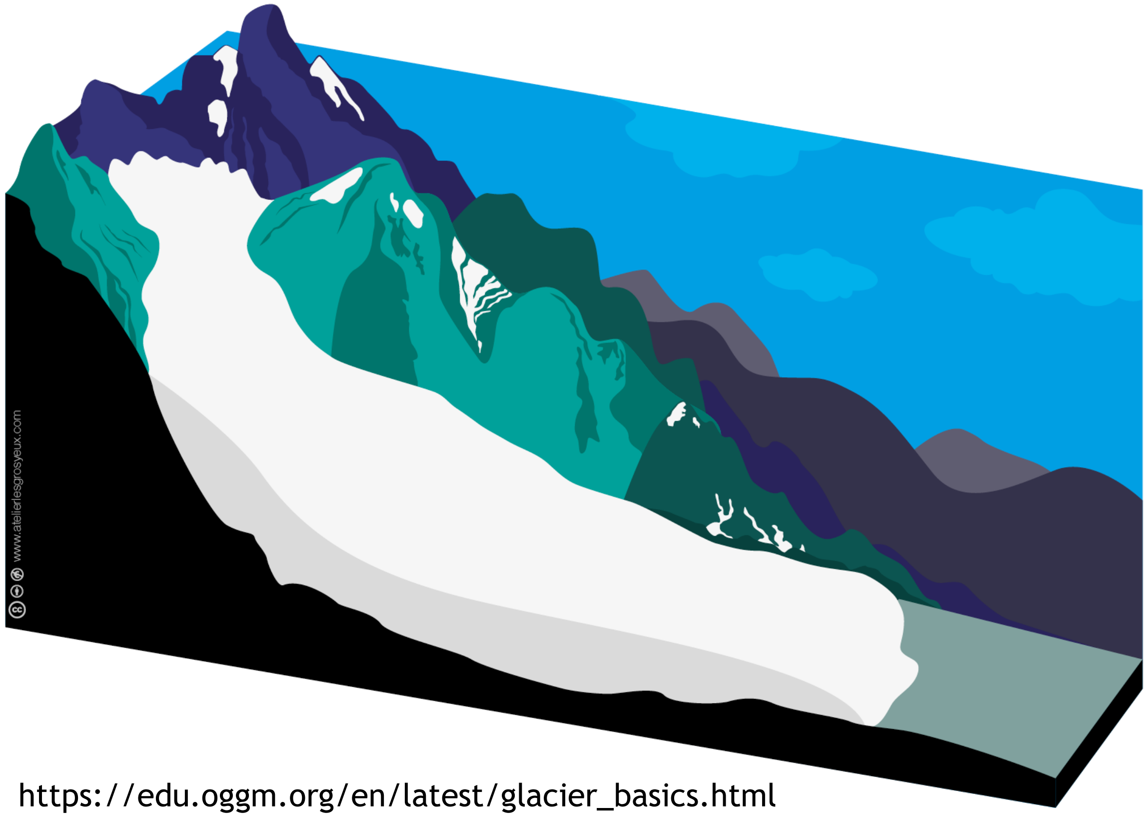
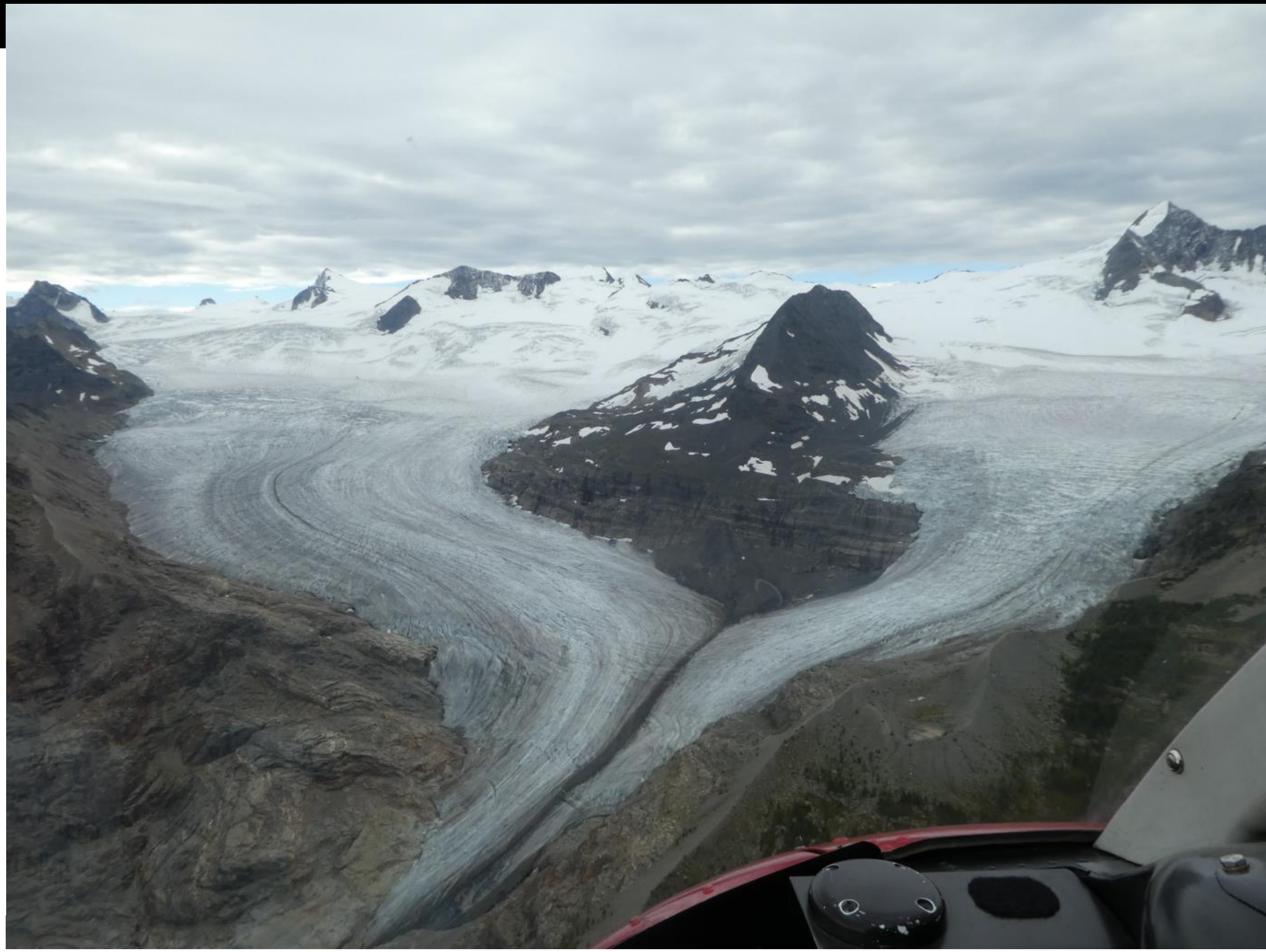
Glacier mass balance | Ben M. Pelto

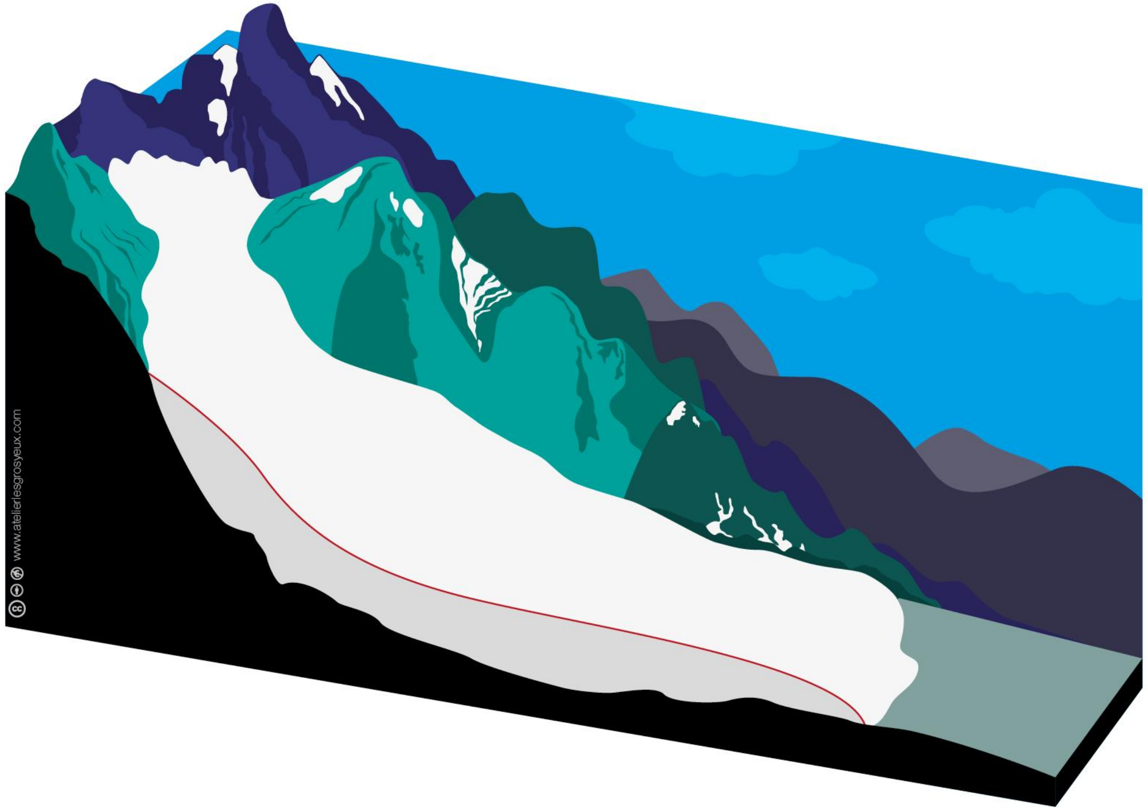
Mountain Glaciers



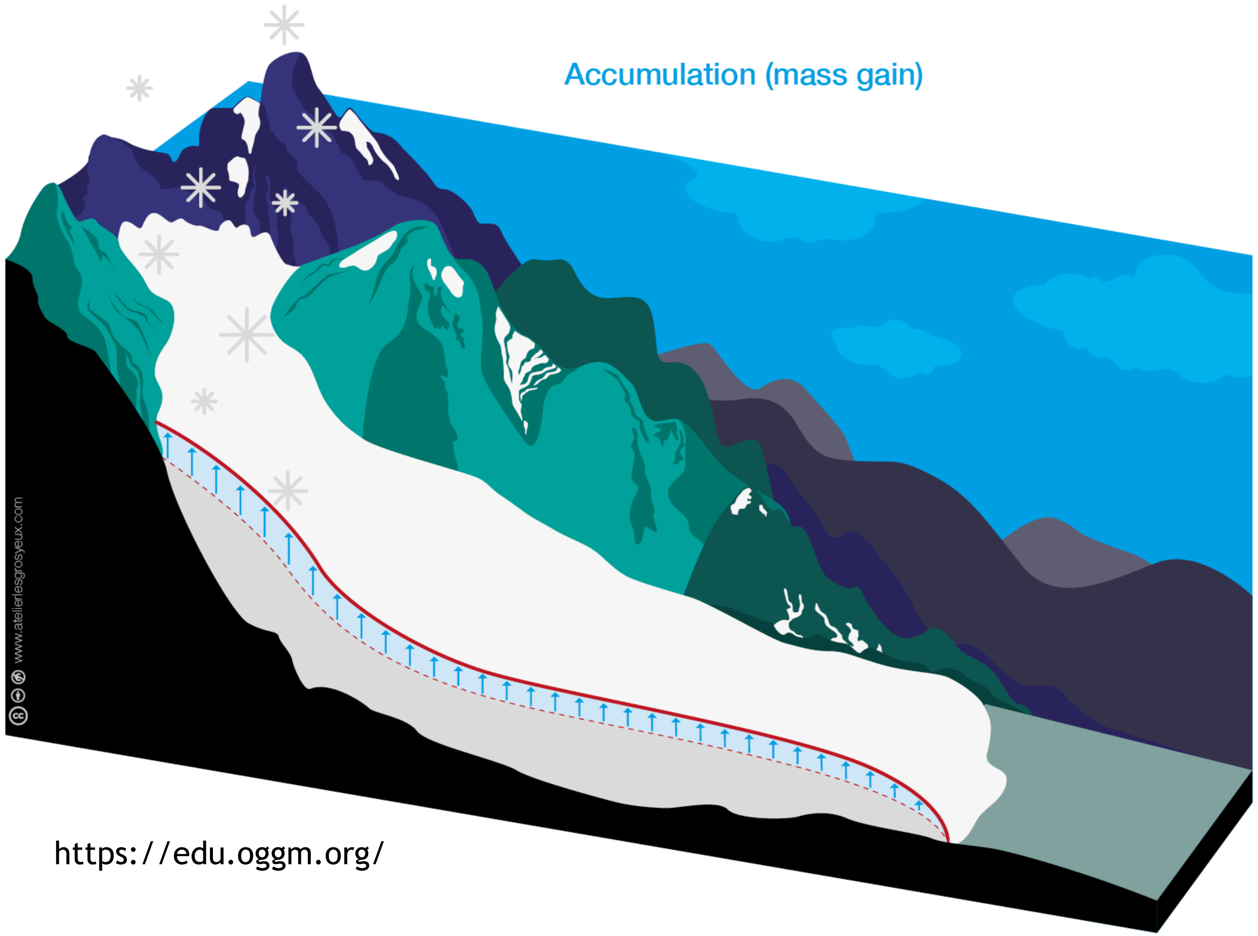
https://edu.oggm.org/en/latest/glacier_basics.html



Glacier surface

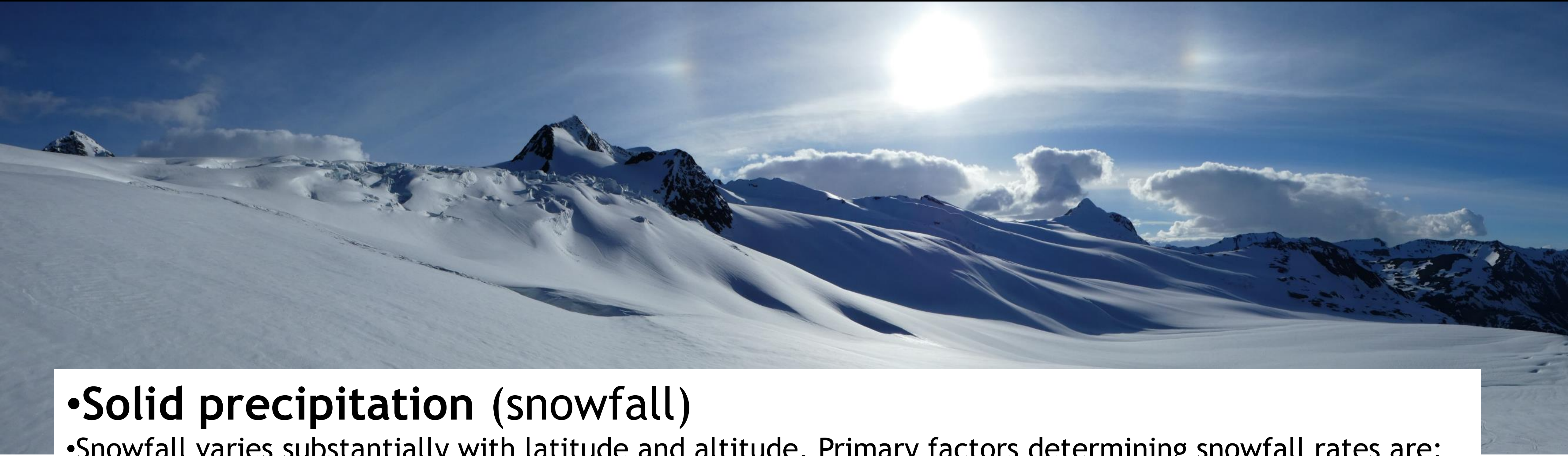


Accumulation



https://edu.oggm.org/

Accumulation processes
processes that add snow or ice to a glacier (surface)

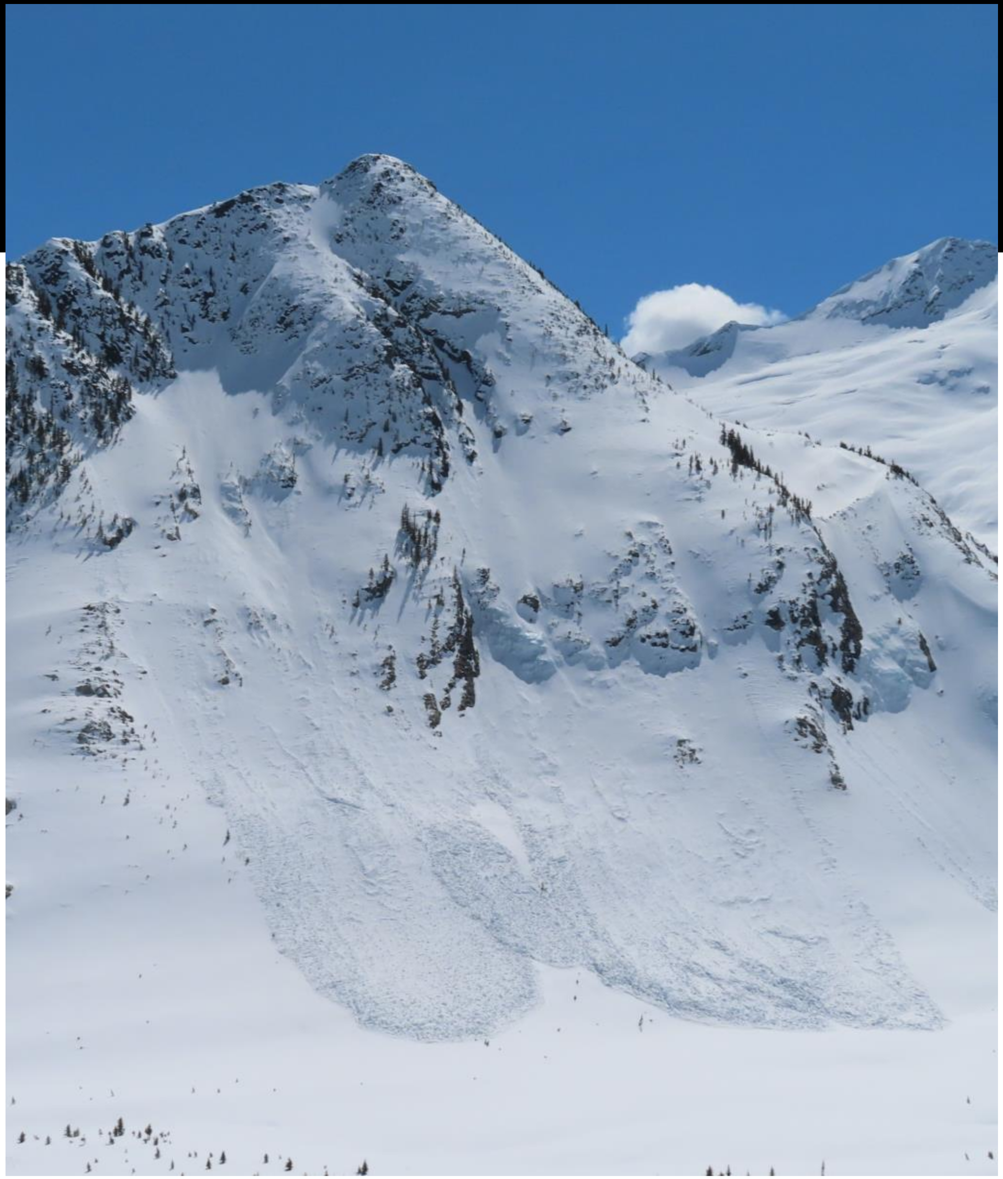


- **Solid precipitation** (snowfall)
- Snowfall varies substantially with latitude and altitude. Primary factors determining snowfall rates are:
  - **Water vapor content** governed by the Clausius-Clapeyron-relationship: the warmer the air, the more water it can hold and hence the more precipitation can form
  - **Stratification** of the atmosphere: a subfreezing layer in the lower atmosphere is required for precipitation to reach the ground in solid form
  - **Cooling rate**: high snowfall rates occur where snow is rapidly cooled, e.g. in frontal systems or via orographic lifting

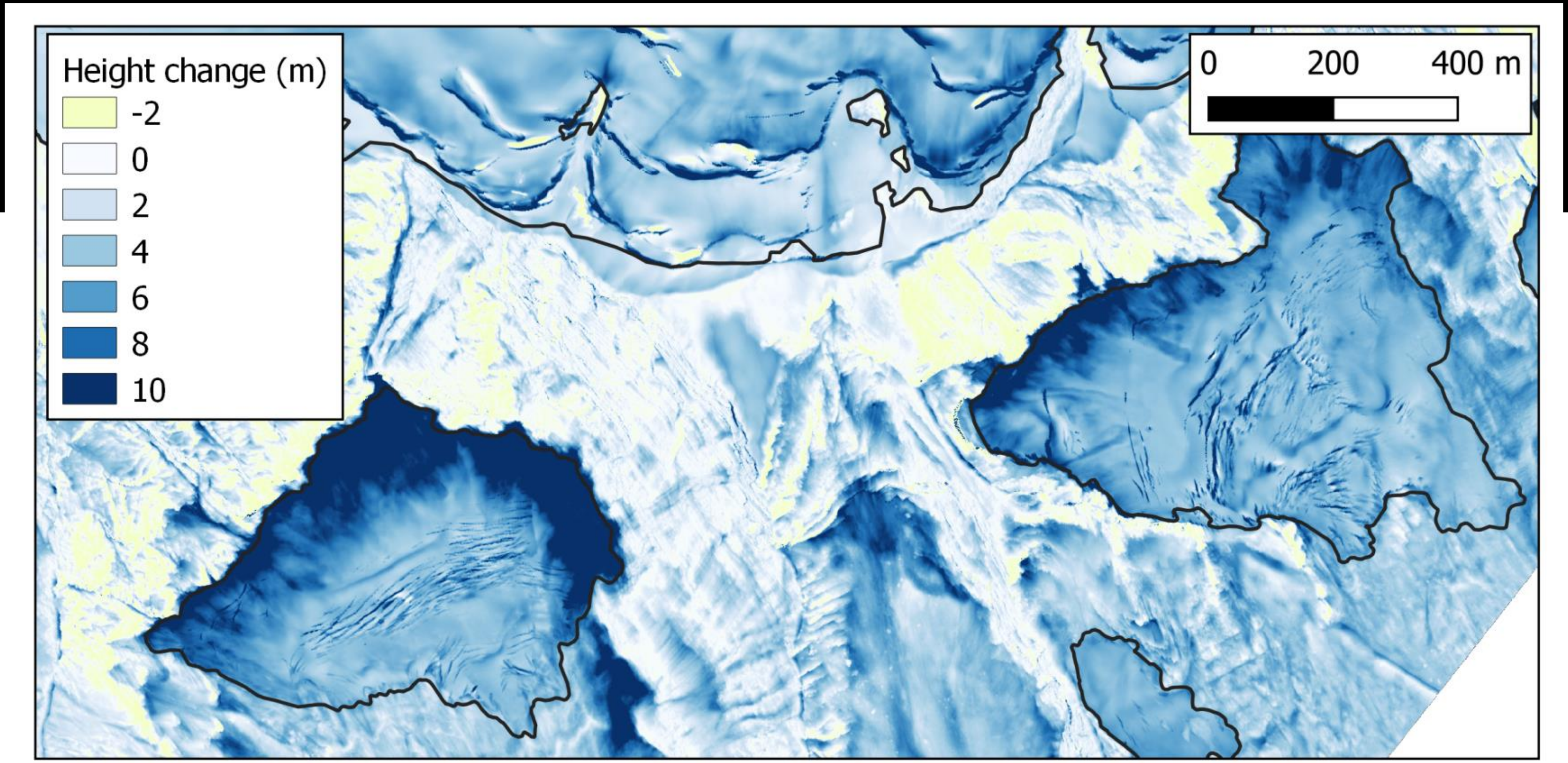
Accumulation processes

Redistribution by wind and avalanching

- Accumulation differs from snowfall due to winds advecting snow over a glacier surface - the interaction between wind and the topography.



Accumulation processes



Avalanches may accumulate unusually large amounts of snow in favorable zones. Particularly important for mountain glaciers in steep valleys.

Accumulation processes

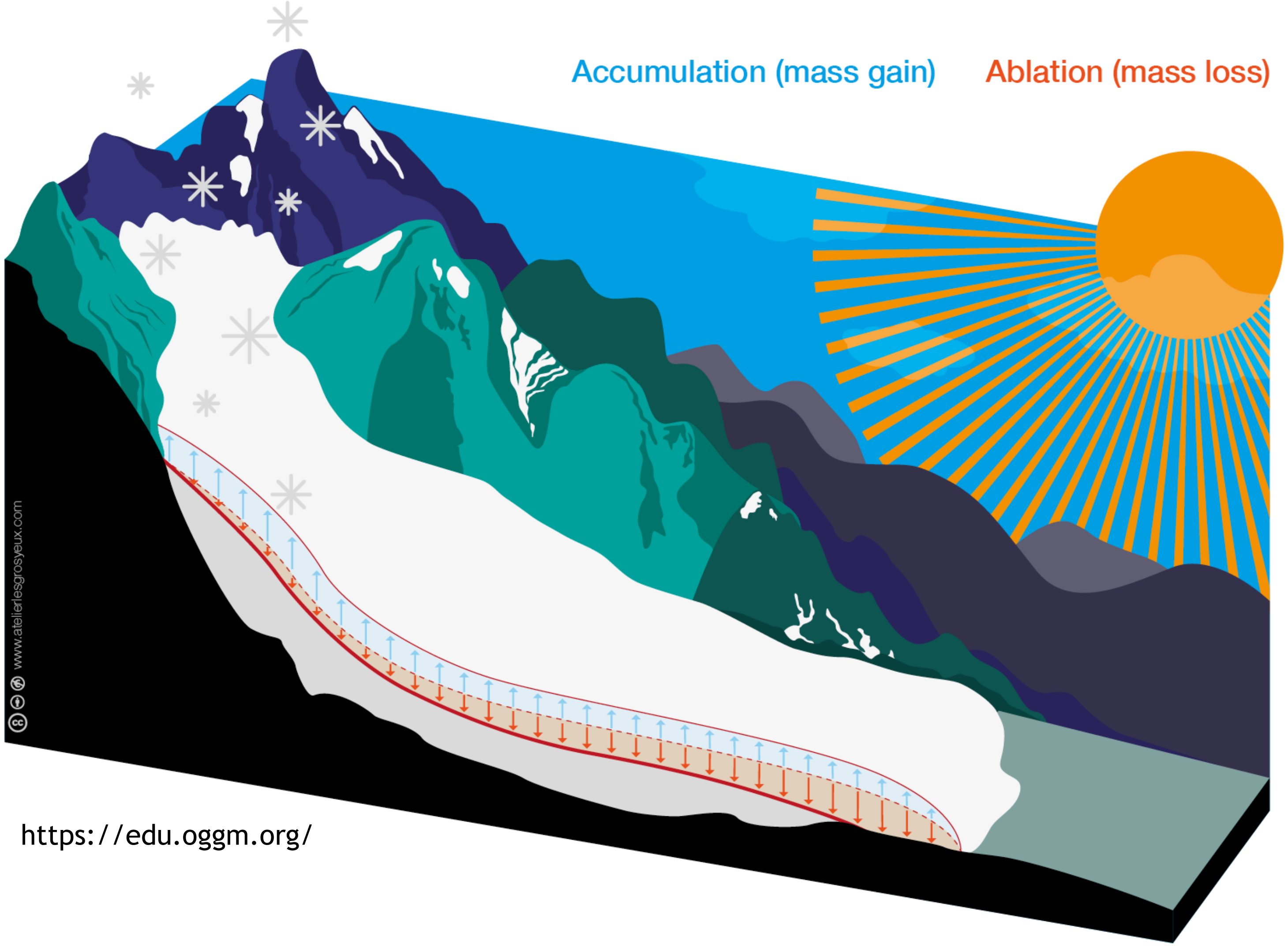
Refreezing of meltwater

- Can either occur at the glacier surface or inside the glacier body, where it is commonly called englacial or internal accumulation.

Deposition

- Deposition refers to processes directly accumulating water or water vapor to the glacier surface, i.e. freezing rain and resublimation.

Ablation



https://edu.oggm.org/

Ablation processes

processes that remove snow or ice from a glacier

Melt and runoff

- Melt and runoff account for most glacier mass loss and are driven by the net energy imbalance between the atmosphere and the glacier surface.
    - The most important contributors are the net radiation and the turbulent fluxes of sensible and latent heat.
    - Once the temperature of the glacier surface is at the melting point, melt rates increase in proportion to the net energy flux.

Ablation processes

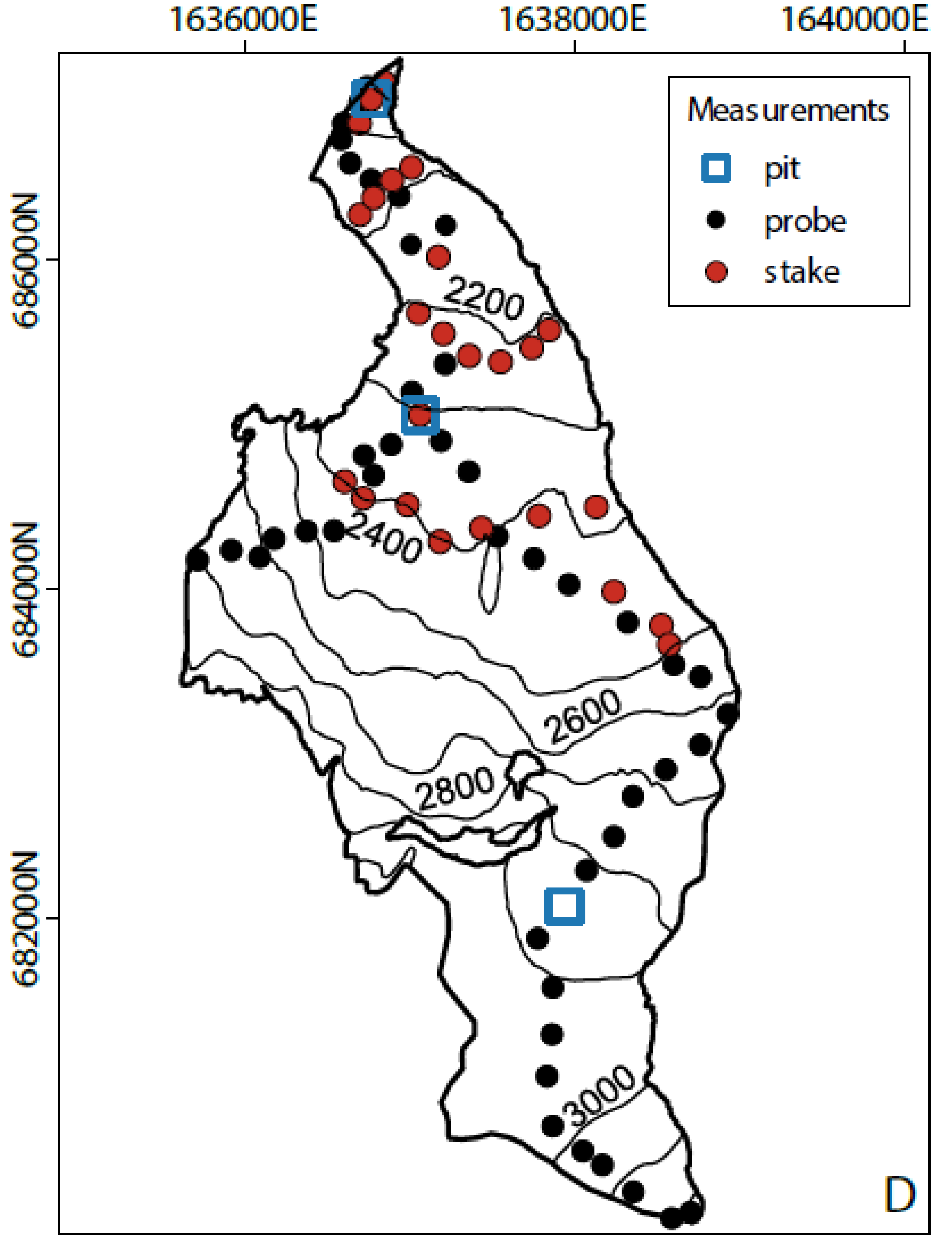
Sublimation

- Direct transition of snow and ice to water vapor
- Dominant source of mass loss in environments where surface temperatures hardly reach the melting point
- Sublimation increases with increasing surface temperature and wind speed and with decreasing humidity

Ablation processes

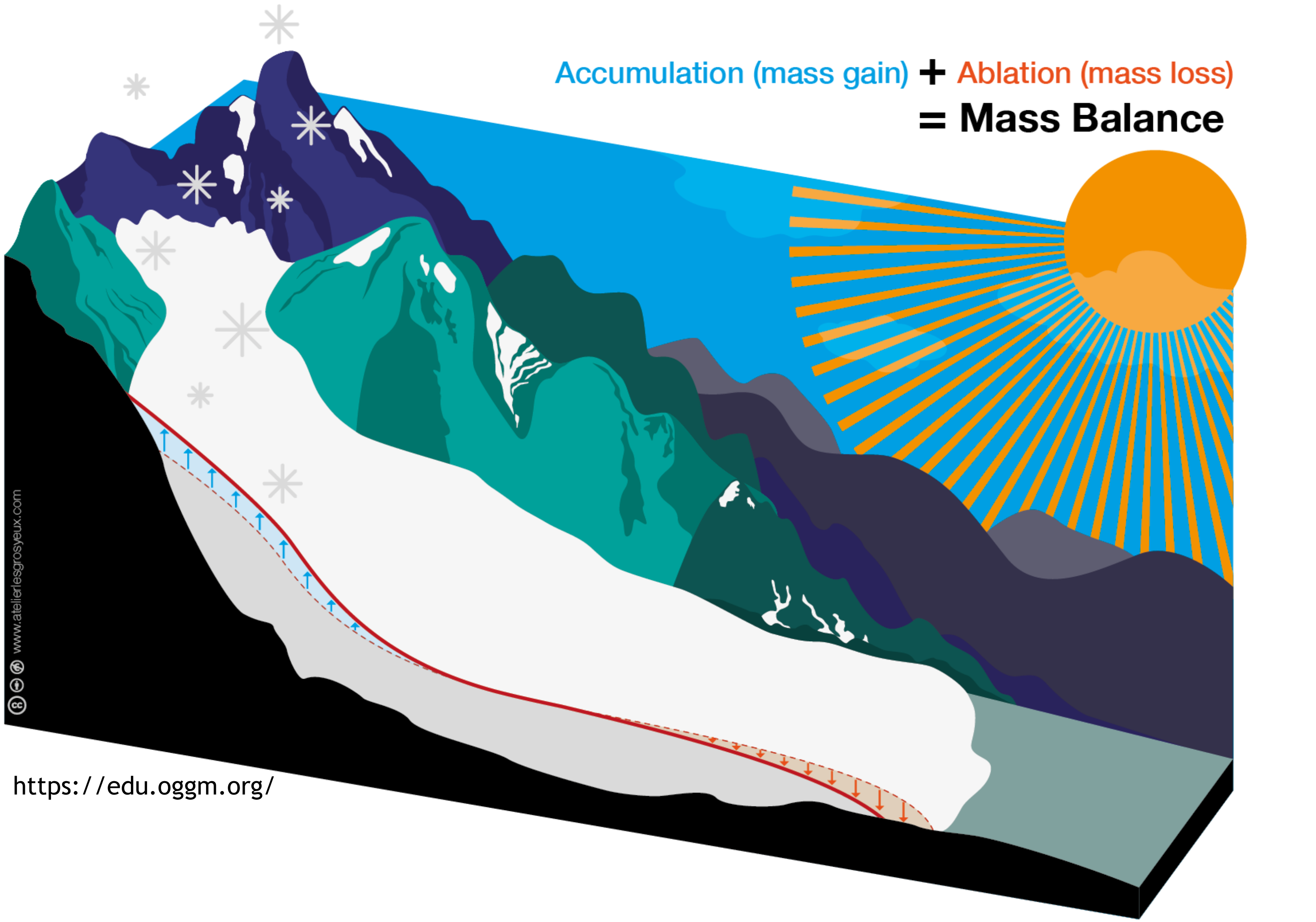
Calving

- Separation of ice blocks from a glacier's margin
- Occurs at margins of glaciers that stand or float in water.
- Calving of glaciers terminating in the ocean, *tidewater* glaciers, accounts for more than 90% of the ablation from Antarctica and about half of the ablation from Greenland.


1636000E
1638000E
1640000E
686000N
684000N
682000N
Measurements
pit
probe
stake
2200
2400
2600
2800
3000
D

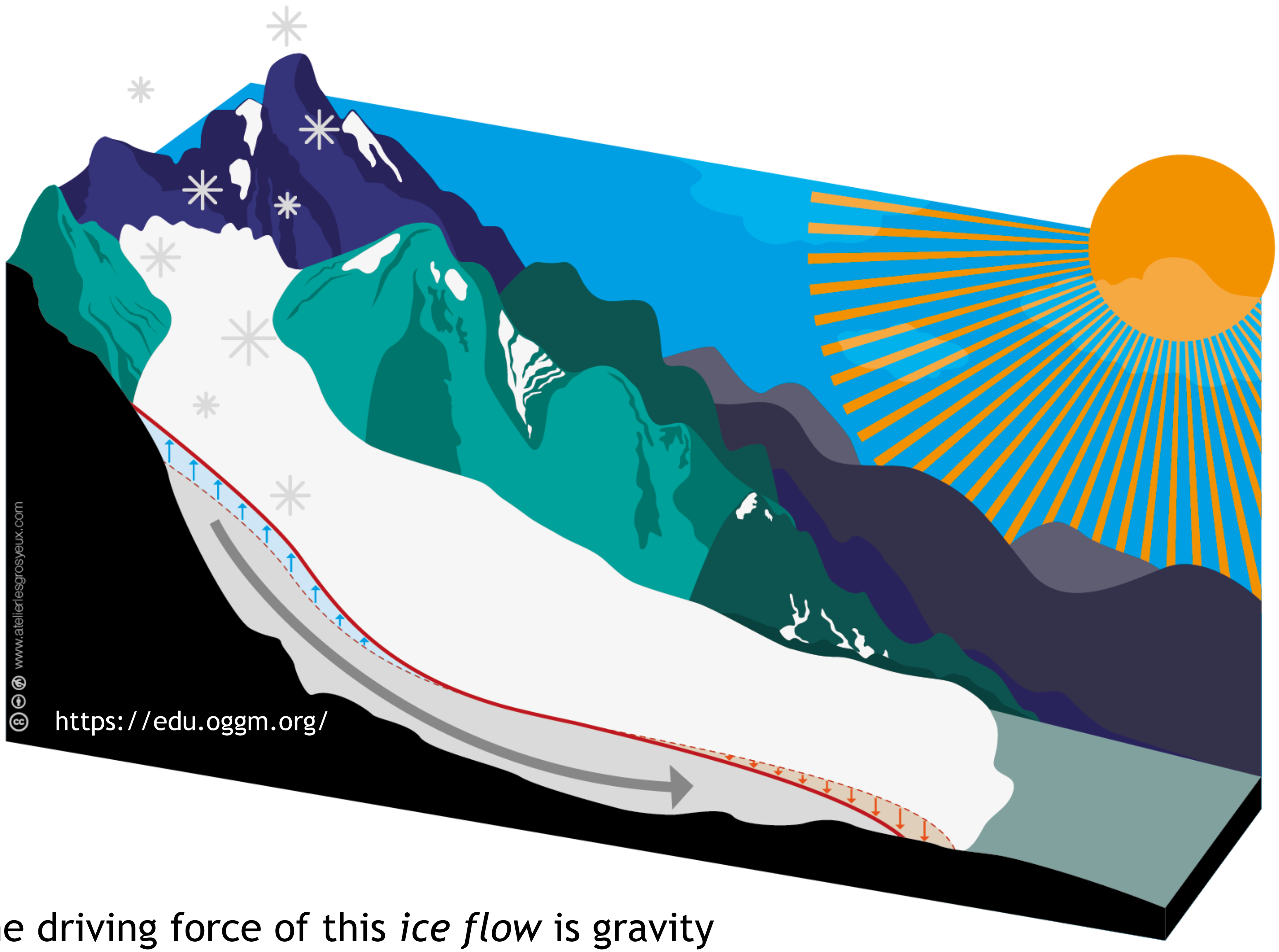
Accumulation + **Ablation** = **Mass Balance ($\dot{b}$)**

Glacier Mass Balance



https://edu.oggm.org/

Ice velocity (flux) – continuity equation

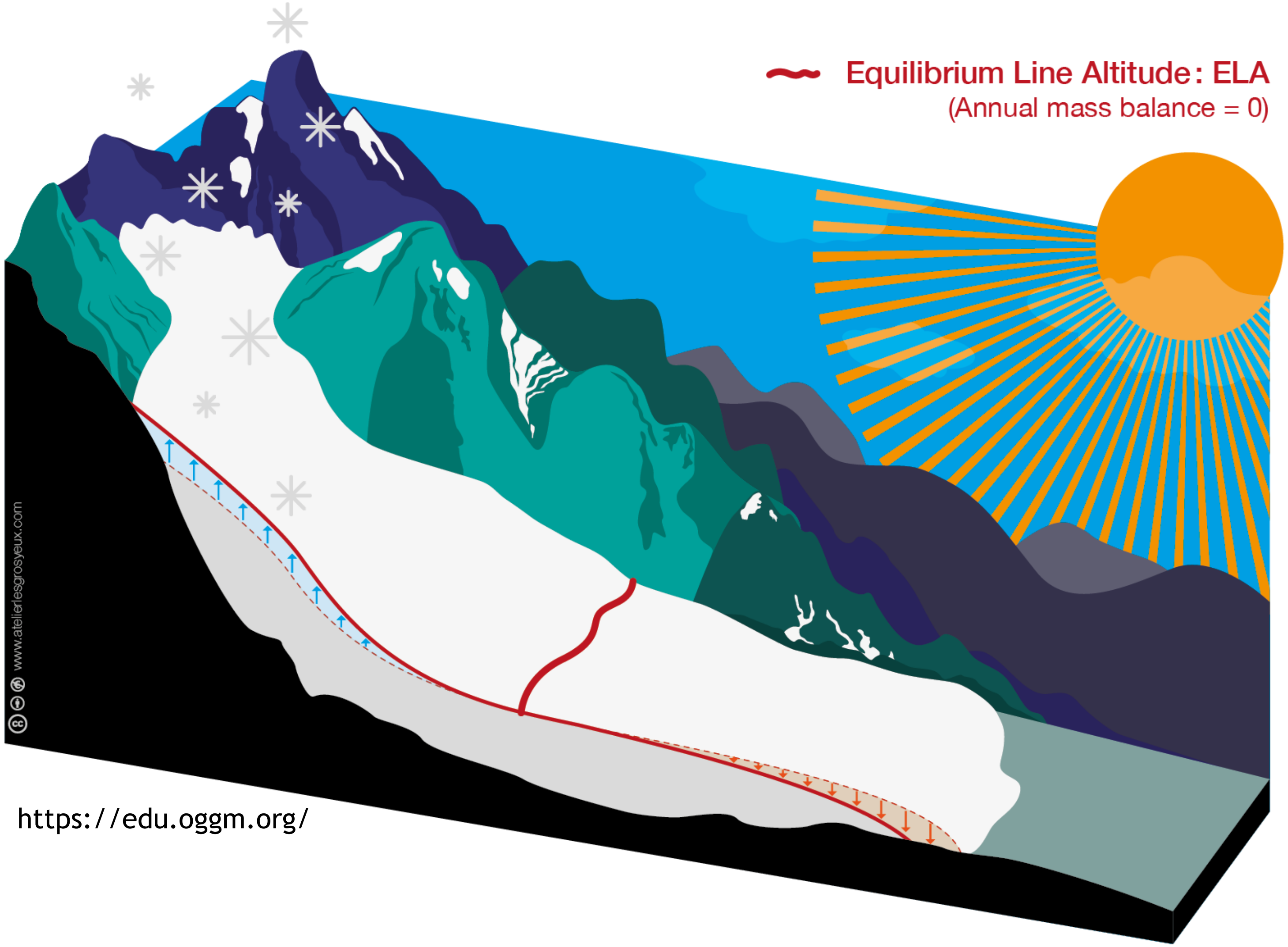


The driving force of this *ice flow* is gravity

$$\frac{\partial H}{\partial t} = \dot{b} - \nabla \cdot \vec{q}$$

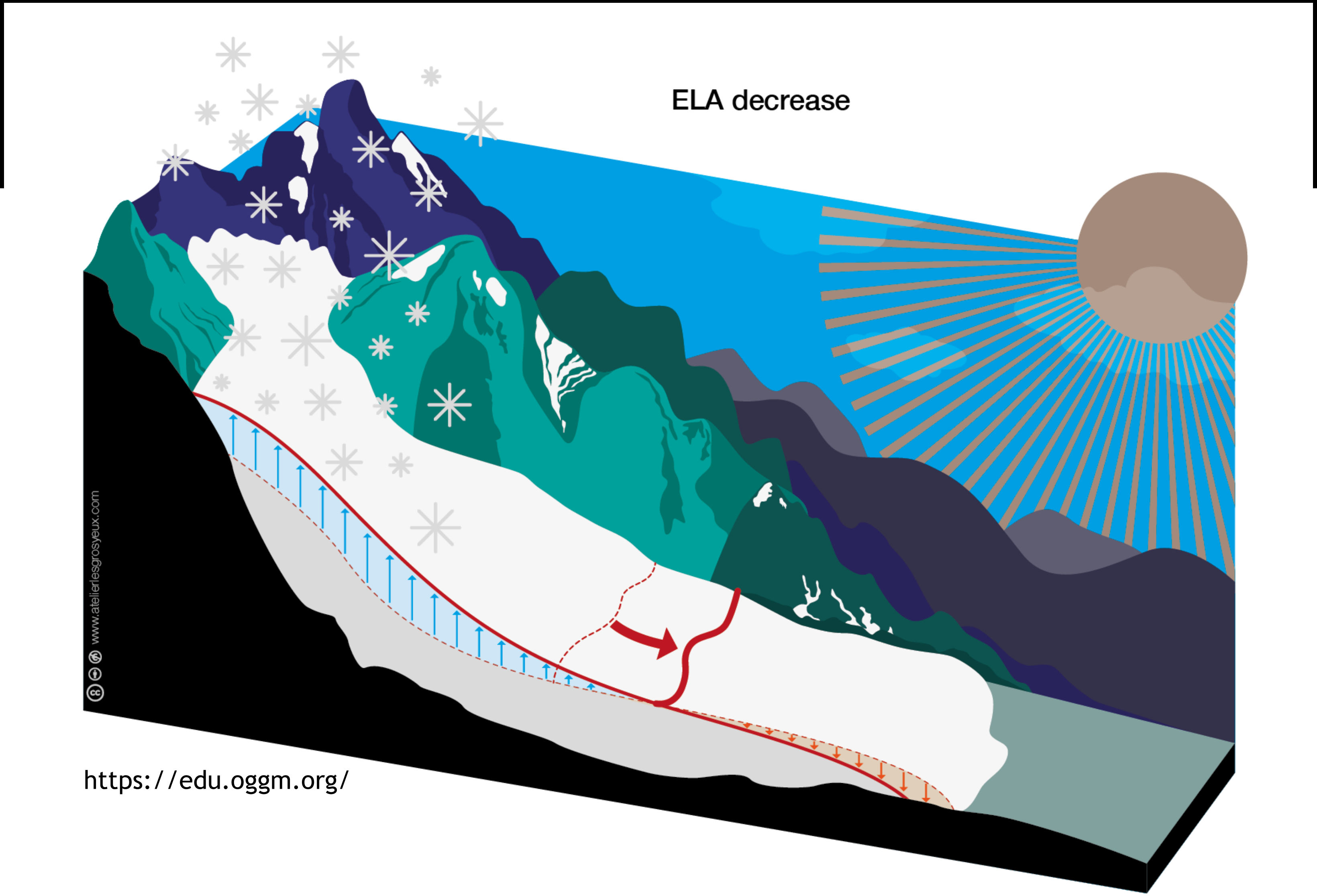
H = ice thickness
$\dot{b}$ = mass balance
$\vec{q}$ = ice flux

Equilibrium Line Altitude (ELA)



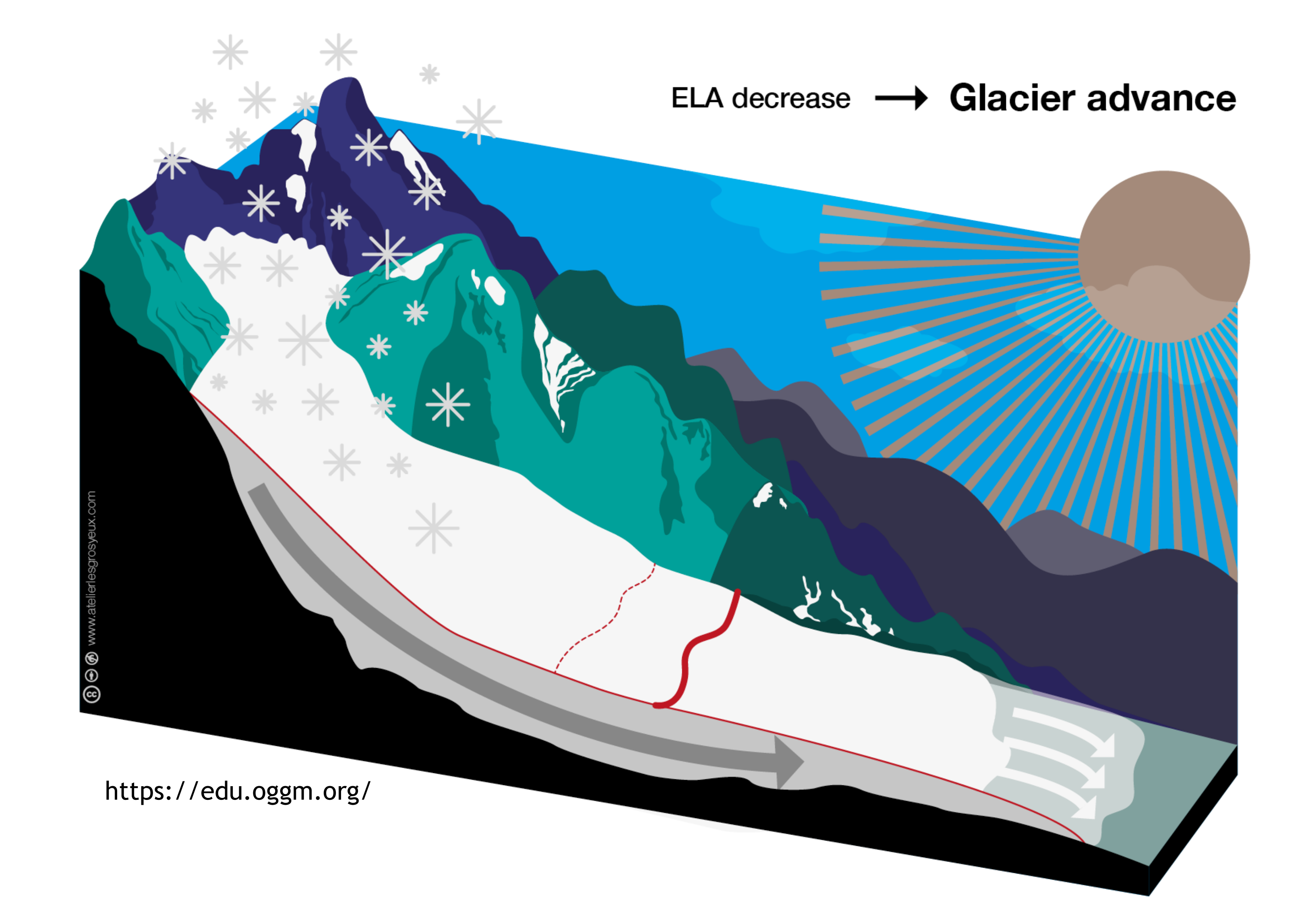
https://edu.oggm.org/

ELA decrease



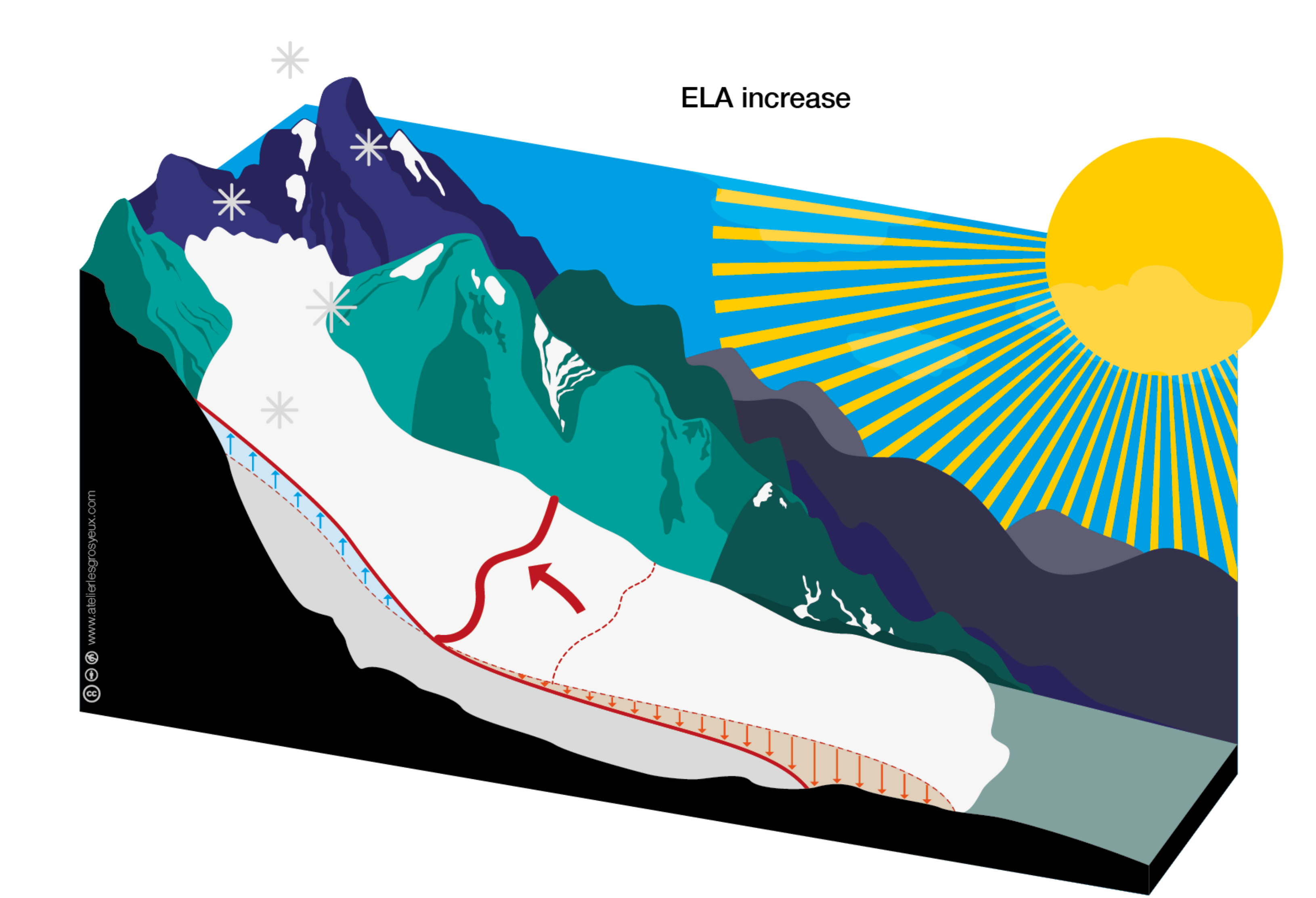
https://edu.oggm.org/

Glacier Advance

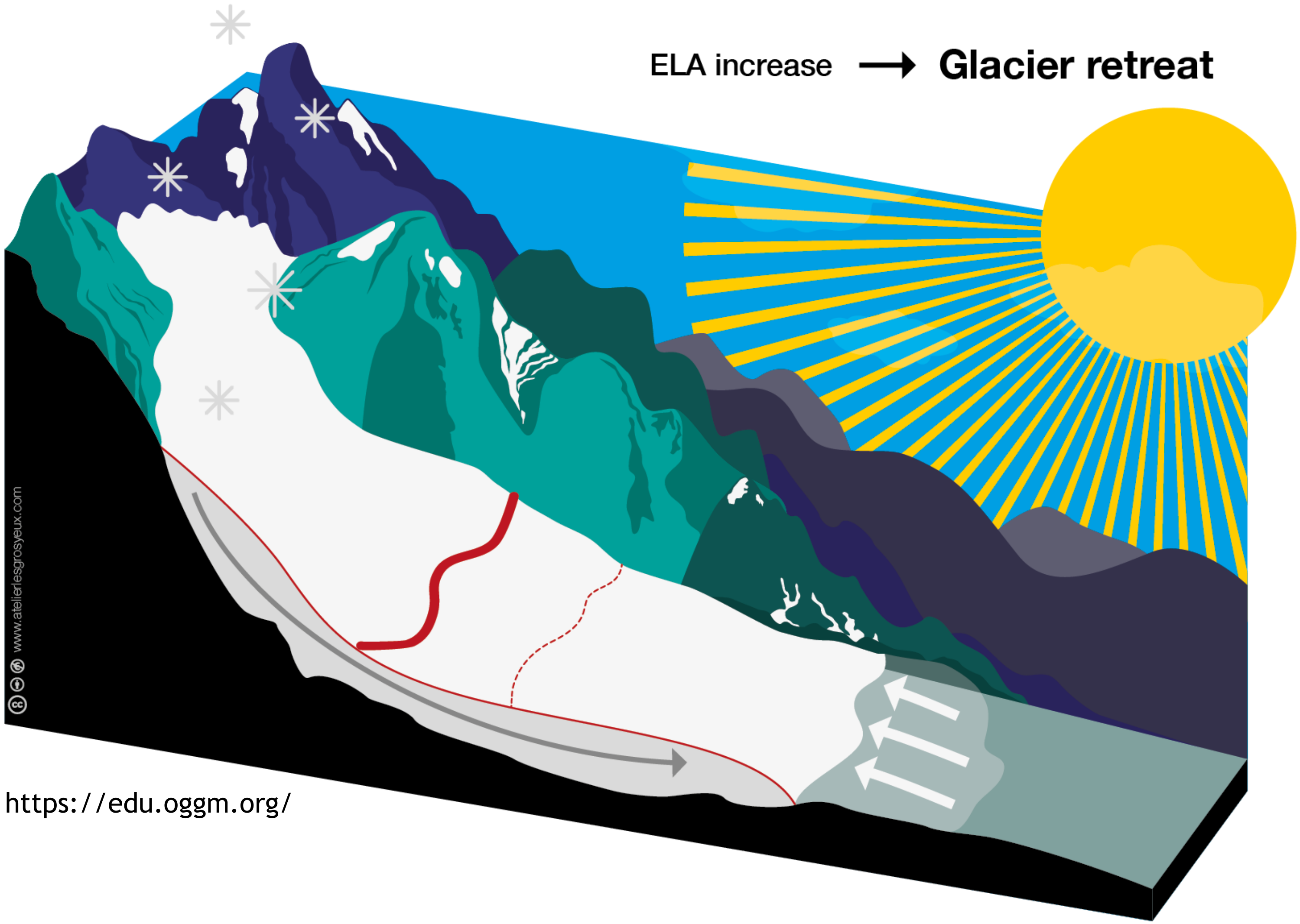


https://edu.oggm.org/

ELA increase – today's scenario

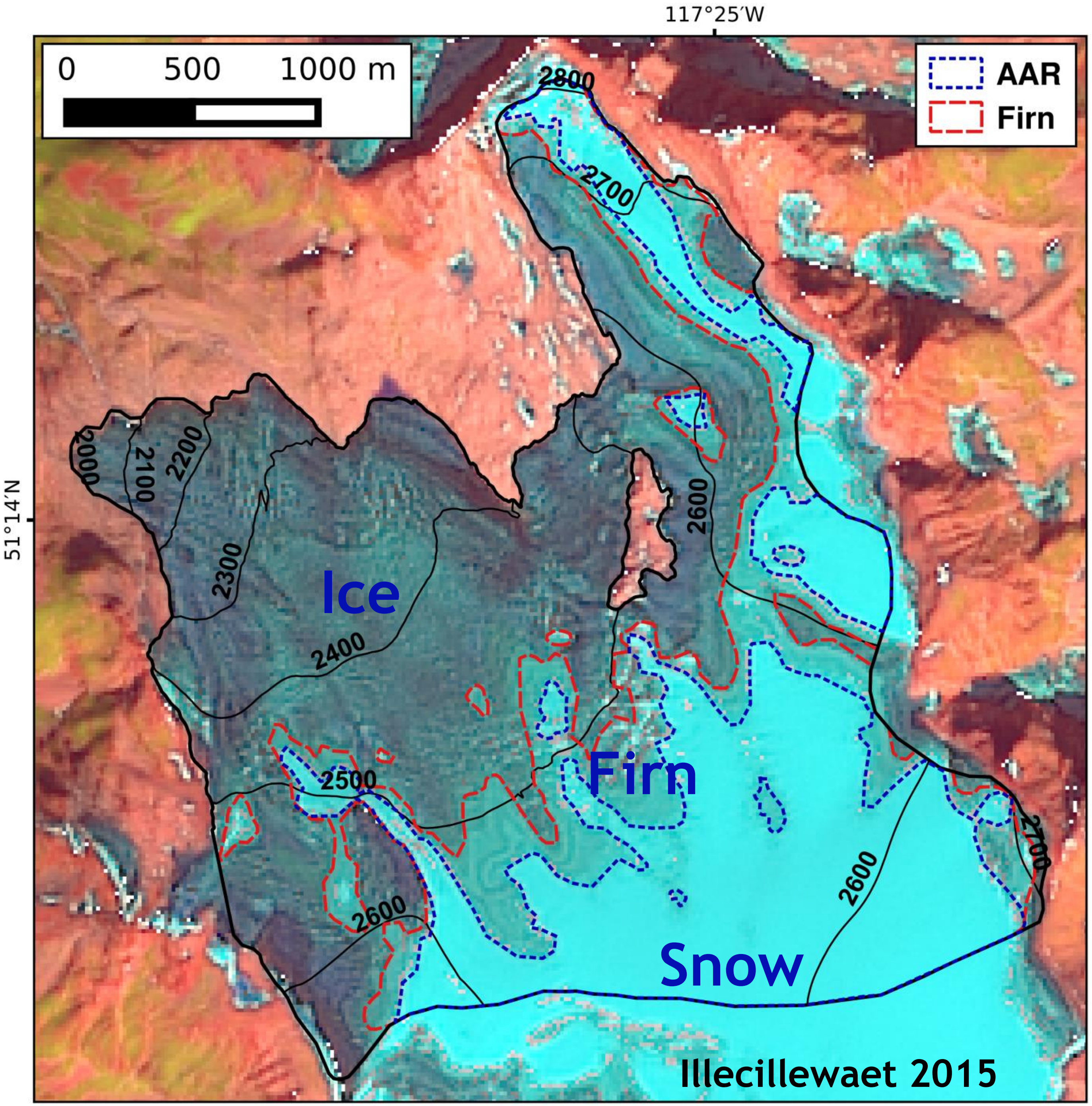


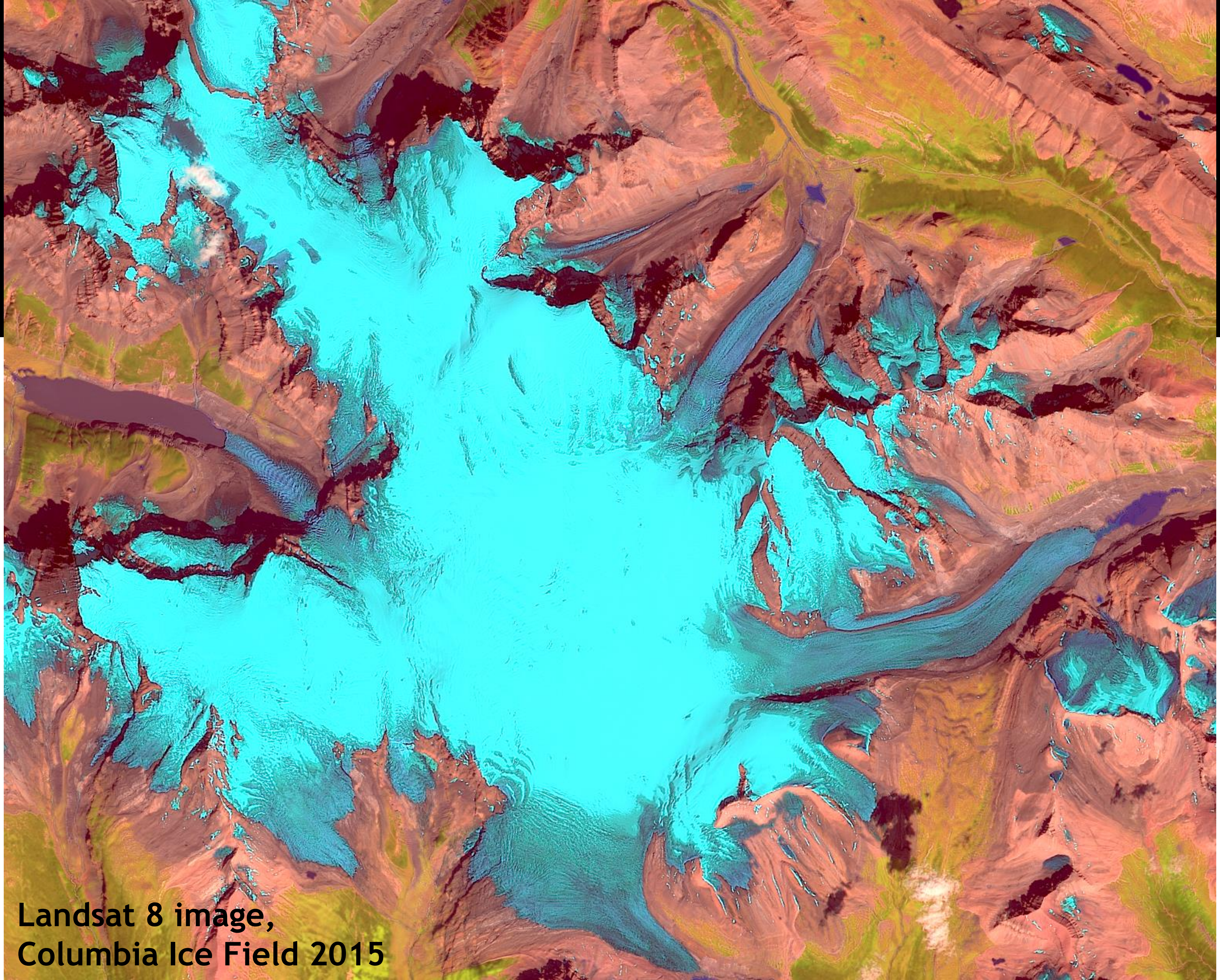
Glacier retreat



https://edu.oggm.org/

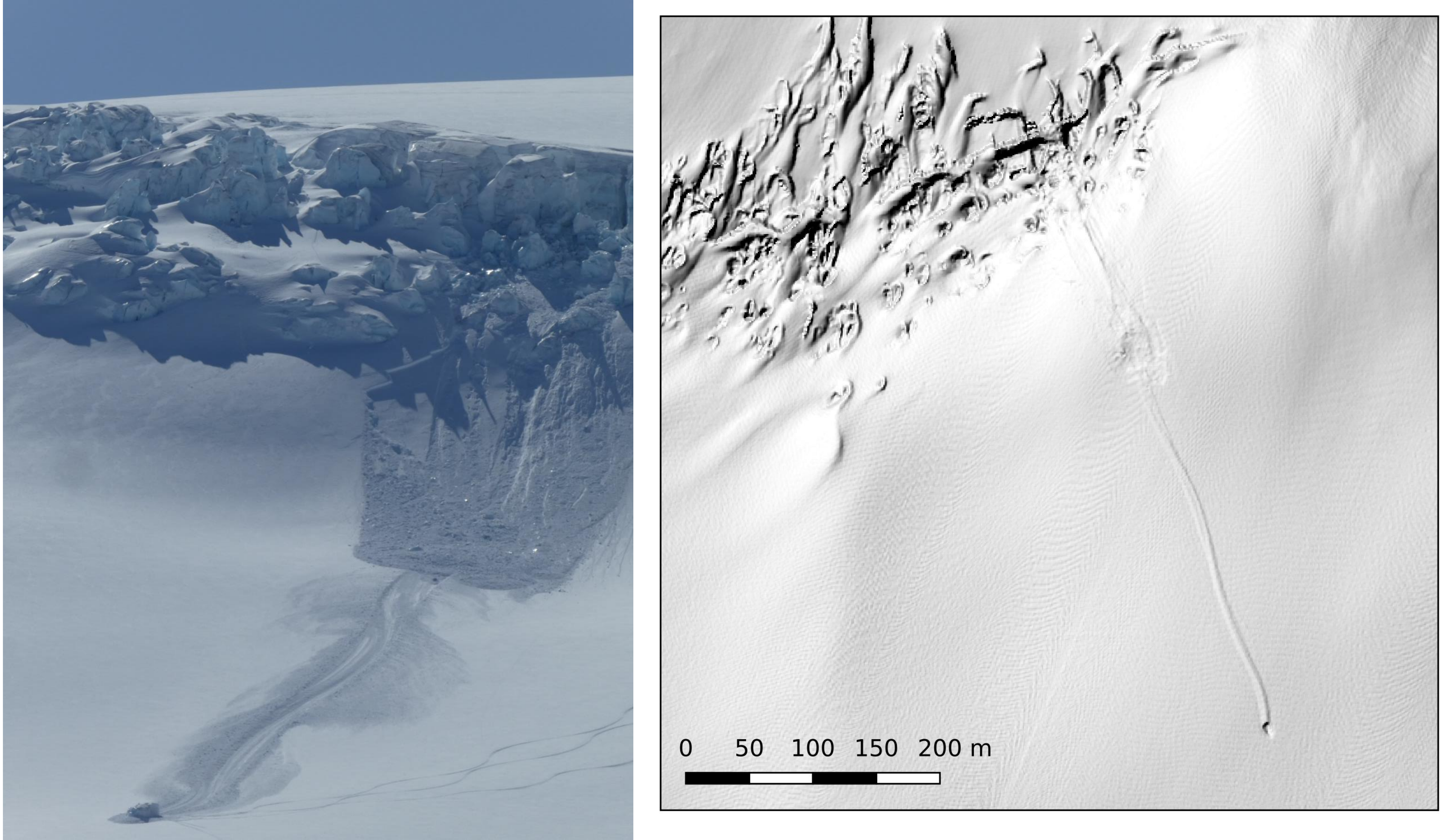
Satellite detection

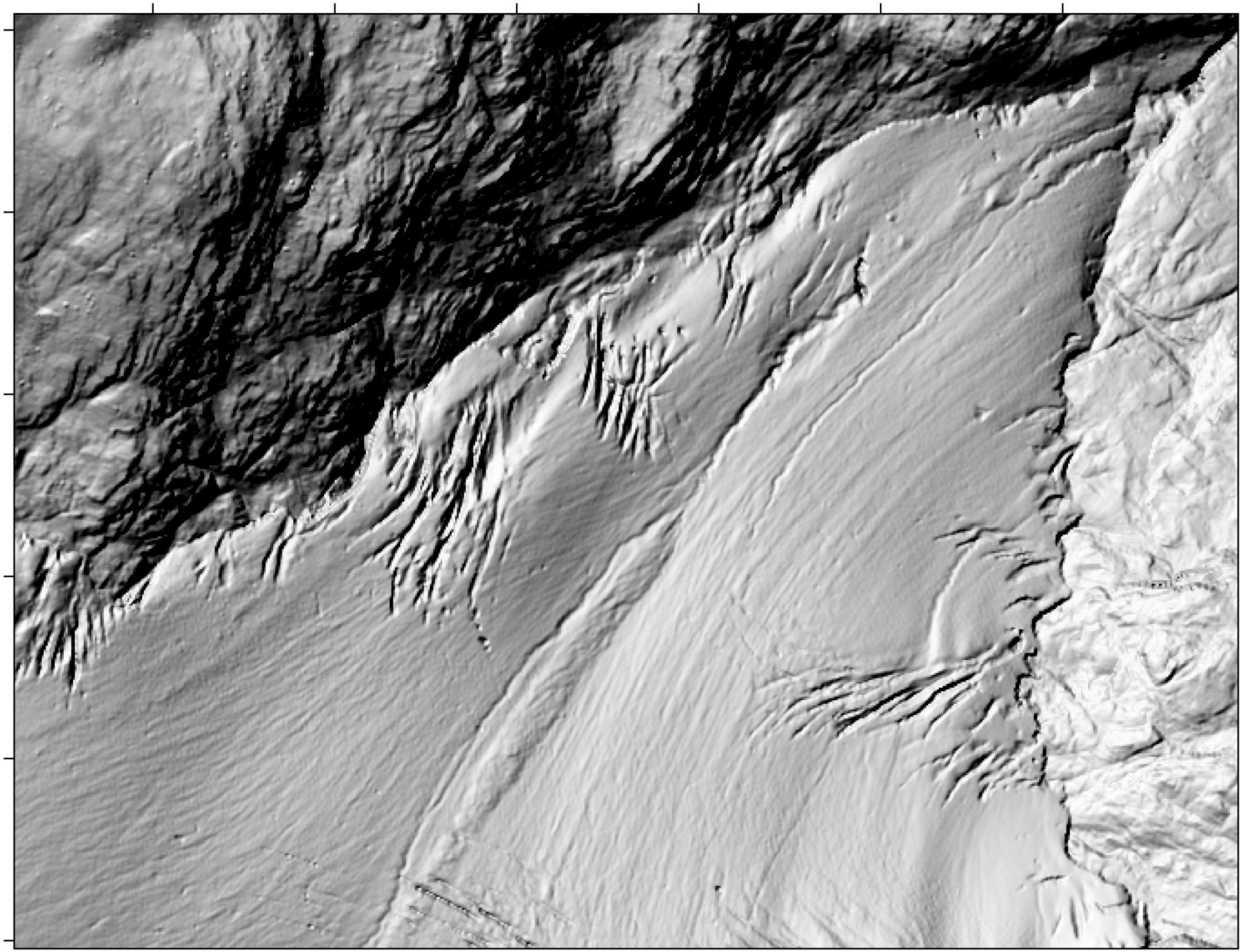


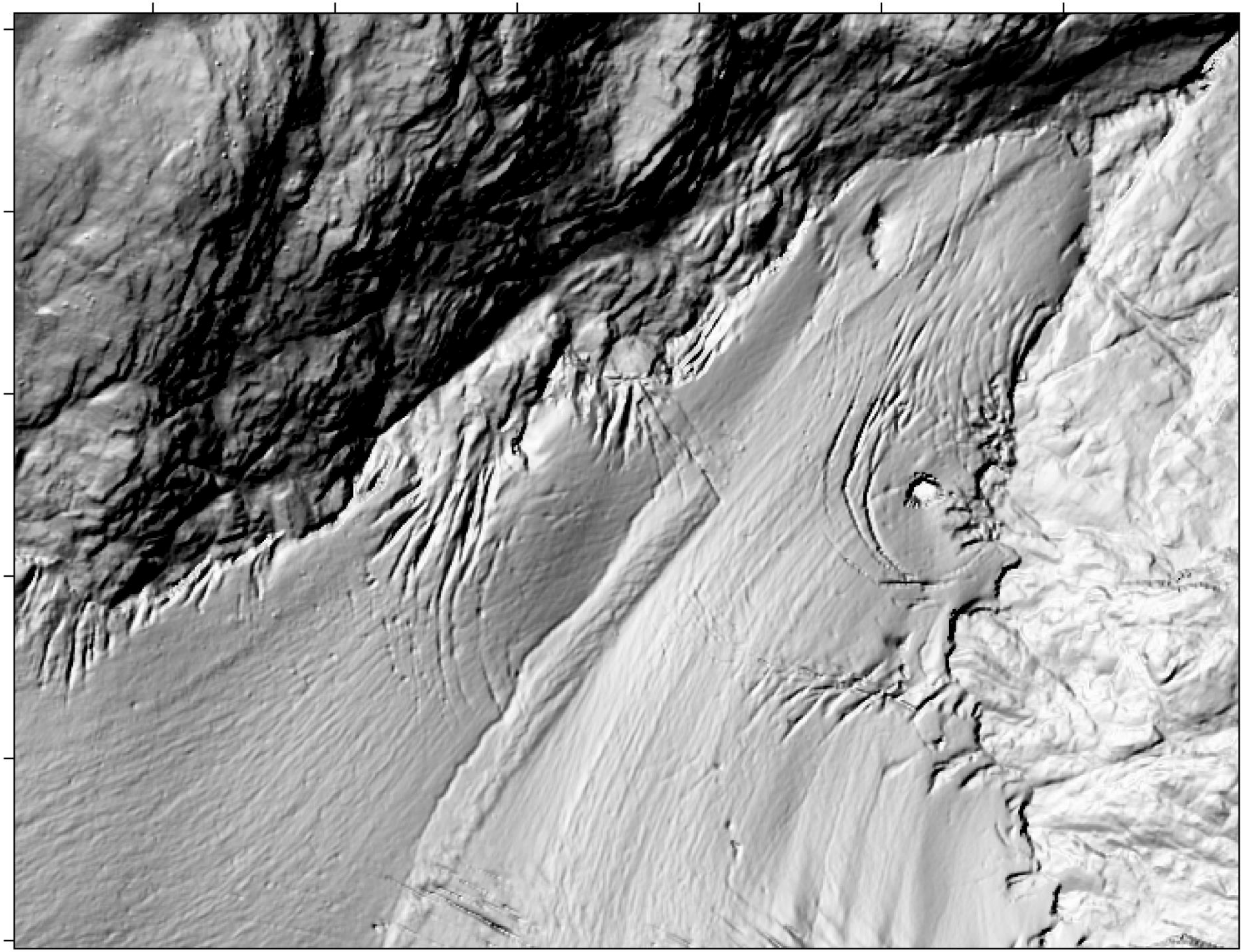

Landsat 8 image,
Columbia Ice Field 2015

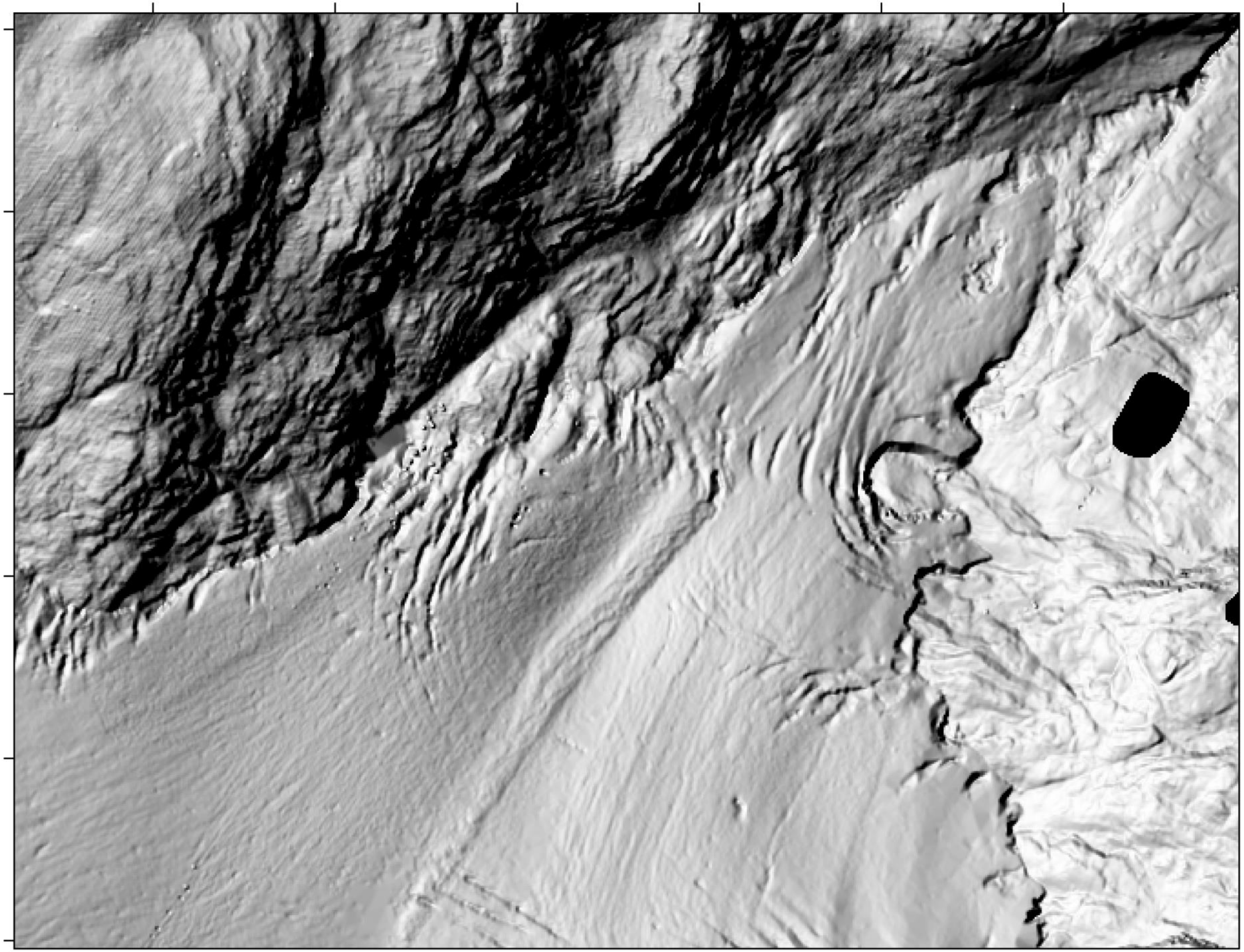
Airborne Laser Scanning (ALS or LiDAR)

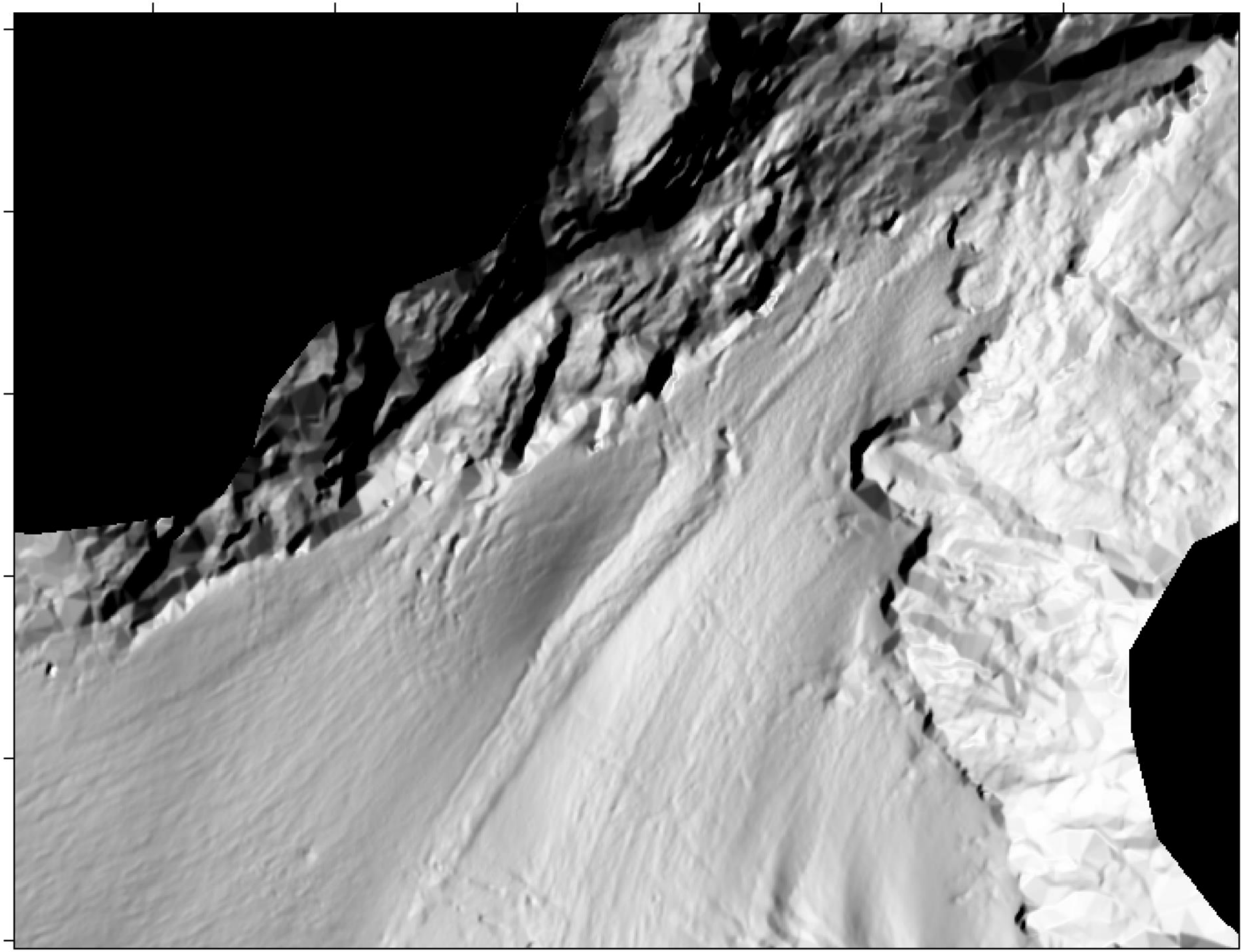
- LiDAR: Light detection and ranging
- Uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth
- Laser scanner (range) + GPS (location)
- Typically around 1-2 laser shots per m^2
- Produce a point cloud of samples (x,y,z)
- DEM is generated from the point cloud

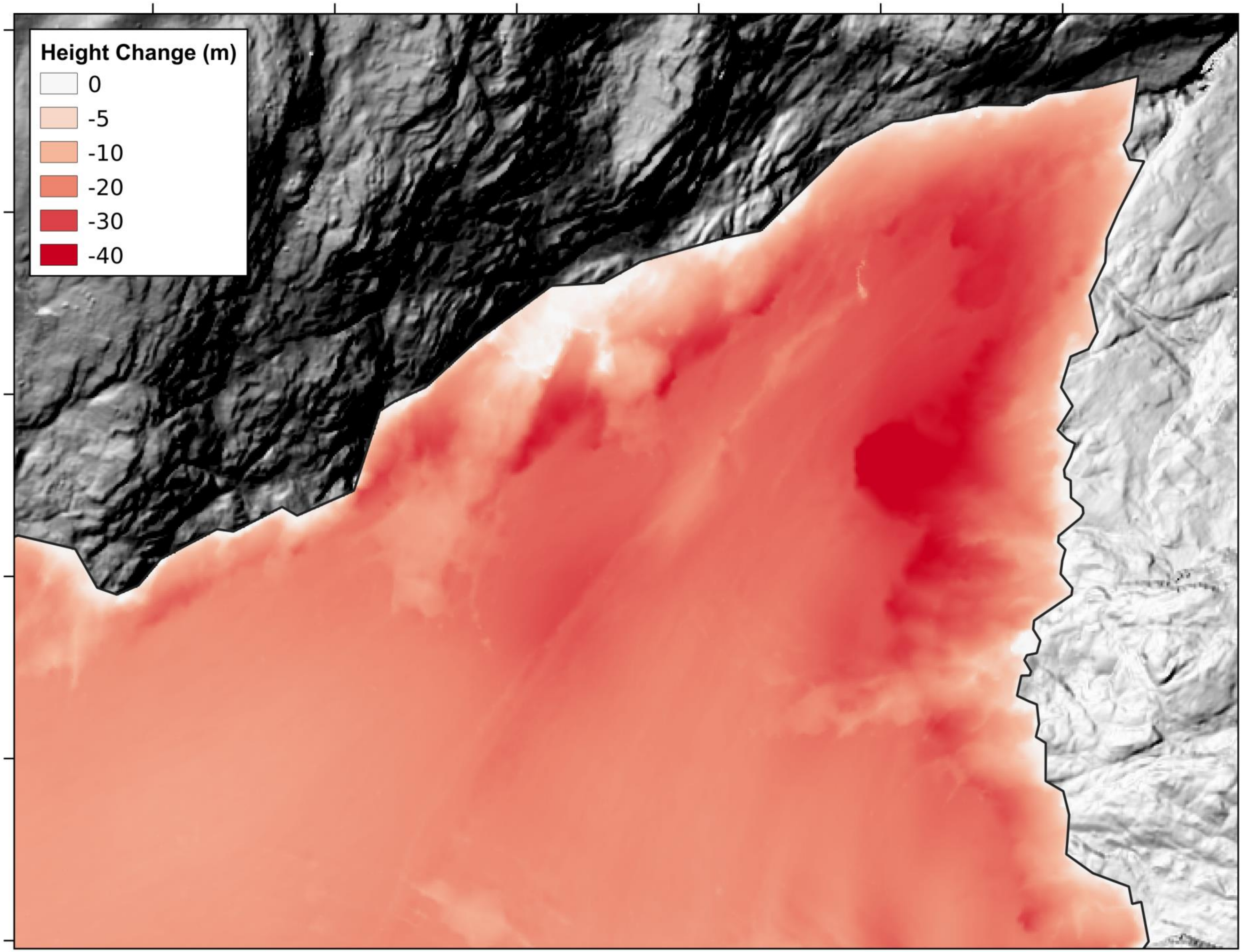

0 50 100 150 200 m

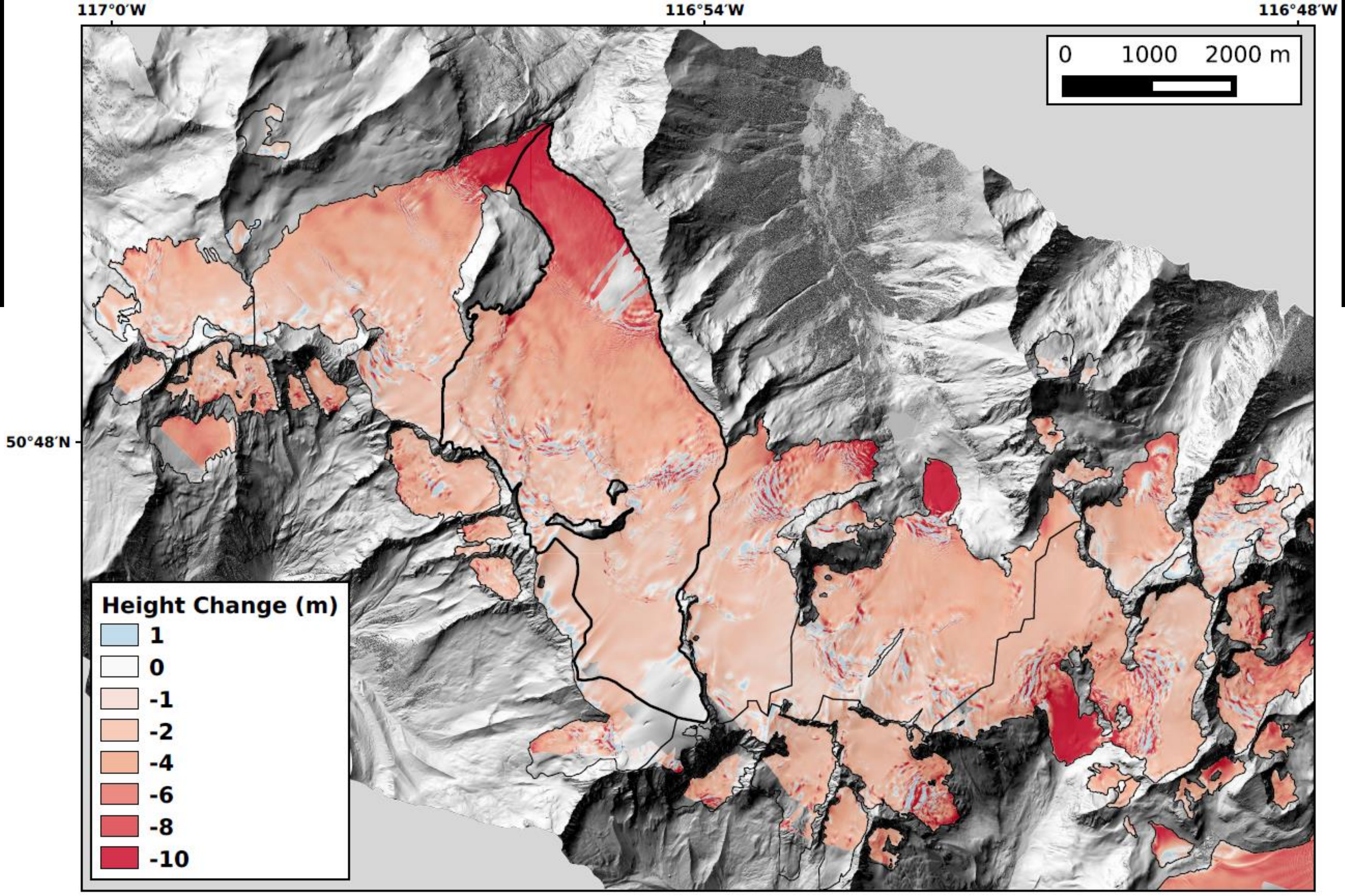






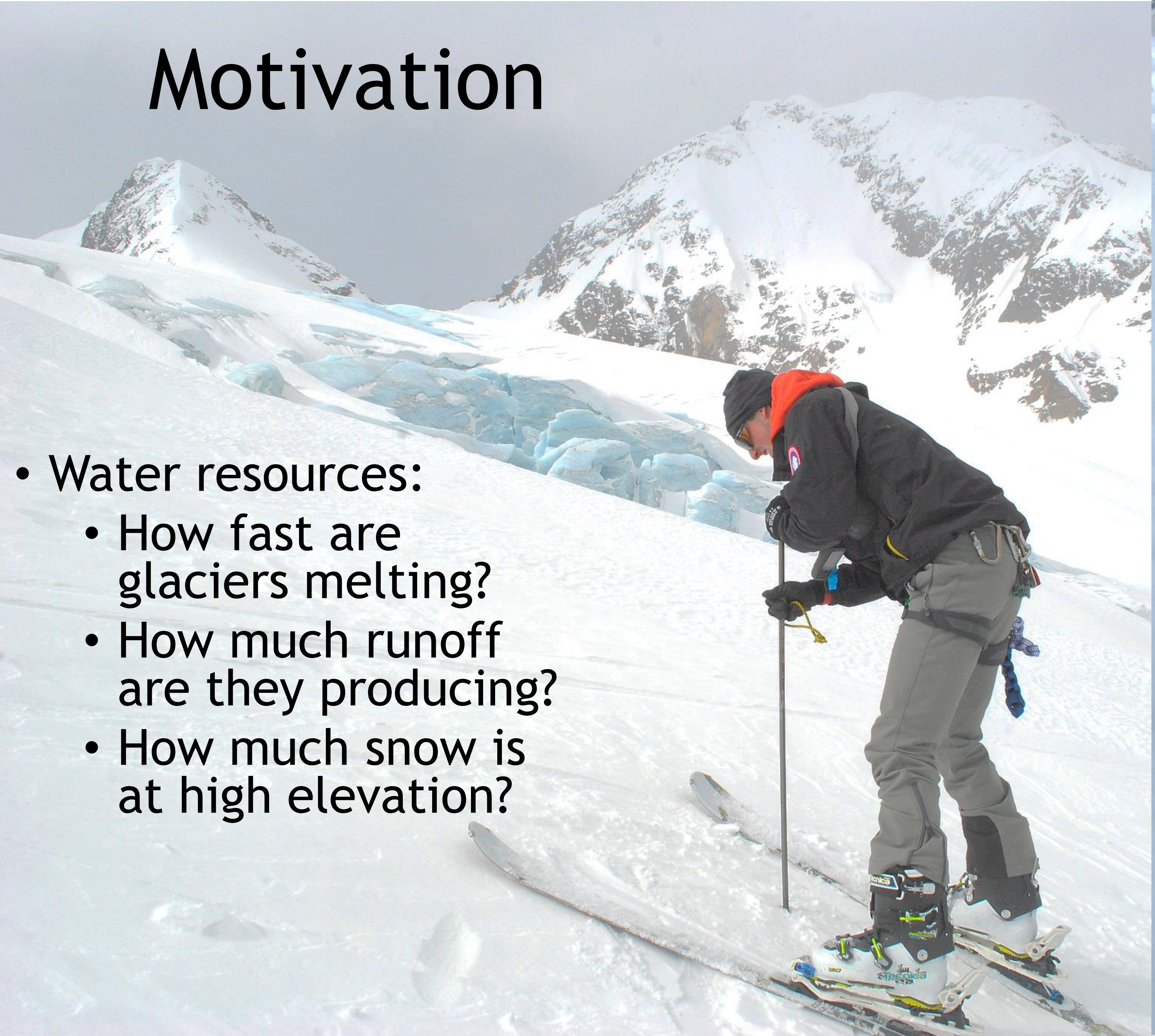



Height Change (m)
0
-5
-10
-20
-30
-40

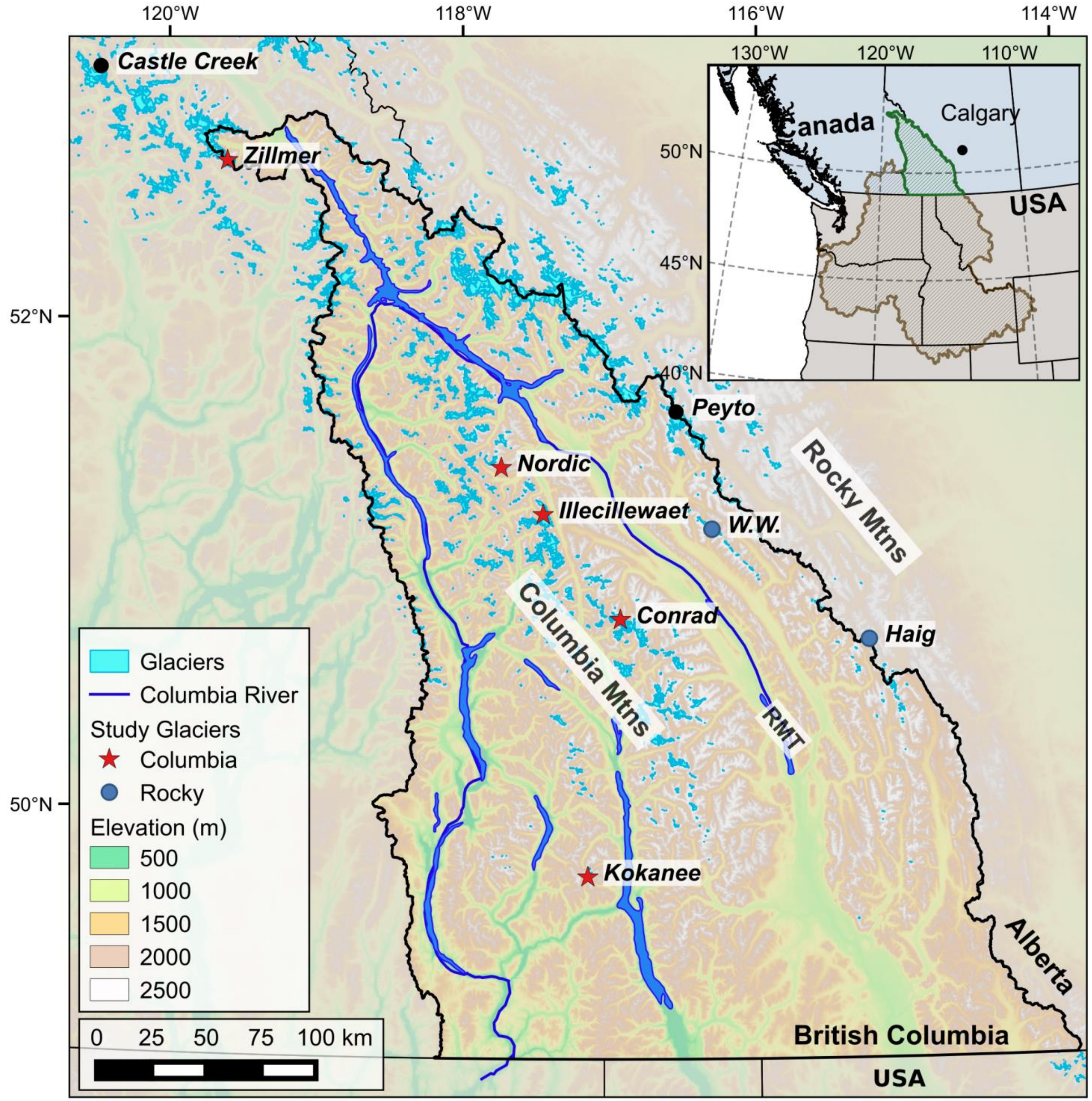

117°0′W
116°54′W
116°48′W
50°48′N
0 1000 2000 m
Height Change (m)
1
0
-1
-2
-4
-6
-8
-10

Motivation

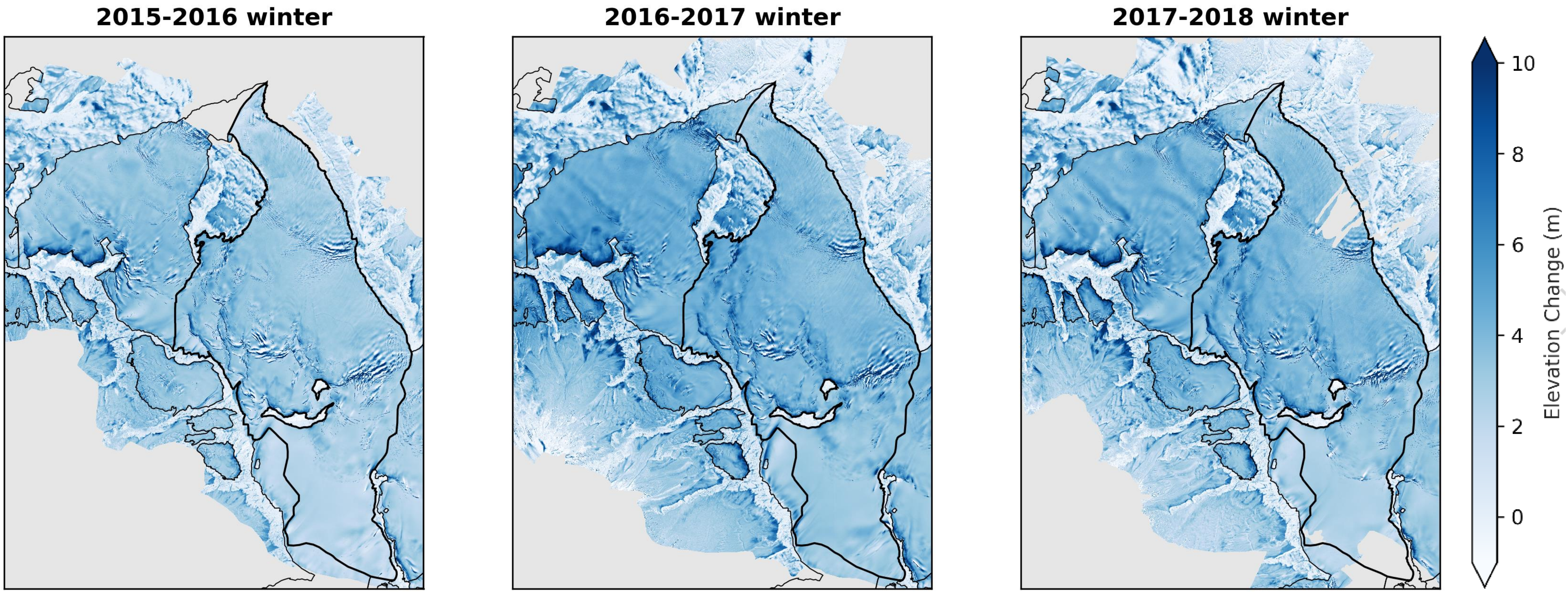
- Water resources:
  - How fast are glaciers melting?
  - How much runoff are they producing?
  - How much snow is at high elevation?

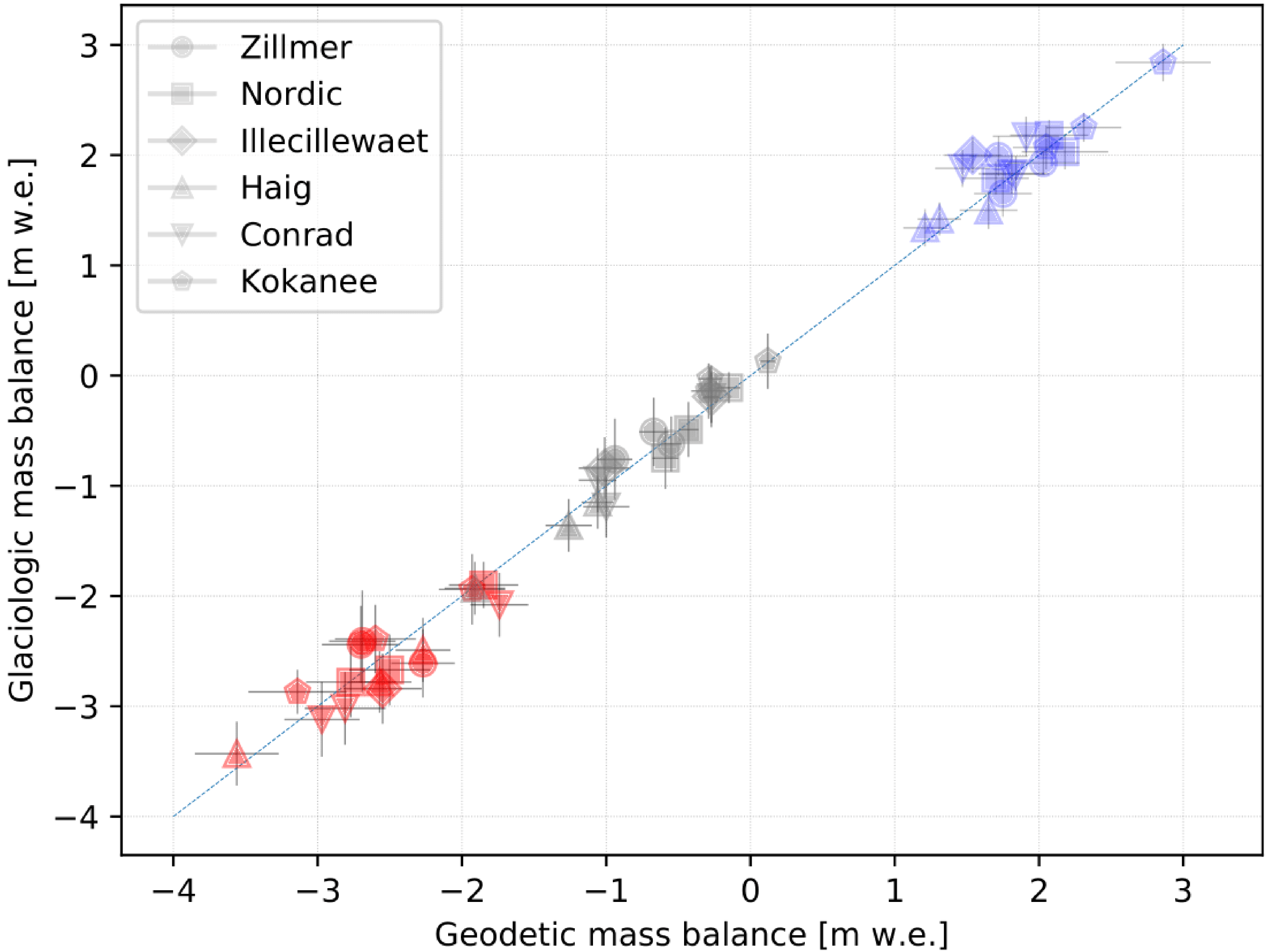


Canadian Columbia River Basin

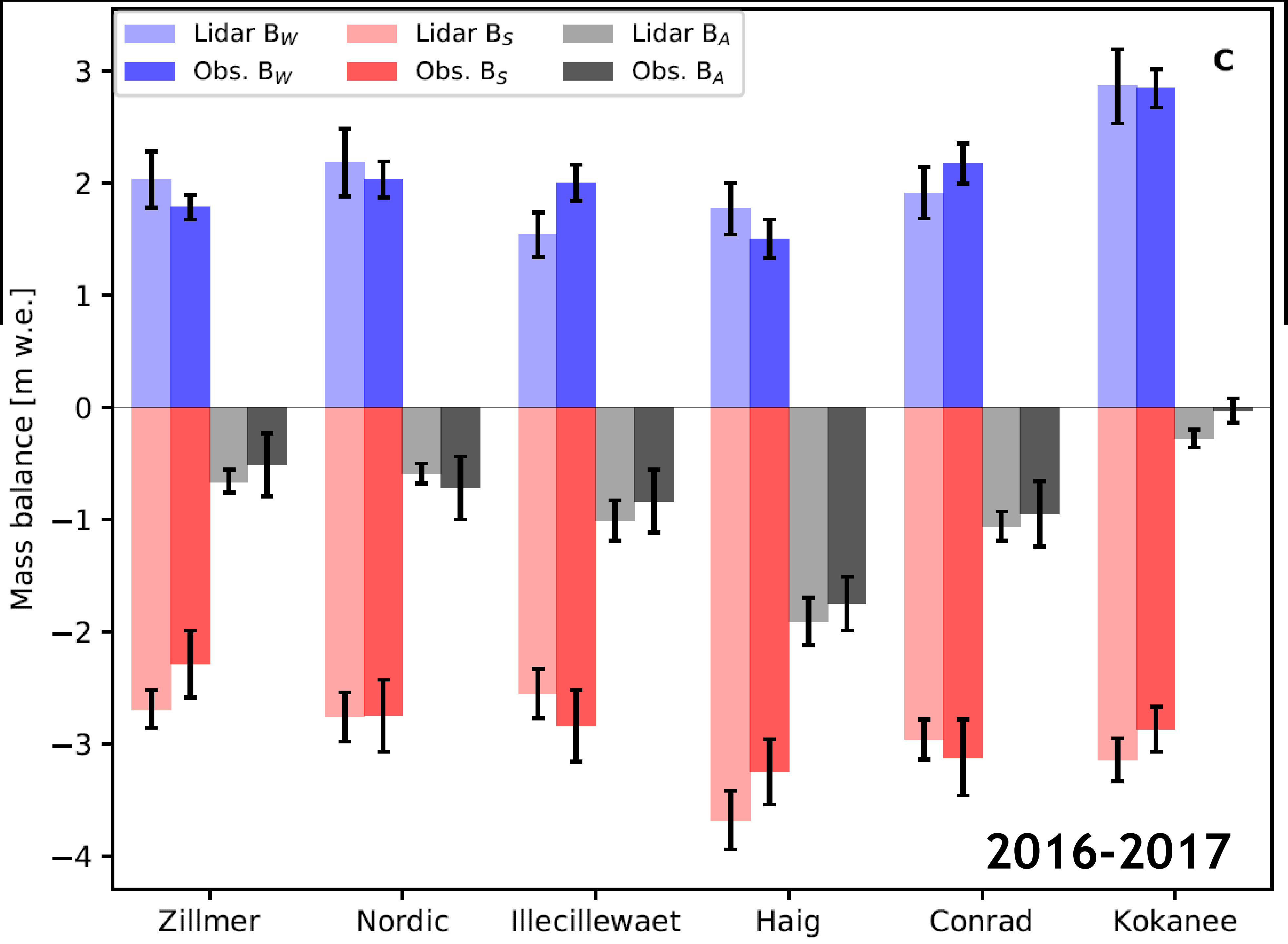


Winter mass balance

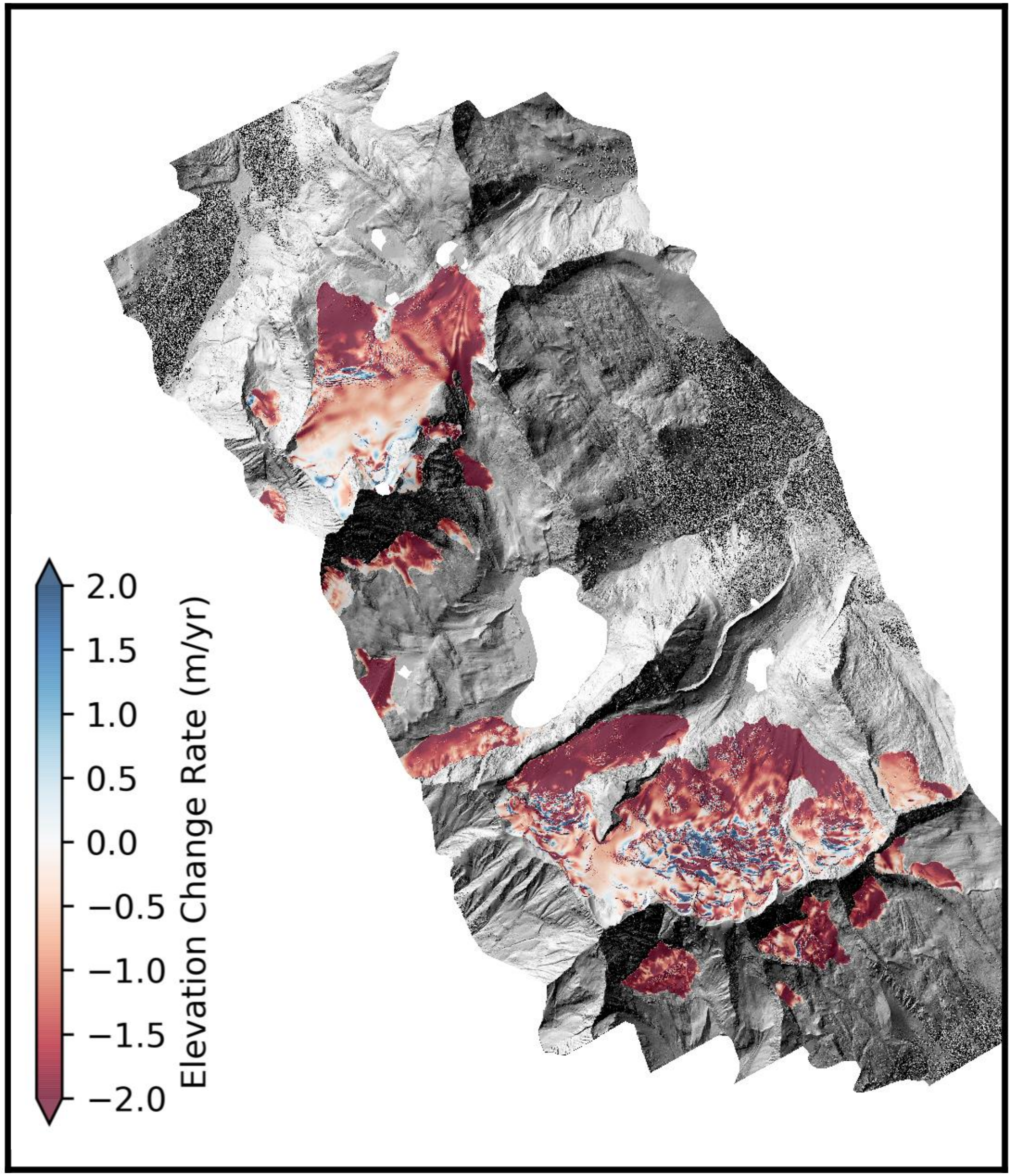


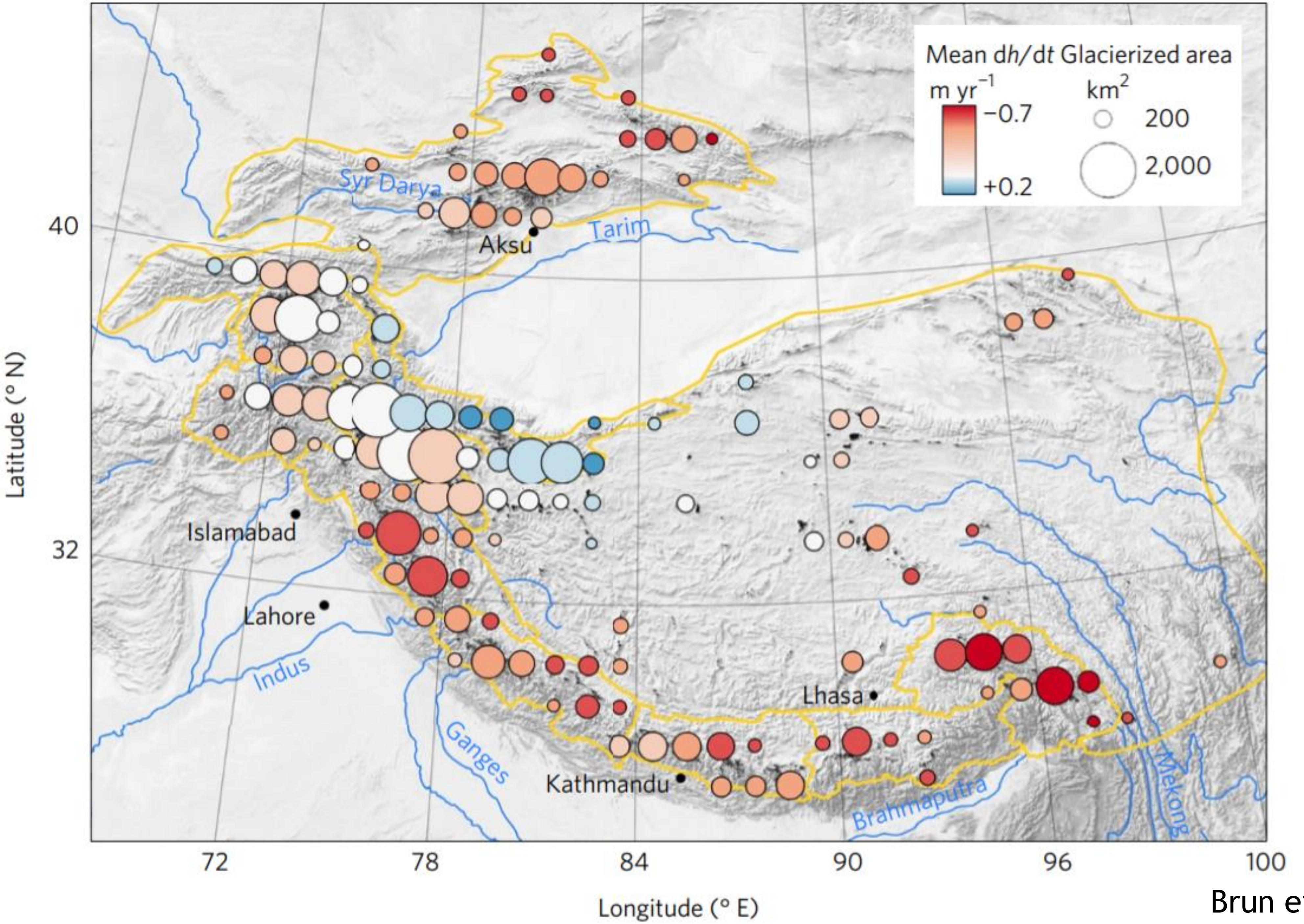


Zillmer
Nordic
Illecillewaet
Haig
Conrad
Kokanee
Glaciologic mass balance [m w.e.]
Geodetic mass balance [m w.e.]
3
2
1
0
−1
−2
−3
−4


Lidar B_W
Obs. B_W
Lidar B_S
Obs. B_S
Lidar B_A
Obs. B_A
c
Mass balance [m w.e.]
3
2
1
0
−1
−2
−3
−4
2016-2017
Zillmer
Nordic
Illecillewaet
Haig
Conrad
Kokanee

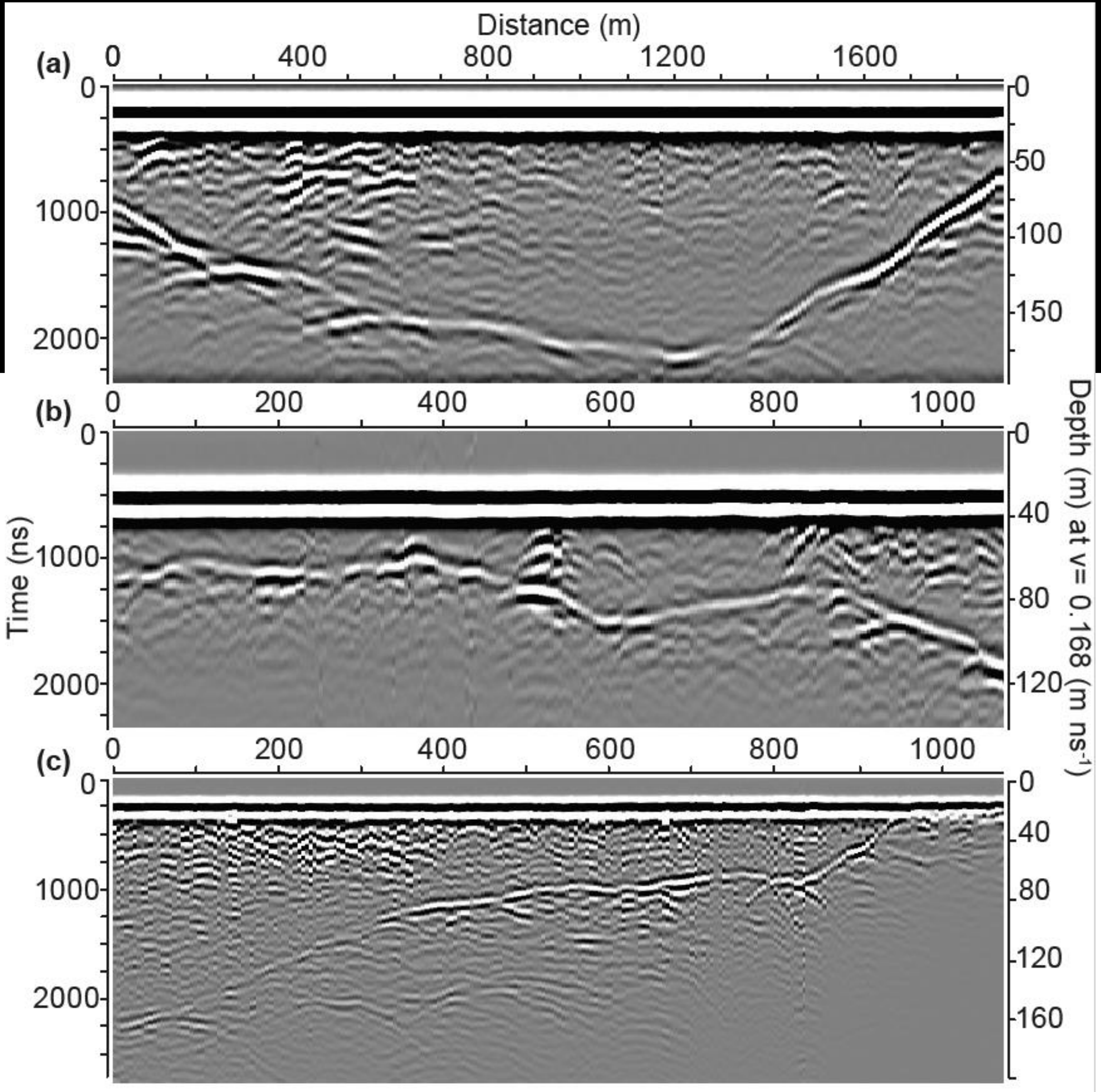
2014 to 2017

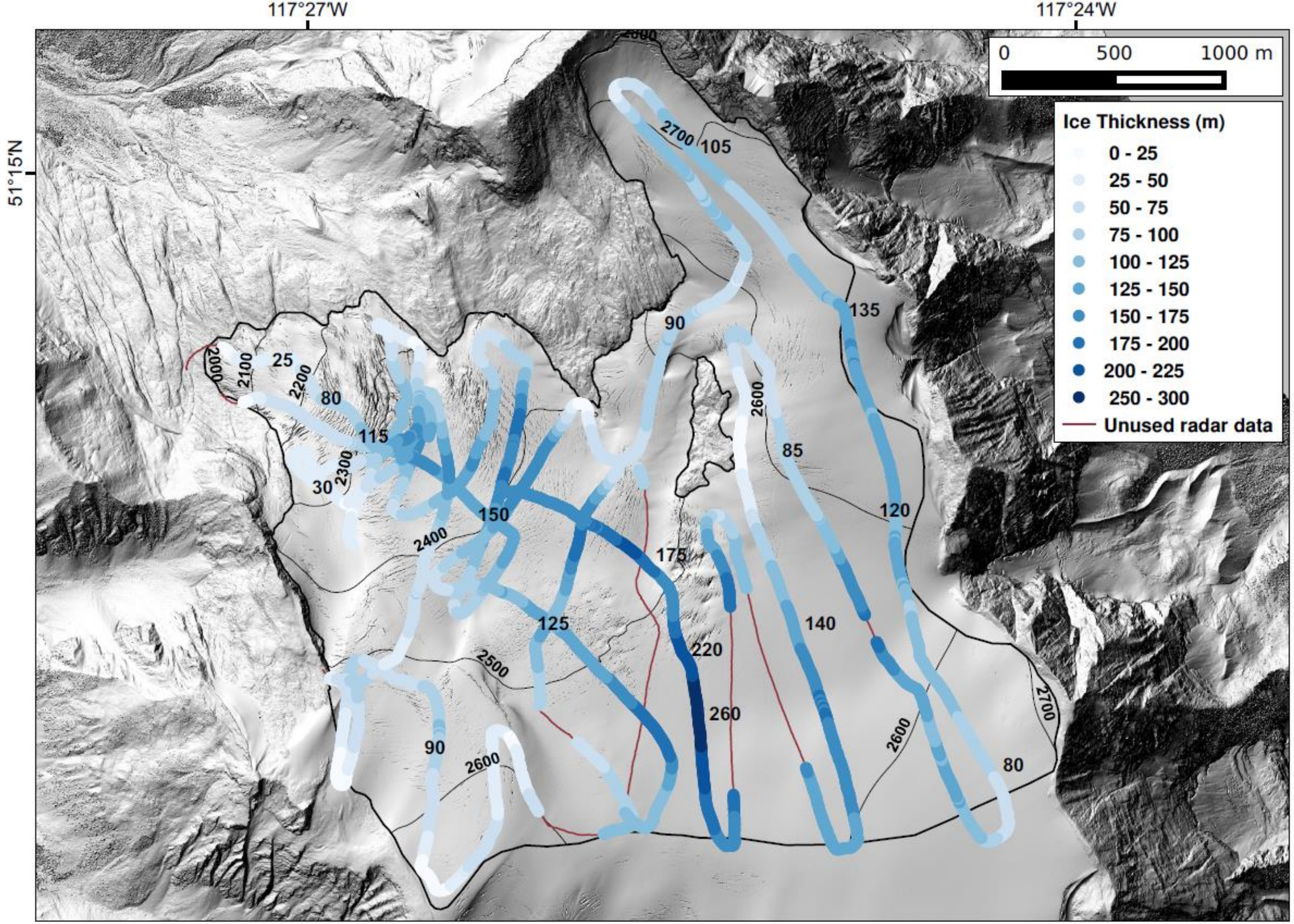


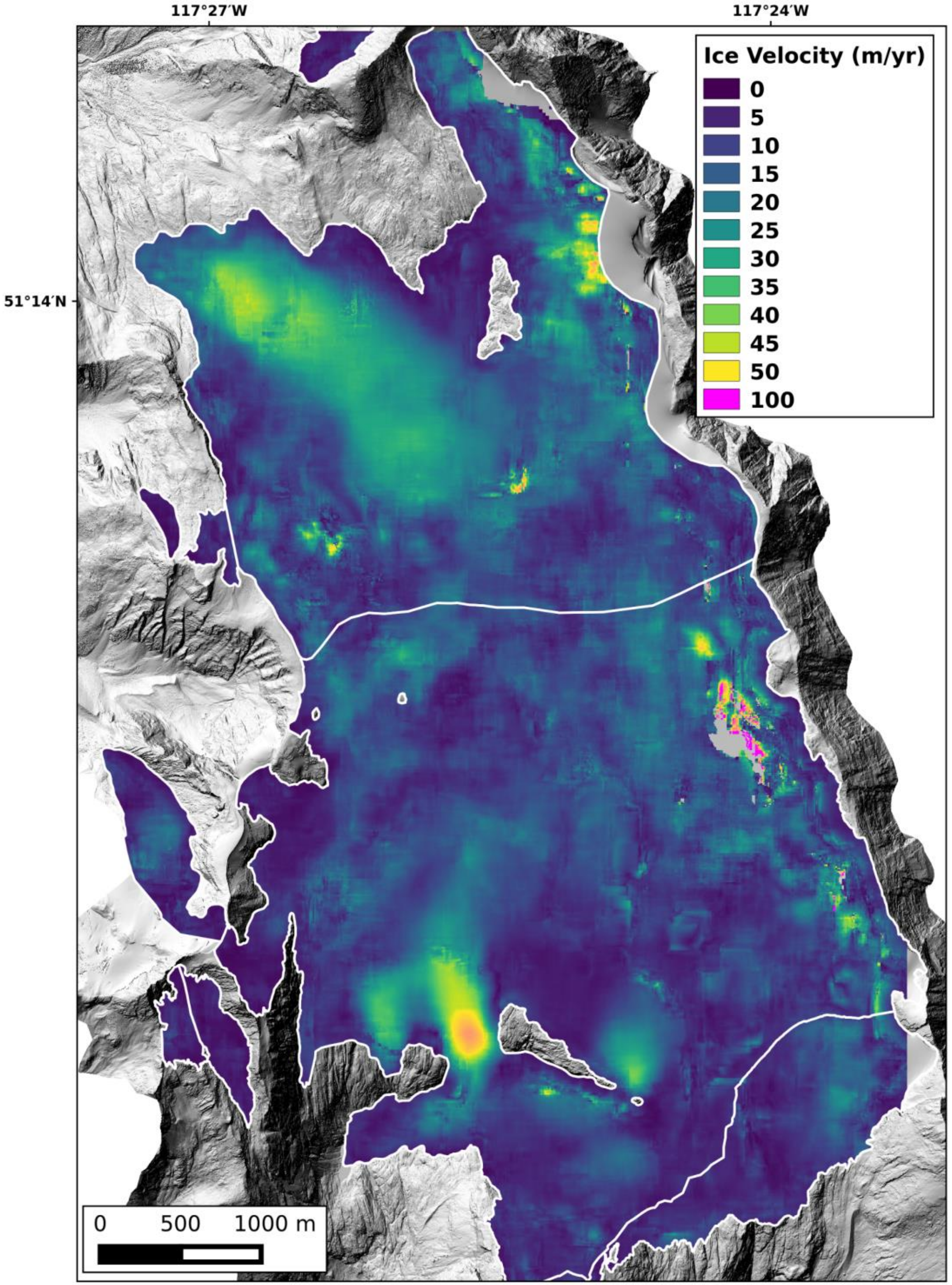


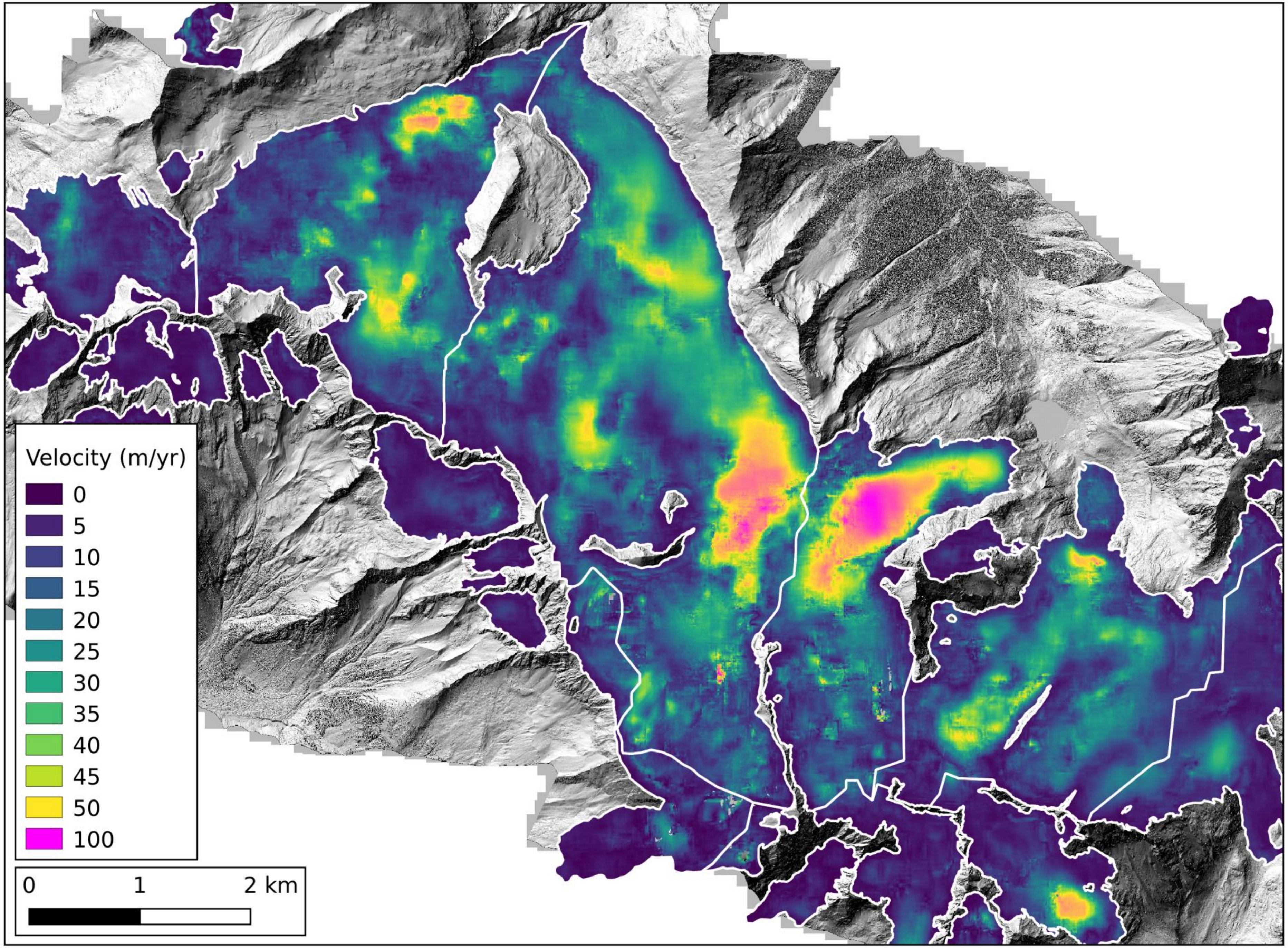
Brun et al. (2017)

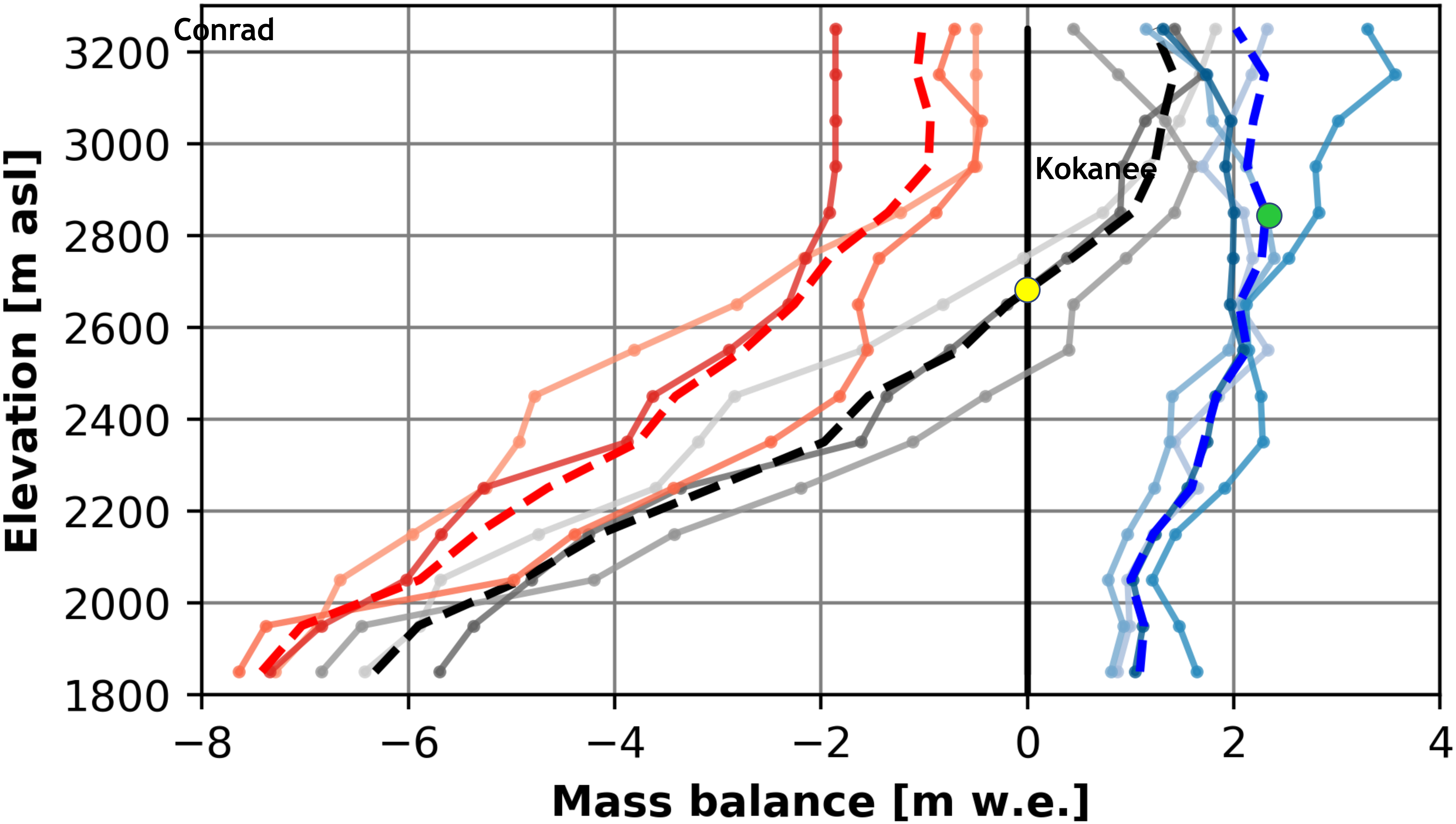
Ice Thickness




117°27'W
117°24'W
51°15'N
0
500
1000 m
Ice Thickness (m)
0 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
150 - 175
175 - 200
200 - 225
250 - 300
Unused radar data
2000
2100
2200
2300
2400
2500
2600
2700
25
80
115
30
150
90
105
135
85
120
175
140
125
220
260
80


117°27′W
117°24′W
51°14′N
Ice Velocity (m/yr)
0
5
10
15
20
25
30
35
40
45
50
100
0
500
1000 m


Velocity (m/yr)
0
5
10
15
20
25
30
35
40
45
50
100
0
1
2 km



Conrad
Kokanee
3200
3000
2800
2600
2400
2200
2000
1800
Elevation [m asl]
−8
−6
−4
−2
0
2
4
Mass balance [m w.e.]

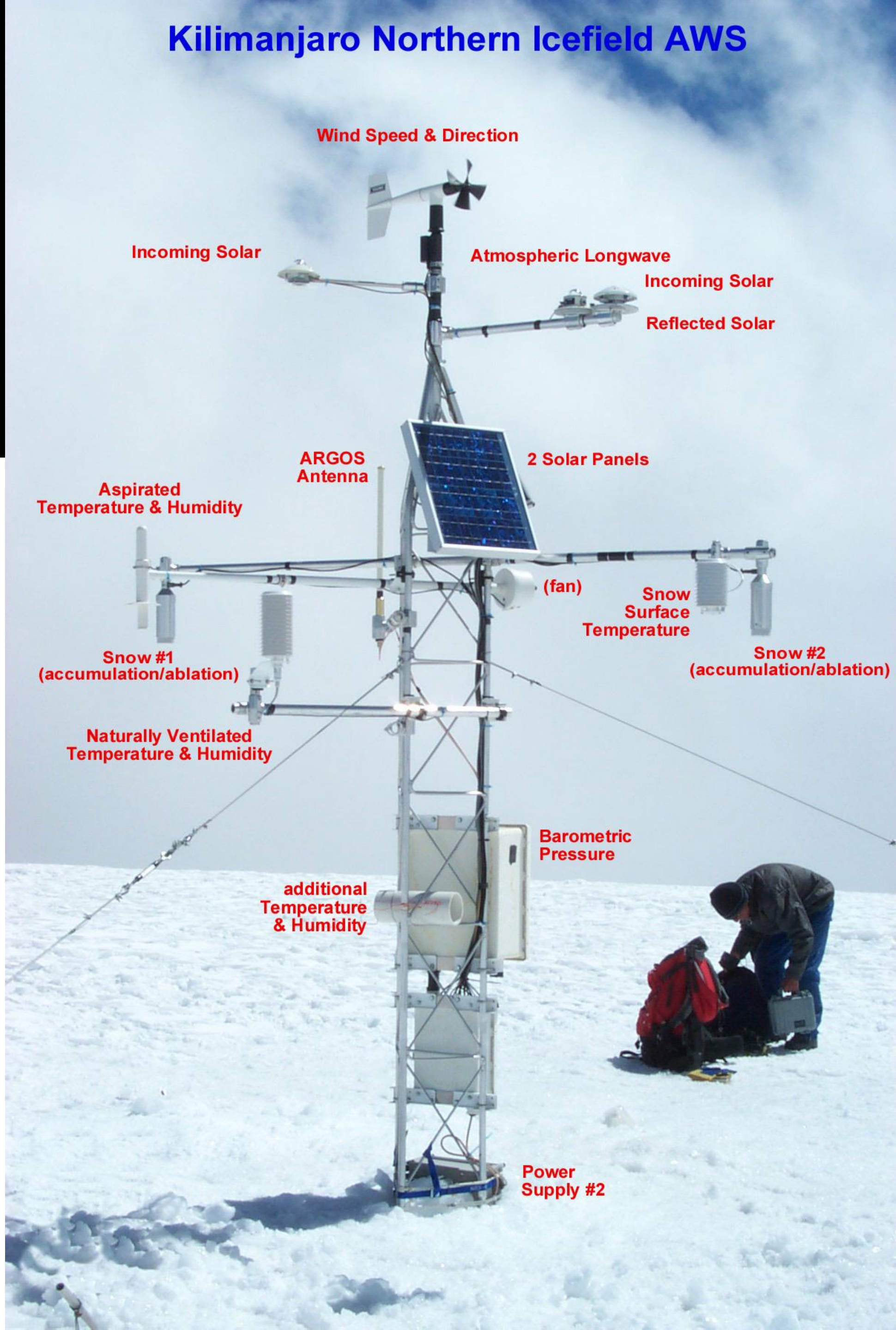
Surface energy balance

$$S_i + S_r + L_i + L_o + Q_H + Q_L + Q_R + Q_G = Q_M$$

- Q_M (energy available for melting)
- Incoming shortwave (S_i)
- reflected shortwave (S_r)
- incoming longwave (L_i)
- Outgoing longwave (L_o)
- Turbulent fluxes of sensible and latent heat (Q_H and Q_L)
- Rain heat flux (Q_R)
- Ground heat flux (Q_G).

Surface energy balance

$$S_i + S_r + L_i + L_o + Q_H + Q_L + Q_R + Q_G = Q_M$$



Degree day models

Melt is a function of temperature!

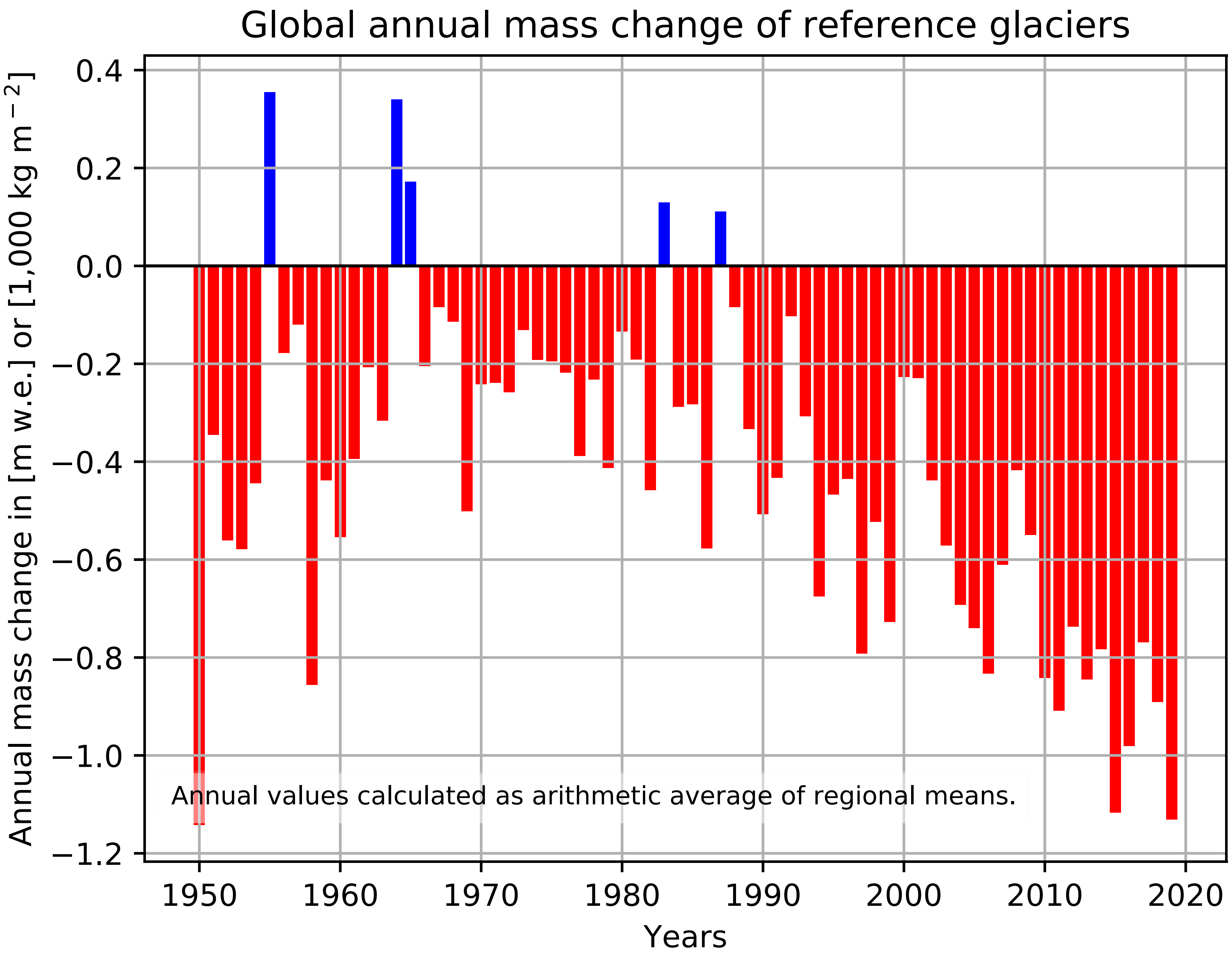
- Technique using air temperature to estimate the amount of melt on a glacier.
- Assume an empirical relationship between melt rates and air temperatures (Positive Degree Days), and this empirical relationship (the Degree Day Factor) varies from glacier to glacier.
- Work well because air temperature data are readily available, and they perform well despite their simplicity.

Degree day models

Melt is a function of temperature!

$$M = K_I\, PDD + K_S\, PDD$$

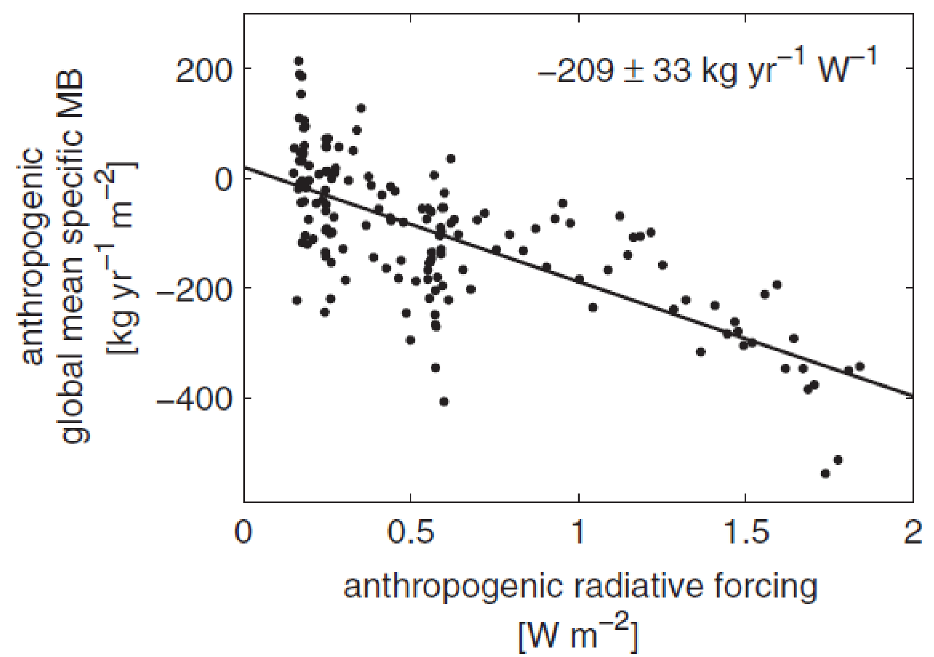
Parameter	Symbol	Units
Melt (depth of snow melted)	M	mm w.e.
Positive degree day sum per year	PDD	°C a^{-1}
Degree day factor	K_I and K_S (for ice and snow)	mm w.e. d^{-1} °C^{-1}



https://wgms.ch/

Anthropogenic glacier mass loss

- From **1851 to 2010**, only **25 ± 35%** of the global glacier mass loss during the period is attributable to anthropogenic causes.
- From **1991 to 2010**, the anthropogenic fraction increased to **69 ± 24%.**



Marzeion et al. (2014)

Hands on Glacier Modeling

https://edu.oggm.org/en/latest/

What else would you like to know?

References

- Brun, F., Berthier, E., Wagnon, P., Kääb, A., & Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000-2016. *Nature Geoscience*, *10*(9), 668–673. https://doi.org/10.1038/NGEO2999
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- Pelto, B. M., Menounos, B., and Marshall, S. J.: Multi-year evaluation of airborne geodetic surveys to estimate seasonal mass balance, Columbia and Rocky Mountains, Canada, The Cryosphere, 13, 1709–1727, https://doi.org/10.5194/tc-13-1709-2019, 2019.
- Surface energy balance: Fitzpatrick, Noel, Valentina Radić, and Brian Menounos. "Surface energy balance closure and turbulent flux parameterization on a mid-latitude mountain glacier, Purcell mountains, Canada." *Frontiers in Earth Science* 5 (2017): 67.
- World Glacier Monitoring Service, https://wgms.ch/