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Glaciers in Equilibrium State

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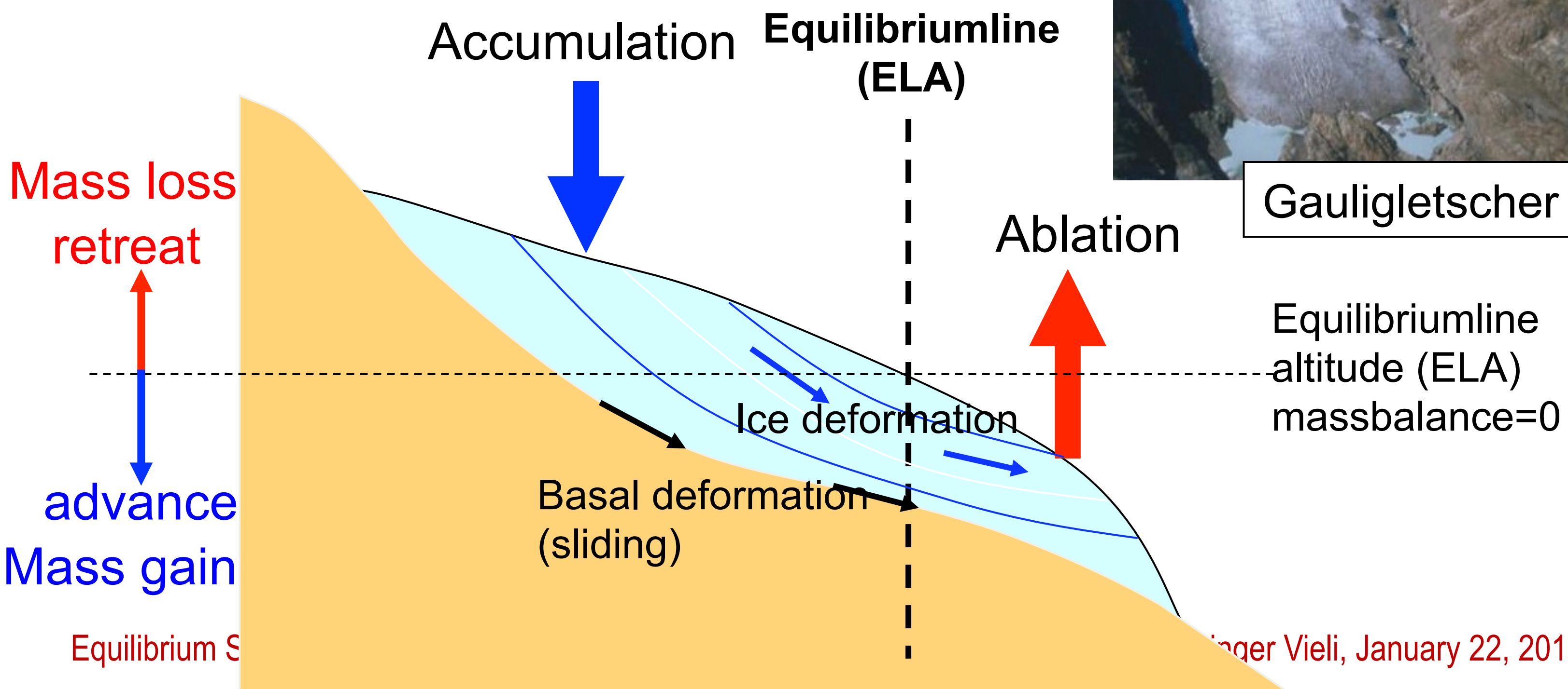
IHCAP – Indian Himalayas Climate Change Adaptation Programme
Capacity building programme "Cryosphere" Level-2 (Jan 5 – Feb 13, 2014)

How a glacier works

- Massbalance (climate):
  - Accumulation (precipitation)
  - Ablation (melting)
- Ice flow by:
  - Internal ice deformation
  - Basal deformation (sliding)

} Mass transfer

Gauligletscher (CH)

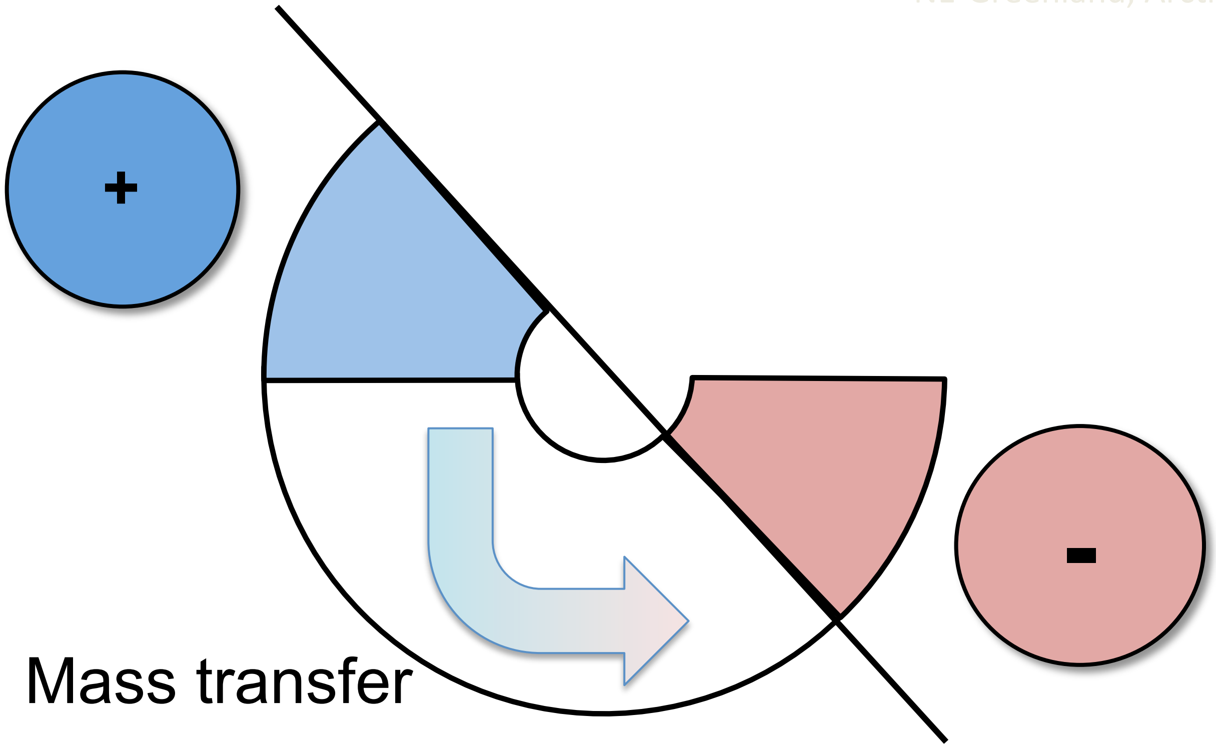


Glacier mass balance & flow

VAW, ETHZ (M. Lüthi)
http://people.ee.ethz.ch/~glacier/acam.html

Mass balance and climatic regimes

NE-Greenland, Arctic



In equilibrium net mass balance = 0

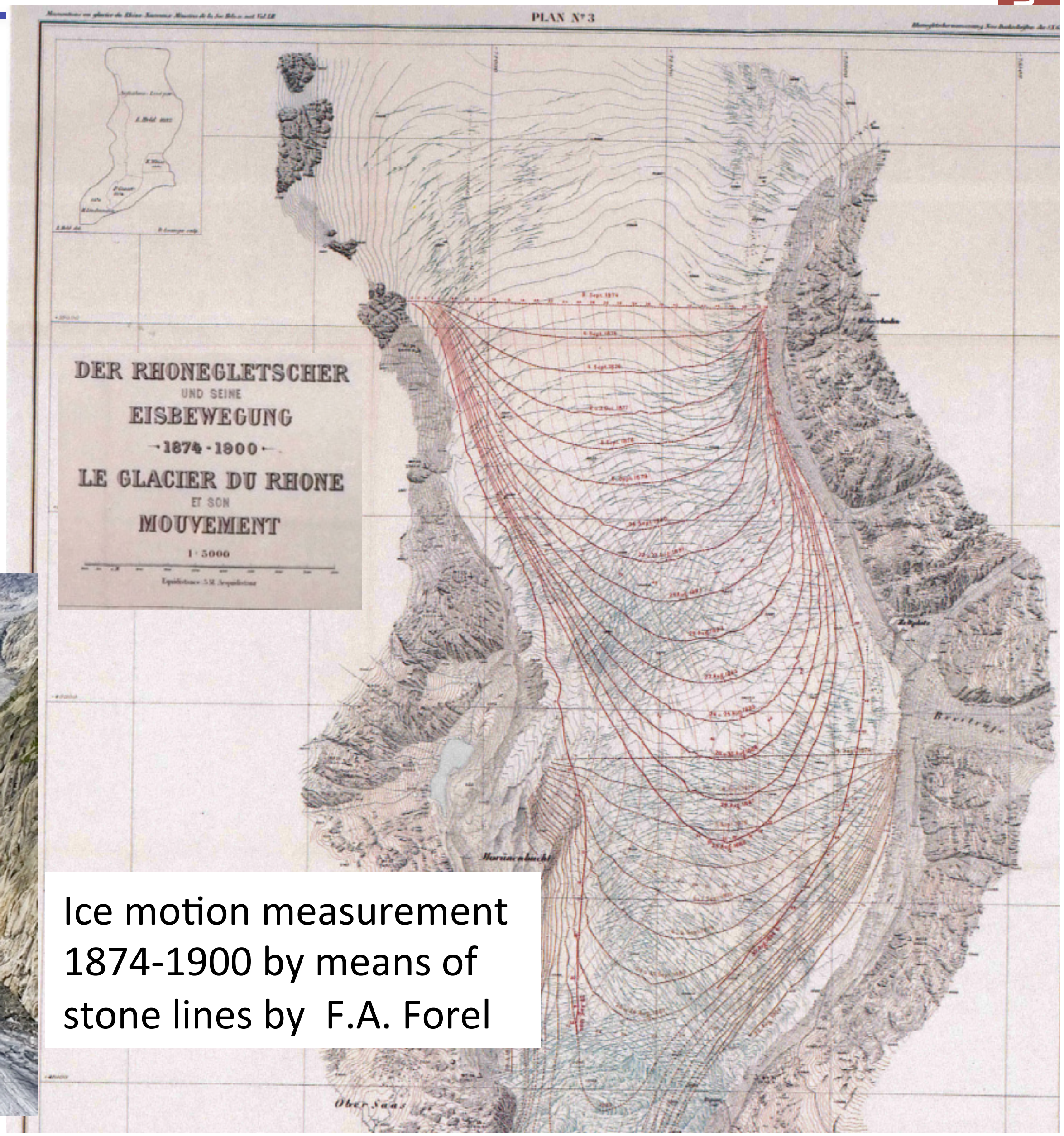
Ice movement

Ice flows

- Internal deformation
- Basal motion

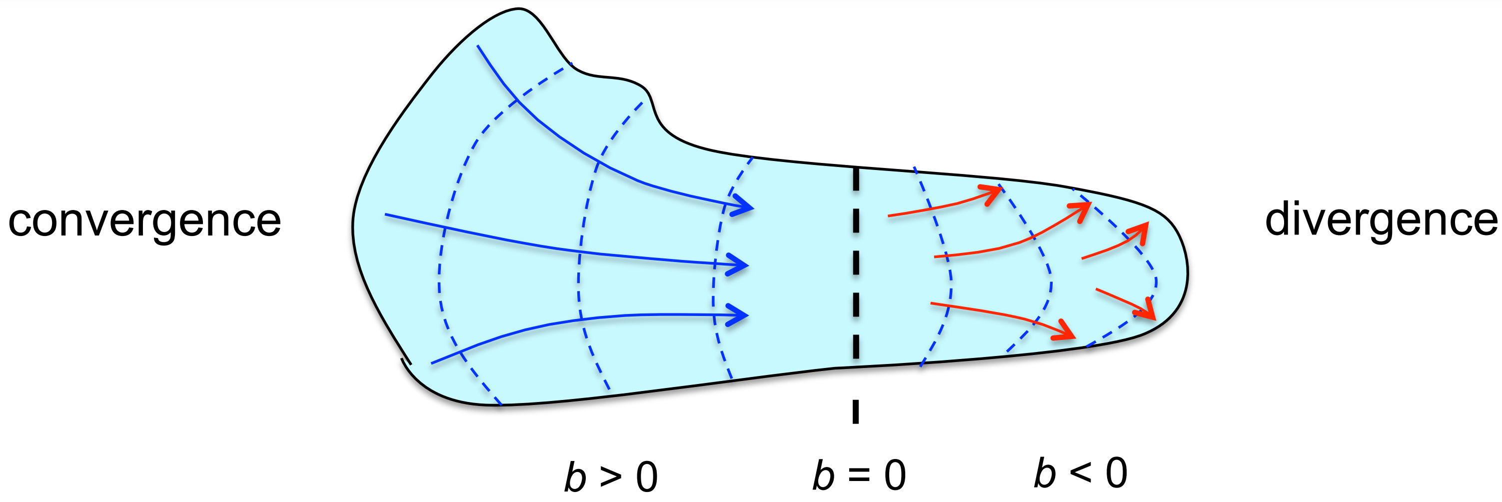
Ogives (flowbands) on Mer de Glace (France).

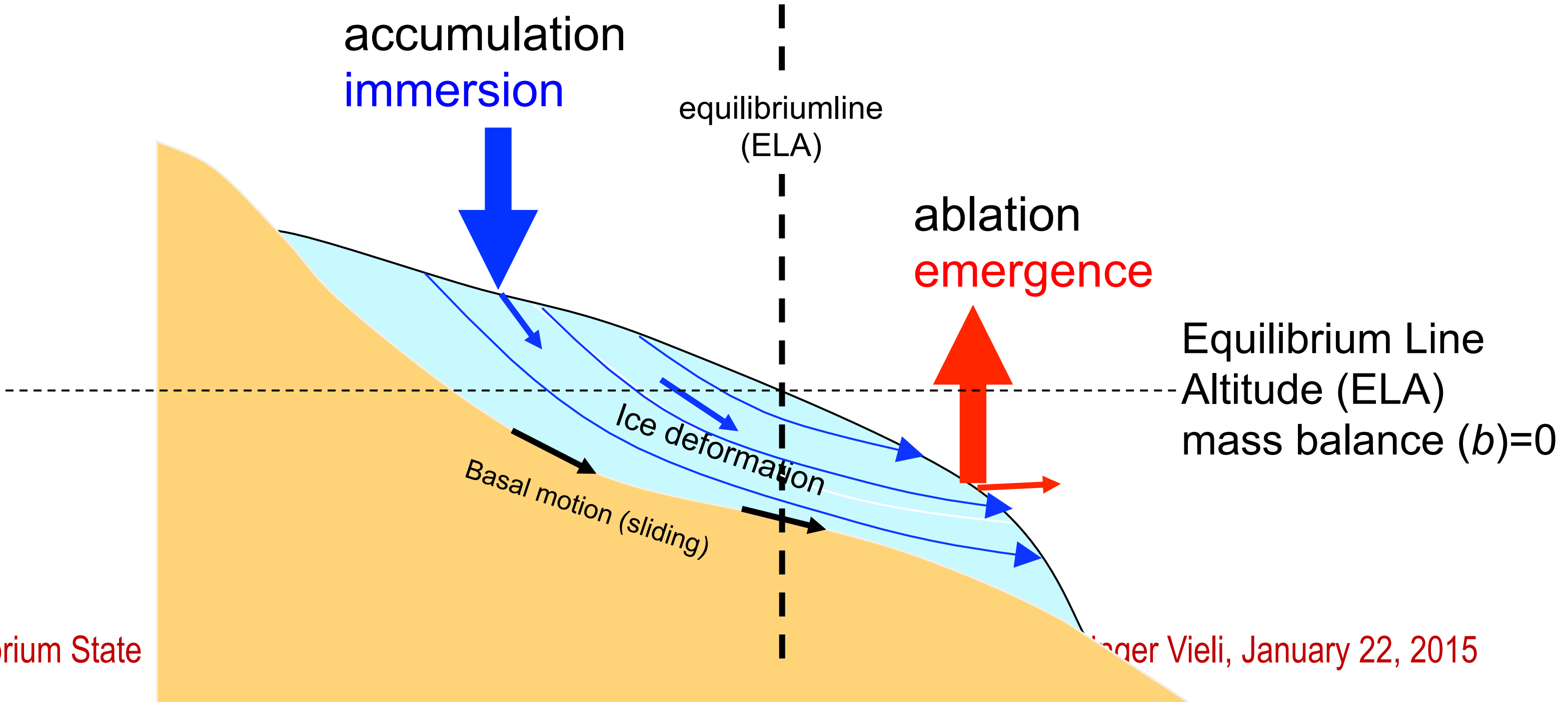
from glacieronline http://www.swisseduc.ch/glaciers/



Ice motion measurement 1874-1900 by means of stone lines by F.A. Forel

Glacier flow





Ice Flux

- Ice from accumulation area ➔ accumulated ice needs to move through to the ablation area
- Ice volume flux:

$$Q = W \cdot \bar{H} \cdot \bar{u}$$

W: width of cross-section
H̄: width-averaged ice thickness
ū: depth-averaged flow velocity

$W\bar{H}$ = cross-sectional area

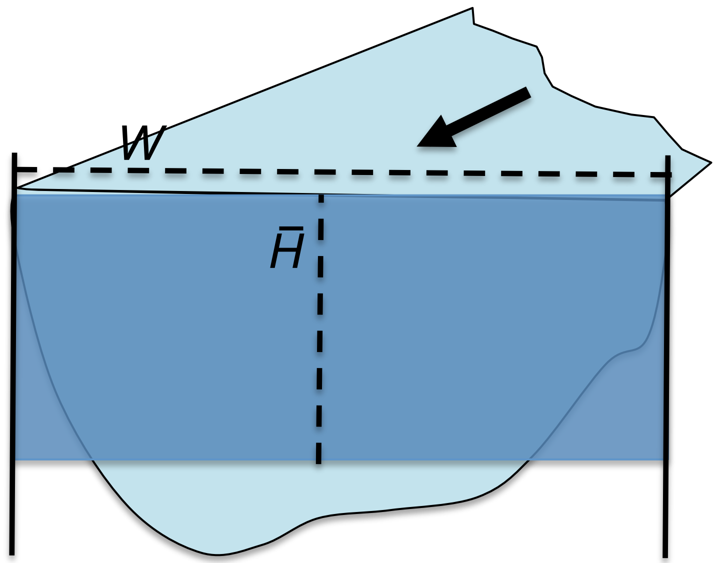
- Flux at position *x*

(x): local

$$Q(x) = W(x) \cdot \bar{H}(x) \cdot \bar{u}(x)$$

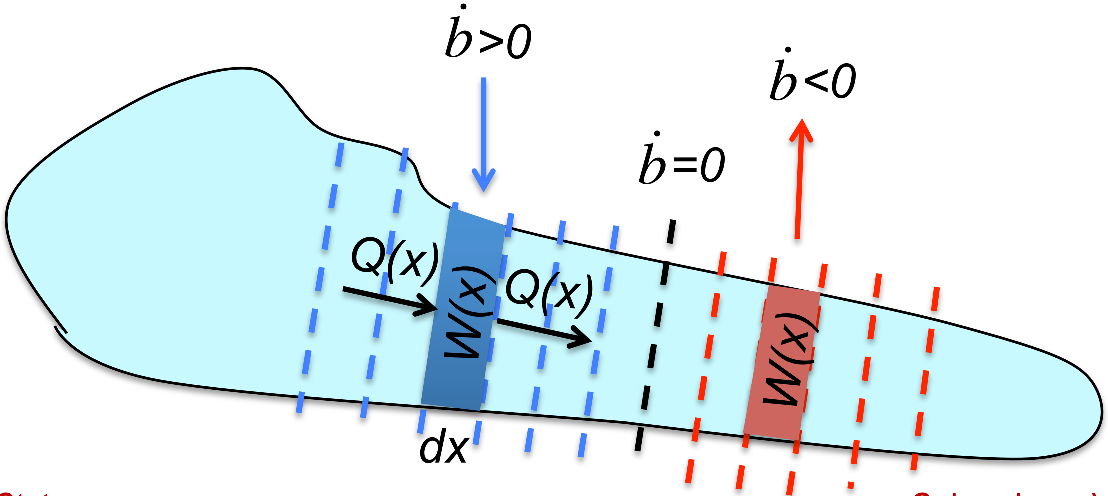
- Velocity at position *x*:

$$\bar{u}(x) = \frac{Q(x)}{W(x)\bar{H}(x)}$$



Equilibrium State (Balance Flux / Velocity)

- *'Balance Flux / Balance Velocity'*
- Based on the principal of mass conservation
  - conservation of volume
  - (nearly) incompressible medium
- Balance between mass input and output
  - Surface mass balance is constant (equilibrium), constant climate
- Add up (integrate) accumulation/ablation along the flow line (glacier surface; top to bottom) ➔ balance flux Q_{bal}



Equilibrium State (Balance Flux / Velocity)

- *Summing up the balance: 'Balance Flux'* Q_{bal}
- Assuming:
  - a constant climate
  - a constant surface mass balance (in equilibrium)

$$Q_{bal}(x) = \int_0^x W(x)\dot{b}_i(x)\,dx = \left(-\int_x^L W(x)\dot{b}_i(x)\,dx\right)$$

$\dot{b}_i(x) = \dot{b}/\rho_i$: *volumetric specific balance rate* [$m^3\ m^{-2}\ a^{-1} = m\ a^{-1}$; $\rho_i \approx 917\ kg\ m^{-3}$] or *ice-equivalent specific mass balance* (thickness per unit time added to the glacier)

$\dot{b}(x)$: *specific balance rate* [$kg\ m^{-2}\ a^{-1}$]

Equilibrium Velocities

➔ balance flux

$$Q_{bal}(x) = \int_0^x W(x)\dot{b}_i(x)\,dx$$

$$Q_{bal}(x) = \overline{u}(x)W(x)H(x) = \overline{u}(x)F(x)$$

F: cross-sectional area WH

➔ balance velocity

$$\overline{u}_{bal}(x) = \frac{Q_{bal}(x)}{W(x)H(x)} = \frac{1}{H(x)} \int_0^x \dot{b}(x)\,dx$$

$$\overline{u}_{bal}(x) = \frac{Q_{bal}(x)}{F(x)}$$

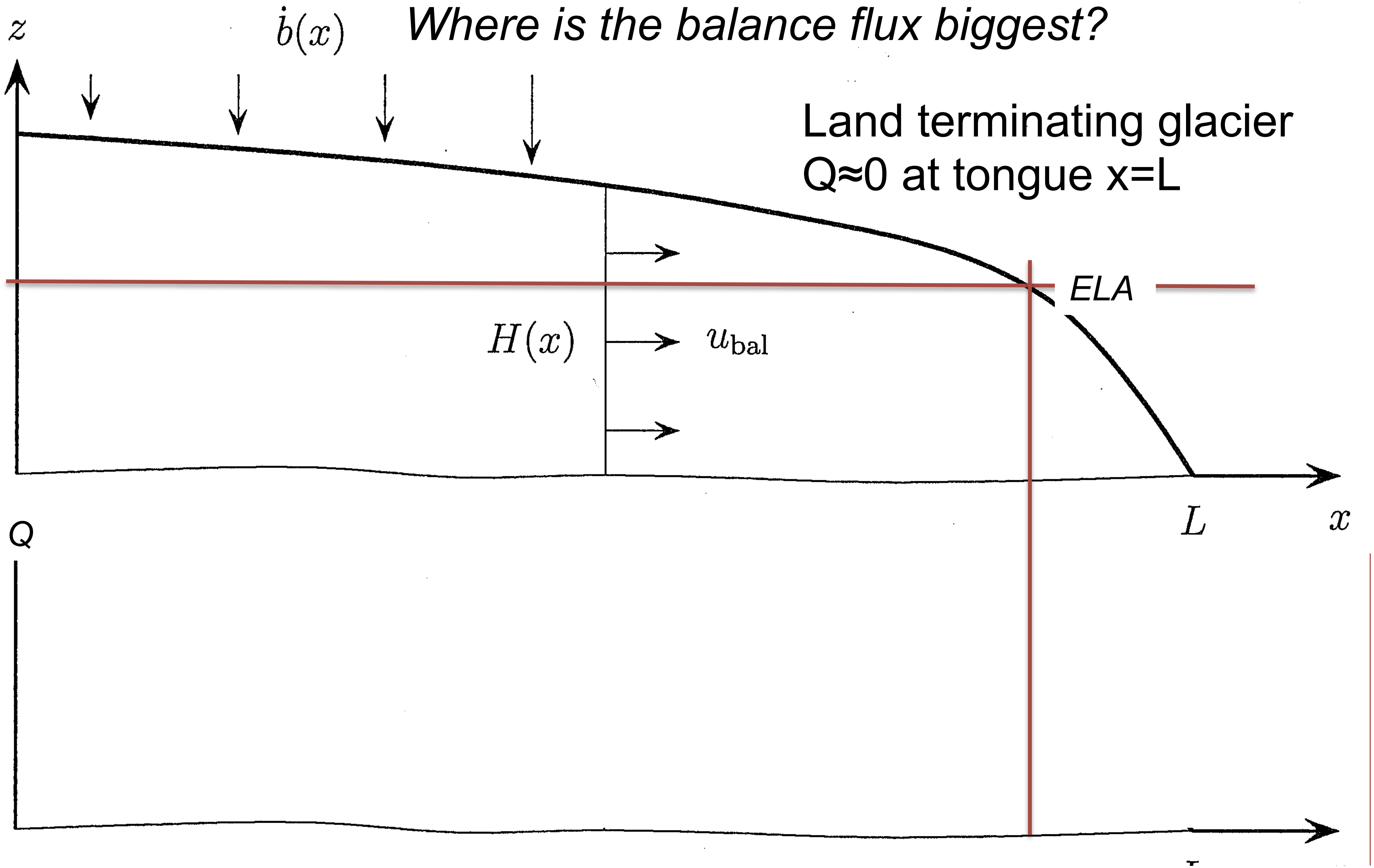
- Under a constant climate and glacier in balance:

$$Q_{bal}(x) = Q(x)$$

Equilibrium Velocities

Where is the balance flux biggest?

Land terminating glacier
Q≈0 at tongue x=L



Equilibrium Velocities

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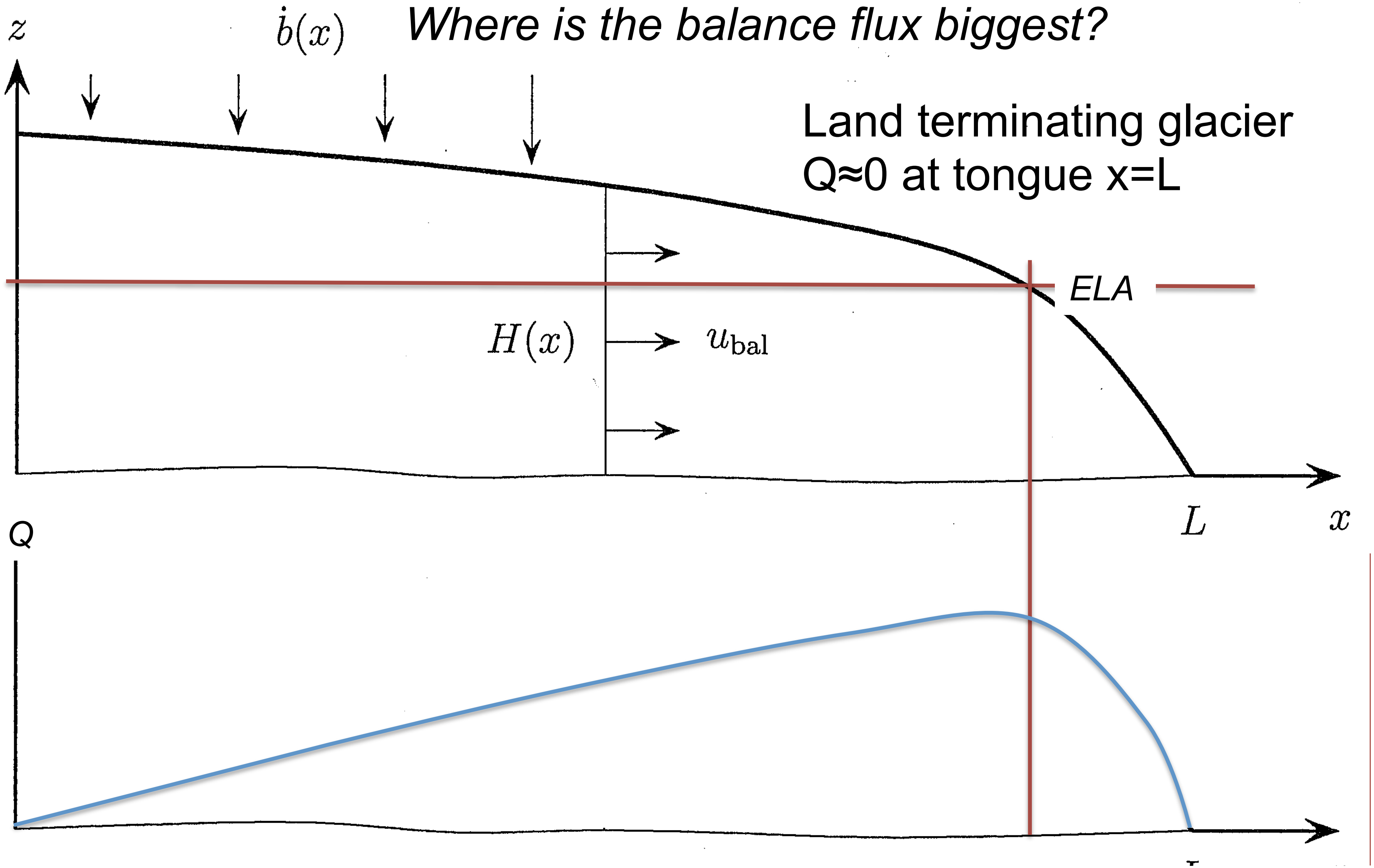
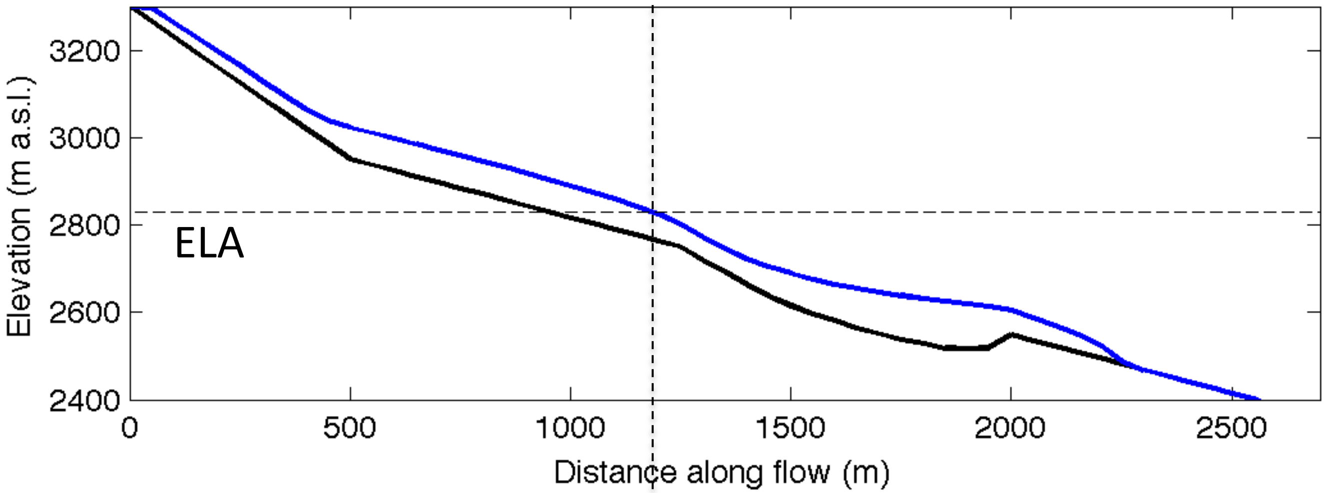
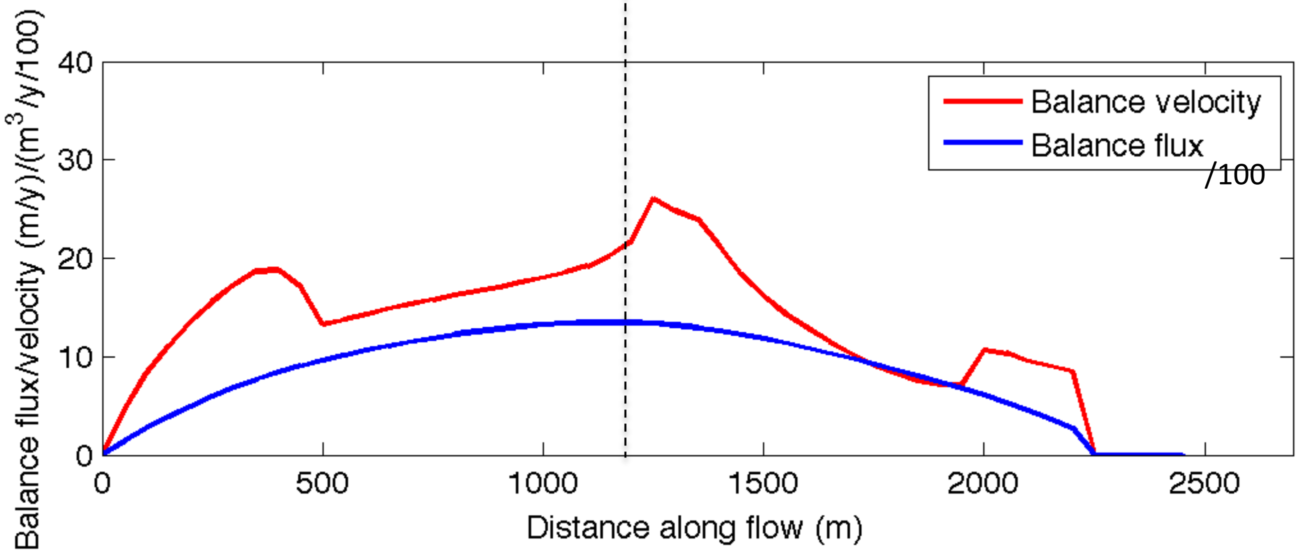


Balance flux/velocity

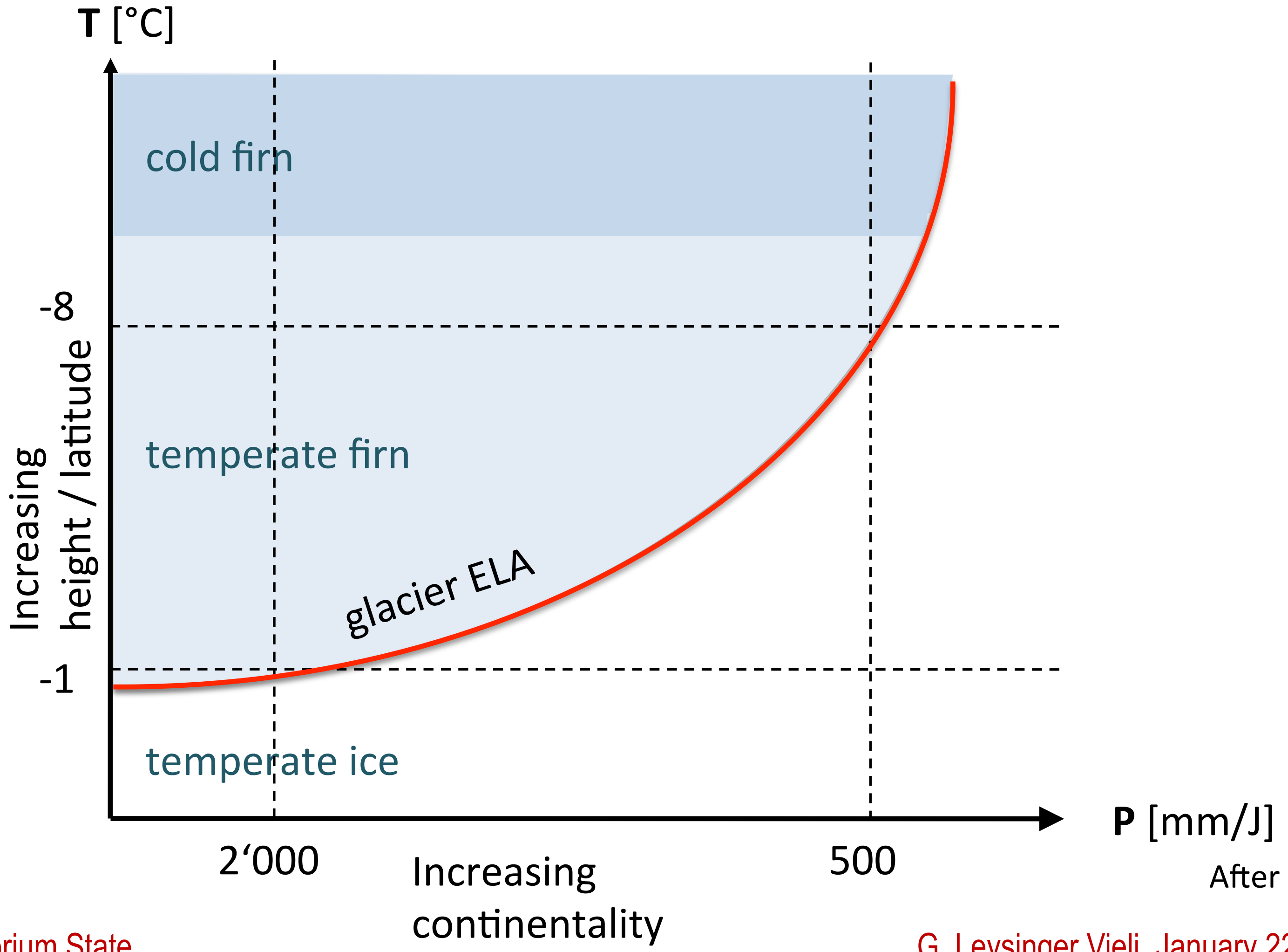




$$\overline{u}_{bal}(x) = \frac{Q_{bal}}{W \cdot H}$$

T/P-relation of the Cryosphere

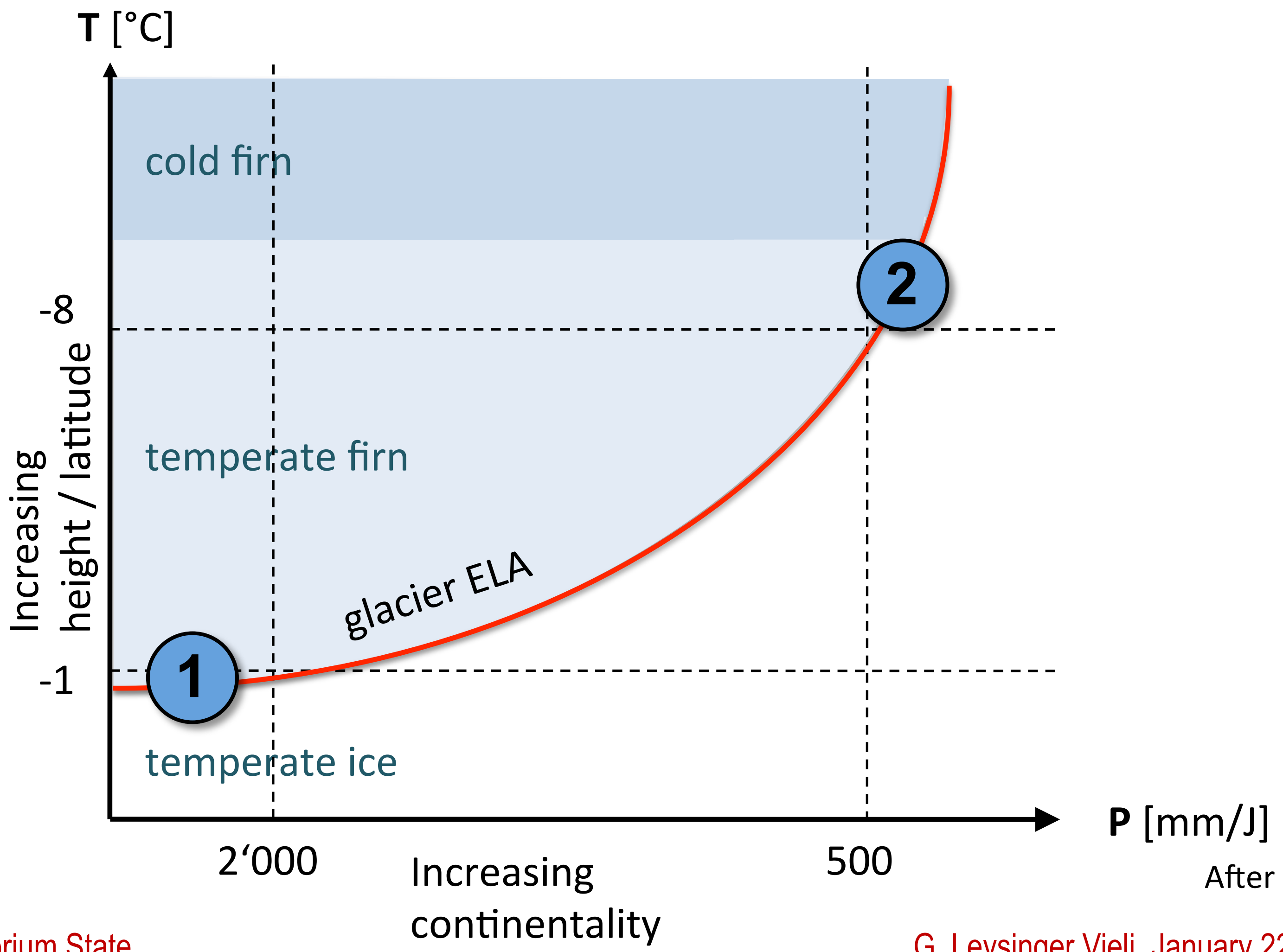
Climatic regime (temp./prec.) for glaciers



After Haeberli 2002

T/P-relation of the Cryosphere

Climatic regime (temp./prec.) for glaciers

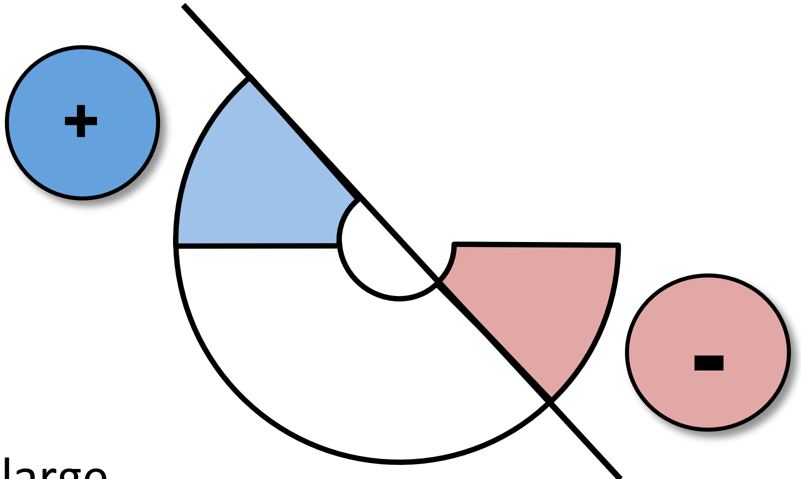


After Haeberli 2002

Massbalance and climatic regimes

1 Maritime glacier

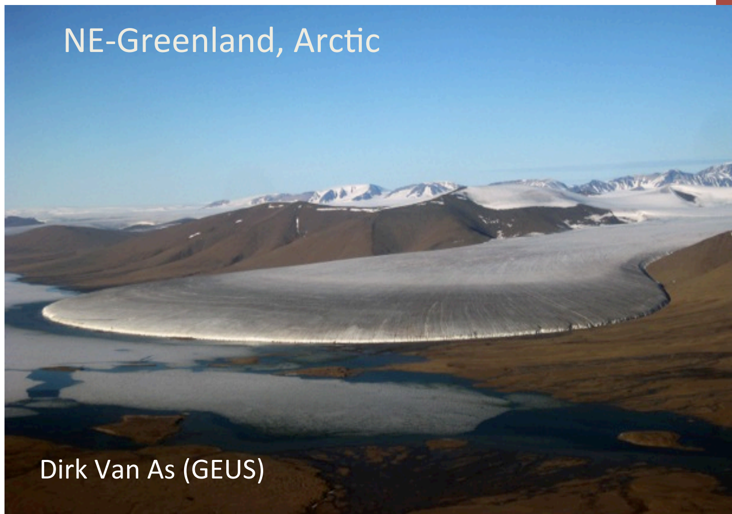
http://www.swisseduc.ch/glaciers/glossary/temperate-glacier-de.html

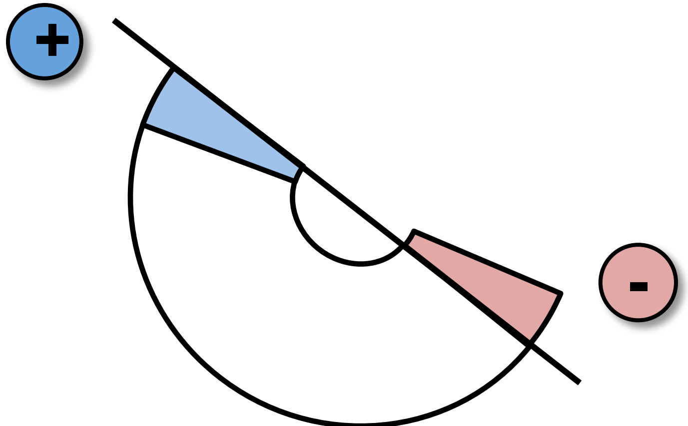


Q_{ELA} large

Large masstransfer

2 Continentale glacier





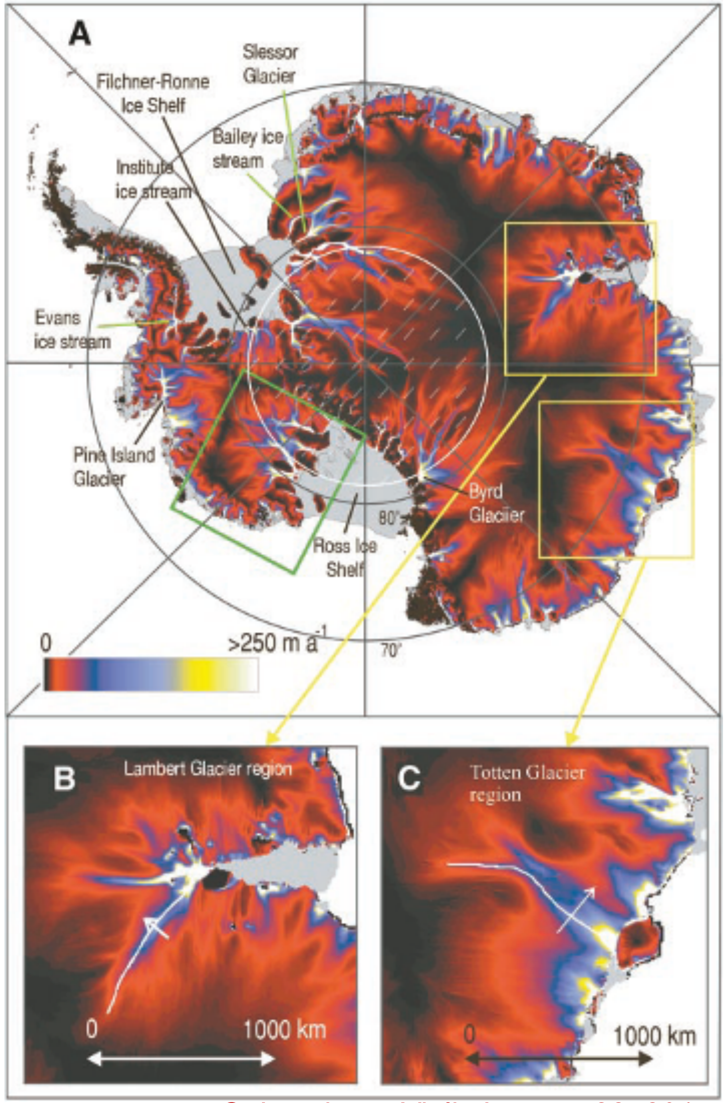
Q_{ELA} small

Small masstransfer

Balance velocities – ice sheets

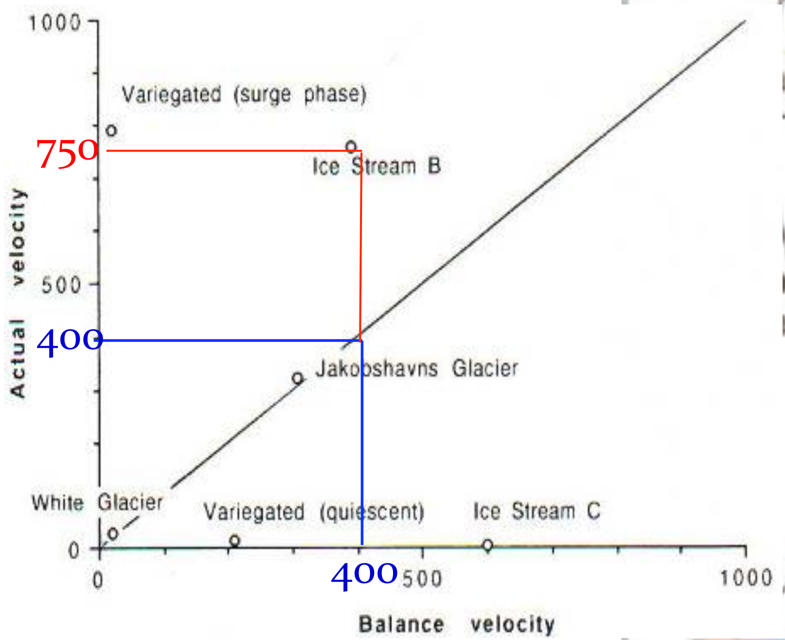
- Recent advances have seen the balance velocities of the large ice sheets calculated (e.g. Bamber et al., 2000)
- Remote sensing has created new datasets on:
  - Surface slope
  - Ice thickness
  - Mean surface net balance
- Discovery of ice tributaries far inland (Bamber et al., 2000)
- Reasonable agreement between balance velocities and measured but also areas of disagreement, which suggests some parts of the ice sheet are not in equilibrium

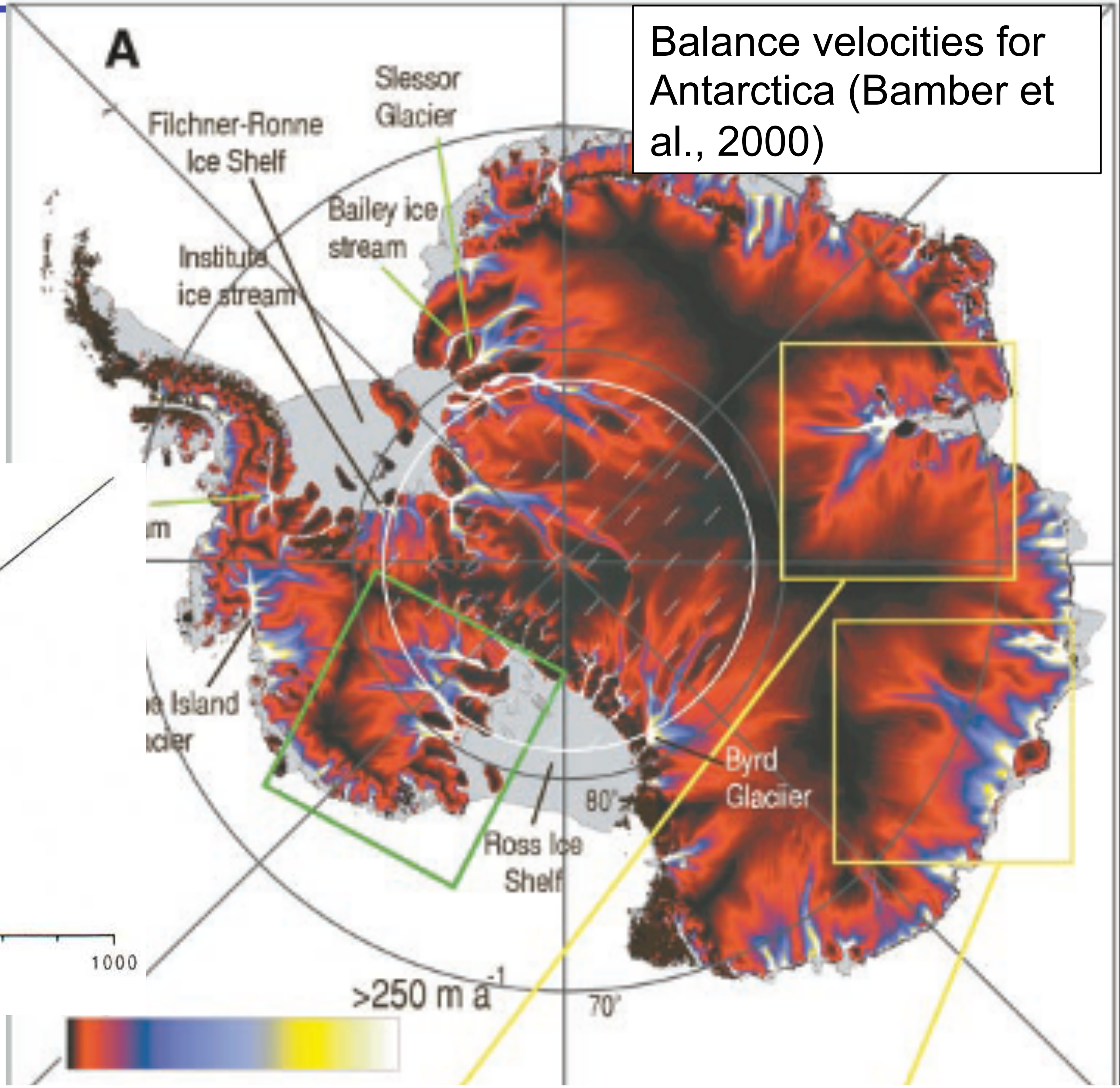
Balance velocities for Antarctica (Bamber et al.



Balance Velocitites, Antarctica

- Calculated from DEM and accumulation rates
- Flow structure of ice sheet (ice streams)
- 'Virtual' flow velocities

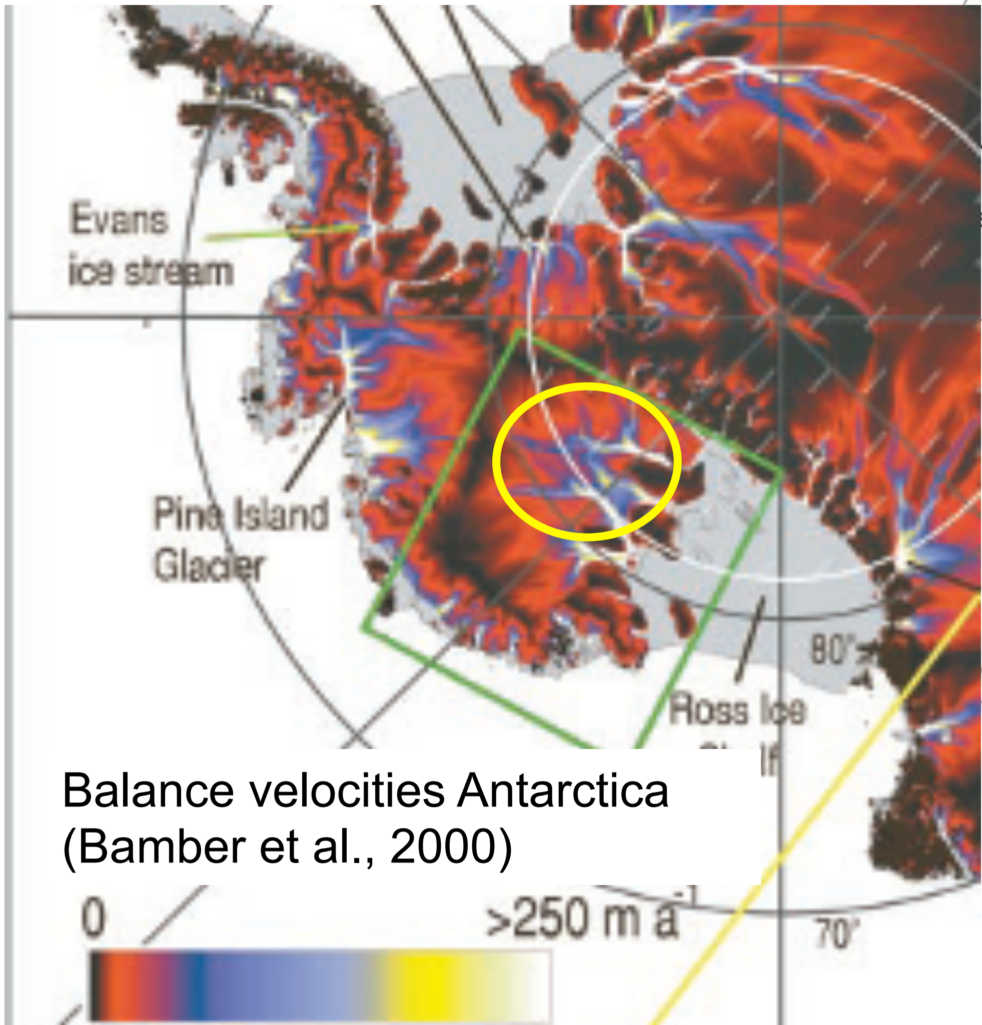




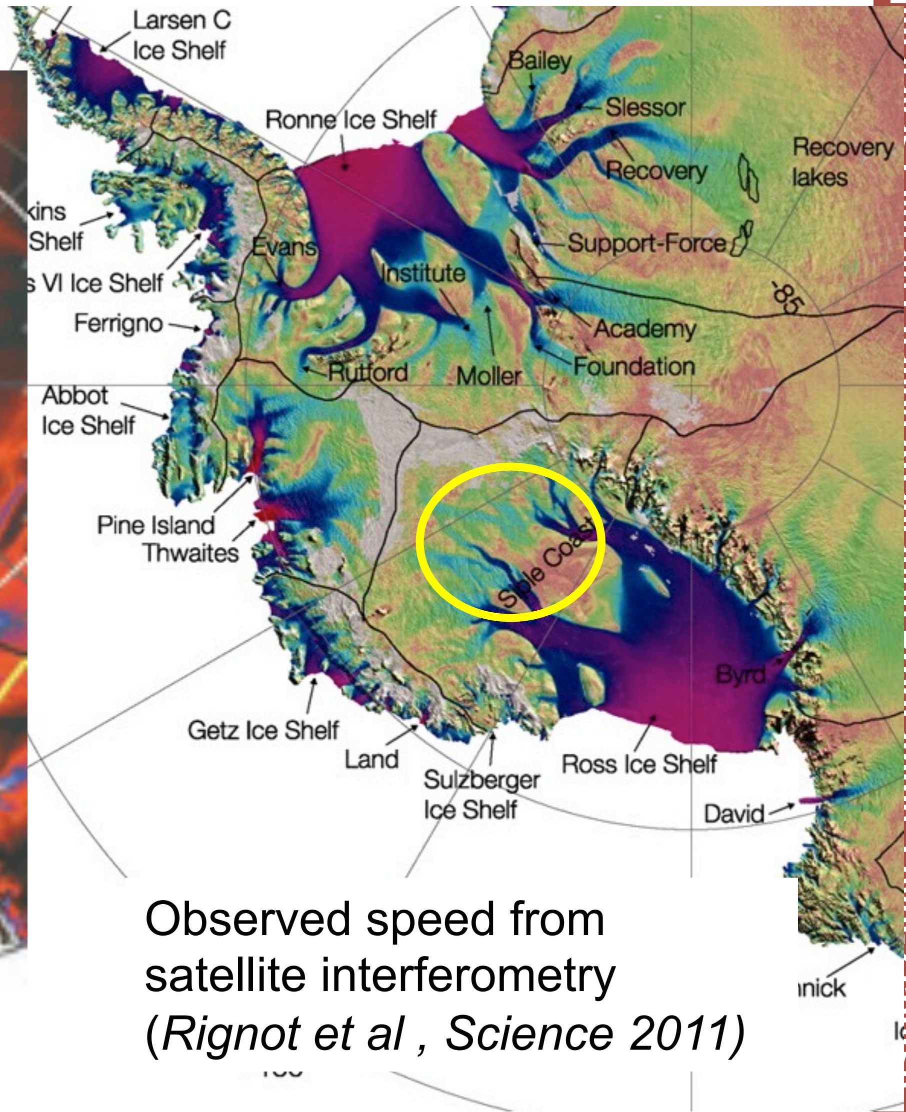
Balance velocities for Antarctica (Bamber et al., 2000)

Equilibrium State After Benn&Evans, 1998

Balance Velocitites, Antarctica



Balance velocities Antarctica
(Bamber et al., 2000)



Observed speed from satellite interferometry
(*Rignot et al , Science 2011)*

Summary – equilibrium state

- Over long time periods, glacier flow is a function of:
  - Climatic inputs
  - Size and geometry of catchment
- Balance flux theory suggests that for a glacier of constant shape and size, ice flow through a cross-section must balance the accumulation up-glacier and ablation down-glacier to maintain a steady state
  - Mass conservation
- No physical knowledge on ice flow or ice deformation
- A first approximation of ice flux and ice flow
  - Gives the order of magnitude for ice flux and velocity

$$Q_{bal}(x) = \overline{u}(x)F(x)$$

$$\overline{u}_{bal}(x) = \frac{Q_{bal}}{W \cdot H}$$

!!!! Strictly only valid in equilibrium state (never the case)

This theoretical treatment suggests that:

- Glaciers with steeper mass balance gradients tend to flow more rapidly
- However, topographic funnelling is an important influence which complicates, i.e. where large catchments of ice are forced to narrow
- Also, glacier driving forces and resistive forces may not be in equilibrium with climate
- Thus, measured velocities commonly differ from balance velocities

Reading suggestions – in general

- *Benn und Evans (2010)* textbook giving a very good qualitative overview (good descriptions given) about physical processes and phenomenon of glaciers.
- *Cuffey & Paterson (2010*) textbook covering the physical processes on and in the glacier
- *Hooke (2005)* good introduction to glacier mechanics.
- The re-print by *Post und Chapelle (2000)* has spectacular and informative photos and good explanation to many glaciological phenomena