Capacity Building Workshop on Glaciology and Disaster Risk Reduction in Bhutan

20 – 25 May 2019

Tomas Saks
tomas.saks@unifr.ch

Response of glaciers to climate change

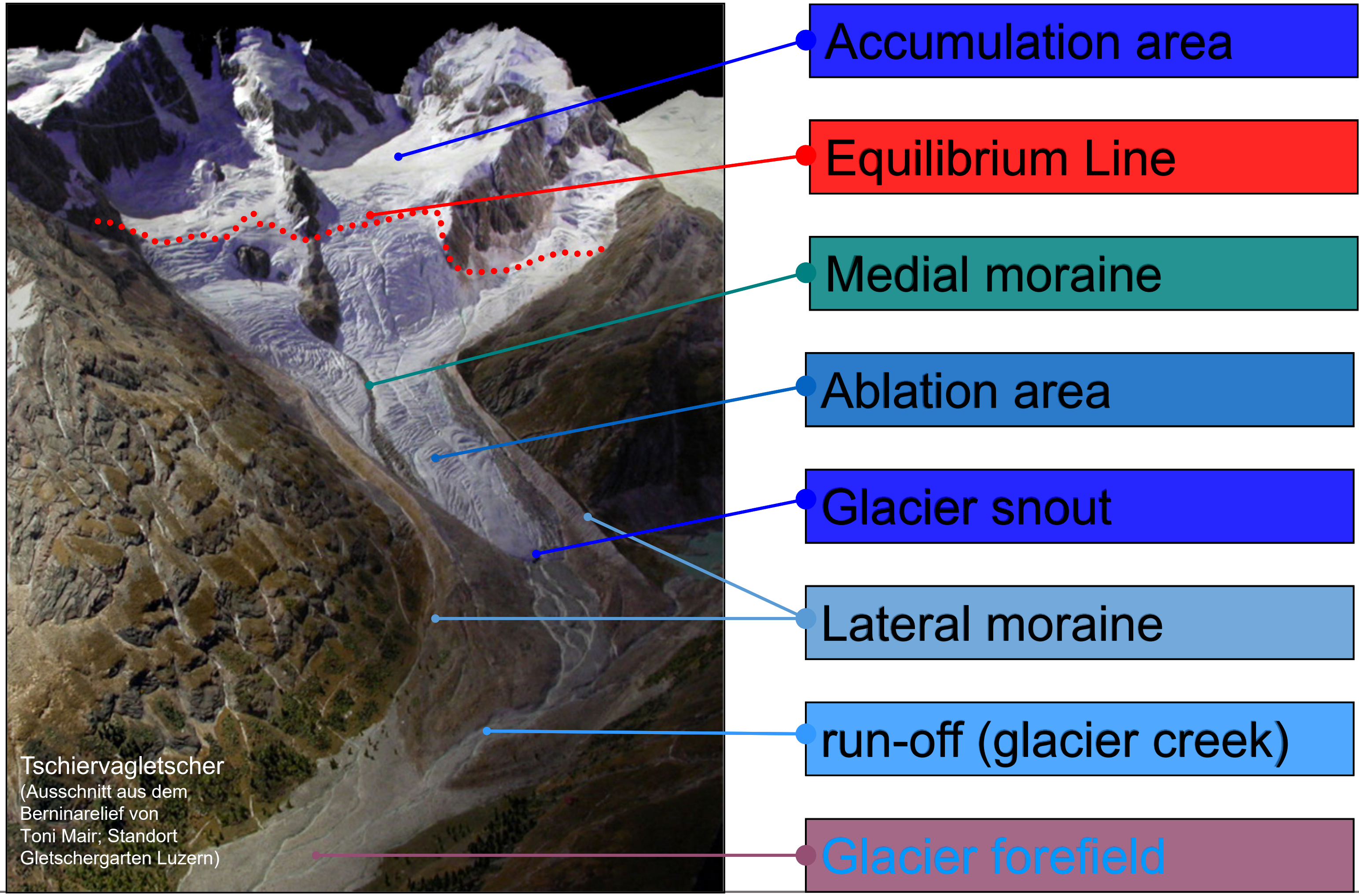
Goals

- Understanding basic driving mechanisms of glaciers
- Understand the basic principles of measuring glacier (surface) mass balance
- Establish a first link between theory and practical application

IPCC, 2007, WG I, chapter 4

What is a glacier?

Basic Terminology

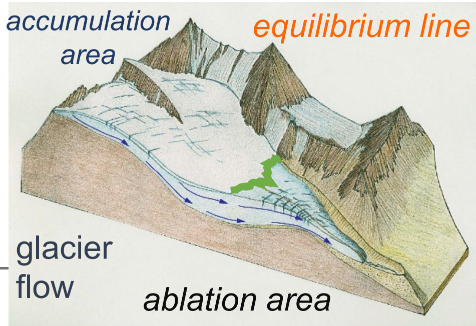


the central processes on a glacier

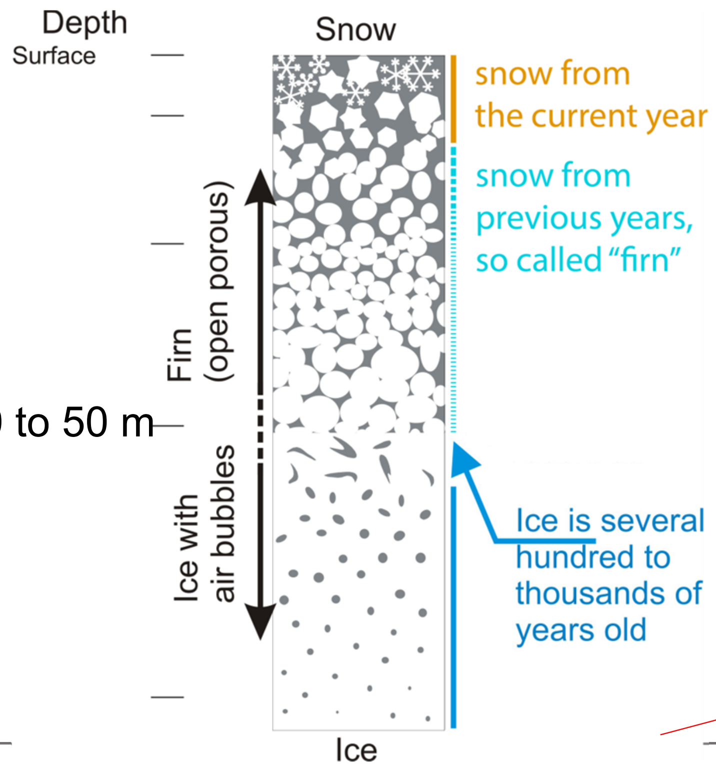
snowfall

melt

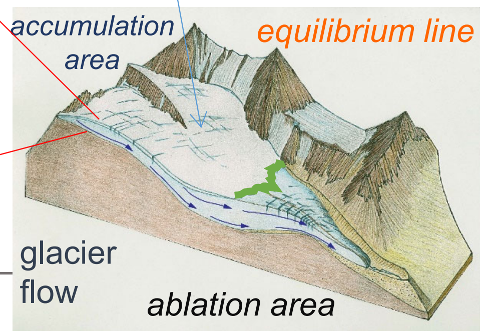
ice flow



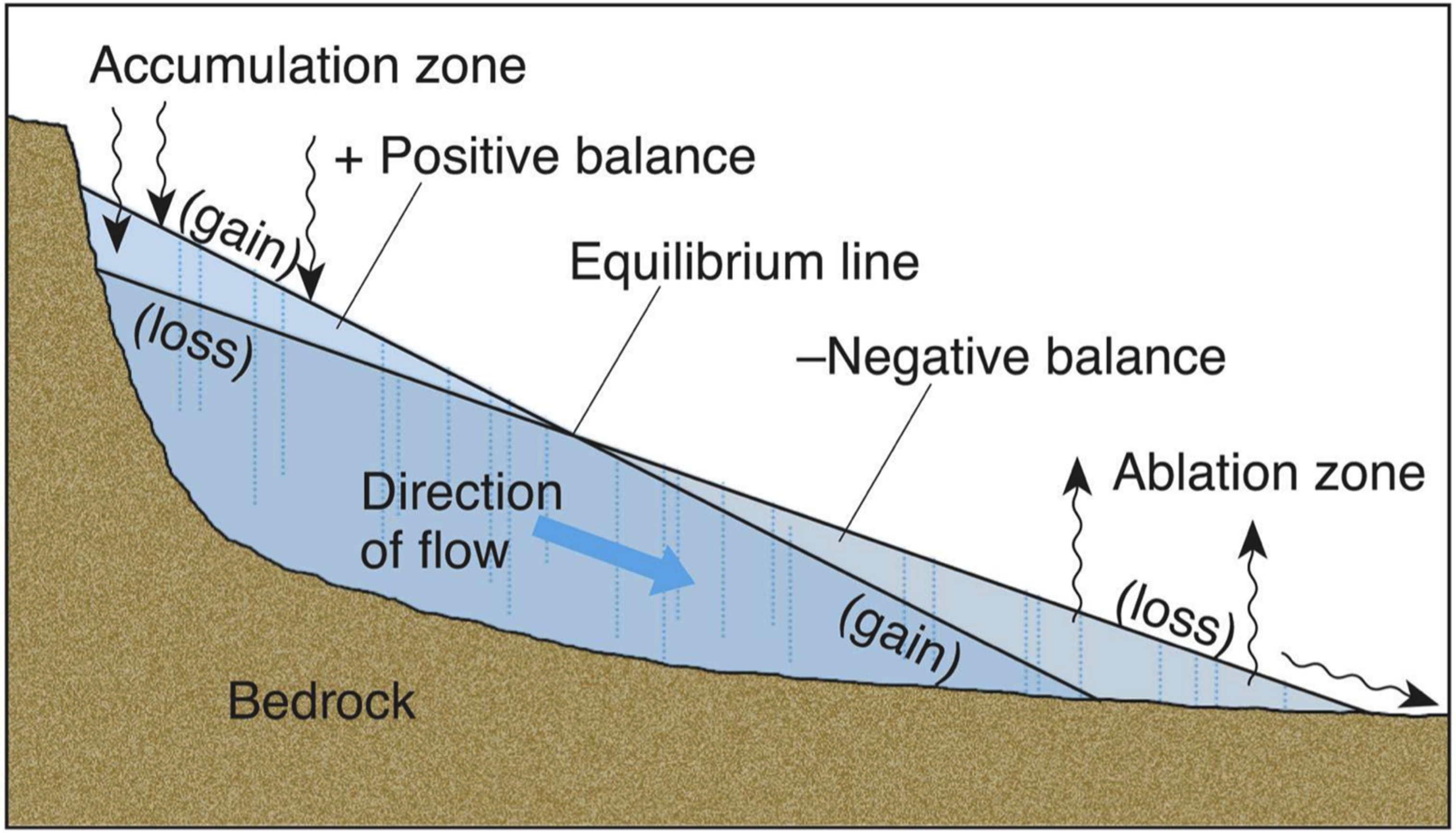
Snowfall


Depth
Surface
Snow
snow from
the current year
snow from
previous years,
so called "firn"
Firn
(open porous)
10 to 50 m
Ice with
air bubbles
Ice is several
hundred to
thousands of
years old
Ice

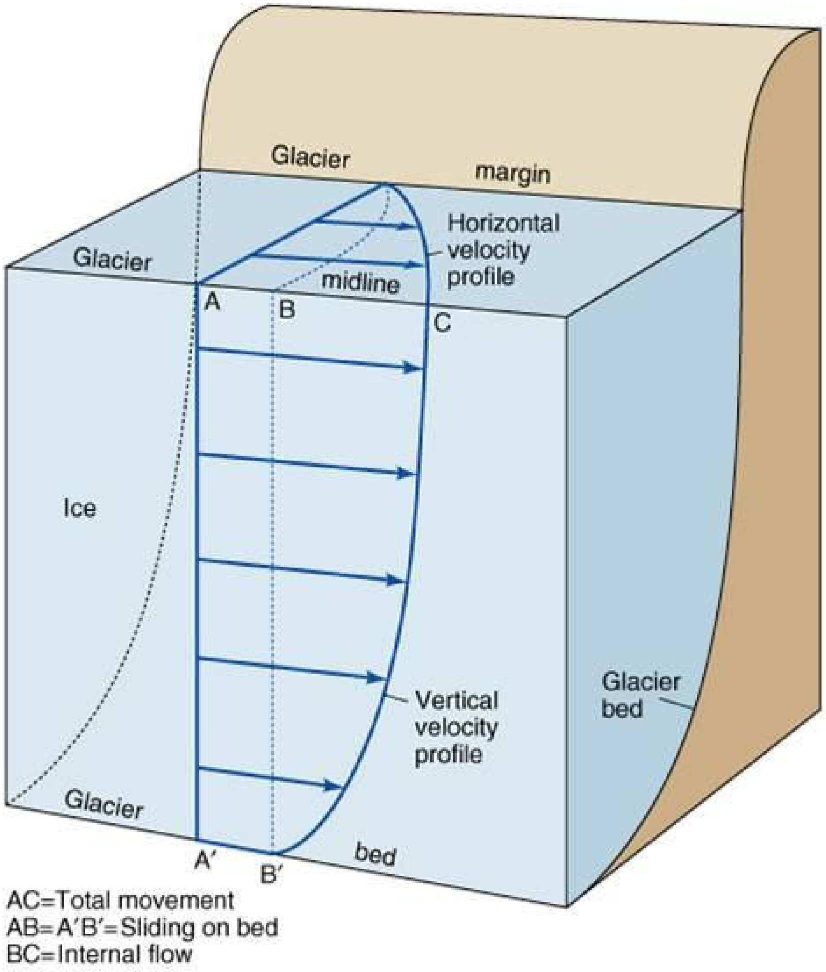

snowfall


accumulation
area
equilibrium line
glacier
flow
ablation area

Basic Terminology



Ice flow



Internal deformation

Basal motion (slip)

Lateral drag

Ice flow

Ogives (flowbands) on Mer de Glace (France)
https://www.swisseduc.ch/glaciers/alps/mer_de_glace/index-de.html?id=1

Glacier flow – continuity analysis

Equilibrium Speed

$$u_{bal(x)} = \frac{1}{H_{(x)}} \int_0^x \dot{b}_{(x)} dx$$

$u_{bal(x)}$ = Equilibrium Speed

$H_{(x)}$ = local glacier thickness

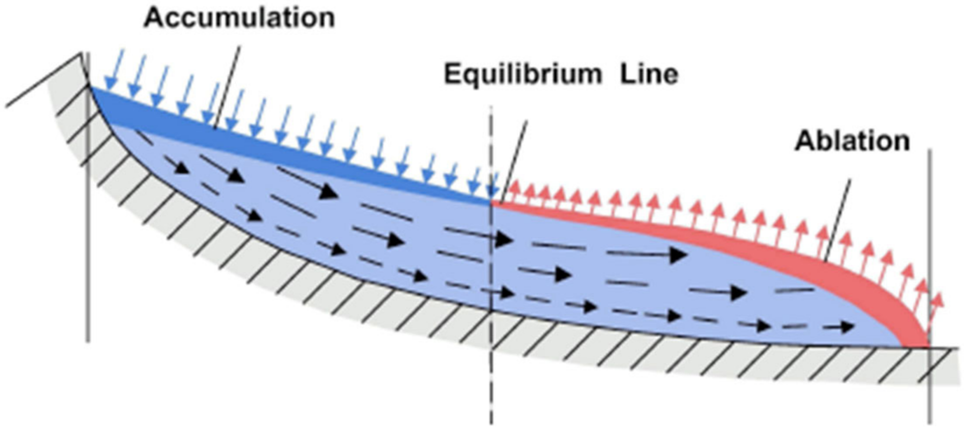
$\dot{b}_{(x)}$ = local Mass Balance rate

Ice Flow

$$Q_{bal(x)} = \int_0^x \dot{b}_{(x)} dx$$

$Q_{bal(x)}$ = Ice flow

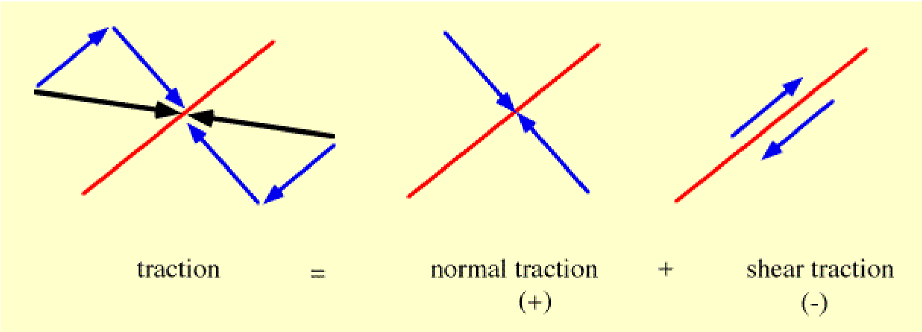
$\dot{b}_{(x)}$ = local Mass balance rate



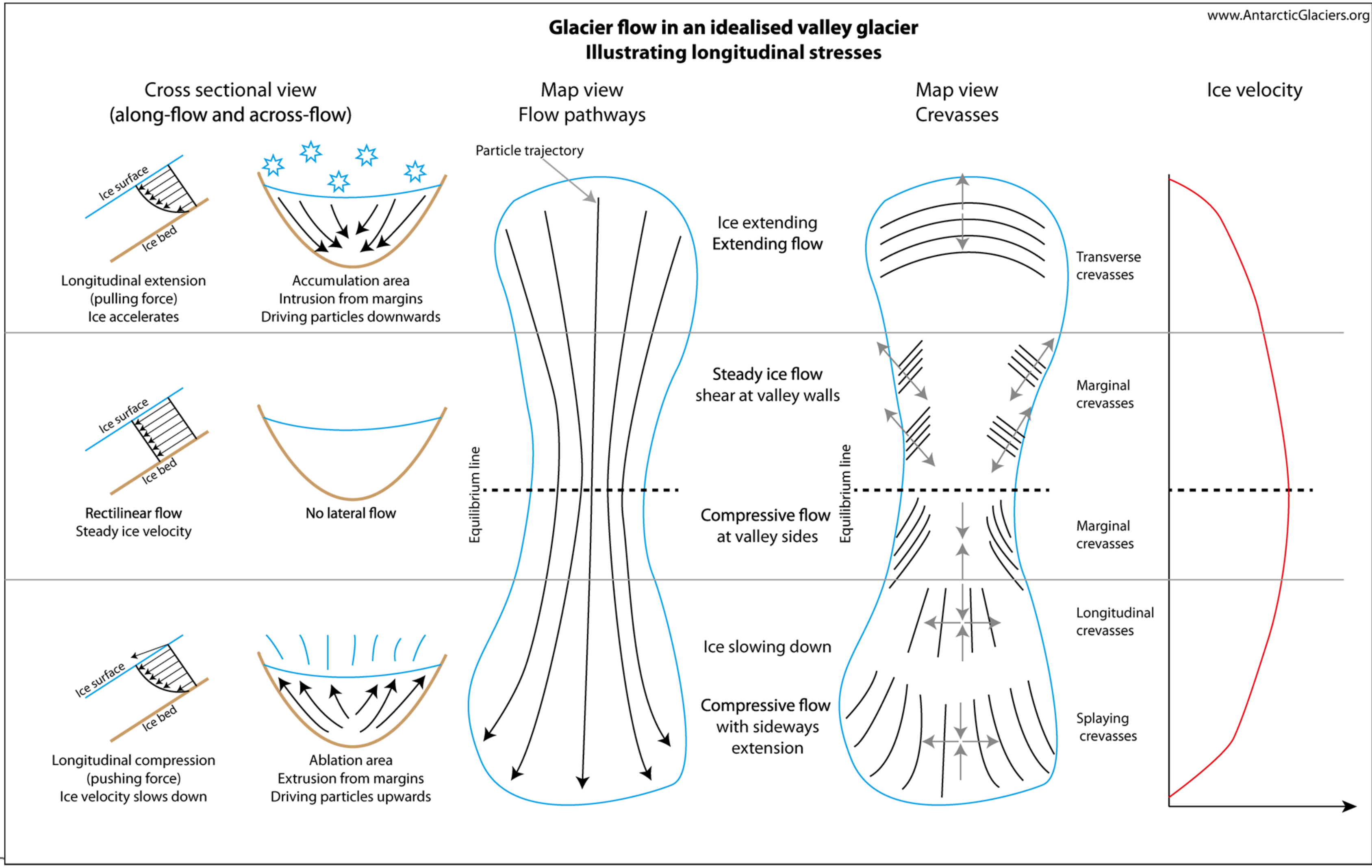
In the equilibrium state (mass balance=0, geometry and density=constant and ice as an incompressable material) for each cross section of a glacier.

Stress

Name	Symbol	Definition	Unit
stress	σ, τ	Force/Area	
Direct stress	σ	Force $\perp$ Area	1 Pa = 10^{-5} bar = 1 N m^{-2} = 1 kg m^{-1} s^{-2}
Shear stress	τ	Force || Area	1at = 0.981 bar



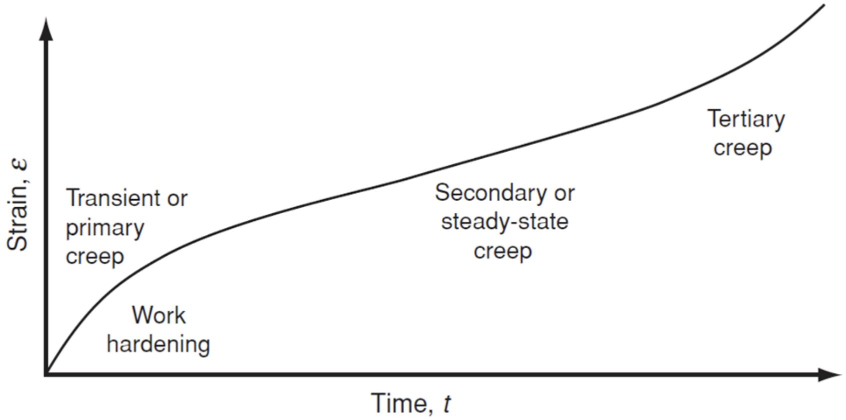
Stress and formation of crevasses



Strain

Name	Symbol	Definition	Unit
Strain (Deformation)	ε	Deformation Length change / length (Δl/L)	1
Strain rate	$\dot{\varepsilon}$	Deformation pro time ((Δl/L)/t)	s^{-1} a^{-1}

Strain rate



$$\dot{\varepsilon} = A\sigma^{n}$$

(Glen‘s flow law)

$\dot{\varepsilon} =$ Strain Rate (s^{-1})

$\sigma =$ Stress (bar or Pa)

$A =$ Flow Law parameters ($s^{-1}kPa^{-3}$)

$n =$ Flow parameter (in Ice ≈ 3)

Strain rate

The flow law parameters A and N (=3) are determined from borehole and tunnel experiments.

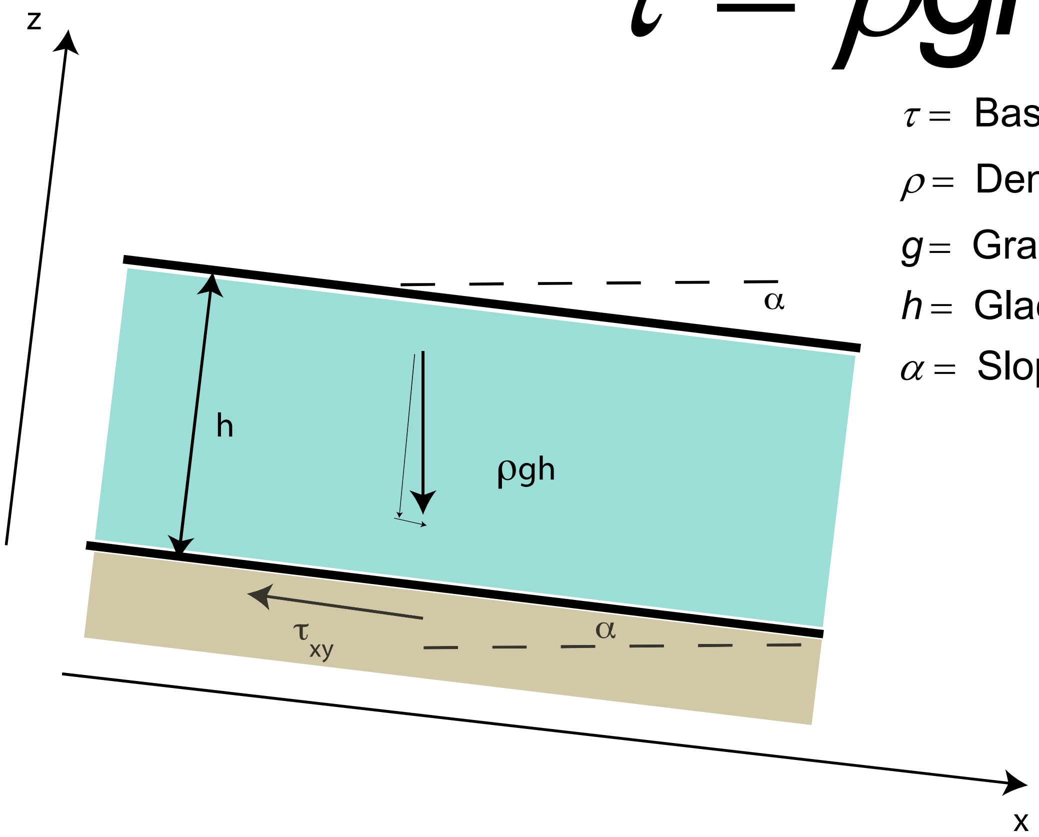
T(°C)	$A(s^{-1}Pa^{-3})$
0	2.4×10^{-24}
−2	1.7×10^{-24}
−5	9.3×10^{-25}
−10	3.5
−15	2.1
−20	1.2×10^{-25}
−25	6.8×10^{-26}
−30	3.7
−35	2.0
−40	1.0×10^{-26}
−45	5.2×10^{-27}
−50	2.6

A is dependent on:

- The temperature (warm=soft, cold=stiff)
- The unfrozen water content
- The crystal size (small crystals=soft)
- Concentration controls the dirt (water+internal friciton+crystal size

Basal shear stress

$$\tau = \rho g h \sin\alpha$$



$\tau =$ Basal shear stress (bar or Pa)

$\rho =$ Density (kg m^{-3})

$g =$ Gravitational Acceleration (m s^{-2})

$h =$ Glacier thickness (m)

$\alpha =$ Slope

Basal shear stress

$$\tau = f \rho g h \sin\alpha$$

$\tau =$ basale shear stress (bar or Pa)

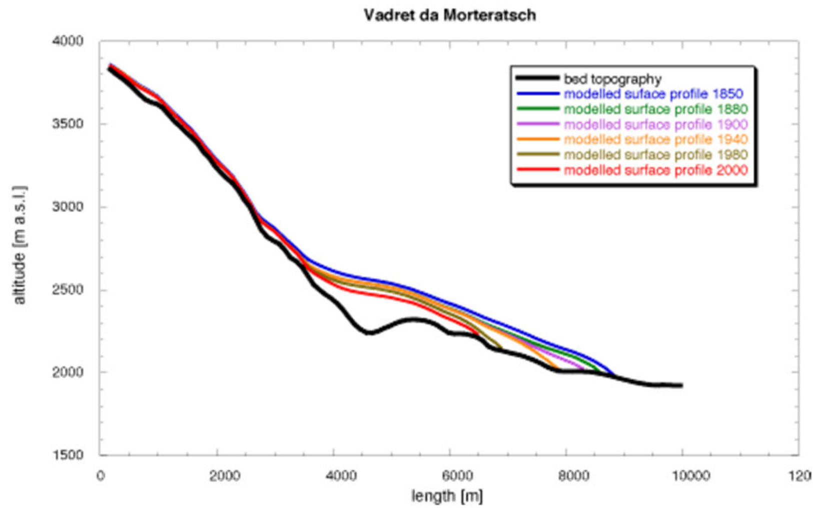
$\rho =$ Density (kg m^{-3})

$g =$ Gravitational acceleration (m s^{-2})

$h =$ Glacier thickness (m)

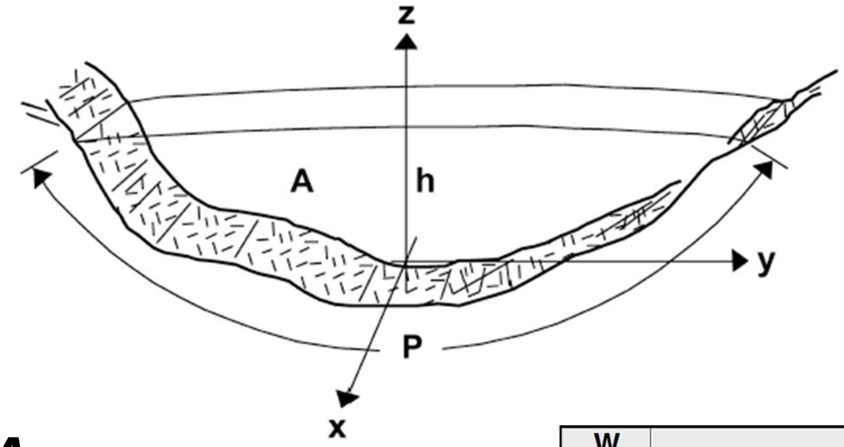
$\alpha =$ Slope

$f =$ Form factor



$$h \cdot \sin\alpha \approx \text{constant}$$

Shape factor



$$f = \frac{A}{P\ h}$$

W	F		
	parabola	semi-ellipse	rectangle
1	0.445	0.500	0.558
2	0.646	0.709	0.789
3	0.746	0.799	0.884
4	0.806	0.849	
∞	1.000	1.000	1.000

Form factor (f) for the calculation of basal shear stress (W=half width/thickness_ on the central flow line of the glacier (Paterson 1981)

Deformation velocity

Replaced by integration over the entire glacier thickness

$$u_s - u_b = u_d = \frac{2A}{n+1}\tau^n h = \frac{2A}{n+1}(f\rho g \sin\alpha)^n h^{n+1}$$

Sliding velocity

$$u_b = B\tau_b^m\left(p_o - p_w\right)^{-q}$$

$B = \text{Material constants}$

$\tau_b = \text{Basal shear stress}$

$p_o = \text{Overburden pressure}$

$p_w = \text{Water pressure}$

$m = 1,\ 2 \text{ oder } 3$

$q = 1$

Sliding velocity

Increased sliding with increased basal water pressure (reduced P_{ef})

Highly variable over time

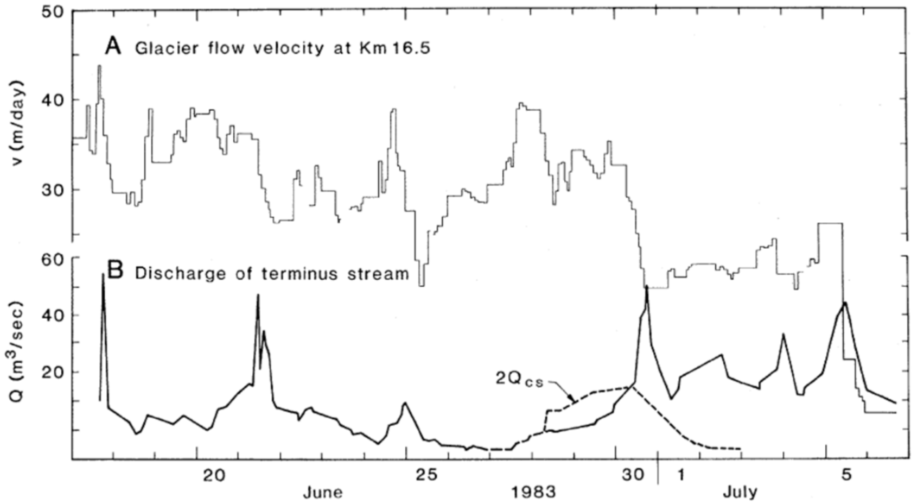
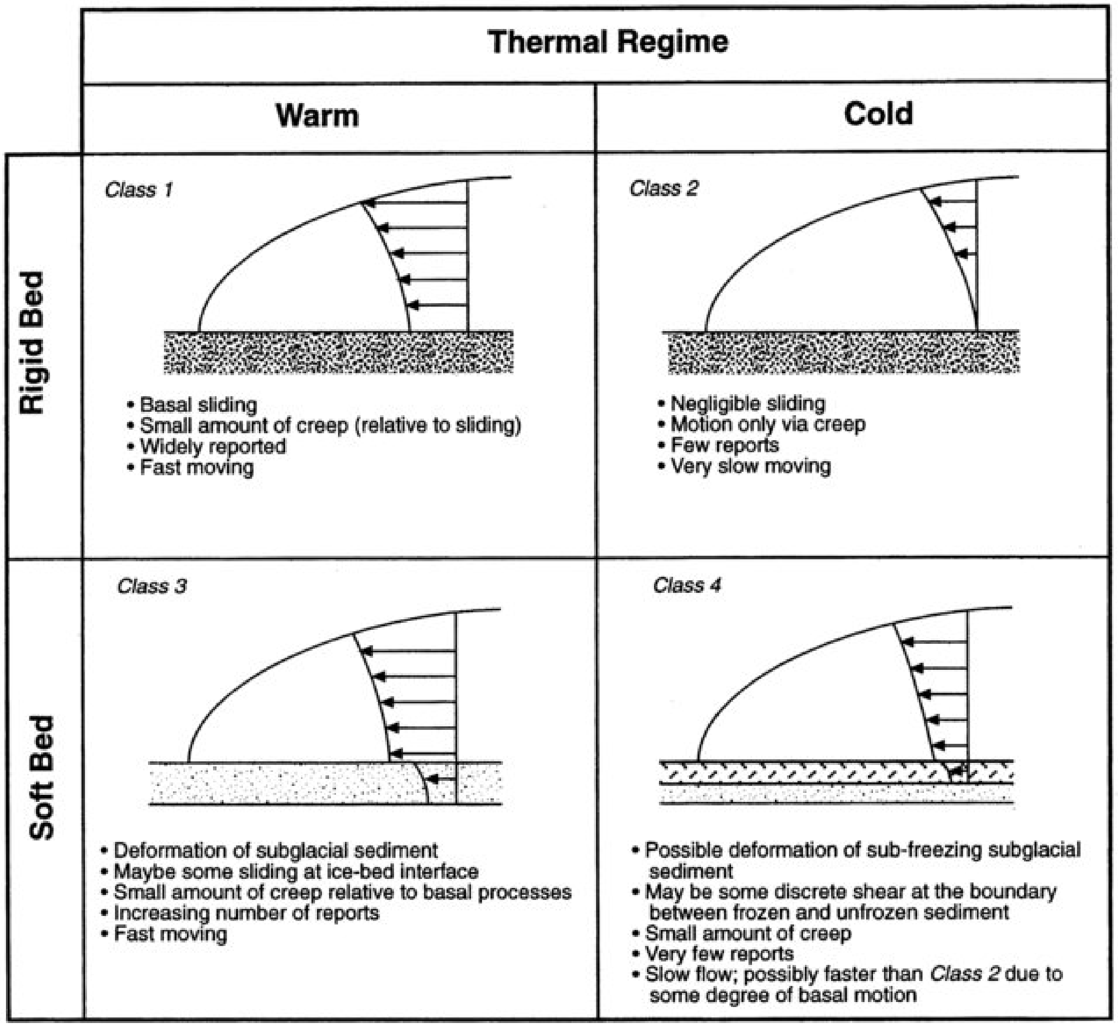


Fig. 10. Time variations of the discharge Q of the terminus outflow stream LTS (B) plotted alongside the variation in glacier flow velocity v at Km 16.5 (A), over the period 17 June to 6 July 1983. The dashed curve in (B) shows the discharge of outflow stream CS, multiplied by 2, over the period 27 June through 2 July; it follows the curve for LTS over 27 June to 10:00 on 28 June.

Kamb 1985

Glacier sliding

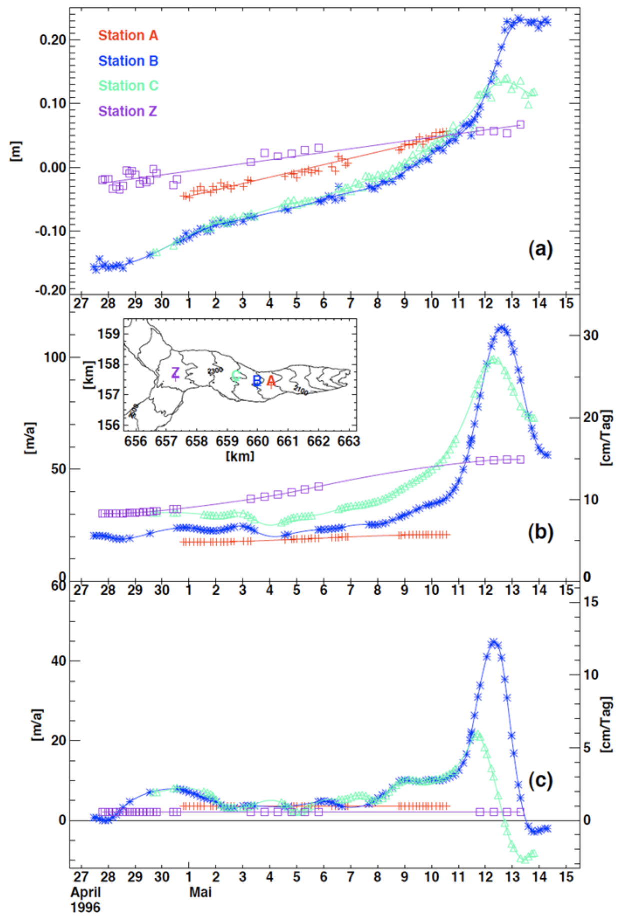
Difference between rigid and soft glacier bed and between cold and temperate glacier



Glacier sliding

Today it is known:

- that the difference between overburden ice and water pressure (P_o und P_w) is crucial for the friction and the sliding at the glacier bed
- that in spring the glacial meltwater is increasing and therefore the water pressure at the bed is increasing too and as well the sliding speed -> large caverns in the pressure shadows are filled with water and reduce the contact between the ice and the ground



Gudmundsson, 1994

Glacier drainage system

Types of subglacial discharge systems (after Benn and Evans 2010):

1. Bulk movement of water with deforming till
2. Darcian porewater flow
3. Pipe flow (channels in sediments)
4. Dendritic channel flow
5. Linked Cavity system
6. Braided canal network

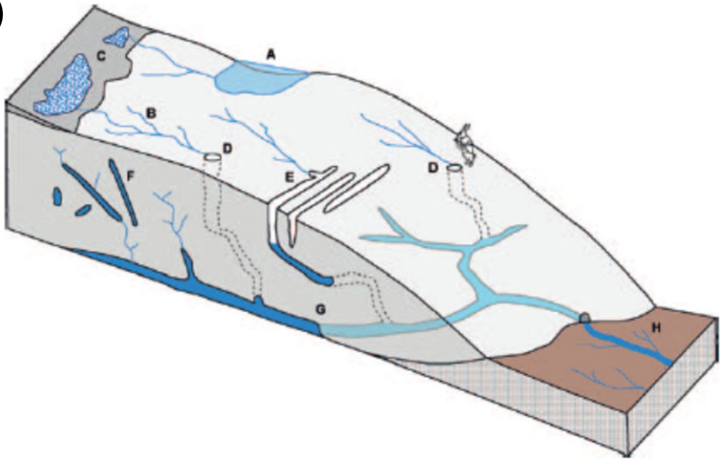


Figure 6.1 Some elements of the glacier water system: **(A)** Supraglacial lake. **(B)** Surface streams. **(C)** Swamp zones near the edge of the firn. **(D)** Moulins, draining into subglacial tunnels (for scale, white rabbit is about 10 m tall). **(E)** Crevasses receiving water. **(F)** Water-filled fractures. **(G)** Subglacial tunnels, which coalesce and emerge at the front. **(H)** Runoff in the glacier foreland, originating from tunnels and also from upwelling groundwater. Though not depicted here, water is also widely distributed on the bed in cavities, films, and sediment layers. Sediment and bedrock beneath the glacier contain groundwater.

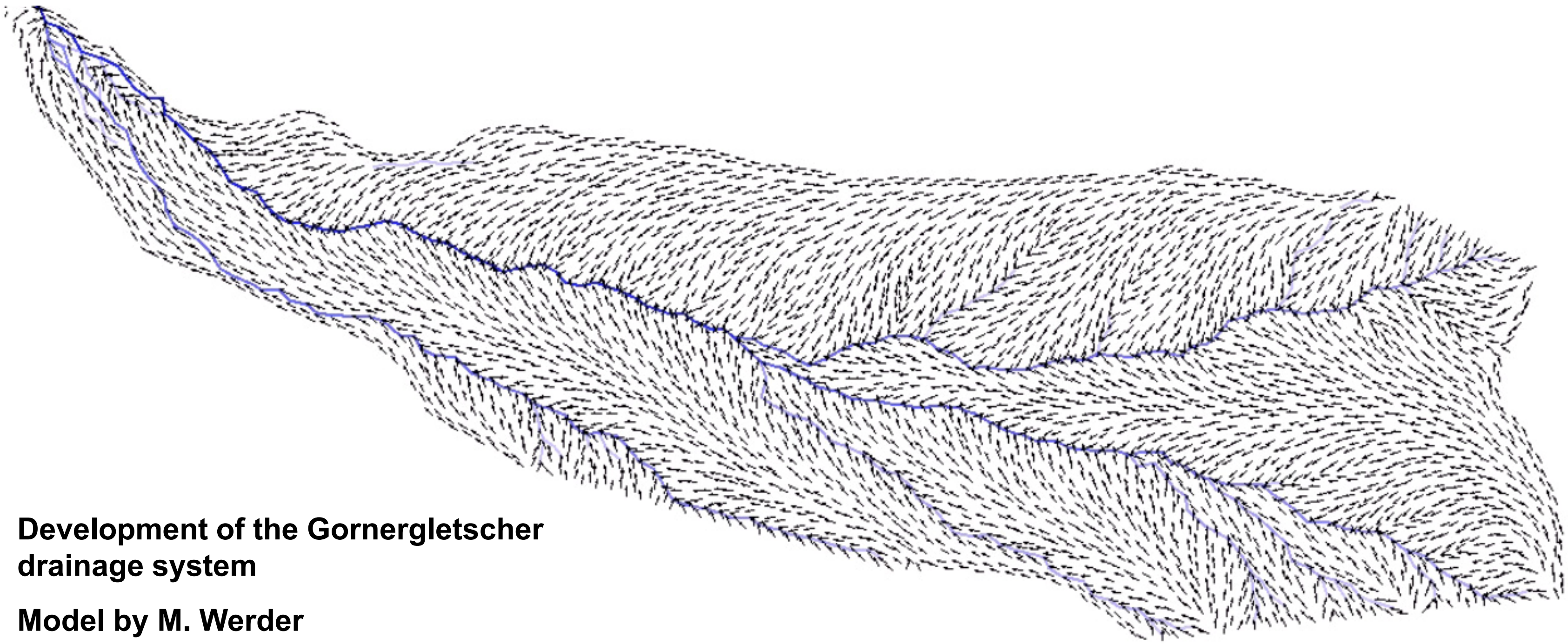
Glacier drainage system

Development of the subglacial drainage system:

1) Distributed water flow at glacier bed (« cappillary system », sheet flow)

2) Development of a channel network collecting water from sheet flow

3) Arrangement of the channel network into a few major channels



Development of the Gornergletscher drainage system

Model by M. Werder

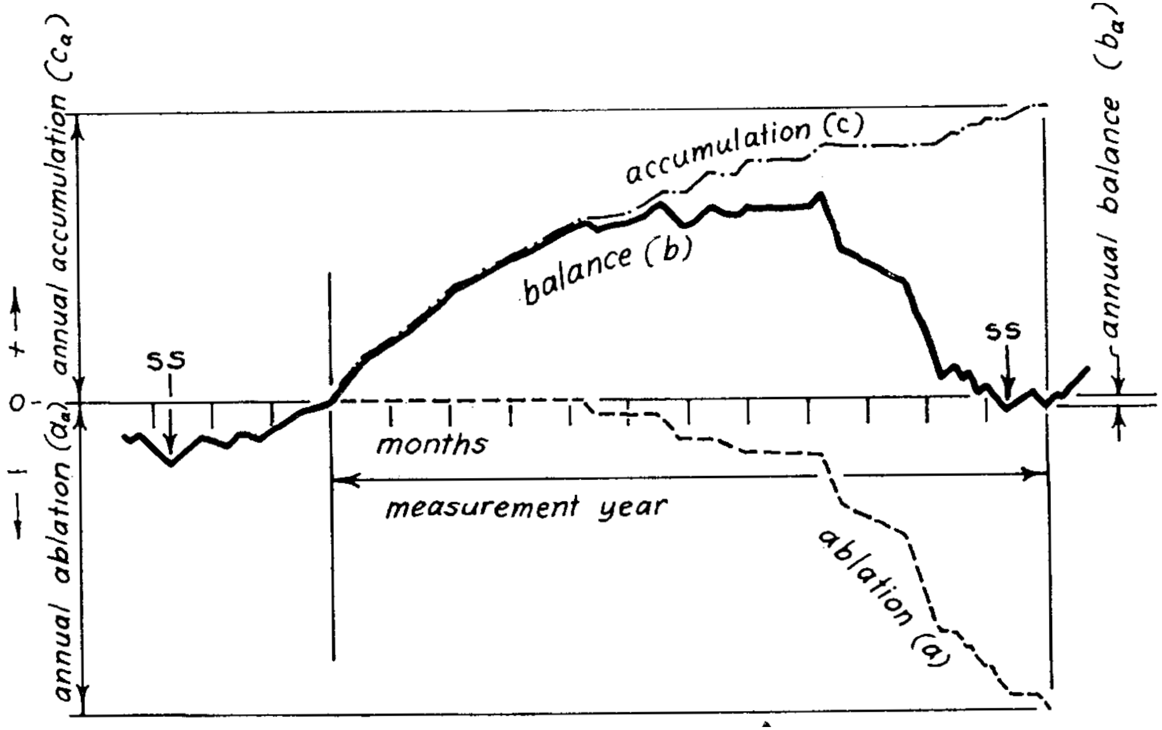
Glacier Mass Balance

$$b = c + a = \int_{t_0}^{t_i} \dot{b} \, dt$$

Accumulation

Ablation

Evolution of mass balance, accumulation and ablation over one year



Glacier Mass Balance

Integration over glacier area

$$B_{\mathrm{n}} = \int_S b_{\mathrm{n}}\, dS.$$

Mean specific mass balance

$$\overline{b_{\mathrm{n}}} = B_{\mathrm{n}}/S.$$

Distribution of glacier mass balance over the glacier

A change in climate usually leads to a change in the distribution of the net balance
b(x) everywhere on the glacier. Consequently the glacier net balance B is different from zero. If the mass balance change was positive, the glacier will reach a new equilibrium by extending its ablation area, which means an advance of the terminus (the glacier gets longer).

Glacier Mass Balance

Specific mass balance

Specific mass balance varies with the altitude on the glacier

Calving

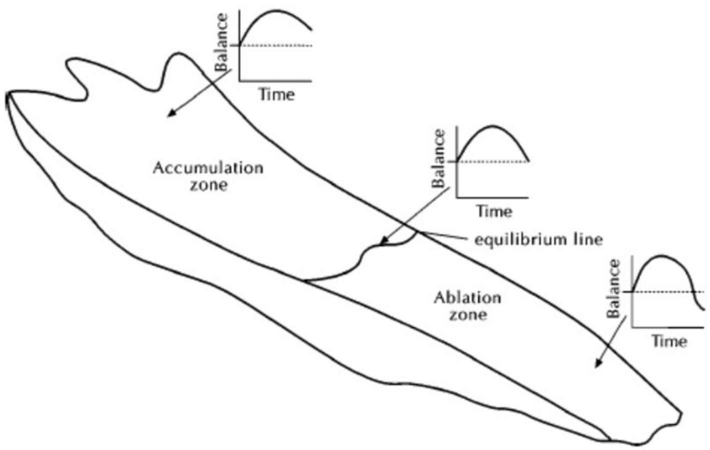
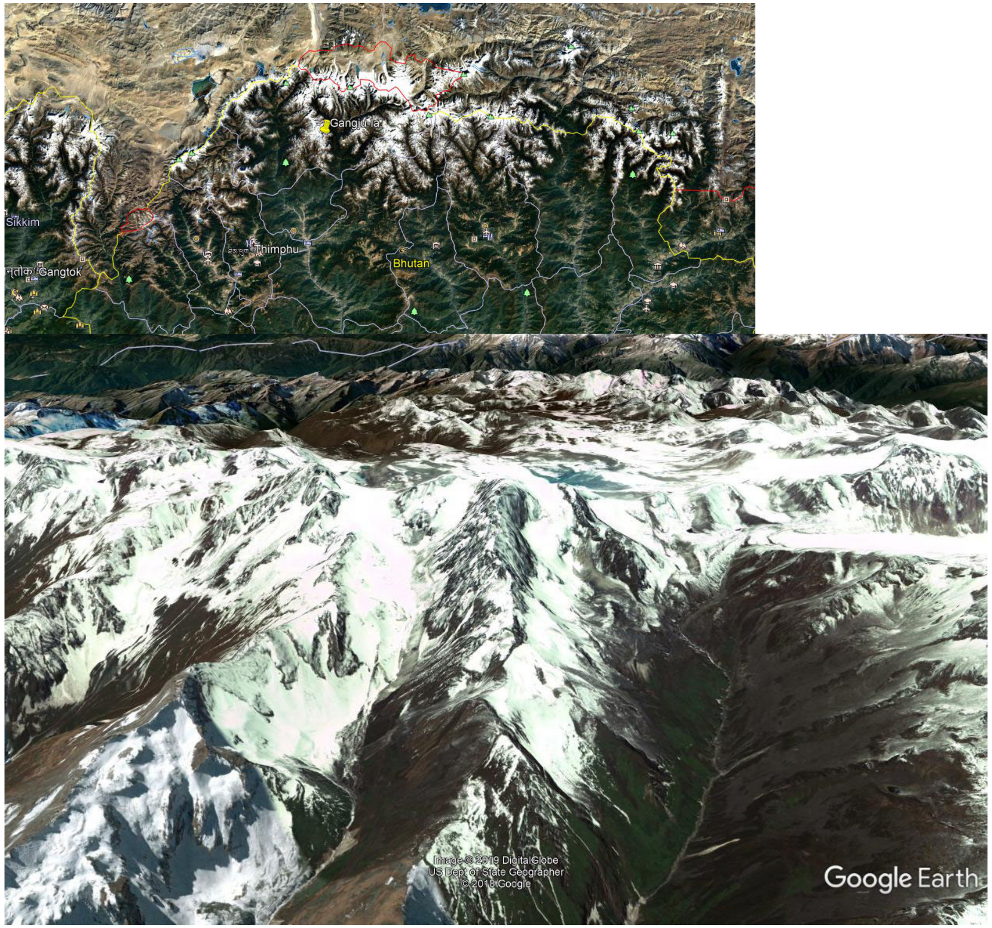
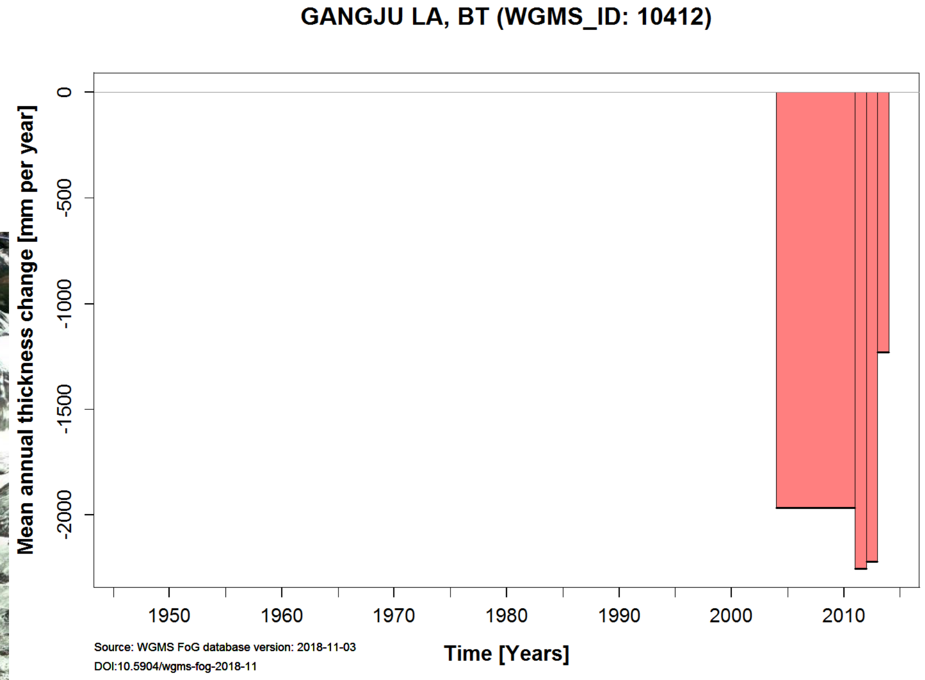


Figure 4.4: How the seasonal progression of specific surface balance varies with distance along a typical glacier. In reality, the plots of balance with time are typically stepped and rough; the smooth curves used here are idealizations.

After Cuffey and Patterson, 2010

Glacier Mass Balance





Glacier Mass Balance

At time $t = t_0$ the mass balance changes due to a climate change by $\Delta b(x)$. After a certain time the glacier has reached a new equilibrium at a new length $L_0 + \Delta l$

$$\int_0^{L_0+\Delta l} \big(b(x) + \Delta b(x)\big)dx = 0, \quad \text{for } t - t_0 > t_R$$

Glacier Mass Balance

$$0 = \int_{0}^{L_0+\Delta l} \big(b(x) + \Delta b(x)\big)dx$$

$$0 = \underbrace{\int_{0}^{L_0} b(x)dx}_{0} + \underbrace{\int_{0}^{L_0} \Delta b(x)dx}_{\Delta \bar{b} L_0} + \underbrace{\int_{L_0}^{L_0+\Delta l} b(x)dx}_{\bar{b}_t \Delta l} + \underbrace{\int_{L_0}^{L_0+\Delta l} \Delta b(x)dx}_{\bar{b} \Delta l \cong 0}$$

The first term is zero because of equilibrium assumption at the beginning of the climate change. The second term is the integral of the mass balance change $\Delta b(x)$ over the original length of the glacier L_0The third term can be written as $b_t\ \Delta l$. The fourth term is a product of the length change and the change of the net balance integrated over Δl. This term can be neglected compared to the second and third term.

Glacier Mass Balance

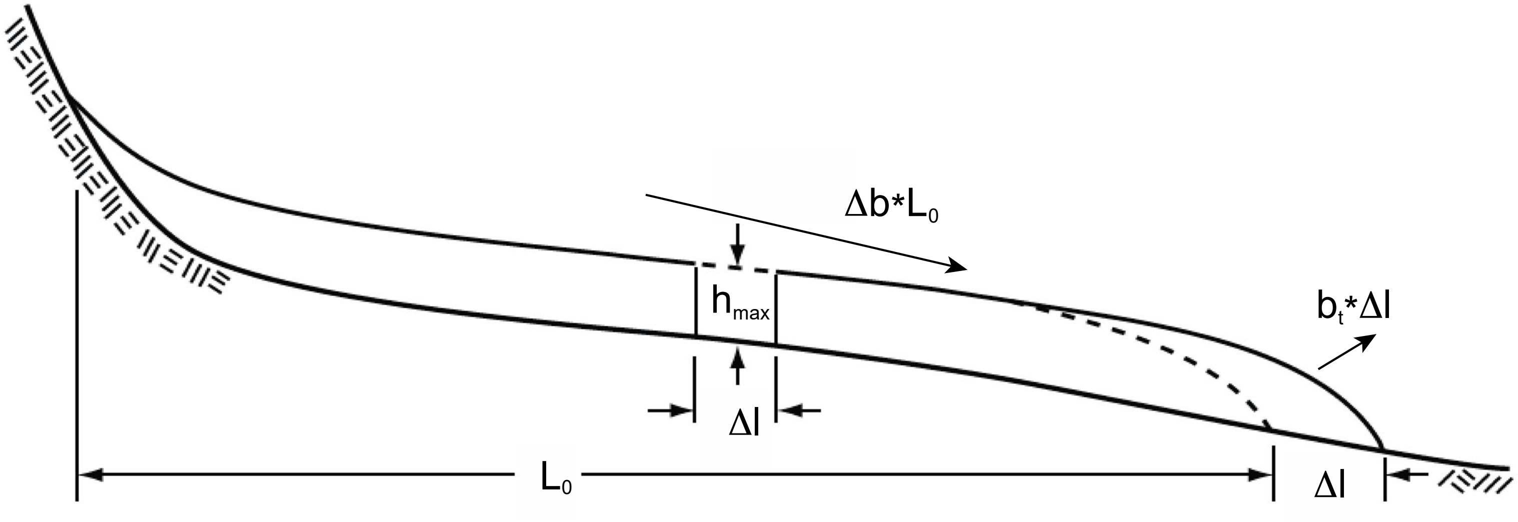
With these simplifications we can now write

$$\Delta\bar{b} = \frac{1}{L_0}\int_0^{L_0} \Delta b(x)dx \qquad \bar{b}_t = \frac{1}{\Delta l}\int_{L_0}^{L_0+\Delta l} b(x)dx$$

$$L_0\Delta b + b_t\Delta l \cong 0$$

This equation expresses the fact, that a change of “input” ($L_0\Delta b$) has to be compensated by a change of “output” ($b_t\Delta l$).

Glacier Mass Balance



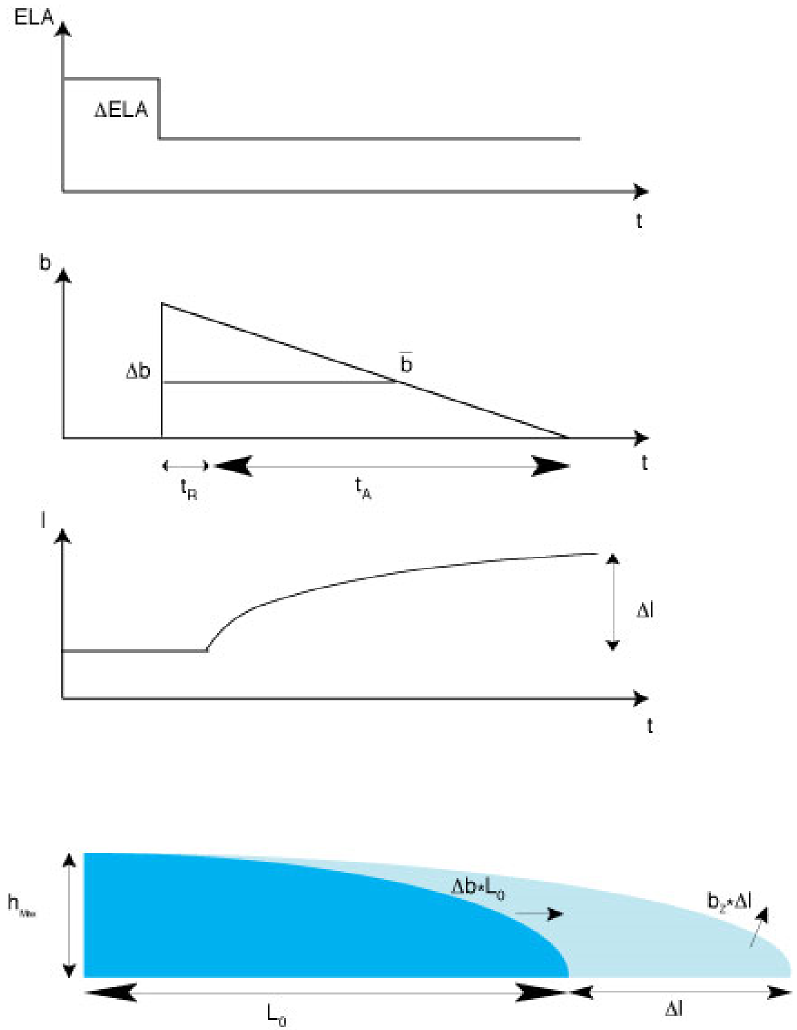
Glacier response time

$$\Delta V \approx h_{\max} \Delta l$$

$$t_V = \frac{\Delta V}{\Delta q} = \frac{\Delta V}{\int_0^{L_0} \Delta b_{(x)} dx}$$

$$t_V \approx \frac{h_{\max} \Delta l}{L_0 \Delta b} \qquad t_V \approx \frac{h_{\max} \Delta l}{-b_t \Delta l}$$

$$t_V \approx \frac{h_{\max}}{-b_t}$$



Glacier response time

$$t_V \approx \frac{h_{\max}}{b_t}$$

Response time defined by Jòhannesson 1989

$$\Delta b \approx \Delta l \frac{b_t}{L_o}$$

Consideration for continuity
Equilibrium conditions

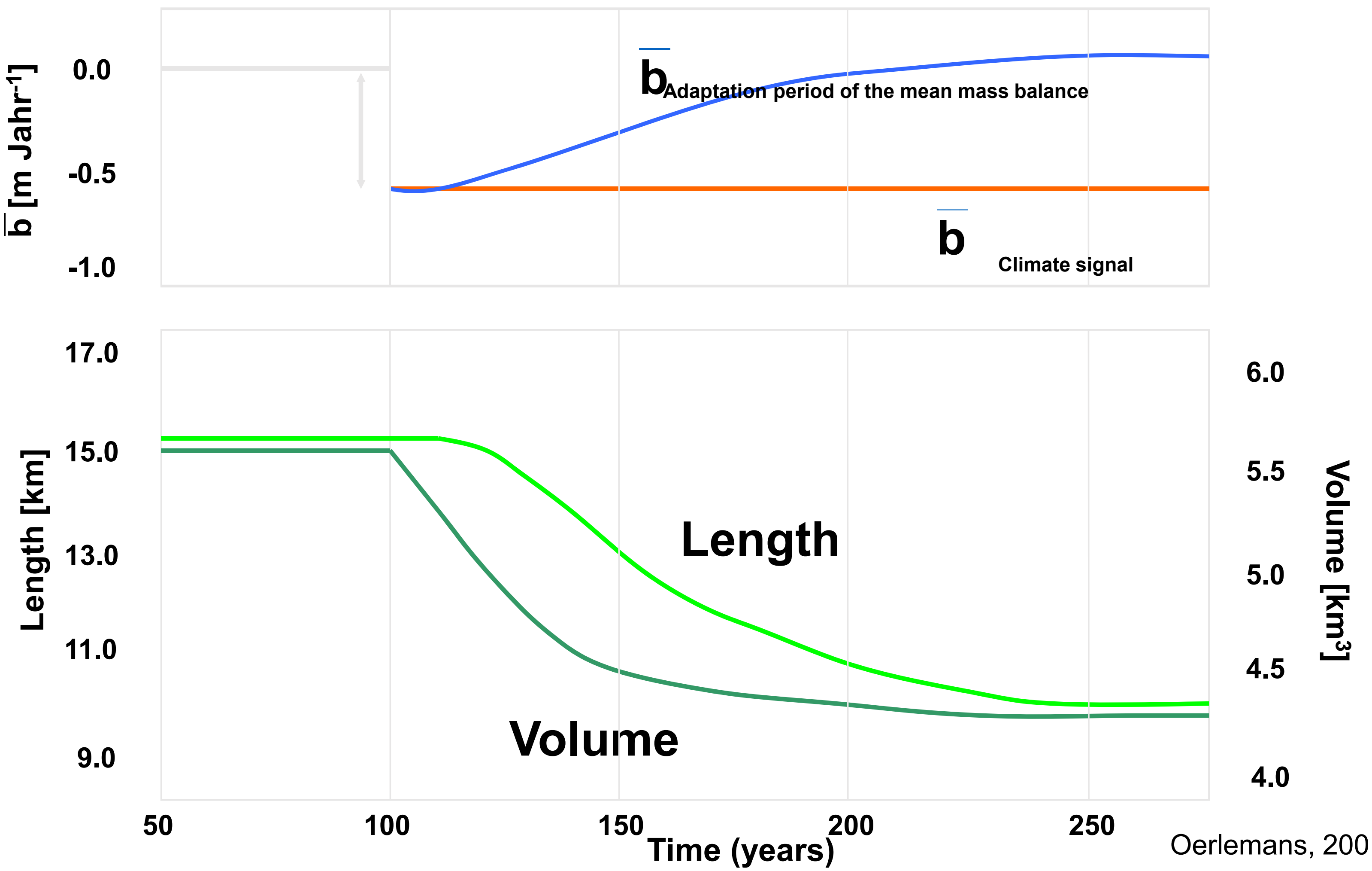
$$\bar{b} \approx \frac{\Delta b}{2}$$

Mean mass balance

$$b_t \approx dh_{t,ELA} \frac{\delta b}{\delta h}$$

Mass Balance
at the glacier tongue

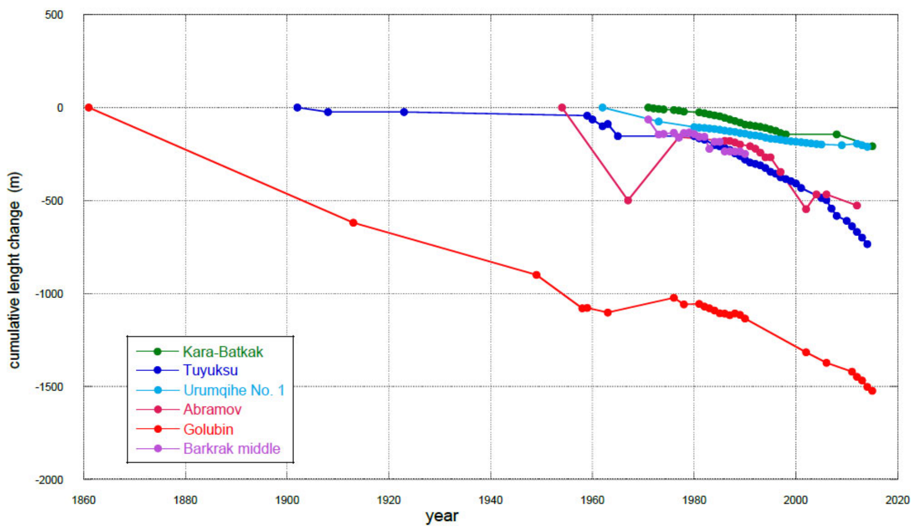
Glacier response time



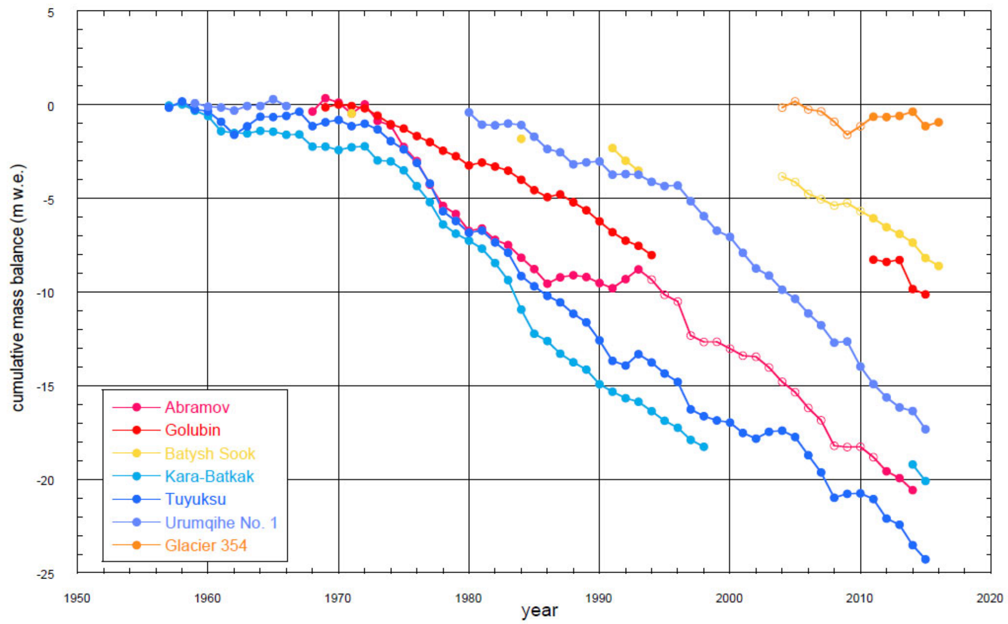
Oerlemans, 2001

Glacier mass change vs glacier length change

Glacier **front** change: **delayed signal**



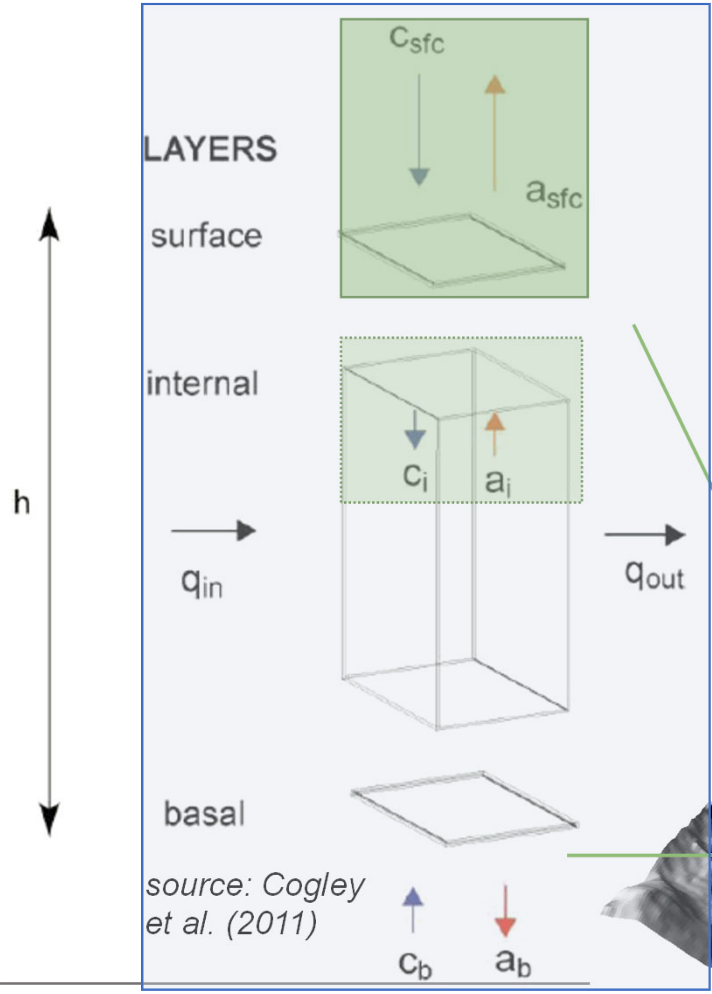
Glacier **mass** change: **immediate signal**



Definitions | glacier mass balance vs. glacier surface mass balance

Surface mass balance

Mass balance

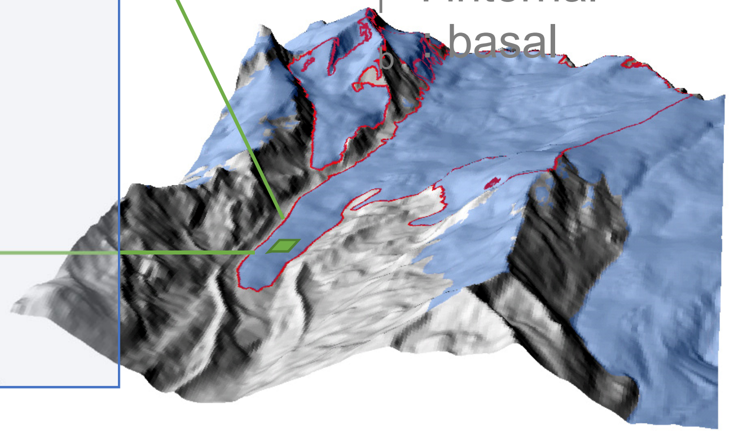


Variables

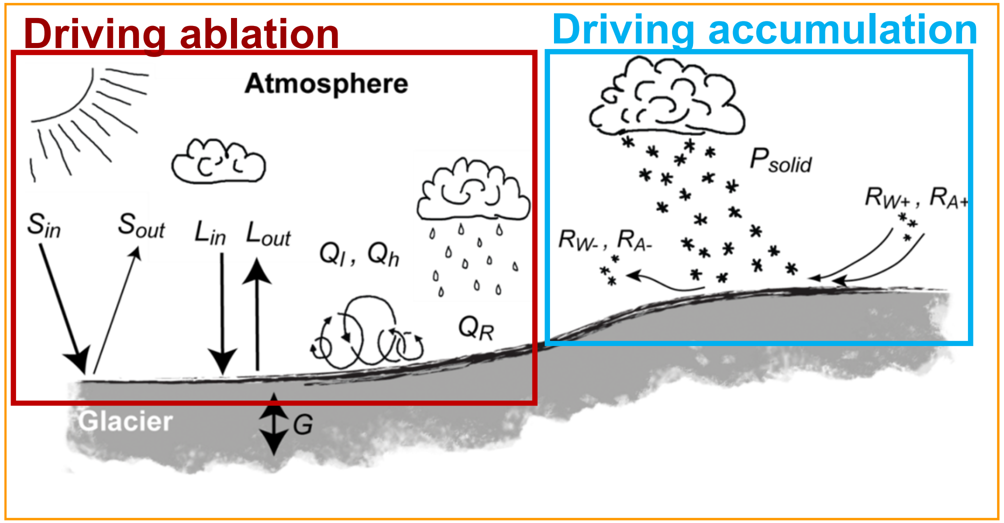
c: accumulation
a: ablation
b: mass balance
q: glacier flow
h: glacier thickness

Subscripts

$_{sfc}$: surface
$_{i}$: internal
$_{b}$: basal



Mass and energy balance at the glacier surface



The surface energy and mass balance drives the changes we measure between two points in time $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$

Mass and energy balance at the glacier surface

$$R = Q\,(1 - \alpha) + I_i - I_o$$

R: Energy provided by radiation
Q: incoming shortwave radiation
α: Albedo
I: incoming and outgoing longwave radiation

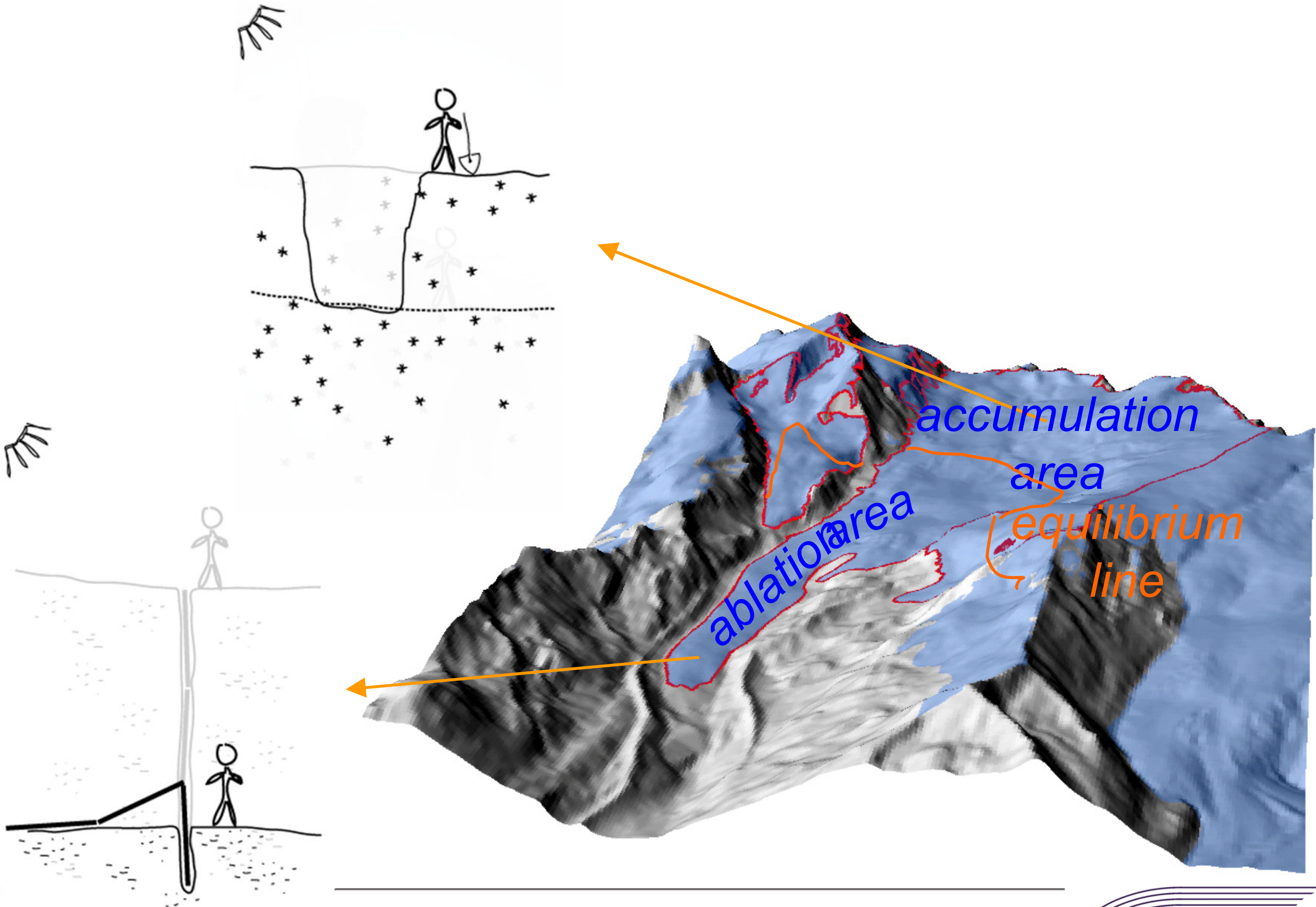
Direct glaciological method – in-situ observation techniques

www.icefactory.ch

photo: E. Heucke

photo: E. Heucke

Outlines of observational network



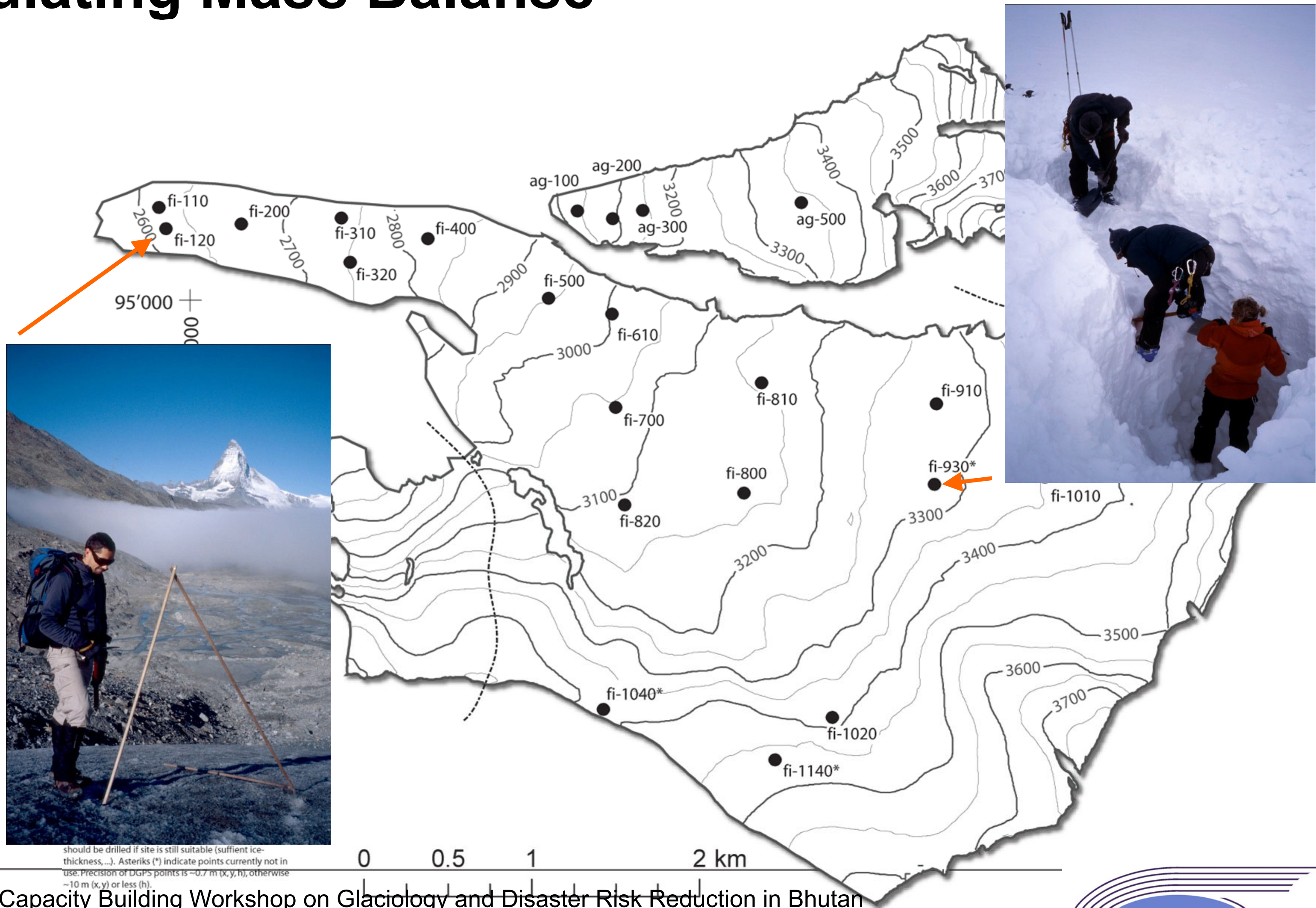
On the glacier

On the glacier

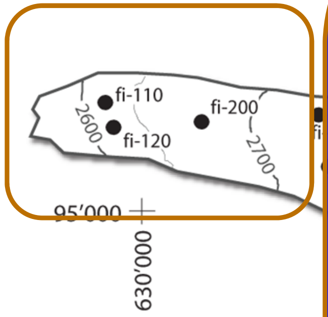
Photo: H. Machguth

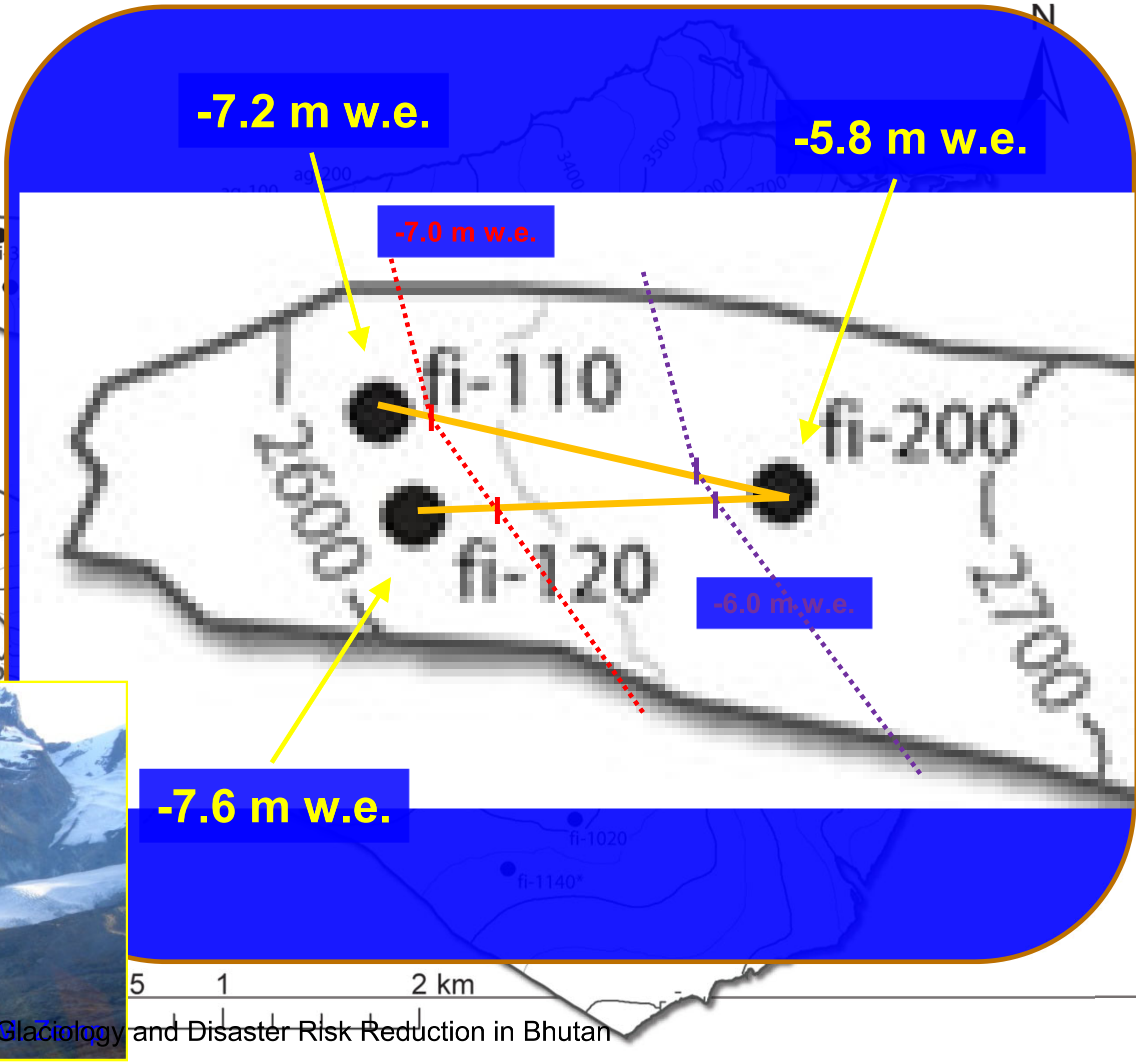
Photos: N. Salzmann

Calculating Mass Balanse



Calculating Mass Balanse

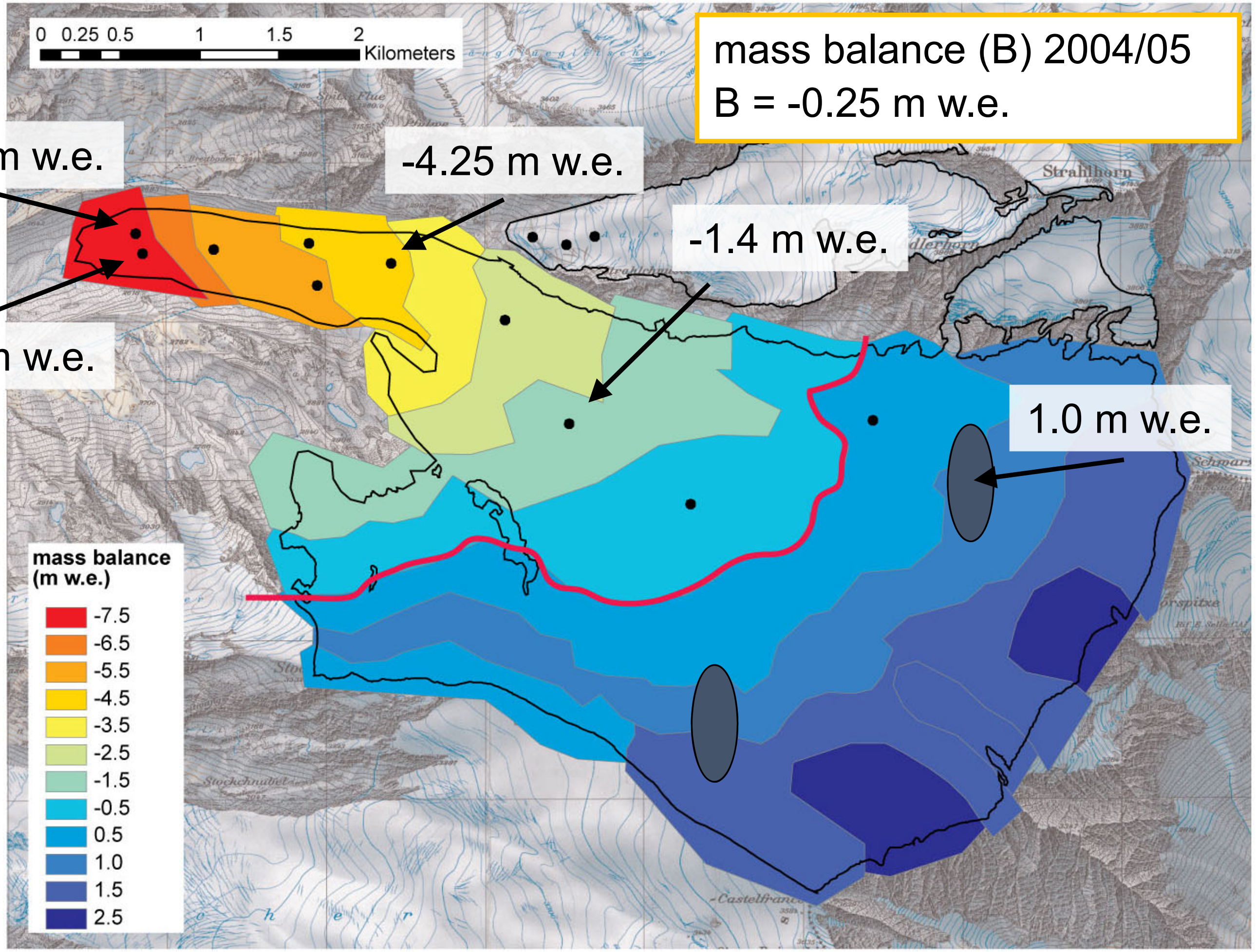




Coordinates of Stakes/Snowpits on Findel and Adler glacier (Oct. 6 2009)

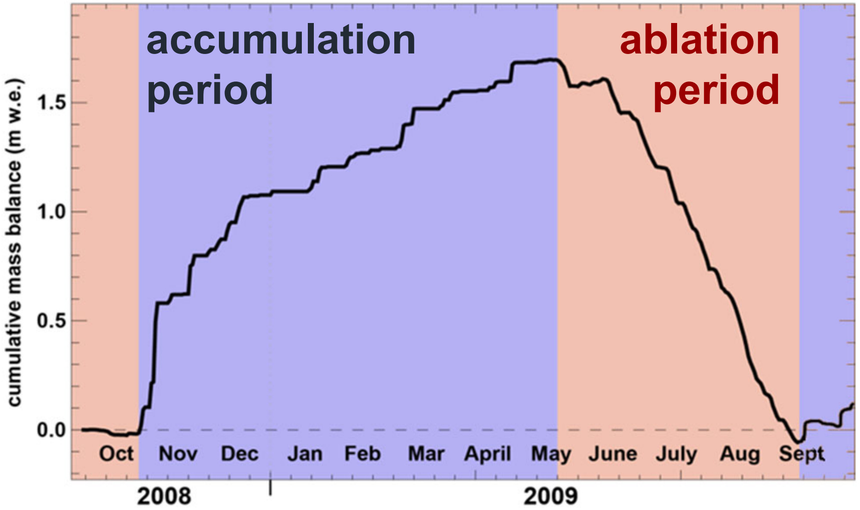
	x	y	h	DGPS
ag-100	632356	95512	3046	x
ag-200	632533	95501	3086	x
ag-300	632715	95542	3136	x
ag-500	633562	95556	3335	x
fi-110	629947	95564	2597	x
fi-120	629988	95430	2586	x

Calculating Mass Balanse (Countour line method)



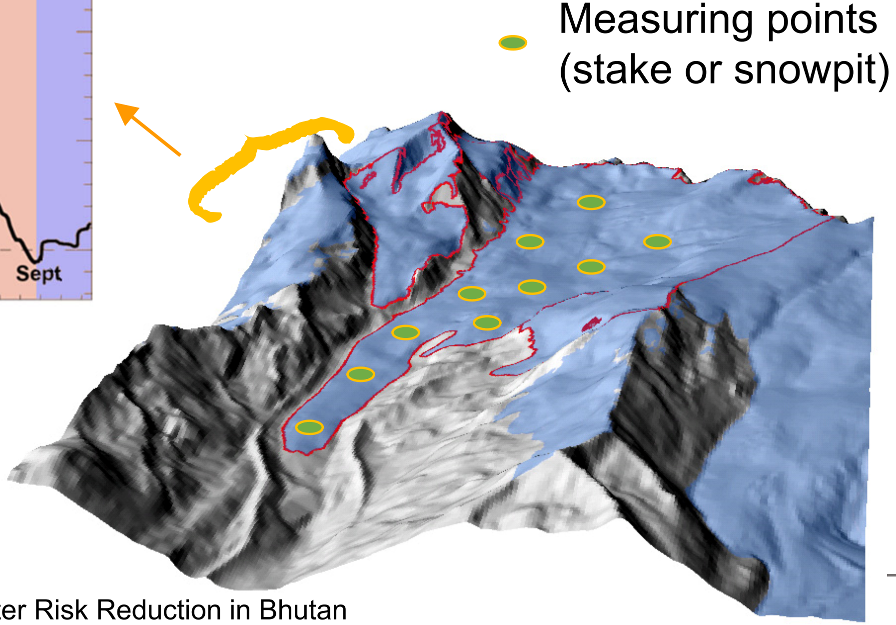
Direct glaciological method | temporal sampling

Temporal evolution of glacier wide surface mass balance *B*



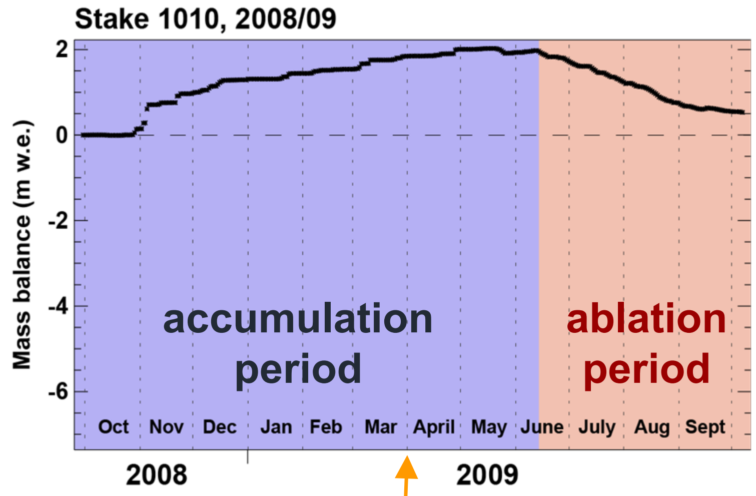
Source of plot: modified after M. Huss

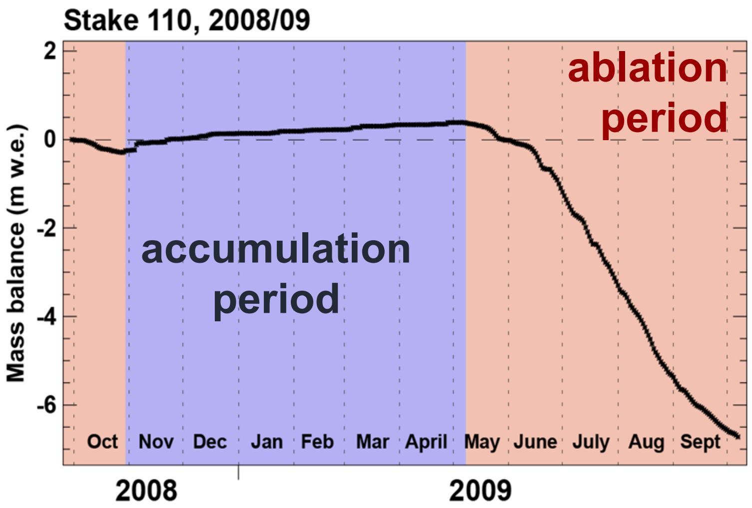
Sampling the unknown temporal function of surface mass balance at **discrete points in time**



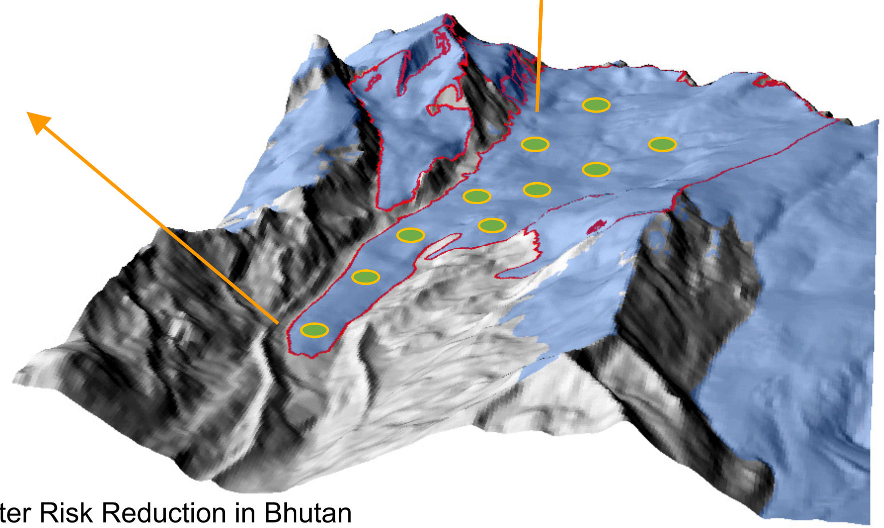
Direct glaciological method | temporal sampling

duration of accumulation and ablation period varies over the elevation zones of a glacier, adding further complications to choosing the «right» timing...

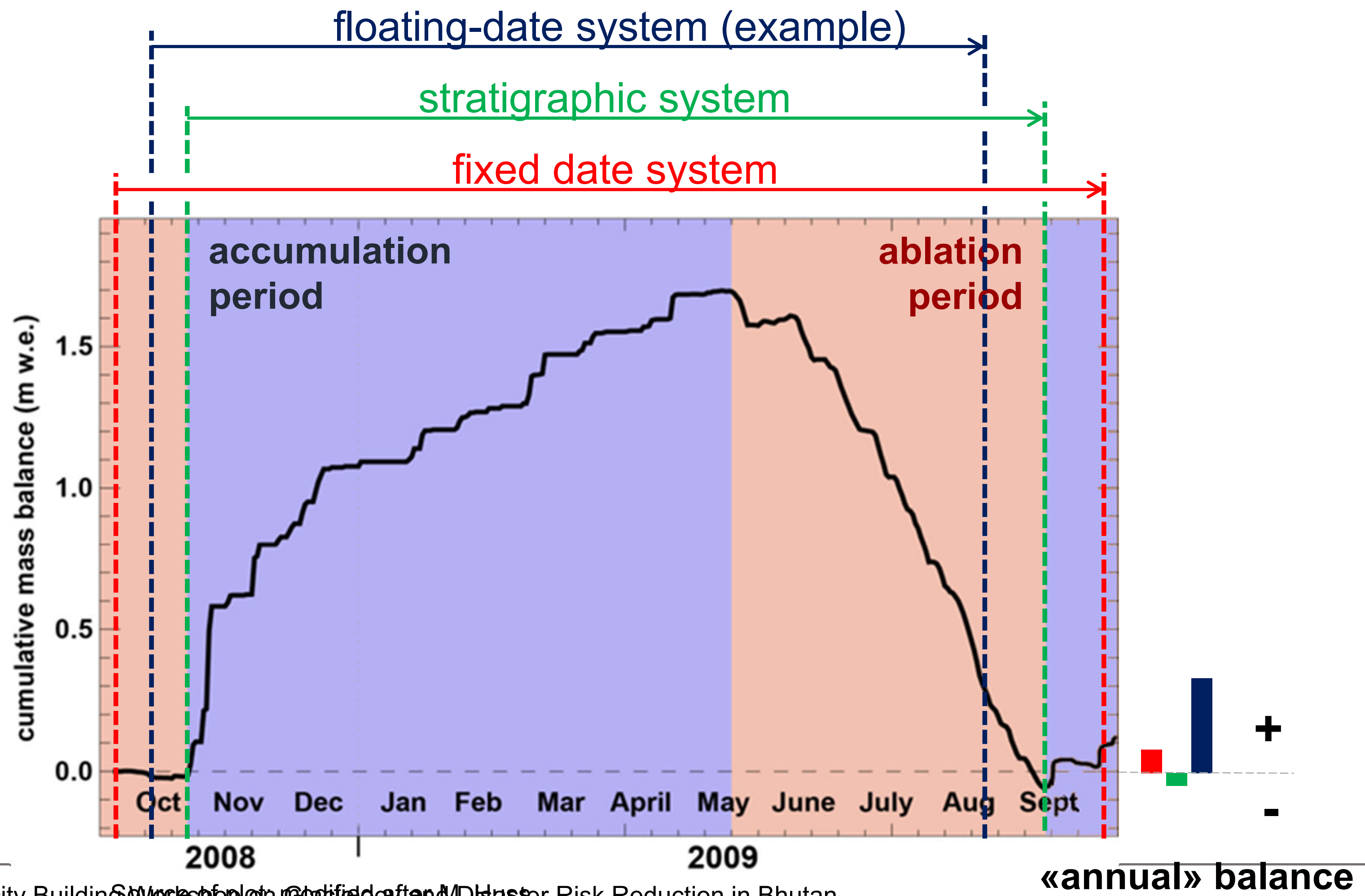




Source of plots: modified after M. Huss



Direct glaciological method | temporal sampling



Source of plot: modified after M. Huss

Direct glaciological method | temporal sampling

There is no universal solution to timing the measurements, thus a number of time concepts have been developed:

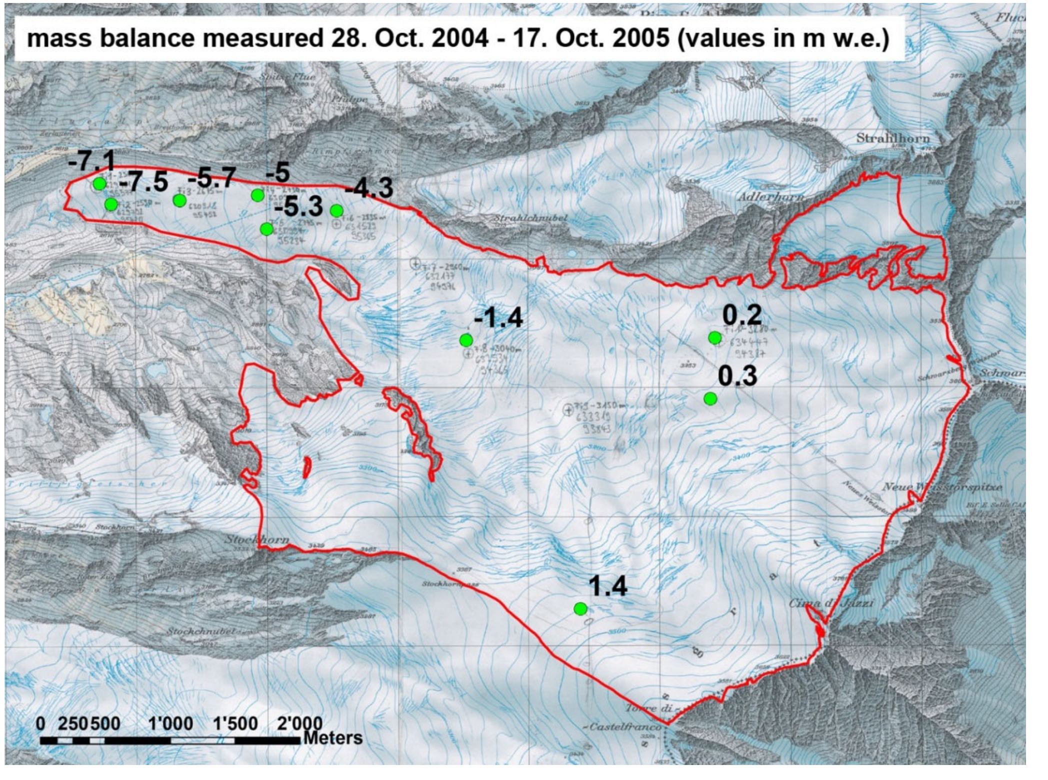
Fixed-date system: The *time system* in which *surface mass balance* is determined by conducting field surveys on fixed calendar dates (often the start of local hydrological year).

Stratigraphic system: The *time system* in which *surface mass balance* is determined by conducting field surveys at subsequent annual minima in surface mass balance.

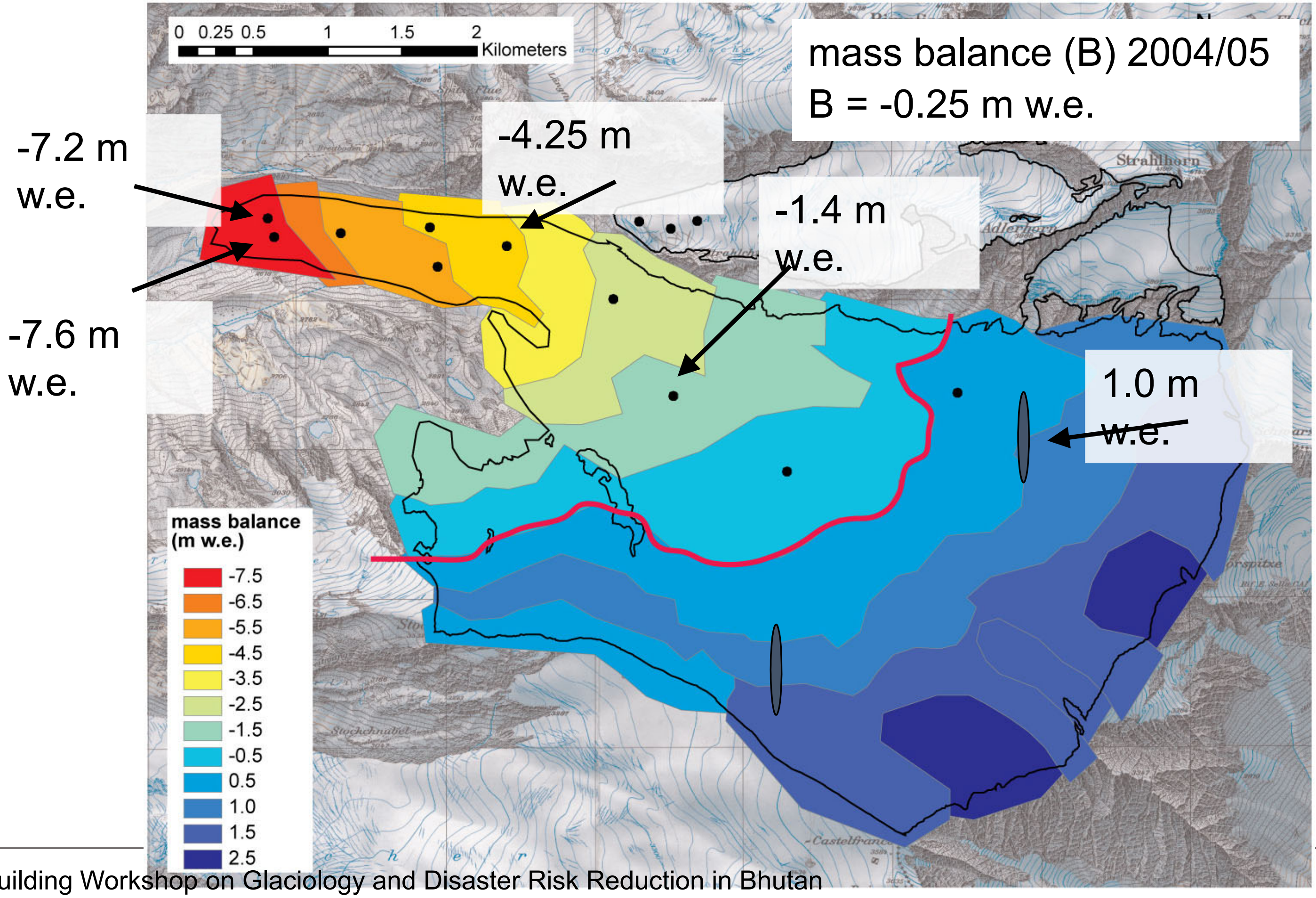
Floating-date system: The *time system* in which *surface mass balance* is determined by conducting field surveys on floating calendar dates (often around start of local hydrological year)

Direct glaciological method | simple contour line extrapolation

- We can measure only at **discrete** points in space and time, but want to know the total mass balance of a glacier
- Example Findel glacier in Switzerland
- ~12 stakes



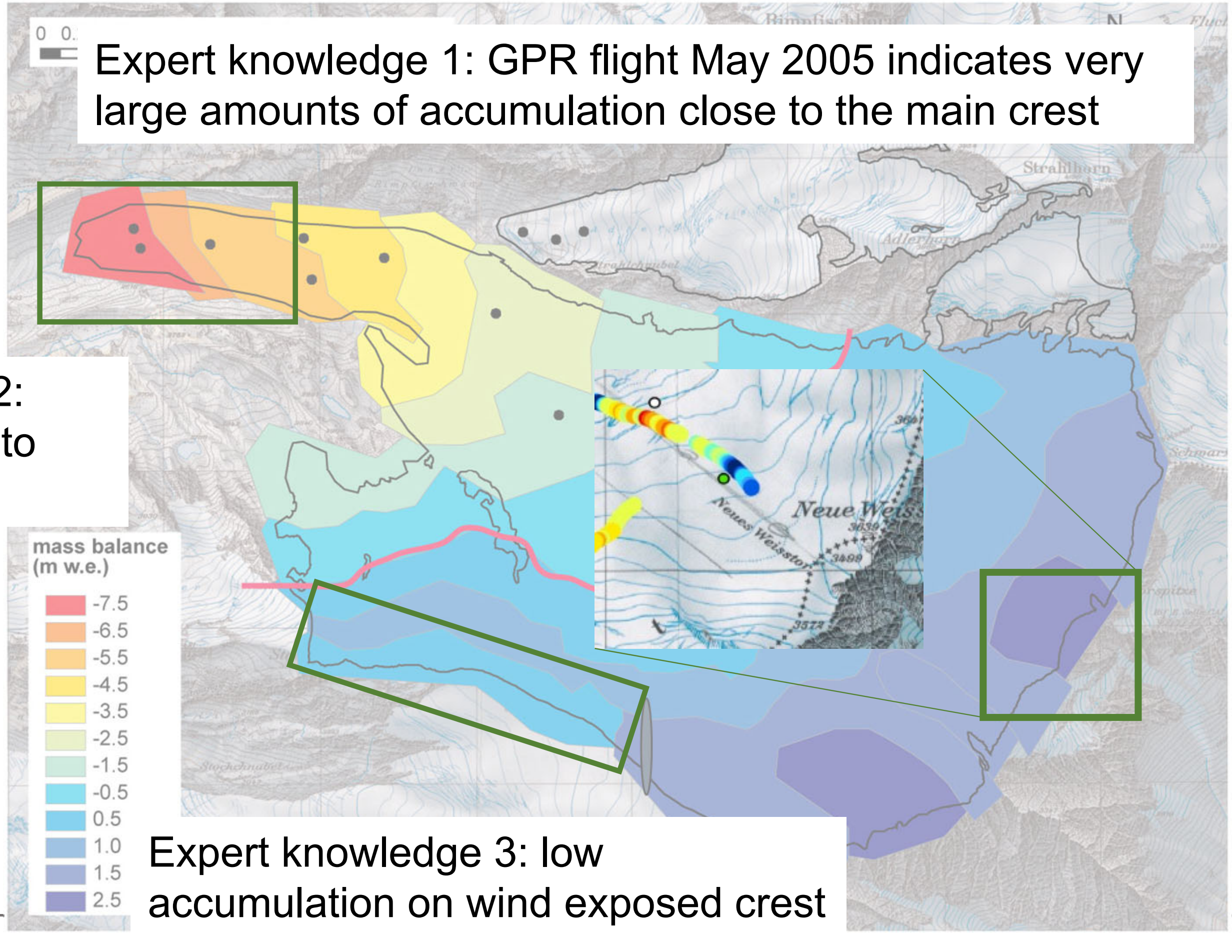
Direct glaciological method | simple contour line extrapolation



Direct glaciological method | simple contour line extrapolation

Expert knowledge 1: GPR flight May 2005 indicates very large amounts of accumulation close to the main crest

Expert knowledge 2: taking exposition into account

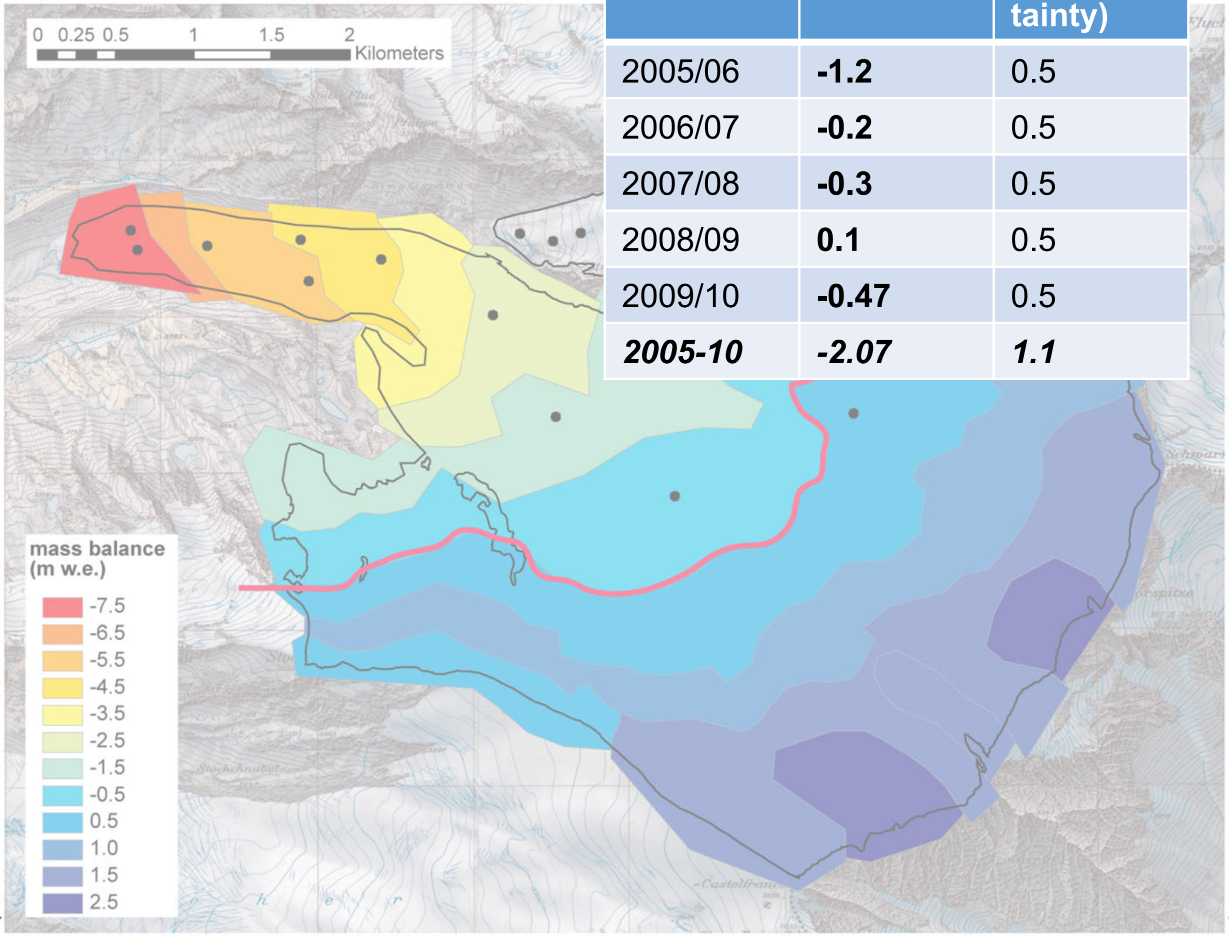


Expert knowledge 3: low accumulation on wind exposed crest

Direct glaciological method | simple contour line extrapolation

- Time series of glacier mass balance
- Over the years 2005-2010 the glacier lost 2.07 m w.e.

year	B (m w.e.)	σ (uncer-tainty)
2005/06	**-1.2**	0.5
2006/07	**-0.2**	0.5
2007/08	**-0.3**	0.5
2008/09	**0.1**	0.5
2009/10	**-0.47**	0.5
2005-10	***-2.07***	***1.1***



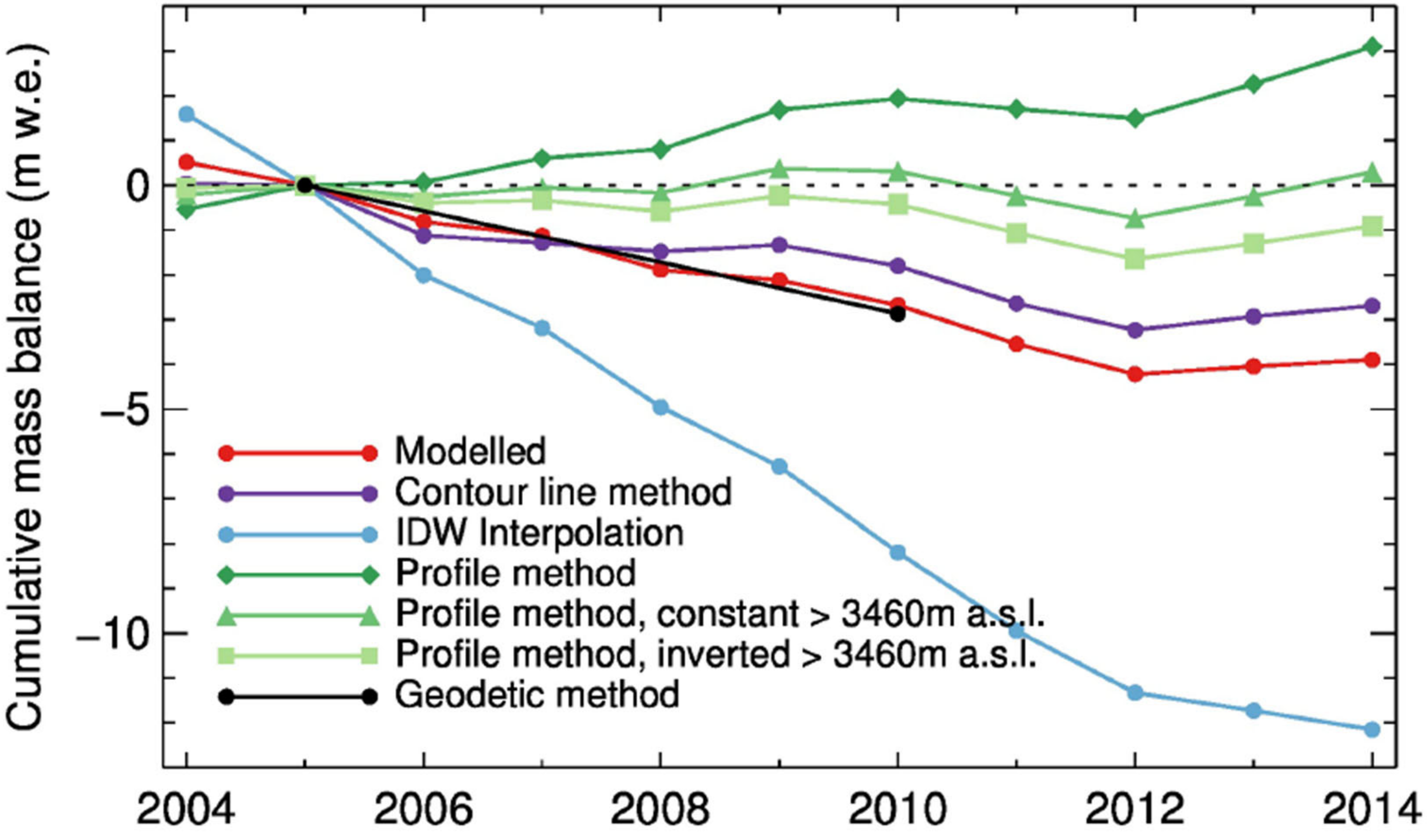
Direct glaciological method | temporal sampling

Traditional (manual contour line)

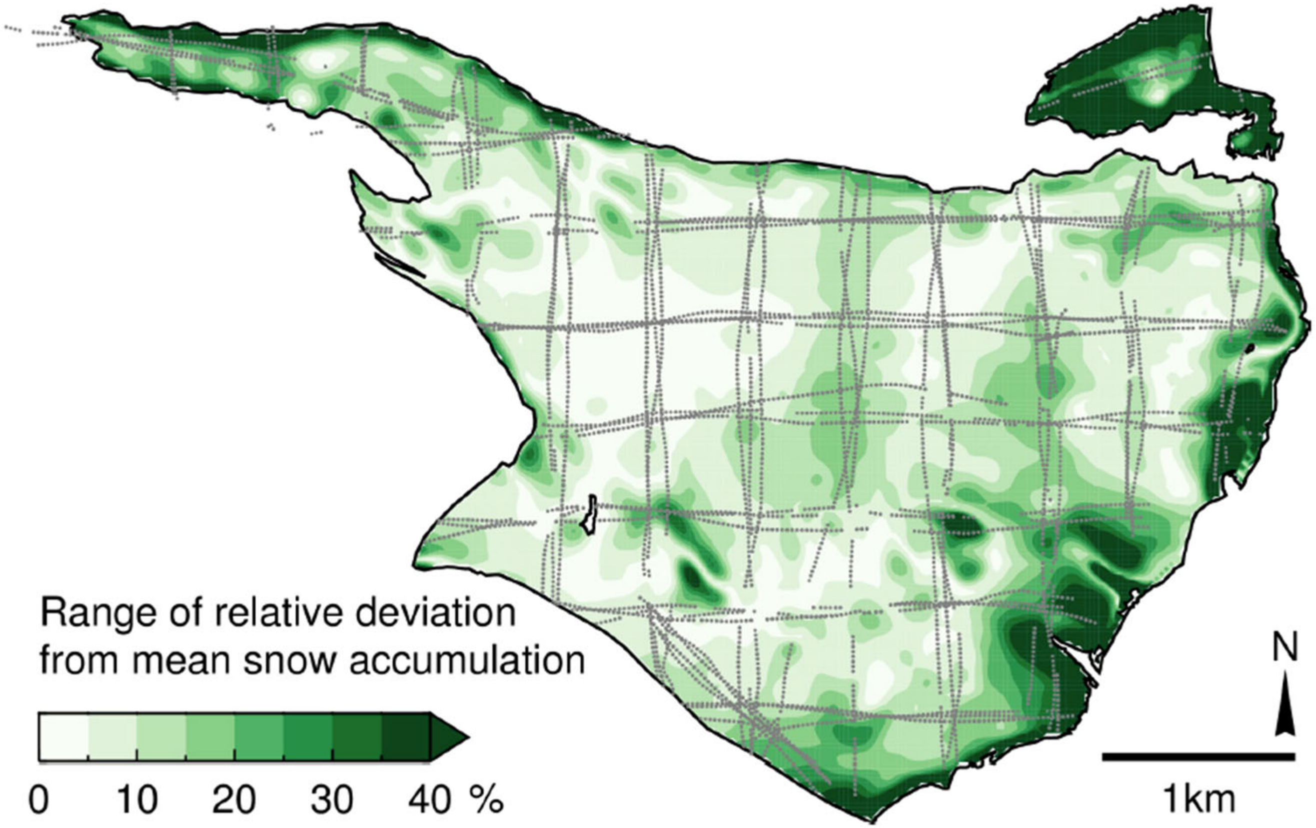
- **Limited temporal and spatial resolution of surface mass balance**
- Direct use of expert knowledge
- **Dependent on availability and quality of field data …**
- … but difficult to include all available data
- Basal and internal mass balance can only be estimated
- **Difficult to reproduce**

Comprehensive field measurements are essential.

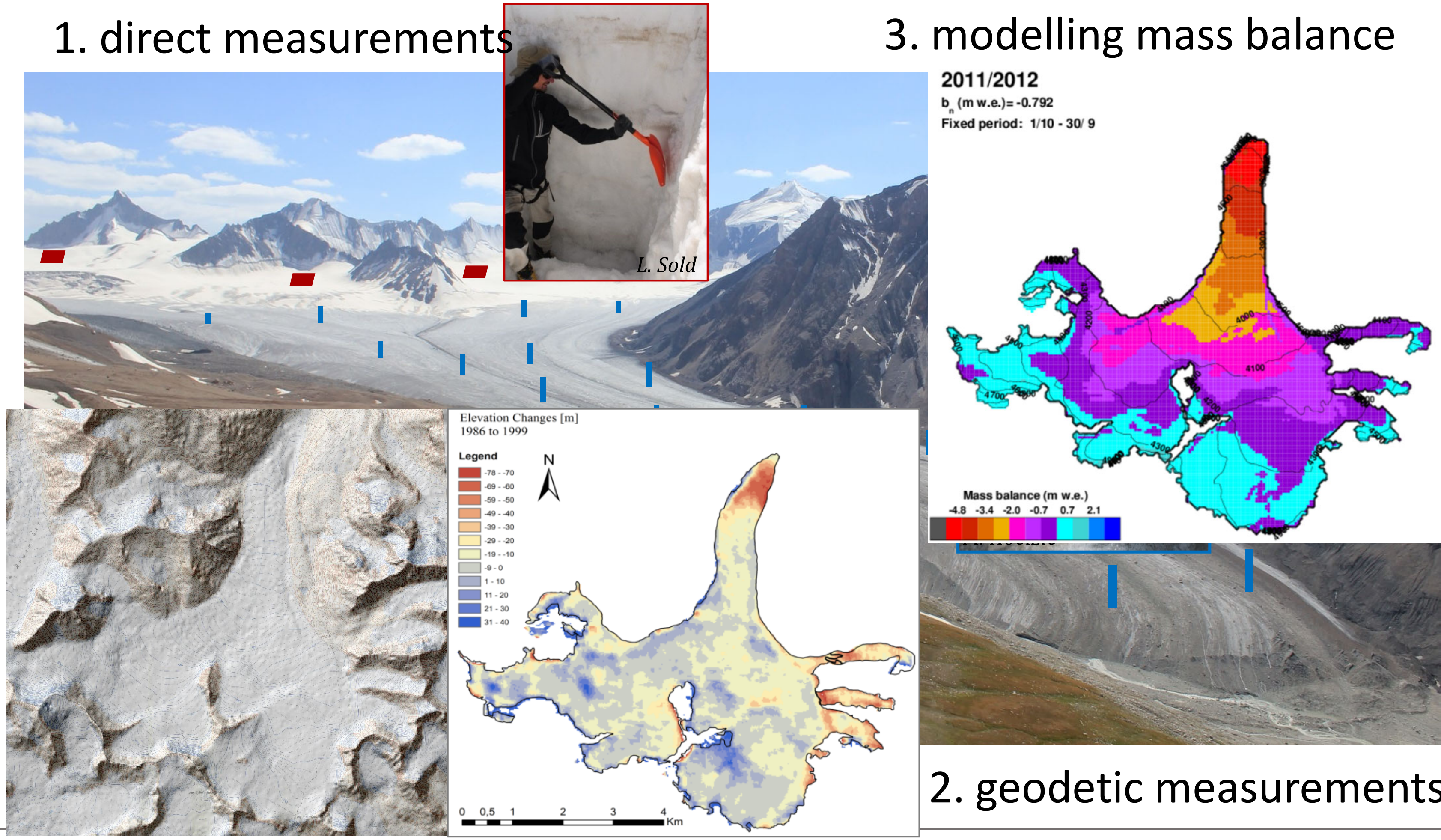
Influence of interpolation method on mass balance



Accumulation patterns



Glacier Mass Balance observation



General approach in Mass Balance studies

glaciological Method

+ good temporal resolution
- restricted spatial resolution

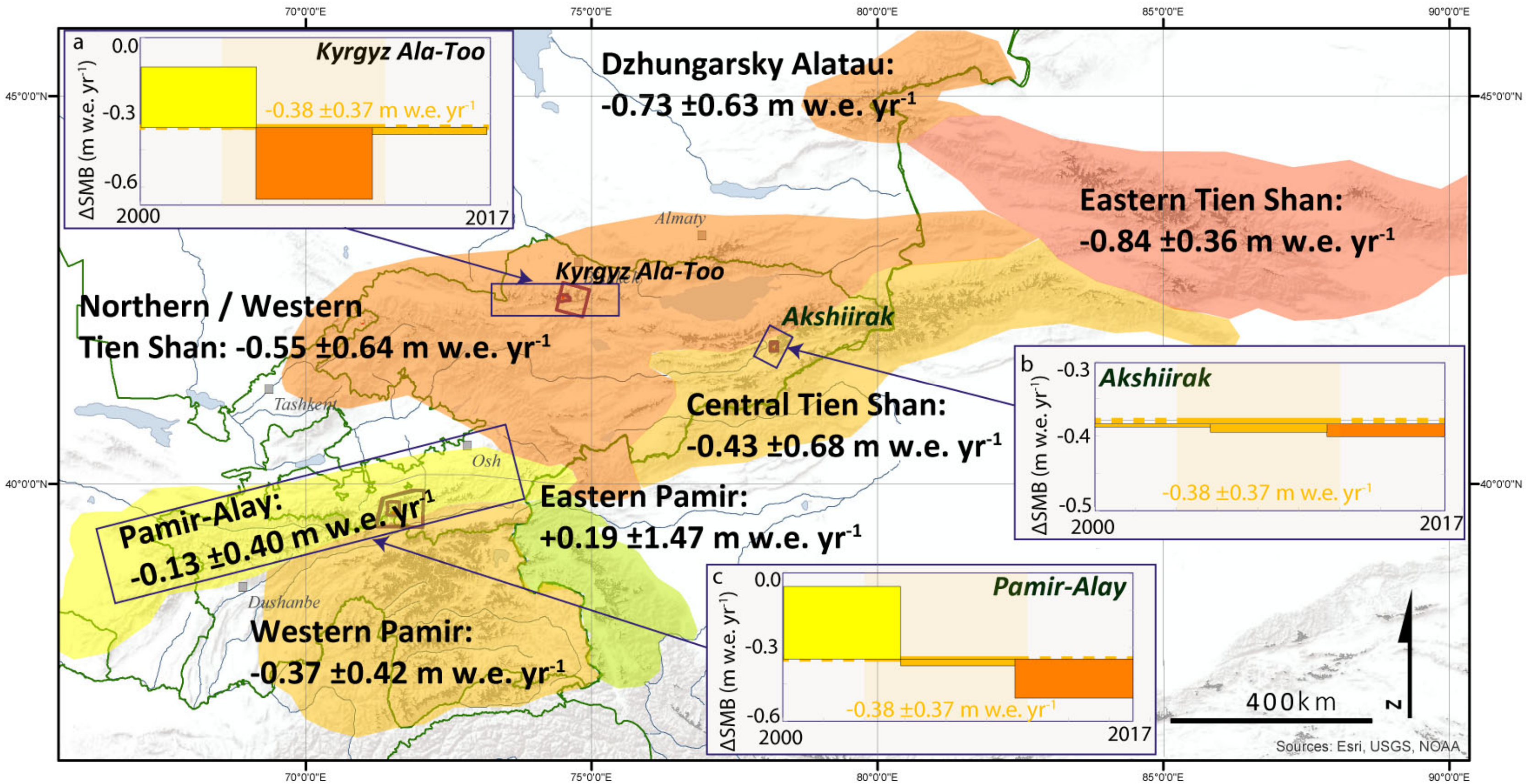
geodetic Method

+ good spatial resolution
- restricted temporal resolution

mass balance modelling validated / calibrated with transient snowline observations

+ good temporal resolution
+ applicable on extended, remote areas
- simulation (not purely observation based)

Mass Balance variability in CA



Barandun et al *in press*