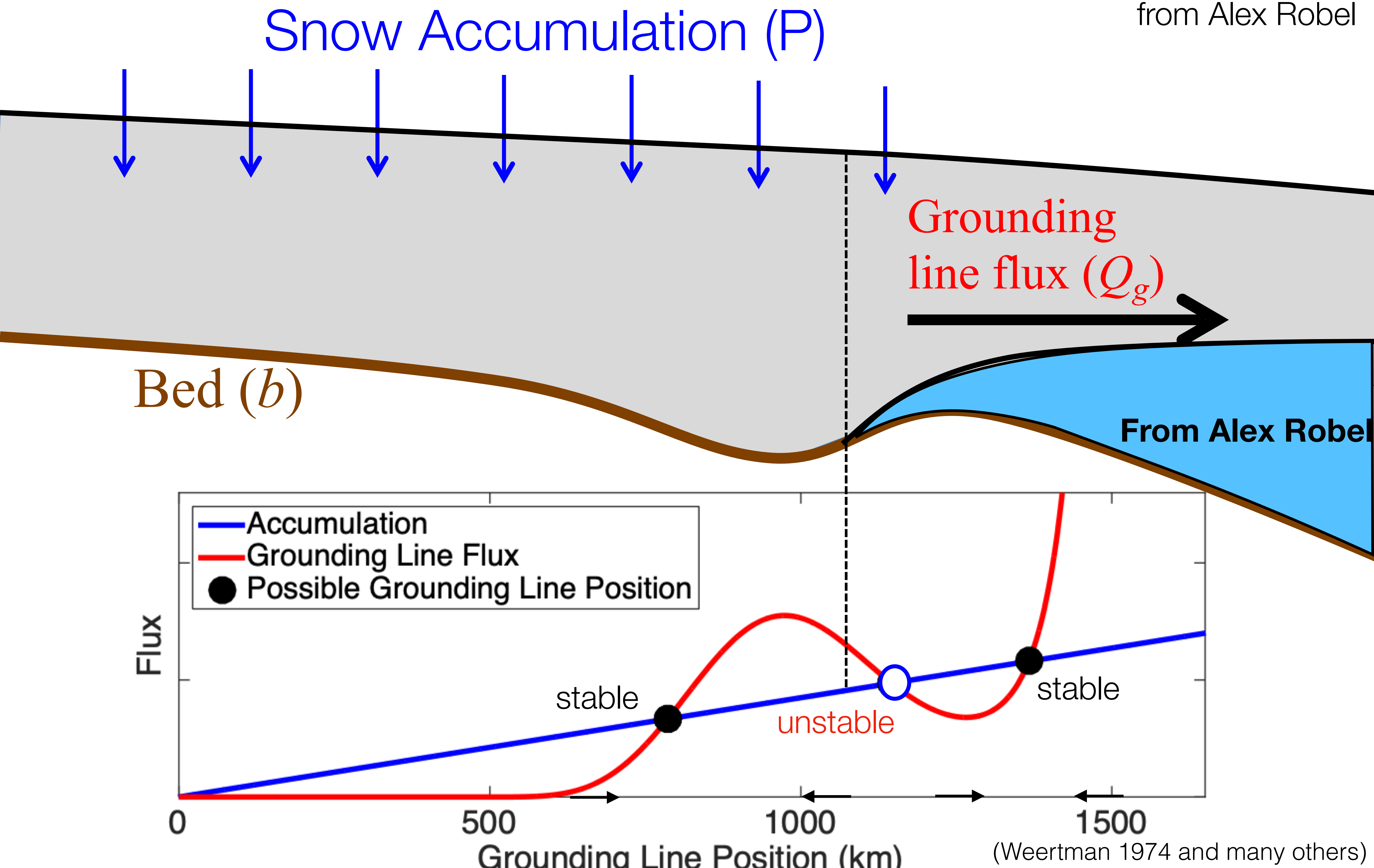
Marine Ice Sheet Instability (MISI)
scenario (1): melting by a warmer ocean

from Alex Robel



Marine Ice Sheet Instability (MISI)
scenario (1): melting by a warmer ocean

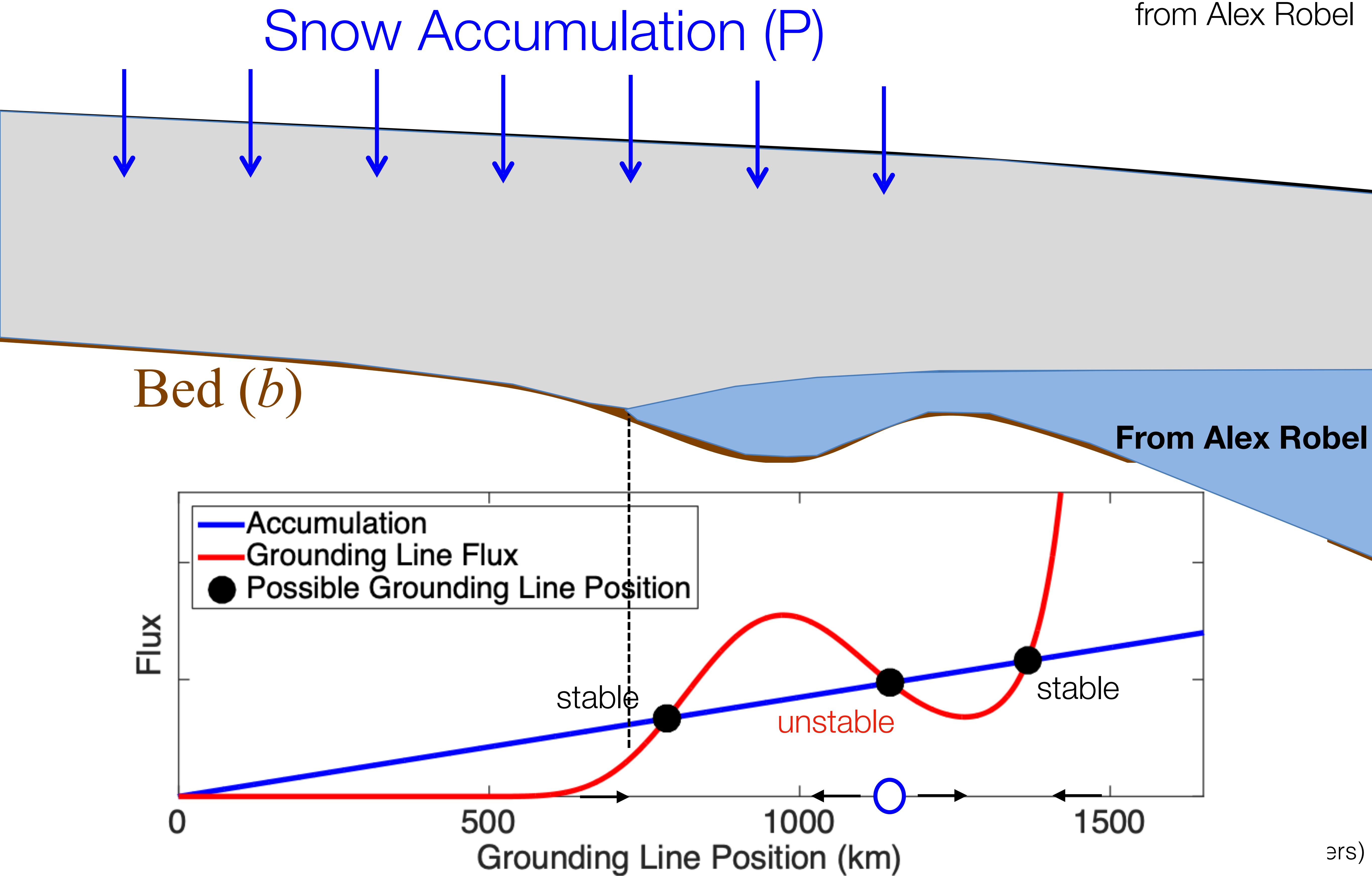
from Alex Robel



(Weertman 1974 and many others)

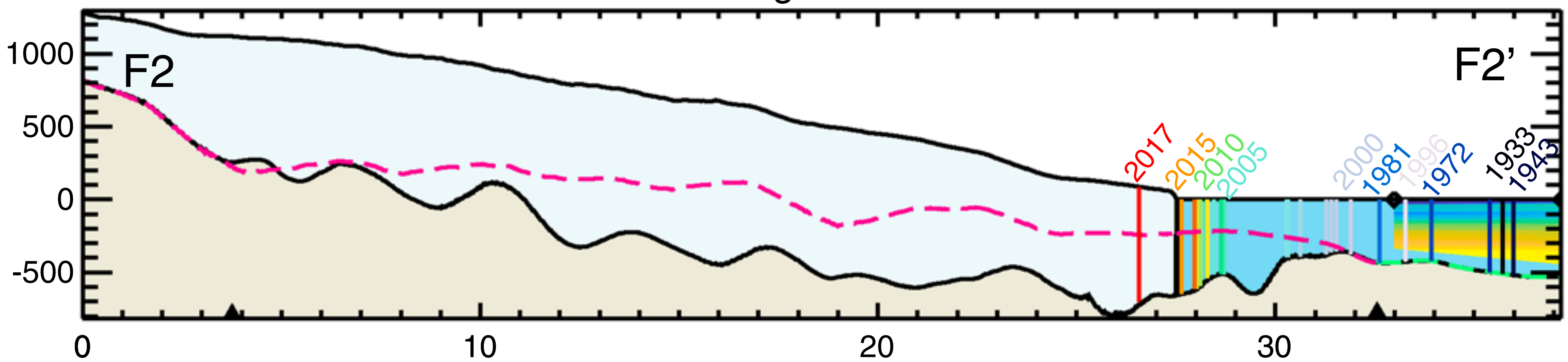
Marine Ice Sheet Instability (MISI)
scenario (1): melting by a warmer ocean

from Alex Robel



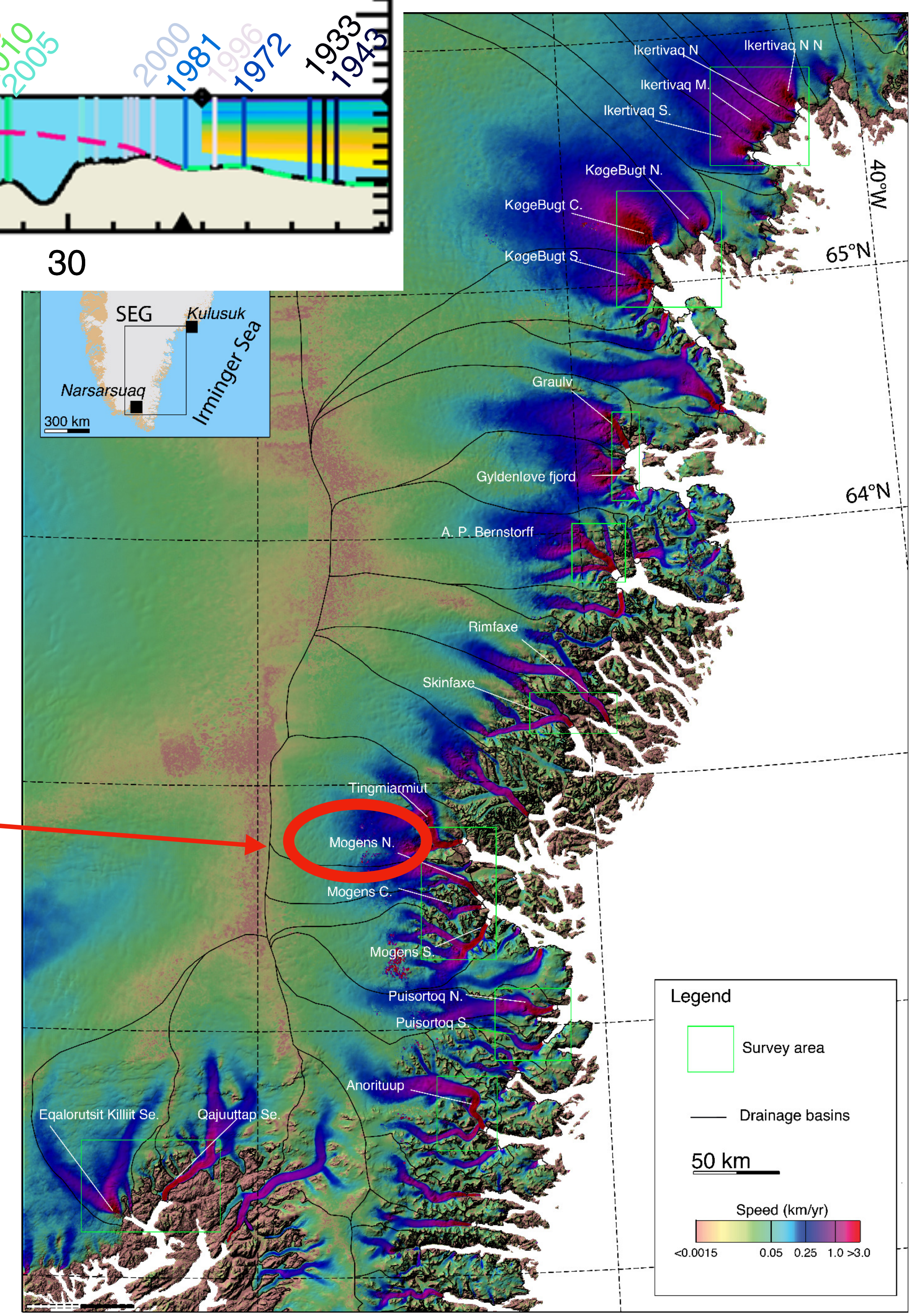
Marine Ice Sheet Instability (MISI) leading to ice retreat in Greenland

Mogens N.

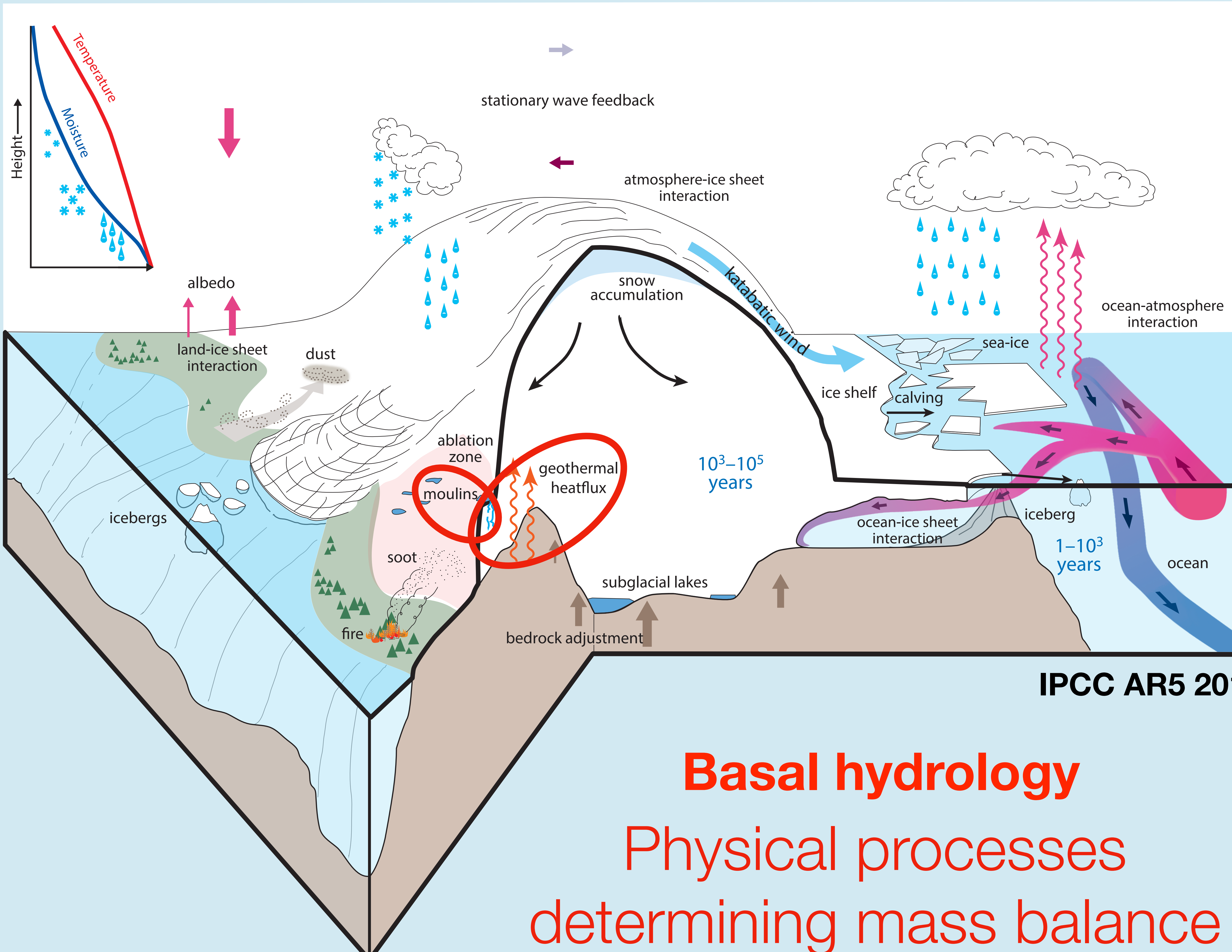


(dash red: previous estimate of topography; note large difference from previous topography)

Morgen N ice stream: "Largest retreat on a retrograde slope after 1965, doubled its speed since 1990s"



Vulnerability of Southeast Greenland Glaciers to Warm Atlantic Water From Operation IceBridge and Ocean Melting Greenland Data
R. Millan, E. Rignot, J. Mouginot, M. Wood, A. A. Bjørk, and M. Morlighem, GRL, 2018



IPCC AR5 2013

Basal hydrology

Physical processes
determining mass balance

Ablation

Moulins and basal hydrology

https://www.yaleclimateconnections.org/2014/09/thousands-of-nameless-short-lived-lakes-video/

Moulins transport water to base, can accelerate ice flow

Ablation

Moulins and basal hydrology

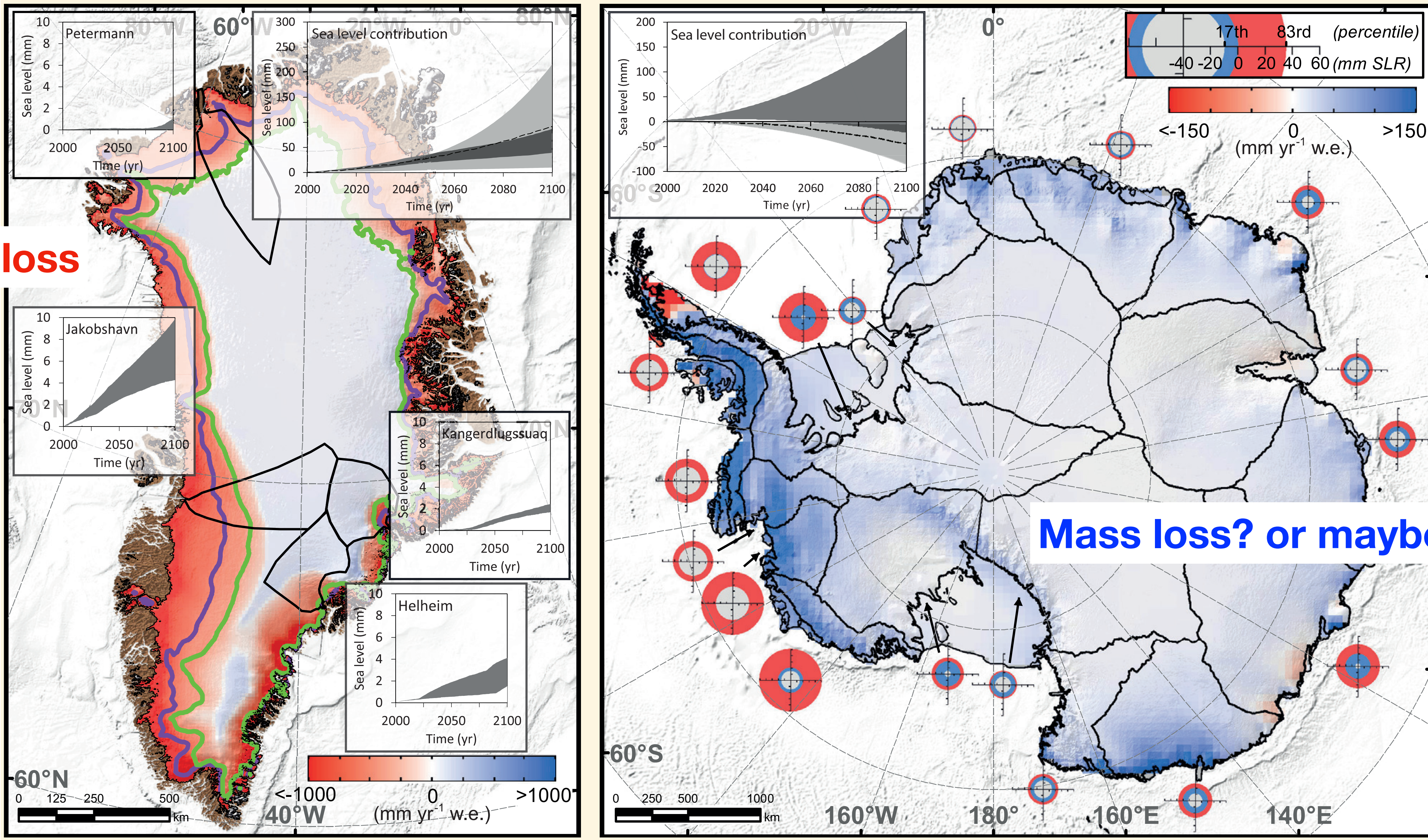
https://www.yaleclimateconnections.org/2014/09/thousands-of-nameless-short-lived-lakes-video/

Moulins transport water to base, can accelerate ice flow

notes section 10.2.5
Basal hydrology

workshop #5
Basal hydrology

Future Projections are highly uncertain



FAQ 13.2, Figure 1 | Illustrative synthesis of projected changes in SMB and outflow by 2100 for (a) Greenland and (b) Antarctic ice sheets. Colours shown on the maps refer to projected SMB change between the start and end of the 21st century using the RACMO2 regional atmospheric climate model under future warming scenarios A1B (Antarctic) and RCP4.5 (Greenland). For Greenland, average equilibrium line locations during both these time periods are shown in purple and green, respectively. Ice-sheet margins and grounding lines are shown as black lines, as are ice-sheet sectors. For Greenland, results of flowline modelling for four major outlet glaciers are shown as inserts, while for Antarctica the coloured rings reflect projected change in outflow based on a probabilistic extrapolation of observed trends. The outer and inner radius of each ring indicate the upper and lower bounds of the two-thirds probability range of the contribution, respectively (scale in upper right); red refers to mass loss (sea level rise) while blue refers to mass gain (sea level fall). Finally, the sea level contribution is shown for each ice sheet (insert located above maps) with light grey referring to SMB (model experiment used to generate the SMB map is shown as a dashed line) and dark grey to outflow. All projections refer to the two-in-three probability range across all scenarios.

The End!