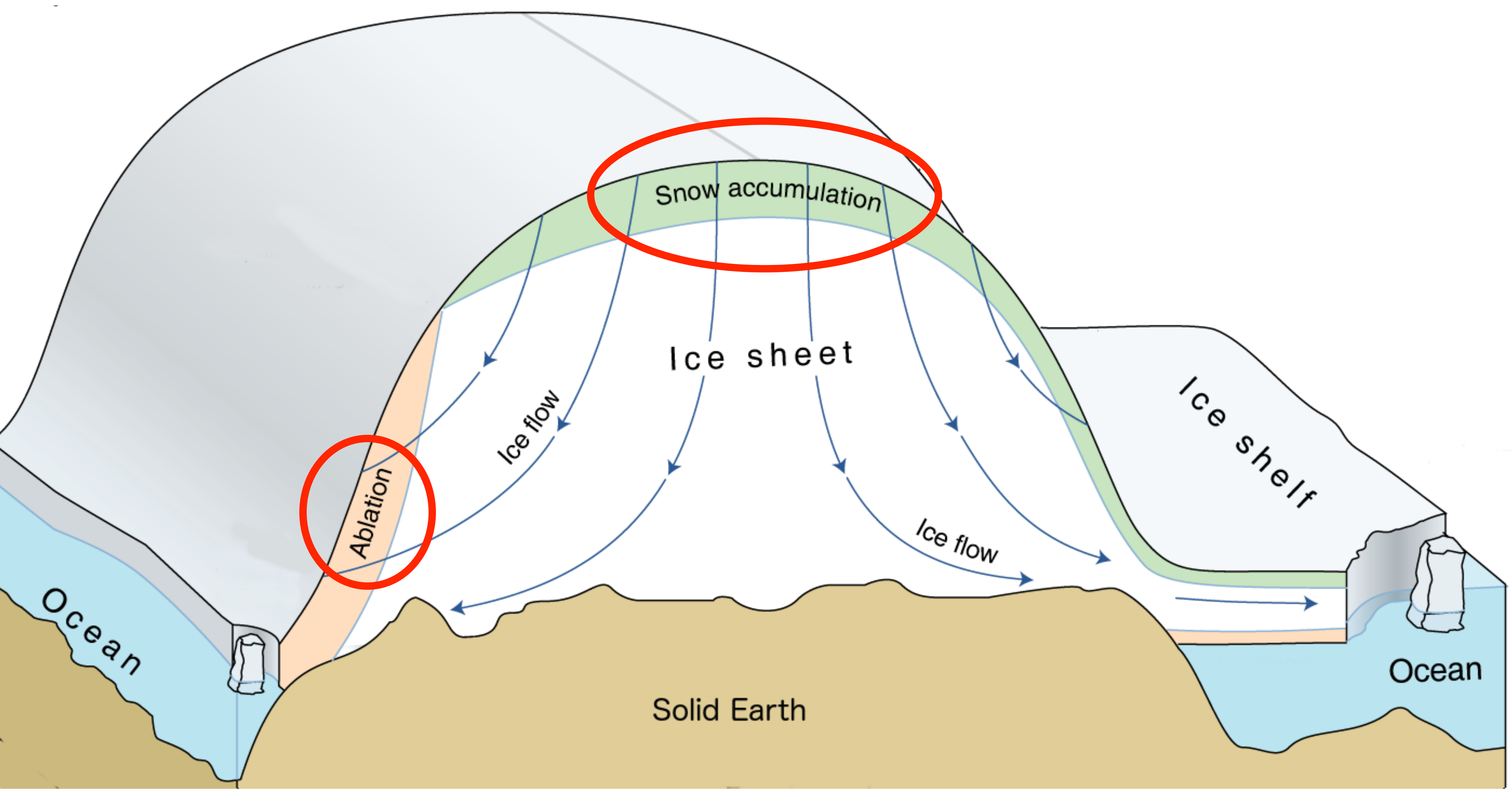
Surface mass balance

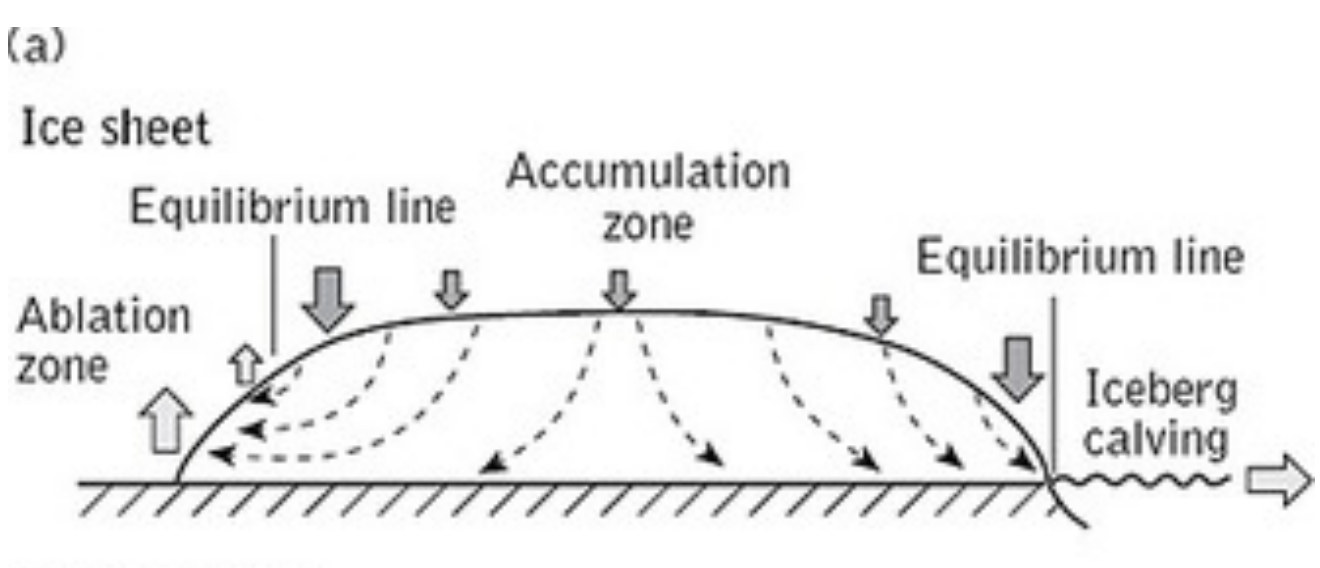
What

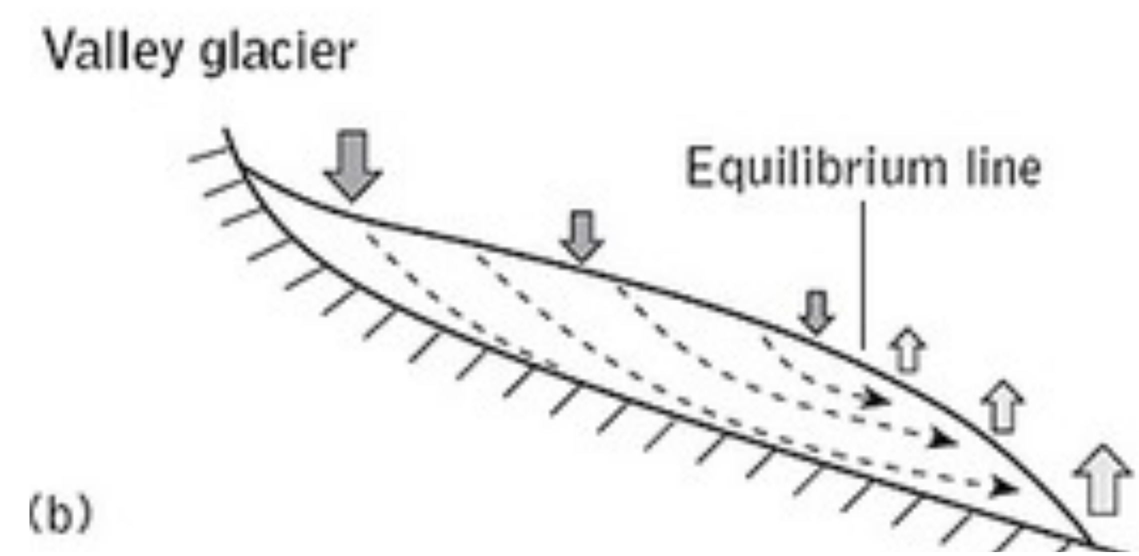

Snow accumulation
Ablation
Ice flow
Ice sheet
Ice flow
Ice shelf
Ocean
Ocean
Solid Earth

Mass balance

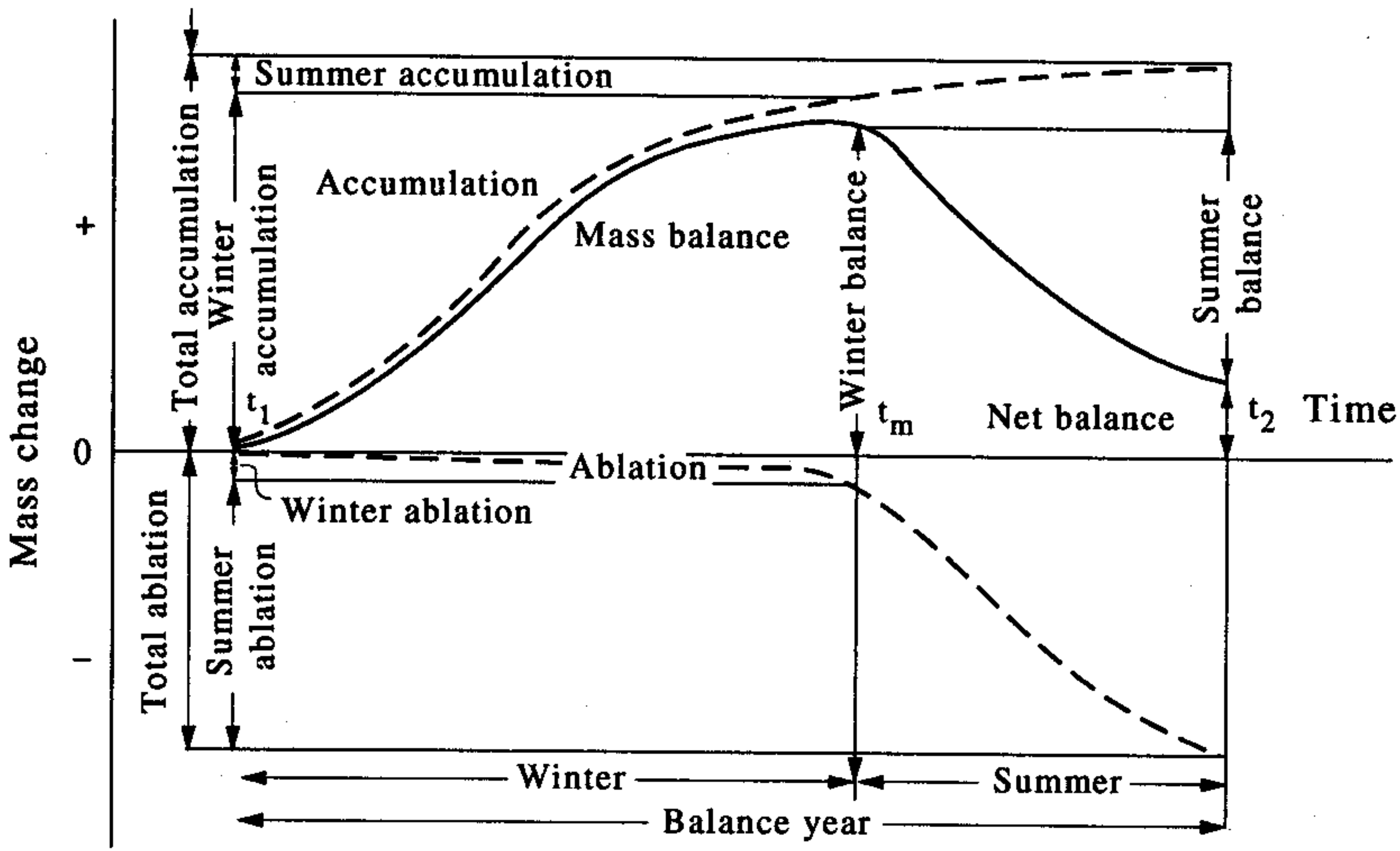
Mass balance: the sum of all sources and sinks of ice in a glacier/ice sheet

For a glacier that is at steady-state, there is typically:
1. An accumulation zone
2. An ablation/wastage zone
3. Ice flow from the accumulation zone to the ablation zone





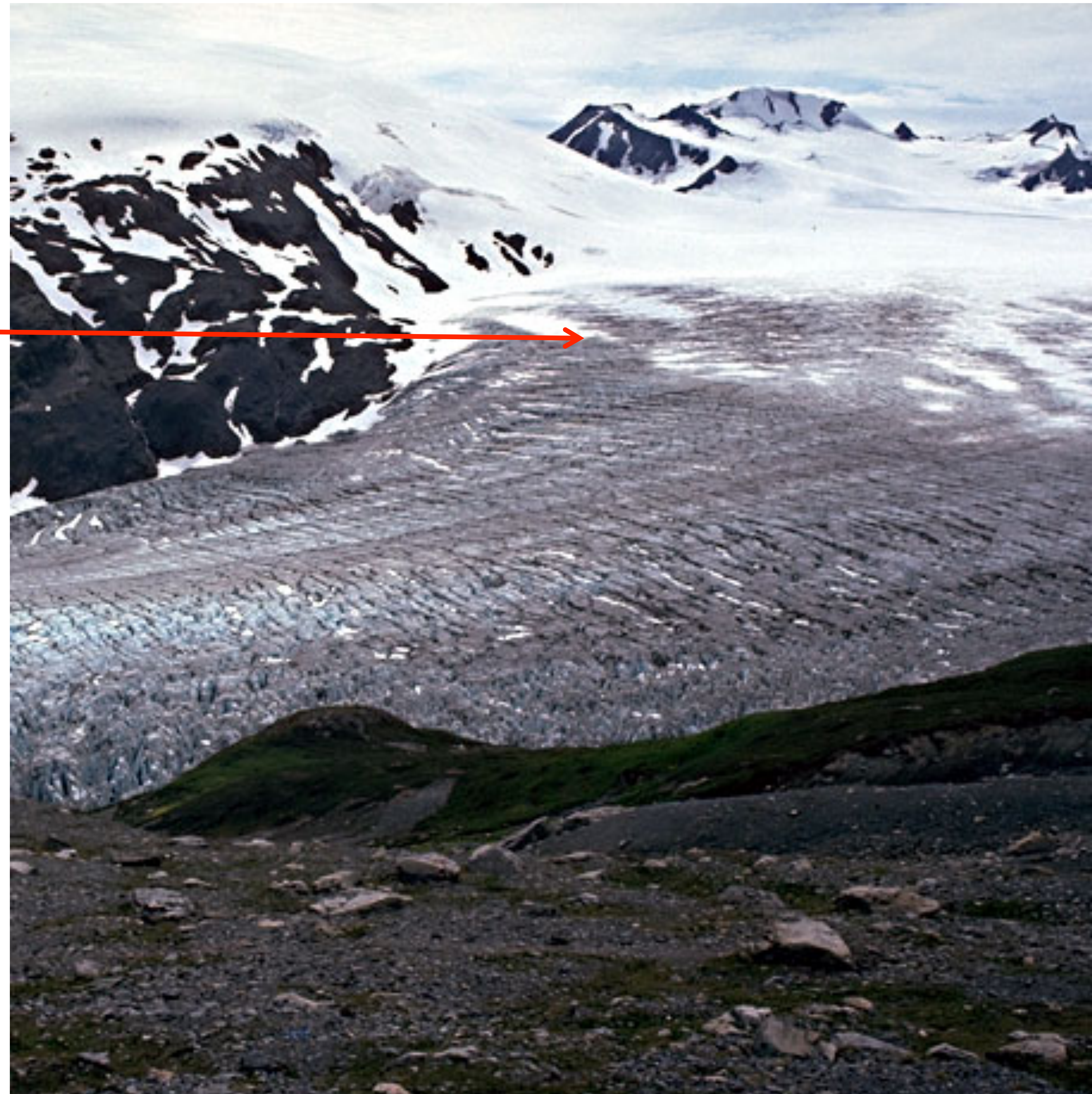
Local Mass Balance



From Paterson (1994)

Equilibrium line

equilibrium
line/zone



Equilibrium line: boundary between accumulation zone and ablation zone where local surface mass balance is zero. Often used as single-number proxy for climate.

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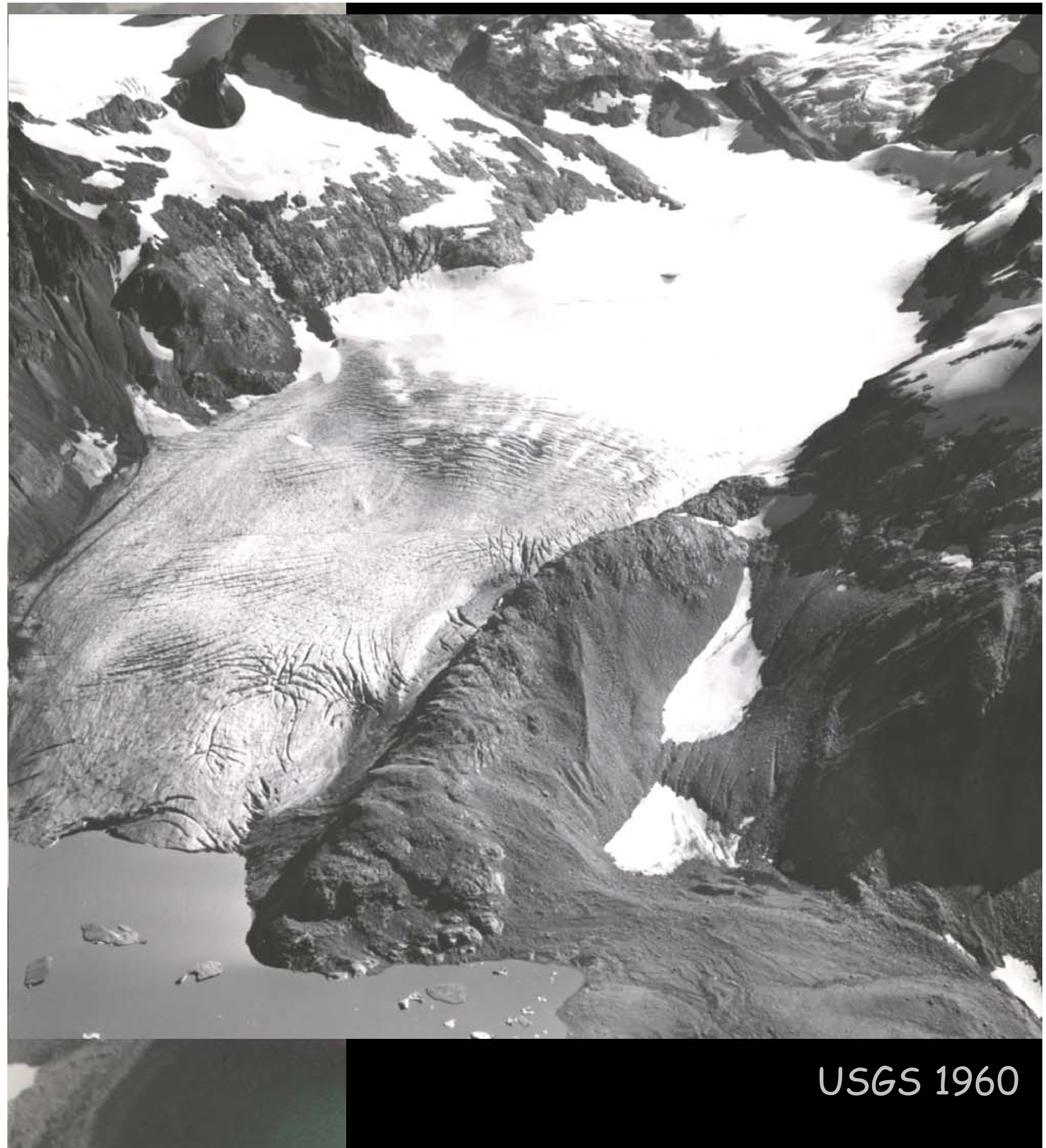
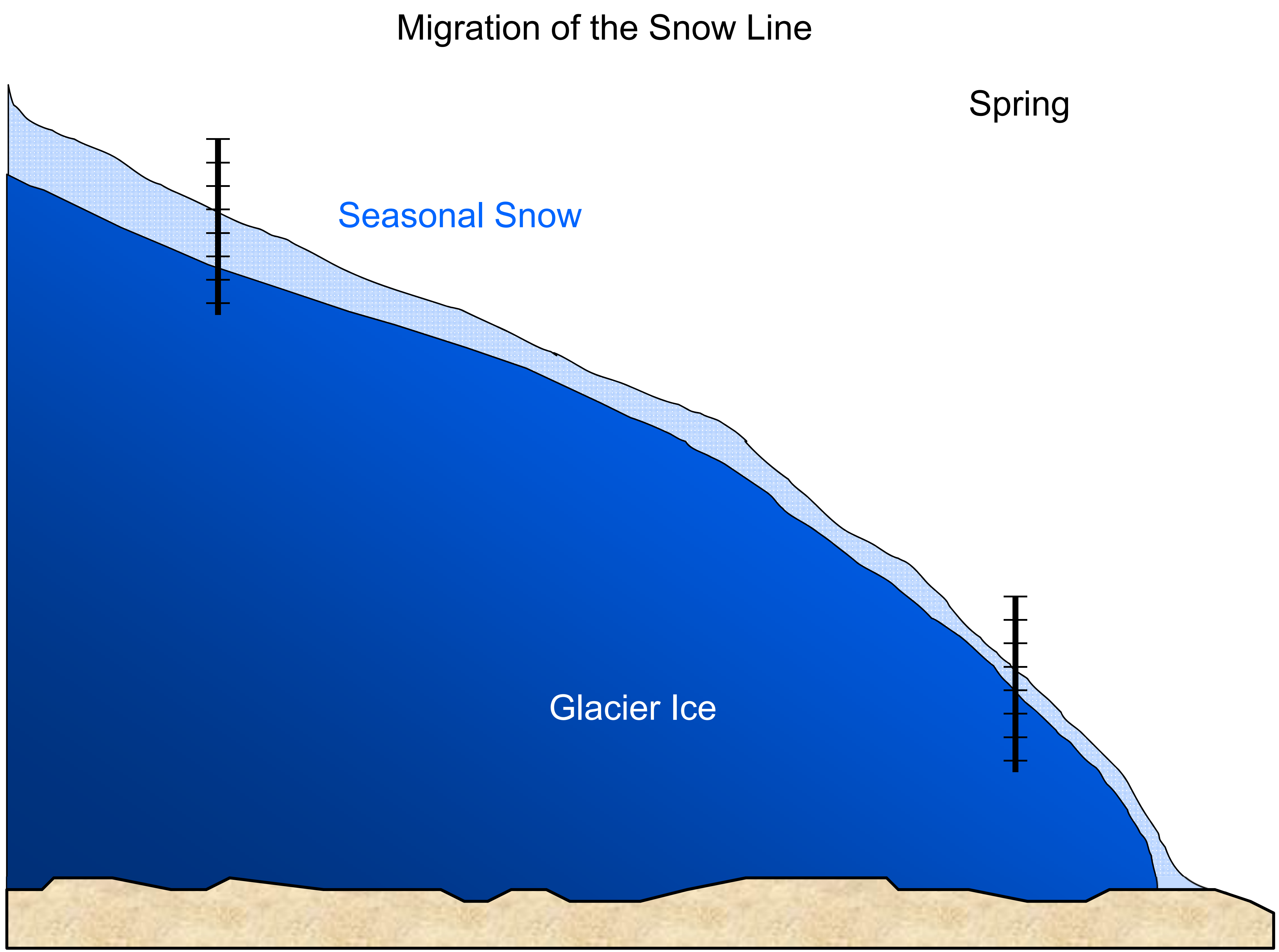
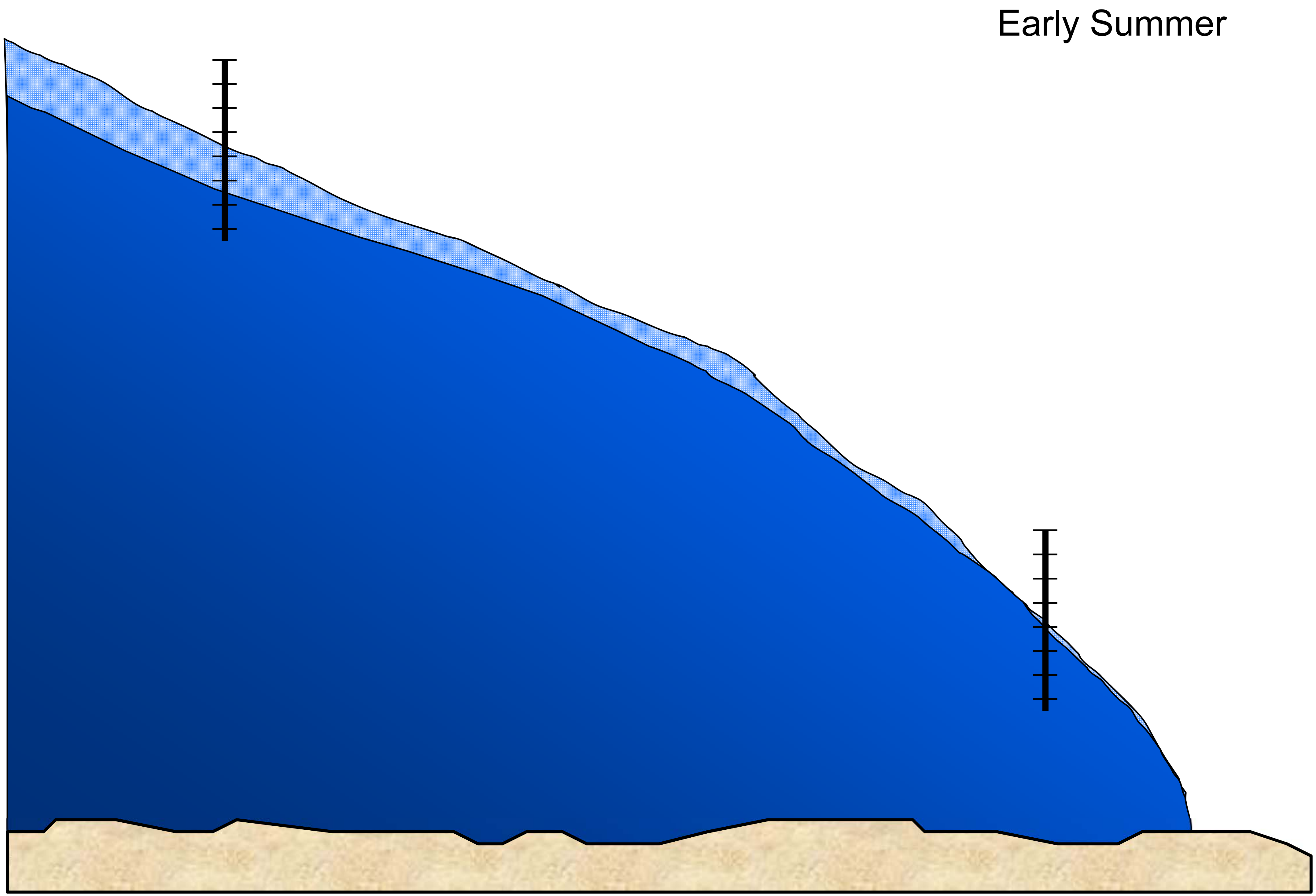


Surface mass balance is strongly seasonal



Slide from UT (G. Catania)

Surface mass balance is strongly seasonal



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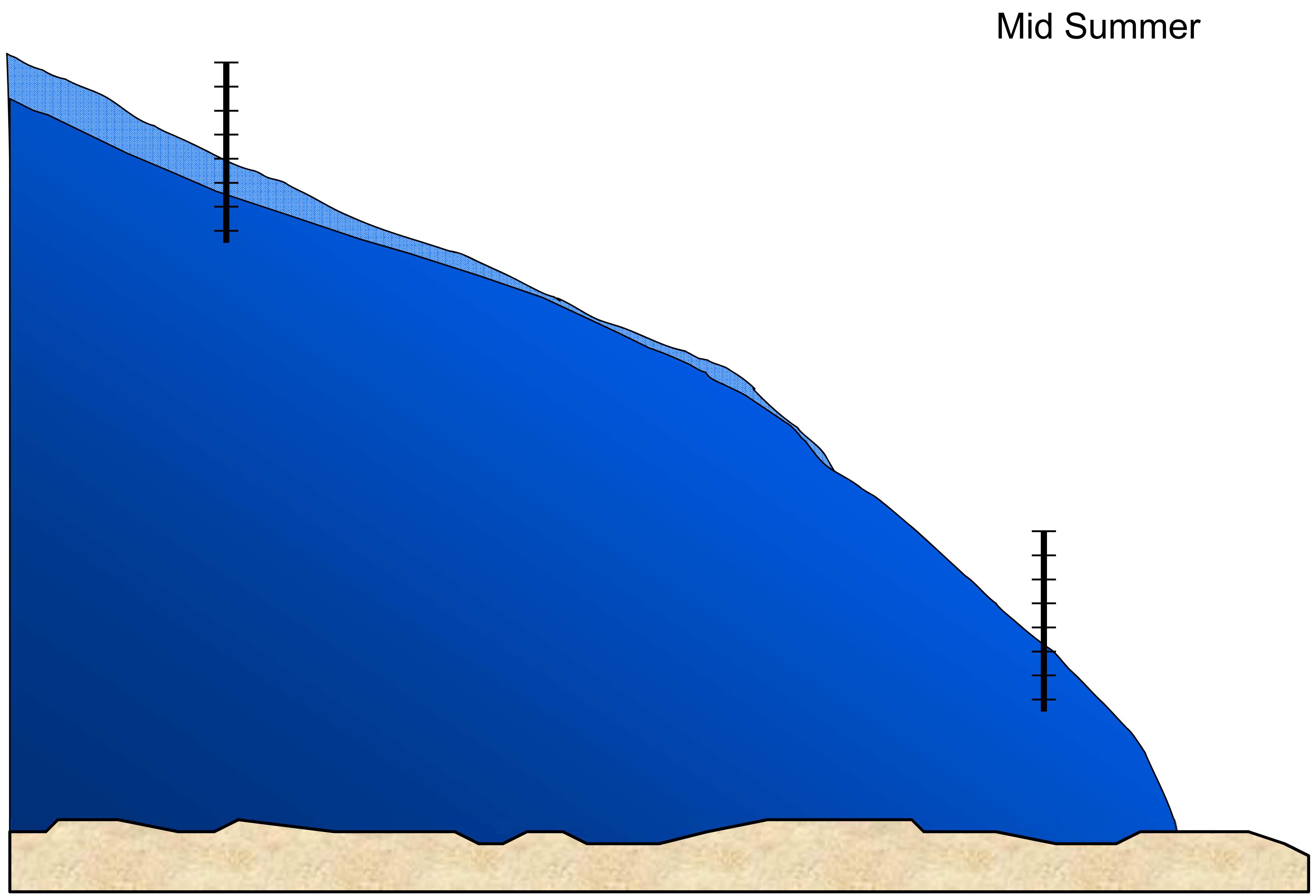

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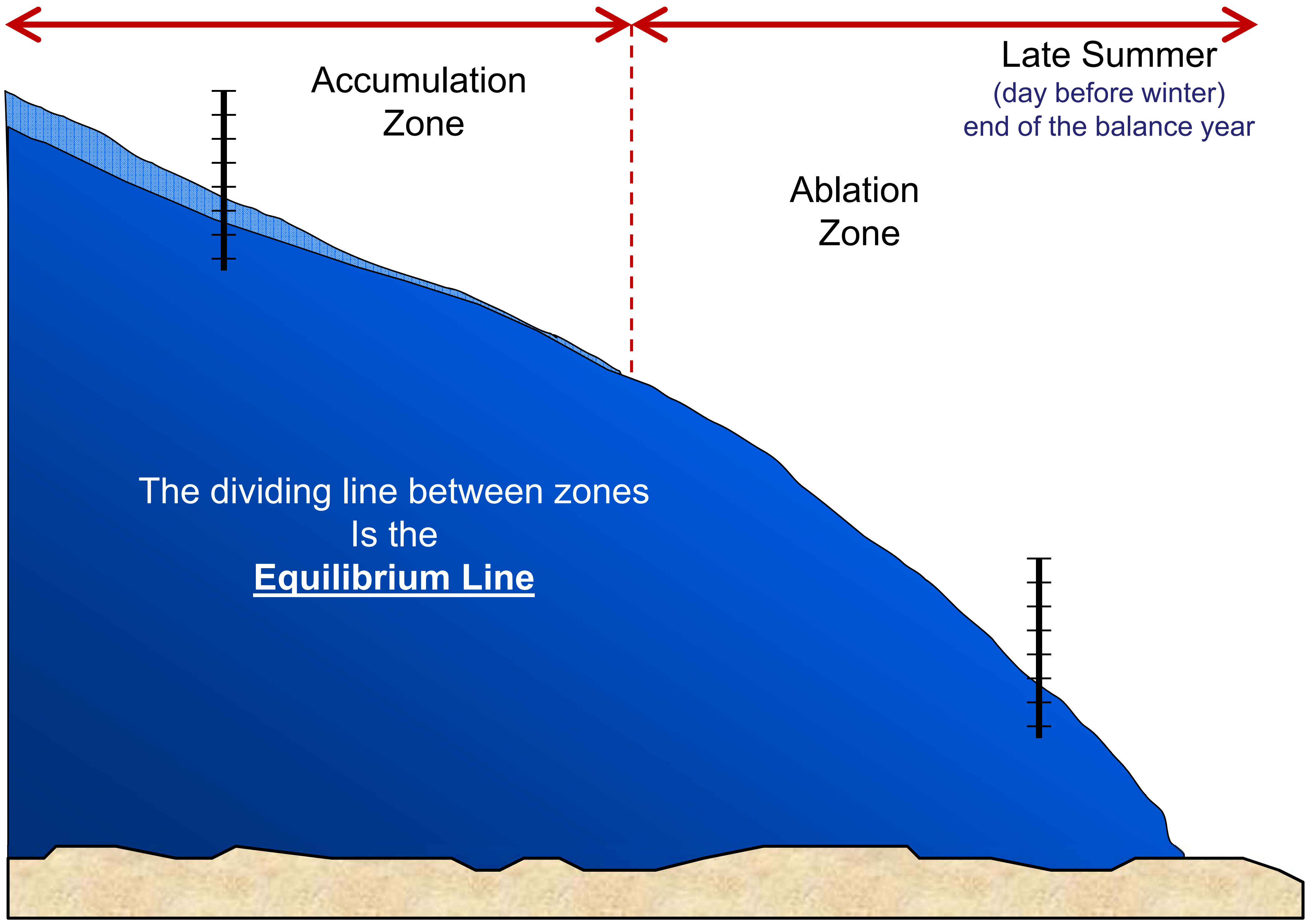
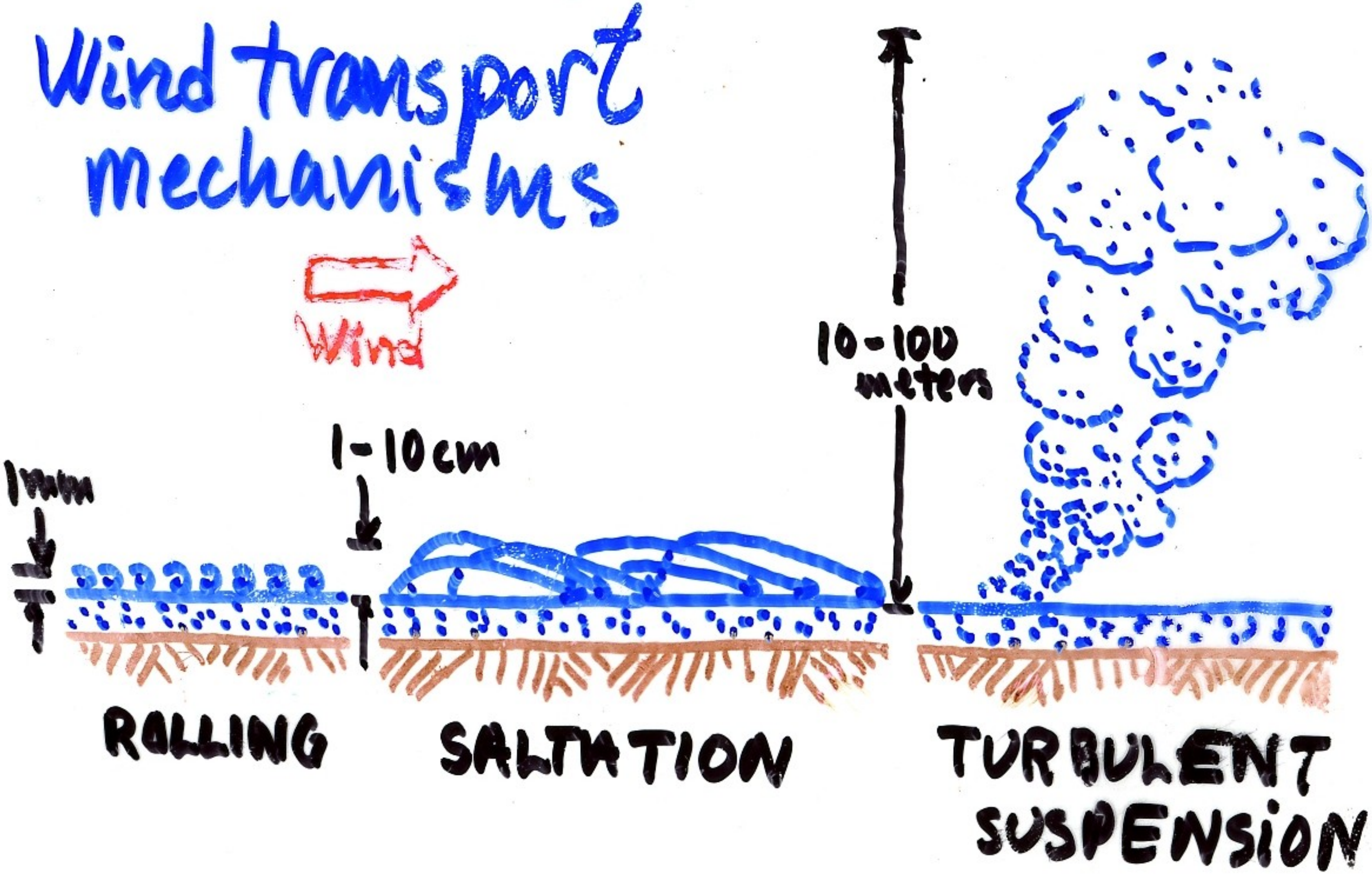


How mass gets in

- Snowfall
- Water freezing in the snowpack
- Avalanches
- Rime formation

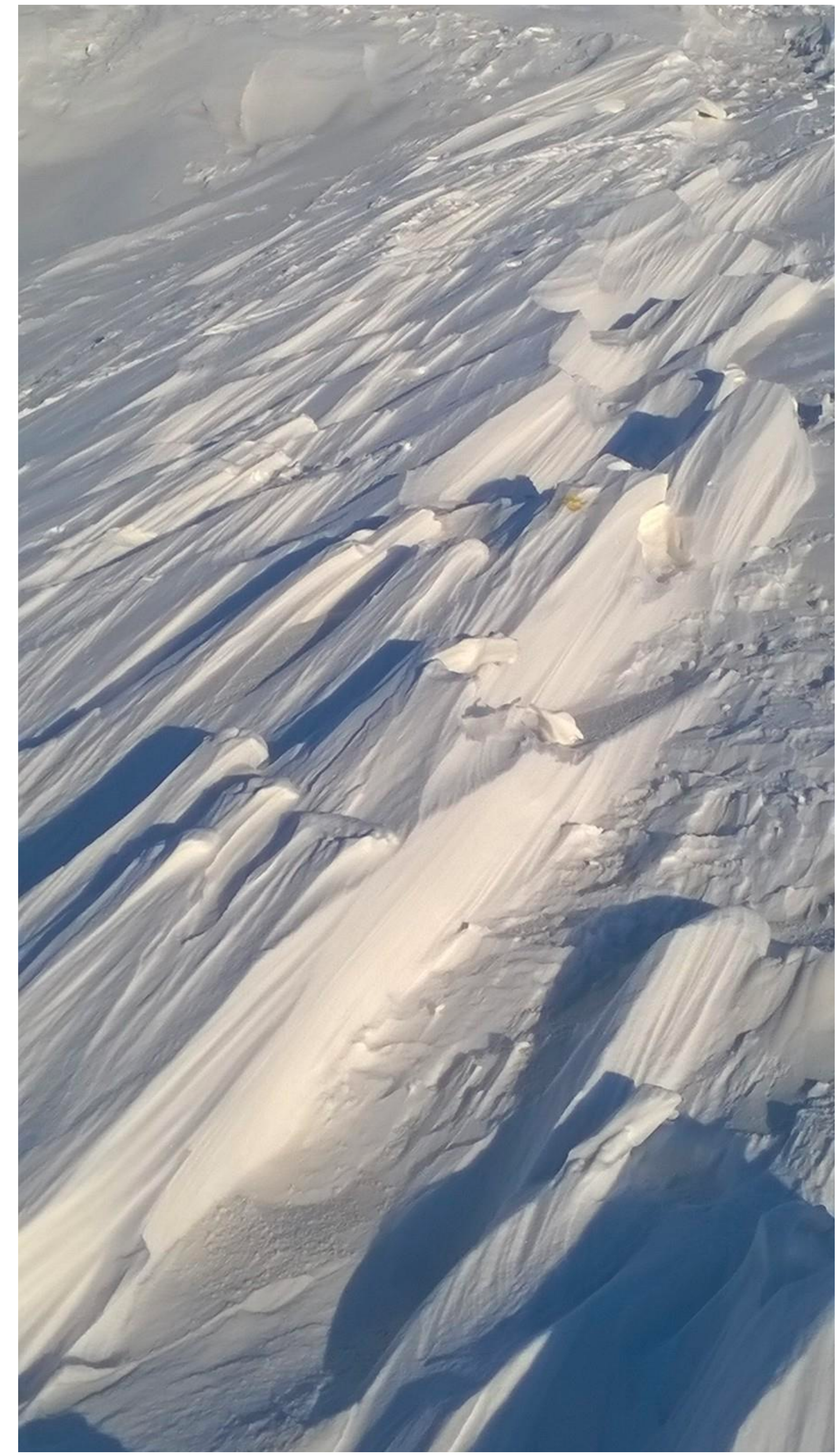
Snow does not just fall



Slide from UW ESS431

Sastrugi

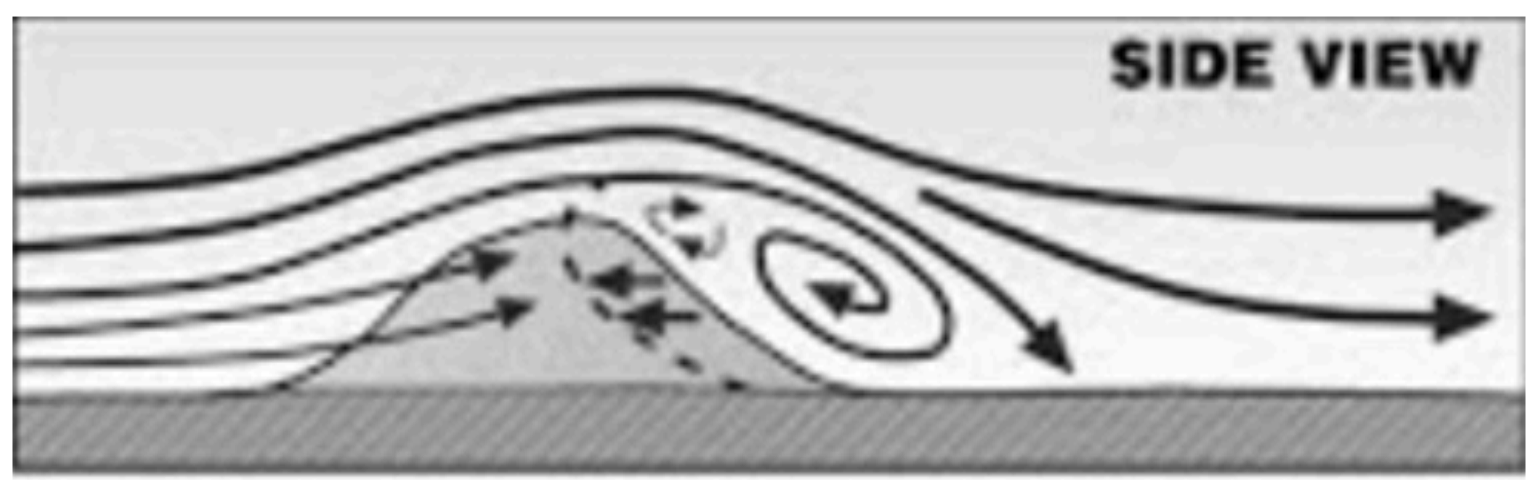
- Irregular grooves and ridges on snow surface
- Formed by wind erosion, saltation, and deposition



Slide from UW ESS431

Snow dunes

- Very similar to aeolian sand dunes in formation, form
- Snow dunes consist entirely of eroded snow, ‘raised’ by blizzard winds
- Saltating snow forms moving dunes



Slide from UW ESS431

Mountain wind and snow

Snow transport depends on wind speed

- Accelerating air can pick up more snow
- Decelerating air drops some transported snow

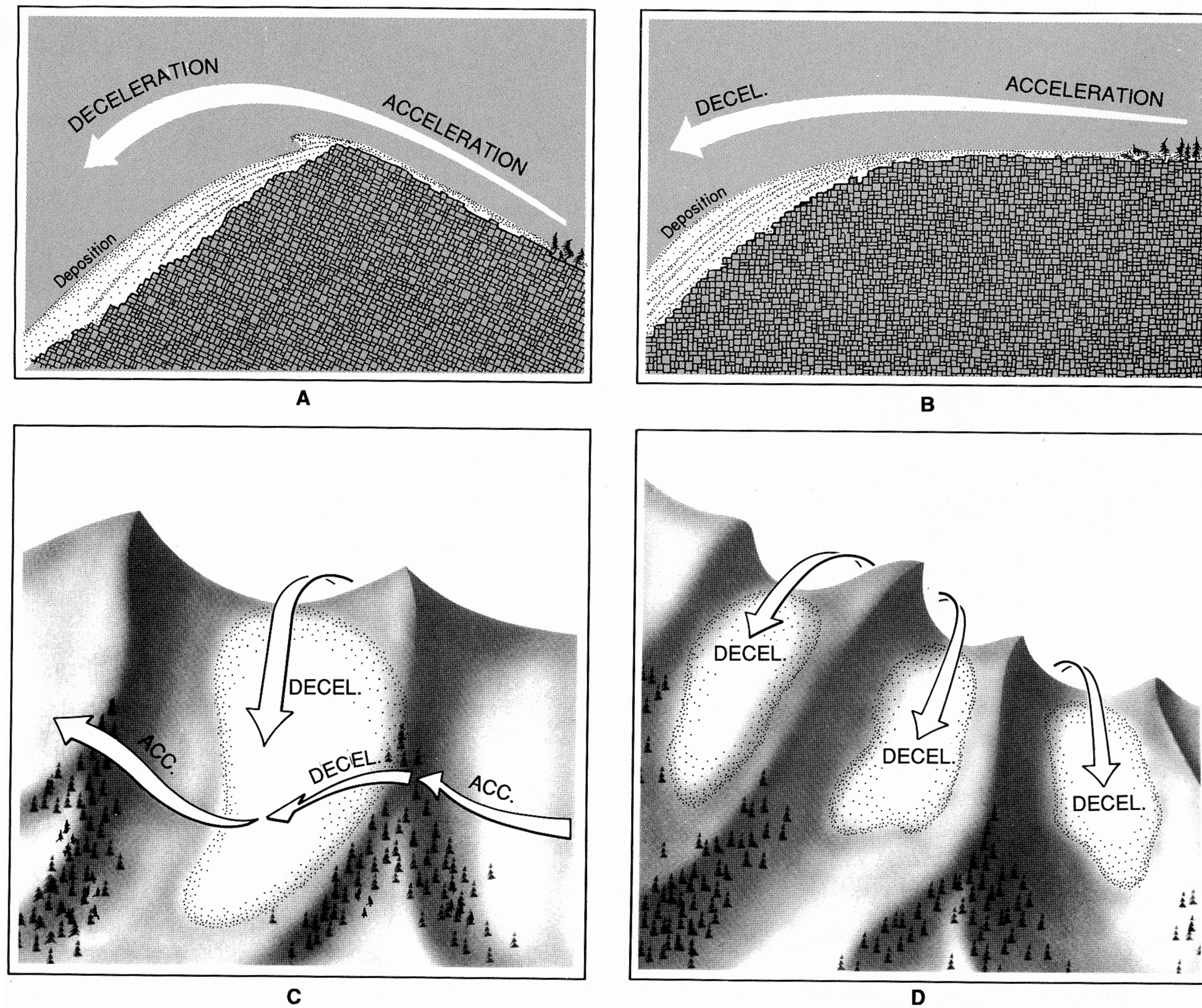


Figure 2.15. Snow is picked up in acceleration regions and deposited in deceleration regions (A, B). This produces lee zone deposition, cross-loading, and deposition in gullies and notches (C, D).

How mass gets out

- Melting and then run off
- Evaporation/Sublimation
- Wind scour, blowing snow
- Ocean heating at ice-water interface
  - Turbulent boundary layer determines rate of heat transfer (Jenkins 1991, and many others)
- Iceberg calving
  - We will talk about more later in the semester

Energy balance pieces

- Transfer through phase change
  - Latent heat

Typical Latent Heat Fluxes

Air	**dry**	**humid (warm)**
	LH↑ sublimation evaporation	*LH*↓ deposition condensation
Snow	**humid**	**humid (cold)**

Important on wet slopes

Important on high plateaus

Energy balance pieces

- Transfer through phase change
  - Latent heat
- Transfer by conduction
  - The turbulent near-surface boundary layer has a temperature which transfers heat to the ice through sensible heating
- Transfer by radiation

Radiation balance contributes to energy exchange between atmosphere and ice/snow surface

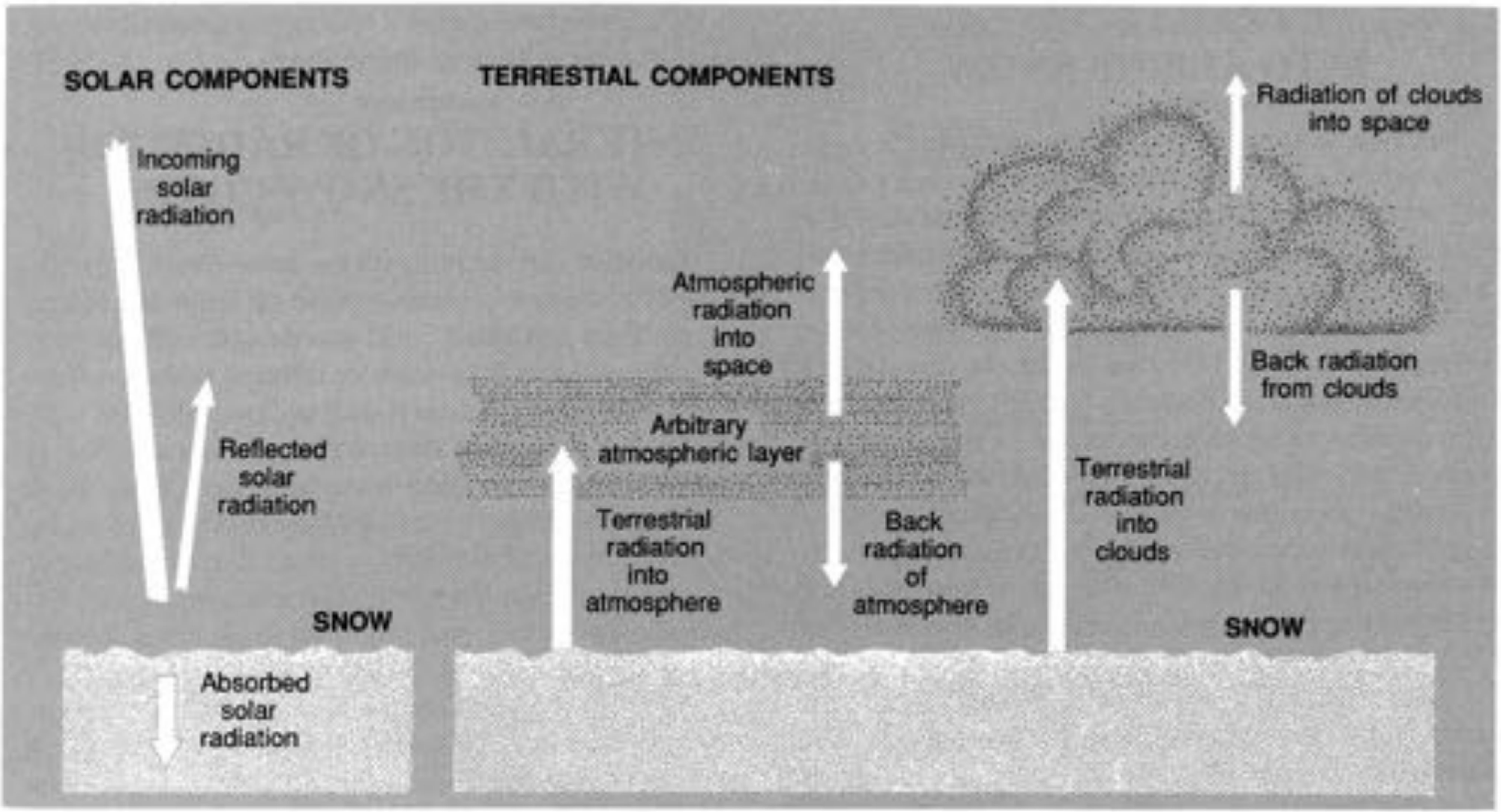


Figure 2.23. Radiation balance at snow surface. Incoming, absorbed, and reflected solar radiation is short wave (visible and ultraviolet). The other components from terrestrial sources are long wave (infrared).

Energy in Melt Season

Source	Typical Importance	Blue Glacier (Mt. Olympus):
Radiation	50-85%	57%
Sensible heat	15-50%	34%
Latent heat		9%

Typically R > SH > LH

Surface Mass Balance with temperature

Ablation: warmer air temperature means more melt due to more rapid heat transfer across snow-air boundary layer

Accumulation: warmer air temperature mean more accumulation because warmer air holds more moisture (clausius-claperon), until precipitation starts falling as rain sufficiently above 0 C

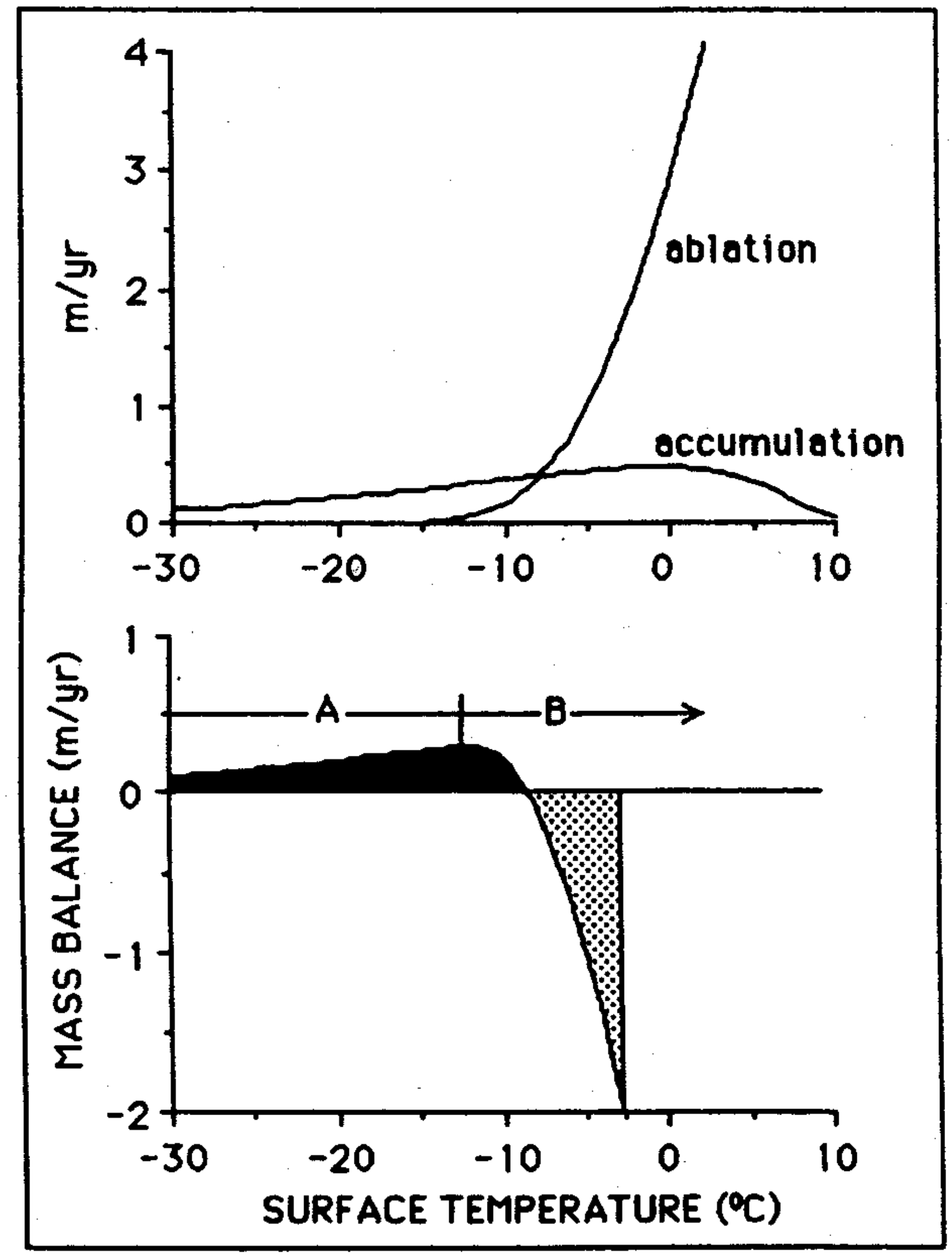
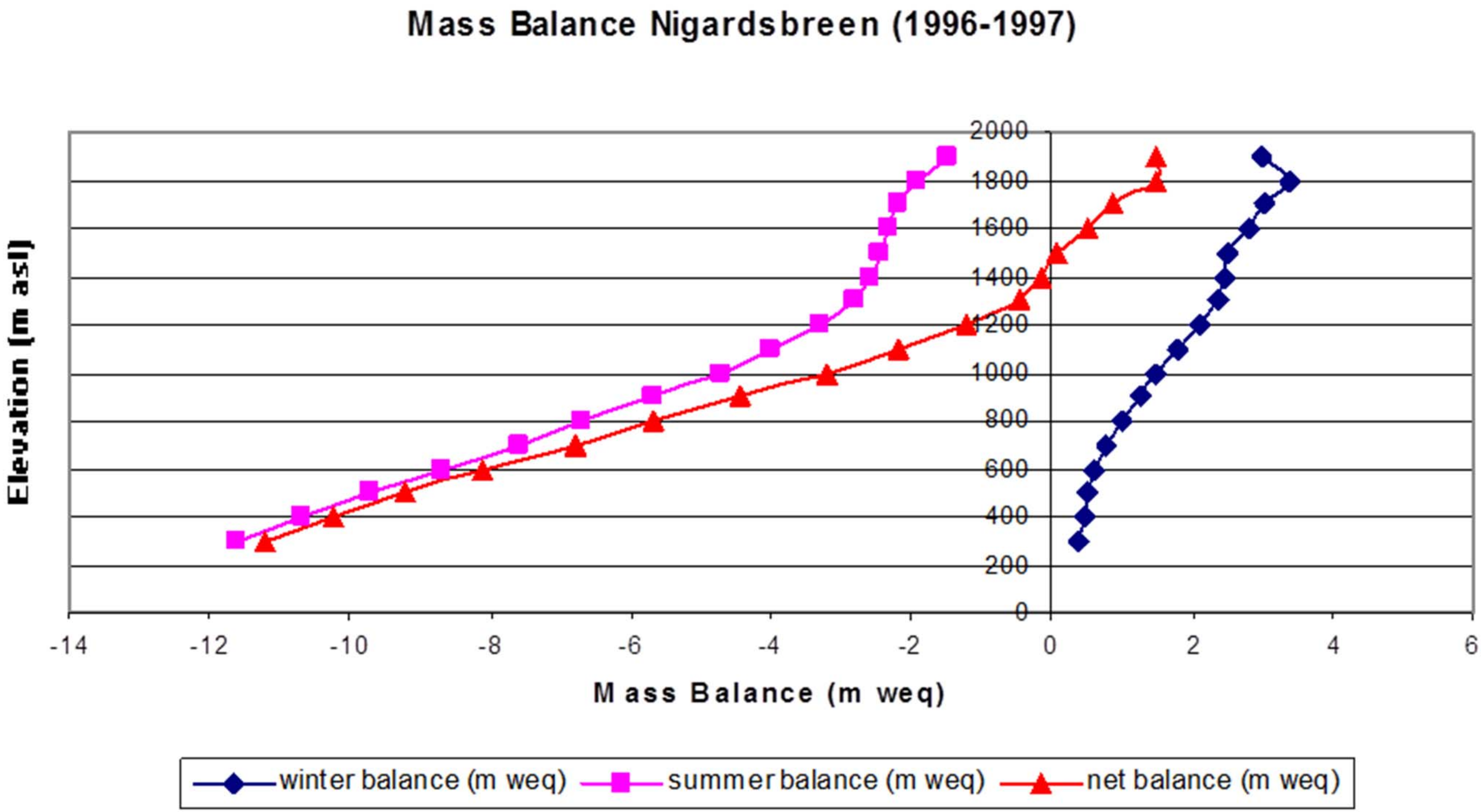


Fig. 3. Components of glacier mass balance at a fixed location in dependence of the annual mean surface temperature, with a given constant annual temperature range. The net balance (lower panel) shows a region where it *increases* with temperature (A) as well as a region where it *decreases* with temperature (B). The Antarctic ice sheet is in region A, the Greenland ice sheet mainly, but not entirely,

Surface Mass Balance with elevation



Surface Mass Balance with elevation

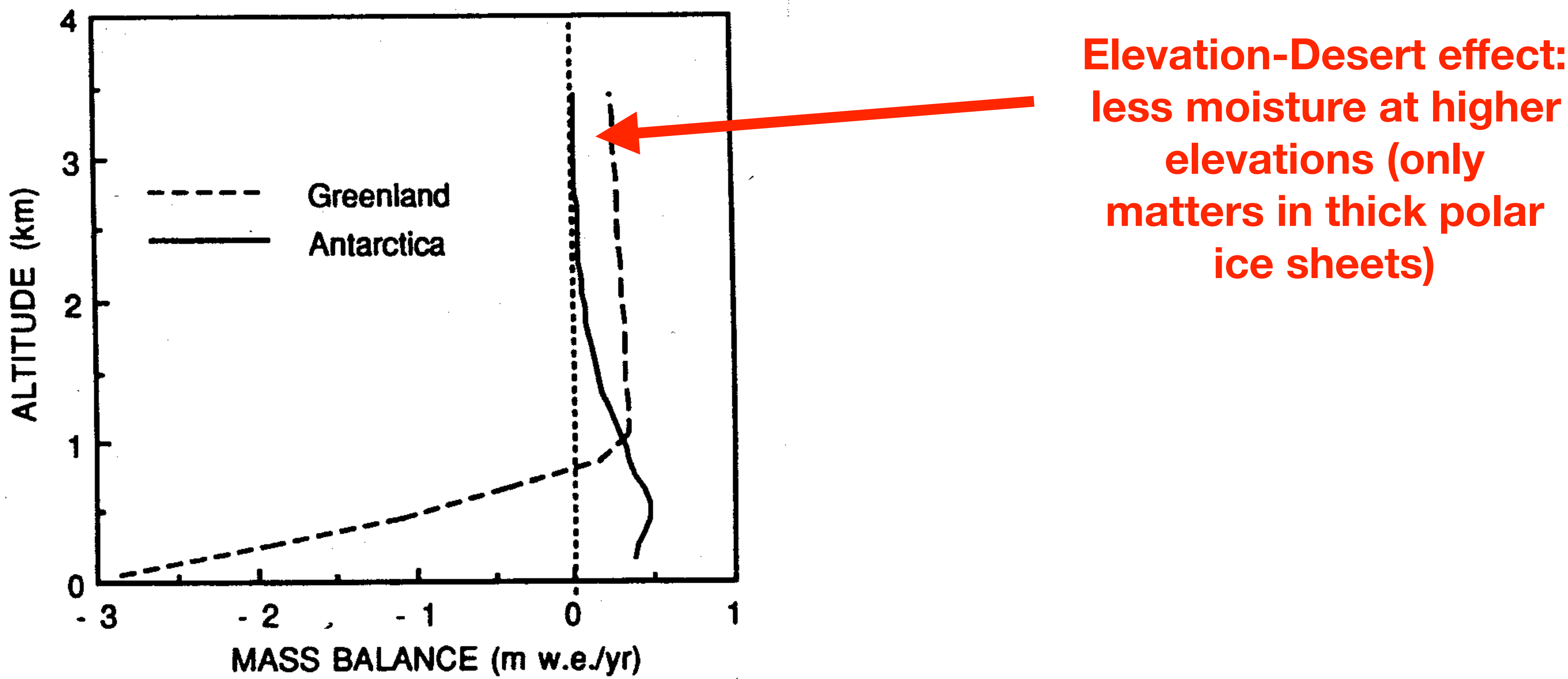
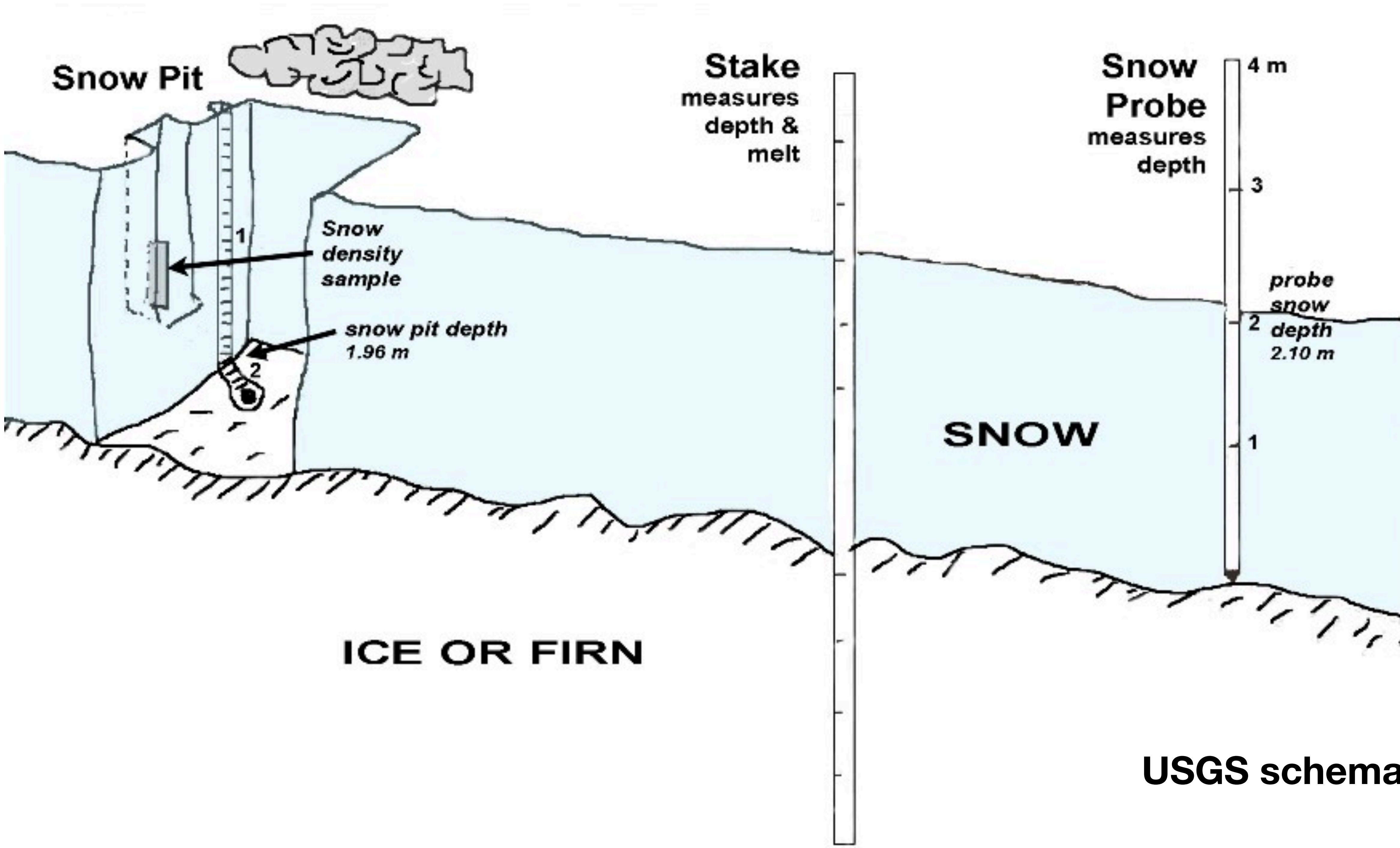


Fig. 2. Mass balance as a function of elevation for the Antarctic and Greenland ice sheets. The curves represent mean values for the entire ice sheets, local conditions may be quite different. Based on Drewry (pers. comm. 1988) and Oerlemans et al. (1990).

Height-mass balance feedback

To the board! (and MATLAB)

Measuring surface mass balance



USGS schematic

Measuring surface mass balance

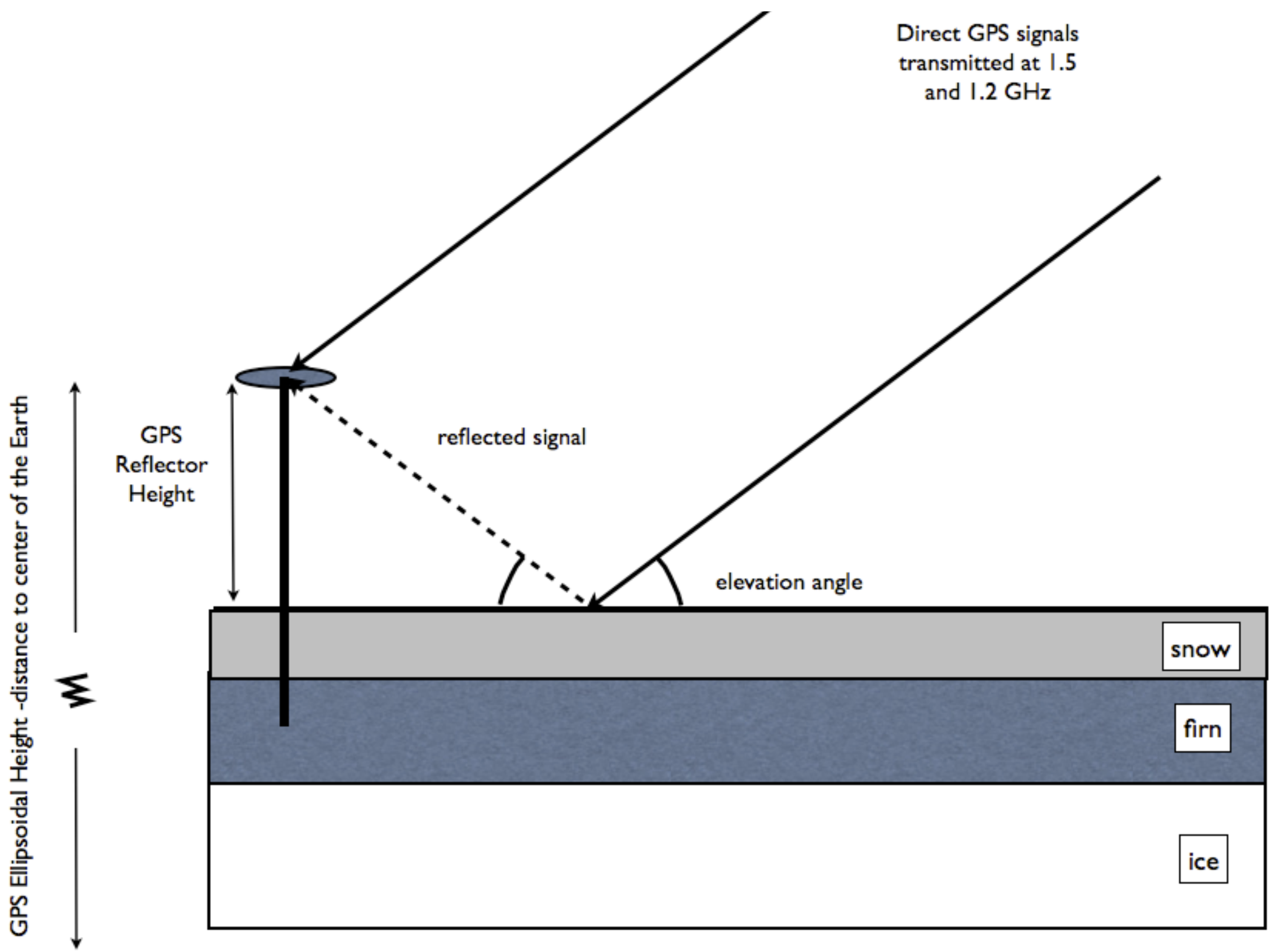
Snow Pits

retrospectively determine accumulation since last summer

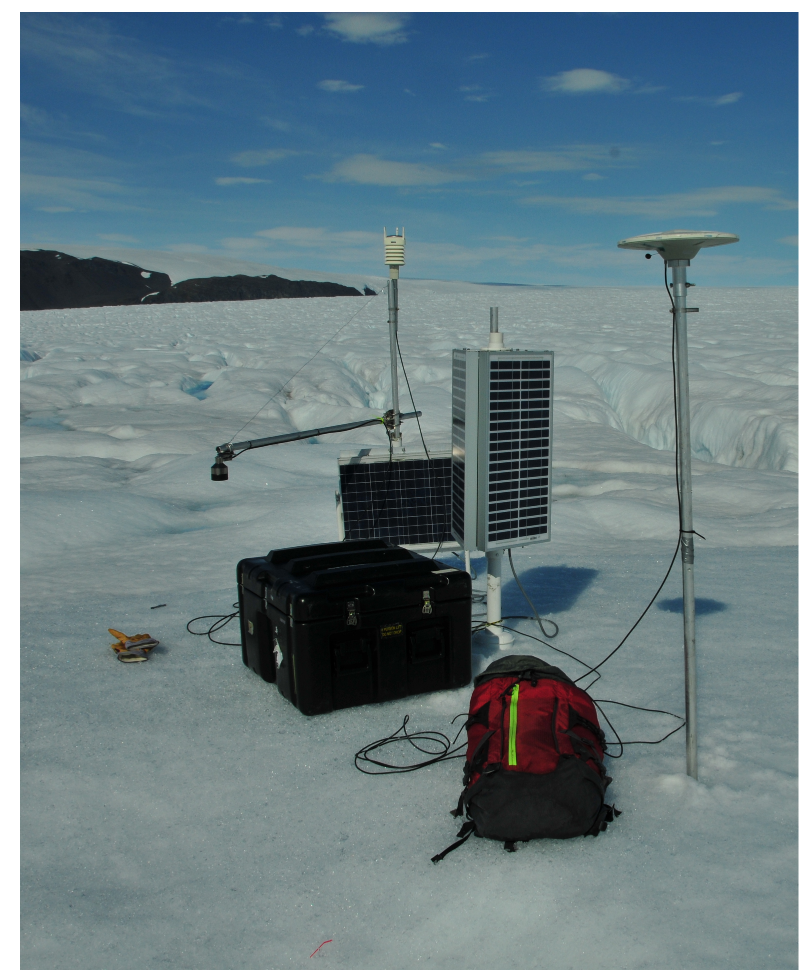
Measuring surface mass balance

Snow Stakes less labor-intensive

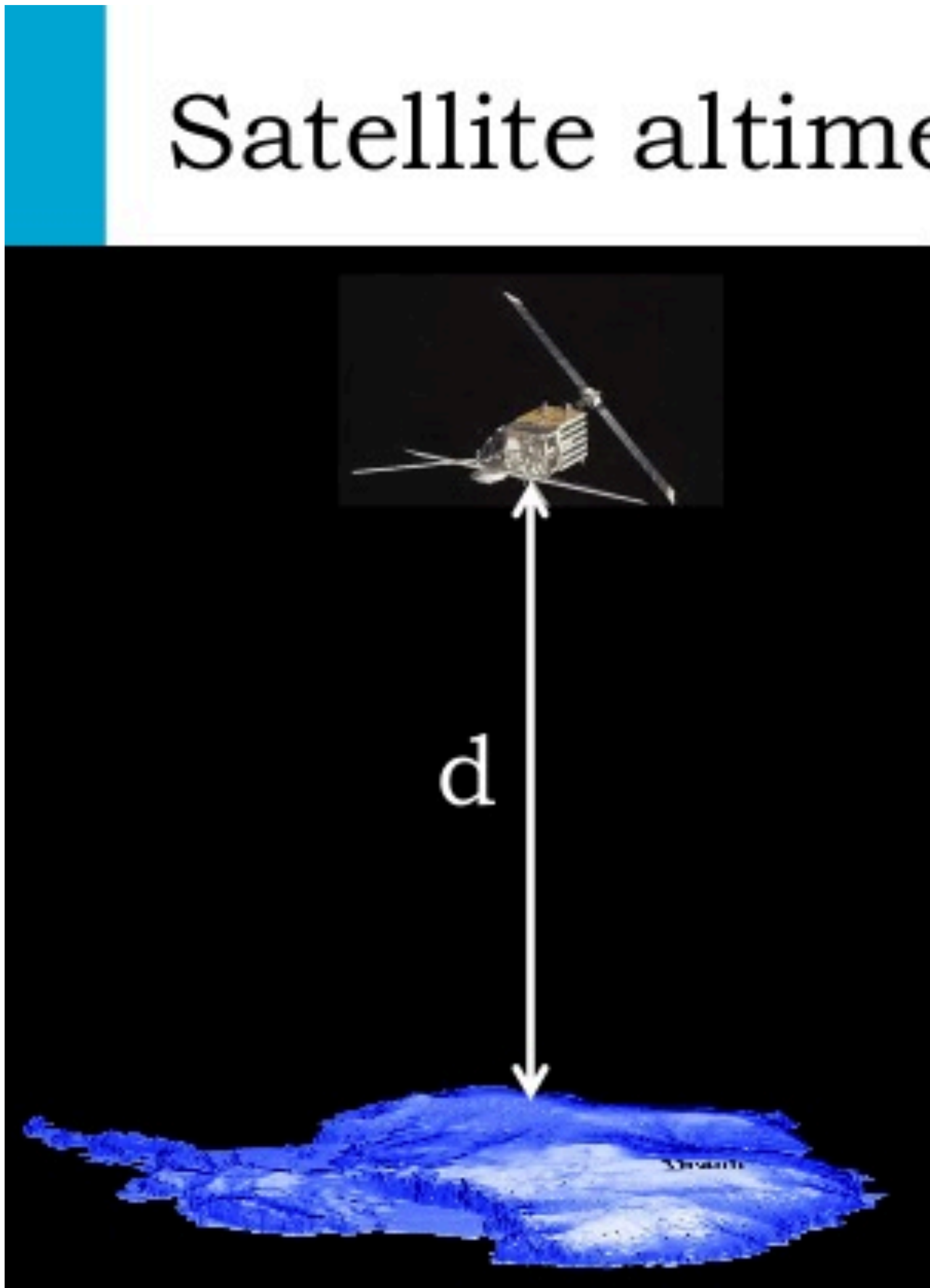
Measuring surface mass balance



GPS reflectometry: more accurate, but requires power



Satellite Laser Altimetry



$$h = Alt - d$$

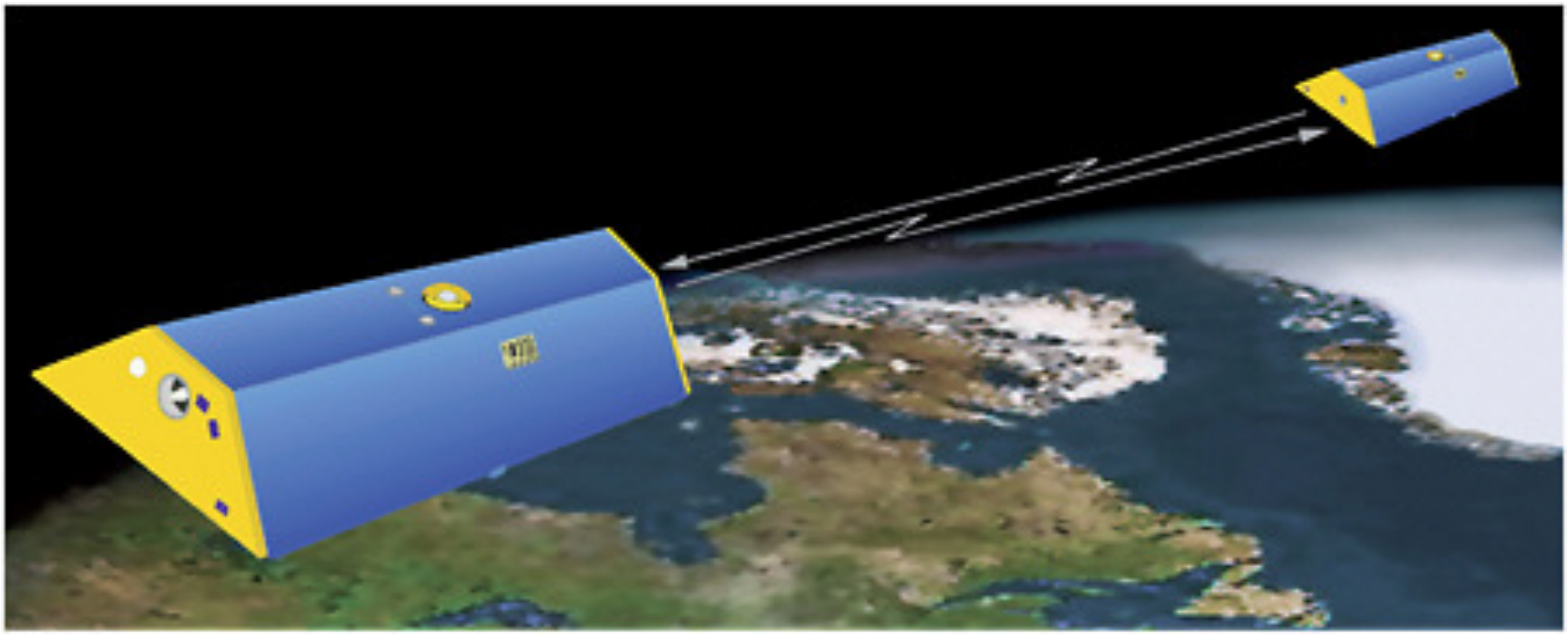
Elevation — Satellite altitude

$$\Delta V = \Delta h * S$$

Volume change — Elevation change — Area

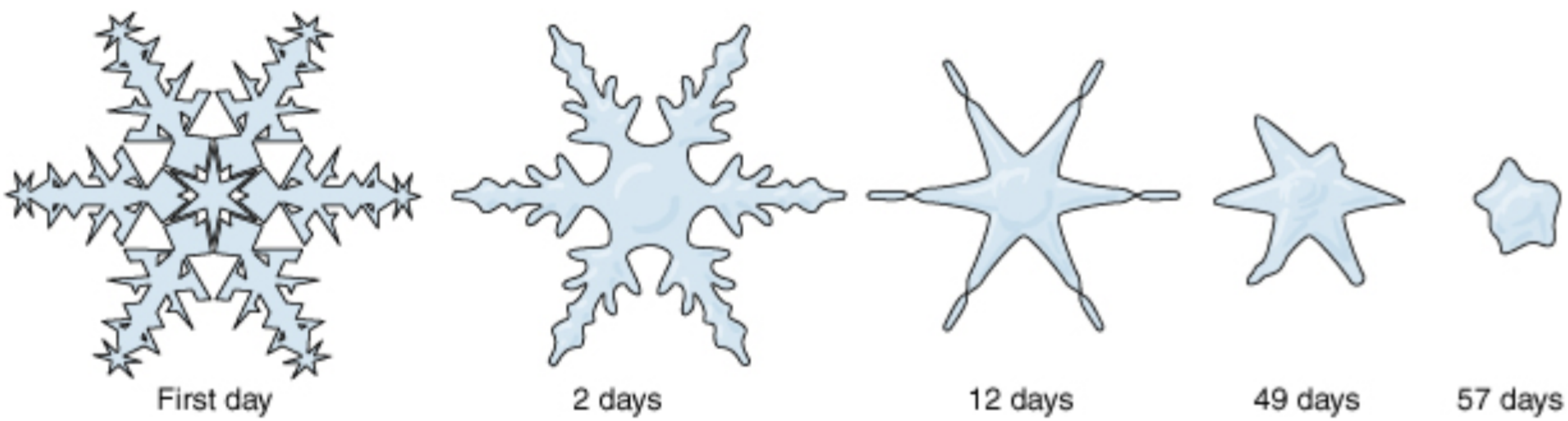
Gravity measurements

GRACE satellites measures small spatial variations in gravitational attraction by using very precise positioning



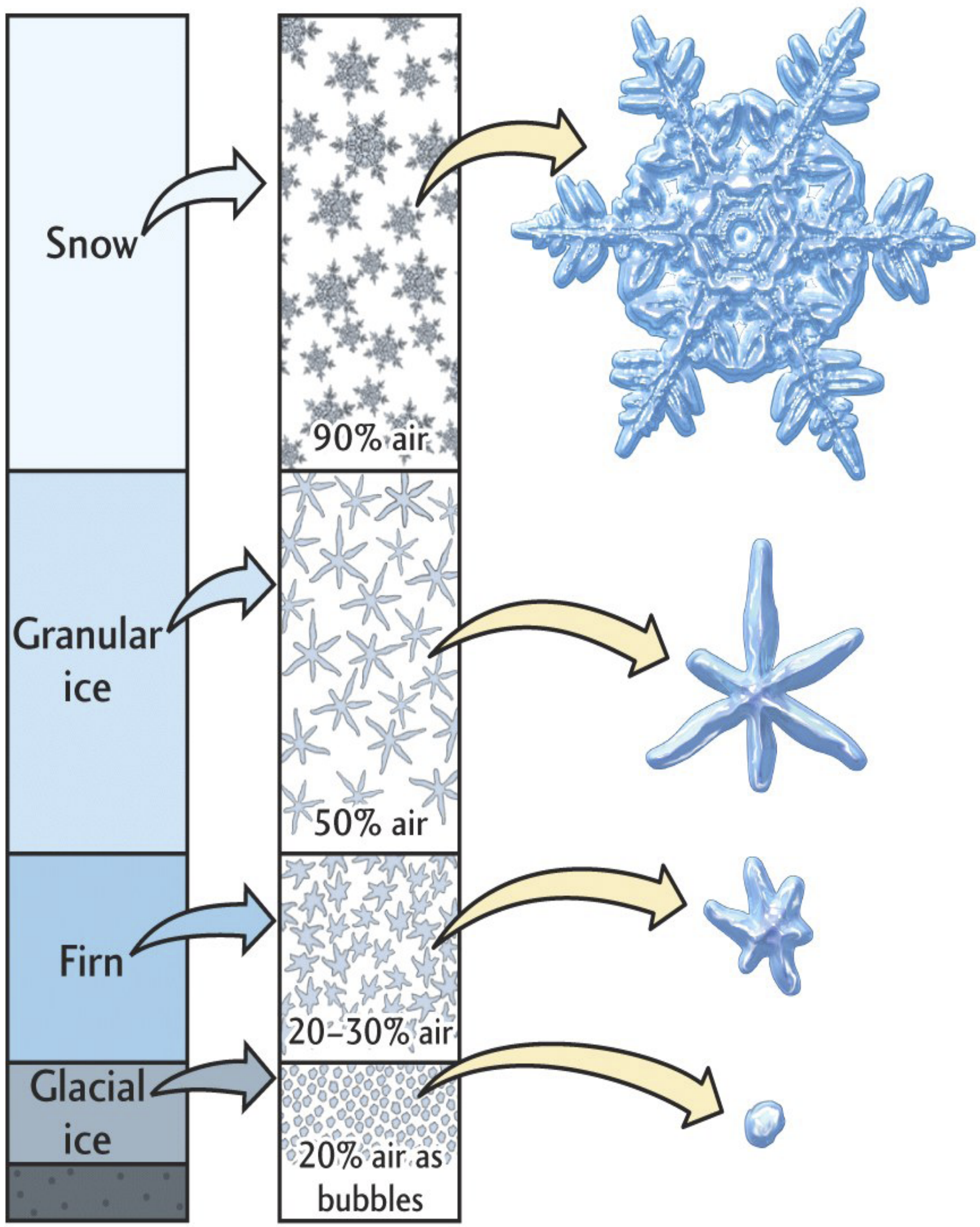
How snow becomes ice

new snow → old snow (firn)



The Answer: Compression

Firn compaction



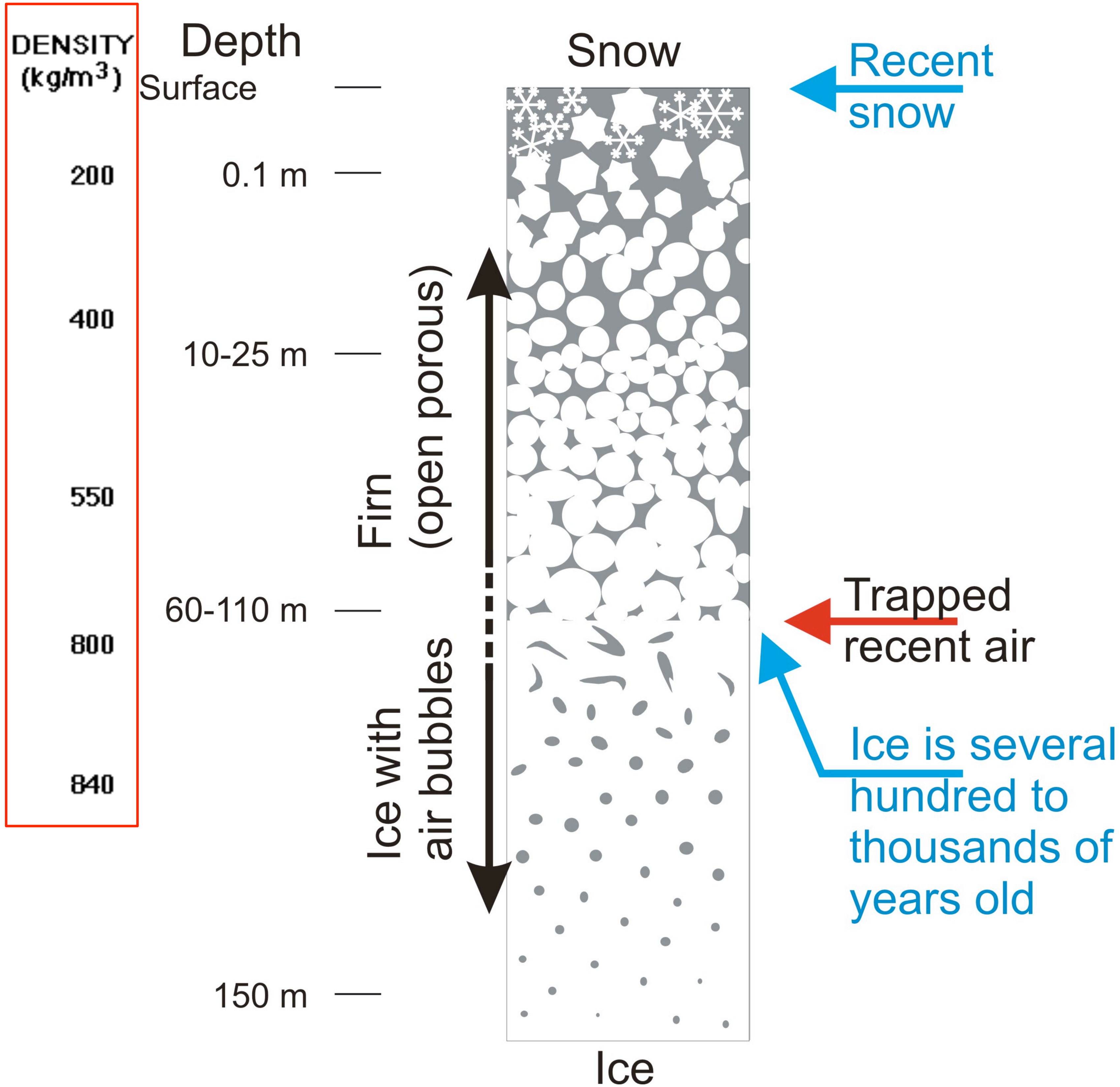
Snow (50-70 kg/m³)

Firn (400-800 kg/m³)

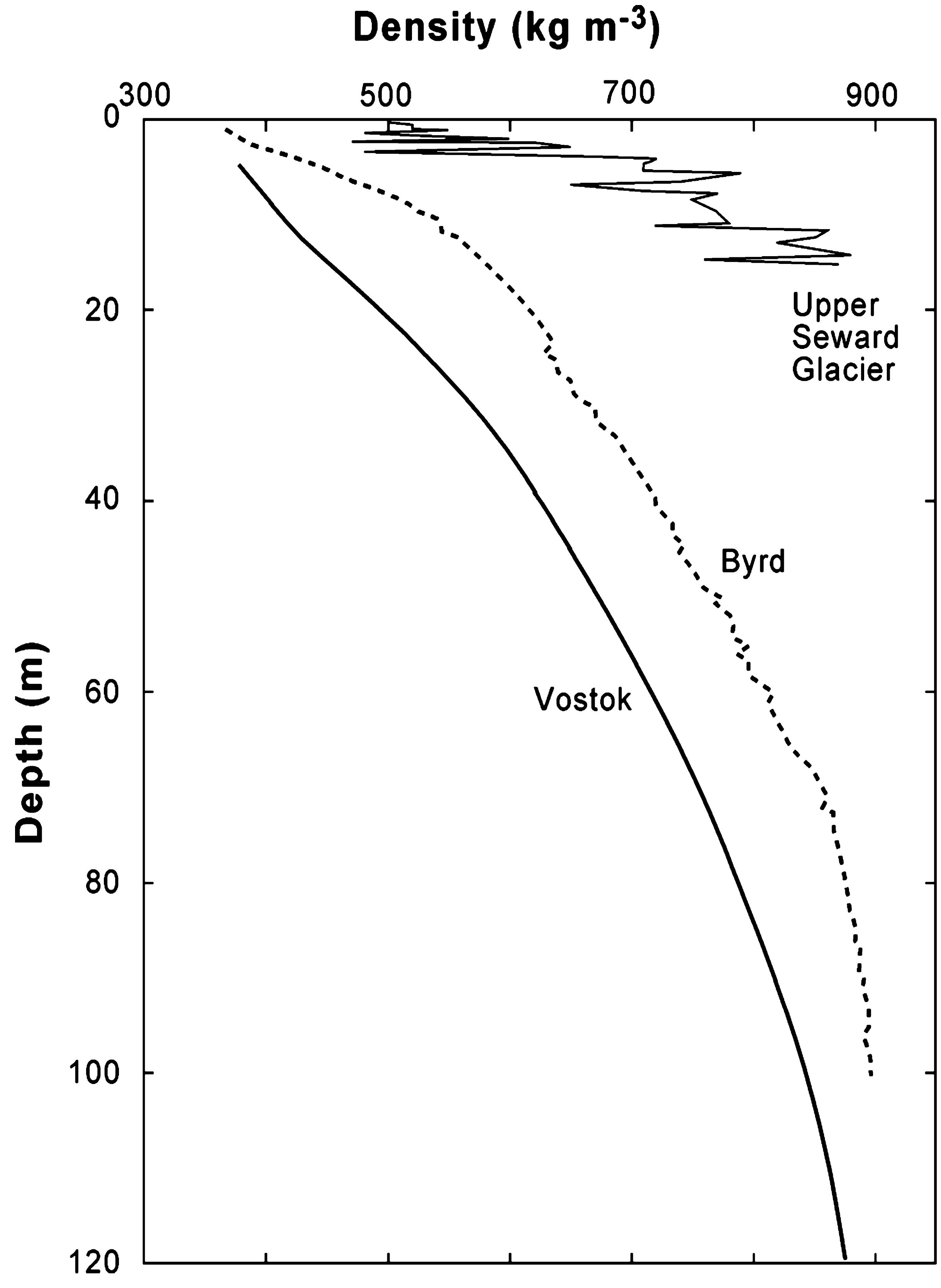
Ice (800-930 kg/m³)

Firn: the intermediate stage between low-density snow crystals and high density glacial ice

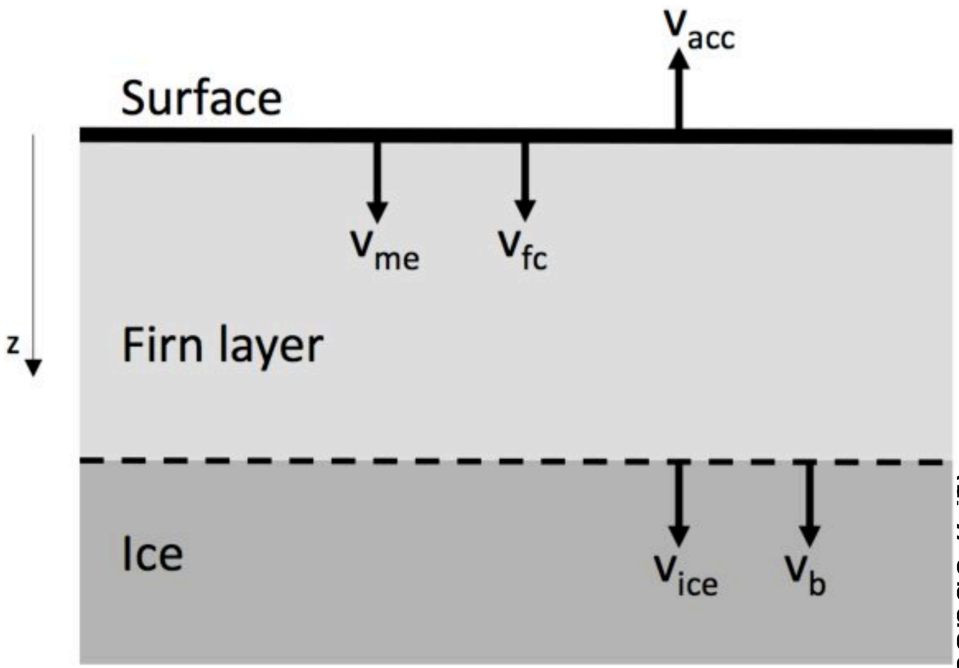
How snow becomes ice



How snow becomes ice

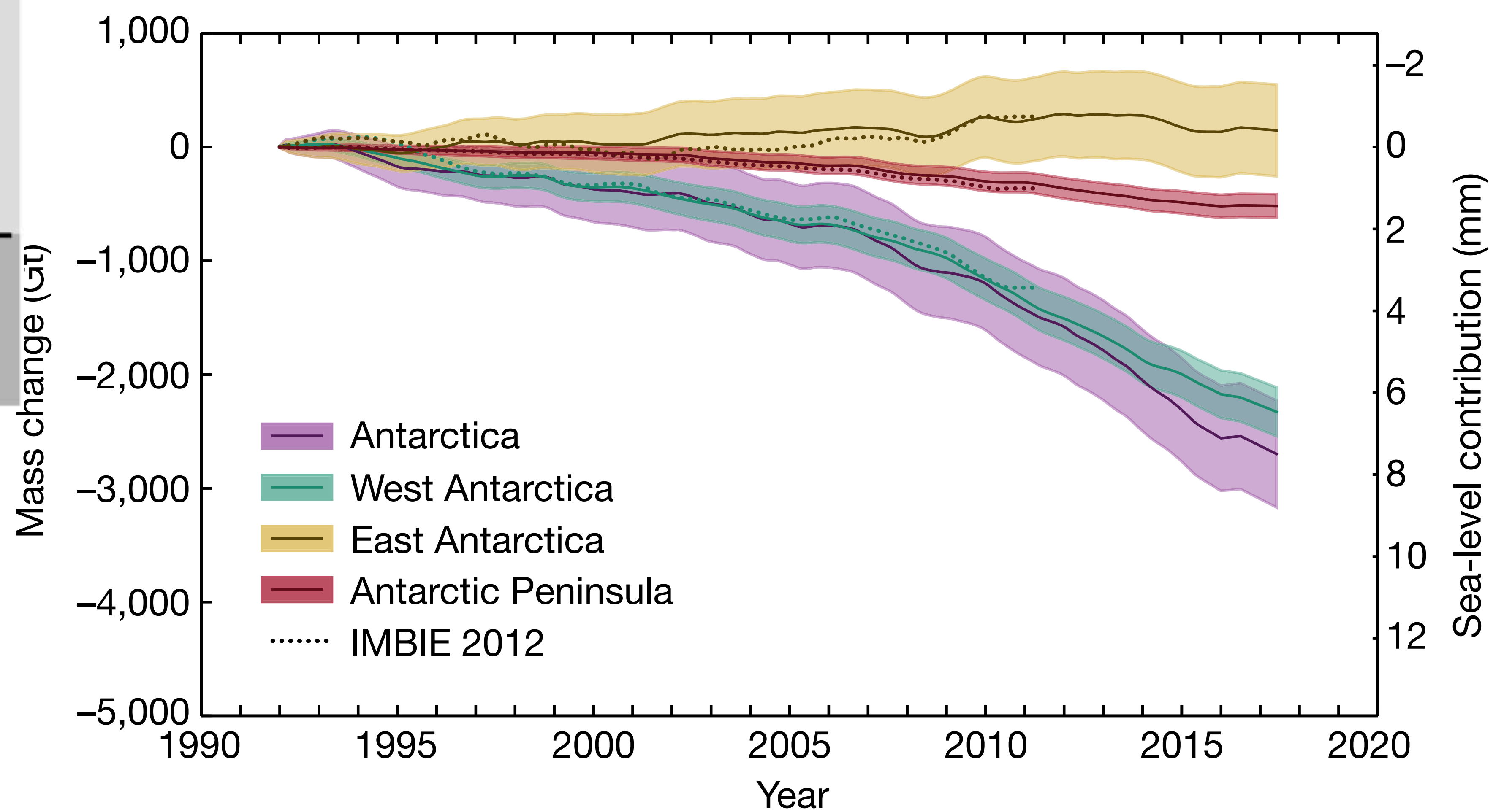


Understanding firn compaction is critical for interpreting elevation changes measured from satellites

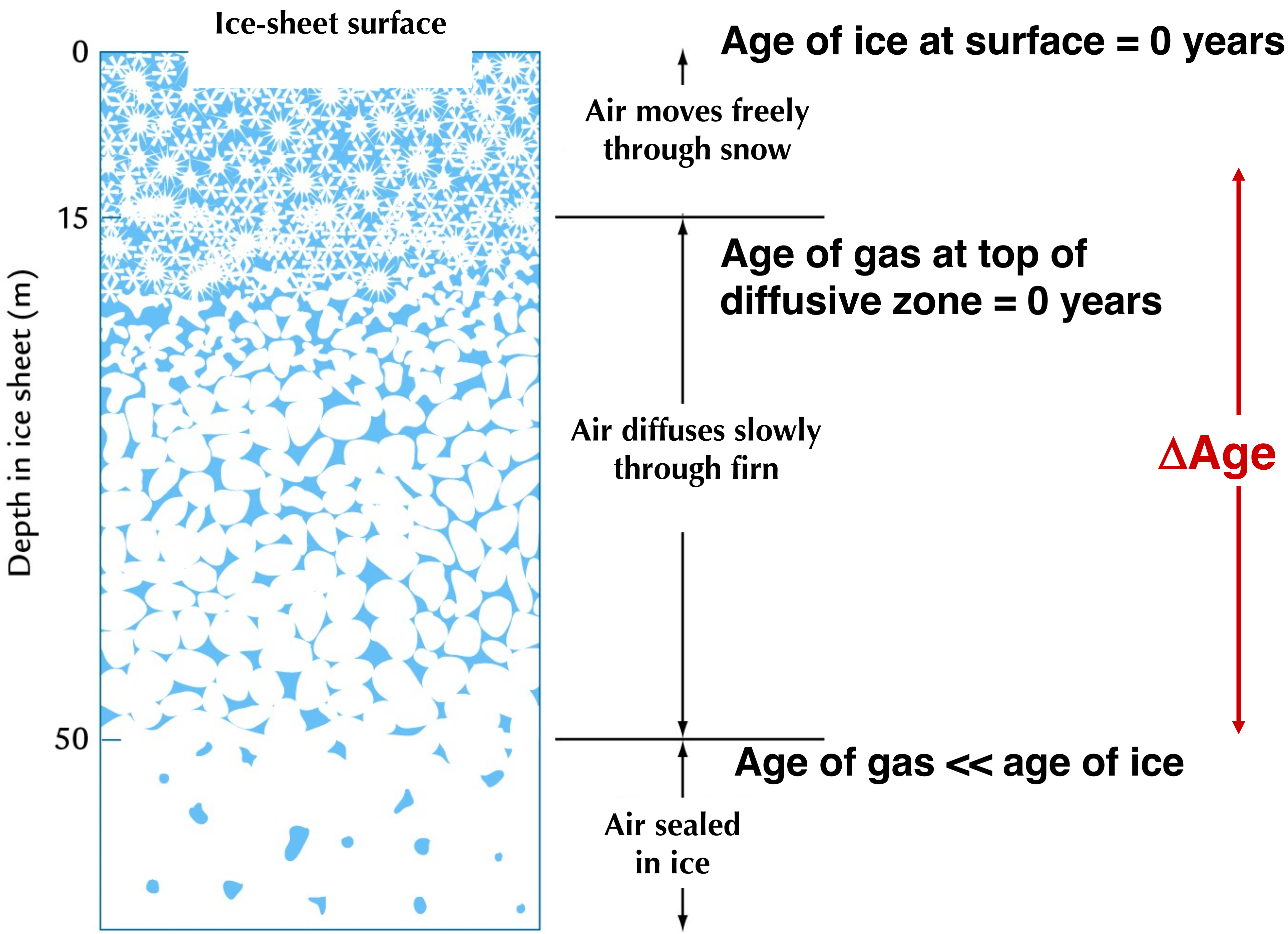


Ligtenberg et al. 2011

IMBIE estimate 2018

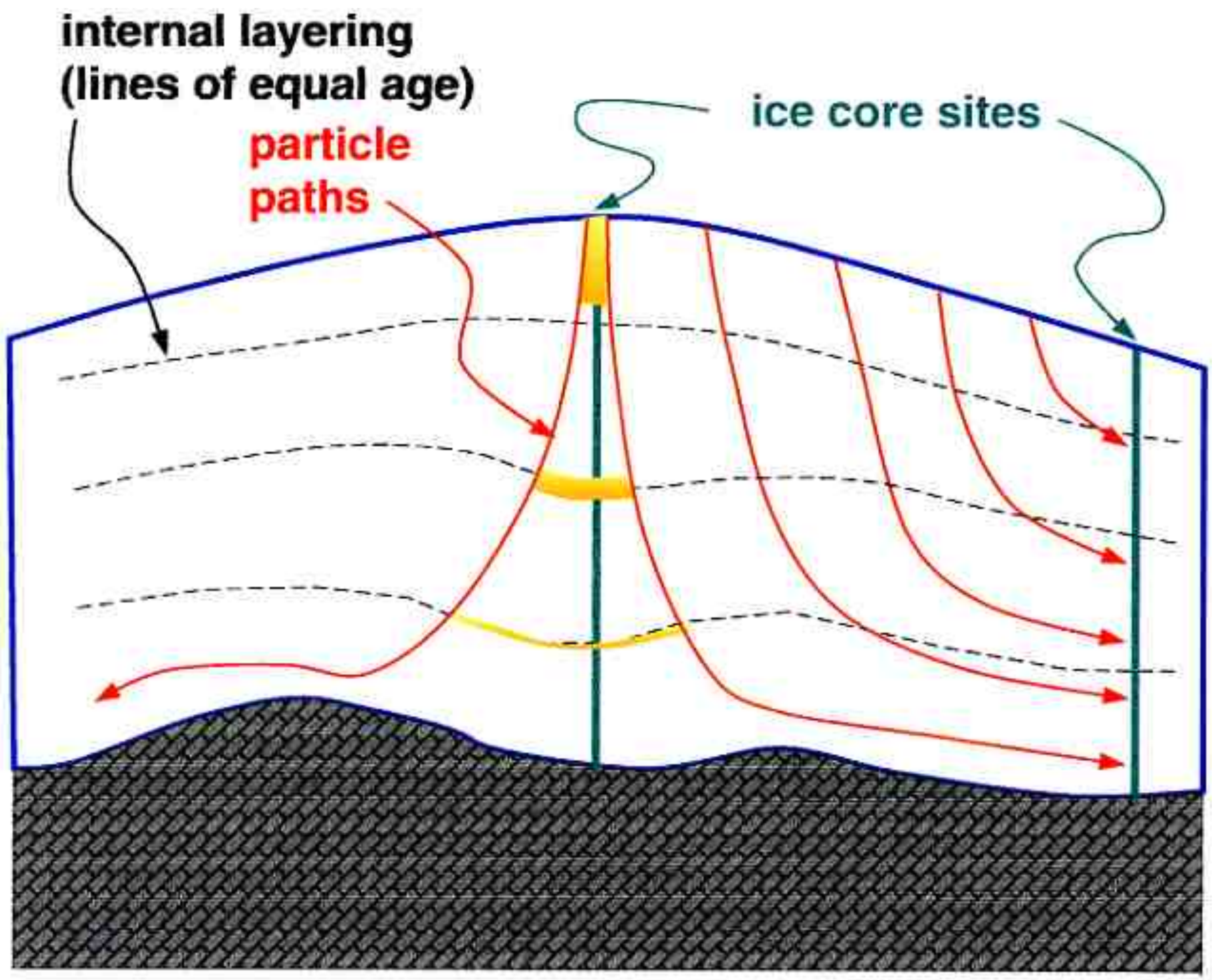


Firn traps atmospheric gases



Slide from UW ESS431

Choosing an Ice-Core Site



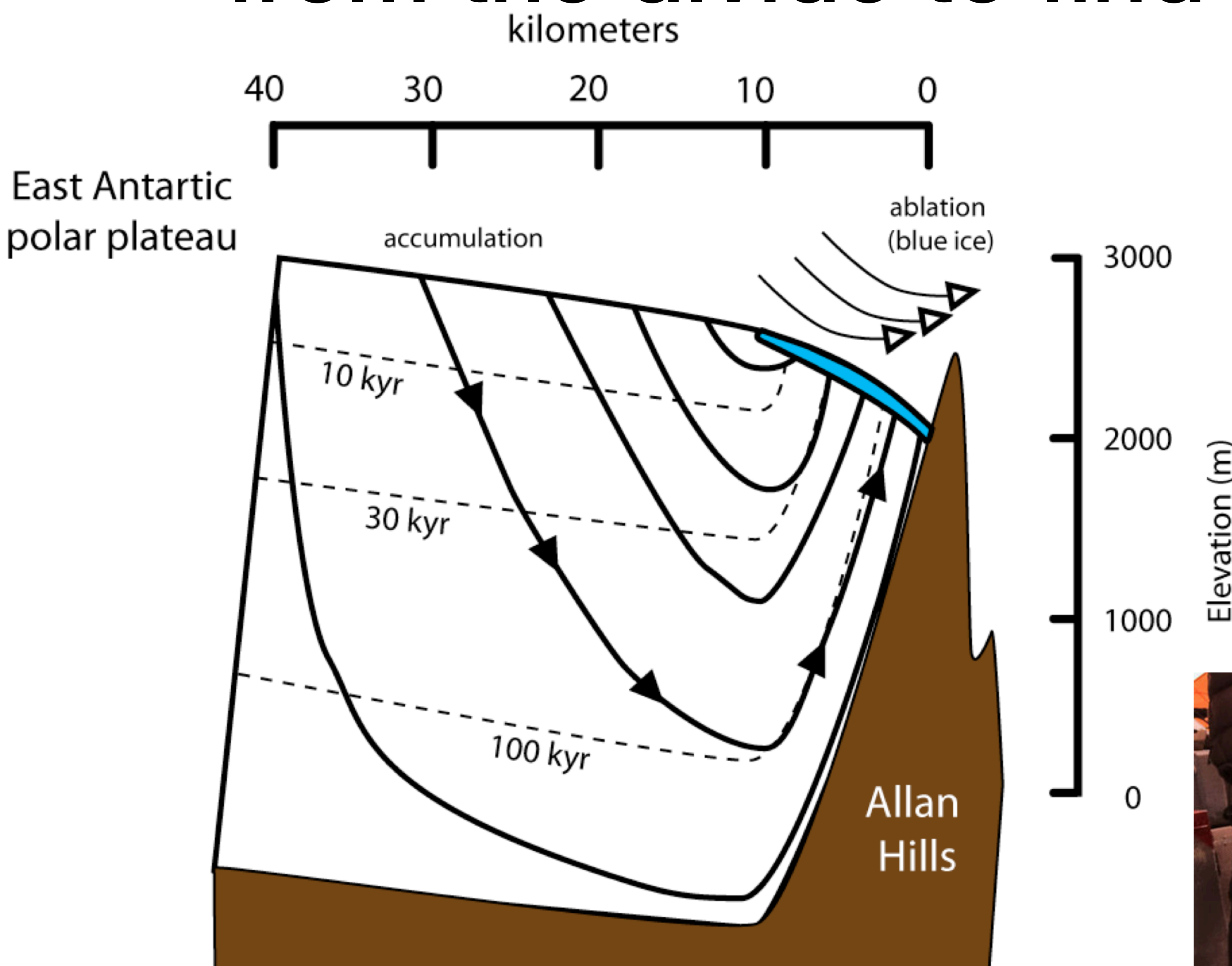
Near the summit is good.

- Climate signal relates to the same place for ice of all ages.

Layers get thinner over time due to flow.

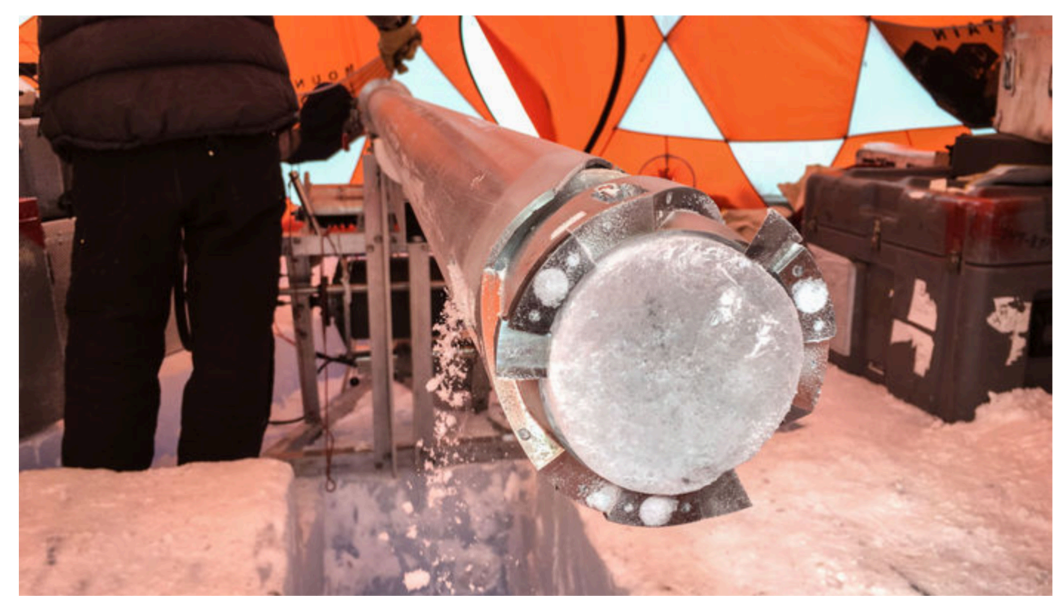
Slide from UW ESS431

But also, you can choose sites away from the divide to find very old ice



Cassidy et al., 1992

The closer you get to the bedrock in the hills, you get small chunks of older preserved ice



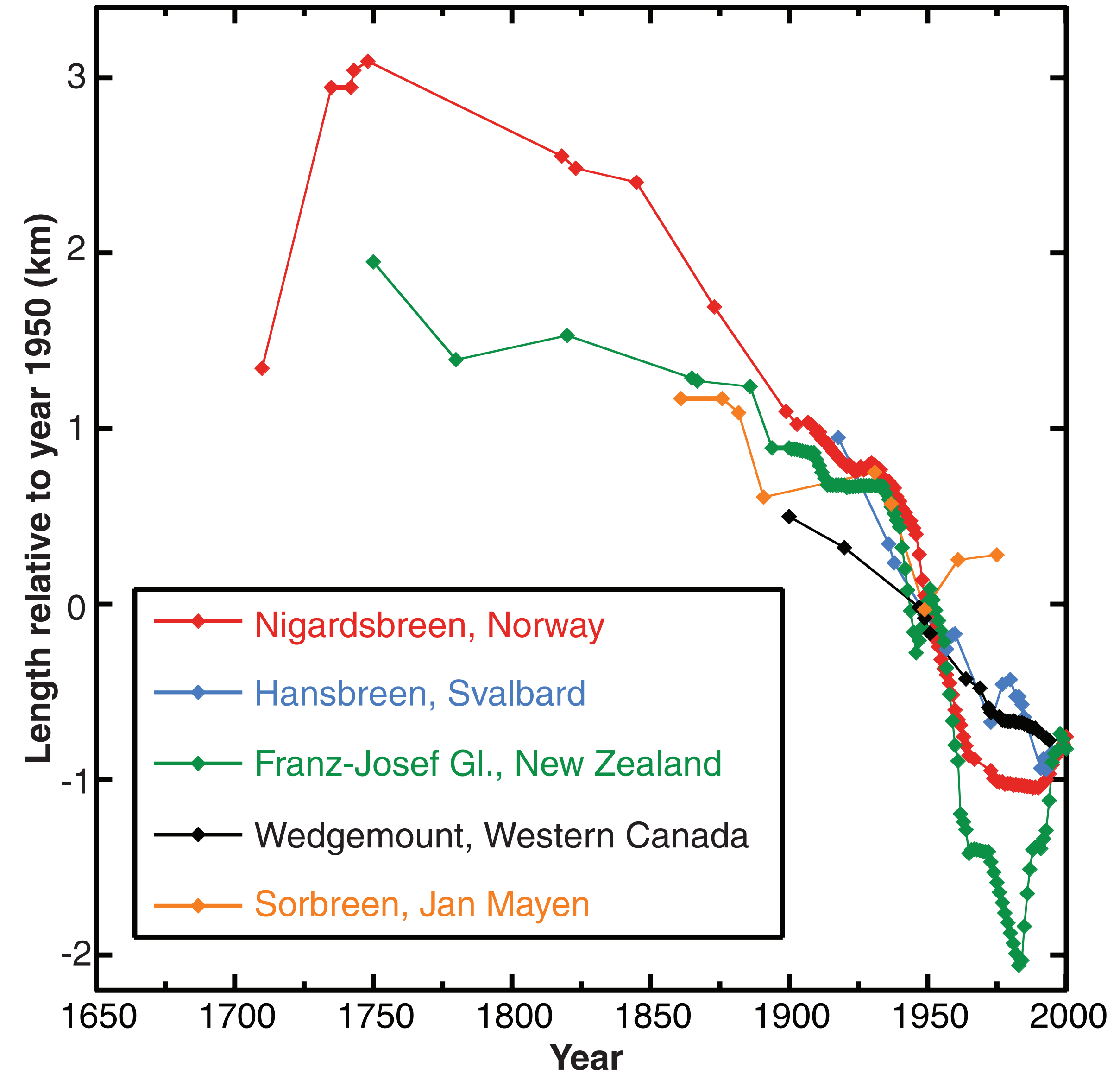
Scientists endured bitter winds to retrieve ancient ice from a blue ice field in the Allan Hills of Antarctica. YUZHEN YAN

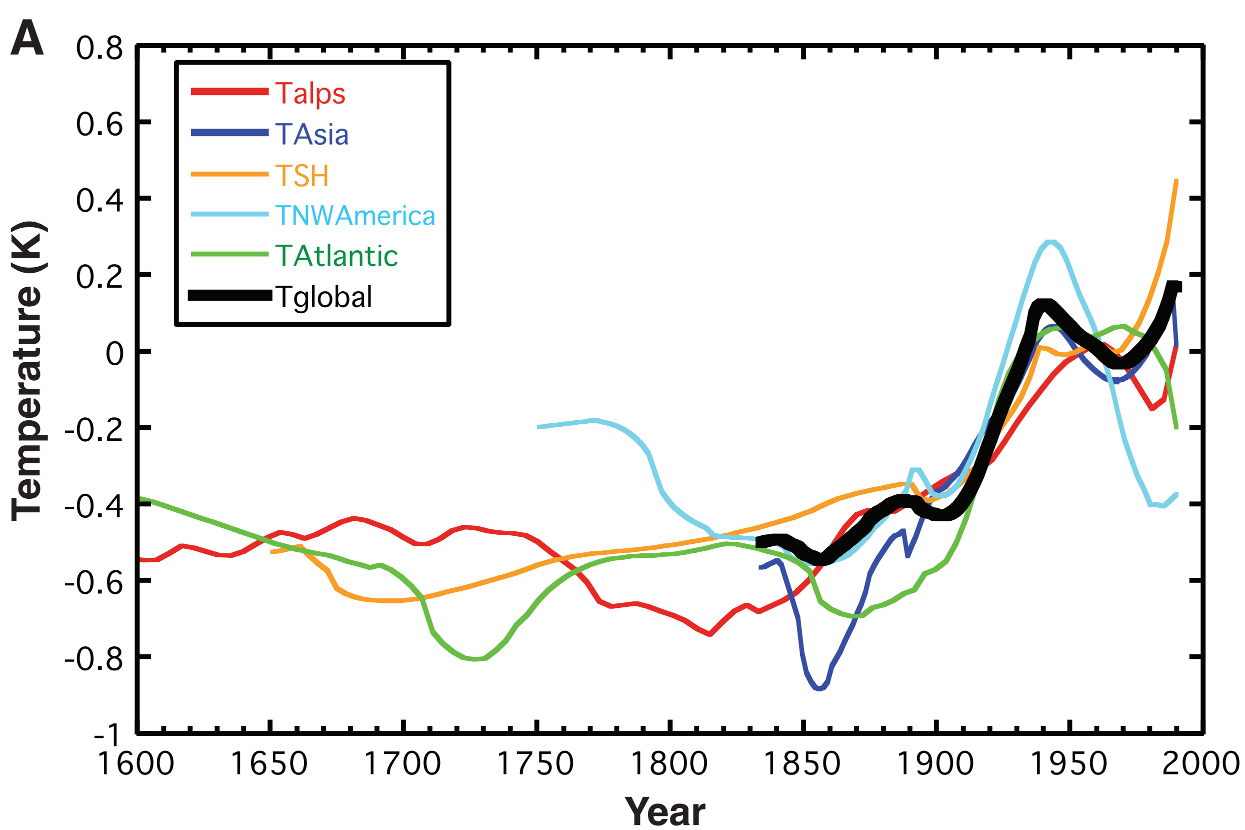
Record-shattering 2.7-million-year-old ice core reveals start of the ice ages

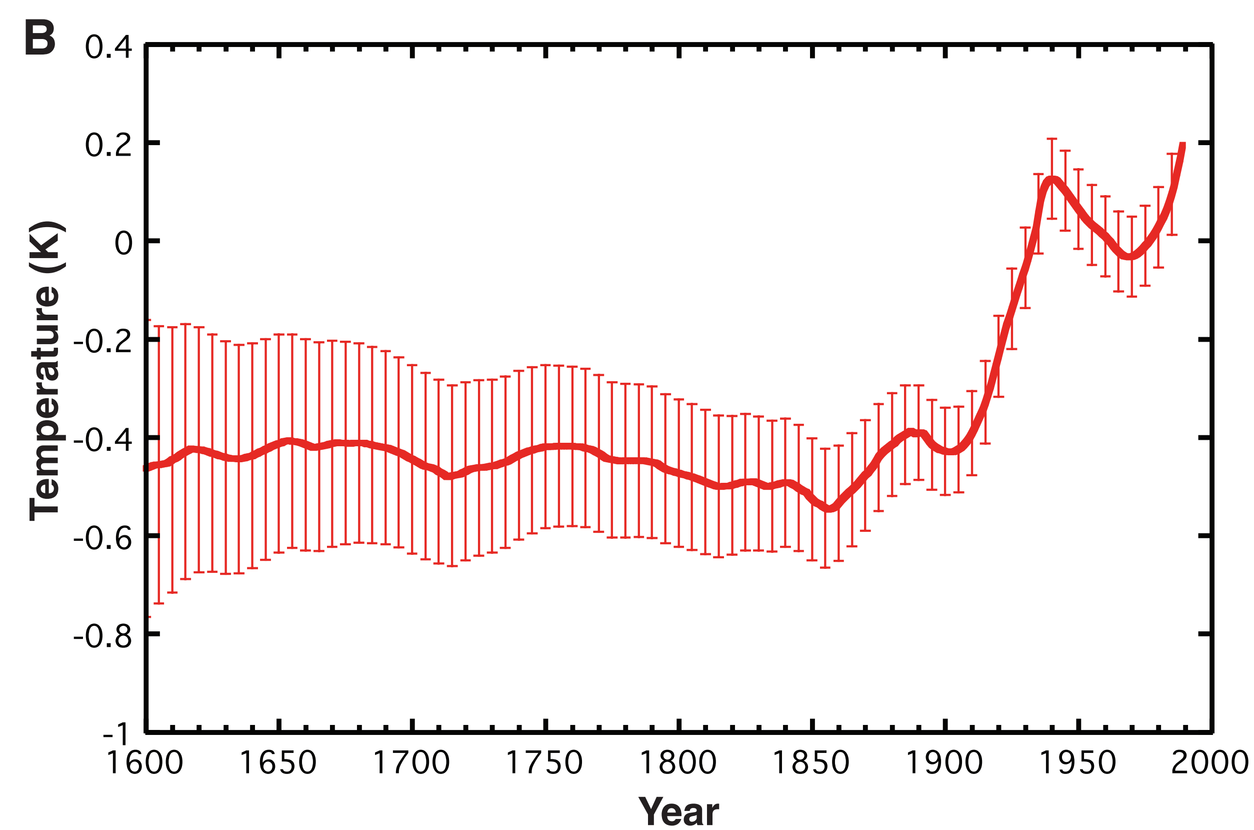
How do mountain glaciers respond to climate forcing?

To the board!

Glacier state as a filters/record of climate (Oerlemans 2005)







Glacier retreat as “categorical” evidence of regional climate change (Roe et al. 2017)