Glaciology
EESCGU4220

Lecture 4: Ablation

Calving

Sub-shelf melting

Surface energy balance
- components
- controls
- how it relates to SMB

Discretization and regional climate modelling (prep. for the practical on Thursday).

Firn densification processes

Its complicated!

Settling

movement of grains relative to each outer increases density up to ~550 kg m^{-3}

Sublimation

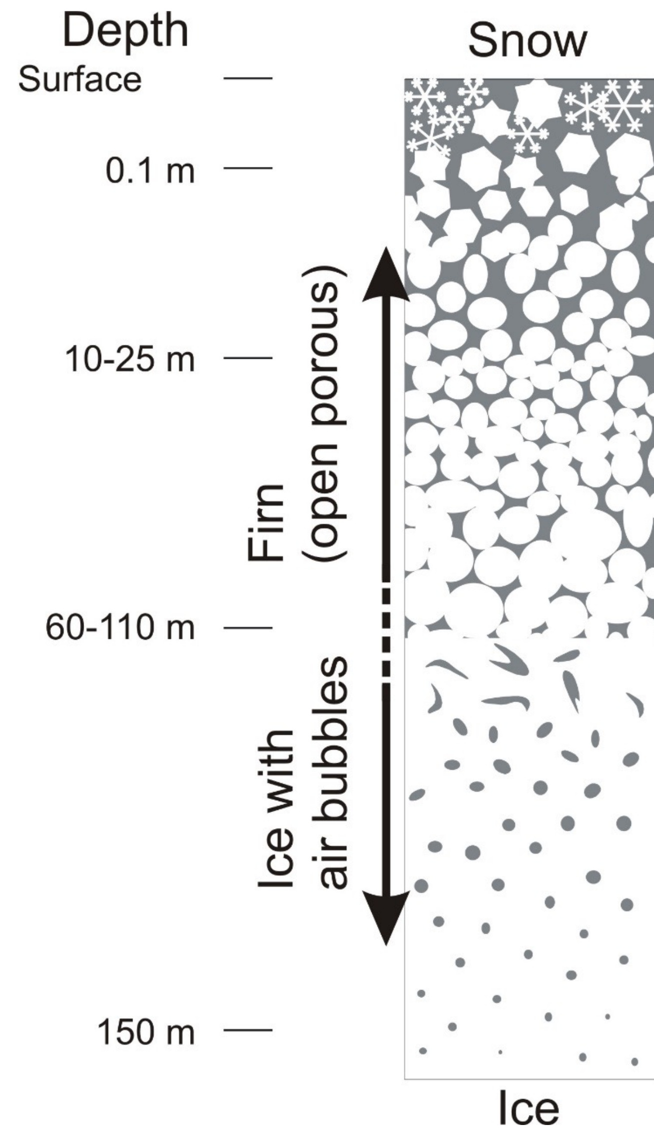
>550 kg m^{-3},
movement of molecules to 'necks' of grains due to vapour-pressure gradients in pores.

Deformation of grains

Through diffusion creep (more details next week)

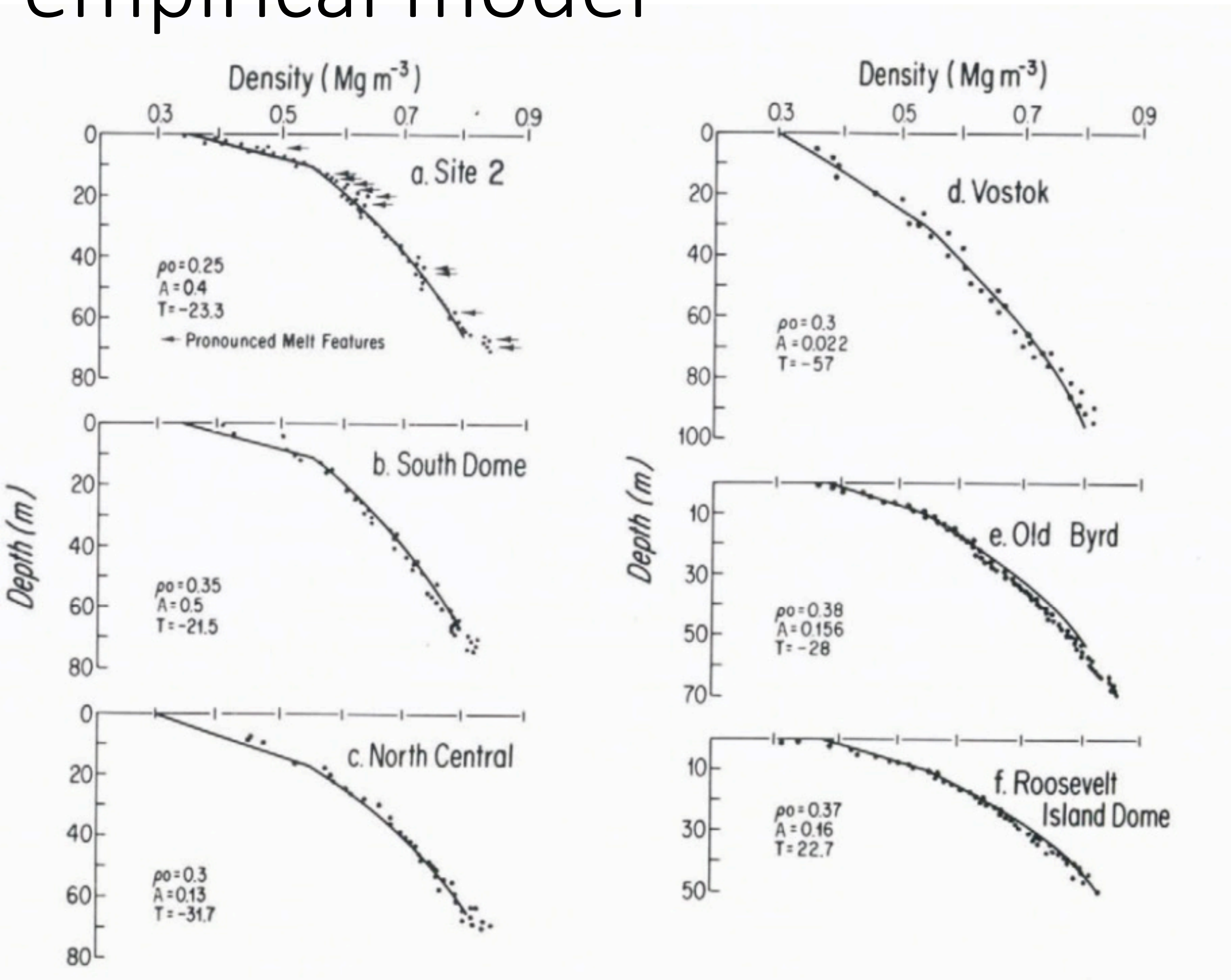
At ~830 kg m^{-3} pores "close off" and firn becomes ice.

Compression of air in bubbles allows ice density to reach ~917 kg m^{-3}.



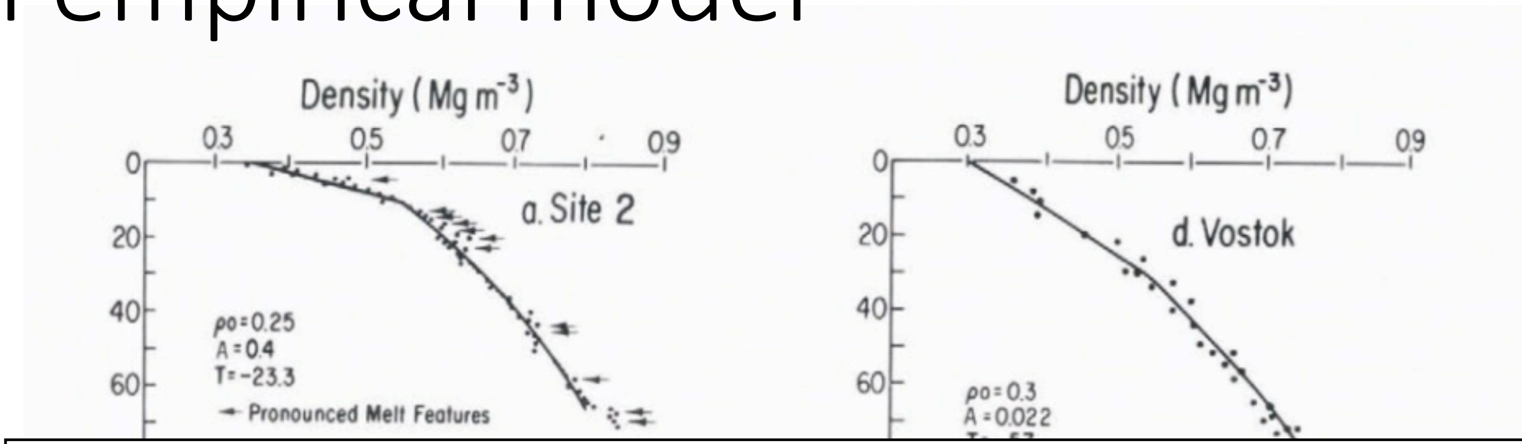
University of Copenhagen, Center for Ice and Climate

An empirical model



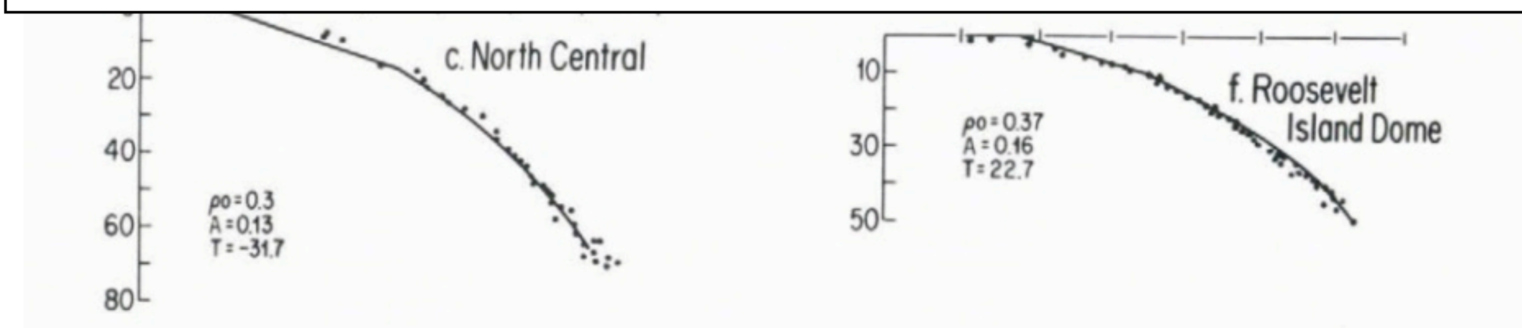
Herron and Langway (1980)

An empirical model



Seems to work, but very little physics in there and it needs tuning each time!

Not very useful for prediction.

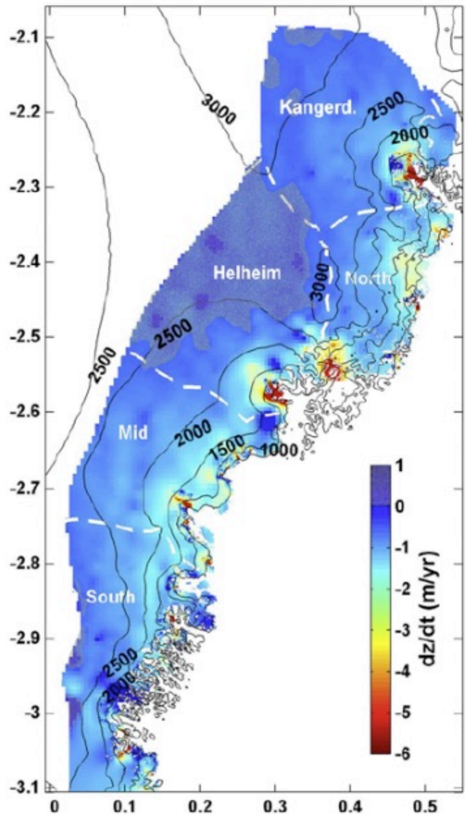


Herron and Langway (1980)

Why is getting this right important?

1. Geodetic mass balance

Howat et al. (2008)



2. Ice core paleo-climate records

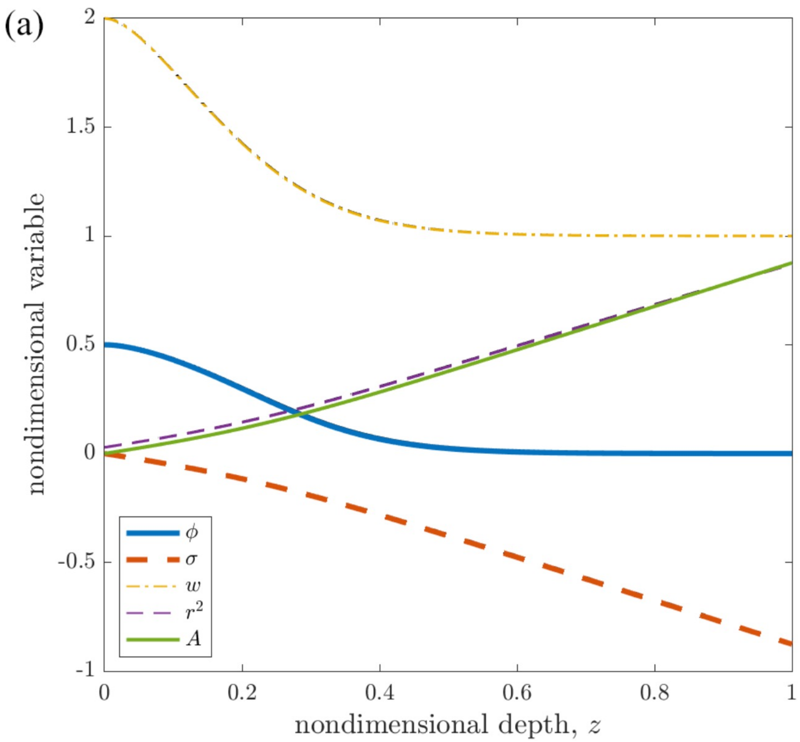
Ice cores preserve old ice and old air.

The ice is older than the air by an amount that depends on firn densification rates.

Grain-size evolution controls the accumulation dependence of modelled firn thickness

Jonathan Kingslake, Robert Skarbek, Elizabeth Case, and Christine McCarthy

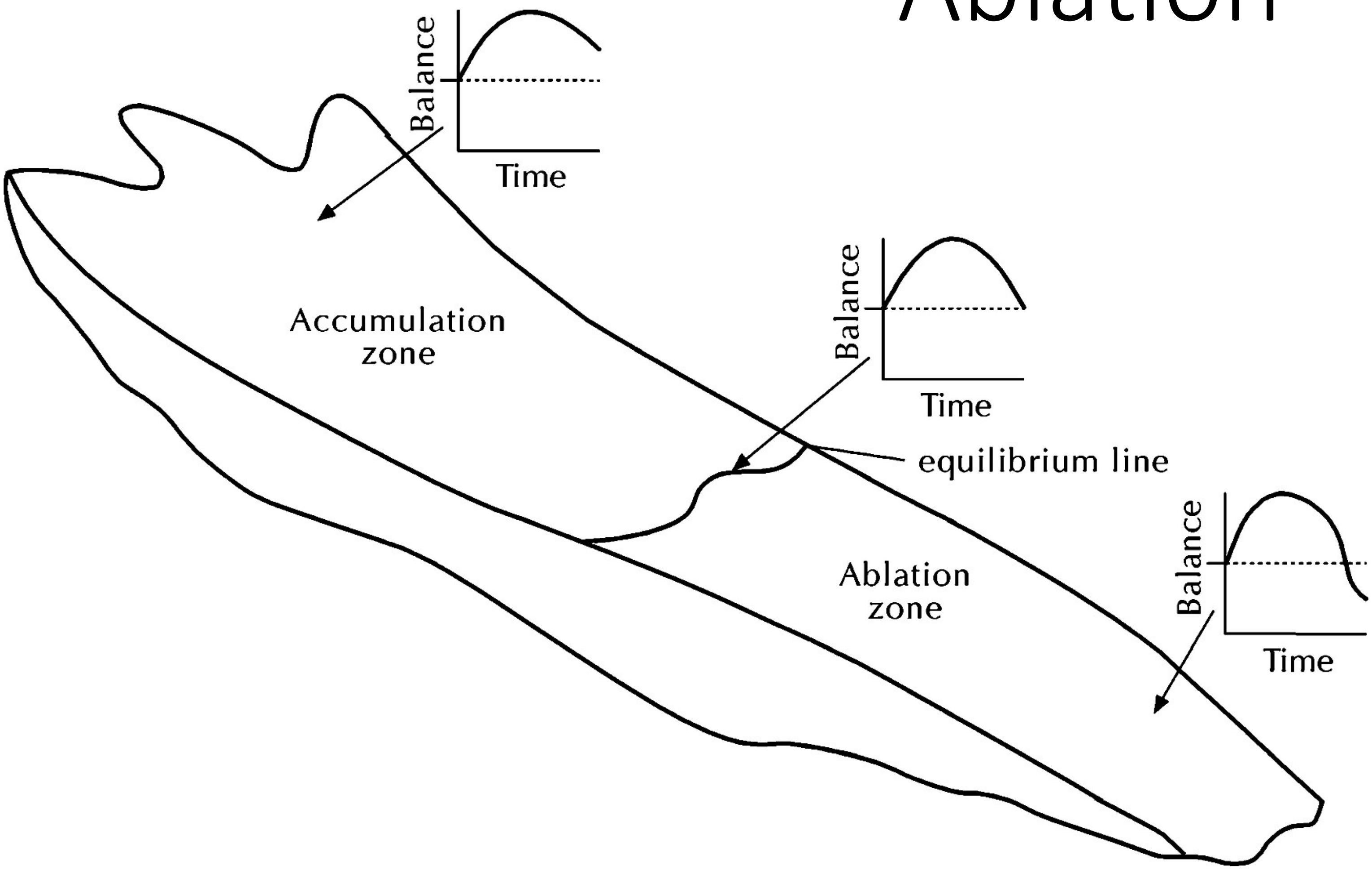
Lamont-Doherty Earth Observatory, Department of Earth and Environmental Science, Columbia University, New York, NY 10027, USA



$$\frac{\partial \sigma}{\partial z} = -\rho_{\mathrm{i}} g (1 - \phi),$$
$$\sigma(0) = 0,$$

The Cryosphere, 16, 3413–3430, 2022
https://doi.org/10.5194/tc-16-3413-2022

Ablation



Balance
Time
Accumulation zone
Balance
Time
equilibrium line
Balance
Time
Ablation zone

Ablating surfaces: 1. Calving front

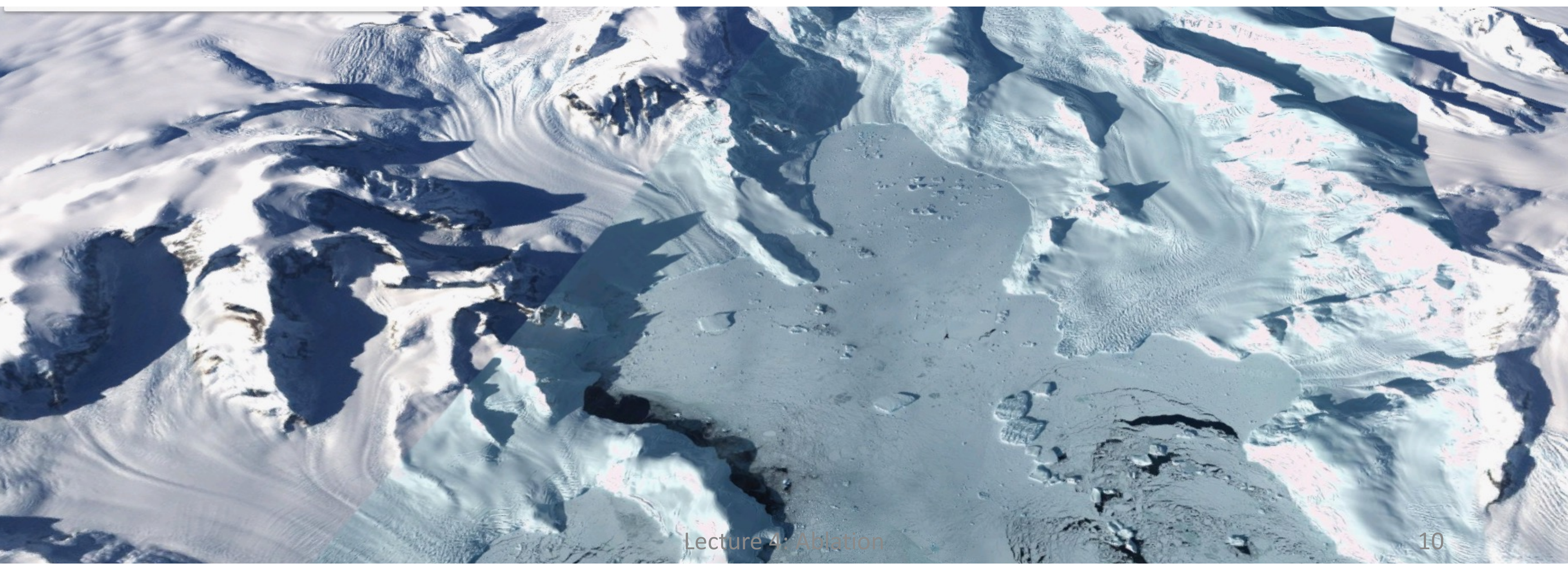
Ablating surfaces: 1. Calving front

Calving rate depends on
strain rates
ocean-driven melt
surface melt.

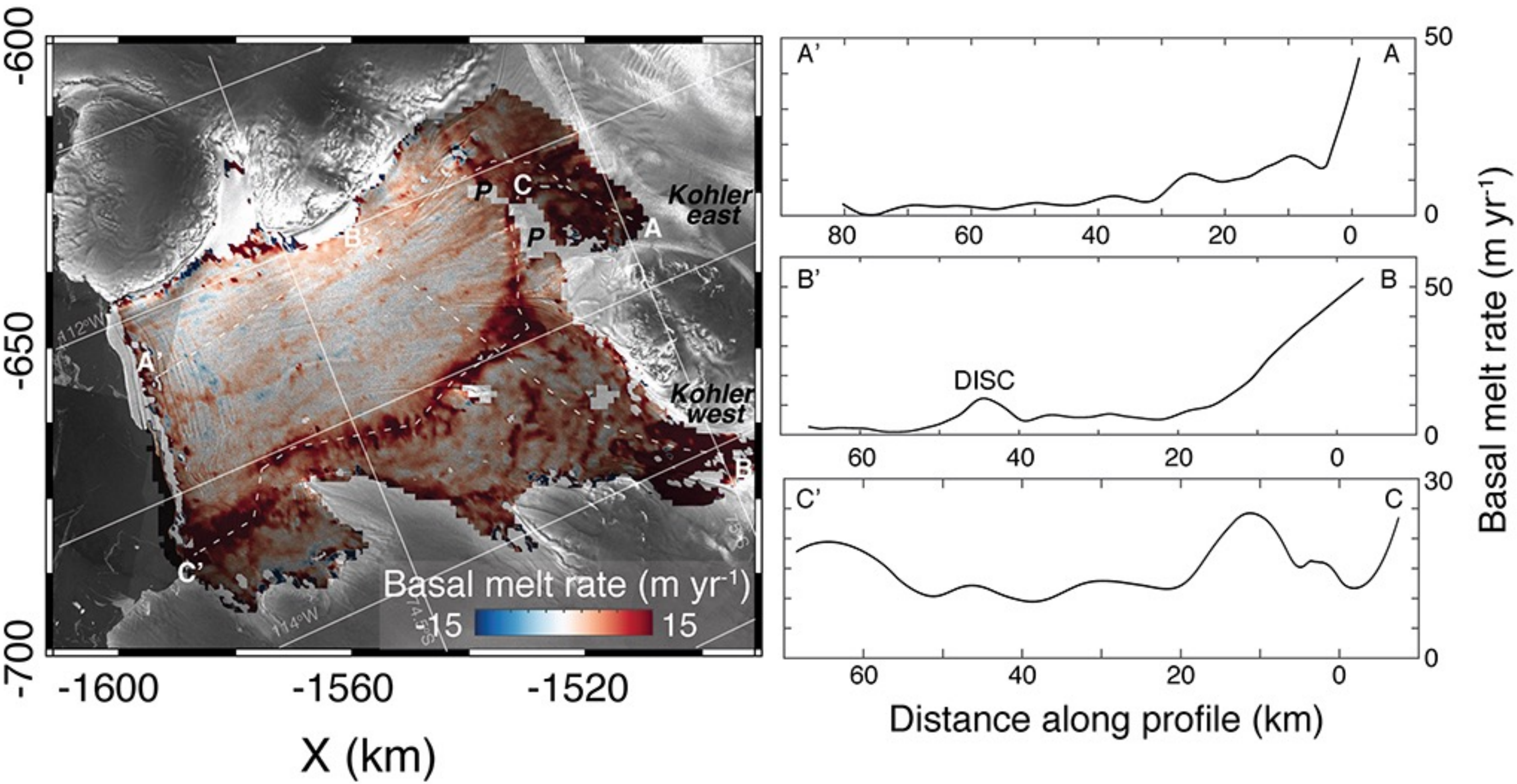
Models try to parameterize calving rate using simple relationships with cliff height, ice thickness, strain rates.

None are very satisfactory!


Kangaamiut
Maniitsoq
Itivdleq
Sisimiut
Kangeq
Nuuk
Atangmik
Sarfánguaq
Kangaatsiaq
Qeqertarsuaq
Niaqornaarsuk
Aasiaat
Disko Island
Niaqornat
Søndre Upernavik
Igdlorssuit
Nûgâtsiaq
Qeqertarsuatsiaat
Kapisillit
Kangerlussuaq
Ikamiut
Qasigiannguit
Ilulissat
Ritenbenk
Sarqaq
Uummannaq
Uvkusigssat



Ablating surfaces: 2. Base



Gourmelen et al. (2017)

Ablating surfaces: 2. Base

Measuring basal melt

Mass conservation leads to:

$$\frac{dH}{dt} = -\frac{dHu}{dx} + \frac{\dot{b_s}}{\rho_s} + \frac{\dot{b_b}}{\rho_i}$$

H is ice thickness,
u is ice flow speed
$\dot{b_s}$ is surface mass balance
$\dot{b_b}$ is basal mass balance

Ablating surfaces: 2. Base

Measuring basal melt

Mass conservation leads to:

Measure or model these

We measure these

$$\frac{dH}{dt} = -\frac{dHu}{dx} + \frac{\dot{b}_s}{\rho_s} + \frac{\dot{b}_b}{\rho_i}$$

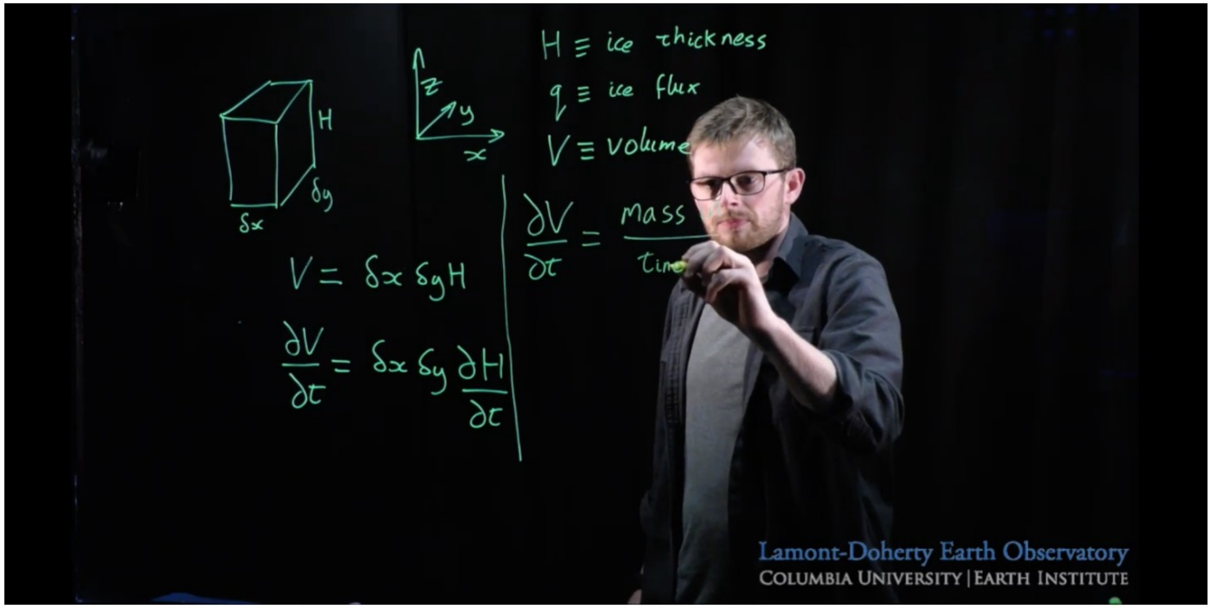
to compute this.

H is ice thickness,
u is ice flow speed
$\dot{b}_s$ is surface mass balance
$\dot{b}_b$ is basal mass balance

Ablating surfaces: 2. Base

Measuring basal melt

Mass cor

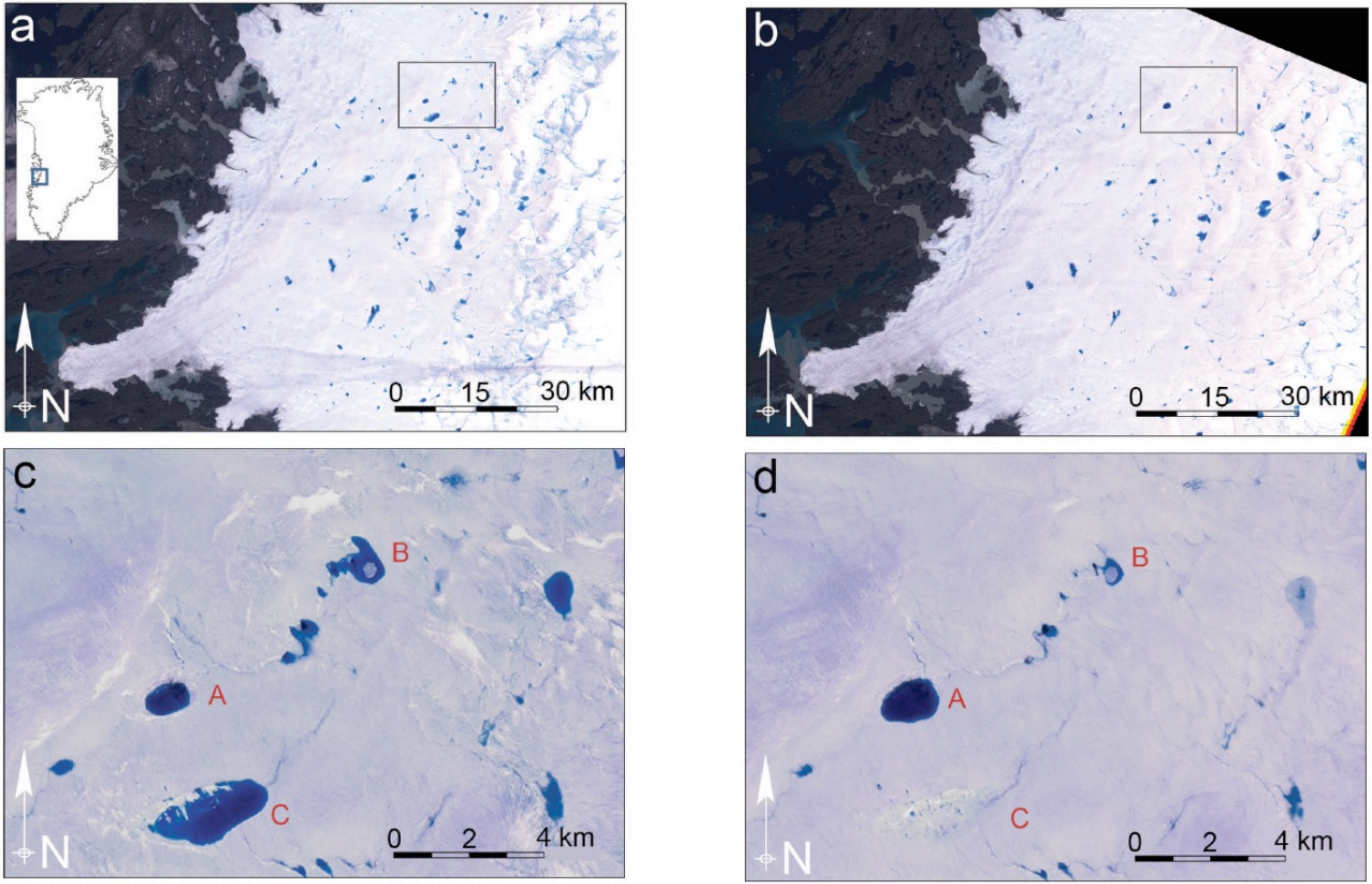


ompute

H is ice thickness,
u is ice flow speed
$\dot{b}_s$ is surface mass balance
$\dot{b}_b$ is basal mass balance

https://ldeo-it.ldeo.columbia.edu/content/lightboard-studio-lamont

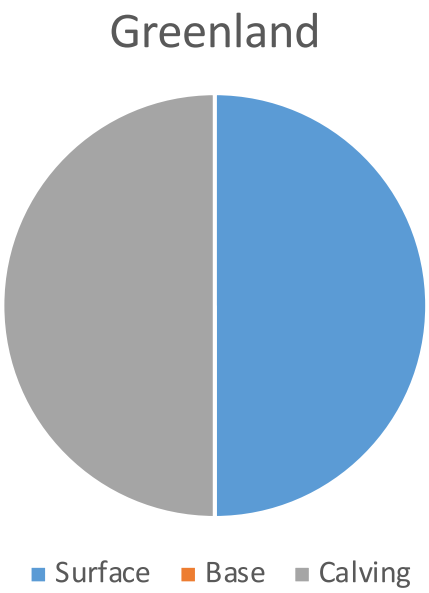
Ablating surfaces: 3. Surface

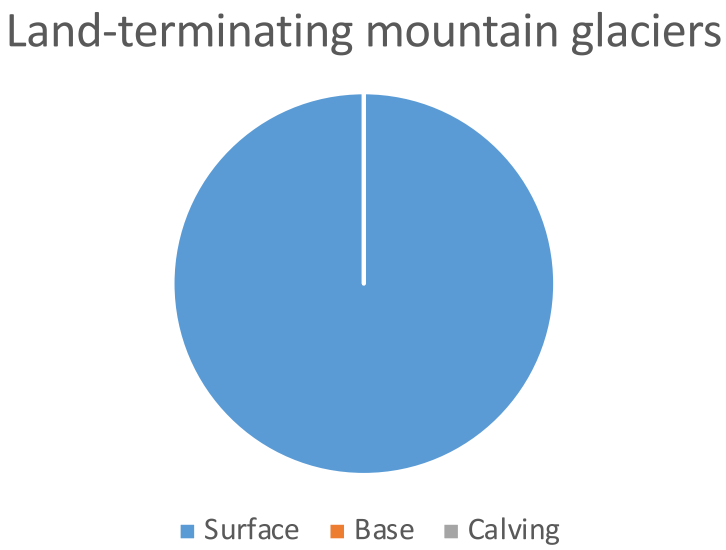


Kingslake et al. (2015)

Ablating surfaces: Surface

Very approximately:





Surface energy balance

$$\boxed{E_N = E_s^{\downarrow} + E_s^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + E_G + E_H + E_E + E_P}$$

Surface energy balance

$$\boxed{E_N = E_s^{\downarrow} + E_s^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + \cancel{E_G} + E_H + E_E + \cancel{E_P}}$$

Surface energy balance

$$\boxed{E_N = E_s^{\downarrow} + E_s^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + E_H + E_E}$$

Surface energy balance

$$E_N = \underbrace{E_S^{\downarrow} + E_S^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow}}_{\text{Radiative fluxes}} + E_H + E_E$$

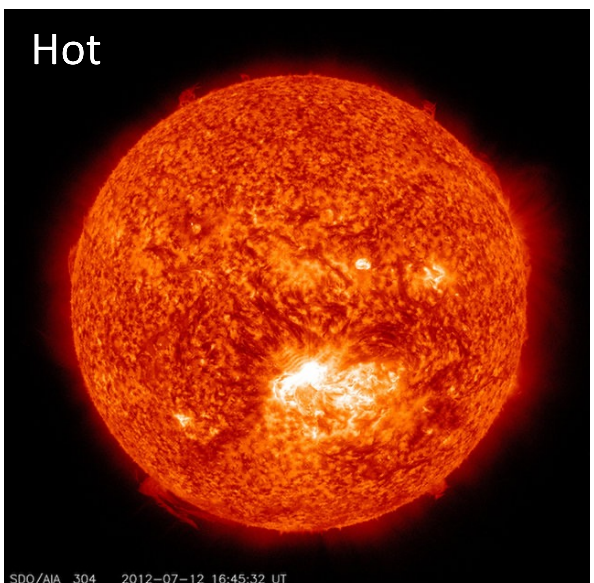
Black-body radiation

$$E = \sigma T^4$$

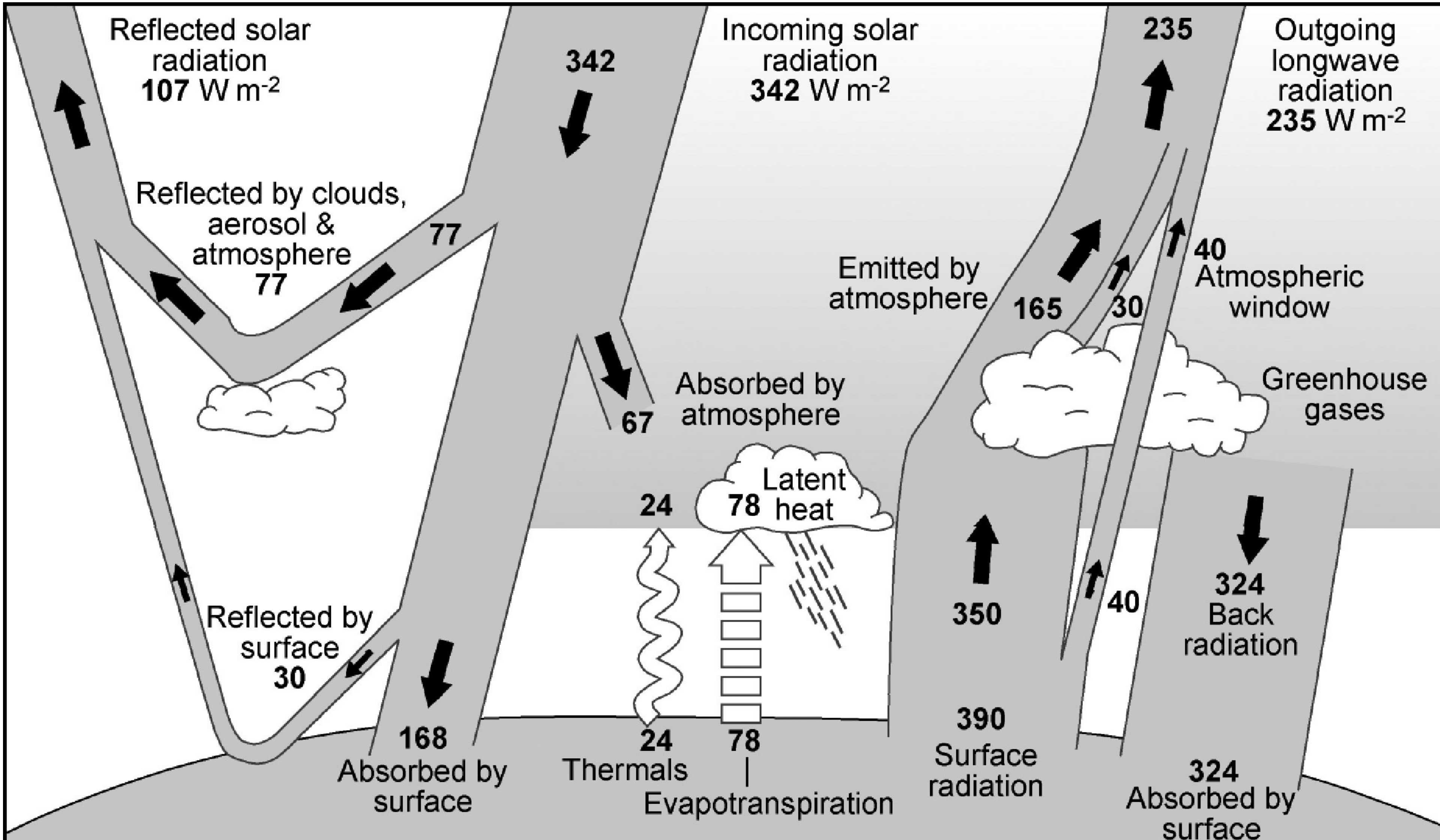
Stefan-Boltzmann equation

$$\lambda_{max} = \frac{b}{T}$$

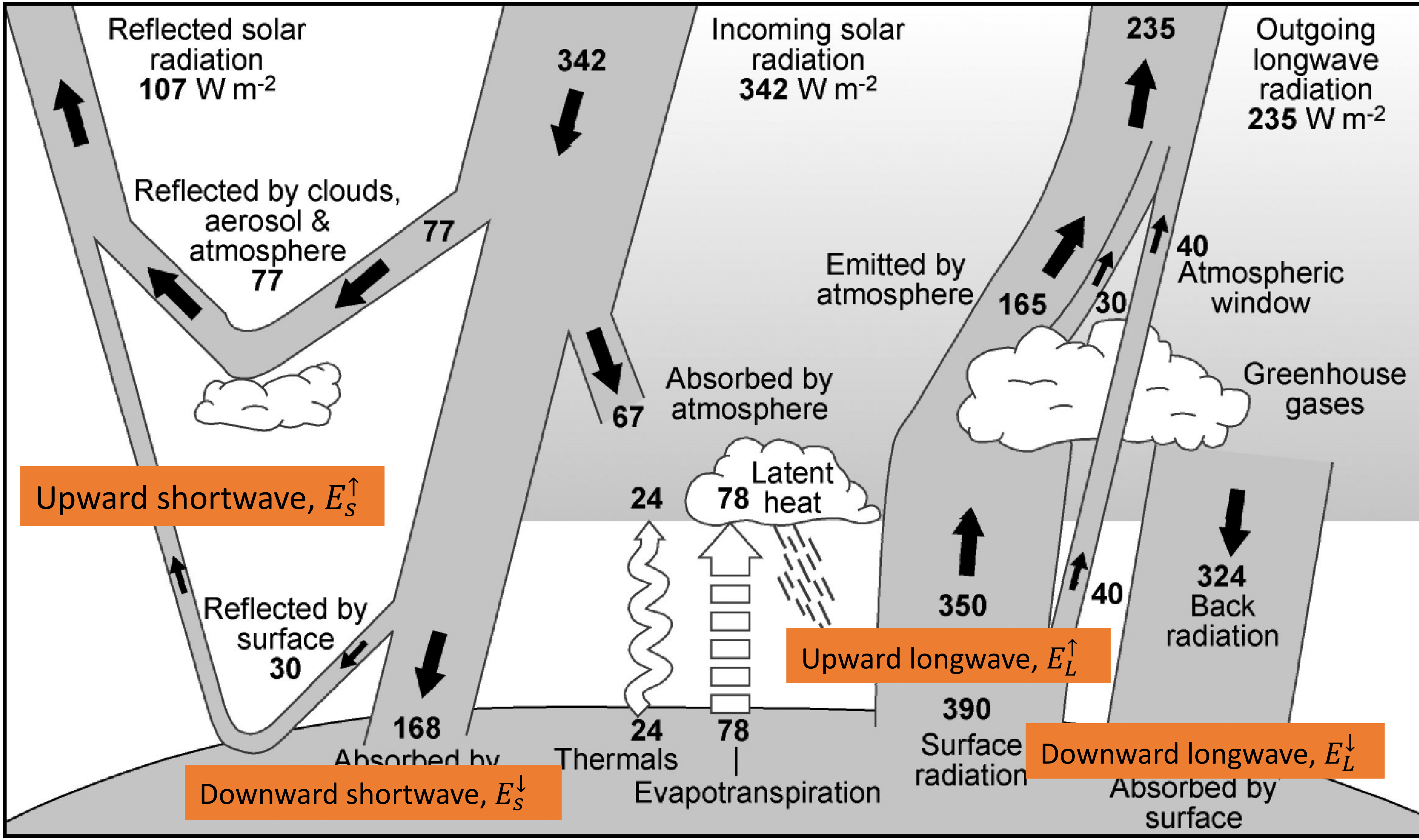
Wein's displacement law

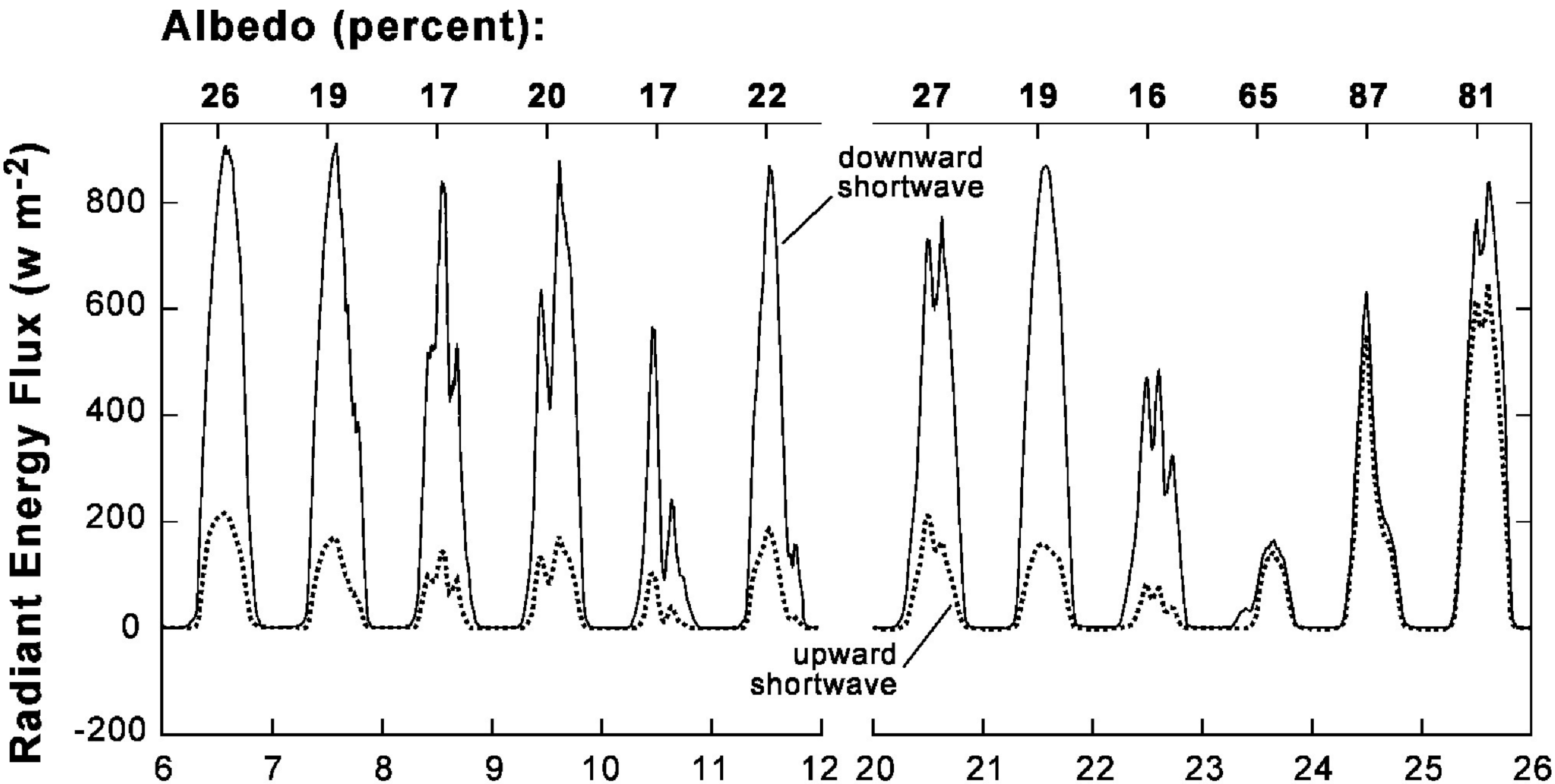


Radiative fluxes in the atmosphere

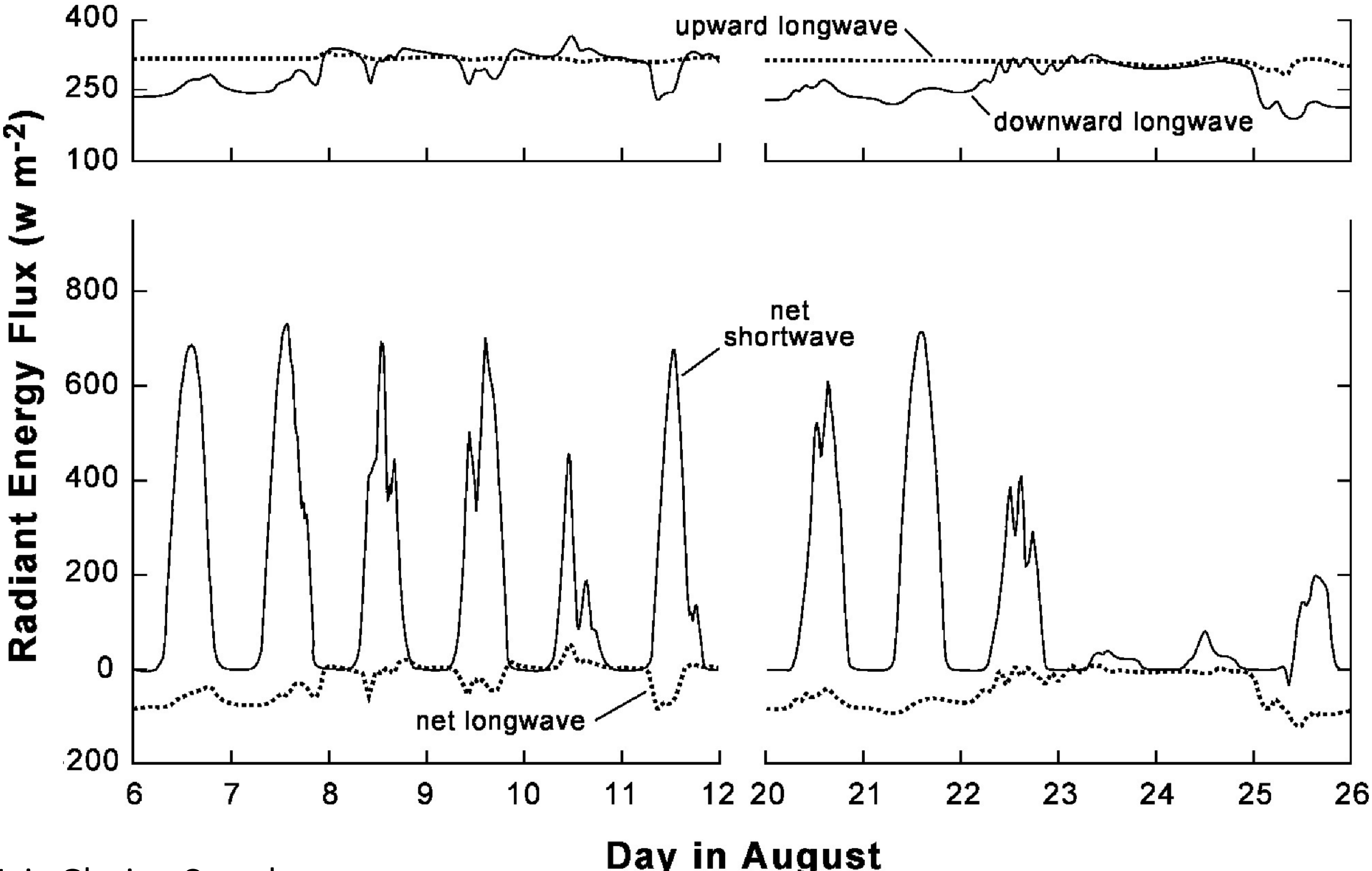


Radiative fluxes in the atmosphere



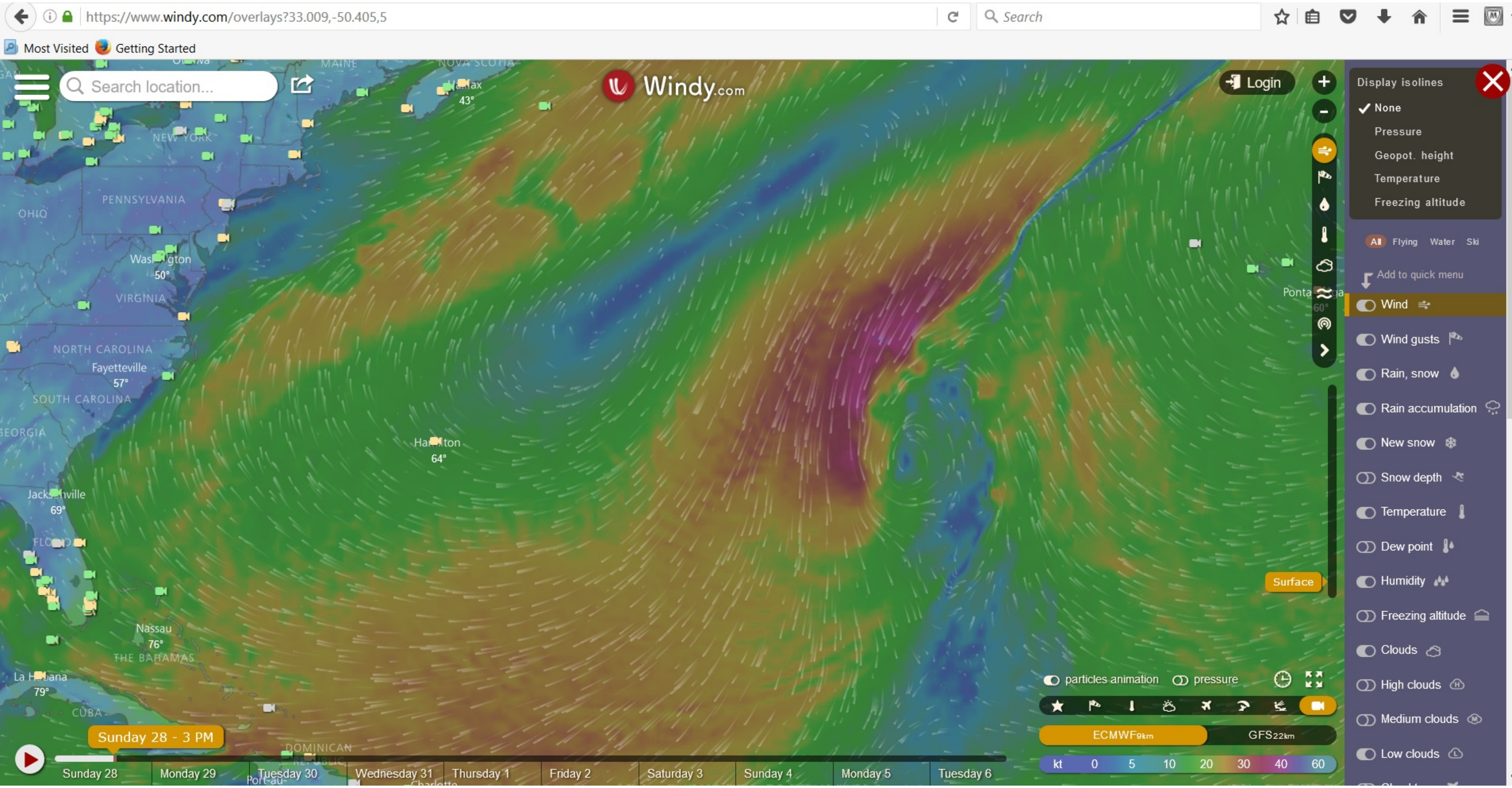


Haig Glacier, Canada,
Cuffey and Paterson (2010)



Haig Glacier, Canada,
Cuffey and Paterson (2010)

Turbulent fluxes



https://www.windy.com/overlays?32.990,-50.405,5

Surface energy balance

$$\boxed{E_N = E_s^{\downarrow} + E_s^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + \underbrace{E_H + E_E}_{\text{Turbulent fluxes}}}$$

Depend sensitively on weather conditions throughout the atmosphere,

Surface energy balance

$$\boxed{E_N = E_S^{\downarrow} + E_S^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + \underbrace{E_H + E_E}_{\text{Turbulent fluxes}}}$$

Sensible heat flux

$$E_H \propto u(T_a - T_s)$$

Latent heat flux

$$E_E \propto u(q_a - q_s)$$

Depend sensitively on weather conditions throughout the atmosphere,
but these eqns use conditions just above the surface.

where,
U is wind speed,
T_a is air temperature
T_s is surface temperature
q_a is humidity of the air
q_s is humidity at the surface

Surface energy balance

$$\boxed{E_N = E_S^{\downarrow} + E_S^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + \underbrace{E_H + E_E}_{\text{Turbulent fluxes}}}$$

Sensible heat flux

$$E_H \propto u(T_a - T_s)$$

Latent heat flux

$$E_E \propto u(q_a - q_s)$$

Corresponds to a mass exchange that can be positive (deposition) or negative (sublimation/evaporation).

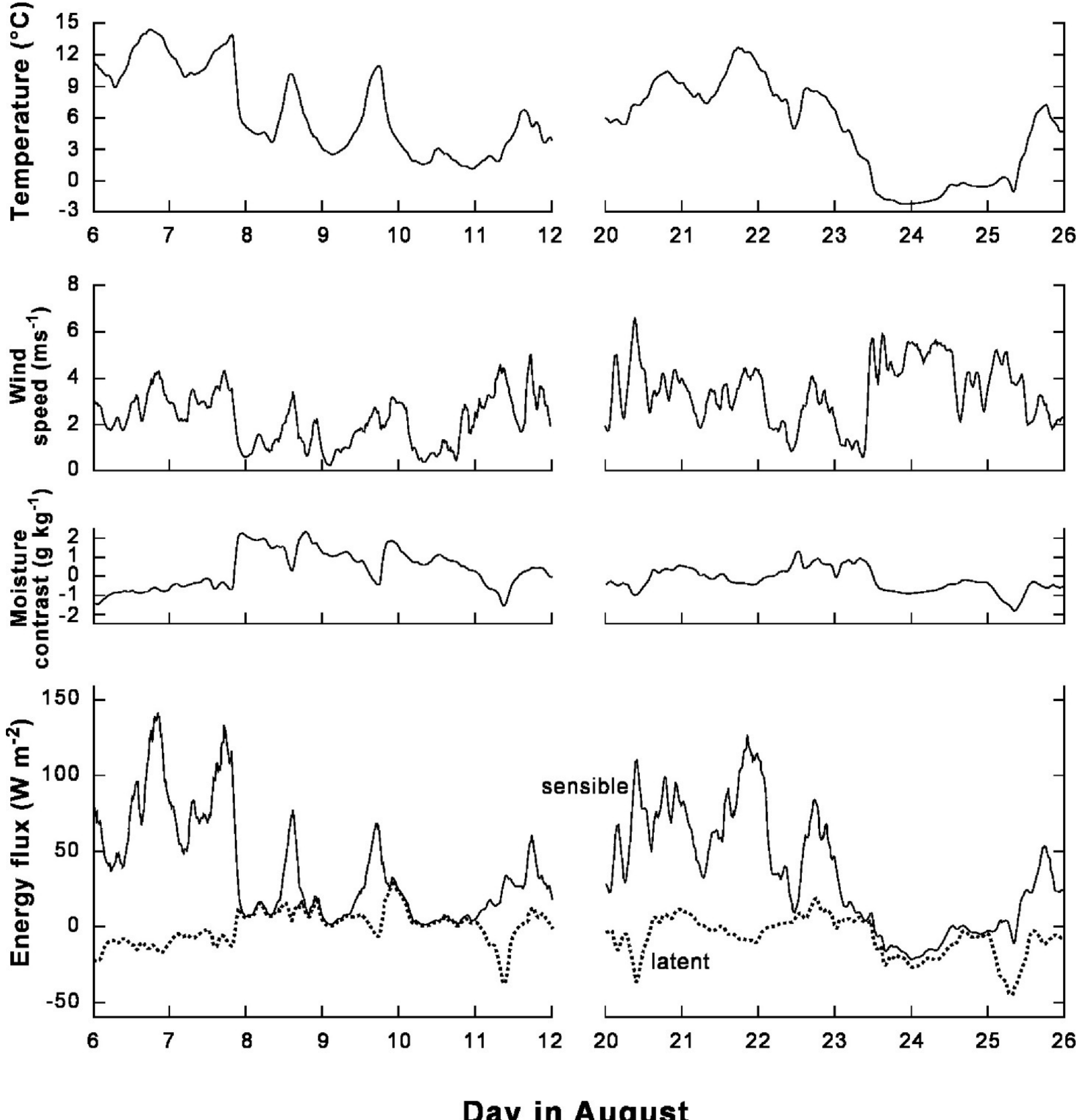
T_a

U is wind speed,
T_a is air temperature
T_s is surface temperature
q_a is humidity of the air
q_s is humidity at the surface

u

q_a

E_H E_E



Haig Glacier, Canada,
Cuffey and Paterson (2010)

$$\boxed{E_N = E_s^{\downarrow} + E_s^{\uparrow} + E_L^{\downarrow} + E_L^{\uparrow} + E_H + E_E}$$

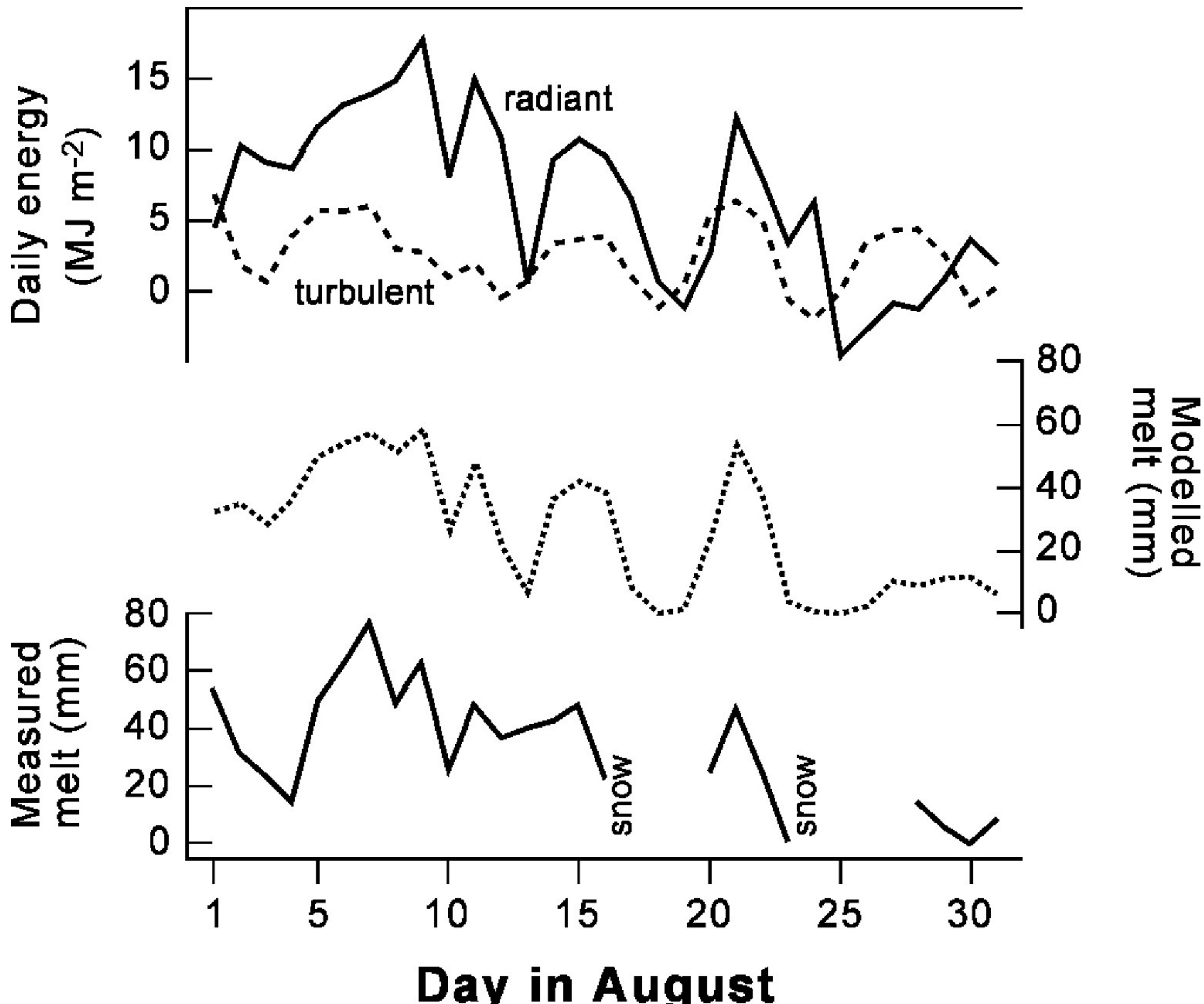
....back to Ablation.

Net energy into the glacier surface = energy used to warm up the surface layer + energy used in melting.

When $T = 0^{o}$C:

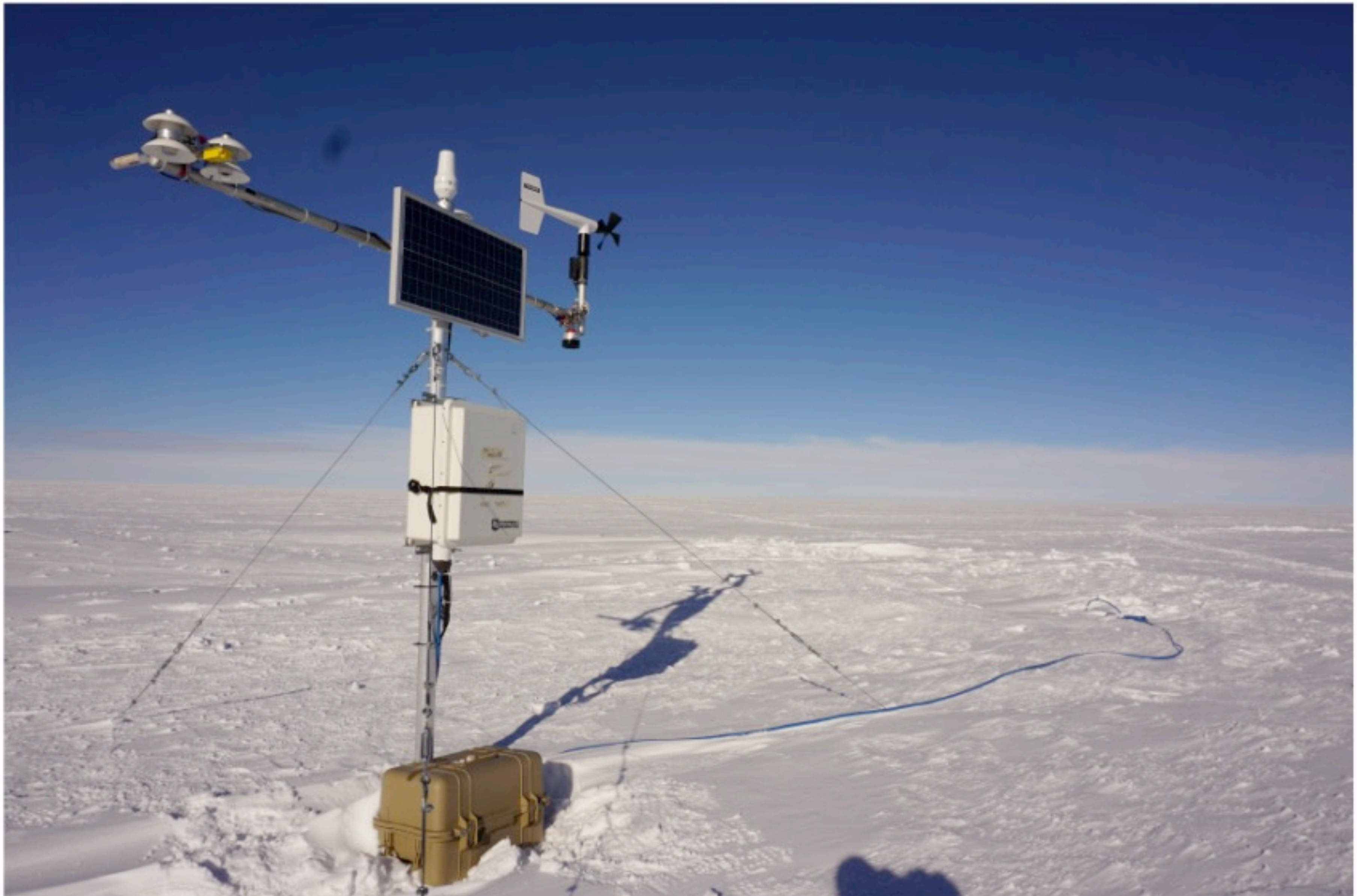
$$E_N = \rho_w L_f \dot{m}$$

$$\dot{m} = \frac{E_N}{\rho_w L_f}$$

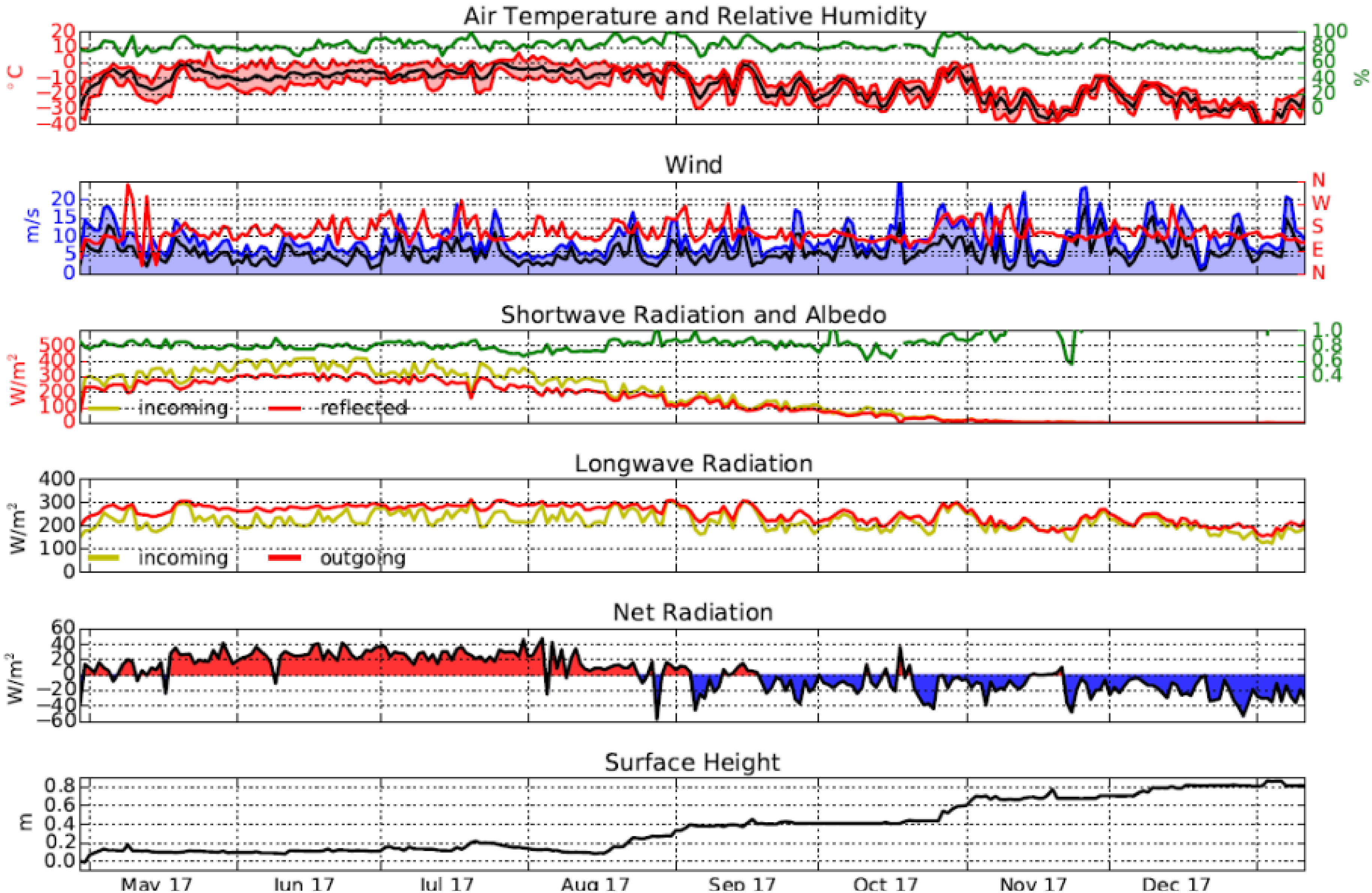


Haig Glacier, Canada,
Cuffey and Paterson (2010)

Automatic weather station (AWS)
Greenland Ice Sheet, 2060 m a.s.l.



AWS - Site J 2060 m a.s.l.



How do increasing temperatures affect melting and mass balance?

Short-term changes

- Increased sensible heat
- Increased downward longwave radiation
- Early exposure of low albedo ice at the start of the melt season
- Longer melt seasons.

Longer-term changes

- Lowering the surface increases surface temperatures further.
- Increases melt water can enhance ice flow.

How do you measure mass balance?

1. Glaciological method

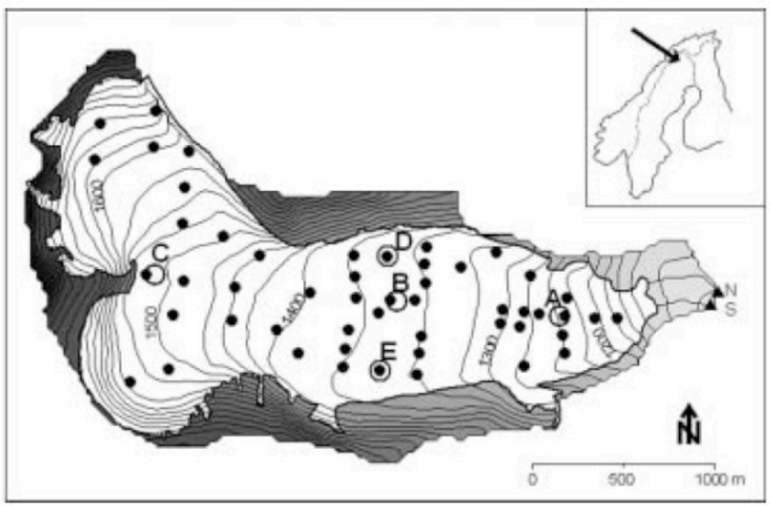
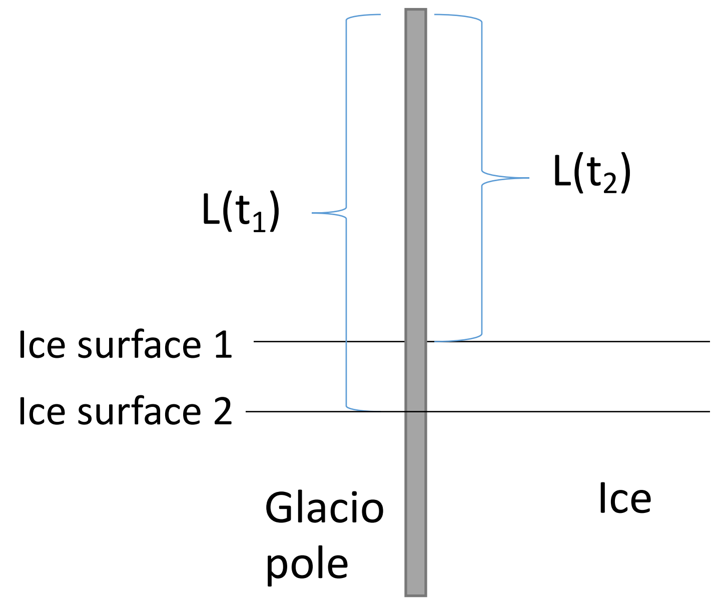


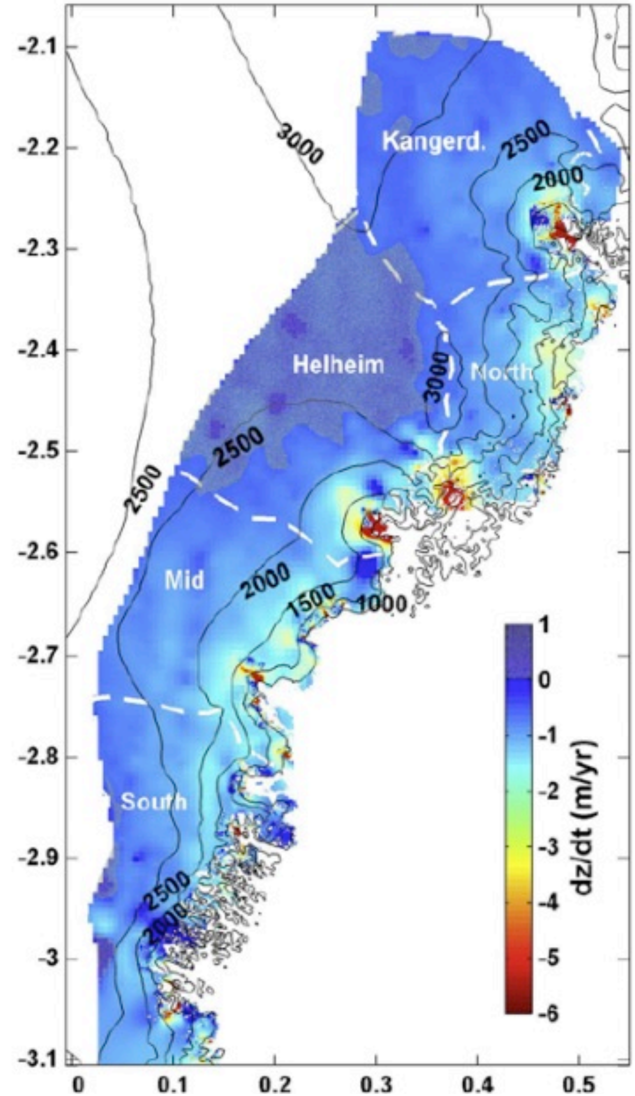
Fig. 1. Drainage basin of Storglaciären with 25 m contour lines. N and S refer to the sites of the water-stage recording stations at the glacial streams Nordjåkk and Sydjåkk. The black dots mark the positions of the ablation stakes in 1994, only slightly differing from those in 1993. The circles labelled A–E denote the sites of five micrometeorological stations on the glacier.

Hock et al. (2005)



How do you measure mass balance?

2. Geodetic method

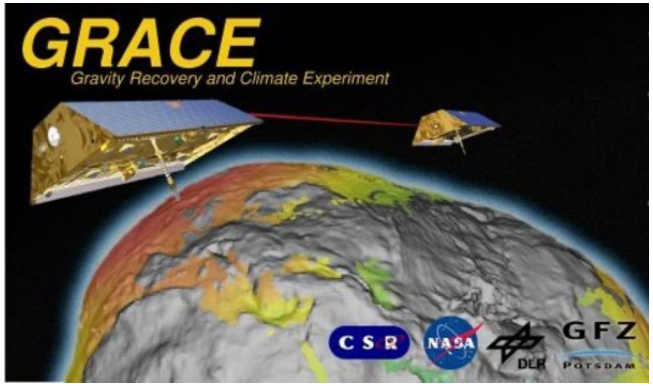


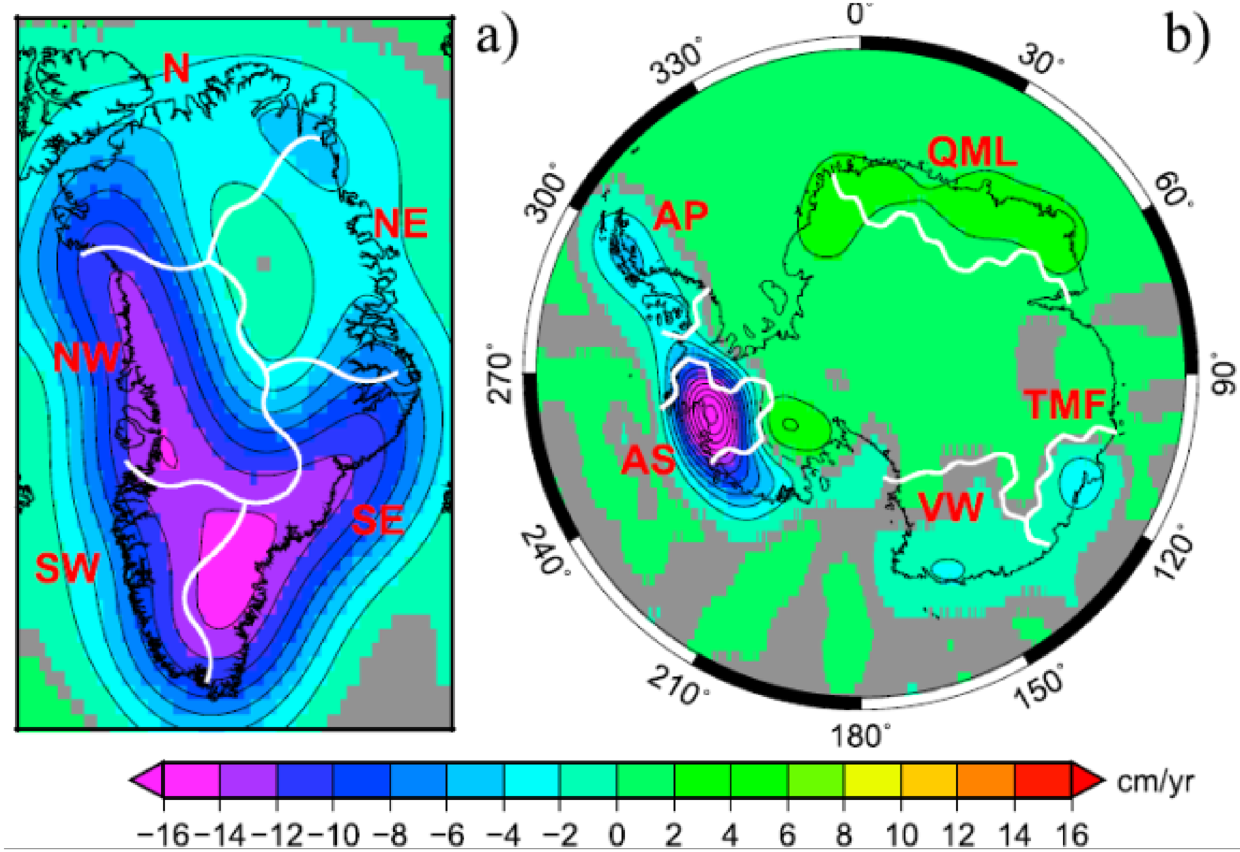
Howat et al. (2008)

How do you measure mass balance?

3. Gravimetric method

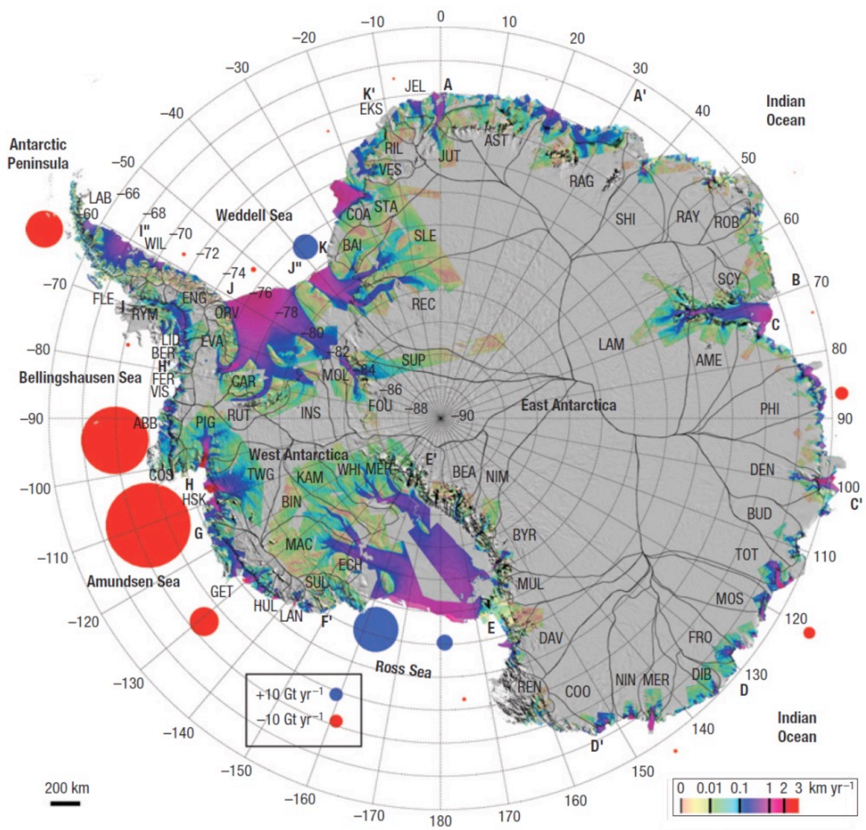
Velicogna et al. (2014)

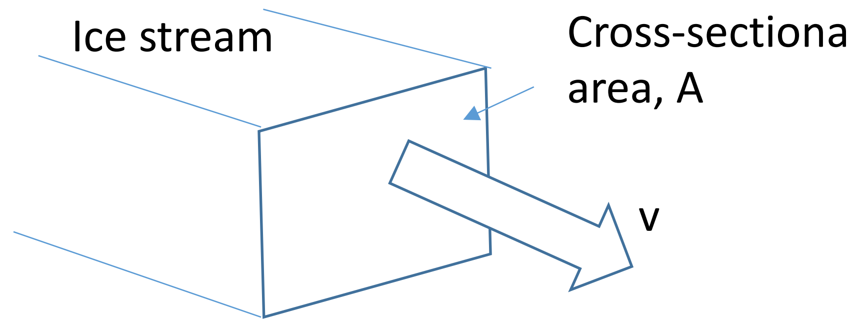




How do you measure mass balance?

4. Input-output method





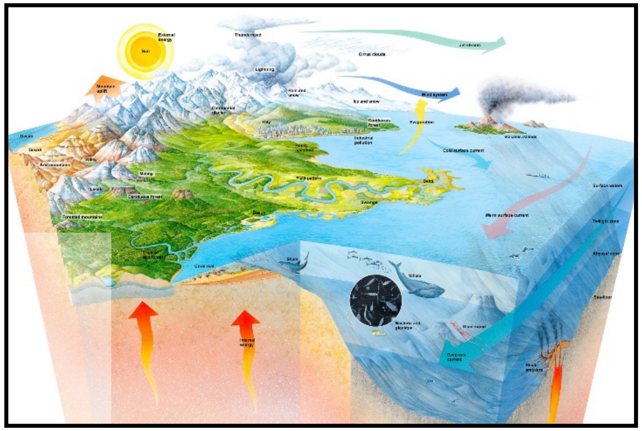
Flux

$$\boxed{q = AV}$$

Rignot et al. (2008)

Climate Models

The real System



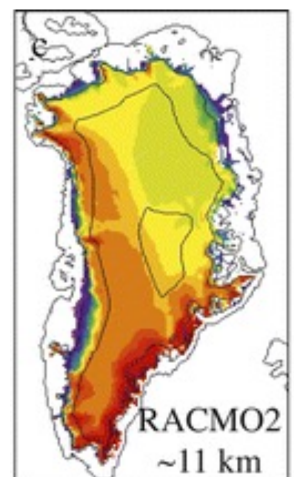
Mathematical model:
e.g. Navier-stokes equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad \text{----- Continuity Equation} \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \mathbf{F} + \frac{\mu}{\rho}\nabla^2 \mathbf{u}, \quad \text{----- Equations of Motion} \quad (2)$$

Numerical model

Simulations

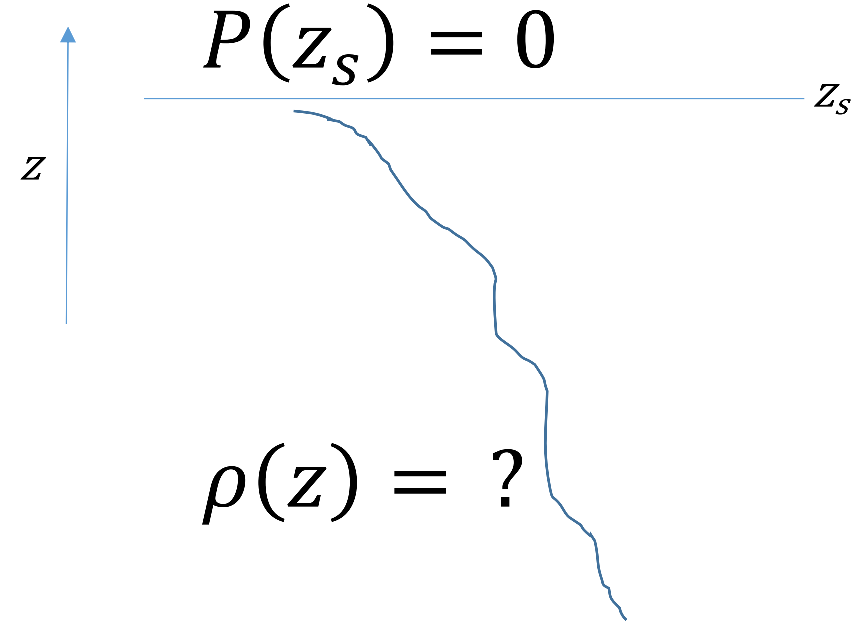


Descritization and numerical integration

- Example: integrating the overburden pressure equation

$$\frac{dP}{dz} = \rho(z)g$$

$$P(z_s) = 0$$



$$\rho(z) = \ ?$$

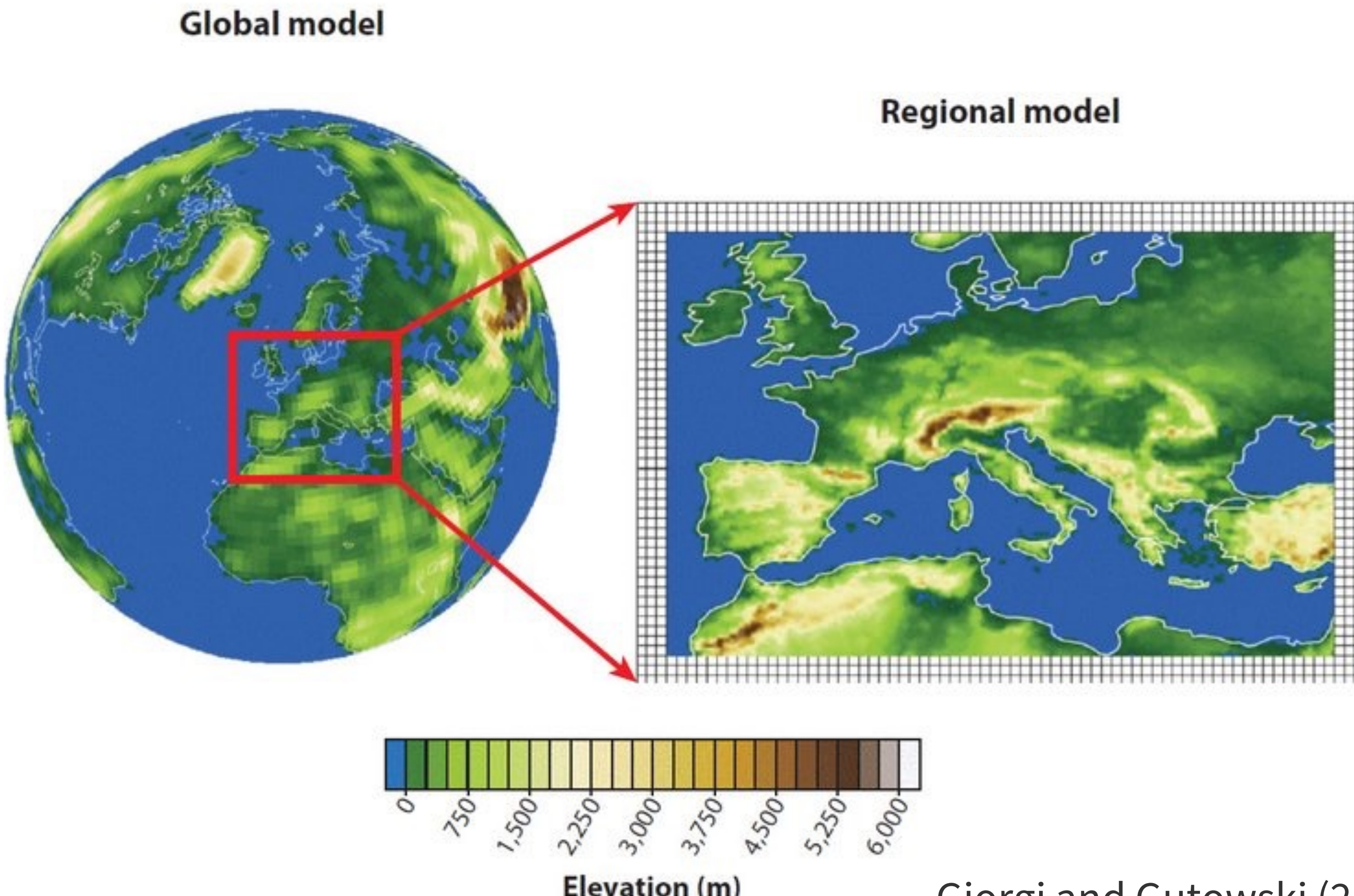
Descritization and numerical integration

Also works in time

$$\frac{dU}{dt} = f(t)$$

$$U(t_0) = U_0$$

Regional Climate Models

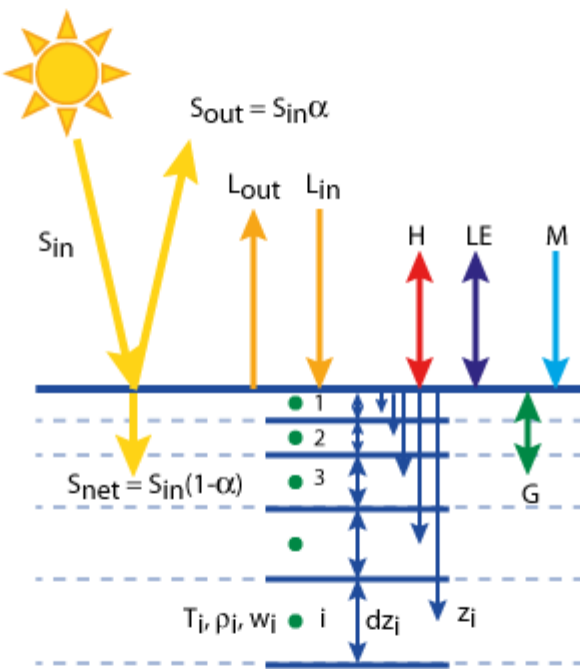


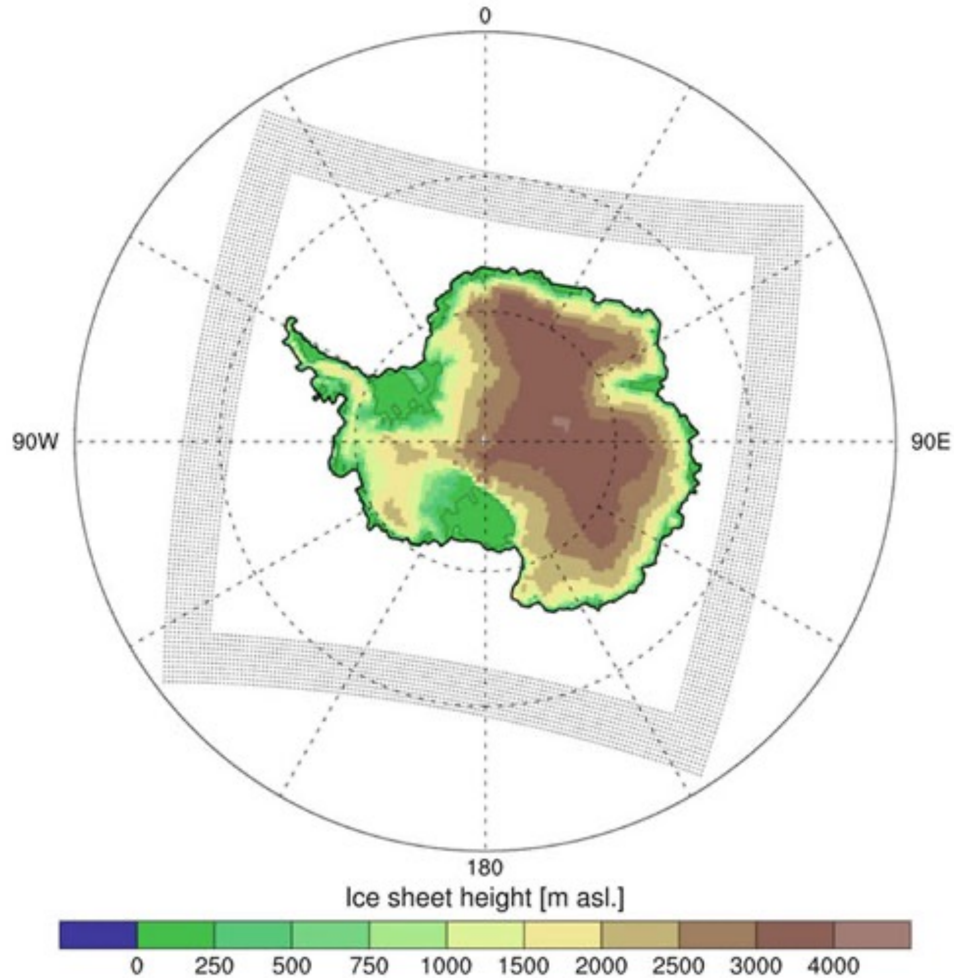
Giorgi and Gutowski (2015)

Regional Atmospheric Climate model (RACMO)

Applied to Antarctica:

RACMO/Ant

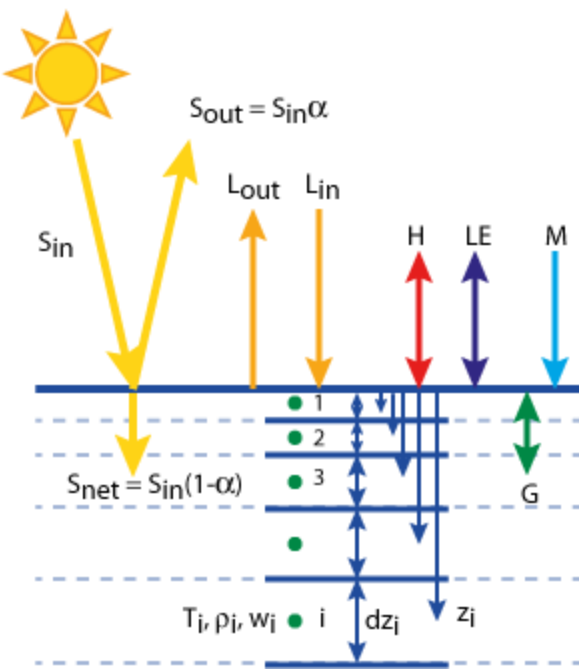




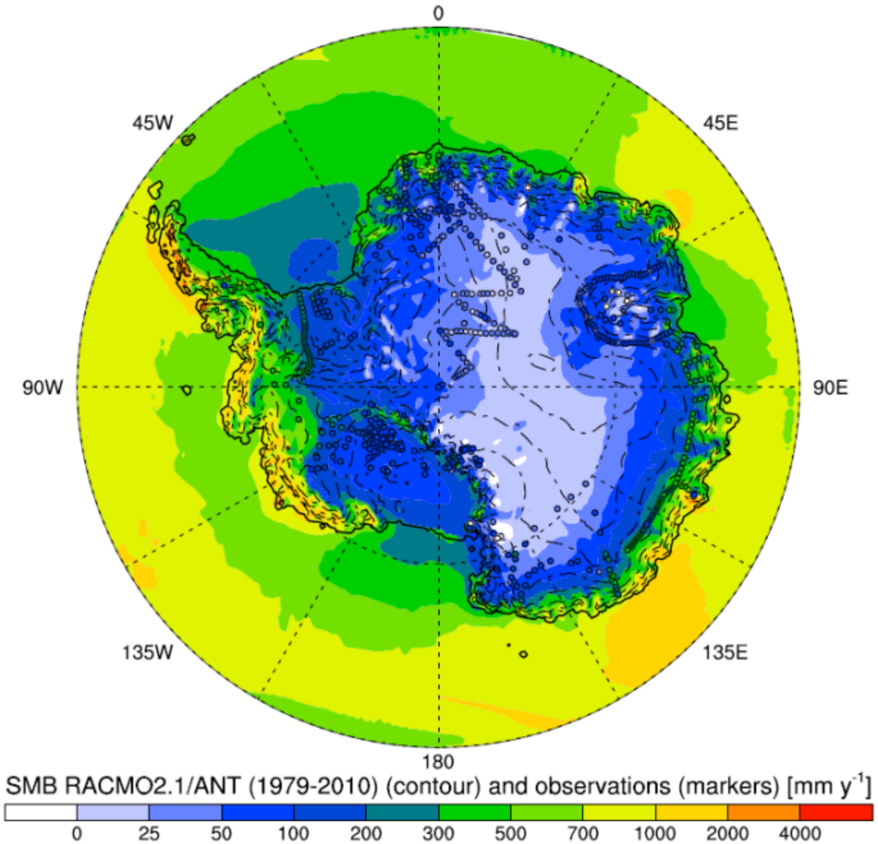
Regional Atmospheric Climate model (RACMO)

Applied to Antarctica:

RACMO/Ant

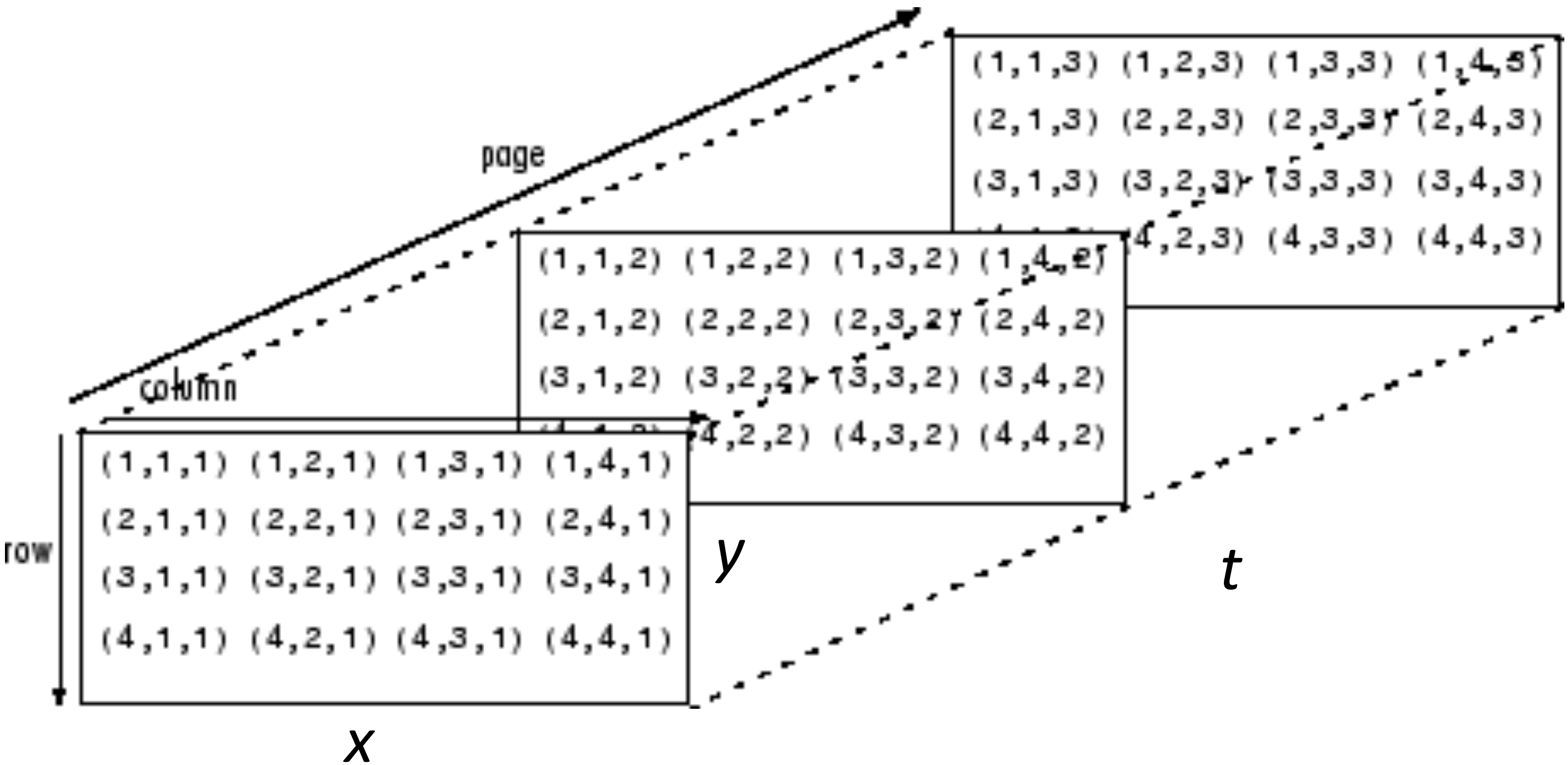


Surface mass balance



Racmo data

2 spatial dimensions + 1 time dimension



Tuesday

- We will be manipulating, plotting, analyzing output from the latest version of RACMO
  courtesy of Michiel van den Broeke, and Peter Kuipers-Munneke, Utrecht University.

  ---> read up on multi-dimensional arrays here:
  https://numpy.org/doc/stable/reference/arrays.ndarray.html

Summary

- Ablation mostly due to calving, basal melt and surface melt.
- Melt is controlled by the surface energy balance. ferent components dominate in different places.
- Many interesting phenomena results from variations in energy balance components.

Reading (for Thursday)
1. Section 5.4.5. of Cuffey and Paterson.

2. Chapter 4, up to the end of section 4.2.2 of Benn and Evans

[pdfs on Canvas]

References

Evatt, G.W., Abrahams, I.D., Heil, M., Mayer, C., Kingslake, J., Mitchell, S.L., Fowler, A.C. and Clark, C.D., 2015. Glacial melt under a porous debris layer. *Journal of Glaciology*, *61*(229), pp.825-836.

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Kieffer, H.H., Chase, S.C., Martin, T.Z., Miner, E.D. and Palluconi, F.D., 1976. Martian north pole summer temperatures: Dirty water ice. *Science*, *194*(4271), pp.1341-1344.

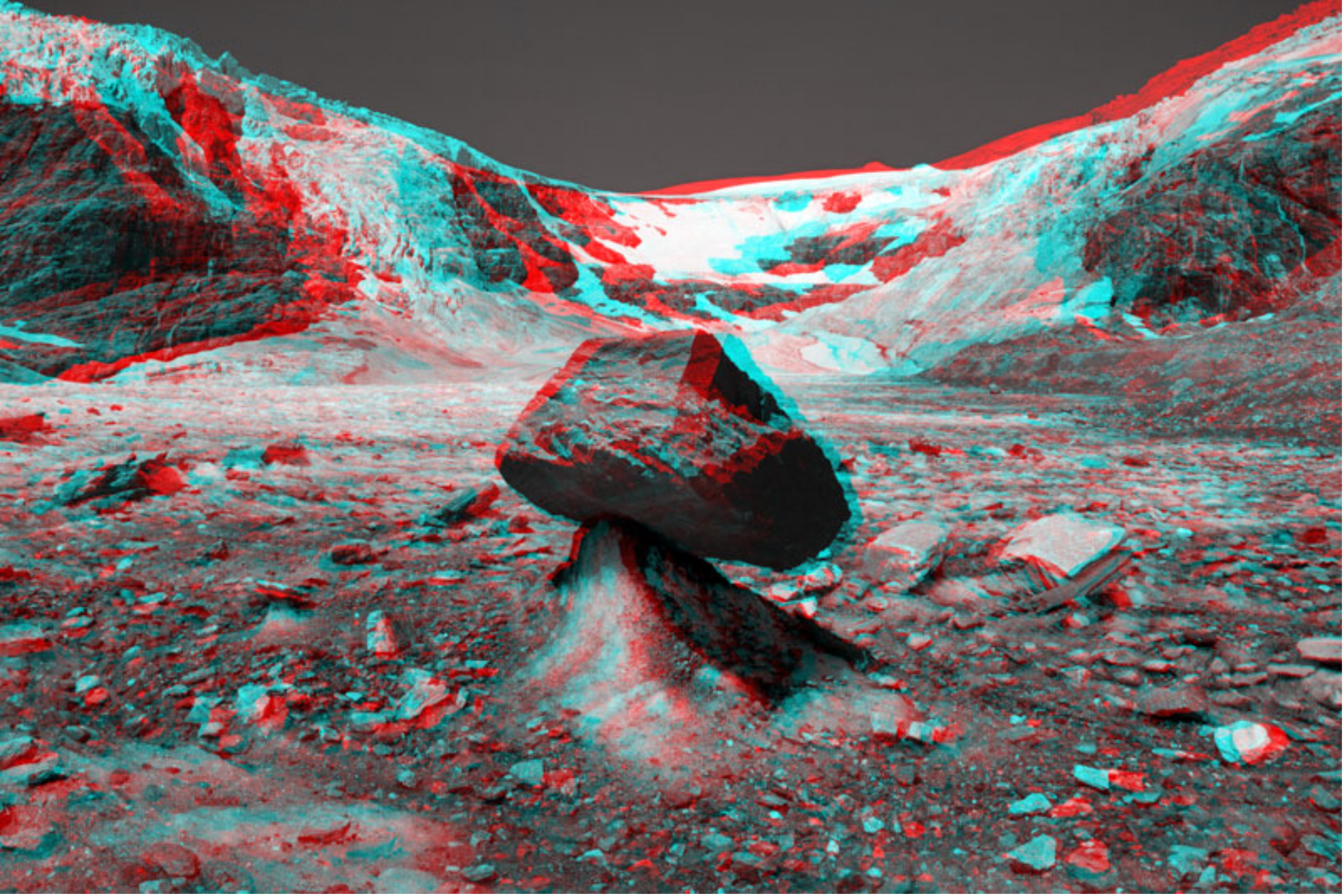
Kingslake, J., Ng, F. and Sole, A., 2015. Modelling channelized surface drainage of supraglacial lakes. *Journal of Glaciology*, *61*(225), pp.185-199.

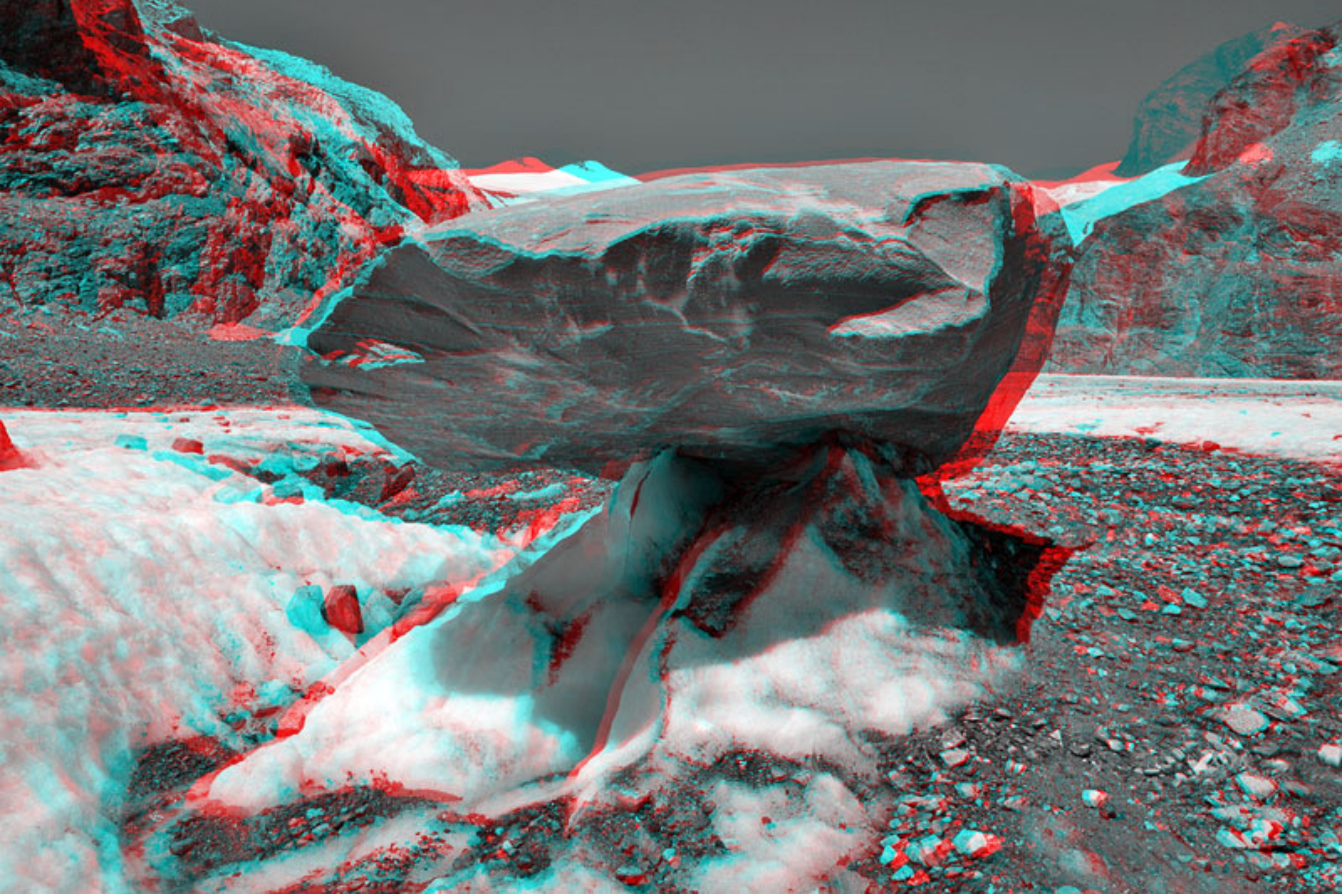
Milkovich, S.M. and Head, J.W., 2005. North polar cap of Mars: Polar layered deposit characterization and identification of a fundamental climate signal. *Journal of Geophysical Research: Planets*, *110*(E1).

Nye, J.F., 1958. A theory of wave formation in glaciers. *International Association of Hydrological Sciences*, *47*, pp.139-154.

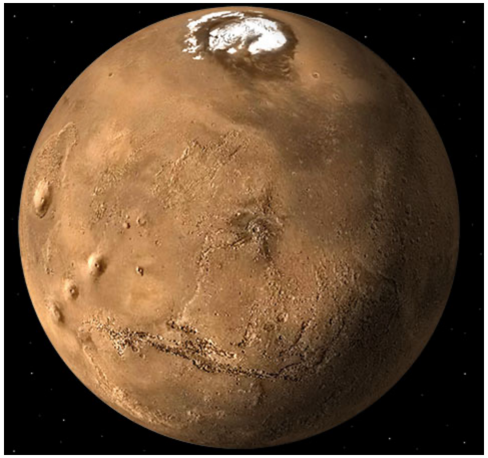
Smith, I.B., Holt, J.W., Spiga, A., Howard, A.D. and Parker, G., 2013. The spiral troughs of Mars as cyclic steps. *Journal of Geophysical Research: Planets*, *118*(9), pp.1835-1857.

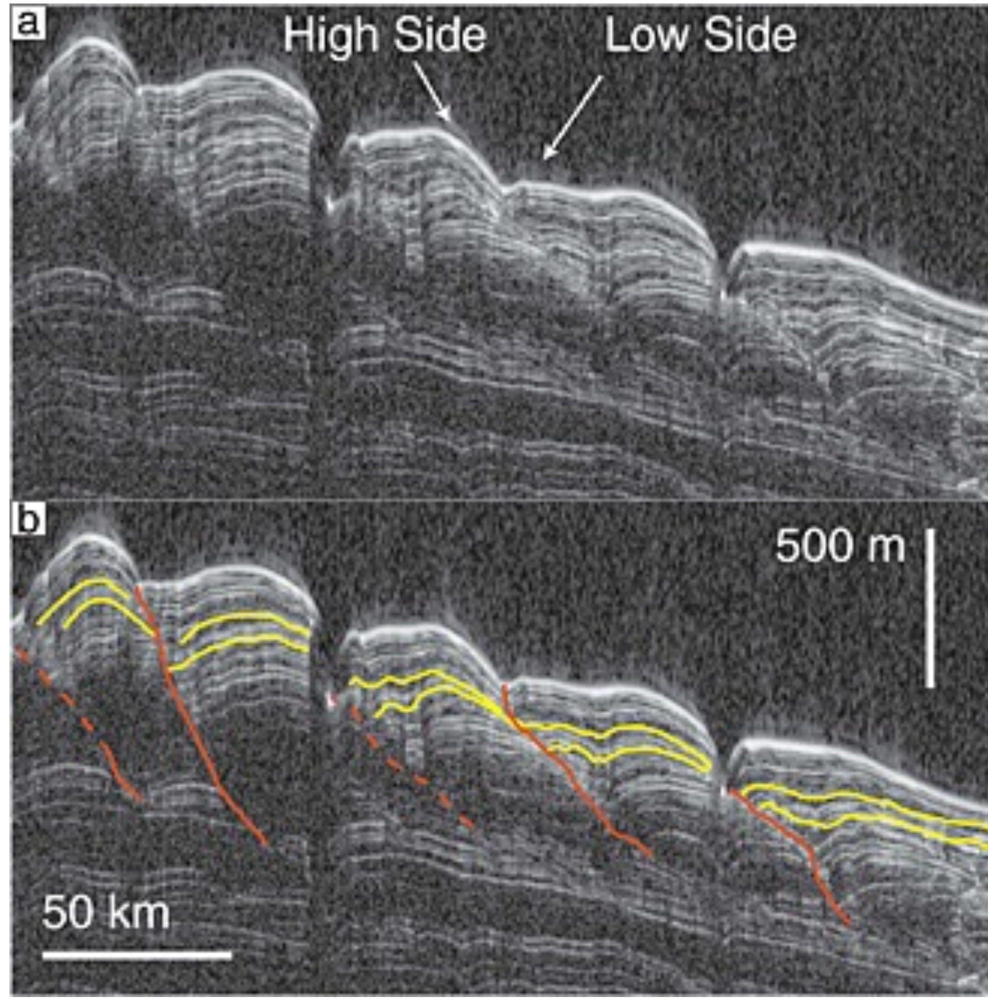
Ablation phenomena 1: Glacier tables



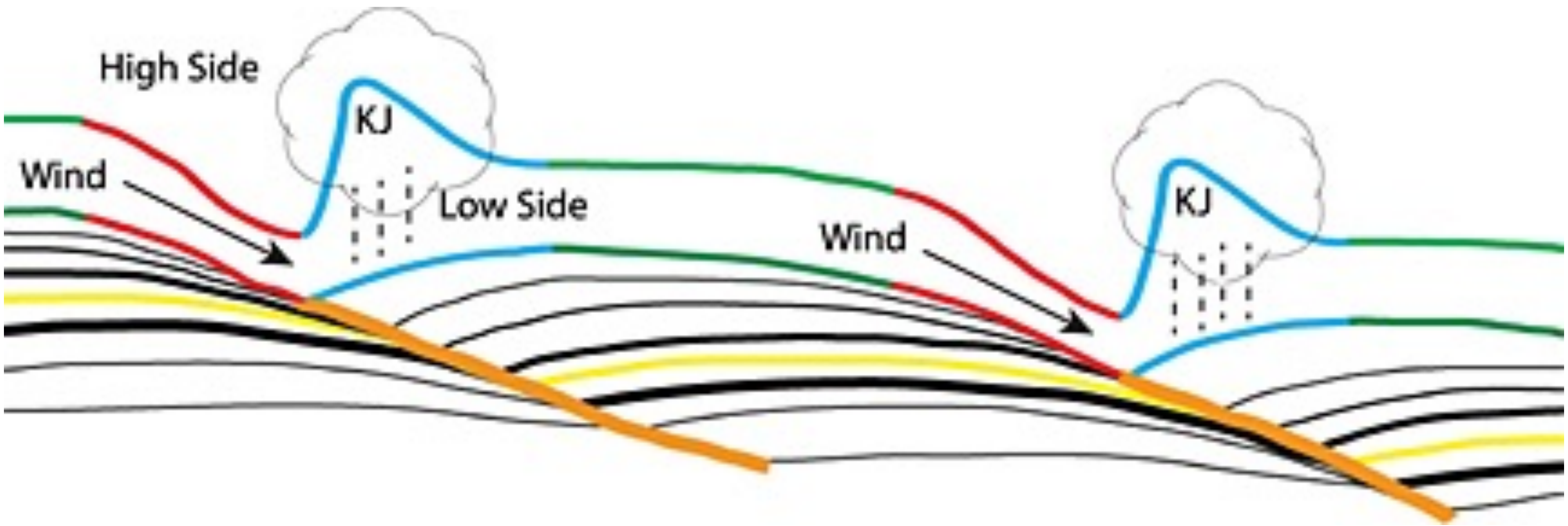


Ablation phenomena 2: Martian spiral troughs

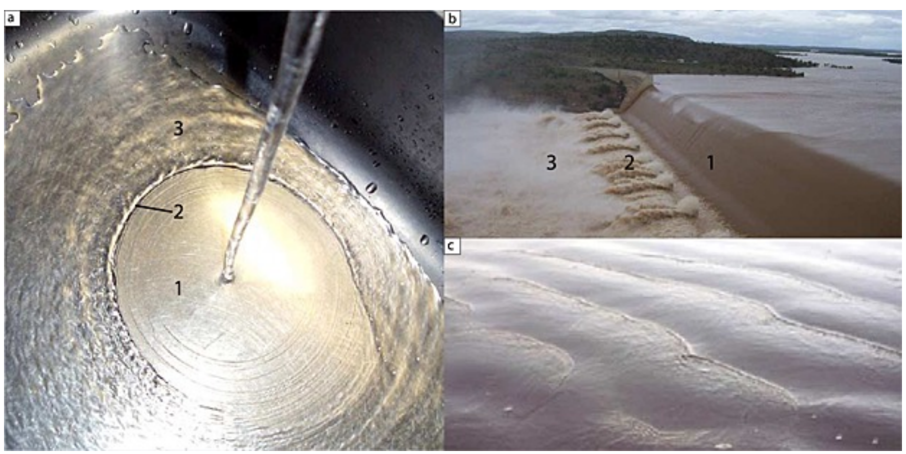




Milkovich and Head (2005)

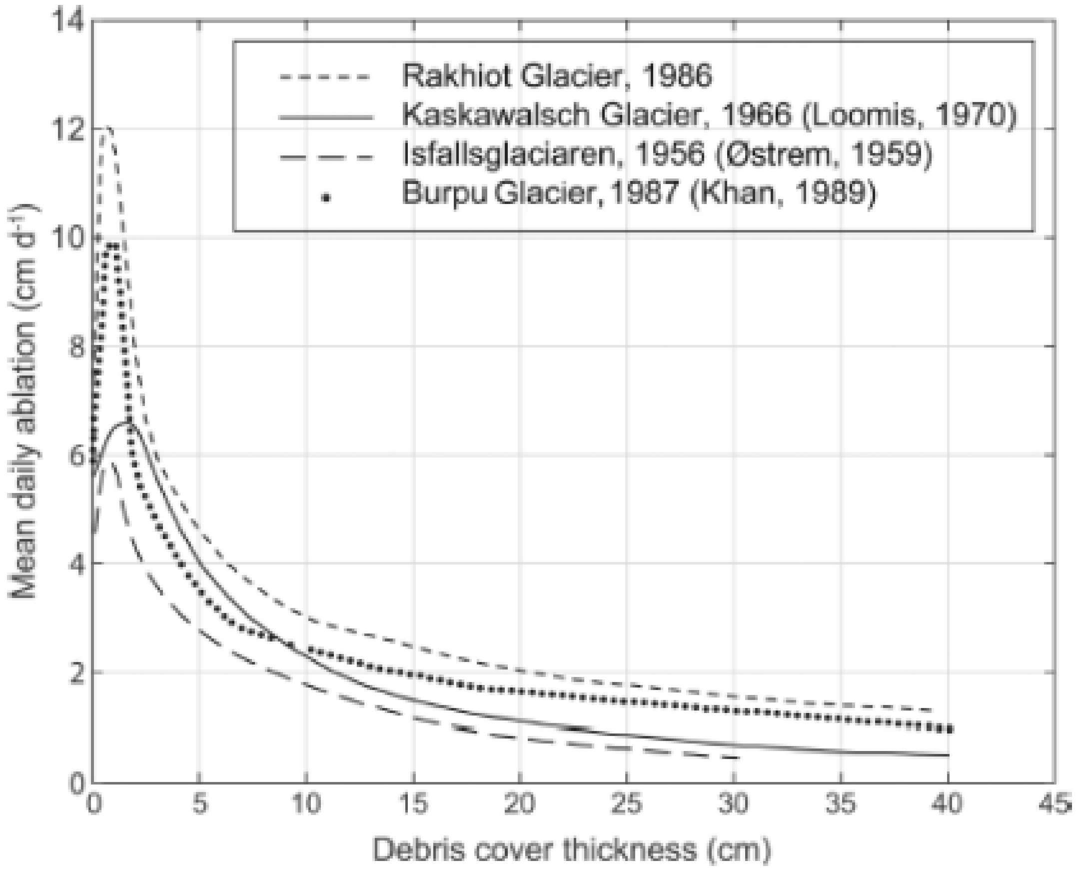


Aeolian counterpart of hydraulic jumps cause erosion on high side and deposition on low side



Smith et al. (2013)

Ablation phenomena 3: Ostrem Curve

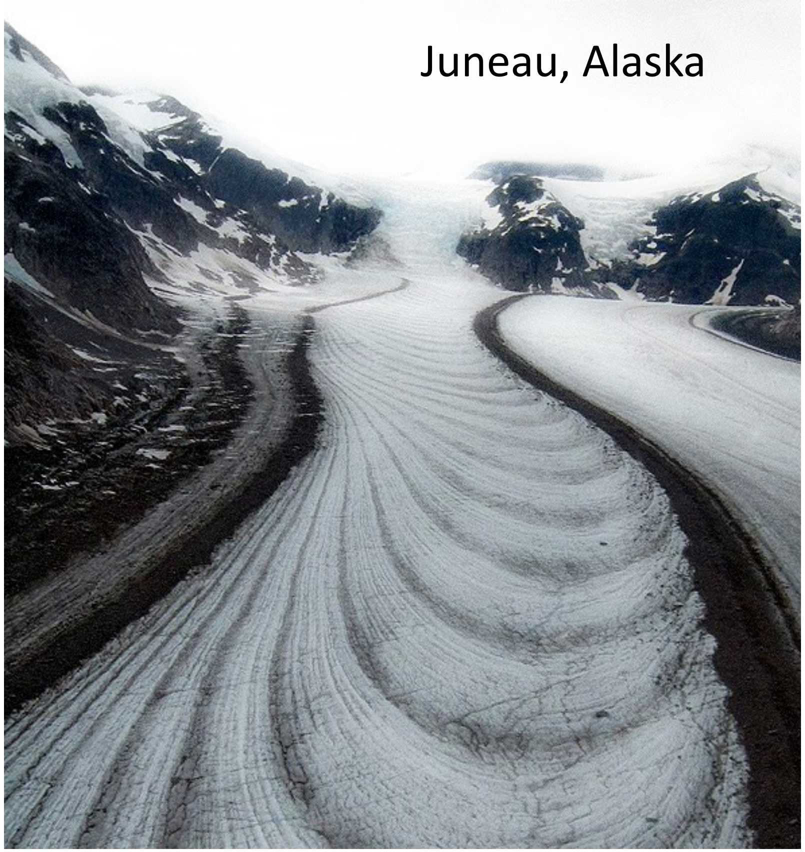


Two explanations for increasing melt rates with thin debris:

1. Decreasing albedo
2. Reduced latent heat flux (Evatt et al., 2015)

Ablation phenomena 4: Ogives

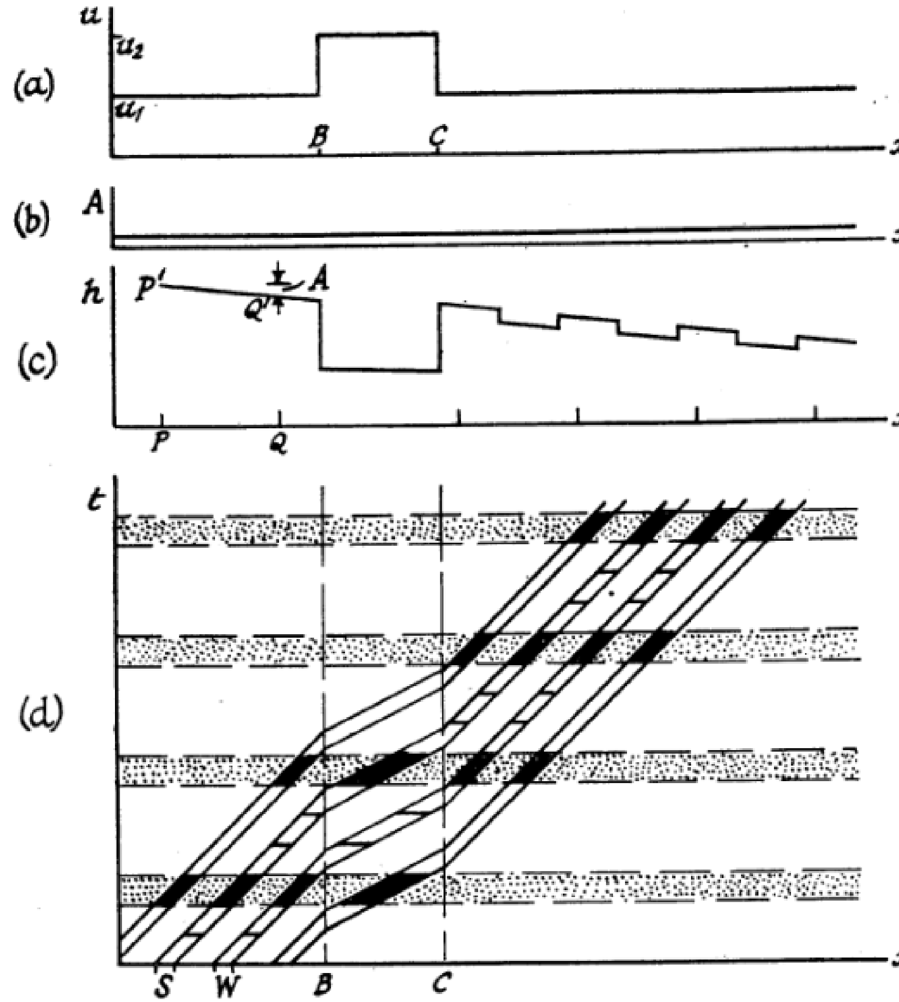
Austerdalsbreen, Norway



Juneau, Alaska

Forbes (1859)

Ablation phenomena 4: Ogives



Nye (1958)